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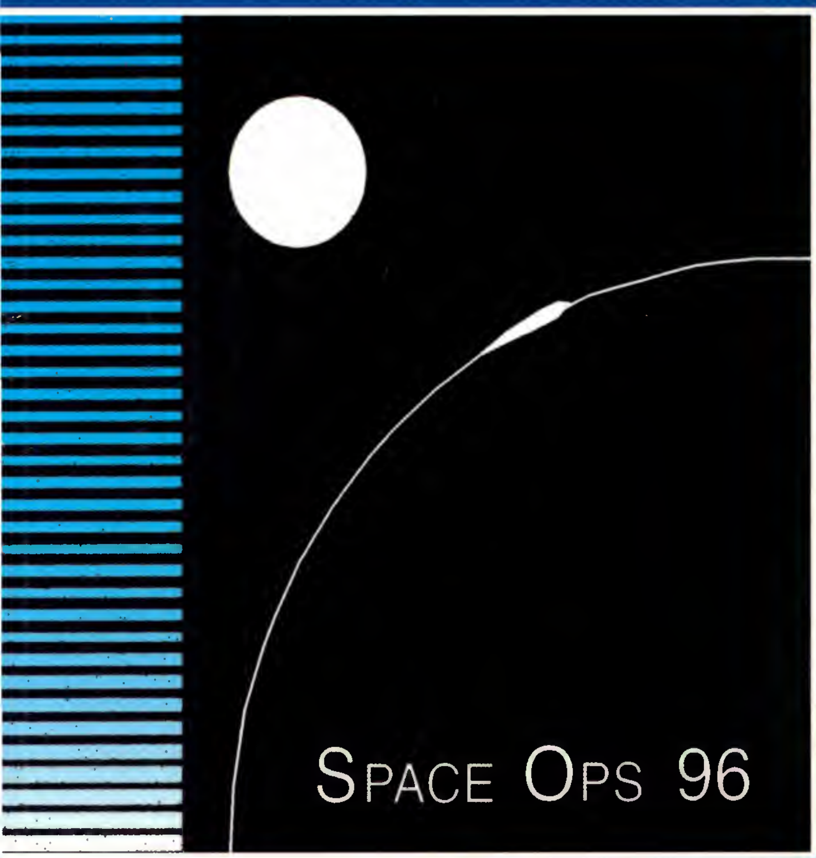
Fourth International Symposium on

Space Mission Operations and Ground Data Systems



Deutsches Museum, Munich, Germany
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Space Mission Operations & Ground Data Systems

'SpaceOps 96'

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Introduction to the SpaceOps96 Opening Session

by
Dr. Joachim Kehr DLR/GSOC
Member of the Organization Committee
Member of the Executive Committee

Ladies and Gentlemen!

It is my privilege and pleasure to welcome you on behalf of the DLR/ESA Organization Committee at Munich - the city of SpaceOps 96.

I would like to welcome our distinguished invited speakers for this opening ceremony which I will introduce to you during the course of this session.

I would like to welcome our sponsors and thank for their generous contributions. I would like to draw your attention to the sponsoring tables on display outside.

I would like to welcome the local and international press representatives and thank for their interest in SpaceOps96, and

I would like to welcome you all as participants and representatives from German, European and International spacefaring companies and organizations

Enjoy your stay in Munich!

I am very proud to announce that the State of Bavaria, through its Ministry of Economic Affairs, Transport and Technology has accepted the patronage for this Symposium.

I would like to give the floor to Dr. Lentrodt to start off SpaceOps96 with an opening statement on behalf of Dr. Otto Wiesheu, the Bavarian Minister of Economic Affairs, Transport and Technology.

ADDRESS OF WELCOME

by

the Bavarian State Minister of Economic Affairs, Transport and Technology

presented by

Dr.-Ing. H.-D. Lentrodt,
Executive Ministerial Counsellor

It is a great pleasure and honour for me to have the opportunity to extend to you a cordial welcome in the name of the Bavarian State Government on the occasion of the opening of the "SpaceOps 96 Symposium". Dr. Otto Wiesheu, the Bavarian State Minister of Economic Affairs, Transport and Technology was very pleased to assume the patronage of this event here in Munich. He regrets it very much that other duties prevent him from speaking to you himself and from personally welcoming you here in Muenchen, the capital of Bavaria.

The space organizations in Europe, France, Japan, Russia, the United States of America and Germany created the SpaceOps Symposium roughly six years ago as an international platform for exchange of information in the field of spacecraft operation. After the conferences held in Darmstadt, Pasadena (U.S.A.) and Greenbelt (U.S.A.) the symposium of this year is held in Germany again. We are, of course, particularly happy about your choice to convene in Muenchen, and hence in the capital of Bavaria.

This has all the more weight with us as it is fully justified to refer to Bavaria as the German aerospace centre. Bavaria is not only the home place of highly renowned enterprises in aerospace industry but also an important place of research in this industrial sphere.

Now as before, in our present times of empty coffers of the state, the number of those is increasing who doubt the benefits of astronautics and demand the withdrawal from this expensive technology. These critics fail, however, to be aware of the fact that astronautics has become an economic reality and normality today. Satellites are, for instance, an indispensable element in global communication networks, and an equally irreplaceable aid for meteorological observation and weather forecasts.

Moreover, we deem it pointless to discuss whether space technology provides, after all, more impetus in other domains of technology, or rather employs technologies originating from other scientific fields for its own purposes. What is decisive in the last analysis is the fact that there is an extensive exchange of technology. Either space technology is adopted in products for terrestrial applications, or - vice versa - high-technology products find their market place in the space industry. From the viewpoint of economic policy both directions are of interest.

We are therefore bound to use the options which astronautics can offer in terms of both technological and industrial policies. We in Bavaria stand by this attitude.

Bavaria is fully aware of the particular strategic importance of aerospace technologies. As a supplement to the instruments of encouragement and promotion available on a national and a European scale, we are therefore going to provide additional funds worth several millions to support research projects in this field.

As an example, I should like to emphasize also the construction of the European Astronautics Centre at the Deutsche Forschungsanstalt fuer Luft- und Raumfahrt, the German Aerospace Research Institution, in Oberpfaffenhofen, for which we have allocated roughly 46 million DM as promotion funds from resources of this federal Land.

Ladies and Gentlemen,

Let me finally address to the Deutsche Forschungsanstalt fuer Luft- und Raumfahrt jointly with ESA our heart-felt thanks and the high recognition by the Bavarian State Government for their efforts to prepare and organize this symposium attended by so many international guests.

In the name of the Bavarian State Government and on behalf of Dr. Otto Wiesheu, the Bavarian State Minister of Economic Affairs, Transport and Technology, I wish you a great success of this "SpaceOps 96 Symposium". We do hope that this event will be a forum of international encounters and of a fruitful exchange of scientific discoveries and latest results of research beyond the bounds set by national borders and continents.

We wish interesting talks and a pleasant time in Munich to all participants of this Symposium. We hope that you will also have ample opportunities, beside your scientific work, to gather at least some impressions of our beautiful Munich and Bavaria and to enjoy your stay here.

Long-Term German Strategy

W. Kröll
Chairman of the Executive Board
German Aerospace Research Establishment
Cologne, Germany

Ladies and Gentlemen,

It is my pleasure to deliver an invited contribution to the opening session of this SpaceOps 96 Symposium. I am particularly pleased to do so, since DLR is participating together with ESA in the organisation of the Symposium. But I felt quite uneasy when reading the ambitious title given to my contribution: Long-term German Strategy. I have to start by admitting that I am not in a position to live up to this title. All of you expecting a comprehensive and coherent long-term strategy on space operations will therefore be disappointed. What I can contribute are certain considerations as elements of a long-term strategy. I expect that this symposium itself will give towards it the clarification of such a strategy.

The SpaceOps forum was created in 1992 in augmentation to the IAF Conference with the goal to provide a forum for engineers and managers oriented towards the ground system and space operations. The growing interest in this symposium underlines the significance and need of such a forum.

The list of participants of this symposium also shows the growing global interest in space missions and their operations - participants from more than 20 countries are registered for this years' SpaceOps Symposium and underlines quite well the chosen SpaceOps96 motto: "Global Operations for the next century".

There are two good reasons to exchange experiences and opinions among experts on space operations:

1. Ground system capabilities have as much influence on the mission success as the design of the flight systems which are becoming more and more sophisticated.

2. Mission Operations is also a significant part of the budget of each space project.

Both arguments underline the need of a long-term strategy for space operations.

Such a strategy - in Germany as in any other country - can of course not be developed per se, for its own sake. It has to serve a space programme and has consequently to be derived from the goals of a national space programme.

Major Goals of German Space Activities

The German Space Committee on Cabinet level has summarised the overall goals of space activities in our country.
These goals are:

- to increase our scientific knowledge on space, the solar system, the Earth and on the living conditions on our planet as well as to generally expand on the possibilities to enhance research activities.
- to contribute to the solution of environmental problems by spaceborne remote sensing of land, ocean, ice and atmosphere and to the research of our climate
- to improve the governmental and commercial infrastructure and services in the fields of space communication and navigation
- to foster developments of space technology to increase the technological capabilities of the German industry
- to make the access to space safer and more economical
- to support international cooperation in the fields of science and technology
- to allow spaceborne verification of arms control, crisis management and -if possible- of environmental treaties together with the European partners.

For the implementation of the German space programme based on these political goals, the well-known decisions of the Ministers of the ESA member states at Toulouse last year are of particular importance.
Of equal importance are bi- or multinational governmental agreements, such as:

- to prepare and (hopefully) implement a satellite system for reconnaissance in cooperation with France,
- to prepare and implement a trilateral military communication satellite system,
- to support the international decisions of ESA and EUMETSAT for a satellite based weather and climate observation system, and
- to support the system preparation of a regional European overlap to the GPS system.

These are the goals to which the German ground system and space operations have to fit, and they have to do so under a very tight budget and serious financial pressure.

How should operations contribute to make these goals
happen ?

The strategy to be derived from the goals is not self-evident.

Let me therefore describe what conclusions DLR as the organisation which in Germany is in charge of space operations has drawn from these goals as elements of a long-term strategy. The four elements I will discuss can be characterised by the keywords:

1. User orientation
2. cost effectiveness
3. decentralisation, work-sharing and networking
4. privatisation and commercialisation.

1. Utilisation must be the driving force in ground segment design and operations

In my opinion the requirements of the **utilisation** community must be the driving force for all future space activities including not only the operational applications of space based systems for communications, navigation and earth observation but also the utilisation of space based systems for scientific use like exploration of our solar system (Moon, Mars, Comets), like earth research and experimentation under micro-g conditions or life science in manned missions.

In the last years more and more users took over work from the „classical" operations control center: monitoring of telemetry data, preparation of command lists, even the generation of detailed parts of mission planning information is performed by users themselves.

In DLR we have a model agreement between DLR Operations and DLR Utilisation based on a decentralised, three level operations concept:
Operations of an experiment will be carried out within pre-determined rules by the Prime Investigator, the operational responsibility for a multipurpose facility will rest with a "Facility Responsible Center", while the overall payload responsibility i.e. "envelope planning", "configuration control" and "safety and health" will be assumed by the operations control center.

I consider this to be an example of how to efficiently implement the concept of „telescience" required by the experimenters nowadays. In the typical scenario of a larger number of „independent" users the „classical" operations control centers will change more to a provider of „network-services". Certainly the comparison with the network-provider in telephone systems would be too far-going. But I see a clear requirement for the operations control center facilities to allow for networking large numbers of users by providing standardised interfaces and tools.

To be really „user-oriented in operations" means nothing else than sharing the operations work with the final user.

By implementing such decentralised operation-networks I expect a further reduction in costs especially on the operations control center's side.

This does not answer the question of how much operations is allowed to cost or how efficient operations must be. The answer to this question is easier in the case of commercial use of space systems where expected revenues will be the decisive factor. More difficult is the ranking of the "cultural legacy" for space exploration. I think that in the future the scientific goals have to be judged against the financial effort in a more thorough way than in the past, because long-duration missions like Galileo generate tremendous operations costs over the lifetime of the mission.

2. Cost effectiveness and cost reduction „Smaller and cheaper"

We all know that in the future the number of huge new satellite systems with a large number of payload elements will be limited. Even in the military field the search for so called small-satellite-solutions has started.
Unfortunately the operations efforts for a smaller satellite cannot be reduced proportional to the size. A miniaturised CCD-camera may need the same efforts as the bulky solutions in the past.
Nevertheless also operation centers must decrease their costs. The DLR strategy for lower cost, high efficient operations will be oriented along the general approach implying maximum use of existing facilities, procurement of „off-the shelf" components and automation of operational tasks. Together with the implementation of advanced automated on-board features cost reduction should be reached.

3. Decentralised approach in operation of ground systems

In the past years the word „decentralised ground- system" was used especially here in Europe for architectures representing national duplications of facilities for non-technical reasons. Cost-effectiveness was certainly not a criteria.

In the International Space Station programme even in the development phase this sharing of work between partners according to their capabilities had to be selected for cost reasons. DLR sees the necessity to decentralise also the ESA ground-segment under cost effectiveness. The recent proposal of CNES, DARA and DLR to implement the respective operations control centers for the Columbus Orbital Facility and Automated Transfer Vehicle in their existing proficient national centers is to my opinion an optimal rate to use existing capabilities for the user-oriented operations system as described earlier.

DLR has chosen this way of work sharing and networking together with NASA from the very beginning of manned space flights in Europe in the early 70ies. DLR also immediately took the opportunity to start a similar operational co-operation with the Russian operational facilities for Mission Control and Astronaut Training. For Germany we thus have a solid basis for a new approach of decentralisation and networking of existing facilities.

Another example I want to mention but not elaborate any further is the co-operation and operational workshare foreseen between CNES and DLR for the French-German Reconnaissance satellite.

4. Transfer of operational responsibilities and risks to the private sector where possible and meaningful

The maturity of some space systems for user applications as well as the trend to involve the final user more in the costs and risks brought up many ideas and proposals. NASA for instance is planning to perform this task through a "Consolidated Space Operations Contractor" who will have the responsibility for the operation and commercialisation of the NASA ground network, space network, mission control centers and deep space network .

In my opinion we should start with considerations for **privatising** certain operational tasks. If a non-agency provider e.g. industry is able to produce the same operational services with the same quality at lower costs then the tasks should be transferred. This will be surely the case in a lot of routine operations. Examples are the commercial exploitation of satellite communications, launch services, navigation aids, weather and earth resource observations.

It is interesting to mention that DLR-GSOC - as most other operation centers - is sharing already today a large part of the work with contractor companies.- they are not sharing the risks with us.

That brings me to the different question of **commercialisation** of space operations. In my opinion it is rather unlikely to make money by providing space operations services accepting the usual commercial risks. It is more probable that specific services by space systems will be marketed together with the operation of the systems.

It is the clear intention of DLR to support this trends as suggested by German and International industry if the conditions mentioned are fulfilled. This is also valid for the privatisation and commercialisation efforts with respect to the International Space Station. The development in the US has to be followed very closely in order to avoid premature steps.

German Participation in the European Ground-Segment for the Space Station Elements (an example)

Let me use the **International Space Station Program as an example** to illustrate the programmatic goals and their association with "Operations" in DLR.

With the long term goal to participate in manned space flight activities, DLR has acquired a remarkable experience in planning and operating space missions. DLR has gained in-depth operations experience for manned missions during the first Spacelab flight (FSLP) and D1 operations in the eighties.

Consequently in 1989 the implementation of the Crew Training Center, and the Microgravity User Support Center at Cologne and a manned space flight control facility at Oberpfaffenhofen was initiated as early contribution to the European Manned Space Programme to be completed in 1992 in time for the MIR 92, D-2 and the EUROMIR 95 missions.

As mentioned earlier, the European goals in the Manned Space Programme for the next century have been decided during the ESA Council Meeting on Ministerial level in Toulouse almost exactly one year ago: The participation in the International Space Station with the "Columbus Orbiting Facility" and the "Automated Transfer Vehicle" has been confirmed - with the budgets set to a bare minimum.

This program will largely replace German national activities. DLR sees the obligation to make its experience and facilities available to this European program.

Unfortunately with regard to operations no firm decisions have been taken in Toulouse, only candidates for particular operation tasks have been nominated. Therefore we have taken the joint initiative with DARA and CNES to propose a decentralised ISS ground segment, based on the available know-how and facilities in their national centers.
DLR will do everything to make sure that its existing facilities for manned space flight are used in the ESA Manned Space Programme to the maximum extent possible. Appropriate decisions are expected within the next half year.

Ideally the built up of the Columbus Orbital Facility Control Center shall be performed in a logical step-by-step manner using national and European precursor and early utilisation flight opportunities.

For the International Space Station the cooperation in operation with other space faring nations must be even more intensified in the future as a strategic goal for the sake of efficiency enhancement and cost reduction.

From a DLR point of view such a cooperation should include and make use of our particular skills for:

- Design and operations of material science and life science experiments,

- Design and operations of earth observation experiments and the scientific evaluation, and the

- Design, implementation of the appropriate ground segments for operations of manned laboratories and unmanned missions.

Final Remark

Let me finish this short and by no means complete presentation with my best wishes for a successful symposium - hopefully with results and achievements to be capitalised on in the future missions to come and with further clarifications of a long-term strategy for space ops.

WELCOME ADDRESS

SPACE OPERATIONS – THE CHALLENGES

J-M. Luton
Director General ESA

Ladies and Gentlemen,

It is with great pleasure that I join my distinguished colleague Professor Kroll, the chairman of the Executive Board of DLR, in the welcome of the participants to the 1996 Symposium on Space Mission Operations and Ground Data Systems. In particular, I welcome the representatives of the German federal Government and of the State Government of Bavaria.

I am particularly happy to see here the representatives of our fellow space agencies NASA, CNES, RSA, along with many colleagues from the worldwide space industry. I would also like to greet specifically the colleagues from the two organising institutions, the German Space Operations Centre (GSOC) of DLR located in Oberpfaffenhofen not far from here, and ESA's European Space Operations Centre (ESOC) in Darmstadt, and thank them for their dedicated efforts in preparing and organising this conference.

SpaceOps History
The SpaceOps series of symposia started fairly small in 1990, when it was realised how many specialists from space agencies and from industry are involved in space data systems and mission operations, and how much technological effort is spent on systems which so far had been handled only as part of general space-related conferences. From these beginnings SpaceOps has developed into a truly international forum of not only specialists but also decision makers, as can be witnessed by this plenary assembly today.

Significance of Operations
Mission operations are activities which are rarely in the limelight of public attention, but we all here do not need to be convinced that operations and the associated facilities are one fundamental ingredient for a successful mission.

Each space mission is supposed to achieve a specific objective, which can be the collection of data or the provision of a service, and it is during the operational phase when the overall success is proven through optimal and timely availability of such data or services.

This is of particular relevance in a period where taxpayers as well as the commercial customers are concerned like never before with the value in terms of mission return they are getting for their money. Simply launching a piece of space hardware for the technological glamour is not enough today to tap public funds or commercial capital.

This being said, operations are usually considered best when performed in an unobtrusive or even transparent way. This is obviously done more easily with proven spacecraft designs of commercial or quasi-commercial nature, and with simple missions of repetitive utilisation patterns.

Complex Operations
Complex missions with space hardware of the latest, highly innovative technology, however, will always require complex operations to exploit the full potential of their mission objectives.

Furthermore, complex satellite technology – like all high-tech – is not immune to faults, and the expertise of operations teams and the flexibility of ground equipment is usually put to the final test when contingency or rescue operations become necessary. ESA had its share of these events with the operations of missions such as Giotto, Hipparcos and Olympus.

Routine operations of large fleet of satellites as they are presently entering the commercial space arena for mobile communications applications pose challenges of a different kind. Even if the individual satellite is not too complex, it is obvious that a large workload has to be handled to monitor all of them continuously and to keep them in good operational condition, not to mention the continuous task of maintaining the orbital configuration and replenishing it with spares put in the correct slot. It will be interesting to hear at this conference about the concepts used to perform these tasks with commercially competitive resources.

The idea of fully autonomous and independent spacecraft is often mentioned in this context. On-board autonomy is of course nothing new; autonomy to varying degrees is always required for periods of hours, days or even months in the case of interplanetary probes. The scope of this autonomy has been extended over the years, as the possibilities of on-board electronics and on-board software have grown.

Satellite autonomy does however not mean the end of operations. Onboard autonomy means in the first instance a satellite of high complexity and built-in intelligence, and high complexity inherently requires adequate means on ground to monitor and to enable intervention in case of malfunction. On-board autonomy should enable us to accomplish more control tasks with less or fewer ground resources, but the in depth operational and system expertise will have to remain at our disposal on ground in order to safeguard the systems in space.

Economic Challenges

The streamlining of resources for ground operations is indeed one major challenge for the coming decade. Financial constraints have become the rule in the space business: in the public sector due to revised priorities in public funding, and in the commercial sector due to the healthy influence of increased competition.

As space segments need to become more cost-effective, ground segments and operations have to follow in order to give the customer, be it a user of commercial services or be it the proverbial taxpayer, more value for the dollar, D-mark or ECU.

For the ground operations this means new engineering approaches to ground segments, more automation of routine tasks, sharper trade-offs between operations availability and safety on one hand and acceptable risk on the other hand.

It also means to entrust more engineering tasks and responsibility to industry in a competitive environment, and the preference for off-the-shelf products over specially engineered ones whenever possible.

Role of Industry

Such an increased role for industry is indeed possible because industry has become fully mature in all aspects of space engineering in orbit and on ground. To this development, I am happy to claim, space agencies and their technical establishments have made significant contributions in the past, as it is, by the way, one of their tasks.

From being a supplier of ground operations subsystems, industry has moved ahead progressively in the field of space operations and is able now to deliver turnkey systems and control centres, and to perform operations of commercial missions from their own facilities. This also benefits the activities of industry in related fields. I was indeed surprised and happy to learn that a satellite control system developed for ESA is at the root of a line of process control software systems, which today, amongst others, control water management systems both in France and England.

Yet institutional multi-mission control centres with their infrastructure continue to be required today to operate experimental and critical missions undertaken under public funding. These centres also still have the very important task of advancing, together with industry, the technology of ground operations, the fruits of which I am sure we will encounter at this symposium. Industrial and institutional ground activities will both coexist together, although in a mode different from the past. All actors in this field will eventually find their roles in the interest of economical solutions.

Ground Infrastructure Coordination

It continues to be true that Europe needs a global ground station network as one of the conditions for its autonomous access to space. This being said, cooperation also in the use of network resources between space agencies has already created significant joint benefits. In a period of shrinking space budgets the efforts to arrive together at an affordable and well-used global infrastructure must be intensified.

Such efforts are even more important at European level. Not all ground network stations in Europe nor the world wide network of European organisations are being used to their full capacity. Therefore we need to undertake an overall streamlining of European assets in the ground infrastructure, and also a better co-ordination of Member States assets with the common European ones.

While the concept applied within ESA and its member states to the common utilisation management of the coordinated test facilities may not be directly applicable to operations ground facilities, we should jointly study which mechanisms could be used in future to assure the most efficient co-ordination within Europe as regards streamlining of existing infrastructure, controlling the creation of new capacities, and the optimised utilisation of these facilities.

Such co-ordination should also take into account future space efforts dedicated to common European defence initiatives, where possible synergies also in the use of ground infrastructure should be exploited to the maximum extent feasible.

I have mentioned a number of challenges, which I am sure this symposium will address. The operational challenges of new missions will certainly be at the centre of your debate, but you should not forget the economic challenges which today are of equal importance. By finding solutions to both kinds of challenges, space operations will be ready for the future, and this will help to advance both institutional and commercial space endeavours.

Ladies and Gentlemen,
I wish you a very successful symposium.

German Operations in the Next 5 Years

F. Schlude

Introduction

Good afternoon, Ladies and Gentlemen,
Dear Colleagues and Friends!

It is a great pleasure for me to welcome you on behalf of the German Space Operations Center (GSOC) of the German Aerospace Research Establishment (DLR) in such a large number here in München. When we jointly with the European Space Operations Center (ESOC) had assumed the responsibility to organize the SpaceOps Symposium of 1996 we could not at all expect such positive response and are therefore very happy. Your reaction shows us that the operations community is in need of such a forum for global exchange of views and information.

Before the many aspects of space operations are to be discussed during the upcoming days of the conference, I would like to present to you our present situation and our plans for future of space operations activities in Germany.

In doing so I would like to describe a typical scenario for a space operations organization striving for safe and efficient space operations services under the stringent constraints in which the space programs have to live with today.

Role of the German Space Operations Center (GSOC) in German Operations

Before starting my summary I would like to remind you on how space activities are organized in Germany. As is in many other European countries, the public funded German space program is organized in two complementary parts: the German contribution to the ESA-program and the national German space program.

In consequence „German" space operations, i.e. space operations for space projects, in which Germany participates, are divided also into those being implemented at the operations center for ESA-projects (ESOC) and those national projects with space operations implementation at GSOC. Both centers do not only have very similar abbreviations but are also both located in Germany, a reason for further confusion.

Let me now focus on the operations part of the German national program being done at GSOC.

Elements of the German Operations for the upcoming 5 Years

Our future activities can best be described by dividing them into four different groups:

Manned Missions

For many years GSOC was the only place outside the United States of America and Russia where operational tasks of manned space missions have also been performed. Let me briefly recall the historical development.

The strong emphasis Germany has given to manned spaceflight since the early 70ties was also a strong motivation to invest into national activities relative to manned space operations. Beginning with the first Spacelab mission in 1983, GSOC had started to contribute to payload operations with a remote Payload Operations Coordination and Control Center (POCC) concept.

After demonstrating this concept during this mission, the two national Spacelab missions D-1 and D-2 in 1985 and 1993 have further validated this concept. All payload related operational tasks were under our responsibility. I mention this because for me it was the first realization of a decentralized approach in a multinational project environment.

Similar concepts became feasible for us in 1992 when we jointly implemented with Russia the MIR'92 mission, the flight of the German astronaut Flade to the MIR Space Station linking together the German Operations Center GSOC at München and the Russian mission control center ZUP at Kaliningrad. The opportunity to support the ESA mission EUROMIR'95 of 1995/96 (we certainly will hear more about this later) provided further expertise and experience in long-term missions of different characters.

In the coming 5 years GSOC will make this expertise and the new control facilities, which required substantial national investments available for:

- the national MIR mission MIR'97 and
- the preparation and execution of respective tasks in the European Manned Space Program.

The 20 days flight of a German astronaut to the MIR station early 1997 will have many operational similarities with the completed EUROMIR'95 mission. It will give us the opportunity to test and verify advanced operational procedures, especially in the mission planning area. We will include in our operations team also personnel from ESA (from the former EUROMIR'95 team) to underline and demonstrate the precursor character of this mission.

Following this mission the main activities in the next 5 years will concentrate on the preparation of the ESA ground segment for the European Columbus Orbital Facility (COF) element as part of the International Space Station Alpha.

It was and is the Germany policy to share the experience gained in the national space missions of the past with the system and payload operations tasks for the COLUMBUS module of ISSA. It is the challenge of today to find adequate contractual relations to start that work immediately to secure the gradual build-up of the European ground infrastructure with the appropriate control centers.

Several papers of this conference will describe the topics we are working on in more detail. Some have been mentioned already in the previous speeches. Therefore I will mention only two points we are working on very intensively at present: the role of the user with the concept of remote User Support Operations Centers (USOC's) and the role of industrial support with respect to operations.

Unmanned Scientific Missions

The second area of our GSOC activities is that of the "classic" space operations. Here the work on one hand is dominated by the routine operations of ROSAT, the German X-Ray satellite, which is in orbit now for more than 6 years. Judging from the unceasing interest of an ever spreading scientific community on it's scientific results we anticipate a continuation of its operations for the mid-term future. This of course is not without problems because of the financial pressure on long-duration missions like this.

GSOC shall continue to implement all cost-saving measures by assuming only acceptable operational risks.

For the next years three new scientific satellites are planned in Germany: ABRIXAS, Equator-S and CHAMP. All three could be classified as „smaller satellites", at least their production cost figures shall be dramatically lower than for former similar projects. Hence there is the requirement to also reduce the operational costs. This can only be done if more than one project can use and implement support activities from others - that is an increase in standardization and commonalization of operational services, i.e. GSOC is preparing a highly standardized ground segment for that group of satellites.

I personally believe that these steps will not be sufficient in a long term perspective. Fostering and expansion of co-operationmeasures between different space operations organizations will be not only be fruitful with respect to the exchange of experiences but is considered to be mandatory wherever possible. I expect steps in a more standardized space operations world of the „smallsats" where the contributions of different control centers can even be provided and integrated along the principle of „code-sharing".

Until today we were seeking to stay professionally unique, competent and indispensable in our own organization. But for the operations of small satellites the public is expecting very low operations costs, and that can only be achieved by further increase of sharing of work with the users themselves and with other organizations.

A good example for this kind of work-sharing is the operations support which GSOC is providing to the DLR MOS payload onboard the Indian IRS-P3 satellite.

Support to Commercial Missions

The ground segment for German commercial missions in the telecommunication area of today is no longer resting with GSOC but with organizations of ownership of the orbital infrastructure. We have indeed supported in former times (when every user implemented his own ground system) the buildup of the Usingen control facility of German Telekom. Today we are providing backup support only, i.e. our support is generally limited nowadays to very specific services that cannot be produced by the customer itself in a cost effective way.

In the upcoming years GSOC will continue to provide support to commercial missions by providing LEOP-services and facility (antenna) support.

Based on the long experience with the positioning of geosynchronous satellites GSOC just recently won a competitive contract for the LEOP operations of the W24 EUTELSAT satellites. GSOC will prepare and execute the 2-3 week LEOP phase for this customer.
This work has to be done under changed technical and contractual conditions also:

Only a couple of years ago, we have been able to devote a specific team and specific computer systems to a certain project . But competition and lower market prices have forced us to reduce costs by combining these activities with other, different projects.
Today we do not expect the large number of LEOP-missions in Europe anymore. To stay competitive with the prices of the world market we have to seek and find further and new ways for cost reduction.
Examples might be a deeper involvement of the satellite manufacturer in operations and the increase of competence for both, the customer and the personnel in charge of the routine operations tasks.

Preparation of New Ground Segments for Military and GPS-Overlay Systems

The next 5 years shall involve GSOC in a new line of work: a military reconnaissance satellite for security related matters and a regional GPS overlay system will require a different approach with respect to ground systems

Both programs are bi- or multilateral and the ground segment design and operations will be done by more than one organization.

In the case of the reconnaissance satellite, the sharing of work shall follow the scheme to divide the responsibilities according to and experience: CNES is planned to maintain the responsibility for the optical satellite, whilst Germany shall maintain the responsibility for the radar satellite. At both organizations the bits and pieces for the implementation of the operational tasks are available already. The challenge will rather be to match things together in a such a way, that the customer can accept design, organization and cost for development and operations.

Both systems have to be complementary and redundant to each other. GSOC is prepared to contribute jointly with the related industry to the development and employment of the necessary ground segments.

What we can observe indeed is a high degree of commonality between this project and the Space Station contribution. There is an ever increasing need to avoid "stand-alone" solutions but strive for international or even global network-type solutions and increased competitiveness

Conclusions

The experience of GSOC shows that operations of today´s space systems are only possible through permanent and continuos adaptation. A self-contained and autonomous execution of operational tasks is no longer the optimal way in most cases. A modern space operations organization as required today shall be open for contributions from and work sharing with all possible competent sides.

Driven by our dedication to space operations, GSOC contributed wholeheartedly to the organization of this symposium because we are convinced that not only SpaceOps96 but all symposia to follow will contribute an indispensable share to stay at the edge of operations technology and to make space operations truly global as an efficient, decisive part of every project also in the future.
I shall follow the conference and proceedings with great interest and wish you a very successful Symposium.

COST EFFECTIVE OPERATIONS

by
F. Garcia-Castañer, Director of Operations, ESA

Ladies and Gentlemen,

1. Introduction

'SpaceOps' symposium, which started in Darmstadt under the name of 'Ground Data Systems for Spacecraft Control' in 1990 has grown now into a world-wide forum for exchanging and disseminating ideas and technical progress in the space operations disciplines.

Since then much evaluation has taken place: certain things have moved forward (and they constitute the subject of this symposium) and other have moved backwards (you all have in mind the decreasing potential for financing space activities).

Since both things have to go together, the current situation produced tensions and this is a salient aspect of the background against which this SpaceOps '96 must be seen. And that deserves attention.

Considerable efforts have been spent over many years to achieve important objectives such as

- Increased performances
- Generic applicability
- Technology advance
- Methodologies.

All these advances must be preserved and extended. Nowadays changes occur so fast, not only in the technical fields but also in the economical environment, that SpaceOps must also be a forum for reflection to see how the application of our knowledge ought to be directed and mapped against non technical realities.

I would like to offer some points for reflection on the points I just mentioned.

2. Increased performances versus cost reductions

Many of the elements of ground systems for operations, specially in the data processing fields, increase their performances dramatically in very short time (PC's, WS's, baseband systems, communications equipment, etc.).

As a consequence, operational systems and operations have become more performant and this has indeed increased efficiency. But mostly in one way only: we get more functionalities for the same money. But not always increased performance should take precedence over cost reductions.

The challenge today is to exploit whenever possible the knowledge and the state-of-the-art to increase efficiency by re-balancing the two factors and giving more weight to cost reductions and may be less to better performances if we can live with them.

Don't get me wrong: We should not slow down progress; let's move forward but with our feet on the ground.

3. Generic Systems versus special to task developments

At system, subsystem and equipment or software package level there is always the need to trade-off the general applicability versus the satisfaction of more restricted requirements from a single user. These two factors are always at the root of design decisions but there is another one which may severely interfere with the proper decision process; this is the funding source.

In all of the national or international space agencies, ground systems for operations have two sources of funding: the so-called general or institutional funding and the project or mission specific funding. The split varies considerably from one Agency to the other.

The requirements for general funding are justified by the real or potential existence of a variety of costumers with a number of common requirements, not always well established given the diversity of projects and their different schedules. These uncertainties may act, if not properly watched, in the direction of over-design or over-performance.

Let us look for a moment at the mission or user specific funding. In this instance a user, a project or mission manager will try to minimise the bill for his specific requirements. In doing so, he does not necessarily descope requirements but tries to demand more from the institutional or general infrastructure.

We see therefore two different causes with equal and cumulative cost effect. This accentuates the difficult situation of the engineers and managers who have to satisfy requirements originating from one source with funding coming from a different one which, in the current circumstances, is getting tighter and tighter. This is why a critical scrutiny of the common or generic infrastructure requirements has become one of the priorities.

These factors are imposing today some re-adjustment on our thinking. The process in the past years has been of an inductive nature with strong move from particular towards general solutions.

The challenge today is to find the optimum balance between generic and specific requirements and take the important step to distinguish between 'generic' (or universal) and a more modest concept of 'multi-project' (by 'multi' meaning multiples of one and not necessarily very high).

This, at least in Europe, is dictated by the reduced number of new space projects in the pipeline and by reduced budgets for general purpose infrastructure.

Again, don't get me wrong: inductive thinking is a pre-requisite and is, by all means, to be encouraged. At the same time the deductive process must be used to go from general solutions to particular ones and map technical possibilities against specific financial reality.

4. Technology push, technology pull and technology speed

A critical problem we are facing is selecting the right level of technology for the future space mission ground systems. It is of course one of the important tasks of the public sector space organisation to help to advance technology: technology development at industry, sponsored by those organisations, eventually enables industry to choose the most adequate and efficient technical solution for both public and commercial space missions.

There are areas where the foreseeable requirements for space mission operations have acted as technology drivers (space link and baseband systems, flight dynamics and others).
This technology push has to continue in order not to loose pace.

At the same time we must be aware that other technologies employed in the ground segment are often not driven by the requirements of space missions: the state of the art in communications technology, process control, data processing, to name just a few, is driven by non-space applications with demanding requirements, and representing a much higher volume of business than space. Trying to push the general state of the art in such areas from the space agencies' end would be very costly, risky in schedule and financial terms and with little guarantee that such developments would eventually influence the mainstream of technology.

This situation is a change with respect to the beginning of the space age, when virtually no relevant equipment existed, and every functionality had to be developed from scratch, using industrial partners with little to no prior experience in space operations requirements. Today, thanks to the effort of the industrial and public space organisations, and also due to the extended application basis, a wide array of commercial off-the-shelf equipment exists which can be used and adapted with relatively little effort, provided that one is ready to adapt one's requirements to what is existing.

In some areas, therefore, ground segment technology moves on, driven - as I have mentioned - by influences much more powerful than space requirements. At the same time the update cycles of technology shorten, the best example being the speed at which desktop computers are becoming obsolete these days. This is what we call the technology pull. The infrastructure of our control centres and our ground station networks has to follow that pace to the extent that unacceptable increases of maintenance cost for obsolete technology are avoided, but with care.

Today, in many disciplines related to the space mission ground segment, the technology evolves faster than the requirements. We cannot ignore this technology pull but we must avoid situations where technology is driving our requirements. Instead, we must reflect and stabilise the infrastructure at an acceptable technology level by skipping one or the other technology cycle, if necessary, since the pace at which new space missions come is slower than the update of certain technologies in ground systems.

Let us not forget that operations, an absolutely essential phase of every space mission, is not an end to itself, but a means to satisfy customer requirements. And the paying customer must in the end determine requirements. Our challenge here is to put our knowhow at work to optimise cost and mission safety and return, by phasing two different evolution cycles.

5. Methodology and systems approach

The points which I have commented upon cannot be dealt with in isolation. How to treat them all is a question of systems methodology.

Much has been advanced in the identification of cost drivers in ground systems and operations and in improving cost/performance ratios. But it is more and more crucial to strengthen our methods to ensure integration of space and ground systems concepts.

Technical choices on spacecraft design, for instance in the area of on-board autonomy, have more and more repercussions on the ground systems and operational requirements. This requires that system engineering for any mission must be a combined effort of satellite and operations and ground segment engineers from the earliest design phase onwards.

Although this is in general recognised, there is still a way to go in determining what is done in space, what is done on ground and what are the trade-offs and repercussions.

I hope that in the course of this symposium useful experiences can be exchanged on this topic.

6. Conclusion

I would like to come to an end now.
I am aware of the risk that my messages with so much emphasis on economies may sound as a restraint to innovative developments. In no way this is the case.

Innovative thinking and sharing experiences is going to be the main subject of this symposium, SpaceOps '96, and , from the program content, I am sure of an extraordinary success, no doubt.

My words should contribute to help digesting and using this vast amount of valuable information in a very demanding context characterised by financial constraints. This is the summary.

Le me encourage everyone to make an important effort to take what you learn this week back to your respective organisations and ensure good cross-fertilisation.

I wish you all good success and I thank you for your attention.

Track 1 – Operations Management

Track Manager: A. Smith (ESA/ESOC)

OVERALL SUMMARY AND CONCLUSIONS

TRACK 1: OPERATIONS MANAGEMENT

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1. INTRODUCTION

I will begin by thanking all of the authors and presenters who contributed to the track. They all made a significant effort and I believe they ensured a successful outcome of the track which was very rewarding for those who attended the presentations at the symposium. Their papers will provide a useful reference source via the published proceedings.

The brief description of the track, which was included in the schedule and technical program summary, was as follows:

"The principal goals of Operations Management are to ensure that the mission objectives are achieved, to maximise mission product return and to minimise operations costs. This track addresses the approach being adopted to operations management for the pre- and post-launch phases of current missions and looks at innovative concepts for the future"

Operations Management is a broad subject which includes the following main topics:

- Interfacing with Users
- Developing operations concepts
- Requirements definition
- Defining and maintaining cost + schedule
- Detailed Design
- System development, integration, test
- Conduct of missions
- Delivery of mission products

With nine tracks to choose from for the symposium, some of which overlap with operations management, authors had a difficult decision to make as to which track would be the most appropriate. The track managers did try to optimise where the papers were eventually placed but there are still some papers in other tracks which address operations management topics; anyone searching for operations management topics should also look under them.

The track was allocated 21 papers, of which 19 were eventually provided or presented. 17 of the authors made it on time to be included on the CD-ROM; 2 more will make it to the Internet version.

There are papers from most of the major Agencies involved in mission operations, including CNES, DLR, ESA, EUMETSAT, ISRO NASA, NASDA, together with papers from Industry in Europe and the USA. They cover a broad spectrum, addressing missions from the conceptual phase through to delivery and utilisation of mission products.

They also cover a wide range of missions and include Earth Observation, Telecommunications, Interplanetary. This is important as the problems to be faced depend very much on the type of mission and can be quite different. Rather surprisingly nothing was submitted concerning manned spaceflight operations.

2. SUMMARY

The following presents a brief overview of the key points of each paper. The papers are loosely grouped together according to common themes, as follows:

- Management techniques and approaches
- Use of tools to help in mission design
- Geostationary missions
- Earth observation and remote sensing
- Interplanetary

Paper 2 presented the experiences of JHU in adapting a major organisation to deal with the demands of the current faster, better, cheaper culture. Using the NEAR mission experience the author highlighted the many constraints which should be considered in such a project. The ability to control overheads and the availability of a pool of trained staff were key elements. There is, as yet, no written paper.

Paper 3 discusses the problems NASA have faced dealing with the multiplicity of mission requirements for space communications support and the progress made with the transition from a paper based system to a software tool, RGS. It is now a requirement for all GSFC missions and future application to other centres is being considered. This could be reconsidered following the recent creation of the Space Operations Management Office, SOMO. (Paper 5)
It is not an Agency wide tool, similar ideas are in place in JPL for example.

Paper 4 is a detailed account of current ESOC practices. One point brought out is the difficulty of managing the inclusion of general infrastructure development projects in parallel with project specific developments.

Paper 5 discusses in detail the new NASA Space Operations Management Office, SOMO, headed by Mr John O'Neill, NASA's Director of Space Operations. The SOMO concept is based on continuing the distributed participation at the various

NASA field centres, with consolidated management through a single lead centre, JSC. One of it's plans is a transition from Government involvement in operations to more involvement and responsibility on a single agency wide operations contractor. This is due for October 19 98 with an initial 5 year contract, and a 5 year follow on.
The presentation triggered many questions and a lot of discussion, particularly from participants from the USA.

Paper 7 addresses the utilisation of simulators in training mission control teams. It strongly recommends a critical assessment of requirements and desired fidelity of modelling as these directly influence the overall development costs, and in some cases are being over specified.

Paper 8 concerns the problems of on-board software management. The current emphasis on increased on-board processing makes this a significant future ground operations task to maintain. The paper gives a good description of the current ESA approach.

Papers 9, 10 discuss some current NASA approaches to modelling elements of the operations functions to establish better confidence in initial concepts and requirements. Paper 9 restricts itself to team sizes for post launch operations but does not include all activities, eg science and system maintenance. It gives a comparison between results from the model and actual teams for seven missions. Application of the model outside the NASA environment would be interesting.
Paper 10 presents a modelling technique to be used when establishing operations systems concepts. It proposes techniques to identify constraints to be considered on the overall system design. Not too much experience has been obtained yet with the technique, which is currently being applied to the MAP mission.

Paper 11 gives a good example of in-orbit mission redefinition. NASDA's ETS-VI data relay satellite was not placed in it's intended geostationary orbit, reaching only a 3 day repeat (8000km x 42000km). NASDA nevertheless were still able to conduct some valuable in-orbit tests to validate the operations concept for their future space network and gain experience for their follow on-missions.

Paper 12 gives a comprehensive view of the approach DLR currently follows to manage it's geostationary satellite positioning projects.

Papers 13, 17 give detailed accounts of operations management for the thriving Indian Space program. The experience from ground operations is being fed back into future space segments. ISRO has extensive experience in inter-Agency cross support for ground station utilisation. They are currently considering developing an Arctic station.

Paper 14 presents the mission operations approach NASA adopted for GOES-8and-9. Two major drivers for change were the increased complexity of this generation of GOES and the requirement to deliver a turnkey system on-orbit to NOAA. A ground operations manager was added to the project team. Extensive use is made of command procedures, 800 per spacecraft to aid operation personnel. An interesting idea was the introduction of a contingency manager as a lead role in the launch team.

Paper 15 presents the approach taken by Eumetsat to reduce the routine workload on it's operators and allow them to operate with leaner teams. Their approach to motivating the staff is discussed. They have achieved very good performance of their ground segment since assuming responsibility for the operations of the Meteosat spacecraft in November 1995. The extensive validation of their automated procedures was underestimated and they have recognised the need to start this much earlier for the next generation.

Paper 16 gives an interesting insight into one application of Meteorological satellite data.

Paper 18 is an overview of NASA's EOS and the way it's operations system concept is developing. It is interesting to note that the mission is probably going away from TDRSS and will utilise new X-band terminals in Alaska. As part of the rebaselining NASA have deleted the quick look science data service for users. They also plan to reduce shift staffing by increased automation, as a result of which they will have to relax their 95% data delivery requirements. The first launch is scheduled for mid 1998.

Paper 19 presents a small prototype mission control system developed using a COTS knowledge based system, also used by INTELSAT, JSC and Iridium. The application chosen was the ESA ATV. In testing the system proved particularly powerful as an aid to ground operators in fault detection, isolation and recovery of the vehicle. It's use could help to reduce mission operations costs for long duration or repetitive missions.

Paper 20 gives a useful insight into some of the problems and solutions found to manage the French participation in the Russian MARS-96 mission. The Russian and French ground segments are also described. CNES needed to adapt to the Russian style of project management where typically different documentation standards are followed. The use of sub-groups was found to be very beneficial to ensure coordination between all parties in the project; these are described.

Paper 21 also discusses a cooperative Interplanetary mission, this time Huygens, which will be carried to Saturnian system by NASA's Cassini spacecraft. Due for launch in 1997, the probe is released in 2004. One problem will be to maintain the expertise of the operations team as there will be very little activity during the cruise period.

3. CONCLUSIONS AND RECOMMENDATIONS

Did the track meet it's summary objectives?

The answer, perhaps not surprisingly, is not completely. It certainly addressed very completely the approaches being followed by different operators for current missions and for some missions now in the pipeline, but it only partially dealt with innovative concepts for the future. It did not come up with a panacea for the many problems currently confronting the operations community, but it did provide an insight as to how management may change and progress into the 21st century.

- Valuable track, much interesting work ongoing and described
- Strong similarities between the ESA, DLR and NASA approaches to unmanned mission operation management as presented.
- Future NASA plans to go to a single operations contractor should be followed with interest.
- The Indian space program is very active and is further developing it's own infrastructure.
- Earth observation missions are drivers for change, with extensive use of automated procedures being adopted to reduce routine load and staffing levels.
- International cooperation on Interplanetary missions is producing new problems and solutions relevant for similar future joint missions.

The theme of this track, operations management, should be revisited at the next Spaceops symposium, and should include:

- Manned spaceflight operations, particularly for the ISS
- European decentralisation
- An update on NASA's SOMO and it's single operations contract.
- Operations management in ESA following the ongoing reorganisation

A REVISIT TO THE REQUIREMENTS METHODOLOGIES FOR SERVICES PROVIDED BY THE OFFICE OF SPACE COMMUNICATIONS

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ABSTRACT. At the SpaceOps 1992, held in November of that year, NASA Headquarters Office of Space Communications presented a paper which outlined a revised requirements processing system to enhance its customer interface and response time.

The methodologies, while good in theory, have never lived up to the expectations of expediting the requirements process flow time and in fact has been overtaken by the concept of "faster, cheaper, smaller" spacecraft, government downsizing and a more internal competitive environment.

The subject of this paper is to revisit the methodologies and present how NASA has responded to the challenges, what has been done to expedite the process, to improve the customer relationships and to expand the scope of participation.

Specifically, NASA has gone to a Client-Server system known as the Requirements Generation System [RGS]. The RGS is a computer supported cooperative work tool that is configurable on a per-mission basis. The RGS can be structured to allow "levels" of requirements, i.e., Mission Requirements Request and Detailed Mission Requirements to be generated, as well as generic reports.

In addition, NASA Code O is coordinating with its counterparts in the international community to create a global RGS for all to use in exchanging requirements and obtaining commitments over the internet.

Details of the Requirements Generation system will be provided, such as the recommended configuration for the RGS; information on becoming an RGS user and network connectivity worksheets for a Mac or PC user.

1. INTRODUCTION

In the fall of 1991, the Office of Space Communications [OSC] of NASA Headquarters issued a revised NASA Management Instruction "Obtaining Use of Office of Space Communications Capabilities for Space, Suborbital and Aeronautical Missions" [NMI 8430.1C]. This instruction provided the guidelines and means for obtaining support from NASA for all programs except Human Flight. These communications services were provided through designated lead centers such as the Jet Propulsion Laboratory [JPL] for the Deep Space Network, Goddard Space Flight Center for the Space Network, Ground Spaceflight Tracking and Data Network, and Wallops Flight Facility, along with elements of Dryden Flight Research Facility and Ames Research Center.

In the past, the procedures specified were based on a paper system with a formal ebb and flow between developers and responders starting at the Program [Headquarters] level and then at the Project [Center] level. The process was coupled to a nominal five year life cycle for the approval and development of each NASA program and was based on staffing levels available at that time.

Today and into the foreseeable future, the life cycle for new programs could be as short as two years, with new launches coming as quickly as once a month. In addition, resources have been cut dramatically at the Headquarters level, and major reorganizations are underway at the Center level. The downward pressure on the budget is projected to continue for the next several years.

2. PAST SYSTEMS

For many years, NASA used the Support Instrumentation Requirements Document [SIRD] and the NASA Support Plan [NSP] as its basic requirements systems for "unmanned" mission support. This would evolve into a Headquarters level NSP with a SIRD/SORD system at the Center level. It was not uncommon that a NSP would be signed in fact after the mission. The 1991 NMI revision was aimed at improving this process timeline.

This revision introduced the Mission Requirements Request [MRR] forms and was designated to be a customer's statement of requirements, which in turn would become an enabling document to initiate the planning process. This key provision would provide formal notification to Code O of requirements at the completion of the Program Phase A studies, nominally five years before launch.

A second key provision included periodic feedback to the requesting customer indicating the degree to which his requirements were to be supported. The third key provision was the delegation of the responsibility for negotiating the detailed requirements between the customer and the OSC Lead Center.

The Detailed Mission Requirements [DMR] document was the designated Center/Project level document which allowed for the delegation of commitments to the Centers and therefore became a joint customer/service provider document. The DMR also required forms to be filled out in detail and was word processor supported.

3. THE PROBLEM

Under pressure of NASA's new policy shift to "smaller, faster, cheaper" missions, the MRR/DMR system began to breakdown:

- The paper based system just could not respond in time. The steps in the process time were simply too slow.
- The processing of requirements became labor intensive, and therefore either increased the cost or resisted any cost savings proposals.

Because of the numerous steps in the paper process, the requirements themselves were either duplicated, overlooked, or were contradictory [in some cases]. This required additional manpower to oversee and monitor the process, without any real improvement.

Finally, the real burden of the system was the fact that it was always "behind" in current actions. The problems, and the resulting surprises were always being worked outside the system, and the MRR/DMR were after-the-fact places to document the decisions.

4. ALTERNATIVES

Faced with a system that was falling prey to its earlier ancestor's problems, NASA looked to what alternatives were available. Five approaches were identified, namely:

- Do nothing;
- Invent something new;
- Buy Contractor Off-The-Shelf [COTS];
- Use an existing system [without modifications]; or
- Recycle/refurbish existing system[s].

5. PROS AND CONS

Do nothing: The present MRR/DMR system was not designed for today's environment. The present process needs to be changed to meet the challenges of the future. To do nothing in the face of an obvious problem is unacceptable to management and individuals alike.

Invent something new: Clearly to start all over again being able to establish new ground rules and utilize the modern technology available today is appealing to the engineering mind. The realities of the present day situation is that the problem is today's problem and growing by the month. Programs in the cue are already using the present concept. Time and resources are not readily available to start all over. Any solution which offers stability today is far more preferable than a currently undeveloped process.

Buy COTS: Existing off-the-shelf capabilities certainly should be considered if they fit into the overall requirements process. NASA needs to maintain flexibility in whatever process it utilizes. An off-the-shelf system is today's solution for the battle, but may not win the war. However, no COTS were identified.

Use an existing system: NASA uses a second requirements systems for its Human Flight programs, Shuttle and Space Station. Derived from a DOD system, the Universal Documentation System [UDS] has been in use since the time of the Apollo program. It is a mix of a paper system with an automatic capability called the Automated Support Requirements System [ASRS]. The system consists of generic documentation with annexes for specific flight missions. The system is highly specialized for human flight and does not lend itself to simple, low cost missions, or those that require a singular one-on-one interface. The UDS is designed to provide a DOD interface which is not required by most NASA or International programs, and contains certain operational constraints not desirable for most NASA scientific missions.

However, an alternative system exists, which was developed by the Goddard Space Flight Center and called the Requirements Generation System [RGS]. The RGS automates many of the activities associated with the development, editing, review and approval of requirements, and the subsequent creation of requirements documents. At the present time, this system is limited only in the scope of its application and is a candidate for upgrading. Additionally, any changes to the RGS will not adversely impact ongoing usage.

6. NASA's Choice

NASA Headquarters OSC believes an enhanced Requirements Generation system would provide the most timely and cost effective solution to the present problem.

The RGS employs an 'open' database to facilitate communications among all requesters and providers of support. The system encourages on-line interfaces vs. paper based work. Flexibility along with control of mission specific user requirements is provided along with a distributed system architecture which joins both contractor and NASA location [including international venues] and operates on existing desk top platforms.

7. RGS

The RGS automates many of the activities associated with the development, editing, review and approval of requirements and the subsequent creation of requirements documents. Individual databases are available to all mission personnel throughout the life cycle of the mission, facilitating communication of information at all levels of requirements, ensuring tracability from one document to another, and provides a historical database. Requirements developers use the RGS interactive processing environment to define, control and structure mission requirements. Users can browse documents and a capability exists to annotate specific requirements .

The RGS allows designated mission personnel to challenge requirements or accept them for inclusion into a Detailed Mission Requirements [DMR] document. These requirements may be 'locked' to prevent subsequent modifications. The RGS produces documents and reports for any or all levels of information in the database.

As a computer supported cooperative tool, the RGS can be tailored on a mission by mission basis, and configured to add additional 'lower' levels of requirements.

The RGS [as shown in Figure 1] is a Client-Server System [CSS]. A CSS is a system that uses client machine[s] along with an operation system and an inter-process communications system to form a composite system allowing distributed computation, analysis and presentation. The

RGS runs on a client's PC within a Microsoft Windows environment. There is no difference in the appearance or functionality between the PC and Mac platforms.

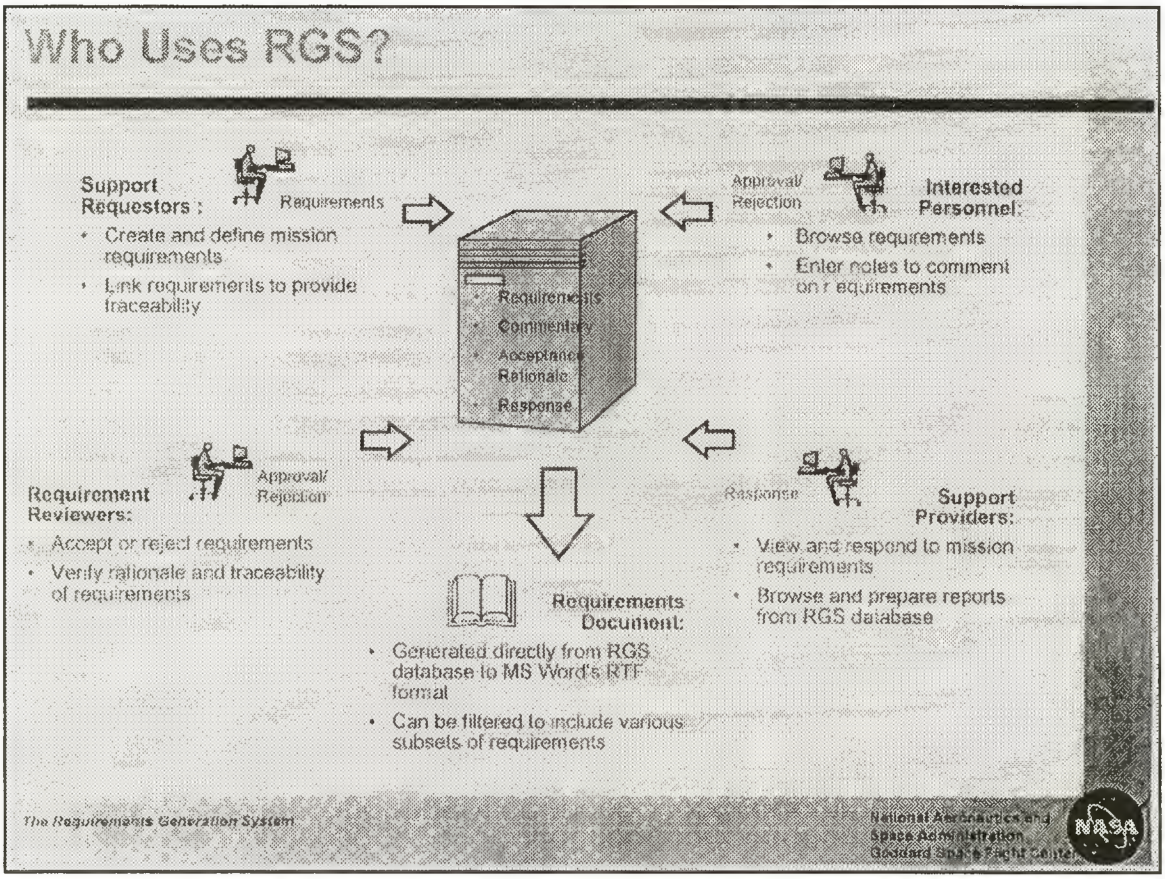

Figure 1 - Who Uses RGS?

Customer Relationships and Participation

At the present time, GSFC is requiring all new Projects to use the RGS for compilation of the DMR. In addition, efforts are underway to utilize the RGS for the documentation of the MRR. External to GSFC, the Headquarters reporting process is now utilizing the RGS for early notification of new Programs. The Jet Propulsion Laboratory is evaluating the system for applicability to its needs. On the international level, the French and German space agencies have agreed to use the system and have implemented the interface. The Japanese Space Agency NASDA, has agreed to setting up a test bed for evaluation while ESA/ESOC is waiting for a candidate program before taking any action.

Changes to the RGS

Several enhancements are presently underway and are of note. The ability to import and export the UDS PRD format is under development. The association of PRD content and RGS fields would simplify certain Expendable Launch Vehicle requirements will utilize DOD launch capabilities and NASA SN TDRSS capabilities. The support of configuration management reviews tied to specific requirements and the recent publication of a MRR/DMR Instruction Manual dictating the format for utilization with its RGS

Technical Specification

For informational purposes, salient RGS user specifications are listed in Figure 2.

	PC	MAC
Processor	486, 66 MHz	68040 (Centris/Quadra)
Memory	16 MB +	16 MB +
Hard Disk Space	15MB Free	15 MB Free
Software	Microsoft Word 6.0	Microsoft Word 5.0 (or greater)

Figure 2 - RGS Configurations

7. ASSESSMENT

The RGS provides an existing capability which can readily be modified or expanded to support any unmanned or robotic mission on NASA's list. By automating the requirements in the RGS, significant time reductions are realized with almost instantaneous distribution and response, not only at a Headquarters notification level, but at a detailed response level as well. Reports, historical databases, rationale for future planning and reissue are readily available. Cost savings should be realized because of reduced preparation time and shortened mission schedules. By proper coding, full cost accounting can also be accommodated. Transportability into the DOD UDS requirements system, should also improve the interfaces, simplify the coordination, and reduce costs.

8. CONCLUSION

The RGS is an existing viable system readily available to resolve present day problems and is adaptable to future needs.

9. REFERENCES

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MISSION OPERATIONS MANAGEMENT INTO THE 21 ST CENTURY

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ABSTRACT. The mandate to prepare for an efficient and successful conduct of mission operations of a major satellite starts several years before launch and the subsequent in-orbit mission phases. The ground systems planning, design, implementation and operations for specific projects and their related management tasks and responsibilities have to adopt a phased approach, well balancing existing and new infrastructure and project needs.

Taking science missions from the ESA Horizon 2000 Programme as an example, the ground segment and operations management along the various project phases will be highlighted, whereby addressing the functional tasks and responsibilities, as well as documentation, project control and review objectives applied.

The paper will highlight some of ESOC's experience and lessons learnt from the successful development and implementation of the ground segment for one cornerstone mission, CLUSTER, and will indicate how this is being applied to ROSETTA, another cornerstone.

1. MANDATE AND RESPONSIBILITIES

The European Space Operations Centre (ESOC) has the mandate to establish and maintain an infrastructure of ground segment facilities (including control centres, ground stations, dedicated computers and network communications), and is specifically responsible for the operations of the Agency's satellites by delegation from the Programme Directorates.

Within this context ESOC is responsible for the ground systems concept definition during the 'Preparatory Phases of Programmes' of future missions, as well as for the ground systems planning, design, implementation and operations during the subsequent phases of 'Approved Programmes'.

For 'Approved Programmes' a dedicated Ground Segment Manager (GSM) is nominated who assumes the following primary responsibilities:

a. The GSM is responsible within ESOC for completion of a Ground Segment system in accordance with agreed project requirements in terms of technical performance, schedule and cost.

b. The GSM represents the Project Manager in all project related management issues at ESOC. He is responsible for all formal interface aspects between the ESOC ground segment implementation activities and the project management, including decisions related to all interface questions concerning ESOC. He ensures that the overall mission and project requirements relevant to the ground segment are properly defined and implemented.

c. The GSM assumes the responsibilities delegated to the Flight Operations Director (FOD) at ESOC for the conduct of the mission operations (as documented in the Flight Operations Plan).

For the routine mission operations phase the responsibilities for the conduct of the mission are delegated to the Spacecraft Operations Manager (SOM).

2. METHODOLOGIES APPLIED FOR CLUSTER

PHASED APPROACH. Figure 1 depicts for a typical mission evolution the phased approach followed throughout the various mission phases.

During the *Preparatory Phases* of Programmes, comprising proposal evaluation, assessment study, and Phase A study, a Study Manager will manage the work done by ESOC in support of project feasibility and project definition in response to mission proposals originating from the Agency's Programme Directorates.

For *Approved Programmes,* comprising Phase B, Phase C/D, launch, mission operation-, and run-down

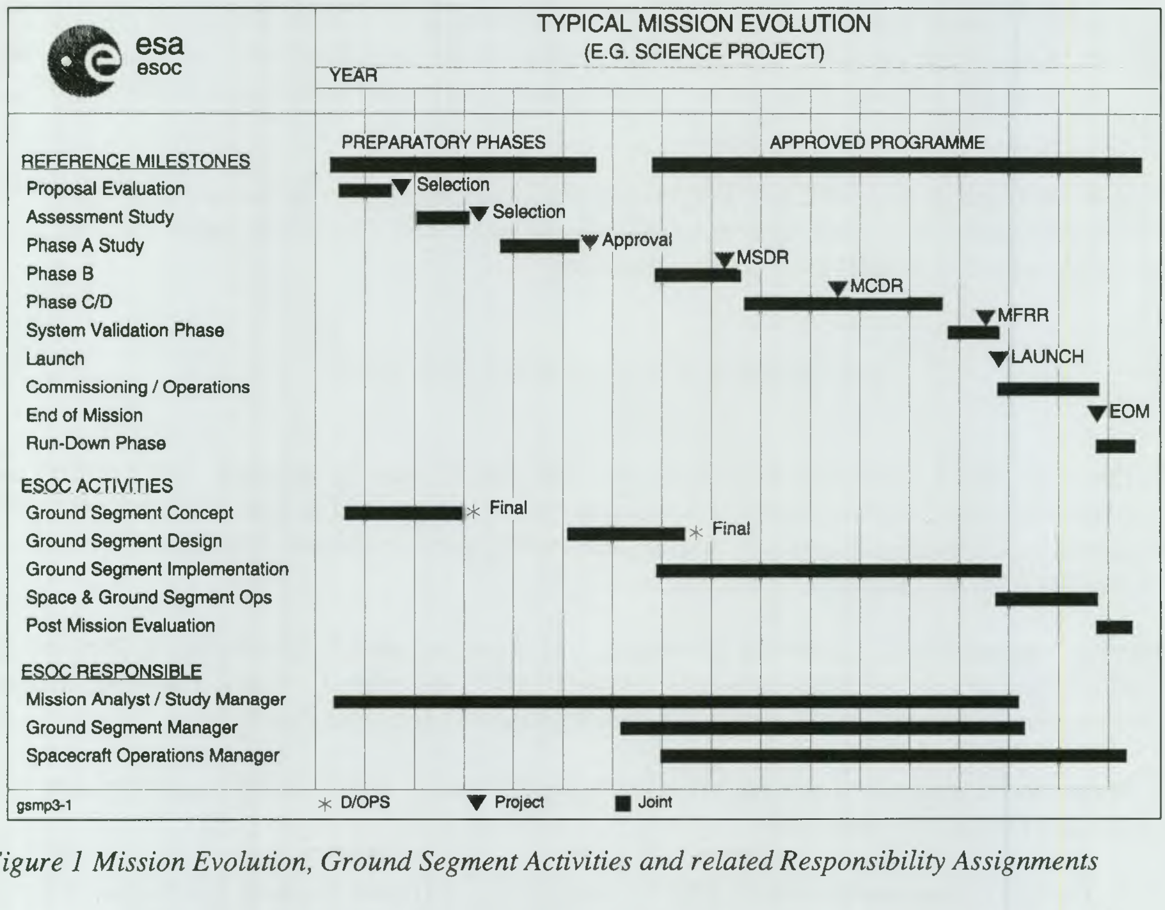

Figure 1 Mission Evolution, Ground Segment Activities and related Responsibility Assignments

phase, the management of all ESOC activities related to the project will be the responsibility of a dedicated GSM.

REVIEWS. The following Ground Segment Review scheme has been adopted:

Ground Segment Requirements Review.- to review the requirements on the Ground Segment, and the proposed implementation concept in order to give the go-ahead for the preliminary design activities of the Ground Segment. (Timing: within 6 months after the start of the Phases C/D of the Ground Segment (normally this is approximately L-5 years).

Ground Segment Design Review.- to review the design status of the Ground Segment in order to give the approval of detailed design, and go-ahead for implementation. (Timing: approximately L-3 years).

Ground Segment Implementation Review.- to review the implementation status of the Ground Segment, in order to give the approval of the finalisation of the ground segment development and implementation, and the continuation of ground segment system test activities. (Timing: approximately L-1 years.)

Ground Segment Readiness Review.- to check that the Ground Segment as implemented meets requirements and specifications and to check that the testing of the Ground Segment, and other preparations for operations are progressing satisfactorily. This shall give a confirmation of Ground Segment Readiness for operations. (Timing: approximately L-3 months)

Mission Commissioning Results Review.- to assess the performance of the spacecraft and Ground Segment, in order to give either confirmation of approved operational baseline, or recommended changes thereto. (Timing: approximately L+3 months).

Infrastructure Development Reviews.- to review the multi-purpose infrastructure focussing on the status of design, schedule and progress, as well as problem areas. This shall enable to correlate infrastructure and mission specific ground segment implementations and shall allow to reveal any inter-related implications. (Timing: held within time intervals of about 6 months).

INFRASTRUCTURE DEPENDENCY. ESOC's prime function to conduct mission operations for the Agency's space programmes and the establishment, maintenance and operation of the supporting ground infrastructure ensures the availability of well proven multi-project infrastructure systems. They cover the relevant domains of spacecraft control, flight dynamics and navigation support, mission analysis, station and communications engineering, as well as data processing. These generic systems are used whenever possible in support of upcoming projects, but they are also subject to modernisation and improvements.

Contrary to normal practice the implementation of project specific ground facilities at ESOC can not fully be performed on the basis of an already existing infrastructure. Instead, infrastructure development to some extent goes on in parallel to mission specific implementations. This means that a project specific ground segment implementation will have to rely on a certain amount of new infrastructure developments, which could have an impact on project schedule and/or cost. Hence, it is important to minimize this dependency as far as possible to reduce associated risks, and where unavoidable to closely monitor the implementation process of multi-purpose infrastructure items.

DOCUMENTATION. The key documents which will be developed and employed in the course of the ground segment definition, design and implementation process are for the 'Preparatory Phases of Programmes' the Mission Assumptions Documents (MADs) and for the 'Approved Programmes' the

Mission Implementation Requirements Document (MIRD),
Mission Implementation Plan (MIP) with related MIP Annexes,
Flight Operations Plan (FOP).

These are complemented by appropriate implementation documents e.g. Interface Control Documents (ICDs), the Network Configuration Document (NCD) and Network Operations Procedures (NOP).

The MIRD, issued by the project, formally defines the system level requirements on the ground segment design, its implementation and operation in conjunction with the space segment. The MIP constitutes ESOC's formal response to the project and contains a section listing all requirements contained in the MIRD as well as any additional requirements which may be derived, to ensure common understanding and unambiguous interpretation of the requirements prior to commitment. A standard scheme for the MIP has been developed, structuring the MIP into the main body and a series of Annexes. This scheme further provides for a standard contents list for the MIP and a standard list of Annexes, which shall be logically an integral part of the MIP. The MIP and its Annexes (and necessary associated reference documents) constitute the complete and definitive set of documents which describe the ground segment and operations.

TOOLS AND PRACTICES. The standard project control methods have been applied throughout all phases of the ground segment implementation. These encompass the preparation, maintenance and control of

a *Work Breakdown Structure* for the definition, design, and implementation of the Ground Segment.

schedules of ground segment activities in the form of networks and/or bar charts.

manpower and cost estimates, based on formal technical requirements in the baseline requirements documentation.

a *configuration control system* to maintain visibility and control of the actual configuration status.

The above items are complemented throughout all project phases by an Action Item Control and a Reporting system for both internal and external interfaces.

In particular, the possibility to apply strict budgetary control on all expenditures on a monthly basis by means of the ESOC Planning, Forecasting and Management System has proved to be a viable and essential tool. This, together with the scheduling control system, based on Artemis 2000 and fully compatible with the system used at the Project Office in ESTEC, enabled to keep the ground segment implementation within required schedule and cost limits.

Furthermore, it is important to maintain the flexibility to quickly adapt to changes, e.g. new technical requirements, schedule delays, etc. In this context, also the information and lessons gained from previous projects constitute a reservoir of expertise which is always taken into account.

DUALISM. One of the most demanding tasks to master is the dualism of the project structure given in the related Programme Directorate and the matrix structure given within ESOC with its Line Department structure. Figure 2 shows this relationship, with the GSM at ESOC being in an intermediary role in-between. The GSM reports hierarchically within ESOC, and also manages the inter-departmental activities, but the GSM also reports functionally to the respective Project Manager (usually at ESTEC), thus constituting the single point interface to the project. The GSM could in principle act in two extreme ways: a) he executes only a coordinating function or; b) he manages a ground segment team acting as he had the full responsibility and hierarchical mandate for all team members and any activities related to the ground segment implementation.

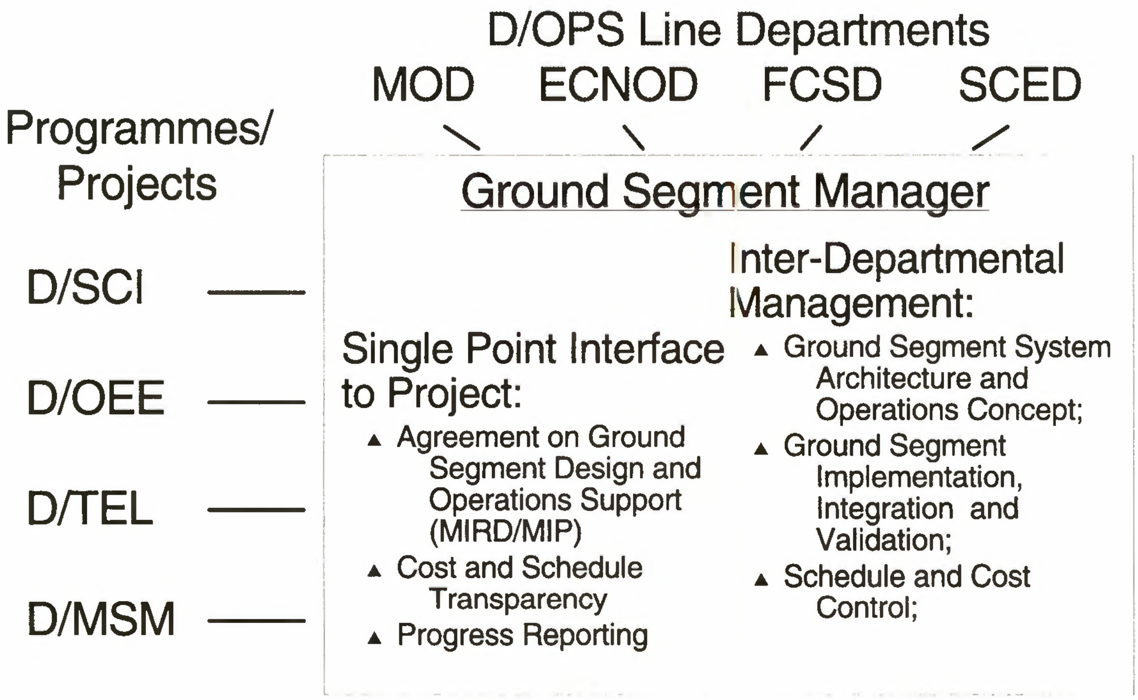

Figure 2 Dualism of Project Structure versus Matrix Structure

TEAM SPIRIT. Already from the very beginning of the project a strong team spirit has been highly encouraged. This encompasses members from other ESOC units (including those not involved to the full extent in the Cluster project), as well as any contractor staff either on site or at other locations. The aim was always to declare a common goal "the Cluster Mission" across given boundaries, preaching that "not my responsibility" mentality should not apply, and propagating "we don't leave you alone in the rain" team spirit. Along these lines, a couple of social events were organised also in conjunction with the ESTEC project team members, the highlights being a visit to the spacecraft at the integration site, a common "Cluster Lunch", and a "Cluster Barbecue".

INDIVIDUALS. A major challenge is to deal with the individual people involved in the project. In particular those who may have only little or no mandate at all in the project specific ground segment implementation. The right way to manage, lead, convince, and coordinate them cannot be taught, it is rather a matter of personality.

3. CONCLUSIONS

The lessons learnt in the course of the preparation and implementation of the Cluster Ground Segment System revealed that the main difficulties relate to the dualism of the project structure given at the Programme Directorate and the Matrix Structure given within ESOC.

Thus, the following two major conclusions can be drawn from this experience:

> An integrated ground segment system team should be formed to define the mission, the satellite, its payload and the ground segment, as well as pertinent standards and methodologies. The team should ideally be formed some three years before the start of the Phase B of the project. The same team should be kept in charge of managing the work in Phase B and Phase C/D. The mission design should be done jointly by the ground segment system team together with the project team, thereby ensuring maximum end-to-end efficiency in the final mission design solution.
>
> This ground segment team should be led by the GSM and with other participants drawn from engineering support and should be grouped together, at least during critical phases of the project. It is necessary that both the functional and the hierarchical responsibilities are vested with the GSM, and that a commensurate approved budget be placed under the GSM authority.

Nevertheless, it will be the technical competence, the dedication and the team spirit of all team members within the ground segment team, the project team, industry and the user community, which will finally govern the successful implementation of a project. This will certainly also remain valid for the 21st century.

NASA OPERATIONS - AN AGENCY WIDE APPROACH TO REDUCE COST

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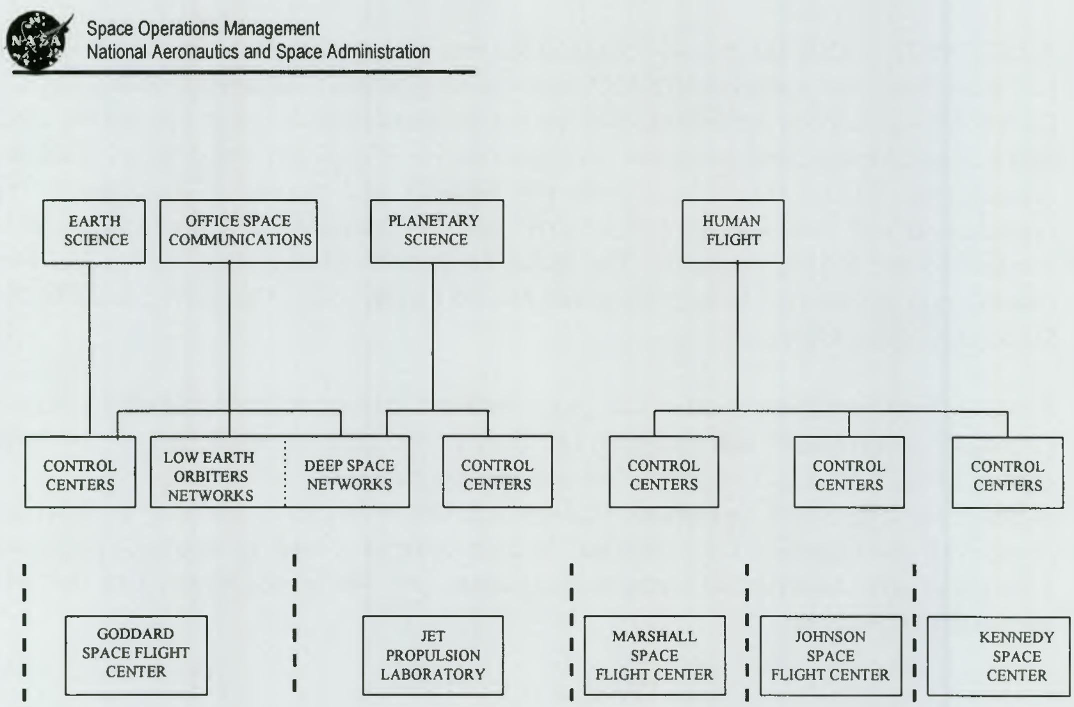
ABSTRACT. NASA has recently changed the way that operations are managed. NASA is transitioning from a discipline/NASA code-based approach to an agency wide approach. Each NASA center has developed, over the last 30 years, approaches to operations. Each center is developing capabilities that have some degree of duplicity and overlap. This new organization will be able to determine the duplicity and overlap of functions. This organization will enable more cost effective mission operations by providing common services to the NASA programs. The Space Operations Management Office has been created, is at the Johnson Space Center and headed by Mr. John O'Neill who is the NASA Director of Space Operations.

Space Operations Management will be performed in a distributed fashion with much more contractor involvement and responsibility than in the past. A single space operations contractor for NASA will be selected as opposed too many contracts with tens of contractors. The Space Operations Management Office Organizations will be described along with the responsibilities assigned to both contractors and government personnel. This paper will describe the changes, approaches and anticipated benefits of this new approach to operations.

1. PROBLEM STATEMENT

There has been an alignment between NASA Headquarters and the NASA Centers/Jet Propulsion Laboratory (JPL) which has resulted in a Center performing operational functions for primarily one NASA Code or Discipline. Thus we find that Code S watches over JPL, Code M watches over both Johnson and Marshal and Code Y watches over Goddard. Code O, the Office of Space Communications funds the Deep Space Network at JPL, the Low Earth Networks at Goddard and the Wide Area Networks at Marshall. In addition Code O funds the Mission Control Centers and capabilities at Goddard while Code S funds the same capabilities for planetary exploration at JPL. These alignments have resulted in each center having one or more contracts to support the development, sustaining and operations of capabilities to support the NASA missions. Some of the contractors have contracts at more than one center, and in some cases due to center internal organizations, more than one contract at the same center. Some of the contractors approached NASA and suggested that by consolidating contracts, and changing to contracting approach from support contracts to performance based task contracts, that savings approaching 30% could be realized. A 30% savings can assist in meeting the budget reduction goals that NASA has accepted in responding to a balanced national budget, and at the same time, attempting to maintain an aggressive space program.

At the same time that this discussion was taking place, an Agency wide review had been held by a board of experts both inside and outside of NASA. This has been called the Zero Based Review (ZBR). This review made recommendations relative to reducing the overlap between centers, reducing the size of the agency and focusing the role of each center. One of the recommendations was that the Johnson Space Center (JSC) be designated the lead center for NASA Space Operations. These two events, the contractor's suggestion that a 30% savings could be realized by combining contracts and changing the contract types, along with JSC being designated the lead center, led to NASA assigning to JSC the task of leading a study to evaluate the feasibility of implementing the contractor's suggestions.



2. STUDY PROCESS AND RECOMMENDATION

Mr. John O'Neill led an team composed of members from each of the NASA Centers involved in operations and JPL. This team confirmed that savings could be achieved by consolidating contracts, however, no specific amount of savings could be estimated. The contractors initial suggestion of a 30% savings, did not specify a baseline that the 30% would be applied to. During the same time period, each of the centers had been going through replanning exercises to reduce staff and costs at the centers, thus the NASA operations related budgets were undergoing significant reductions, and in many cases, the reductions in out year funding was accepted without a definite plan on how the operations functions could be performed for the agreed upon budgets.

The team that supported Mr. O'Neill soon found that they could discuss operations in a way that each understood. Common terms were defined as each member described what functions were performed at each center, what development functions were performed and discussed the supporting budgets. The team soon understood that there were obvious areas of duplication between centers, there were many common approaches, and several areas where each of the centers were undergoing transitions from mainframe based systems to work station based systems. The team built up trust in each other, and became convinced that there was some merit in forming a common approach to operations across NASA. The members from JSC were fast learners in the ways of robotics spacecraft, and the differences between manned missions, and the missions that GSFC and JPL were involved in. Thus in a few short months, a group of about 15 formed what was to become the nucleus of a new NASA Operations Organization.

The teams' report to the NASA Administrator recommended that:

1. An implementation team be established to initiate commercialization of the Wide Area Networks.
2. A full time transition team be established under the leadership of an acting Space Operations Functional Manager.

3. THE SPACE OPERATIONS MANAGEMENT OFFICE

The recommendations made in the study phase resulted in NASA defining a new agency function to oversee and manage all operations activities. This agency function is the first agency function to be moved from NASA Headquarters in Washington D.C. to a NASA field center. Thus the Johnson Space Center (JSC) was designated as the space operations lead center. A Space Operations Management Office was established at JSC and Mr. John O'Neill was designated Director, Space Operations (DSO). The Space Operations Management Office is the Functional manager for space operations and for space operations facilities and systems including:

»World wide space networks
»Mission and network control facilities
»Mission control facilities
»Data processing and planning systems
»Telecommunications systems.

The major. Near term task for this new organizations is to consolidate all of the existing operations contracts that exist at JPL, GSFC, JSC and MSFC that related to robotics operations and the providing of operations facilities to all NASA Missions into a single Consolidated Space Operations Contract (CSOC). In addition, SOMO is required to advise the Enterprises on the acquisition of new space operations facilities and systems. The DSO approval is required on all major operations related acquisitions.

Guidance to the SOMO is provided by a NASA operations council. This council is chaired by the Associated Deputy Administrator (technical), who reports to the NASA Administrator. The membership of the council is composed of the

»five enterprise associate administrators,
»Chief information officer
»Director, space operations

Operations funding starting in September 1998 will be provided on the basis of service level agreements. The Enterprises will allocate funding for these services to the Director, Space Operations.

The Agency has developed a set of goals for space operations. These Goals are:

- Reduce operations costs.
- Consolidate and integrate operations across the agency to eliminate duplication and achieve cost efficiencies.
- Transition the civil service and JPL/Cal Tech work force from day-to-day and routine operations to science, research and development, except for core competencies.
- Transition all day-to-day and routine operations to a consolidated contractor, including end-to-end service responsibility.
- Transition all operations contracts for products and services to performance based contracting.

- Participate in transitioning the agency to full cost accounting.
- Transition functions of operations that generate products and services to outsourcing, privatization, and ultimately to commercialized services.
- Form a partnership with the centers, such that, technical management of operations is delegated and distributed across the centers by areas of expertise.
- Stress technology to reduce operations labor costs and increase standardization and inter-operability.

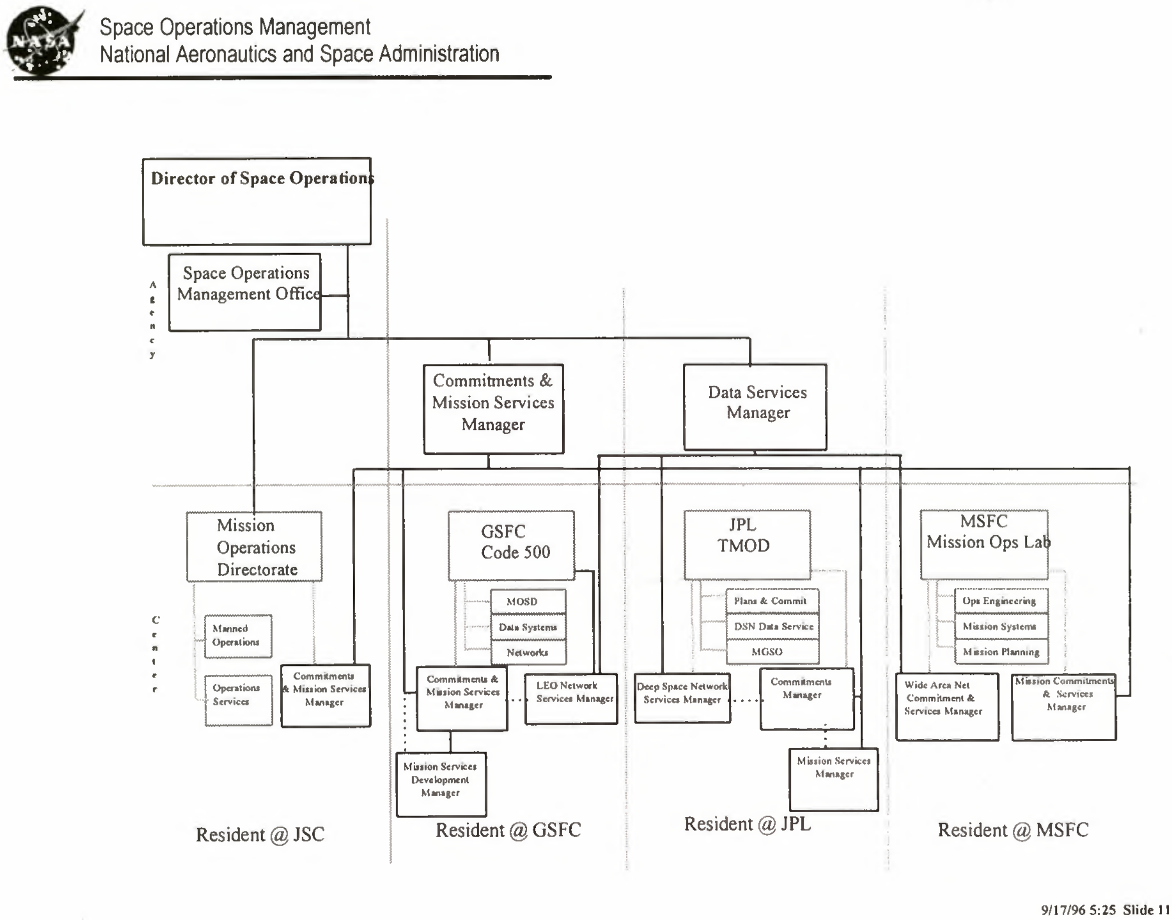
4. THE ORGANIZATION

The concept of the Space Operations Management Office (SOMO) is based on the approach of distributed participation at the field center level and consolidated management through the NASA Lead Center for Space Operations, Johnson Space Center. The intent is to establish an appropriate balance between the service provider's authority and accountability and the consolidated management's financial and architectural control.

The vision of SOMO is to form a space operations team that:

(1) understands and responds to customer needs through close personal liaison using distributed participants,
(2) achieves service excellence and cost efficiencies through centralized policy, architecture, resource, and management leadership with a management team that integrates the distributed expertise
(3) promotes opportunities to privatize or commercialize service support that lead to efficiencies and lower costs.

The distributed Space Operations Management Office organization is shown below. The three boxes above the horizontal line are the functions that are performed by staff members assigned to JSC. Those boxes below the horizontal line are responsive to the SOMO staff but remain at the Centers and assigned to the centers as shown by the vertical alignments.



The SOMO staff reporting to JSC have three primary responsibilities. The Space Operations Management Office under Mr. Steve Bales is responsible for the system engineering of the NASA Operations assets, and the management of the Consolidated Operations Contract (CSOC). This contractor will perform functions at each of the centers and thus one entity will have the visibility of common processes that take place at each of the centers. It is through the combination of the SOMO organization looking across the centers and the CSOC looking across the centers that NASA will change the approach to operations within the Agency.

The Commitments and Mission Services Manager is responsible for the process that results in one or more commitments being made between SOMO and a space project. These commitments will define the total set of services that are to be provided by SOMO to the project. These services include both Mission Services -- value added processing to spacecraft, payload or radiometric data, and Data Services, the delivery of data transmitted between space vehicle and a control center or a user location. The characteristics of these services such as quantity, quality, continuity and latency are specified along with the cost for these services. The added dimension of providing in a commitment document, the charge for providing these services is new to the Agency. In the past, many of these services have been provided to a project "free." The services were funded under a separate budget by the Office of Space Communications. This budget was to provide "necessary services" to the flight projects. As with any commodity, the projects tended to use the "free service" to lower the costs that projects were responsible for such as the design and development of the spacecraft and payload. The Commitments and Data

Services Manager (C&MSM) is also responsible for the design, development, sustaining and operation of the Mission Services that include control centers, orbit determination, scheduling, sequencing and planning systems and data processing. Again, for the first time NASA has created a position that looks at these services across the agency as opposed to a center view of these processes.

The Data Services Manager (DSM) is responsible for the reception and delivery of data transmitted from a spacecraft to a control center or a user location. Assets which NASA has for these services include the Deep Space Network (DSN), the Low Earth Orbit (LEO) networks, Data Relay Satellite System (TDRSS) and the Ground Network and the Wide Area Networks. Together these networks receive data from satellites, transmit commands and information to the satellites (DSN and LEO Networks) and deliver the data between the control center or user and the tracking assets (WAN). The Ground Network is used primarily to receive high rate science data (10 to 100's of megabits per second) from LEO satellites. In most cases these LEO satellites use the TDRSS for TT&C.

Both the DSM and the C&MSM have individuals at each of the centers reporting to them. It is this 'team' that will be changing the NASA approach to operations.

The Space Operations Management Organization then has the following attributes

1. Johnson Space Center has been delegated the lead center for operations.
2. The Space Operations Management Office, at JSC, has been established to administer this responsibility.
3. The Office utilizes the expertise of individuals and organizations located at the Centers, it will not become a centralized office that performs all operation functions at Johnson.
4. This organization chart shows this relationship of the center roles with respect to the SOMO.
5. The functions performed by the Headquarters Office of Space Communications will, in a large measure, be re-assigned to GSFC, MSFC, JSC and JPL.
6. The SOMO will be involved in the approving:
   ⇒ New development initiatives
   ⇒ The review and approval of new customer agreements
   ⇒ The NASA operations architecture
7. The execution of space mission operations will remain the responsibility of the NASA Program and Project Offices. Thus the SOMO will provide services to a project like HST or Cassini, but the project will be responsible for the execution and the conduct of the mission.
8. All new operations facilities and capabilities will be reviewed and concurred with by the SOMO. If a capability is needed at JPL, and resources exist at GSFC, then SOMO will recommend to the requesting Headquarters Office that the existing capability be utilized.

5. CONTRACTOR INVOLVEMENT

NASA plans to issue a RFP in the fall of this year. This RFP will call for a 9 month study of the overall architecture of NASA operations including the S/C through the delivery of scientific products to the investigator. This the contractor with the best architecture will then be awarded the Consolidated Contract. This will enable the transition from Government involvement in operations to the involvement of a single agency wide operations contractor in these currently either Government roles or Government directed efforts. This agency wide operations contractor will replace the tens of individual contracts that exist now throughout the agency.

6. SOMO INVOLVEMENT IN ANNOUNCEMENT OF OPPORTUNITIES AND MISSION APPROVAL

The leverage to reduce lifecycle costs is greatest when the mission concept development during Phase A and B includes representatives from the operations services areas. Two actions have been taken to strengthen this involvement. First, SOMO is generating the information for inclusion in future AO's which associate prices for services provided. Thus the cost of using a 70 meter antenna for example, will be included in the AO. The future missions that are selected will be selected based on both science merit and life cycle costs. Thus a mission that minimizes the S/C development costs, but requires 24 hours per day of tracking services, will have to compute the cost of those tracking services in the life cycle cost of the mission.

Secondly, SOMO will have an input and participate in the approval process of NASA selecting studies to go into approved and funded missions. Once again, the prudent use of existing operational assets, as opposed to the design of a mission that does not use standards, and proposes to duplicate existing capabilities will most likely not be selected.

7. THE CHALLENGE

While all this is going on, we are still operating missions. The challenge is to restructure our approach to operations, and to do this in a way that maintains our current support to flight projects while changing NASA's approach to Space Operations.

PREPARING MISSION CONTROL TEAMS FOR LAUNCH USING OPERATIONAL SIMULATION PROGRAMMES

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ABSTRACT

Launching and commissioning spacecraft are high risk, high profile tasks. A spacecraft on the launch pad represents a large investment of time, money and effort which can only be justified once the spacecraft is safely in orbit, operational and providing mission return. Protecting this investment means ensuring that not only the systems that have to perform this task are tried and tested, but also that the people involved are well prepared.

When the risk of incurring mission failures is increased due to the use of new technology in the spacecraft or ground segment then the requirement for a high quality training programme for the mission control team is very strong.

This paper describes the manner in which operational flight simulations are used as a effective means of providing this team training at the European Space Operations Centre (ESOC) in Germany. It is based on experience gained during the ERS-2 and CLUSTER simulation programmes and it attempts to highlight the techniques used to make the simulation campaigns cost effective.

1. INTRODUCTION

It is a fact of life for spacecraft operations engineers and managers that the first time they carry out a critical procedure on their spacecraft in a realistic environment it will be in-orbit. The implications of making mistakes at this time can be disastrous and in the extreme case result in a loss of mission. Clearly there is a requirement for pre-launch testing and training which allows time for confidence in the system, procedures and people that perform these activities to be built up. How this is performed depends on the cost balance between the risks and benefits.

The risk/benefits analysis will depend on such issues as

- Is the technology used in the system (launcher, ground segment and spacecraft) new?
- Has the technology already been proved to be reliable?
- Is the mission concept already proven?
- Is the spacecraft or the operational concept complex?
- Is the mission control team experienced in this type of operations?
- What level of error is the mission concept/spacecraft robust enough to accept?
- Are the engineers involved in the pre-launch preparation phase going to be carried forward to the exploitation phase?

The European Space Agency's operations centre, ESOC, in Germany deals with high profile, technologically advanced spacecraft and ground segments. They are usually one-off scientific or technology demonstration satellites and following the launch and commissioning phase ESOC is also usually responsible for the exploitation phase of the mission. The requirement for high quality pre-launch preparation in these cases is particularly strong.

Providing spacecraft command and control functionality during the launch and early orbit phases of a mission involves the interaction of complex systems which are distributed geographically. Also the mission control team performing these activities is made up of many smaller support teams each with their own areas of responsibility. All these systems and teams must work together as one unit to maximise the chances of mission success. The key challenge is to provide a method in which this training and testing can take place in an integrated environment.

The philosophy employed at ESOC to provide this is to maximise the representativeness of the training environment by using as many of the real systems and teams as possible. The one real item which cannot be used, the spacecraft in it's operating environment, is represented by a software system known as a simulator. This approach is especially effective in spacecraft operations due to it's remote nature. The mission control team can interact with each other and the simulator through the ground control system as they would in reality.

The approach adopted is, not surprisingly, expensive. The two most significant cost drivers are:

(1) The procurement of one-off simulator.
(2) The utilisation of real systems and people.

It is paramount therefore to ensure that both the modelling requirements on the simulator and the planned training programme are valid. That is that they are directly related to the risk analysis of the operations. This paper argues that the risk analysis should drive the planning of the training programme which in turn should drive the requirements on the simulator. By focusing on how the simulators are actually used in training, during the simulator requirements phase, substantial cost savings can be made. This can be achieved by focusing effort in essential areas while reducing the number of modelling requirements overall.

It also attempts to communicate some of the experience gained in the planning and management of the training programmes. This experience has led to several management practices which contribute to making sure that each individual simulation is as effective as possible. This in turn ensures that the training objectives can be met while minimising the cost and time needed to attain them.

2. SIMULATION CAMPAIGNS

In order to present the conclusions from this paper it is important to understand what constitutes an ESOC simulation and how the programme is planned.

The simulations are not "teacher led" as the participants take responsibility for their own training. An independent simulation officer is appointed who oversees all the planning, execution and monitoring of the campaign.

2.1 Initial Planning

About 18 months before the start of the simulation campaign the simulation officer starts a dialogue with all the team leaders regarding the content of the simulations. At the core of this process is the selection of the 'scenarios' i.e sections of the mission timeline to be simulated. The format of the simulation campaign is to take these scenarios and then to repeat them several times in a "do and review" cycle.

These inputs are then combined taking into account such issues as the training aims and the simulators ability to support them. A proposal based on the resources available and detailing the simulation scenarios and the planned number of repetitions. After review and modification a consensus is reached within the team and then the plan is formally approved. Typically a simulation campaign will be executed in the last 4 to 6 months prior to launch depending on mission complexity.

2.2 Execution

On each simulation day the simulation officer briefs the mission control team on the scenario and briefly explains the operations ahead.

The simulation itself constitutes the execution of a part of the mission timeline under realistic conditions. It is a "free play" exercise under the supervision of the simulation officer who monitors the progress of the team as they attempt to reach their mission objectives within the constraints of the flight control procedures.

After the end of the simulation a de-briefing session is held in which each participant makes a public self assessment of their own performance and they highlight any problems encountered. Then other members of the team are asked to give their observations on that team member's area. Special attention is given to identifying problems relating to the interaction and interfaces between the different teams. Once these problem areas are identified actions to find solutions are allocated during the meeting.

2.3 Simulation build-up

Initially only the core flight control team participate in the simulations. However over time, other teams are added including flight dynamics and spacecraft experts, network controllers and ground station personnel.

The initial simulations are run with no injected failures. However as the programme progresses contingencies are injected by the simulation officer and the team are forced to enter contingency recovery procedures in order to achieve their mission goals. These failure scenarios are made increasingly more complex, sometimes to the point at which continency procedures themselves have to be designed and approved during the operations.

3. SIMULATION PROGRAMME MANAGEMENT

In order to effectively manage a campaign it is important to know what are the aims and objectives of the campaign. Terms such as "team training" or "mutual confidence building" are often used but these do not really help when trying to justify the cost of the campaign and attempting to make it more efficient.

This paper argues that the primary aim of a campaign must be to reduce mission risk down to an acceptable level. The main sources of risk should have been initially identified by the analysis that resulted in the requirement for the training. This therefore should be used as the driver in the campaign planning and the reference with which the cost-effectiveness of the training must be measured.

As a starting point for the whole simulation campaign (and as is argued later, the simulator design) a risk analysis of the operations should be performed early in pre-launch preparations. The output of this analysis should be the high level aims and objectives of the campaign and a selection of simulation scenarios with a corresponding test criteria.

At ESOC this process is done by each of the team leaders, who identify those parts of the timeline in which the risk in their area is greatest. This input is collated and the result is the selection of the simulation scenarios. Unfortunately this approach lacks the coordination necessary for an agreement on objectives and test criteria to be reached. It is also done very late in the pre-launch preparations reducing it's potential impact significantly.

These simulation scenarios then become a test bed in which mission risk and team performance can be measured. The scenarios are repeated with the conditions gradually worsening on each cycle. When the mission control team can demonstrate that it can attain the simulation scenario mission goals under worse case conditions one can say that the mission risk has been reduced to an acceptable level and the training was successful.

In this case "worse case conditions" is the test criteria used for the training verification and it needs to be defined clearly and early. It defines the level of competence the organisation requires from the team before it accepts the risk is acceptable.

Again at ESOC the test criteria is usually that the mission control team have to be able to reach mission goals under far worse conditions than those that could reasonably be expected. This is not necessarily cost effective as the approach is used for all missions, be they high or low risk.

In order to make the process cost-effective every effort is made to maximise training benefit gain on each cycle through a scenario. Using this approach the unacceptable mission risk will be eliminated in the minimum cycles possible which produces the maximum saving in time and money.

Various training and management practices are used at ESOC to maximise the training benefit from the simulations. These range from careful consideration of timings and schedules through to methods designed to encourage skill transfer between mission control team members.

3.1 Schedule Management

Schedule planning should try to minimise costs by considering obvious costs such as travel expenses for those team members not permanently based at the operations centre such as industrial spacecraft experts. However cost savings can also be made by ensuring that the training value of individual simulations is maximised. It has been found that simulations executed in the middle of the week are much more effective than those executed on a Monday or Friday. This is simply because the preparation work and post simulation analysis can take place on the day before and after the simulation in normal working hours. Also after every simulation there is a certain feedback time required before actions identified, such as updates to procedures, can be implemented. Therefore executing simulation scenarios of a similar nature too close together is not efficient as the same errors will often be repeated.

As has been explained the simulation campaign relies on the repetition of selected scenarios. The first few simulations will be nominal and a substantial gain can be made if all parties participate in one of these early simulations even if they then only re-join the campaign much later. These early simulations provide an opportunity for all parties to become familiar with the each other and the operational environment in which they must work. It also ensures that the core team is not working with any major assumptions which when proved to be incorrect later in the programme would result in a major loss of time, effort and motivation.

Repetition in the schedule forms one of the cornerstones of the simulation campaign strategy. It enables the team to monitor its own performance as it improves and therefore build up confidence in the system and each other. It also enables the simulation officer to slowly exert more pressure on the team by injecting more complex and more frequent failures in the same scenario. As the team members become more confident and cohesive they are eventually able to cope with failure levels much higher than that which can be reasonably expected in the real mission.

3.2 Time Management

Simulations tie up people and equipment which could be utilised in other preparation activities or other areas. It is important to realise that this cost can only be justified if a significant training return is gained. The training return from intense simulations decrease if they are left to run over too long a period as the team becomes exhausted and simply cannot absorb any more. Therefore it makes sense from both a training and financial point of view to plan and execute simulations which can be kept within a normal working day of 8 hours. However a simulation must also be terminated in a way which relates to the aims and objectives detailed in the briefing. One technique for this when these aims have not been achieved is to request a meeting in which both the present status and the planned operations required to reach these goals are presented but are not actually executed.

A additional disadvantage of exhaustion is that the team will not de-brief efficiently. During a simulation the team members are effectively role playing and they must step out of that role in order to extract and make an objective assessment of the lessons learnt during the day. This becomes much harder when the team members are exhausted and still emotional from the day's activities. This in tern makes the de-briefing sessions longer and less productive.

3.3 Simulation Organisation

Training is much more effective when all team members understand the whole operational concept and their place in it. To help this the simulation's aims and objectives are explained to everybody involved before the simulation begins. This is followed by a brief explanation of the operations about to be performed from a broad perspective.

Similarly in the debriefing each member is asked to contribute, not just team leaders. Also all simulation documentation is issued to all participants to help establish an atmosphere of open trust and involvement.

Team members not actively involved in the simulation are asked whenever possible to role play other positions not occupied. For example an off duty flight control engineer might be asked to provide an industrial support role to the flight control engineer participating.

During a simulation important events, problems and the rationale for decisions are recorded. They are then issued in a report as soon as possible to all members of the mission control team (including those who did not participate) to provide feedback within an appropriate timescale. This also helps to keep everything open and available for discussion within the team.

3.4 Training aspects

An important part of the training is the transfer of skills and knowledge from specialists in one area to a wider group of team members. Often this is directed towards the top of the team hierarchy as this will help managers with decision making in the real operations but there are also significant advantages in passing this knowledge down as well.

An extremely effective mechanism for achieving this is by using team briefings. These are part of the ESOC operations concept and are usually held in response to a failure. The flight director will ask the operations engineer responsible to brief key positions in the team on the failure and it's implications and then manage a discussion on the best way to proceed. In simulations these briefings can be opened up to all members of the team not active at the time and enable skills and knowledge to be transferred to a much wider group of team members. For this reason it is common practise to instigate these briefings far more frequently in simulations than would occur during the real mission.

Simulation is a very powerful training tool. The team members experience increased involvement and gain experience in performing and making operational decisions under stress levels which they might face during the real operations. The training effect this produces depends to a large extent on the amount of realism achieved in the simulation. It must be understood that realism is largely subjective and in order to achieve it the whole mission control team must co-operate. Again this largely depends on explaining this requirement to the team and gaining agreement that everybody will act exactly as in reality unless instructed otherwise by the simulation officer. No amount of sophisticated simulator modelling software can replace the contribution this makes to the effectiveness of a simulation.

However it is sometimes advantageous to forego realism but only if a significant training advantage is achieved. For instance it is often common practise to compress timelines if the real operations are not intense enough to achieve a good training effect.

The monitoring and supervision of the simulations is a very essential task. Simulators are never completely accurate and although the term 'free play' is used to describe the interaction of the mission control team with the simulator this can be dangerous when performed without supervision. The simulation officer must be very careful to avoid reinforcement of errors by team members in response to incorrect simulator modelling. He has access to extra information internal to the simulator which enables him to decide whether a problem is due to simulator modelling or an operational error. Using this information he must guide the team in order to maximise the training value of the simulation. This does not always mean that a simulator problem is declared immediately - for example there may be significant training value in letting a mission control team assess all possibilities before declaring that the telemetry they are seeing is completely unrealistic.

4.0 SIMULATOR PROCUREMENT

Procuring a one-off piece of complex modelling software is not cheap and the more complex the modelling required the more expensive the software will be. Therefore once the decision to buy a simulator has been made it makes financial sense to make sure the modelling effort is focused in the correct areas.

4.1 User Requirements

If one is to adopt the philosophy that user requirements cost money then a good approach before starting to write them is to perform an extensive needs analysis. Typically this will reveal several areas in which the simulator will be needed in the pre-launch activities:

- test tool for the ground control system
- verification tool for flight control procedures
- training tool in the simulation campaign

An analysis of these areas reveals that the majority of the modelling requirements will come from the simulations campaign as the other two uses are mostly subsets of this although the other areas cannot be ignored. However it is sensible to use the campaign as one of the starting point from which the initial requirements can be derived. As has been stated earlier the planning for the simulation campaign relies on the selection of various simulation scenarios based on a risk analysis of the operations. Presently at ESOC this is not performed until 18 months prior to launch by which time the simulator has already been designed and delivered.

If this was available at the user requirements stage of the simulator development with a explanation of the operational activities that take place within each scenario it would provide an extremely good basis from which to abstract essential requirements. It would also be a major step forward in communicating to the development team an understanding of how the simulator will be used. This will help them considerably in making decisions at the design phase.

Also there is a natural tendency to leave the responsibility for defining modelling requirements solely with flight control engineers. Although these engineers are the technical domain experts they usually have less idea of how the simulator can or cannot be effectively utilised in a campaign. As a result requests are sometimes made for detailed modelling to be provided in areas where a much simpler model combined with simulator manipulation tools would be more effective and considerably cheaper. It is suggested that a early definition of the campaign contents will enable engineers to make an informed selection of requirements focusing on needs and usage rather than purely technical considerations. This will reduce the requirements and produce a cost saving while improving the quality of the campaign.

5.0 CONCLUSIONS

Simulation campaigns are expensive. They require an investment in a complex, one-off, software simulator and the use of people, equipment and time just in the pre-launch preparation phase when all three are extremely precious. However this cost must be weighed against the risk of a degraded or lost mission. When a mission incorporates new elements in the form of technological advancements, mission concepts or personnel this risk will increase. One method of reducing this risk is providing a high quality training simulation programme for the mission control team.

The purpose of a campaign should not be to perform team training, end to end testing or to validate the flight control procedures although these may be gained as by products. The purpose of the campaign is to reduce the mission risk down to acceptable levels. An analysis of the operational risk should be performed which will yield the simulation scenarios. Using these the campaign can be initially planned and this should then drive the user requirements used in the simulator design. Relating the requirements to how the simulator will be used in training can result in substantial cost savings as effort is focused on the essential areas and not wasted in others.

During the campaign, as the simulation scenarios are run in cycles, it is possible to use them as a measure of team performance and mission risk. When the mission control team demonstrates that it can attain mission goals in worse case conditions then the team is ready, mission risk is at acceptable level and the training has been successful. Every effort must be made to keep costs to a minimum in this process. This is achieved by ensuring the maximum training benefit is gained from each simulation allowing the number of simulations required and their associated cost to be minimised. The management practices outlined in this paper have been refined over many years by ESOC simulation officers and they all attempt to do just that.

A Prototype for an Operational On-Board Software Maintenance Infrastructure

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Abstract

The European Space Agency and its Operation Centre (ESOC) has experienced in the past years increasing difficulties in the maintenance of on-board software, especially during later phases of long term missions, where application expertise tends to vanish at the system providers side. In addition, the maintenance setup differs between missions, and in the past, no real standards were followed with respect to error reporting and configuration management. In most cases, the manufacturer is responsible for configuration management and updating of source code [1].

Increasing de-facto standardization with respect to programming language used for on-board software construction, reusable software components and a defacto standard for the on-board processor enables the transfer of the responsibility for the maintenance activities from the software manufacturer to the operation centre (maintenance of payload systems is not considered).

The establishment of an on-board software maintenance facility is guided by the fact that the maintenance process represents an ordinary software development life cycle. The facility therefore must include the tools used during the software development, e.g., compilers, a configuration management facility, a documentation tool, and verification support, and in specific Software Validation Facility (SVF). The main objective of the maintenance facility is to enable smooth integration of the tools used during software development, and support reuse of maintenance expertise across the missions.

Introduction

Post-launch maintenance of on-board software has been carried out in an ad-hoc manner on a mission specific basis. In order to ensure high quality of maintenance activities, a more standardized strategy is required.

The operation centre is responsible for the day-to-day management and control of mission satellites. This implies that the operation centre obtains considerable knowledge about the mission and that the centre early will be aware of abnormal behaviour of the satellite. Through the functions of the mission control system, operations has the necessary services to detect on-board malfunction and assess the corresponding mission impact. Moreover, expertise on the on-board software is increasing within operations during the mission, while the expertise at the on-board software manufacturer will diminish after launch, caused by difficulties with maintaining the necessary capacities, i.e., experienced staff and dedicated testing and validation facilities. Thus, the most natural target for the responsibility of on-board software maintenance will be the operation centre, which has the closest contact to the spacecraft throughout the mission.

The European Space Agency (ESOC) has initiated a study for investigation of the feasibility of concentrating maintenance activities at the operation centre, based on the existing infrastructure. The study has focused on:

- identification of required services, expressed in terms of a User Requirements Document [1].
- discussion of existing facilities at the operation centre in view of the above mention user requirements.
- specification of a supporting architecture.
- establishment of a prototype to illustrate the architecture.

First, this paper describes maintenance and validation in general. Then a number of critical attributes for a maintenance facility are discussed, and finally a prototype for a subset of the maintenance capacities is outlined.

Maintenance

Maintenance can be classified as follows:

Corrective Maintenance: Activities undertaken in reaction to erroneous behaviour of the system.

Adaptive Maintenance: Activities necessitated by changes in the environment of the system in order to adapt to the new conditions.

Preventive maintenance: Activities that improves the maintainability and adaptiveness of the system.

A domain analysis [1] showed the distribution of the maintenance activities between the different maintenance classes. The table below shows that in the projects mentioned, corrective maintenance dominates the maintenance activities.

Project	Size of OBS	Maintenance
Eureca	2.7 MB	corrective : 12 adaptive : 1 preventive : 2
Hipparcos	32 KB	corrective : 15 adaptive : 6 preventive : 0
ERS-1	64 KB	corrections
Olympus	32 KB	most adaptive

Maintenance of on-board software is mainly concerned with corrective or adaptive maintenance. Corrective maintenance can be caused by malfunctioning software, in which case the maintenance is carried out as problem analysis, software modification, verification and validation and finally release of modified software. Changes between the phases are controlled by maintenance management, while actually transferring the software source code and documentation is supervised by configuration control. In principle, maintenance of critical software follows the traditional development cycle, but with special focus on testing and verification of changes, before the updated system is introduced. Figure 1 illustrates the maintenance process.

transfer: the transfer of the software system and accompanying tools and documentation is carried out during the delivery of the tested and validated system.

problem analysis: a software problem report is received, and the observed behaviour is compared to expected behaviour. The problem is identified and a software modification request is produced.

software modification: based on the modification request, the software is changed, and unit tests are performed.

verification & validation: the changed software system is verified and validated against test sequences etc.

releasing: the changed software is handed over to the control centre. The mission control centre is responsible for generation of uplink sequences and for the final uploading.

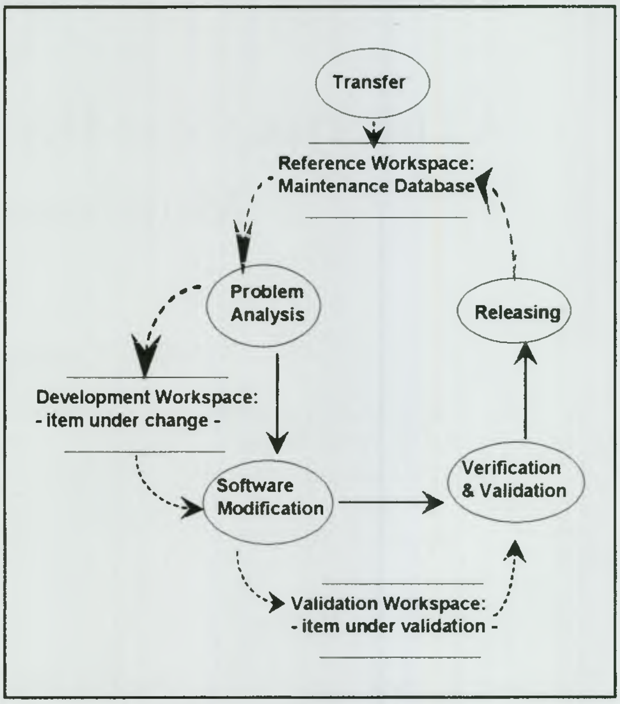

Figure 1: Maintenance Process

Each of the different roles of the maintenance process puts specific requirements to the maintenance facility. An important point is, that facilities for these activities exist and have been used. To provide a maintenance facility is therefore a question of identification of the required services, and establishment of supporting facilities to exist throughout the lifetime of the on-board software.

Verification and Validation

Verification and validation is used during design and construction of the software following a software life-cycle as described in [2]. In addition, independent validation is used to discover hidden faults in the software, that may cause undesired spacecraft situations. Independent software validation is carried out outside the software vendor, and plays today an important role due to the increasing demand for more software on board.

As shown in figure 2, validation covers all test aspects as defined in [2]:

unit testing: verification of the module functionality (black box test) and module implementation (white box test).

integration testing: verification of the interfaces between modules, i.e., data exchange across interfaces between modules conforms to the definition.

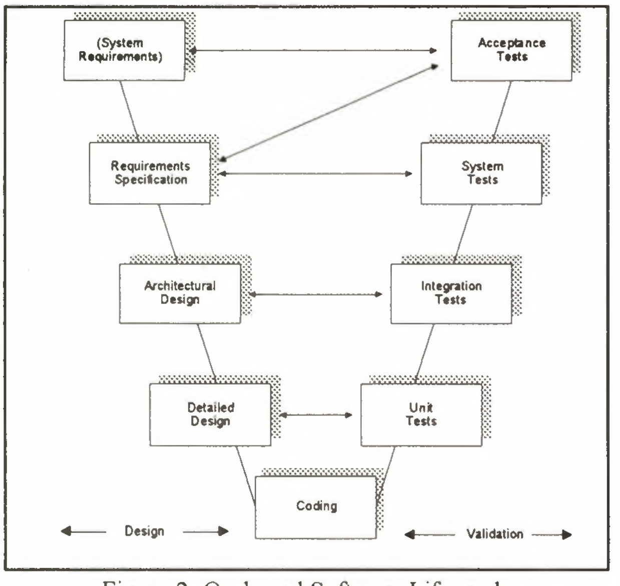

Figure 2: On-board Software Life-cycle

system testing: validation that the system complies with the software requirements.

acceptance testing: validation that the system complies with the user requirements

The validation activities are in operation during the software development as well as during formal (independent) software validation. An essential part of the maintenance process is an efficient validation of the changed on-board software. The purpose of the validation is to ensure:

- that the corrected software has obtained the goal of the maintenance activity, e.g., removed a program error (corrective maintenance) or circumvented changes in the environment (adaptive maintenance).
- no new problems have been introduced by the changes.

Support tools for verification and validation of on-board software are essential parts of a maintenance facility. Software validation facilities (SVFs) are matured, and provide today a framework for establishing generally applicable environments for independent software validation, based on a client/server architecture. In addition, an SVF has proved helpful during maintenance activities, [8].

Standards

One of the roads to operational maintenance is the use of standards, enabling the maintenance teams to reuse experience across different missions, and also supporting the reuse of existing maintenance facilities. Standards are emerging, and focus has been on the applied programming language for on-board software, and the usage of a standardized on-board computer in several mission. Another approach is the reuse of software components, which makes software development faster and more reliable, and which definitely will ease the maintenance activities. In addition standards have been specified for telecommand and telemetry structures and processing, and finally considerable effort has been put into standardization of the simulation environment used during test, validation and training.

This can lead to a standardized strategy for the maintenance task, thereby satisfying requirements on mission quality.

The Maintenance Facility

The purpose of the maintenance facility is (1) to support the transfer of knowledge between the on-board software vendor and the maintenance team, and (2) to provide tools and facilities for supporting the maintenance process.

Transfer includes the transfer of the on-board software system, documentation and design documents, user manual and test reports. With respect to maintenance, the transfer also includes the transfer of dedicated tools and facilities used during the software development. This includes the Software Development Environment, e.g., design tools (such as HOOD tools), documentation tools, compiler and debugger systems. The Software Validation Facility is also essential, as discussed above. The transfer also includes the simulation environment and setup.

It is clear, that a maintenance facility is designed with two conflicting goals:

1: inclusion of specific tools and facilities used for the mission in question in order to enable reproduction of mission specific documentation and object code.

2: provide a generic environment for maintenance of missions in general in order to enforce expertise reusability.

After the transfer, the maintenance process consists of problem analysis, software modification, software validation and finally releasing of the software. The process is controlled by maintenance management in order to ensure progress of the process according to the maintenance cycle (e.g., confirming the release of maintained software), and configuration management is used to ensure consistency of versions.

During *problem analysis* the software to be maintained is investigated, using the existing documentation, software and simulation facilities, log files generated during the mission, etc.. This requires the use of a number of facilities, the simulation environment (e.g., SIMSAT, [3]), mission control system (e.g., SCOS , [4]), design tools (e.g., HOOD, [6]), documentation tools, debugging facilities and reverse engineering.

Software modification covers the required changes of the software and the accompanying documentation. Here, the main usage is the compilation environment. In addition, the software validation facility is in use for testing purposes, e.g., the unit tests. The main focus during validation is on white box testing.

Software validation is essential, and includes the formal test and approvement of the changes of the on-board software. The software validation facility established during the transfer is used, and the relevant tests are performed. Software validation covers white box testing as well as black box testing, with main focus put on black box testing.

During *software releasing*, the approved software changes are handed over to the mission control system for uploading. The changed software and accompanying documentation is transferred to the reference work space.

As indicated in the above discussion, the maintenance facility is providing a mixture of already existing capacities. The main objective is to provide an environment for smooth integration of tools and facilities already used during the development and validation of the on-board software. In addition, the maintenance facility should provide one simple and effective configuration to be used during all phases of the maintenance process. Figure 3 shows a maintenance facility workstation. It should be noticed, that the workstation is representing access points for the capacities included in the facility rather than containing the facilities themselves, e.g., the workstation will provide an interface to the simulation environment, which may be running on a different workstation.

As mentioned above, the keywords for the on-board software maintenance facility are flexibility and genericness.

Flexibility:

The maintenance facility shall be flexible with respect to the application of the tools and facilities used during the development and validation of the system in question. This implies, that it shall be easy to integrate different tools into the maintenance facility.

Genericness:

The maintenance facility must focus on genericness,

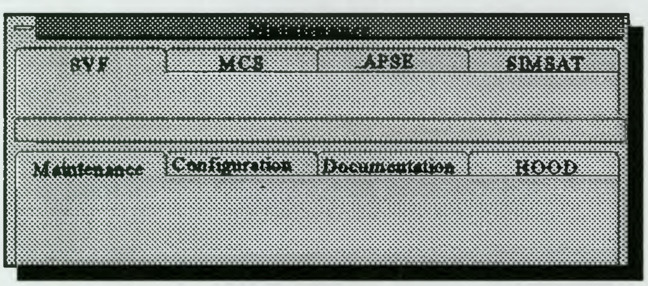

Figure 3: Maintenance Facility Workstation

meaning that the same maintenance facility can be used for several missions. An objective of the project has been to establish one maintenance configuration suitable for all parts of the maintenance process, including management of the maintenance process and configuration management.

Tool Standards:

For a mission, the maintenance facility might have to be configured with mission specific tools for every facility, which introduces overhead with respect to achieving the needed expertise for the maintenance staff. Different levels of standardization of the tools will support the flexibility and genericness requirements, e.g., the same documentation tools should be used [or weaker, the documents produced shall conform to specific formats]. In this way, a standard documentation tool can be included in all maintenance facilities, thereby supporting reuse of expertise across missions. The following tools are to a certain degree standard for development, validation and maintenance of on-board software:

maintenance management: the actual maintenance management is introduced in the maintenance setup. This implies that maintenance management is independent of the software development, and a feasible commercially available tool can be selected as the standard tool.

configuration management: configuration management must be capable of combining versions from different, independent tools. This implies, that the configuration management consists of a commercial tool combined with specific configuration management procedures.

documentation tool: the documents delivered must be in a format understood by FrameMaker.

software validation facility: : a software validation facility with the target on-board computer integrated in the facility.

HOOD tool: the HOOD specification must be delivered in the Standard Interchange Format.

reverse engineering: reverse engineering is required when extracting documentation of software structures from the source code.

Ada compiler and debugger: TLD Ada compiler and debugger. If different Ada compilers are used, an generic Ada Programming Support Environment should be used (*Life**ADA, [7]).

on-board computer: A 1750A computer (MAS281, [5]), which is supposed to be the on-board computer for future missions.

simulation environment: SIMSAT run time kernel with mission specific simulation models.

mission control system: the future mission control systems will have their own configuration management system, i.e., the maintenance facility configuration management must be able to reuse the information stored in the mission information base of the mission control system.

A Prototype

A subset of the required functionality has been selected for prototyping. The prototype architecture supports the construction of one physical configuration to be used throughout the maintenance phase. The prototype is based on the following assumptions:

- the maintenance facility shall be based on the infrastructure existing at ESOC.
- the maintenance workstation is a Sun SPARC workstation.
- the simulation environment is running on a DEC Alpha computer.
- the target computer is used for hardware-in-the-loop testing and simulation.
- the target computer is connected to the DEC Alpha computer for usage either during (remote) debugging (white box testing) or during functionality testing using the simulation environment (black box testing).
- the maintenance workstation and the simulation workstation are connected via an Ethernet, and both are supporting the TCP/IP protocol.
- the Ada compiler/debugger runs on the maintenance workstation, which provides access to the simulation environment (running on the DEC Alpha, the access is performed by X-Windows).

Specifically, the prototype implements services to be used through software modification and software validation, and is made out of (1) debugging facility used for white box testing (TLD Ada debugger), and (2) simulation facilities used for black box testing (Cluster spacecraft simulator using the SIMSAT simulation kernel [3]). The target board is an implementation of a 1750A computer (MAS281 SHAM board, [5]), which is also used in connection with Cluster simulation based on hardware-in-the-loop configurations. Figure 4 illustrates the hardware configuration. The underlying architecture allows the target board to be connected to either the DEC Alpha as in the prototype, or to the Sun SPARC workstation. As shown in the figure, the DEC Alpha is the host for the target board in the prototype.

Client/Server Protocol:

The actual physical location of the target computer (i.e., using the maintenance, the simulation or a third workstation as host) should be transparent to the end users of the maintenance facility. A client/server protocol is defined and implemented as part of the prototype in order to support this transparency. The requirements are:

- the host runs a server module, that accesses the target board (via the VME bus, [5]).
- workstations with client programs (i.e., debugger or simulation environment) must contain a client module for each client program.

In the prototype configuration, the TLD debugger is a client program running on the Sun SPARC station, and the SIMSAT system is a client program running on the DEC Alpha workstation.

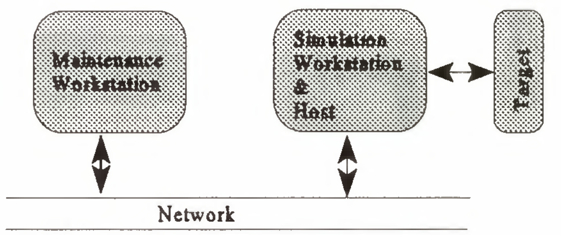

Figure 4: Prototype Hardware Configuration

Software Architecture:

The client/server structure has been designed to allow concurrent usage of the target board, i.e., more than one client can be connected to the server at the same time. This requires that each client program must be able to react reasonably to interventions made by colleague client programs. For example, the client programs in the prototype require that the simulation environment can handle single stepping the on-board software, introduced by the debugger. At present, the simulation environment has not been designed for this, and the concurrency aspect of the server/client protocol is therefore not used in the prototype. Meanwhile, based on the concurrency aspect, it is possible to combine the rich simulation of the environment performed by the simulation facility with debugging facilities for a close inspection of internal status of the modules.

The design of the client/server structure takes into account the possibility of:

- replacement of the on-board computer: the server module works with command families, where the basic family is loaded by default. For each target computer, dedicated families will enable the utilization of the target specific capabilities.
- replacement of client programs, e.g., introduction of new debuggers: the client system is designed as a layered set of libraries, where each library specifies a well defined set of capabilities. The basic library implements the basic functionality (TARGET_CLIENT on figure 5), reflecting basic operations as reading and writing values at addresses in addition to administrative functions such as connection and registration.

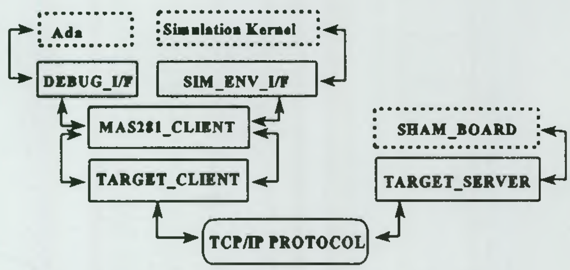

Figure 5: Prototype Software Architecture

On top of the basic library a library that provides the functionality of the firmware on the target computer (MAS281_CLIENT in figure 5). This includes operations like setting breakpoint, start and stop execution etc. This firmware library is used by dedicated libraries (DEBUG_I/F & SIM_ENV_I/F in figure 5), which provide operations intended for a specific purpose, e.g., by the simulation environment. It is clear that introduction of new client programs can be based on the basic library, but that the firmware library is a more suitable candidate.

Approach in future missions

The concept of transfering on board software maintenance responsibilities to the Operations Centre, in particular for long lasting missions, has been adopted by several ESA future Science Projects (e.g. Huygens, XMM, etc.).

The prototype architecture discussed above is generic in the sense that it is found in several software validation facilities (SVF) planned for delivery from the projects to Operations. In this paragraph a comparison between the architecture of the prototype above and of the proposed software validation facility (SVF) for the XMM mission is presented.

The XMM SVF proposed architecture is shown in the figure below,and further described in [10], Fig. 6 XMM SVF architecture.

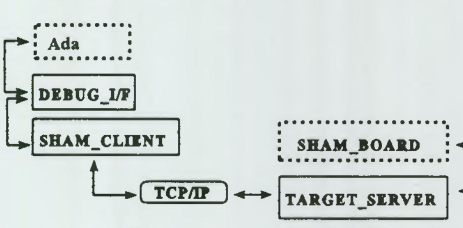

Figure 6: XMM SVF proposed Software Architecture

The basic characteristics of the two architectures are summarised in the table below:

	XMM-SVF	OBSM prototype
Server Module	Provides services corresponding to the SHAM board operations [9] and the specific services provided by project specific emulator software. This level corresponds to the MAS281_CLIENT library part of the OBSM prototype architecture.	Provides basic sservices corresponding to reading/writing memory locations. In addition a SHAM family of commands. The server handles administrative operations like connecting and registration anc concurrent access of the SHAM board.
Client Module	The debugger client uses the services provided by the server, i.e. the SHAM board functionality, for setting breakpoints, loading on-board software, etc.	Client programs contains layers of software librairies, where the lowest level is responsible for the transformation of high level commands as "set breakpoint" into bitstreams.
Commu-nication	Based on the tcp/ip protocol. This implies, that the server "follows" the SHAM board, i.e. if the board is located on a remote machine, the server is installed there as well. The communication between the client and the server works on the level of SHAM commands.	The communication between the client and the server in the form of a bit-stream protocol. Based on tcp/ip. This implies, that the client programs are responsible for packing/unpacking the stream contents.

From the Table above, the basic architecture of the XMM-SVF and of the OBSM prototype is in principle the same:

- A server module follows the SHAM board, and is responsible for the communication with the board.
- The communication between the server and the client modules is based on tcp/ip.

The main differences are where the different levels of abstraction are located. In the XMM-SVF, the server module contains the levels up to the SHAM board functionality (lies on the server side of the tcp/ip connection), while, in the case of the OBSM prototype, this is part of the client modules (is on the client side of the tcp/ip connection). When client modules exclusively use MAS 281-client servers, from the top level client programs there will be no difference between the two architectures.

Conclusion

The work presented has focused on

- analysis of requirements for an on-board software maintenance facility.
- prototyping a subset of the required functionality in order to investigate the approach.

The maintenance process contains all aspect of the software development cycle. This implies that the facilities used during software development must be available during maintenance. In addition, the maintenance facility must support the management of the maintenance process and the software system and documentation. Finally it is important to reuse expertise (mission expertise, tool expertise). The basic requirements are found to be:

1: The maintenance facility must allow smooth integration of the development and validation tools used by the mission in question (design tools, compiler and debugger, validation setup, simulation environment).

2: The maintenance facility must support problem analysis by providing tools for analysing mission log history, source code (mission control system, reverse engineering).

3: The maintenance facility must provide support for management of the maintenance process and for configuration management.

4: The maintenance facility must support reuse of expertise across missions.

In principle, the required tools and services are available at the operations centre, and the objective of a maintenance facility is therefore to enable the integration of commercial, independent tools into one coherent maintenance environment. It turns out that standardization of development and validation tools will ease the construction of a generic maintenance facility and will facilitate reuse of tool expertise.

An architecture has been developed to investigate the following:

- establishment of one physical configuration for black box testing and white box testing
- support transparency with respect to the actual physical configuration
- support the replacement of target boards and/or white box test facilities/black box test facilities

The architecture has been prototyped and the implementation validated against a selection of the user requirements. The prototype supports white box testing, using key aspects of an Ada debugger, and black box testing, based on the SIMSAT simulation environment, both on the same physical configuration, using a 1750A board as the target computer.

Future work:

Future work encompasses testing for the transparency of the actual physical configuration. This is investigated by using the maintenance workstation as host, and running the client programs as shown above.

Finally, changes required for the replacement of part of the configuration (e.g., the Ada debugger) should be investigated.

References:

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A MISSION OPERATIONS WORKLOAD MODEL FOR BENCHMARKING TEAM SIZES

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ABSTRACT. A Model has been developed for assessing the workload associated with ground operations and data processing support for unmanned space missions. This model comprises a set of algorithms which predicts the workload associated with each of the major mission operations functions. Model estimates are based on parameters related to mission complexity, operations performance policies, spacecraft and instrument control requirements, ground system architecture, and project management structure. The models are an encoding of those sensitivities identified by people who have been directly involved with performing each of the functions. The parameters used in the model are presented as well as the general model structure. A preliminary comparison with some NASA mission team sizes is given. More complete results will be provided at the conference after more data have been collected. How the model might be used to assist benchmarking team sizes among dissimilar missions and to assist in targeting process improvement efforts is discussed.

1. BACKGROUND: WHY A MODEL IS NEEDED

With the perceived need to reduce the cost of space mission operations, managers responsible for missions are scrutinizing their programs to determine where costs can be most readily reduced. For example NASA is moving toward full cost accounting for the control, communications and data processing support for missions, whereas they have previously been included broadly within institutional budgets. Studies are underway to identify the full costs of each support function throughout its life-cycle for several NASA missions. Managers will use the relative support expenditures to prioritize budget reductions. As operations budgets are almost totally derivable from personnel costs, team sizes are especially being examined, and proposed for reductions. However, the planning for reductions are generally not taking into account any measure of the size of the job being performed relative to the existing team size. These activities would be better focused if comparisons of existing mission team sizes (and related budgets) took into account the relative demands of each mission as determined by:

- The innate complexity of the intended mission objectives and related operational complexity
- The amount of ground oversight the spacecraft requires, as determined by the flight systems' design
- Performance requirements of the mission's customers in quantity, quality and timeliness
- Breadth of each team's operational responsibilities
- Complexity of the team's external interfaces and the resulting effort needed for coordination with other entities

A model provides the means of translating these mission operations demands into a metric which can be compared to the existing team size.

2. BASIS FOR THIS MODEL'S VALIDITY

Traditional cost models for space missions are based on statistical fits to historical data. There are several reasons why this approach will not work for mission operations. First, the mission operations workload is determined by the interplay of every aspect of the mission: the complexity of the intended output, as well as design decisions for both the spacecraft and ground system. Within each of these general areas there are many factors that need to be addressed separately. A second reason that statistical models can't be built, is that data of actual expenditures are not available for past missions, and what data are available is not structured against consistently defined operations boundaries. To some extent this problem is being addressed by a thorough data collection effort on a few currently operating NASA missions. However, this will still be a very limited data set compared to the number of parameters needed to characterize operations. Finally, the current rapid change in methodologies for operations make historical data not directly usable for modeling current and especially future missions.

The model being presented uses a codification of expert opinion rather than statistical fitting as a basis for its validity. While it takes into account actual workforce size to scale the model estimates, its sensitivities are determined by an approximation of the collective inputs of experts on the various operational functions as performed on several currently operating missions. While a formal consensus process was not used, some centering of opinion was achieved by iterating preliminary sensitivities with experts for most functions and requesting recommendations to adjust them. A detailed work breakdown structure was used to define the functions performed within each model element. Thus the problems of lack of data and inconsistency of data structure were avoided.

To address the effect of changes in the way operations are performed, many of the parameters were chosen to reflect the changes that might be made in redesigning a mission or its operations. Thus the experts also provided the degree to which these changes might affect operations effort in their estimates of sensitivity to those changes.

3. MODEL STRUCTURE AND FEATURES

The model estimates workload in Full Time Equivalents (FTEs) for seven of the mission operations functions commonly used within NASA. These include:

- Activity Planning (Scheduling)
- Realtime Mission Control
- Navigation
- Spacecraft Planning and Analysis
- Payload Planning and Analysis
- Payload Data Processing
- Management

Payload data processing has been separated in the model into Level 0 Processing (LZP) and Level 1 Processing, as these are commonly provided by different organizations and have different drivers. This separation allows for more precise modeling and more consistent data collection among missions. Tables 1 - 5 show the parameters used to estimate workload for each of these functions. Tables 1 - 4 show those parameters that affect more than one function. Table 1 identifies those parameters which are determined by the high level concept of how the mission will be executed. For NASA programs this is usually determined by the program office working with the scientific community, before full program funding.

Table 1. Mission Complexity Parameters

Functional Elements-> Parameters	Activity Plan/ Sched	R/T Mission Control	Naviga tion	S/C Plan/ Analys	P/L Plan/ Analys	P/L LZP	P/L Lvl 1 Proc
# of payload operational changes/day	X	X			X		
% of daily operations that are largely repetitious	X	X	X	X	X		
# of attitude changes/day	X	X	X	X	X		
Attitude knowledge precision			X		X		
# of different FOVs			X		X		
# of trajectory maneuvers/week	X	X	X	X			
# of trajectory maintenance events/week	X	X	X	X			
MBytes/day downlinked						X	X

Table 2 identifies those parameters determined during spacecraft and instrument design. Mission complexity may drive up some of these parameters unless the spacecraft of instrument designers incorporate features in the design to offset them. For example, a complex and sensitive spacecraft may have many operational constraints that would be reflected in flight rules, making planning and control challenging, unless many of these constraints were programmed into the onboard control system. Tight margins in onboard resources would increase the ground based management for data storage or command memory. Many of these parameters could be used as metrics for spacecraft autonomy.

Table 2. Spacecraft and Instrument Design/Condition Parameters

Functional Elements-> Parameters	Activity Plan/ Sched	R/T Mission Control	Navigation	S/C Plan/ Analys	P/L Plan/ Analys	P/L LZP	P/L Lvl 1 Proc
Data storage mgmt.		X		X	P		
Command memory mgmt.		X		X	P		
Power margin mgmt.		X		X	P		
Telemetry downlink mgmt.		X		X			
S/C reliability/self-safing		X		X			
# of passes/day	X	X				X	
# of flight rules not in flight s/w	X	X		X			
# of payload recalibrations/day	X	X			X		
# of ground commanded S/C subsystem config. changes/day	X	X		X			
# of ground controlled attitude control maintenance activities	X		X				

"P" refers to parameters specific to payload operations.

Table 3 indicates those parameters that can be determined by operational policy. These can also be thought of as reflecting the quality of customer (i.e., investigator) service: These address such questions as: how responsive will operations be to late revisions in science activities, how many activities will be fit into a schedule and with what precision, what percent of data downlinked will be guaranteed to be delivered, and how carefully will the health and safety of the mission by managed.

Table 3. Operations Policy Parameters

Functional Elements-> Parameters	Activity Plan/ Sched	R/T Mission Control	Navigation	S/C Plan/ Analys	P/L Plan/ Analys	P/L LZP	P/L Lvl 1 Proc
Latest payload operations change request requiring rescheduling allowed	X		X	X	X		
Timeline margin/criticality	XX	X	X	X	X		
% data capture		X				X	
Mission Risk Aversion	X	X	X	X	X		

Table 4 indicates those ground system characteristics which affect more than one function. Space/ground data service quality is determined by both the amount of data errors or outages of the data transport service. This directly affects the workload of the immediate recipients of flight data. Many of the element specific parameters in Table 5 also reflect ground process design decisions, such as the number of separate products a function must deliver to other elements each day. A definition of the more ambiguous parameters is supplied to missions who are requested to supply values, so that responses will be consistent. Level 1 processing deliveries are generally to investigators, and therefore represent a level of service to customers.

Table 4. Ground System Architecture Parameters

Functional Elements-> Parameters	Activity Plan/ Sched	R/T Mission Control	Navigation	S/C Plan/ Analys	P/L Plan/ Analys	P/L LZP	P/L Lvl 1 Proc
Space/ground data service quality		X				X	
# of control center configuration changes/pass	X	X					

Table 5. Element Specific Parameters

<u>Mission Management</u> % of other FTEs # of project external interfaces # of institutions involved in the mission # of management layers within the mission # of active PIs	<u>Spacecraft Planning and Analysis</u> # of spacecraft states actively commanded <u>Realtime Mission Control</u> % of operations requiring realtime interaction # of mission control deliveries/day Manageability of pass schedules
<u>Navigation (Orbit & Attitude)</u> # of navigation deliveries/day # of thruster recalibrations/day # of attitude sensor recalibrations/day Propellants management rating # of attitude constraints	<u>Level 0 Payload Data Processing</u> # of LZP deliveries/day LZP output quality required LZP delivery timeliness required
<u>Activity Planning and Scheduling</u> % of initial ground support requests accepted # of scheduling deliveries/day # of ground operations facilities	<u>Level 1 Payload Data Processing</u> Level 1 delivery timeliness required # of master products/day # of data input events/day Total # of physical copies/day # of distinct electronic files/day

The model's algorithms typically sum up several terms relating to the frequency of each of the major activities within the function. These are multiplied by several factors representing overall level of demand of the function's environment. Most of these factors have a vlaue between 0.8 and 1.5, representing "operationally easy" to "very challenging" respectively. The tables used to infer the factor values could be expected to change as technologies or operations processes improve.

4. PARAMETER SENSITIVITIES

The sensitivity of the total estimated operations workload for a mission to changes in any one parameter depends on the value of other parameters for that mission. To get an overall measure of the relative sensitivity to each parameter, the model was applied to the most complicated mission in the study mission set (SOHO) and one of the least complicated (ACE), replacing each parameter value for those missions with values corresponding to the minimum and maximum values used in the total mission set. The following parameters averaged between these two missions had at least a 50% effect on the total mission workload:

- # of instrument operations changes per day
- % of operations that are repetitious
- % of operations requiring realtime interaction
- Timeline margin/criticality
- Mission risk aversion
- # of passes per day

The following parameters averaged between these two missions had at least a 20% effect on the total mission workload:

- # of attitude changes per day
- % data capture
- spacecraft reliability/self safing capability
- # of spacecraft flight rules not in software

The following parameters averaged between these two missions had at least a 50% effect on the indicated functions:

Parameter	Function
% of initial data transport service requests accepted	Activity planning (scheduling)
Manageability of pass schedules	Realtime mission control
# of thruster recalibrations per week	Navigation
# of LZP deliveries/day	Level 0 processing
LZP level of process review	Level 0 processing
Level 0 data delivery timeliness	Level 0 processing
Level 1 data delivery timeliness	Level 1 processing
Total # of physical copies per day	Level 1 processing

Data processing appears to be driven by the data systems and data delivery requirements to a greater degree than mission operations functions, where mission characteristics dominate. This suggests a greater opportunity in data processing for process and system improvements to save costs without altering the mission.

5. PRELIMINARY RESULTS

This model was developed for NASA Space Physics missions to provide a independent rating to compare to the relative operations support budgets among these missions, which have varying complexity and organizational structure. Results to date, shown in Table 6, are based on partial inputs from those missions. The model is very close overall for SOHO and SMEX, slightly high for Wind/Polar operations, and predicts workload as much as 50% below the current staffing for Ulysses, ACE, Voyager, and Pioneer. More complete results will be provided at the conference when more complete data will have been collected.

Table 6. Preliminary Estimates of Workload in FTEs vs. Actual Team Sizes

	SOHO	Wind & Polar	Ulysses	ACE	Voyager 1&2	Pioneer 10	SAMPX & FAST
Management: Model	6.83	3.85	2.55	1.35	1.76	1.20	2.21
Management: Actual	7.10	3.00	8.50	1.60	3.50	5.30	3.60
Activity planning: Model	11.52	5.86	0.29	0.23	1.09	1.08	1.86
Activity planning: Actual	5.50	2.00	2.00	0.80	4.60	1.90	0.74
S/C planning/analysis: Model	8.16	3.81	2.06	1.16	3.62	0.99	5.75
S/C planning/analysis: Actual	6.00	2.00	5.80	0.70	6.40	2.20	3.09
Payload plan/analysis: Model	17.87	4.05	0.41	0.07	0.07	0.24	5.78
Payload plan/analysis: Actual	16.00	1.00	2.00	0.30	1.30	0.00	3.29
R/T Mission control: Model	19.16	6.69	4.10	0.85	3.34	3.00	2.54
R/T Mission control: Actual	18.00	8.00	5.50	2.80	3.00	6.00	2.54
Navigation: Model	4.35	1.63	0.27	0.96	0.40	0.53	6.39
Navigation: Actual	9.00	4.50	0.70	2.00	0.00	0.50	5.20
Level 0 data proc: Model	1.65	2.25	0.20	0.17	0.83	1.20	1.28
Level 0 data proc: Actual	4.90	0.00	0.60	0.60	0.00	1.00	0.90
Level 1 s data proc: Model	4.03	2.96	1.00	1.05	2.00	0.20	0.65
Level 1 data proc: Actual	5.00	6.00	2.50	1.20	2.00	1.00	7.15
Total Model	73.58	31.08	10.87	5.84	14.31	8.44	26.46
Total Actual	71.50	26.50	27.60	10.00	20.80	17.90	26.51

6. APPLICATION TO BENCHMARKING AND REENGINEERING

The model and the associated collection of actual workforce sizes by function can be used in several ways as part of benchmarking relative operations efficiency. It can also assist in process reengineering planning. The model can provide a normalized comparison of missions and can help to focus the source of those differences, and therefore where improvements are most likely to be achievable. Some examples follow.

- Actual FTE data alone can identify "tall poles" for initial targeting where the greatest savings are available
- High actual staff sizes relative to total model results will identify candidates areas which might exhibit the lowest overall productivity. Thus improved automation or better operations management alone might provide savings. This comparison provides a normalized benchmark metric of operations productivity among missions.
- High operations performance policy values (Table 3) indicate opportunities for process simplification that might be possible if these policies were relaxed.
- High values related to ground system architecture (Table 4 plus number of ground operations facilities and manageability of pass schedules) might indicate that the mission would be better served by a different or improved data transport infrastructure.
- High activity levels within individual functions (most of Table 5) might indicate savings could be derived by reducing the frequency with which activities are performed or products are delivered.

7. FUTURE PLANS

Continued development of this model will be aimed at making it applicable over a wider range of missions, adding factors related to current issues in space mission systems engineering, and creating a cost trade tool for total mission engineering.

The functional structure and generic operations parameters should make the model adaptable to other mission types. The immediate plans are to extend its application to NASA Astrophysics and Earth observing missions. Additional mission types with different characteristics and operations profiles will undoubtedly cause some revision of the parameters used and some sharpening in the way existing parameters are defined. The mission set may eventually be extended beyond NASA missions and perhaps beyond missions whose primary purpose is to measure phenomena.

Another future activity will be to add an algorithm for maintenance. This is needed to more completely address the mission operations phase, as maintenance can be a major contributor to post launch costs, and is a significant factor in system versus human functionality in life-cycle cost trades.

How to add ground system automation and address spacecraft autonomy beyond the parameters in Table 2 will be investigated. These will strengthen the model as a tool for mission trade studies as these are both popular strategies for reducing future missions' costs.

Finally, opportunities will be sought to integrate the model with mission development models (both flight and ground systems) to build a complete mission life-cycle trade capability.

A FRAMEWORK OF MISSION OPERATIONS SYSTEM MODELS

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ABSTRACT. The purpose of this paper is to show how modeling tools and the models they produce can be intermeshed so as to correlate the various views of a space mission operations system. The framework which coordinates such multiple perspectives is intended to provide the essential common language by which user, developer and technologist can communicate more clearly. A short IDEF modeling demonstration is used to suggest avenues for further exploration.

INTRODUCTION

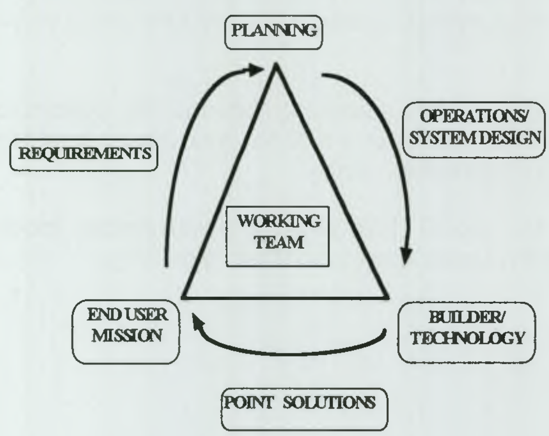

Figure 1: The Space Mission Operations System Generation Cycle

Modeling should be a common tool found alike in every planner, designer, analyst and builder's tool box. It brings to the surface and into focus basic issues, issues that would otherwise go unnoticed until becoming major cost factors. A view of the cycle of system generation is commonly thought of as that shown in Figure 1. For space missions there are certain generic kinds of operations activities that allow us to anticipate outcomes by developing models early in a life cycle. This practice gives us the best chance of producing viable, adaptive and yet, robust operations systems.

It provides the necessary common language in order that coordination of the triumvirate of user, planner and builder can occur at the earliest possible stage of a mission. It is applicable at the pre phase A, later life cycle phases, and even after termination, when a review of a planner's rationale can help determine if similar thinking is applicable to current work. This might occur, for example, when considering a change in technology.

FRAMEWORK

Beginning a system concept development task entails modeling, basically, two of the system's abstractions: one its processes, and another its entities. Processes can be broken down into functions; entities into system components or data. A function is the act of performing a specific role. An entity is any thing having existence at some place or time in the system. The term entity may even cover an intangible such as a discrete state or condition of the interfaces between entities. Models describe the relationships between these entities and functions. There are other centers of focus or abstractions which different modelers add as needed, such as location or timing relationships, in order to press home a critical point about the system. Even an enterprise's organization chart might be useful! It is necessary to cover the bases when considering any operations system concept. As shown in Figure 1, operations and system planners translate requirements and constraints into a foundation for the builder to enable him to select data server, computing and communication environments. It takes integrative tools in the planner's hands in order to do this in an organized fashion. A framework is a powerful tool for organizing this integration process, especially when constraints begin piling on top of one another as the system's concept develops. The authors found that a matrix framework, proposed several years ago by John Zachman,[12i3] was a useful tool for ordering the way one looks at modeling the different aspects of a system. The framework we have used is shown in Figure 2. Our matrix uses the conceptual approach of the original Zachman, but inserts an extra row between Enterprise, i.e., our "mission" counterpart, and System, in order to present the "Operations" perspective. This is because the space mission operations planner/engineer is in the unique position of being able to present the operations perspective of the end user's mission design to the information system or data system designer.

The framework is a 6 x 6 matrix. The contents of its rows are used in order to delineate different perspectives of a system concept. These are: Scope, Enterprise, Operation, System, Technology, and Actually Built. They capture inputs for system trade offs provided by the project office, end user, operations planner, data systems designer and contractor/ builder, and finally, the end product vision. The rows imply gradations of individual perspectives from the conceptual to the concrete in going from top to bottom. In a parallel manner, for each perspective, there are six framework columns, each one modeling a different aspect of the mission's operations system. These are the interrelationships of the system's entities, process functions, network node locations, organizational components, procedural steps or scenarios, and design rationale. These columns are intended to answer the questions: what, how, where, when, who, and why concerning the proposed system.

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[1] A- "A Framework for Information Systems Architecture" John A. Zachman. IBM Systems Journal, vol. 26, no. 3 1986, 1987. IBM Publication G321-5298.

B- "The IDEF Framework." IDEF-UG-0001. September 1993 IDEF Users Group. 513-259-

Techniques change with time. What is in season today, may not be so next year. However, what is important about this type of framework is that it is a general approach to the organization of the

Abstraction / Perspective	Data	Process	Geometry	Organiz.	Timing	Rationale
Scope	Instrument/ Spacecraft Subsystems/ Data Access	Diagnose on orbit perform.				
Enterprise	*Mission Rule* Mission Data Recording 2	*Process* On board triggered 1	*Location* Sun Synchr Orbit		*Timing* Data for Replanning of Mission	
Operations	*Entity Rel* Anomaly Status Def. 4	*Process* On Orbit Eval. 5 3	*Location* Distributed I/S 7		*Scenario* Evaluate P/L Activities 6	
System	*Data Rel.* State Model: ACS vs Instr. 10	*Function* Diagnostics Design 9	*Location* Processing Distribution 8			
Technology	Data Delivery Knowledge Base	*Processor* Rules Based Inference Engine	*Nodes* Network Architecture			
As Built		OL-MP-01				

Figure 2 Framework of models for mission operations systems. Numbers within squares inside of each cell trace the course of the discussion of models in sequence.

complex sets of detail found in system architecture. The key appears to be in unifying threads running horizontally and vertically which provide for a consistency of viewpoint along any row and a constant center of focus down any column. The authors have found this particularly useful when it came to characterization of mission operations functions and architecture of the mission payload, operations or data system. This will be demonstrated in the paragraphs that follow. We will henceforth refer to the matrix using notation: r[n] = row number and c[n] = column number.

Some of us have been introduced to functional modeling and have experienced difficulty separating the mission, operations system and data system from one another. Part of this difficulty is that pure functions are abstractions and are difficult to conceive of in isolation from their context. One way of insuring that the abstraction we are considering is in fact, a function, is to use the transitive case of the verb. A function acts on an object in order to transform it into a product. Its output is the result of this action.

A Mission Example

One way of describing this framework method is to apply it to a mission system segment of a hypothetical mission; one that is a fair representation of the new era of autonomy in space. The spacecraft payload is an autonomous scientific instrument. The modeling framework is intended to guide concept developers in their discovery of the inherent mission rules with such a payload, as well as some of the constraints these rules impose on mission design, operations and data system. In using the framework, constraints are traced from one diagram to the next using the framework as an index. The framework matrix will be the jumping off point to the demonstration of each specific model for this exercise. As an orientation aid, the reader will be given the coordinates of the framework cell which corresponds to the diagram figure under discussion. The "r,c" key of the previous page is to be used. As one migrates from cell to cell, the power of the framework to organize one's thinking towards a developing concept should become apparent.

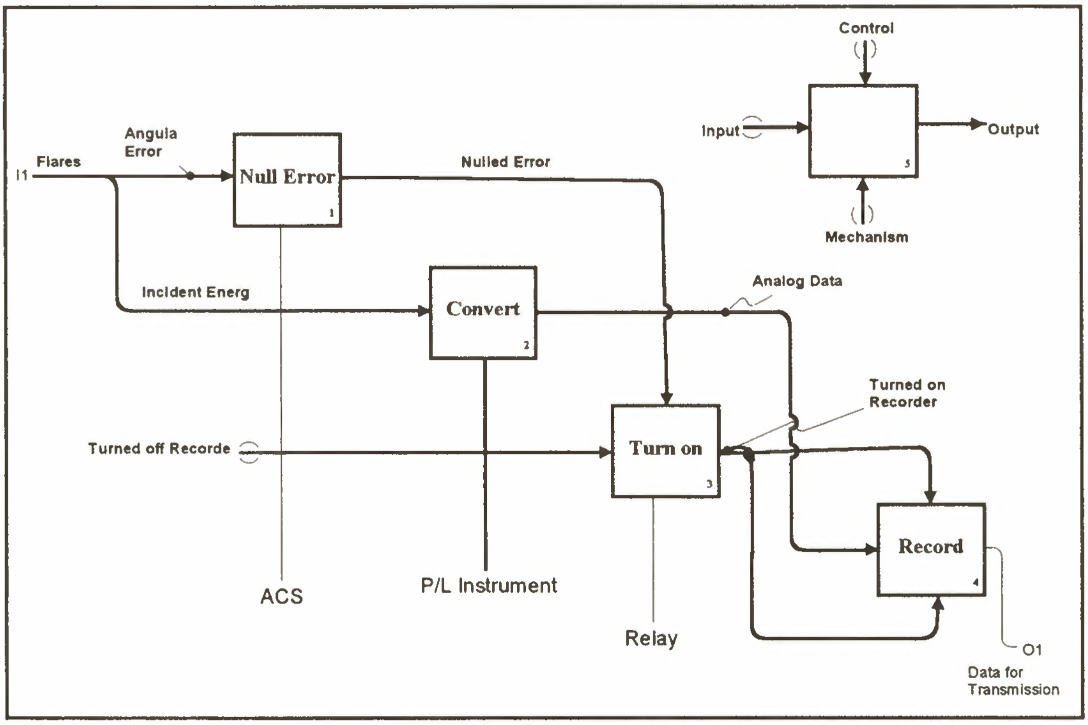

Figure 3: IDEF$_0$ FEO of an Autonomous Payload Target of Opportunity Recording Process

Framework cell r2,c2 deals with mission process modeling. We have picked the payload instrument data recording function as our specimen. Its triggering process is modeled as shown in Figure 3. IDEF$_0$ modeling methodology is used. The payload user's intention here was to show that payload pointing alone is all that is necessary in order to turn on the payload data recorder.

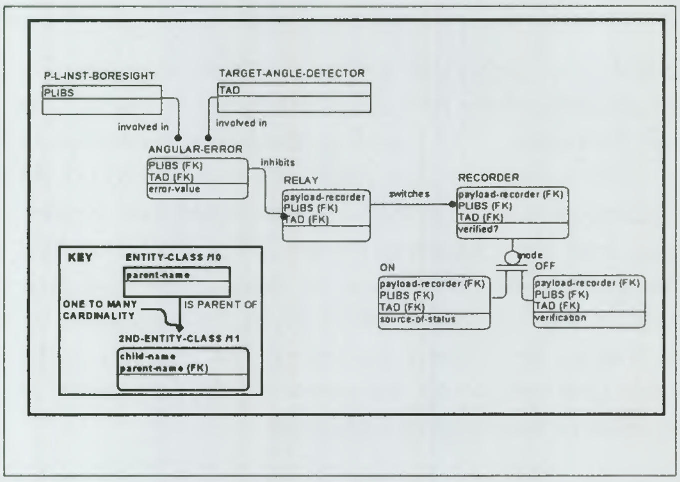

Figure 4: Entity Relationship Model of the Payload and Its real-time Attitude Determination Sensor Through Which Pointing Input is Determined.

Entity Relationship Modeling Defines Operations System Objects

R2,c1 is shown in Figure 3. It establishes the mission payload operations rules in the form of an entity relationship model of some of the elements and their interrelationships in this function. In this case, the two entities responsible for source data for computation of payload pointing error are shown: P/L instrument boresight and Target angle Detector. The connection with the on board recording is established, the rule being that only by pointing on a target can the recorder be turned on. The relationship between this model and general space operations is to be seen in the next set of figures beginning with Figure 5.

Generic Mission Operations Process Model

Figure 5 shows a process model from the Operations perspective, r3c2 in the framework. It is the "Mission Accomplishment" function. This model is discussed at length in another session.[2] There are two points of interest, context and hierarchy. Figure 4 shows various institutional support mechanisms, subsumed under the arrow labeled M1, Necessary Resources. They are shown entering from the outside, at the bottom of the diagram. Arrows which enter or which leave the diagram form what is called the diagram context, to use IDEF terminology. Context definition is important in considering the data system perspective. As for hierarchy, Figure 2 modeled part of the Mission perspective, the process of recording target of opportunity surveillance as a top level. The converse is true coming from the Operations Mission System". The successive decomposition of this node would finally reveal this to be so. Before we leave Figure 4, another note of interest. Target surveillance is a sub function. It is located within node 2 of Figure 5. Node 2's output arrow, labeled "Problem", is one of two. The lower arrow carries useable mission information and forms the input to node 3. The one we are concerned with, "Problem", indicates the occurrence of a situation which requires updating the mission planning. In modeling language, "Problem" is a control on node 1, "Plan Mission". This control is transferred as negative feedback from node 2, "Operate Mission System". Ability to characterize feedback in this manner is a special feature which distinguishes $IDEF_0$ from other IDEF techniques.

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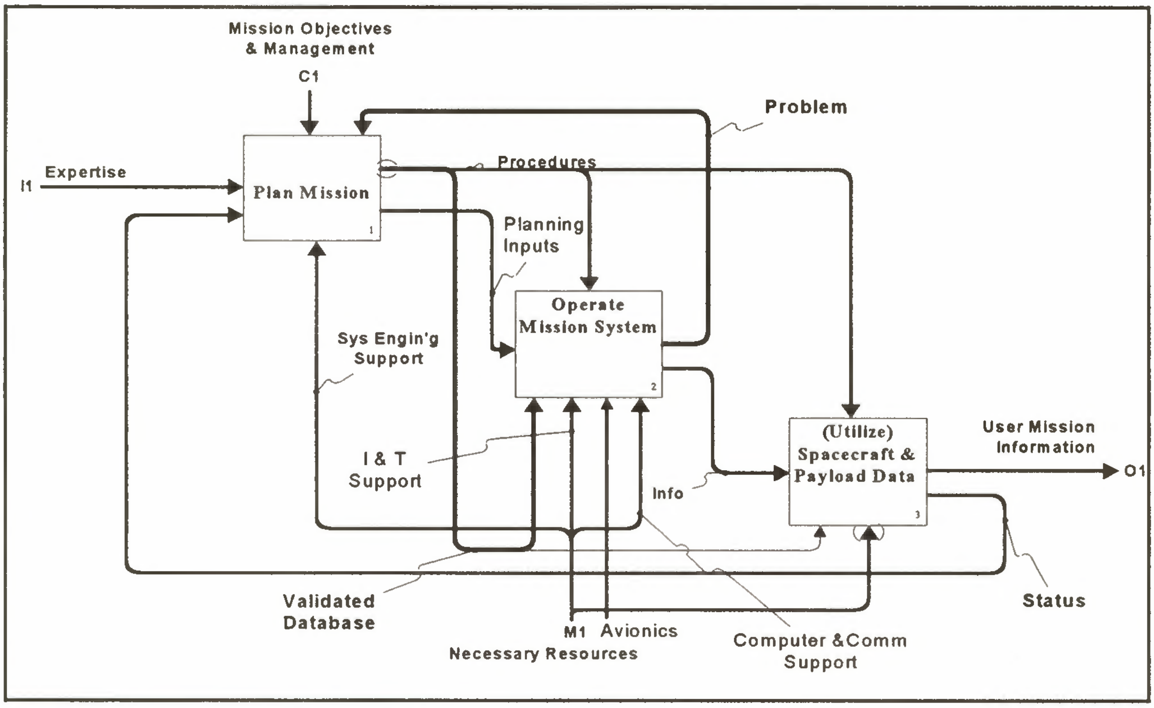

Figure 5: "Accomplish Mission", an IDEF Process Model of a Generic LEO Mission

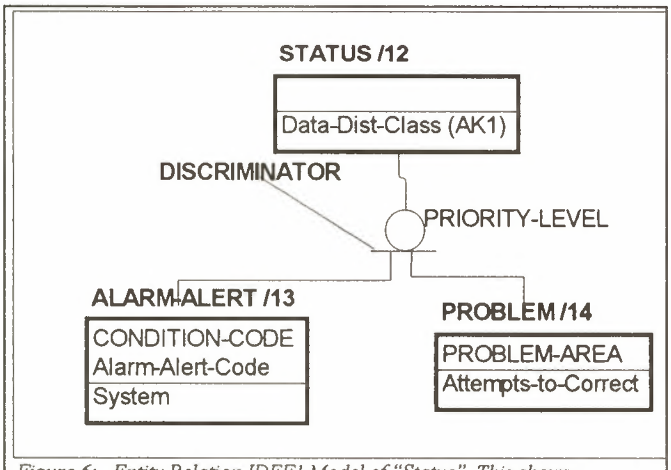

Figure 6: Entity Relation IDEF1 Model of "Status". This shows the Different Levels of Priority and the Significance of Anomaly Determination Ability On Board

Return to Figure 3, again, the Framework. This time we will focus in on cell (r3c1). This refers us to the entity relationship model of Figure 6 for the information describing feedback labeled, "Problem" in Figure 5. Figure 6 shows "Problem" to be of an entity class labeled "Status". We will show how the treatment of this entity class drives the delivery system for, and storage of, mission control data.

The IDEF$_0$ model of Figure 7 allows us to locate the anomaly status reports produced by functions during mission orbit operation. Node 3, "Evaluate Activities and Background", has two outputs: one, routine performance evaluation or "Info"; the other, "Alarms and Alerts". Recall, this latter is one of the status entity priority types previously shown in the entity relationship diagram, Figure 6.

Figure 7 shows the "Operate Mission System" functional detail.

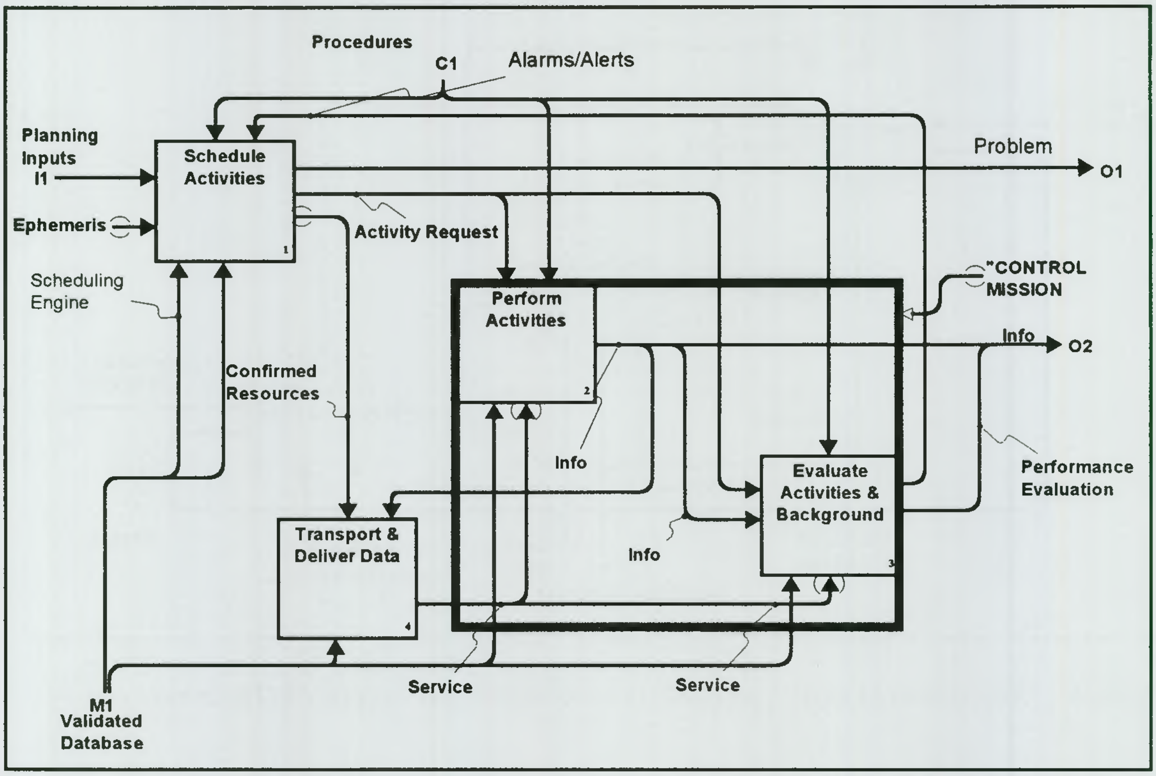

Figure 7: "Operate Mission System", Node A2 of Figure 4 Showing Mission Execution On Orbit

The other status type, "Problem", is produced here by node 1, "Schedule Activities". It is shown to emerge from the "Operate Mission" function as feedback to "Plan Mission", as described previously. Coordination of Operations and System Planning as well as the computer and Services sectors perspectives will be required at this point in order to develop the operations concept further. This coordination involves the trade off between possible processing locations and routing of the anomaly and other problem status messages. Figure 3 states that "Instrument Pointing Error Null is all that is necessary to start "Record Data". However, conspicuous by their absence are any payload system inputs to the data base to show the status of the operation. For this particular payload operation design, basically an open loop control, there are no convenient electronic messages to intercept which would reveal a failure or its cause, should one occur. Therefore the end user must interface with various members of the mission team to determine how this should be arranged. Figure 7 told us that generic activity monitoring functions do exist, which feed a scheduling function. How would the same status information be obtained for the instrument and recorder
operation since they are autonomous? There is also the question of how "Scheduling Activities" should be treated in light of the open loop? Framework r3c5 shows a possible scenario for on board payload evaluation and an output for feeding back to scheduling. Figure 8 shows an IDEF$_3$ description of such a scenario. The explanation follows.

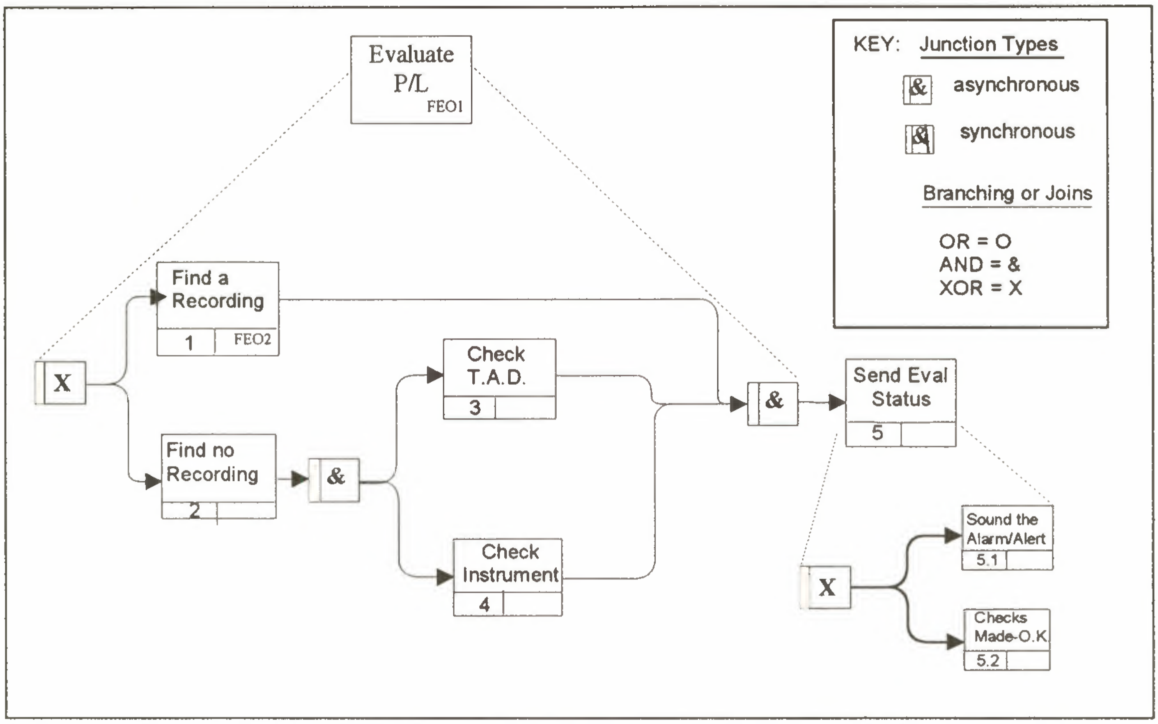

Figure 8: Decomposition of "Evaluate Activities" Using $IDEF_3$, Process Flow Description.

It is assumed that ground truth data is obtained, either on the ground or on board. This is necessary to provide a source to verify that data should have been recorded if the system had been working properly. (r3,c3) would show this to be true. Then, in Figure 8, we see that recorder records are either, (or are not), discovered that can match the time of occurrence of the ground truth records. If not, sensor and payload instrument checkout takes place, with the result sent to scheduling for subsequent recontact from the ground to attempt a correction. It is not unusual to find $IDEF_0$ and $IDEF_3$ models crossing over in this manner.

SYSTEM PERSPECTIVE

The framework, r4c2, is to be a logical model of the information system design without consideration given to the hardware, software or even what part of the information system will be manual or automated. The models would show an information system approach that is consistent with the information requirements of the mission operations inclusive of payload status reporting and operations scheduling as shown by Figures 3 through 8. This logical model emphasizes the integration of information systems across the entire end to end system. Note that ancillary status data must be included as an input to "Plan Mission", Figure 5. This is the ground truth data, the need for which was established above. Framework (r4c3) is to be a model of the distributed information system showing support for the operations process functions shown as Framework (r3c2). It shows the distribution of ground truth site, spacecraft and ground control center and the data interfaces between them.

DEVELOPMENT OF NASDA'S SPACE NETWORK SYSTEM

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ABSTRACT. National Space Development Agency of Japan(NASDA) has a plan to install its own Space Network(SN). The development started from an experiment with Engineering Test Satellite-VI(ETS-VI), whose objective was to obtain basic technologies. Experiments are to be upgraded through the second step experiment with Communications and Broadcasting Engineering Test Satellite(COMETS). NASDA's development of a Space Network will be finalized at the system with Data Relay Test Satellites(DRTS-W & DRTS-E). The Space Network operating system will consist of subsystems for network planning, realtime operations and orbit calculations. The system will be an efficient operation system being equipped with an automated subsystem monitoring and controlling both the network segments and the network establishing sequence. Towards the practical system development, basic technologies had been implemented and the performances were verified at the ETS-VI experimental ground system. In cooperation with National Aeronautics and Space Administration(NASA), ETS-VI demonstrated the NASDA's first inter-satellite communication with Upper Atmosphere Research Satellite(UARS).

1. INTRODUCTION

NASDA completed its development of tracking and data acquisition network, through the first phase of the Space Operations and Data System (SODS) program. The network is, however, basically configured with a few ground stations located so locally in Japan, that the visibility of orbiting satellites is limited to small. It is called as a Ground Network(GN), because it only depends on the ground stations and the connecting networks to Tracking and Control Center(TACC) at Tsukuba Space Center(TKSC) near Tokyo.

As the second phase of the SODS program, NASDA started a development to establish its own SN, which is named in the contrast with a GN. A SN provides wider coverage for orbiting satellites than a GN does, with a geostationary data relay satellite acting as a tracking and data acquisition station in space. The Tracking Data Relay Satellite System(TDRSS) developed and being operated by NASA is a similar system. European Space Agency(ESA) also has the plan to develop its own SN.

NASDA, NASA and ESA work together for interoperability for possible cross support in the future.

2. MILESTONE OF THE DEVELOPMENT

The development of NASDA's SN had started as an experiment of ETS-VI which was launched in August 1994. ETS-VI mounted equipments for inter-satellite communication. With no satellite capable inter-satellite communication at the time, a Dummy Satellite Station(DSS) was prepared on the ground as a satellite simulator. The objective of ETS-VI Experiment was to obtain necessary technology for a SN system and the operation. Figure 1 indicates developing steps of NASDA's SN together with the concept of the system configuration.

As the second step, COMETS will be launched for experimental operations of the SN, in 1997. The onboard communication equipment will have wider bandwidth than ETS-VI has, to perform inter-satellite communication in several different frequencies with actual satellites such as Advanced

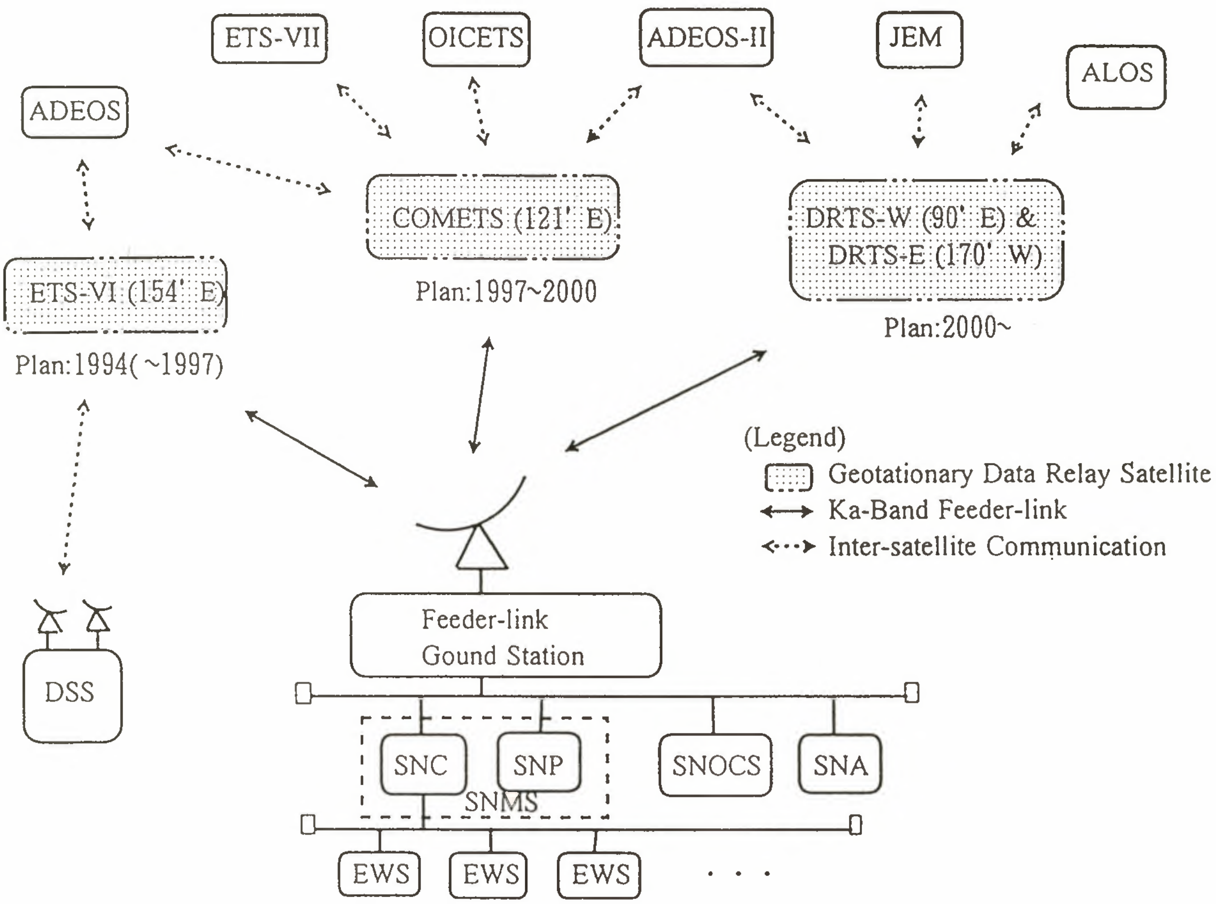

Figure 1 SN System Development Concept

Earth Orbiting Satellite(ADEOS), Engineering Test Satellite-VII(ETS-VII), Optical Inter-orbit Communications Engineering Test Satellite(OICETS), and ADEOS-II, to be launched in 1996, 1997, 1998 and 1999, respectively. Configuration change control of the SN contingent to each satellite's operation mode forms a key aspect of the development. COMETS will also experiment with other space agencies' satellites: Tropical Rainfall Measuring Mission(TRMM) satellite of NASA to be launched in 1977, and Satellite Pour d'Observation de la Terra-4(SPOT-4) of Centre National Des Etudes Spatials/France(CNES) to be launched in 1997.

The SN development will conclude with a proof experiment with two DRTSs around 2000. An integrated operation system is to be developed for cost effective operation. A planning support system also would be beneficial. The candidate prime user satellites of the DRTS-SN are ADEOS-II; Japanese Experiment Module(JEM), an attachment to International Space Station(ISS); and Advanced Land Observing Satellite (ALOS).

3. SYSTEM CONFIGURATION

A Ka-Band feeder-link connects the ground to a geostationary data relay satellite. Aboard the data relay satellite; antennas, transponders and other equipments form a space segment of the SN. A feeder-link ground station transmits forward-link signals to a user satellite through the data relay satellite, and receives return-link signals in the opposite direction. The feeder-link ground station works as a SN ground segment.

In the NASDA's SN concept, the space segment equipments are controlled from the ground in conjunction with controls to the equipments of the ground segment. The system control and the monitoring of the ETS-VI experimental ground system was supported by Space Network Management Subsystem(SNMS), which is now functionally divided into Space Network Planning(SNP) subsystem and Space Network Control(SNC) subsystem at the development of the COMETS experimental ground system. SNP hands detailed operation plans over to SNC, after providing a network planning aid to arrange user satellites' requirements from months before operation. SNC monitors and controls not only segments of the SN, but also the sequences of initial acquisition and network establishment between a user satellite and the data relay satellite. Figure 2 is an extraction of SNMS displays of the ETS-VI system, and shows an example of the terminal display.

Several information data used for antenna pointing and compensating Doppler frequency shift are calculated at Space Network Orbit Computation Subsystem (SNOCS). SN system performance

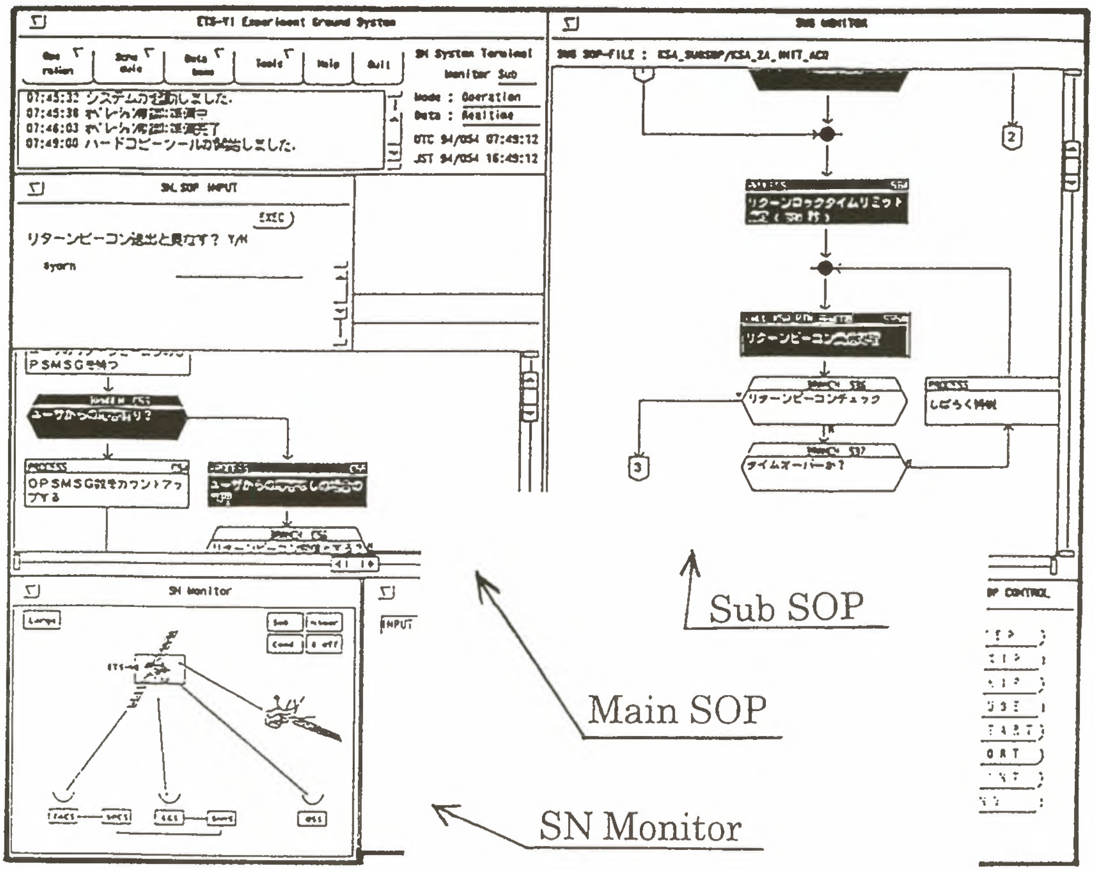

Figure 2 Example Display of SNC Terminal

data is stored and analyzed at Space Network Analysis(SNA) subsystem.

4. EXPERIMENT WITH ETS-VI

ETS-VI was launched in August 1994, but unfortunately located on a three days sub-recurrent orbit instead of a geostationary orbit. Because the ground segment of the experimental SN system located at TKSC had been designed with a baseline that ETS-VI ought to be a geostationary satellite, the available experiment opportunities were much shortened to two or three hours in three days cycle. The experiment had started in December 1994, and terminated in November 1995 because of weakened ETS-VI's solar array panels through Van Allen belt.

The ETS-VI experiment was to confirm some key technologies for the SN development at the performance of communication equipments of both space and ground segments. Pseudo-random Noise(PN) codes, for instance, were adopted in S-Band to spread spectrum. Basic characteristics and the system parameters such as acquisition time and threshold levels were measured and verified.

4.1 SN-SOP PERFORMANCE

The Space Network System Operations Procedure(SN-SOP) method is an attempt of NASDA to develop new automated operation procedures. A SN-SOP consists of combinations of process boxes and flow lines, the same as a flow chart has. The SNMS provides a Man Machine Interface(MMI) for creating and modifying a SN-SOP easily. Some SN-SOPs prepared for the ETS-VI experiment operations were used. These SN-SOPs haven't been completed for useful shape, but it was assured that the easy modification capability of operation procedure was helpful in such case of the ETS-VI's orbit anomaly.

4.2 INTER-SATELLITE COMMUNICATION

The ETS-VI experiment originally planned to test the inter-satellite communication with ADEOS and then with some NASA's satellite, in late experiment period. But it was suspicious whether ETS-VI would stay alive until the ADEOS's launch. In cooperation with NASA, Upper Atmosphere Research Satellite(UARS) was assigned for the test. While the test was in preparation, a SN compatibility test was also performed in cooperation with ESA, having ESA User Spacecraft Transponder(EUST) connected to DSS, in May 1995. For the inter-satellite communication test between UARS and ETS-VI, there needed some adjustments to the ground segment; because the

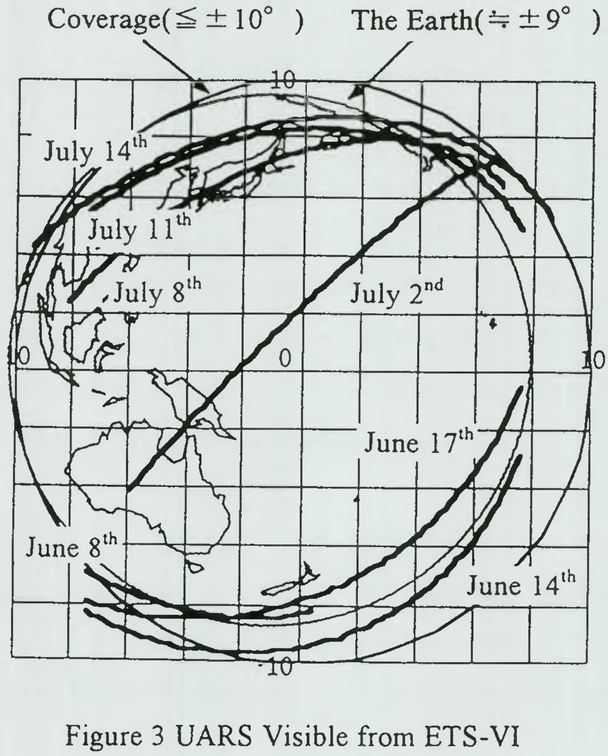

Figure 3 UARS Visible from ETS-VI

ETS-VI was not a geostationary satellite. The test was done through total seven passes of UARS in June and July 1995. The initial acquisition, telemetry reception and commanding operation in connection with Goddard Space Flight Center(GSFC) were performed and assured. It was the first experience for a NASDA's data relay satellite to communicate with an actual orbiting satellite. Figure 3 shows the passes of UARS used at the inter-satellite communication test.

5. CONCLUSION

The success of the inter-satellite communication with UARS demonstrated good coverage of the Space Network. UARS orbiting almost above Antarctica, the data through ETS-VI could be gained at TKSC in Japan. For the second step experiment with COMETS, the experimental ground station is under modification. Even though the COMETS-SN will be still under experimental operation, some user satellites, ETS-VII for instance, will rely on the network for longer support. Functions for network planning, network configuration setting and realtime monitoring and controls are being developed. For the final step, the system design of the DRTS-SN has yet to start. DRTS is categorized as a single mission satellite, and so operations of the SN and the satellite house keeping could be simplified to a single operating position. Furthermore, the existing GN and the future SN might be operated in combination for cost efficient operations. With the experiences of precursor systems and accordingly adjusted system requirements, the DRTS ground system development starts late this year.

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POSITIONING OF GEOSTATIONARY SATELLITES AT DLR/GSOC - PROJECT MANAGEMENT AND CONTROL -

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ABSTRACT. Starting with a short description of the German Space Operations Center (GSOC) and its role within the wider framework of the research institute DLR, this paper provides a review of the geostationary telecommunication satellites positioned by GSOC. The paper then proceeds to describe the organization of Launch and Early Operations Phase (LEOP) services as it was performed at GSOC using the example of the EUTELSAT II program. Finally the paper reflects the configuration control as it is established at GSOC. It is an adequate method to manage configuration changes within a satellite control centre. The organization and the procedures for the configuration management are presented.

1. INTRODUCTION

During the past 25 years DLR's German Space Operations Center has operated an extensive variety of satellites. In particular, GSOC has specialized in the Positioning and Operation of Geostationary Satellites. Twelve of those were brought successfully to their designated on-station positions. In the frame of the last project, the EUTELSAT II program, project management and project control was performed at GSOC with regard to the special requirements that such a mission defines for staff and the ground segment.

Over the years GSOC has developed and improved its systems and operational management methods. This ongoing evolution of project management and control methods has been effectively used to successfully accomplish the high demands of a mission like EUTELSAT II.

The paper examines in detail the following major topics:

- GSOC and its responsibilities in the preparation and execution of spaceflight projects with special emphasis on GSOC's track record in the field of telecommunication satellites;
- Management methods and organization as it is performed at GSOC for positioning services especially concerning the relationship of the overall project management with the GSOC project organization;
- Project Configuration Management as performed during the EUTELSAT II Project; in particular the change control system that has proved to be an adequate method to manage configuration control for facilities and software within the satellite control center.

2. GSOC's TRACK RECORD FOR COMMUNICATION SATELLITES

The German Aerospace Research Establishment (Deutsche Forschungsanstalt für Luft- und Raumfahrt - DLR) is Germany's largest research institution for the engineering sciences and employs over 4.500 people at seven Research Centres.

Situated on the DLR site at Oberpfaffenhofen near Munich, the German Space Operations Center (GSOC) has over the past 25 years provided services for the operation and support of a wide variety of manned and unmanned space missions.

They include amongst others:

- Geostationary Satellites (SYMPHONIE, TV-SAT, DFS, EUTELSAT II)
- Interplanetary Missions (HELIOS, GALILEO)
- Earth-Orbiting Scientific Missions (AZUR, AEROS, AMPTE, ROSAT)
- Manned Spaceflight Missions (FSLP, SPACELAB D1 & D2, MIR, EUROMIR)
- Sounding rocket programs (ARIES, TEXUS, MAXUS)

Currently the GSOC operates several control rooms at the Oberpfaffenhofen site and a ground station complex in Weilheim with several S-Band, X-Band and Ku-Band antennas.

In the positioning of Geostationary satellites GSOC has been active for over 20 years, starting with the first European efforts in this area - the German/French SYMPHONIE program. Since 1974 DLR/GSOC has successfully positioned twelve satellites in geostationary orbit. GSOC has been awarded various contracts not only for the positioning of satellites in geostationary orbit, but also for the completion of "In Orbit Tests", routine operations and so called "Hot Standby" operations phases (Figure 1).

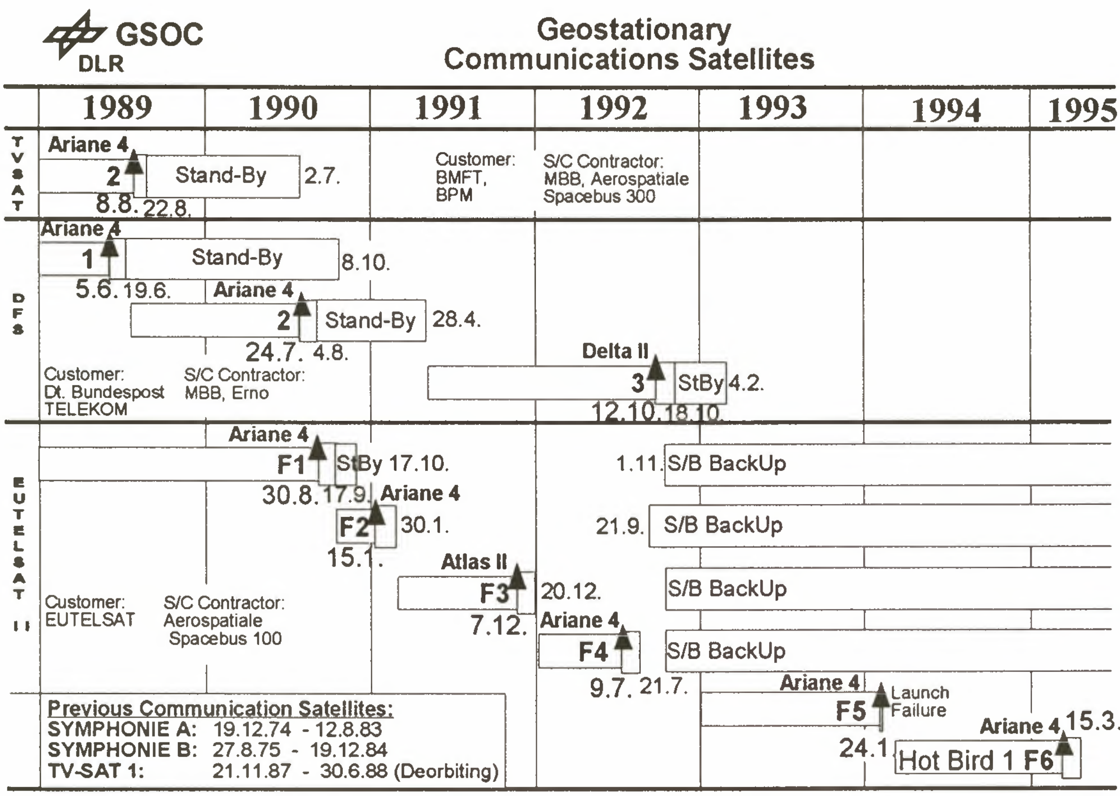

Figure 1. Geostationary Satellites positioned by GSOC

In 1987 the GSOC was awarded a contract by the European EUTELSAT organization for the positioning of six satellites of the EUTELSAT II spacecraft series between 1990 and 1995. One of the key factors in winning the contract was the ability to offer LEOP Services which met not only the requirements of the RFP but also encompassed the highest of technical standards. Using the basis of the TV-SAT/DFS system, it was possible to derive a reliable and effective mission operations system for EUTELSAT II which reflected the state-of-the-art. Furthermore, this system was progressively fine-tuned and optimized during the different

LEOPs carried out through the years 1990 to 1995 starting with EUTELSAT II-F1 and finishing with EUTELSAT II-F6 (=Hot Bird 1). Within the EUTELSAT II programme the customer had a relatively wide right of co-determination and a relatively strong control function (Reporting System, Reviews etc.) during the design and implementation of the mission operations system. As described in the next chapter the realization of the different positioning phases itself was also performed in a very close co-operation with the customer.

3. ORGANIZATION OF THE MISSION OPERATIONS WITHIN GSOC

The organigram (Figure 2) shows the principals of the organization of Mission Operations for the EUTELSAT II programme within GSOC, whereby the interfaces for operational matters between the customer and contractor are portrayed.

The "LEOP-Services"-Project Manager has the overall responsibility not only for the preparation phase (ground segment implementation), but also for the completion of the positioning where he performs the role of Mission Operations Director (MOD). The Project Manager is supported by a Project Configuration Manager primarily for project control. In addition the project management is supported by an independent Quality Assurance Manager.

The DLR Mission Operations Team led by the Team Leader (MOTL) is created from Satellite and Ground System specialists who are allocated to the project from the various specialist departments of the DLR. This team of experienced Flight Dynamics, Flight Operations and Ground System Engineers is responsible not only for the preparation, but also for the execution of the mission which is executed according to the Flight Plan including all nominal satellite operations together with a selection of predefined contingency procedures.

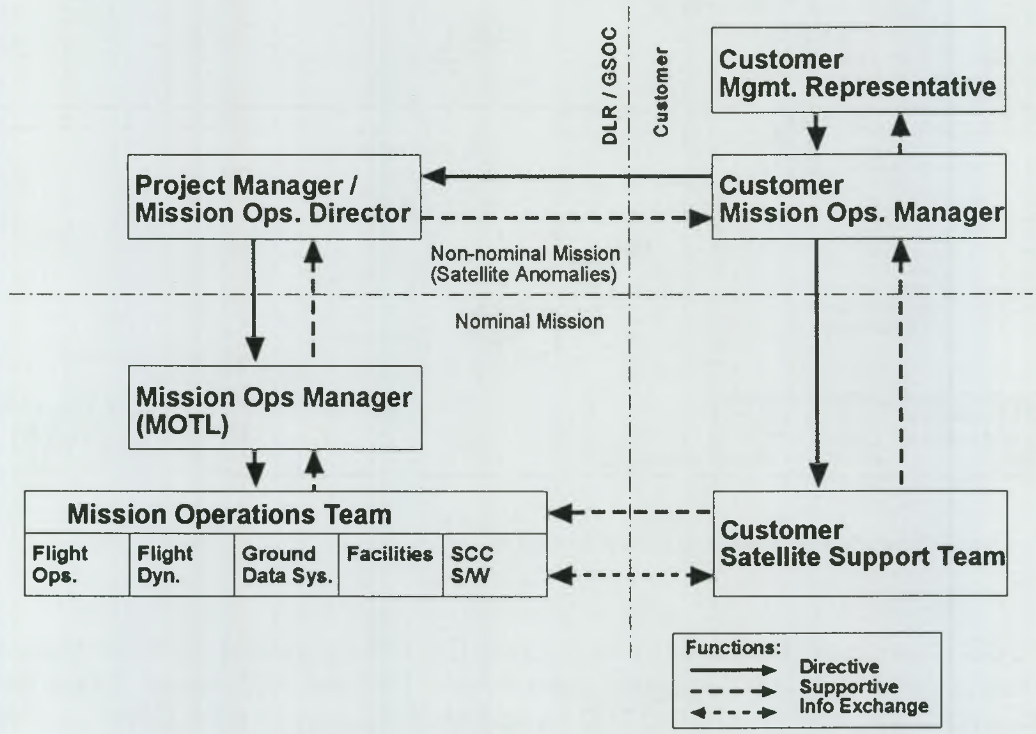

Figure 2. Organization of Mission Operations

The customer is represented by the Customer Management Representative, Customer Mission Operations Manager and Customer Satellite Support Team. The Customer Management Representative is responsible for the regulation of all mission related tasks including contractual matters as far as they relate to the responsibilities of the Customer Mission Operations Manager.

The Customer Mission Operations Manager follows the execution of Mission Operations, authorises the execution of emergency procedures and gives directives in the case of non nominal behaviour of the satellite. He is the only person who is authorised to give directives to the DLR Mission Director or to the Customer Satellite Support Team.

The Customer Satellite Support Team, which is created from experts of the customer and the satellite manufacturer monitors the execution of the mission and compares the actual with the expected behaviour of the satellite. In case of non-nominal behaviour of the satellite, the Satellite Support Team provides the Mission Operations Team with inputs to correct the failure.

If the Mission Operations Team or the Satellite Support Team determine non nominal behaviour which is not covered by the Flight Plan, a special procedure has to be produced to cater to this behaviour. These special procedures are regarded as extensions, changes or adaptations to the existing Flight Plans and are produced in the form of "Recommendations". After release by the Customer Mission Operations Manager and the DLR Mission Operations Director, they are passed to the Mission Operations Team Leader (MOTL) for execution.

4. CONFIGURATION CONTROL

A satellite control system (hardware, software, facilities, procedures) underlies changes and modifications during the whole preparation and mission execution phase. It is extremely important to establish a proper Configuration Change Control that covers all relevant changes to a defined system. The configuration change control procedures have been formally established with begin of the project "Positioning of EUTELSAT II satellites". They have now been running for more than seven years and have proved to be an adequate method to manage configuration changes within a satellite control centre. They were developed using the experience gained from preceding projects like TV-SAT and DFS Kopernikus and will be used for follow-on projects.

Configuration changes affecting GSOC's satellite control centre system are divided in two groups, the Engineering Change Requests (ECR) and the Non-Conformance Reports (NCR) / Discrepancy Reports (DR):

- **Engineering Change Requests:**
  ECRs are raised whenever it is intended to add or modify a certain topic to the specifications or the existing configuration; this may be a change in the telemetry processor software which will result in changes of the software code or the hardware modification of a special console or the replacement of a computer.
- **Non-Conformance Reports and Discrepancy Reports:**
  NCRs and DRs are issued whenever a deviation with respect to the specifications is observed or if the system or subsystem behaviour differs from the expected behaviour. This may be for example a unexpected delay of a transmitted command, an incorrect display of a telemetry parameter or the slow performance of a computer.

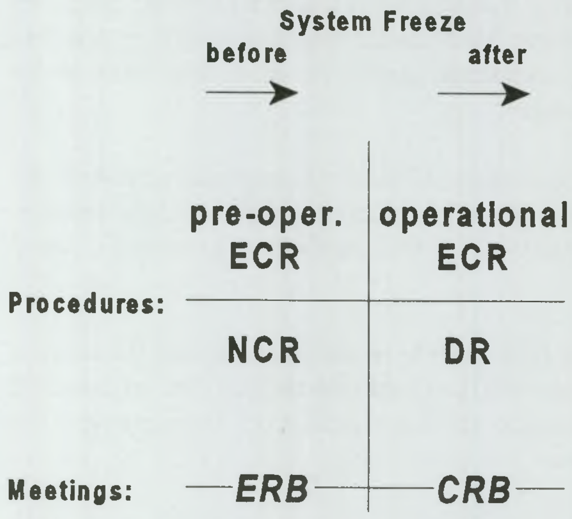

Figure 3. Configuration Control at GSOC

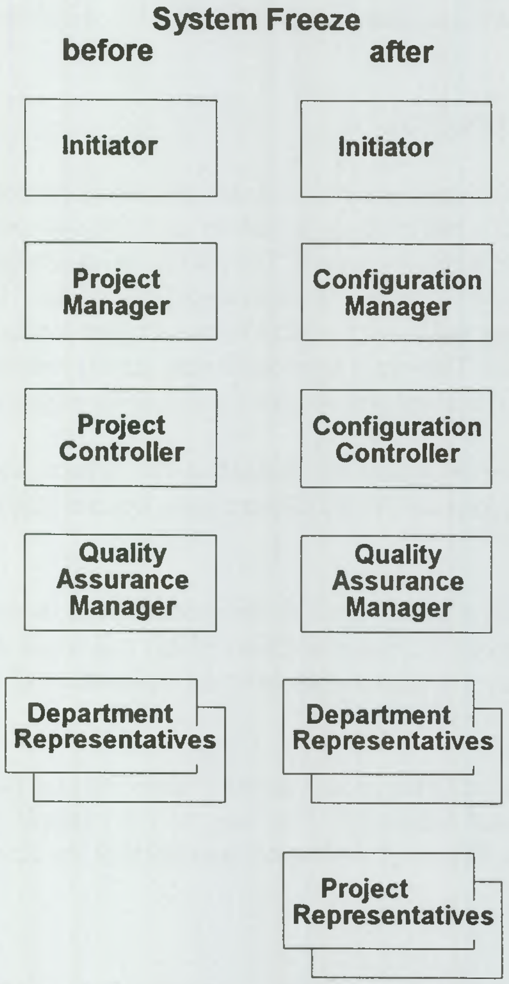

Figure 4. Involved Persons before and after System Freeze

Two phases are defined for the handling of the configuration change control procedures:

- **pre-operational phase** (until System Freeze): the personnel that is permanently involved in the Configuration Control are the Project Manager, the Project Controller, the Quality Assurance Manager and the project related department representative.

- **operational phase** (after System Freeze until end of project/mission): the personnel involved are the Configuration Manager, the Configuration Controller and the Quality Assurance Manager, representatives of the involved departments and representatives of the particular projects.

Procedures exist at GSOC covering both the Engineering Change Requests and the Non-Conformance/ Discrepancy Reports. The difference is that the responsibility of the Configuration Control lies with the project before system freeze and with GSOC's multimission system before system freeze. Accordingly the number of involved persons after system freeze is much higher (depending on the number of running missions).

Two Control Boards are established:
- the Engineering Review Board (ERB), in pre-operational phase on project level
- the Configuration Review Board (CRB), in the operational phase on system level.

The boards meet regularly every 4 weeks (ERB) respectively every 6 weeks (CRB). If there is demand for an earlier board meeting the Quality Assurance Manager is free to organize an ERB or CRB on a short-term notice.

Engineering Change Request Procedures

Change Requests are typically raised after having received new documentation that impacts software/facilities or after simulations. ECRs are normally issued in packages of at least five ECRs thus avoiding too many meetings and other formal activities.

The procedure itself is divided to five steps of which two have to be processed with at the ERB or CRB meetings. If urgent cases occur a change could be implemented even within one day.

Depending on the project phase it is distinguished between two phases:

- Engineering Change Requests in the pre-operational phase (under project control)
- Engineering Change Requests in the operational phase (under system control)

Figure 5 shows the "Flow of Actions" of the ECR procedure, Figure 6 shows the relevant form sheet. This form sheet is filled out manually, as an electronic version based on Microsoft Access in under preparation.

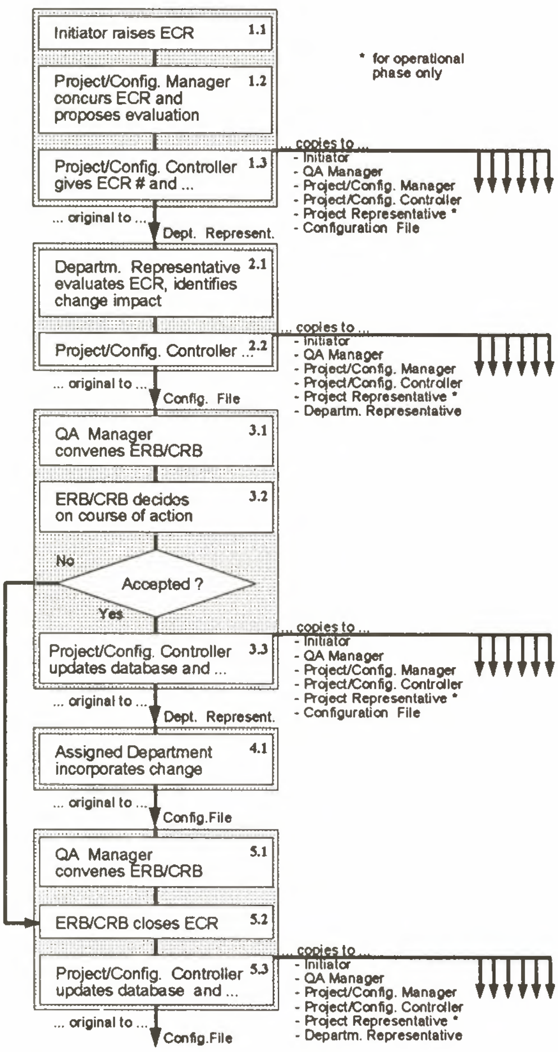

Figure 5. Engineering Change Request - Flow of Actions

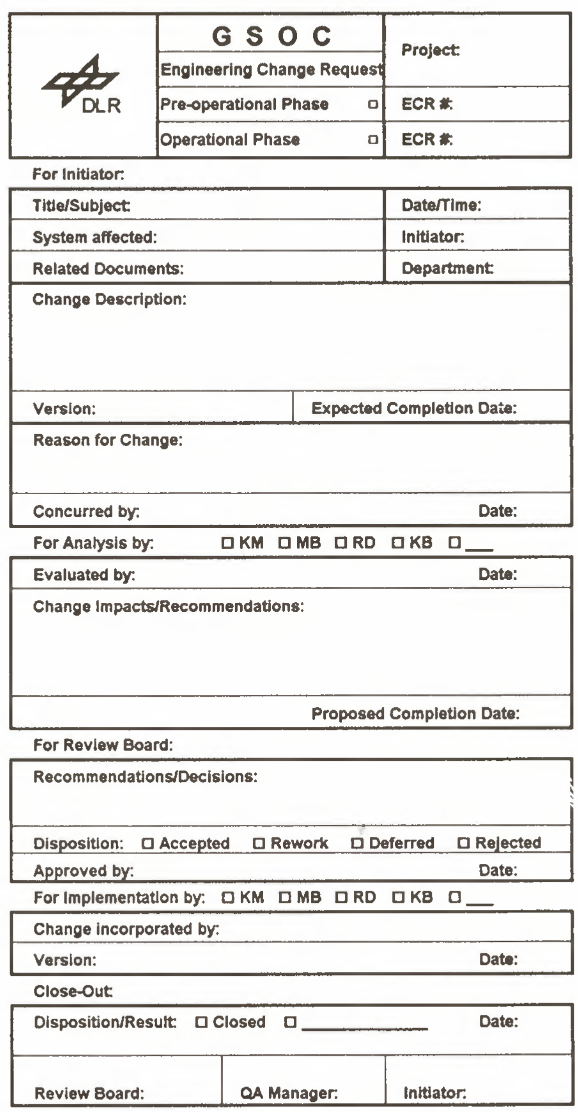

Figure 6. Engineering Change Request Form

Non-Conformance (NCR) / Discrepancy Report (DR) Procedures

Non-Conformance Reports are typically raised after the completion of acceptance tests. Discrepancy Reports are issued whenever a discrepancy occurs during the daily operations.

The NCR/DR-procedure itself is divided to five steps of which two have to be processed with at the ERB or CRB meetings.

Depending on the project phase it is distinguished between two phases:

- the Non-Conformance Reports for the pre-operational phase (under project control)
- the Discrepancy Reports for the operational phase (under system control)

Figure 7 shows the "Flow of Actions" of the NCR/DR procedure, Figure 8 shows the relevant form sheet. This form sheet is filled out manually, and as for ECRs an electronic version based on Microsoft Access in under preparation.

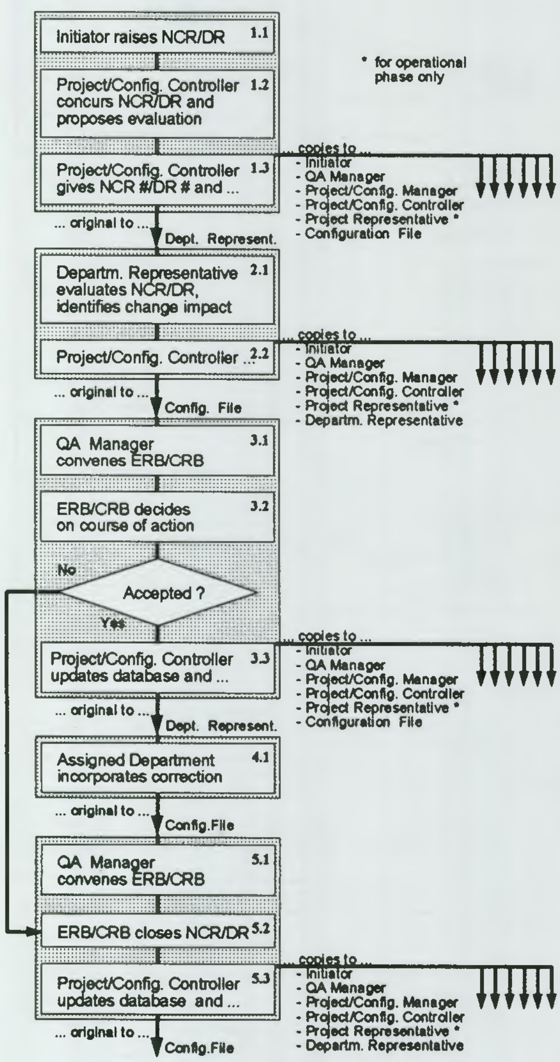

Figure 7. Non-Conformance / Discrepancy Report - Flow of Actions

DLR	G S O C	Project:
	Nonconformance Report ☐	NCR #:
	Discrepancy Report ☐	DR #:

For Initiator:

Title/Subject:	Date/Time:
Proposed Priority: ☐ High ☐ Normal	Initiator:
Location: ☐ GSOC-OP ☐ GSOC-WHM ☐ EXT	Department:
Description of Nonconformance/Discrepancy and Operational Impact:	
Assigned by:	Date:

For Analysis by: ☐ KM ☐ MB ☐ RD ☐ KB ☐ ___

Problem Area: ☐ SW ☐ HW ☐ Proc. ☐ Other	
Suggested Action / Impact if not corrected / Workaround:	
Evaluated by:	Date:

For Review Board:

Recommendations/Decisions/Approvals:	
Agreed Classification: ☐ Major ☐ Minor	Date:
Review Board:	QA Manager:

For Corrector: ☐ KM ☐ MB ☐ RD ☐ KB ☐ ___

Corrections made by:	Date:

Close-Out:

Disposition/Result: ☐ Closed ☐ ___________		Date:
Review Board:	QA Manager:	Originator:

Figure 8. Non-Conformance/Discrepancy Report Form

CONCLUSION

Starting with the SYMPHONIE program in 1974 GSOC has been careful to systematically review and update the operational and management procedures and methods applied to positioning projects. This approach has allowed the development of a set of standard geostationary positioning procedures and working methods which are optimized for modern communication satellites. These procedures and working methods have proved themselves during successive positing activities.

The configuration management as used at GSOC can be applied to multi mission systems as well as to single projects or routine operations where a low number of changes / discrepancies is to be expected. Applying the configuration control procedures the standards of both, the customer and Quality Assurance Department can be met. On the other hand the needs of the mission operations team for fast response times can be achieved. A good balance between these constraints was found allowing the determination of the configuration status at any time. The well defined procedures help to reduce the number of interface meetings and the number of involved persons and will therefore reduce time and costs in the area of configuration management.

OPERATIONS MANAGEMENT OF INSAT SATELLITES

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ABSTRACT. INSAT series of satellites are multipurpose geostationary communication satellites carrying direct broadcast, communication and meteorological payloads. The operation management of these satellites is carried at Master Control Facility (MCF) located at Hassan, India. The operation management strategy has been evolved based on the experience of earlier satellites and is extended to multi-satellite operations. This paper describes the operations management strategy of these satellites for station-keeping maneuvers, eclipse management, contingency handling, anomaly resolution, interactions with different agencies for payload operations and feedback mechanism to designers for improvement in future satellites.

1. INTRODUCTION

INSATs are multipurpose, geostationary satellites positioned over the Indian Ocean, providing services in communications, meteorological imaging and data relay, TV and radio broadcast, disaster warning and distress alert. The INSAT Space segment concept makes use of these multipurpose satellites at three orbital slots of 74, 83 and 93.5 deg East longitudes to meet the total communication capacity requirements of 1990s. In order to meet the increased capacity requirements from a specific orbital position, two spacecrafts are collocated so that they are seen as a single capacity source by the ground stations.

A contract to build two INSAT 1 spacecraft was awarded to Ford Aerospace Corporation (FAC) of USA (now Space Systems/Loral) in 1978. INSAT 1A was launched in April 1982 but failed in orbit in September 1982 due to propellant depletion. INSAT 1B was launched in August 1983 and proved to be the mainstay of INSAT system till July 1990 when INSAT 1D was operationalised. The failure of INSAT 1A prompted the ordering of INSAT 1C as a replacement. A series of launch vehicle catastrophes delayed the launch of INSAT 1C till July 1988. INSAT 1C suffered a massive short circuit in one of its power buses soon after launch and operated with about 50 % of its capacity for about sixteen months. Soon after, it lost earth lock due to a single event upset and could not be recovered. In 1985, a decision to procure INSAT 1D as a gap-filler between INSAT 1 and INSAT 2 series was taken. INSAT 1D was to have been launched in June 1989. However, an accident at the launch pad damaged the spacecraft and it had to be repaired, re-tested and launched only in June 1990. INSAT 1D is operating satisfactorily as on date.

The INSAT 1 spacecraft payload consists of

- 12 C band transponders with 32 dbW primary coverage EIRP (PCE)
- 2 S-band transponders with 42 dbW PCE
- 401 MHz Data Relay Transponder (DRT)
- A Very High Resolution Radiometer (VHRR) operating in visible and infra-red bands.

The INSAT system strategy is an on-going programme level exercise that is constantly up-dated to reflect the status of the spacecraft in orbit and under fabrication, the requirements as projected by users and as foreseen and the technology upgradation and new services to be introduced. The chosen strategy was to phase out INSAT 1 spacecraft and transition to indigenously made INSAT 2 series in the time frame of 1991-92. Each of the INSAT 2 spacecrafts has 18 C band transponders (12 in normal C band and 6 in Extended C band), two high power S band transponders, one VHRR instrument with improved resolution and one Data Relay Transponder.

In 1987, India joined in COSPAS-SARSAT systems as a ground segment provider. In the course of examining the various possible follow-up actions it was realised that by simple modification and additions to the 401 MHz Data Relay Transponder, a 406 MHz Search and Rescue package can be added to INSAT 2. This package can provide instantaneous alert by receiving the signals from the emergency beacons carried by ships, aircraft or individuals on any expedition. INSAT 2A and 2B carry the search and rescue package, making these the only geostationary platforms in the Indian Ocean region and only the second system after GOES of the USA in the world to provide this service.

INSAT 2A was launched in July 1992 and INSAT 2B was launched in July 1993. Though the INSAT 2A and 2B were originally planned as Test spacecrafts, they were ultimately commissioned for operational use and are successfully providing the services desired. The INSAT 2C which is expected to meet the changed communication service requirements in the late 90s is the first follow-on operational satellite in the INSAT 2 series. INSAT 2C carries in addition to the Normal C band and Extended C band channels, Ku band and Mobile satellite service transponders. There is no meteorological payloads on INSAT 2C. INSAT 2C was successfully launched in December 1995 and operationalised in February 1996.

In the transfer orbit the spacecraft configuration is a cuboid with the appendages like antennas, solar panels and solar sail / boom assembly stowed to accommodate inside the launcher envelope. The INSATs had been launched by Delta , Space Shuttle and Ariane 3 and 4 launch vehicles into geosynchronous transfer orbit. From that condition, through a series of maneuvers the spacecrafts were positioned at geosynchronous orbital slots in a fully deployed configurations.

In the synchronous orbit, INSAT 1s, 2A and 2B have sun tracking solar panels in the south face of the spacecraft and a solar sail / boom extending in the north face to compensate for the torque imbalance. INSAT 2C has sun tracking solar panel both in the north and south faces. Two deployable antennas on the East and West face provide for the communication requirements.

INSAT 1A, 1B and 1C had two 12 AH, INSAT 1D, 2A and 2B have 18 AH and INSAT 2C has 24 AH Ni-Cd batteries for power support when solar array power generation is insufficient. On-board command reception is through omni antennas. Telemetry down-links can either be through directional antennas or through omni antennas. The propulsion system consists of Nitrogen Tetra-oxide as oxidiser and Mono-Methyl Hydrazine as fuel stored in various tanks. Twelve thrusters of 22 Newton in the case of INSAT 1 and sixteen thrusters in INSAT 2 series provide impulses for orbit and attitude control.

The on-orbit control is achieved through bias angular momentum along the pitch axis aligned parallel to the orbit normal by skewed momentum wheels. Infrared earth Sensors provide pitch and roll attitude data whereas the yaw control is got by kinematic roll yaw coupling. The attitude data is processed by Attitude and Orbit Control System (AOCS) to vary the wheel speeds. The accumulated disturbance angular momentum is periodically unloaded by thrusters selected either from East or West face. In addition Magnetic torquer coils interact with Earth's magnetic field continuously to provide for desaturation of wheels for roll / yaw disturbance thus saving precious on-board propellant for attitude hold. During station-keeping operations, three axis control is achieved using thrusters and the data provided by Earth Sensor, Sun sensors and gyros.

INSAT Master Control Facility(MCF), Hassan was established in 1981 as part of space segment to become the prime control center supporting on-orbit management of INSATs right from injection into the orbit and through the mission life. The facility originally conceived to cater two INSATs was augmented from time to time to carryout the multi spacecraft operations.

Two 14 m, one 11 m fully steerable and one 11 m limited steerable antennas with C and Extended C band trans-receive Satellite Control Earth Stations (SCES) and a Satellite Control Center (SCC), interfaced with SCES and serving as the focal point for data processing done on a host of computing systems for health monitoring, commanding and ranging operations form the main functional units of MCF. The computer systems range from centralised PDP 11/70s, VAX 8350s, micro-VAX and distributed UNIX based workstations using DEC ALPHA systems. During the orbit raising operations, remote INTELSAT ground stations located around the globe provide remote TT & C support, in the periods of spacecraft non-visibility to MCF. With the available limited ground station resources, both orbit raising operations and on-orbit operations were carried out to realise successful operationalisation of many INSATs within a short span of time after their launch.

1. MISSION PLANNING AND MANAGEMENT

Extensive mission planning and analysis as well as establishment of a good ground support system resulted in the successful operationalisation of the INSAT mission. Generating the requirements, planning, developing and establishing compatible ground system consisting of both hardware and software elements proceeded concurrently with spacecraft development. Another vital aspect under mission planning, analysis and operations was effective integration of space and ground segment configurations to arrive at a mission plan to the realisation of the entire mission goals. Nominal mission sequence was generated and the detailed flight operations plan including normal, contingency procedures and simulation schemes for conducting the mission operations were generated applicable to each of the INSAT missions.

The lessons learnt from early INSAT missions were suitably reflected in the subsequent missions. Generally, in the first transfer orbit from spacecraft injection to first apogee many critical activities are involved because every major subsystems has to be validated just after lift-off. For example, INSAT 1 missions call for deployment activities to free a stowed antenna thus making available redundant block of thrusters and to make partial solar array deployment for power management.

INSAT 1A mission encountered non-deployment of antenna causing loss of precious time in the first transfer orbit. To avoid any deployment related activities till geosynchronous altitude, the INSAT 2 spacecraft configuration was arranged in such a way that no deployment is called for until such time. Solar array deployment related anomalies were observed during INSAT 1B mission sequence due to the changed thermal environment compared to assembly and integration on ground. For the subsequent missions, this was taken care by including special re-orientation sequences to cool/heat the solar array deployment mechanisms to ensure error free deployments. This strategy was successful in all the subsequent INSAT 1 and 2 missions.

Development of appropriate mission plans and procedures is a definite pre-requisite for satellite operations. Good understanding of subsystems and their functions helped to evolve suitable telemetry processing schemes and tele-command operations. Close interactions with the design team during early orbit phase was indeed very much helpful in this aspect. This understanding in combination with the mission goal was instrumental in developing operational procedures both for nominal and special operations.

Standardised and modular procedures were written taking into considerations the ground support availability. Using these procedures and with the help of software simulation exercises, the operations personnel were trained / kept up to date with the current operational status of the spacecraft. The modular approach was essential because a single operations person or team might be involved in carrying out multiple spacecraft operations. Once the logic or concept behind any nominal or special operations were made clear to the operations personnel, the modular approach became simpler because the software was configured to provide the required transparency of the spacecraft to the operations team that was handling. Another positive aspect of this approach was continuity of operations even in the case of loss of monitoring of a particular parameter due to some on-board failures or limitations. Using the similarity in design, either previous records or extrapolation of other INSAT data had proven to be effective for trend monitoring and for any corrective actions.

In the following paragraphs typical examples of operations management are discussed.

3. ECLIPSE MANAGEMENT

One common but very important operation for any geosynchronous satellite is the power management during eclipse season. The INSAT batteries were designed to provide adequate margin during solar eclipse periods lasting for about 45 days around equinox season for a daily duration of maximum 72 minutes provided the bus loads were kept under a minimum condition. In order to ensure such a margin exist as well as to remove any memory effects on the batteries, they have to be reconditioned prior to start of each eclipse season. The reconditioning involves slow discharge almost completely and recharging back.

Each spacecraft has two batteries and in order to provide necessary back-up for any unforeseen contingencies, both batteries can not be reconditioned simultaneously. A procedure is evolved to sequentially recondition each of the batteries. When multiple spacecrafts are handled simultaneously, the procedure is extended also to cover the optimisation of ground support in case of emergencies. Table 1 gives a typical sequence followed for the just concluded season involving INSAT 1D, 2A and 2B.

TABLE 1 Reconditioning of INSAT 1D, 2A, 2B (name plate capacity 18 AH)

Battery	Operation	Date	Start time in UT	Date	End time in UT	Measured capacity	Cell Volts and # @ termination	Charge returned in %
B #2(1D)	DISC	03/02/96	03:00	06/02/96	03:40	26.6	0.4967 (15)	-----
B #2(1D)	CHG	06/02/96	03:42	07/02/96	11:46			70
B #1(2A)	DISC	07/02/96	05:00	09/02/96	13:20	25.25	0.4994 (25)	-----
B #2(1D)	CHG	07/02/96	11:47	08/02/96	12:10			40
B #1(2A)	CHG	09/02/96	13:26	10/02/96	17:40			90
B #1(1D)	DISC	10/02/96	04:00	13/02/96	03:23	26.55	0.497 (14)	----
B #1(2A)	CHG	10/02/96	17:41	11/02/96	03:00			15.57
B #1(1D)	CHG	14/02/96	03:24	14/02/96	12:29			70
B #2(2A)	DISC	14/02/96	04:00	16/02/96	08:47	24.24	0.4914 (26)	----
B #1(1D)	CHG	14/02/96	12:30	15/02/96	14:14			40
B #2(2A)	CHG	16/02/96	08:48	17/02/96	11:55			92.22
B #1(2B)	DISC	17/02/96	04:00	19/02/96	09:24	24.38	0.4941 (28)	-----
B #2(2A)	CHG	17/02/96	11:56	17/02/96	23:18			13.04
B #1(2B)	CHG	19/02/96	09:25	20/02/96	12:30			90
B #1(2B)	CHG	20/02/96	12:31	20/02/96	23:58			20
B #2(2B)	DISC	21/02/96	04:00	23/02/96	10:57	25.26	0.4852 (14)	----
B #2(2B)	CHG	23/02/96	10:58	24/02/96	12:35			90
B #2(2B)	CHG	24/02/96	12:36	25/02/96	00:20			20

4. STATION-KEEPING OPERATIONS MANAGEMENT

INSAT 1D is currently located at 83 deg E , INSAT 2A is at 74 deg E and INSAT 2B is at 93.5 deg E longitude. Additionally, INSAT 2C is collocated with INSAT 2B at 93.5 deg E. Earlier INSAT 1B was operated mainly from 74 deg E and at the End of Life at 93.5 deg E. The longitude allowance is +/- 0.1 deg and the inclination allowance is 0.1 deg.

INSAT 1B located when it was at 74 deg. E close to an equilibrium point had provided valuable data for longitude drift behaviour in such a slot. The triaxiality perturbation is small close to an equilibrium point. Hence the conventional one sided East-West Station-Keeping strategy applicable for slots away from an equilibrium longitude was not relevant. For attitude hold using wheels, momentum unloading pulses from east and west face were occurring about 10 to 25 per day depending on season. Each of these pulses delivered a delta-V of the order of 0.0003 m/s. Thus over a day, contribution from such momentum dumping pulses were greater than required for longitude hold. A strategy was worked out to switch thrusters between east and west face at suitable times of the day. This had helped in maintaining the allotted dead-band of +/- 0.1 deg from the beginning of the mission without resorting to actual station-keeping mode of operations.

Studies were made to optimally use the forces arising from attitude control thrusters to counteract the force due to solar radiation pressure, thereby reducing the perturbation on the eccentricity vector which in turn would reduce the longitudinal libration. It was demonstrated that the thruster switching method did produce less perturbation for the sun-pointed perigee strategy at a correspondingly lower value of constant eccentricity, thereby reducing the longitudinal libration.

The longitude keeping strategy evolved using INSAT-1B was put to effective use for INSAT-1D also. INSAT-2 series of spacecraft use dual thrusters for single axis attitude control, for example momentum unloading in yaw. The two thrusters would be selected from East and West face. If the thrust level match, non contribution towards delta-V would be expected. But in practice, slight imbalance was observed. Extending the earlier strategy of pulsing for longitude control, in the wheel control mode itself, small pulses (say, typically 65 msec duration) were fired for suitable thrusters thereby reducing the burden of longitude station-keeping. Several variations of this strategy was implemented on INSAT-2A and 2B. This experience had led to the strategy of pulsing one or two pulses at 12 hours apart for longitude maintenance of INSAT-2B and 2C when they were collocated.

The operational experience gained over using the 22 Newton thrusters over a wide temperature range and different pulse-widths were valuable in characterising these thrusters at their acceptance level tests in order to have better attitude and orbit control.

The inclination correction or out of plane manoeuvres were done at the descending nodal crossing by firing a pair of south face thrusters for a specified duration. To hold the attitude, the same pair was to be used. If the thrusters exhibit imbalance a net disturbance torque would be felt. To correct this disturbance, the stronger of the two thrusters was off-modulated. In the cases where the imbalance became too large, there were occasions of attitude loss. To prevent any such mishap, operational procedures were evolved to do pulse mode firings to annul the daily build-up of inclination. To minimise the arc losses, these pulses of suitable pulse-widths had to be spread over a two hour span around the time of nodal crossing.

In the nominal case, when the disturbance torque is within bounds, for the period of delta-V firing, one can expect in-plane delta-V contribution also. This is because of the thruster mounting. Apart from the intended, axis control, each thruster would produce cross axis components. To balance the disturbance torques during the delta-V firing, the pitch and yaw axis thrusters would also fire with a heavy duty cycle. In the case of INSAT 2 series, the pitch and yaw axis control are by dual thrusters and hence the effect on the in-plane component would be to the extent of thrust imbalance between east and west face thrusters. In the case of INSAT 1 series, one thruster for a particular axis is used. By suitable combination of thrusters and after calibration, it was possible to cancel the in-plane contribution when the total delta-V firing was split into parts. In certain cases, it was demonstrated that by the attitude limit cycle pulse, the required delta-V correction either in East or West direction was achieved. The in-plane correction while doing out of plane manoeuvre becomes very significant in the case of collocation of two spacecraft, because any non-nominal performance would call for a collision avoidance manoeuvre.

In the time frame of INSAT-1B, there was no direct monitoring of thruster activity. It was monitored using the current drawn from the bus. The importance of direct monitoring was emphasised in the subsequent spacecraft. From INSAT 1C onwards, the thruster on-time was available in near real time. Using this data, manoeuvre planning and operations had become the standard practice. The other benefit for monitoring thruster activity was to have estimate of propellant usage and planning for further manoeuvres.

If the thrust imbalance was to be characterised for every manoeuvre, the imbalance in terms of attitude errors could be commanded as bias values for control system. In this fashion, the communication beam shifting during any such delta-V firing would be minimised. This was also effectively carried out in INSAT 2 series after calibration exercises.

5. CONTINGENCY MANAGEMENT

In the course of generally smooth operations, certain anomalies were encountered needing conventional, unconventional and unprecedented solutions. There were attitude losses due to thruster misbehaviours, control processor hung ups, momentum wheel failures and spacecraft power loss. Each of the situation was handled in the best possible way without jeopardising the entire mission. Some of the contingency situations were immediately recoverable and others demanded more time to recover.

During nominal operations as well as prior to any launch operations special teams were identified to list out the possible failure modes and identify suitable recovery procedures. At each step of major operations, possible indicators were identified for smooth and non-nominal behaviour of the spacecraft. If any contingency situation was encountered, identified contingency recovery procedures were taken up. If the situation was still irrecoverable, the approach taken was to put the spacecraft in a safe situation and thrash out all possible ways of recovery including all simulating exercises.

In the case of INSAT 1B several telemetry channels were progressively lost, and by 1990 except AOCS telemetry channels, almost all analogue parameters had become anomalous. Since August 1989 no north-South station-keeping manoeuvres were done due to uncertainties in the propellant balance. Both on-board batteries failed - one in October 1989 and the other in May 1991. New control modes were required for survival during solar eclipse and lunar shadow. Considering all possible modes of recovery, the only choice left was passive spin stabilisation to tide over the eclipse season. The spacecraft was put under yaw rotation and recovered at the end of eclipse season. These manoeuvres enabled INSAT 1B to survive through four eclipse seasons and one instance of lunar shadow when the power generation was less than 100 watts. The yaw spin mode was proven to be safe from power and thermal points of view. It was demonstrated that a fully functional spacecraft can also be maintained in the yaw spin mode as in-orbit spare. The advantage here would be saving in the recurrent propellant consumption for three axis attitude control, in addition to reduced operational activity. The satellite can easily be brought back to use from this hibernation within a short time.

There were occasions when the momentum wheels exhibited anomalies. Due to sudden change in friction, the safe operational temperature conditions were violated or were in that trend. The increase in friction made the control torque available to be near zero leading to attitude loss. Alternate wheel configuration was effected in some cases before attitude loss. Those steps were possible by setting trend monitoring parameters before the situation became out of hand. Upto INSAT 1C, the momentum wheels were from Bendix Corporation of USA. INSAT 1D uses TELDIX, Germany wheels. Both the TELDIX wheels in INSAT 1D exhibited anomalies which were operationally overcome. INSAT 2A and 2B also use TELDIX wheels. Based on the experience of INSAT 1D, the operational speeds were lowered. However, one wheel in each 2A and 2B had exhibited similar anomalies and the operational mode of the control systems was suitably changed.

Control processor hang-ups due to Single Event Upset in certain cases resulted in low body rates and in certain cases high body rates. When low body rates were encountered, the attitude recovery was made by momentum bias adjustment in open loop fashion instead of using any thrusters as back up. This procedure was effectively used on a number of occasions.

During recovery process many unconventional sensors like frequency of reception of specific RF signals (for example TM beacons), solar array power generation cycles and thermal parameters on specific locations were used. The goal of the recovery process was to keep the service interruption to the minimum extent possible if it could be avoided altogether but at the same time spacecraft safety was never compromised.

6. EFFORTS TO RESOLVE ANY ANOMALY

Real time contingency recovery apart, the major effort of the operational management is to understand what was the cause of the anomaly and what would be the necessary steps to be taken if the same situation recurs. In order to generate suitable operations procedure, a thorough understanding of the anomaly would assume high importance. Nominally the events just prior to anomaly would be checked bit by bit for any trend and corroborative evidences in terms of power, thermal and individual control responses. In the years of operations, many kinds of anomalies were encountered in various subsystems like Telemetry, Telecommand, Payloads, Thermal, Power, Propulsion and AOCS.

In the initial phase of INSAT 1B operation, the orbital performance after north-south station-keeping maneuver was showing under performance leading to suspicion of Roll thrusters. There was no thruster activity monitoring in direct telemetry. However, it was possible to monitor bus currents in dwell mode telemetry i.e., at every 8 msec rate, whereas normal telemetry was at 512 msec. The current changes were discretised into different levels. During the delta-V firings the level change was expected to be equivalent of at least two thrusters demand. In closer analysis it was found that soon after delta-V firing there were level changes for two, one, zero thruster demand apart from occasional three or four thruster demands. The one level was explainable because of off-modulation of stronger thruster within the pair. What was surprising was the zero level indicating both thrusters used for delta-V getting shut off to control attitude errors. This revelation explained that though the delta-V firing was commanded for a specific duration the actual firing was taking place for a less duration other than off-modulation. The revised delta-V firing duration was consistent with the orbital results. This is a typical case where an indirect parameter was analysed to bring out the cause of reported performance degradation.

Such exercises had been carried out for other cases of anomalies. Another typical example was the study about the telemetry frame loss in a systematic fashion. Later it was traced to occasional burst error occurring onboard at the time of frame formatting perhaps caused by spurious level changes in the spacecraft harness lines.

7. INTERACTIONS WITH USER AGENCIES

As discussed earlier, INSAT system envisages coexistence among various users. The spacecraft after reaching its final slot would be subjected to various in-orbit tests to validate the payload performance. At the time of in-orbit tests the user communities were also involved and their appreciation of results and test limitations if any were discussed. The C-band communication channels once they were allotted require only a little change in terms of attenuation settings depending on various services carried through that channel. Any characterisation studies would be supported from time to time. Failure of allotted channel due to unforeseen circumstances warrant alternate arrangements which would be negotiated. As a nominal practice, alternate arrangements would be known apriori for important channels.

The meteorological payload require much more interaction in terms of number of imageries required for different seasons and any special requirements like any celestial body in the Field of View of the VHRR. Occasionally, either due to various spacecraft operations or due to loss of signal at the time of ground processing, the imageries might become anomalous. On one such occasion it was analysed to be caused by thermal control system of the VHRR. On some other occasions, the processing software at the user's side needed minor correction to reflect changes in spacecraft configuration at the time of imagery which was not incorporated by the third party vendor.

8. FEEDBACK MECHANISMS TO DESIGNERS

The spacecraft data is continuously monitored and analytical studies are being carried out to characterise individual subsystem performance. Any anomaly observed during the operations is immediately brought to the attention of concerned design team and higher management. Moreover, periodically status reviews are conducted wherein the on-orbit observations along with analysis results are presented to the specialists in the review. In this process adequacy / any inadequacy in the spacecraft design is brought out. Any design modifications possibly required would also be discussed in the review meetings and suitably implemented. One such modification was the thermal design change for some of the thruster valves in INSAT 2C to bring down the operating temperature range after observing higher range in INSAT 2A and 2B. Another area of improvement implemented was in the addition of special control modes for attitude control.

The spacecraft operation management and review is a continuing quality improvement process which has been successfully incorporated in the INSAT system management.

9. CONCLUSION

In this paper the various components that make up the successful operation of INSAT system were identified and their role was illustrated. The experience gained over operating INSAT class of multi-mission satellites for more than a decade was multi-faceted. Many new strategies for operations were developed and implemented. The interactions played by operational centre with users and designers in the quality improvement scheme has been highlighted through various case studies.

10. ACKNOWLEDGEMENT

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GOES-8 AND -9 MISSION LAUNCH AND OPERATIONS SUPPORT OVERVIEW

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ABSTRACT: The new series GOES-8 and -9 launched in 1994 and 1995 provide more flexible instrument coverage and higher resolution than previous GOES spinners. This added flexibility and the 3-axis stabilized operating mode however resulted in a more complex satellite system with independent Imager and Sounder, and on-board image navigation systems requiring more daily commanding. Nearly 5000 realtime commands are currently sent each day to each GOES-8 and 9 spacecraft compared to 200 commands per day for GOES-7. These new technological advancements in spacecraft design presented new challenges for the NASA operations support personnel. In order to prepare for launch, post-launch test, and on-orbit operations, a rigorous mission planning scheme was developed to assure safe commanding of the flight system and monitoring of its state of health. This paper overviews the key mission operations approaches and philosophies developed for the GOES I-M missions and key operations tools that were developed to aid operations personnel in performing complex routine and special operations tasks. .

1. GOES MISSION: AN INTRODUCTION

The primary objective of the Geosynchronous Operational Environmental Satellite (GOES) Mission Operations Team is rather unique in that, unlike most other programs, providing an on-orbit asset or capability to the parent organization is not the primary goal. In fact, the primary objective is more indicative of commercial spacecraft production than a typical government agency's approach to satellite operations: that is to provide a meteorological satellite in geosynchronous orbit to another organization (government agency, in this case) for its exclusive use. Acting as the technical acquisition experts for the National Oceanic and Atmospheric Administration (NOAA), NASA has responsibility for designing, developing, testing, launching and delivering on-orbit, a fully operational spacecraft system for generation of state of the art weather products for the United States. With the technological obsolescence of the GOES-7 series spinners and introduction of the 3-axis stabilized GOES I-M series with dedicated imaging and sounding instruments, the ability to meet the requirement of delivering a turn-key system on-orbit was jeopardized under the previous Operations Team approach. In addition, due to the technological leap from GOES 1-7 to GOES I-M, continuous engineering support for NOAA was mandatory after handover to minimize or eliminate interruptions in operational product generation. Considering the problems that had plagued the GOES program in the late 1980s and early '90s, a derived requirement of the NASA/GOES Project, and NASA Operations, was to re-establish a 2-observatory constellation as quickly as possible (GOES operated with a 1-satellite system approximately 2.5 years after the loss of GOES-6 at launch) while concurrently testing and comprehending an entirely new state-of-the-art meteorological satellite, two rather conflicting yet daunting requirements.

2. NASA's MISSION OPERATIONS APPROACH

With these requirements, the time constraints imposed, the technological advancement, growth in complexity, and the need for continued engineering support from the developer (NASA), four core principles to re-engineer

NASA/GOES Operations evolved. These approaches and principles were rudimentarily formed during the GOES-8 launch campaign, but came to full fruition, and a permanent part of GOES, for GOES-9.

The first principle was establishment of a single authoritative Project Office Lead for the Operations function, the GOES Operations Manager (GOM). This position has traditionally been a non-Project Mission Operations Manager (MOM) co-located with the Project, from NASA/GSFC's Mission Operations and Data Systems Directorate (MO&DSD). The emphasis under MOMs had been launch-to-orbit operations, but with the GOES I-M series and establishment of a Project GOM, and only mission support provided by the MO&DSD, the fundamental emphasis shifted from simply raising and establishment on orbit to spacecraft engineering and total mission support to NOAA. This sea of change also provided a consistent, dedicated interface for NOAA for the life of the mission, and a direct link to development activities at NASA.

The second core principle was establishment of a self-contained Operations Team for launch and post launch test. This Team must consist of experts in the hardware/software systems of the spacecraft, with a strong operational overtone, thus requiring a multi-organizational approach to Team construction. Team composition was targeted to each particular mission phase as well. Satellite expertise in every subsystem was acquired for the critical launch-to-orbit and activation phases of the mission. A core contractor Team was selected to lead the effort (Computer Systems Corporation and Swales and Associates), bringing solid subsystems experience and operational experience to the Project. This core Team was heavily augmented by the spacecraft and instrument contractor's engineers (Space Systems Loral and ITT) to provide in-depth hardware knowledge to round out launch Team composition. The Team was led real-time by NASA-assigned personnel in the critical leadership roles of Mission Director and Contingency Manager. These positions were solely responsible for mission conduct, and had complete authority of the GOM and Project office. Training was a major component of developing the Team's synergy and efficiency. Six mission simulations and at least 2 launch simulations are conducted in the 6 months prior to launch of each GOES I-M satellite, each lasting up to 96 continuous hours and covering both nominal and contingency operations. For GOES -8 and -9, simulation realism wasrequired to flush out numerous personality conflicts, positional mismatches, and other flaws in the initial Team structures that would have significantly degraded effectiveness if Team refinements had not been made prior to launch. The end result was a strong, well balanced Team that effortlessly handled adverse situations, e.g. aborting of the first apogee motor firing on GOES-8 and complete replan of the mission profile, while concurrently dealing with repetitive Electro-Static Discharge events during the delay in transfer orbit.

The third principle was to thoroughly test the spacecraft prior to launch to ensure a strong knowledge base for the primary NASA Operations Team. An extensive test program evolved encompassing both ground-based testing of each spacecraft by the Operations Team from the Satellite Operations Control Center (SOCC), and comprehensive on-orbit testing. Significant issues were routinely uncovered in the pre-launch End-To-End (ETE) test program, thus the program evolved into a series of ever-more complex ETEs including complete archiving of test data at SOCC for future reference, data trending test-to-test, and troubleshooting of anomalies both real-time and through additional testing. The program has now been adopted as a baseline for the GOES program in the future, is being standardized, verification matrices established, and the program placed under configuration control. The second portion of this test philosophy is comprehensive Post Launch Test program (PLT). Two phases developed consisting of an Activation phase (ACT) and a System Performance and Operational Test phase (SPOT). ACT is a typical series of functional tests and deployments of operational subsystems, and basic characterization of performance. The SPOT phase is significantly more elaborate and complex, including establishment of critical Image Navigation and Registration (INR) functionality. ACT and SPOT combined constitute a total of approximately 350 tests of the instruments, spacecraft bus and ground system.

The final principle was to develop operations tools that enhanced the GOES ground systems ability to aid launch, PLT, and on-orbit operations personnel in real-time spacecraft command execution and telemetry monitoring and non-real-time telemetry evaluation. Perhaps the most critical and complex set of tools developed were Command Procedures (CPs). Because of the added operational complexity of the GOES I-M series over the previous GOES, the NASA operations group developed standalone CPs, over 800 per spacecraft, that systematically execute spacecraft command functions. These CPs utilize safety checks contained in the command database and pre-programmed logic constructs built to provide automated real-time pre-command and post-command checking and reporting. CPs were developed to provide a multi-layer safety checking approach to ensure that no commands were erroneously executed out of sequence at anytime during the mission. A secondary benefit of CPs is to provide a means of retaining engineering knowledge. As is typical with many multi-spacecraft series, retention of knowledge is very difficult to maintain over the entire spacecraft series due to personnel attrition. Because of the strict configuration control required for commands, CPs provided an excellent means for retaining this engineering knowledge derived from experienced gained through testing, and collaboration with the initial spacecraft developers. Another significant ground system enhancement was the development of complex telemetry processing algorithms (PSEUDO-B points) that are used to provide additional information to the spacecraft operator on the overall health of the spacecraft. Many of these PSEUDO-B algorithms are also used to detect and alert the operator when mission threaten conditions exist. For this reason safety monitor alarms were developed to provide additional alarm capabilities over the standard database Red/Yellow High/Low telemetry alarms. NASA working closely with NOAA developed the GOES Engineering Analysis System (GEAS) to provide enhanced offline telemetry analysis capabilities. The GEAS was developed to handle the extremely large engineering analysis needs for all mission operations elements, provide engineers quick data access, produce plots and reports for large volumes of data, and provide autonomous output of routine trending plots.

3. END-TO-END TEST PROGRAM

The ETE test program is the focal point of ground based testing performed by the NASA operations team at the SOCC. These tests have been proven to be an invaluable and necessary tool for ensuring that the ground system, operations teams, and spacecraft are fully prepared to support launch, PLT, and on-orbit operations. The primary test goals of these tests are to:

- Fully demonstrate the SOCC ground systems capability to send all commands to the GOES spacecraft in each command mode and receive and accurately process housekeeping telemetry and wideband data.
- Validate spacecraft CPs grouped in logical operational sequences identical to actual sequences performed during nominal and contingency orbit raising, PLT, and on-orbit operations.
- Demonstrate a closed-loop, end-to-end utilization of the GOES primary ground system elements including the validating the ground systems ability to determine the Attitude and Orbit Control Electronics (AOCE) interaction with the Payload instruments, perform flight software reprogrammability, and accurately process Wideband data.
- Provide an accessible archive for aiding operations personnel in troubleshooting on-orbit anomalies.

These goals are achieved through a series of 6 separate ETE tests for each spacecraft. Four ETE tests are performed while the spacecraft is in the clean room in Palo Alto, one while in the Thermal Vacuum chamber, and a final test while in the launch payload processing facility near the NASA Cape Canaveral launch site. In addition, the NASA operations personnel are able to monitor all thermal vacuum testing activities and launch pad activities through archived telemetry data at the SOCC during periods when the spacecraft is powered on. The ETE test team is composed in a similar manner to the multi-organizational launch team. Development the test plans and detailed test scripts are performed by NASA operations team, and reviewed and approved by SS/L and ITT Integration and Test personnel. ETE test execution is lead from the SOCC and coordinated through GSFC voice line with the SS/L and ITT team members.

4. LAUNCH AND EARLY ORBIT PROGRAM

GOES orbit raising command sequences present challenges to the NASA operations team, in that all commanding activities are initiated in real-time from the ground. There are no pre-stored command capabilities on-board the spacecraft so all elements in the ground system and network must be fully operational during several time critical maneuvers and deployments required early after launch. The orbit raising network for GOES is made up of the Deep Space Network (DSN) operated out of the Jet Propulsion Laboratory (JPL), the Air Force Space Network (AFSCN) operated out of Onizuka Air Force Base, and GSFC operated NASA Wallops and Bermuda stations. The spacecraft is injected into a highly elliptical orbit following separation from the launch vehicle with the perigee radius approximately 6550 km and the apogee altitude approximately 6500 km above geosynchronous altitude (42,164 km). The supersychronous altitude is desired to conserve on-board fuel. Following separation from the Atlas/Centaur, the NASA operations team begin a systematic turn-on of spacecraft bus components. With the exception of telemetry transmitters and command receivers, most spacecraft components are off at first contact, including all attitude sensors. Upon first contact at the Air Force Indian Ocean Station, an initial separation spacecraft spin rate is determined by measuring the duration of telemetry outages caused by the spacecraft spinning through a T&C antenna null. Following the critical first solar array panel deployment, the NASA operations team performs a series of orbit raising maneuvers over the next 14 days using the restartable bi-propellent Main Satellite Thruster to boost the spacecraft into a circular geosynchronous orbit. The first three maneuvers are used to raise perigee and the fourth to circularize the orbit by lowering the apogee to a geosynchronous altitude. The operations team completes the orbit raising activities by deploying the magnetometer boom, final solar array panel, Solar Sail and spinning momentum wheel up to normal on-orbit operating speeds.

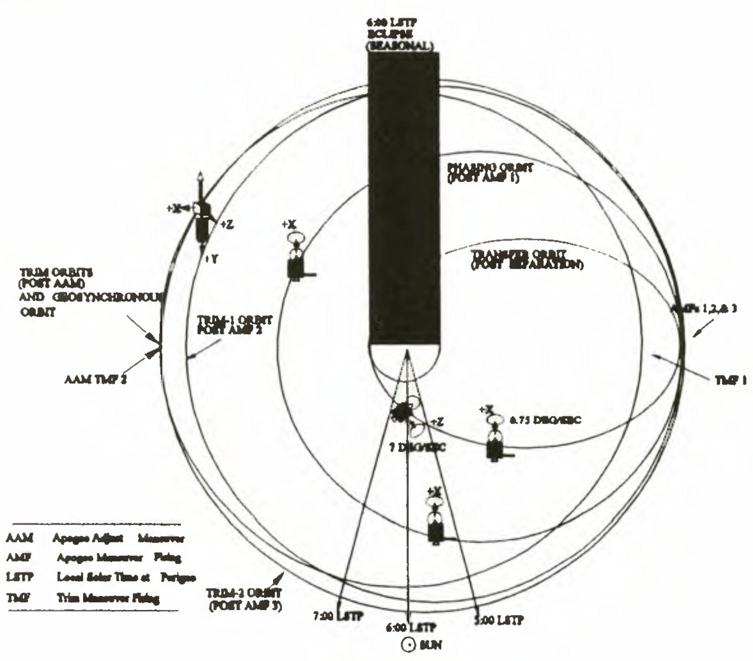

Figure 1. Orbit Raising geometry

The operations team members work in a three shift rotation supplemented with a special events crew during all deployments and orbit maneuvers. As with other GSFC programs, all nominal command sequences are scripted with branch points to Contingency Operations Procedures (COPs) in the event of a contingency. Over 100 detailed COPs are available to the launch team during orbit raising and Post-Launch Test activities. During all commanding situations (nominal and contingency) CPs are used to ensure proper command sequence execution.

5. POST LAUNCH TEST PROGRAM

The 2 phased PLT program evolved from a combination of other NASA and SS/L program's on-orbit test experience, and the complexity of the first new-generation GOES spacecraft. The need to fully characterize the spacecraft, instruments and especially the Image Navigation and Registration (INR) system was an over-riding factor in the extensiveness of the GOES-8 test program. Testing is performed in a logical, systematic manner, similar to most other project's test programs. A PLT plan is developed, approved, and under configuration control months prior to launch. During PLT only the Mission Director or GOM have the authority to modify the test program, or any individual test within the program, thus providing pre-planned operations so that product users can receive and process data as early as possible in a pre-defined, logical sequence. All functional testing is completed first in the ACT phase (approximately 45 days after establishment on orbit) with methodical turn-on and characterization of each subsystem by the applicable engineers from the NASA/Contractor Team. NASA delivers the spacecraft's health and safety responsibilities to NOAA at the completion of ACT, and NOAA fulfils console operator and other routine operations positions at this time. Calibration is the next sequence, to understand and normalize each channel's performance, followed by specification compliance testing.

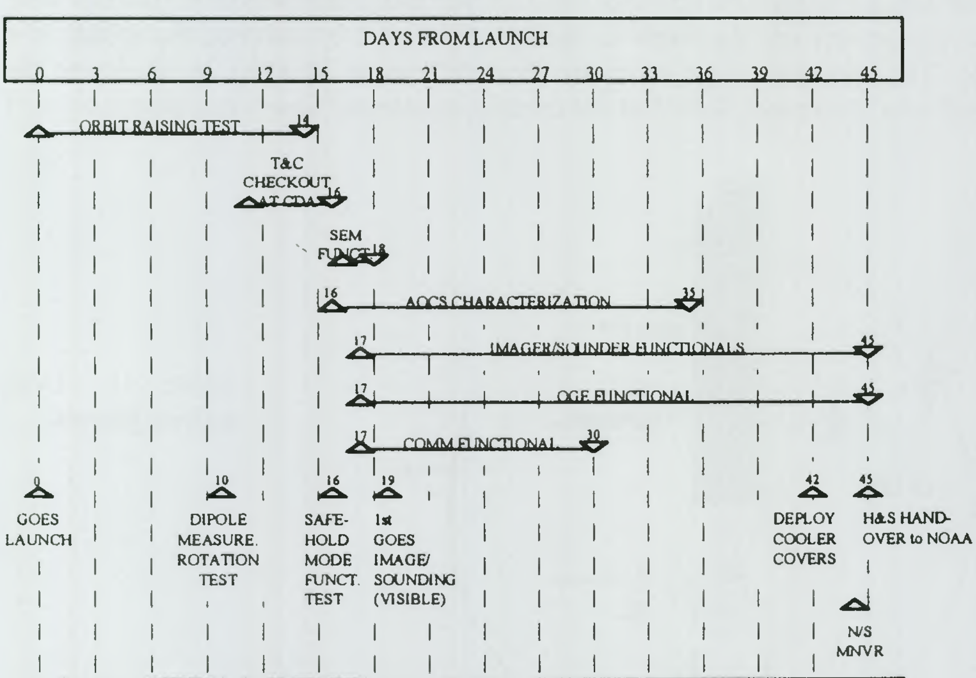

Figure 2. Typical time line for GOES Post Launch Test ACT phase

The SPOT phase for GOES-8 spanned approximately 135 days after the completion of ACT. INR startup occurs at the beginning of the SPOT phase, when most of the functional and calibration activities are complete. INR startup includes the first landmarking and star sensing operations, and testing of various motion compensation routines. SPOT concentrates on specification testing, and routine operations schedules are introduced at this point. These schedules allow the end weather service users to begin collecting and analyzing the new spacecraft's products while concurrently accomplishing test requirements and establishment of spec-performance. At the completion of SPOT the spacecraft is under full operational purview of NOAA, and NASA's launch and PLT job is complete. National Weather Service priorities and products become the only focus.

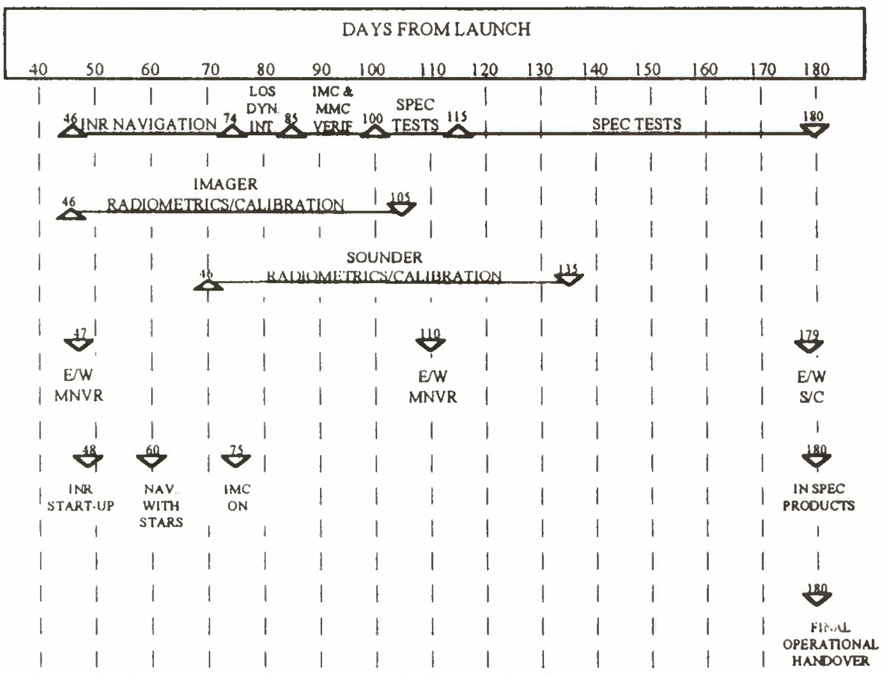

Figure 3 Typical Time line for GOES SPOT Phase

The SPOT phase has seen significant streamlining from GOES-8 to GOES-9, and will see another significant improvement in GOES-K concentrating less on individual tests and more on quickly transitioning into "routine" operations with off-line data analysis for system performance measurement. Streamlining from GOES-8 to -9 resulted in a net reduction in spacecraft and instrument testing from approximately 291 for GOES-8, to 177 on GOES-9, entirely due to efficiencies from improved system knowledge. Future GOES SPOT reductions are planned, to both reduce the complexity and number of dedicated tests, provide more routine operations for more realistic products sooner in test, and to reduce the 135 day SPOT test period to allow progression into operations as soon as possible for the NWS.

5. ON-ORBIT OPERATIONS

Complexity of operations, compared to GOES 1-7, is significant and requires diligence from the NOAA operations teams, with continued anomaly and trending support from the NASA Operations and development Team. With the number of required routine commands sent to the spacecraft an order of magnitude greater than GOES 1-7, the NOAA operations team is presented with challenges to ensure command schedules are built properly and executed correctly and on time. During the on-orbit phase, NASA continues to provide support to NOAA by maintaining CPs and On-orbit COPs required by NOAA operations personnel.

Figure 4. Example of the significantly increased complexity of operations from the GOES 1-7 to the GOES I-M series spacecraft

	GOES-7	GOES-8/-9
Number of Discrete Commands	260	800
Number of Commands Daily	200	5000
Number of Schedule Lines Daily	250	14-18,000
Number of Image Frames Daily		
Full Disk	48	48
Routine	88	124
Rapid Scan	--	200
Number of Soundings	1400 daily	2500 hourly
Total Lines of Ground Systems Code	120,000	850,000

NOAA schedulers use CPs as building blocks in the development of routine 24 hours command schedules that are initiated by NOAA operations personnel and autonomously executed by the ground system. NOAA on-line operations personnel monitor the execution of the command schedules to verify command activities successfully complete. If a command schedule suspends at any time during the execution, due to a command execution failure or a failed CP logic check, a message to the operator is displayed on screen indicating the severity of the failed command check, the subsystem affected, and pointer to a detailed message text providing the operator with instructions on how to rectify the problem. In the case of high severity levels, indicating potential mission critical situation, message texts may point the operator to detailed COPs in order to safe the spacecraft. Over 1500 message text exist for GOES 8 and 9 spacecraft.

COPs that are supplied to NOAA for on-orbit operations are formatted differently than orbit raising COPs. On-orbit COPs have been streamlined to allow easier contingency identification and a more straightforward approach to safing the spacecraft since NOAA on-line operations personnel do not have the advantage of having all the engineering support provided during launch. It was therefore the goal to provide NOAA on-line operations personnel with COPs in pre-canned script format that systematically walk the operator through the steps in determining the type of anomaly and command activities required for safing the spacecraft.

6. CONCLUSION

The approach to Mission Operations for this new GOES series requires more manpower and more monitoring and commanding than some of the new easy-cheap-autonomous commercial and governmental trends in satellite design and mission operations. However, the United States' meteorological community relies extensively on the products from GOES for hourly and daily forecasting. The national asset status of GOES and the vast user community across the nation (in excess of 10,000 users) demands a methodical, evolutionary approach to change, especially from one spacecraft block change to the next. With the significant leap in technology, related escalation in complexity, and increase in data and products, our methodology for GOES I-M had to be centered on making no immediate, radical change in SOCC operations or data distribution. This methodology, therefore, required significant levels of compatibility with existing data and product processing and distribution systems, and a gradual phase in of ground systems autonomy (begun with the logic-systems of the CPs in a format familiar to the existing operations personnel). With the re-establishment of the GOES constellation we have begun investigating and implementing spacecraft and ground system improvements. While gradual improvements are being brought on line for GOES I-M, visions of the future GOES ground system are being formed. It may never be as evolutionary, or revolutionary, as some of its contemporary scientific and commercial mission's systems, but the path to increased autonomy and reduced cost is being mapped and pursued for the next generation of GOES.

ADVANCED OPERATIONS CONCEPTS OF THE MTP AND MSG GROUND SEGMENTS

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ABSTRACT. An entirely new ground segment for meteorological satellites has been established by EUMETSAT. One of the main design goals for the ground segment of the METEOSAT Transition Programme (MTP) was the introduction of a high level of automation for satellite and ground segment operations. An advanced Operations Concept was the basis for the ground segment architecture which is characterised by the integration of all relevant elements for satellite and ground segment control. The MTP Operations Concept includes the use of a suite of modern Man Machine Interfaces at all levels of the ground segment. This covers Mission Management functions as well as support functions such as Flight Dynamics. The efficient and flexible production of operations schedules for the different satellites and the ground segment is ensured by the Mission Planning System. The role of the operator which is traditionally associated with direct execution of control, is shifted into the supervision of operations. This requires on one hand an exceptional validation effort but on the other hand minimises the possibility of human error. The Operations Concept for the METEOSAT Second Generation (MSG) foresees a further degree of automation. The central management of all ground segment elements, including those for mission product generation, is foreseen as well as the central execution of all system level operations. This paper presents the Operations Concepts for MTP and MSG and puts them in context with the respective ground segment architectures. It highlights advantages and limitations of these concepts and provides a summary of the experience of the initial phase of the MTP routine operations.

1. THE MTP OPERATIONS CONCEPT

The MTP system consists of two meteorological, geostationary satellites (1 operational, 1 standby) and its associated ground segment. The mission objectives of the system include:

- Image Taking of the earth and its atmosphere in the visible part of the spectrum and two bands of the infrared spectrum. A complete picture of the full earth disk is taken every half hour;
- Image Processing and Dissemination of the data to User Stations distributed over Europe, Africa and surrounding areas;
- Reception of the transmissions from over 1000 Data Collection Platforms located on land, at sea and in the air and the dissemination of their messages to the User Stations and via the GTS.

The definition of the MTP Operations Concept to fulfil these objectives was driven by the requirements to provide the METEOSAT services with a very high availability but at the same time to minimise operation costs. The chosen approach is based on a high degree of automation, thus minimising the need for human interaction. Since a large part of the operation costs are incurred by manpower associated with operating and maintaining the system, the minimisation of the required manning level consequently leads to a reduction in costs.

The operation of the two in-orbit satellites requires in addition to continuous health monitoring the execution of a number of mission related tasks:

1. programming of the on-board imager for a new image every 30 minutes;
2. orbit longitude and inclination, attitude and spin rate manoeuvres at intervals of several weeks;
3. decontamination of the imager;
4. seasonal operations like battery reconditioning and eclipse operation..

In addition to these space segment related tasks operational activities need to include the following ground segment functions:

5. reception of raw image, data collection platform messages, and housekeeping telemetry data, and the uplink of dissemination and telecommand data;
6. image processing, production of dissemination and data collection platform data;
7. meteorological product extraction;
8. image data and meteorological product archiving and retrieval;
9. mission planning and scheduling;
10. ground segment control;
11. performance analysis.

Whereas tasks 5 to 8 are mainly data driven and hence require a minimum of operator interaction, all others are traditionally laborious tasks. The level of automation in these areas is one driver of operations costs and reliability. Based on this assessment, an analysis was performed to identify potential improvements in the following areas:

- Spacecraft and Ground Segment Control;
- Mission Planning and Scheduling;
- Flight Dynamics.

1.1 SPACECRAFT AND GROUND SEGMENT CONTROL

METEOSAT operations in the past were largely based on paper based procedures documented in the Flight Operations Plan. This document contained all the spacecraft control procedures, the Flight Control Procedures (FCP), which were foreseen to be executed during the various mission phases. The execution of FCPs required in most of the cases the manual entry of the telecommands listed in the FCP and uplink of them under manual control. Validation and Verification of the telecommands were supported by processes within the control system. Limit checking and presentation of telemetry were further basic functions performed by this system.

Control of the ground segment elements was performed separately from spacecraft control. It consisted of control of the remote ground station and the communication links. Additionally, the application processes for Image Processing, Dissemination and Meteorological Product Extraction were also separately controlled.

For the definition of the MTP Operations Concept an analysis of all required operational tasks was performed. It was recognised that in order to achieve a high degree of automation the following aspects of system design should be considered:

- Control of the spacecraft and the ground segment by using a single integrated system, thus allowing the implementation of procedures requiring synchronised control of spacecraft and ground segment elements;

- Description of all operational procedures in a high level operations language and execution of these procedures by the control system without the need for operator interaction for all repetitive activities;

- assigning a supervisory role to the operators and provision of modern WIMP based MMIs allowing to access all frequently required functions quickly, easily, and with a low probability for error.

A Control System architecture satisfying all of the above points was developed. It is embedded in the MTP Core Facility which includes in addition to the Spacecraft and Ground Segment Control Element also elements for Image Processing and Dissemination.

The implemented Operations Language (OL) includes statements for the sending of telecommands and the checking of telemetry, as well as constructs allowing flow control and interaction with the operator. The possibility to call sub-procedures from within a procedure and to supply run-time procedure parameters (arguments) are further features of the language. The automatic operations procedures, which are described in OL, can either be selected manually by the operator for immediate or timed execution, or invoked by an operations schedule produced by the Mission Planning and Scheduling System.

1.2 MISSION PLANNING AND SCHEDULING

The operation of a complex system such as the MTP Ground and Space Segments requires a Mission Planning System (MPS) which is able to support a large number of concurrent activities. These include spacecraft related activities like image taking or manoeuvres and ground segment related activities like maintenance or configuration changes. In order to minimise the workload required for planning and scheduling tasks the MPS needs to allow:

- automated scheduling of repeating activities;
- automated conflict resolution;
- reception of activity requests from other ground segment elements.

The implemented MPS is fully integrated into the Spacecraft and Ground Segment Control Element within the Core Facility. As planning inputs, the MPS requires:

- inputs from the Flight Dynamics Element - e.g. geometric events, imager pointing data, manoeuvres;
- scan pattern definitions for image taking and detector gain changes;
- inputs from the planner detailing other operational requirements - e.g. spacecraft or ground segment configuration changes.

From these inputs, the MPS generates the executable schedules containing automated procedures and commands which are used to execute routine operations as follows:

- spacecraft specific executable schedules containing calls to spacecraft automated procedures and spacecraft telecommands;

- the ground segment executable schedule containing calls to ground station automated procedures, ground station commands and MCC commands (high-level commands to other elements of the Core Facility).

The following diagram (Fig. 1) illustrates the interfaces of the MPS with the other elements of the Core Facility:

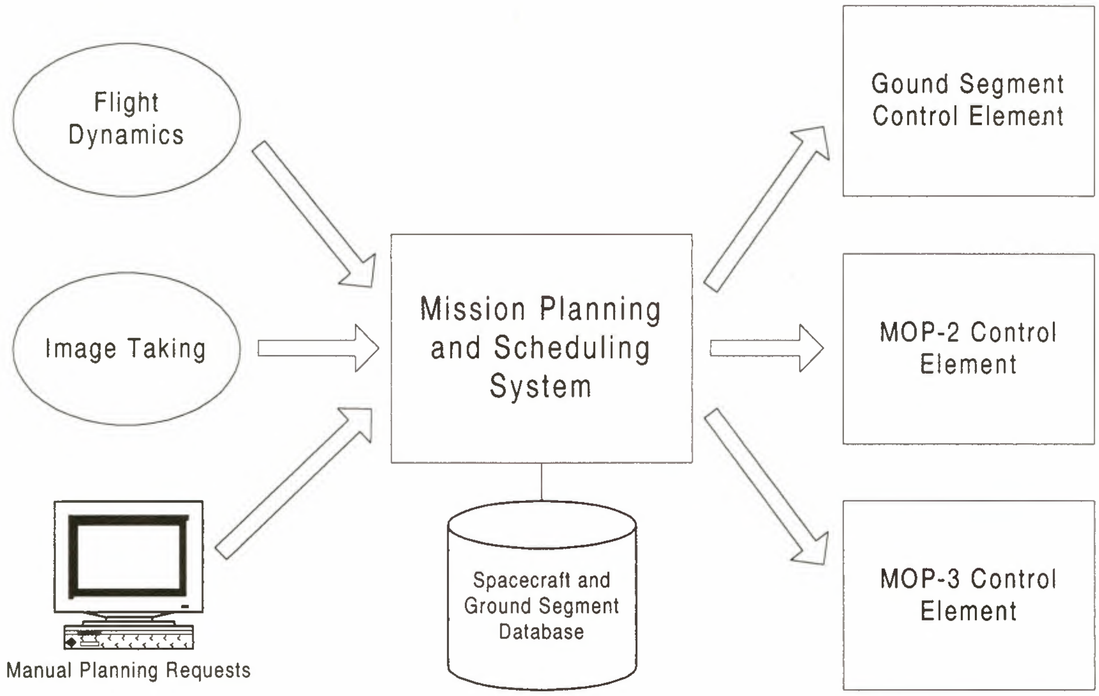

Figure 1: Interfaces of the MPS with other Core Facility Elements

1.3 FLIGHT DYNAMICS ELEMENT

For the execution of the MTP Mission Requirements the capabilities of the Flight Dynamics Element need to include:

- Attitude/Orbit Determination and Prediction;
- Spin Rate Determination;
- Manoeuvre Planning;
- Orbit Event Prediction;
- Antenna Pointing Data Generation;
- Fuel Budget Management;
- Imager Parameter Generation.

Input data to the FDS are Ranging and Tracking data provided by the ground station in Fucino, telemetered attitude sensor data from the spacecraft control system, and refined attitude data provided by the Image Processing Element. Depending on the type of output data Flight Dynamics products have to be generated within regular intervals of 24 hours (for Imager Parameters) to 1 week (Event Prediction).

The Flight Dynamics Element as a part of the Core Facility can be run in manual or automatic mode. In manual mode, the following functions are provided:

- Full control of -
  - data retrieval and editing;
  - state determinations;
  - predictions and product generation;
  - transfer of products;

- Management of Databases -
  - dynamic and static databases;
  - state vectors, manoeuvres.

In automatic mode, the system is controlled by high-level commands from the ground segment executable schedule thus allowing to run time consuming tasks without operator intervention. This is the normal mode of operation and is represented in the diagram below:

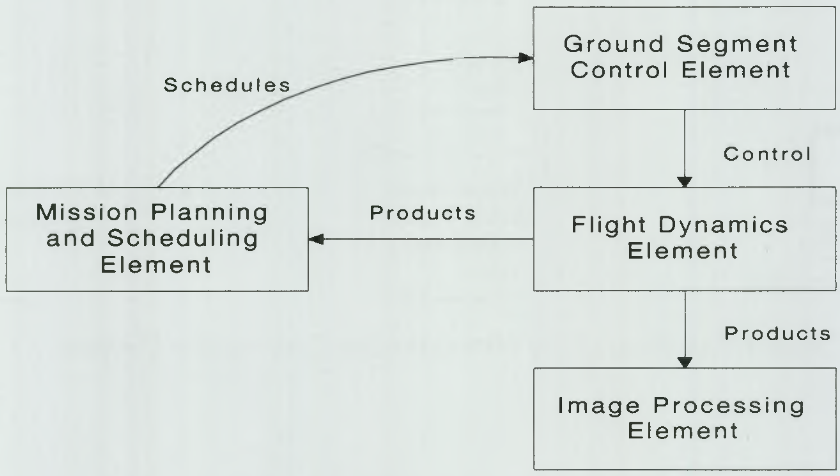

Figure 2: Flight Dynamics Element Context

2. EXPERIENCE OF OPERATING THE MTP SYSTEM

From an operations point of view, the MTP system is a large and complex system incorporating two spacecraft and a number of ground segment facilities performing all spacecraft and mission data processing in real-time. The ground system has a high degree of inherent automatism to support routine operations. This high degree of automatism has been implemented in such a way as to fully support the routine operations of the ground and space segment with the minimum of manual operator intervention.

It should be stressed at this point that few automated procedures have been implemented for failure recovery from either space or ground segment anomalies. Quite sophisticated facilities exist for ground or space segment failure detection, but the development and implementation of automatic recovery procedures is still at an early stage. The goal is to cover all anomalies which require a fast response by the control function.

As far as the electronic, executable schedules are concerned, each shift operator is responsible for the execution of an electronic schedule or timeline. However, his activities are restricted to supervisory tasks and the intervention in case of unforeseen anomalies.

System level operations like reconfigurations to redundant processing chains or the switching to alternate data lines are also within the scope of responsibility of the shift operators. In these tasks the operator is not supported by automated control procedures but has to operate by direct interaction with the ground segment M&C MMIs.

A further observation to be noted is the central and critical role which the mission planner now plays in the overall operations process. A high degree of emphasis has been placed in MTP operations on the quality control of the schedule and timeline generation. This is a manual activity, similar to inter-schedule co-ordination, which is not supported by the system.

2.1 PROCEDURE VALIDATION AND MAINTENANCE

One of the effects of integrating such a high degree of system automation into a spacecraft operations environment is that a significant level of effort is required in order to validate and maintain the automatic procedures. For the MTP system, an Operational System Validation phase was built into the preparations for spacecraft and mission hand-over from ESA/ESOC.

A major component of this phase was the validation of all the automatic space and ground segment procedures, including all possible execution paths, against the ground and space segment simulators. The validated routine procedures subsequently formed part of the operational scenario tests, involving all elements of the ground segment and an in-orbit METEOSAT spacecraft in representative operational scenario configurations.

2.2 THE ROLE OF THE OPERATOR

One of the issues raised by the move towards a higher level of automatic control in the MTP system concerns the role of the operator in routine and contingency operations.

Even for the MTP system, where the execution of routine operations requires no direct intervention from the operator, there may come a time when the motivation and possibly the ability of the operator to intervene in an anomalous situation could be severely compromised.

The approach currently adopted within MTP routine operations is to re-orient the role of the operator away from the direct execution of operations and more into tasks associated with system analysis e.g. routine and contingency procedure development and maintenance, anomaly investigation ...etc..

This approach serves a number of goals - to stimulate the operators to improve their level of knowledge of the system, and to improve their ability to react in cases of anomaly.

2.3 OPERATIONS MANNING

The MTP ground system is operated by a total of 3 shift positions on a 24 hours per day basis. The shift roles have been broken down as follows:

- Space Segment Controller with responsibility for all spacecraft operations;
- Ground segment Controller with responsibility for the Prime Ground Station, communications links, Core Facility configuration and mission data processing;
- Shift Meteorologist with responsibility for the generation and quality control of the meteorological products.

For spacecraft and mission operations, the shift staff are complemented during working hours by an operations team of 6 operations and mission engineers who have responsibility for the operations and management of MTP spacecraft and missions.

3. PERFORMANCE OF THE MTP SYSTEM

Prior to the hand-over of METEOSAT spacecraft and mission operations from ESA/ESOC to EUMETSAT, mission performance statistics were compiled on a weekly and monthly basis in order to track the performance of the ground and space segments at both system and sub-system level. Since hand-over, similar figures have been compiled by EUMETSAT for exactly similar reasons, but also so that the performances of the two systems could be compared.

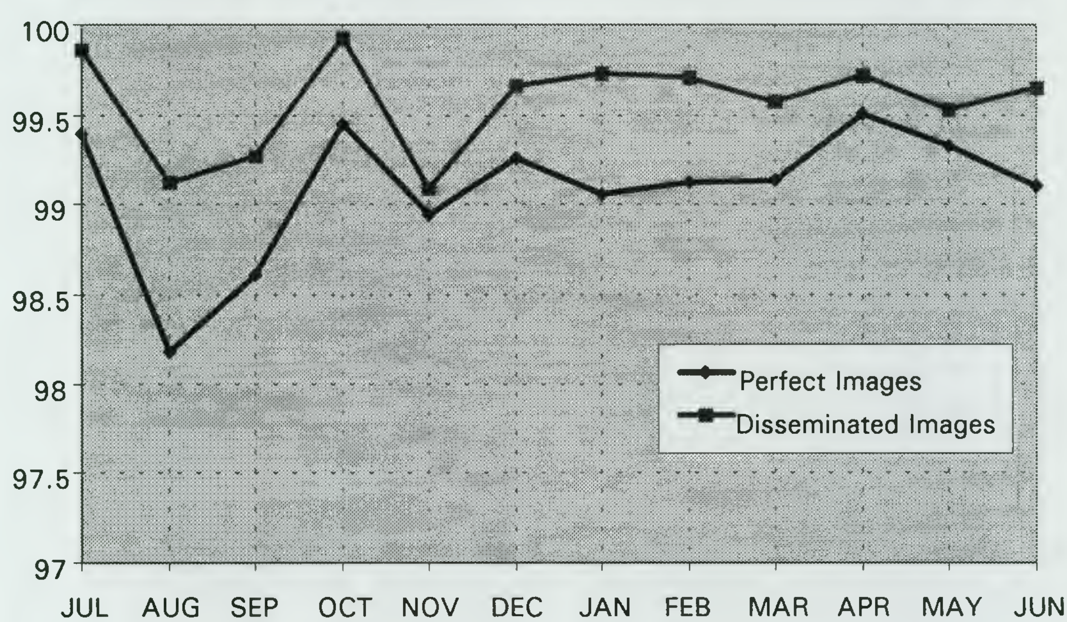

Figure 3: MOP/MTP Mission Performance

The above chart (Fig. 3) shows the performance of the MOP and MTP Imaging missions from July 95 till June 96. The "Perfect Images" figure represents the number of half-hour images that were acquired and processed without any problem (e.g. missing lines). The "Disseminated Images" figure represents the number of images that were received, processed and disseminated to the users but which could have contained missing data.

It can be seen that after the MTP system became operational in November 1995, the Imaging Mission performance stabilised on a high level with an average of 99.7% and 99.2% for "Disseminated Images" and "Perfect Images" respectively. Investigations into the reasons for losses of image slots have shown that all of the losses can be attributed to communication line outages and hardware or software failures. The human factor did not play any significant role.

4. THE MSG OPERATIONS CONCEPT

The METEOSAT Second Generation system is planned to become operational in October 2000 with the launch of the first MSG spacecraft. The Mission Requirements are very similar to the MTP requirements with the major difference being the higher geometric and radiometric resolution of the imager and double the image acquisition rate. The satellite design will be a modern one with improved autonomy features.

The experience gained with the MTP system has confirmed the suitability of the overall approach and in particular the appropriateness of the Operations Concept. However, some potential areas for improvement have been identified:

- extending centralised ground segment control by adding network management, redundancy switching and control of mission product extraction and archiving elements;
- provision of enhanced tools for preparation, validation and maintenance of automated control procedures;
- improvement of the Operations Language to simplify automated control procedure definition;
- extension of the applicability of the Operations Language to Mission Planning, definition of derived parameters, macro commands, event generation, data analysis;
- implementation of yet more user friendly MMIs for increased visibility and management of system functions.

These features will allow fully centralised routine operation of the entire MSG System by using common M&C facilities across all elements of ground and space segments.

5. CONCLUSIONS

The Operations Concept of MTP has been presented, along with a summary of operations experience and performance during the initial phase of operations. Lessons learned from the implementation of the MTP Operations Concept have been identified and analysed in the context of the MSG operations concept. The main conclusions that can be drawn are:

- an Operations Concept basing on the use of automated control procedures has led to a highly reliable system;
- whilst the validation effort is significant, the overall cost efficiency is notably improved.

This approach of minimising the need for human interaction with spacecraft and ground segment operation will be consequently continued with the aim to further increase the reliability of the system and to reduce operations cost.

ESTIMATING THE EVAPORATION OVER NASSER LAKE IN THE UPPER EGYPT FROM METEOSAT OBSERVATIONS

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ABSTRACT

The water loss from Nasser Lake in the South of Egypt is one of the national problems, where the lake is the water bank of Egypt and the evaporated water range between 10 to 16 billion cubic meter every year, which represent 20 to 30 % of the Egyptian income from Nile water.

Correlation analysis between the cloudiness observed by Meteosat in the infra-red band (10.25 -12.5 μm) and ground station measurements for atmospheric infra-red, temperature and water vapour content at the north head of the lake near Aswan High Dam. Models and empirical relations for estimating the evaporation over the lake are deduced and tested.

Using Meteosat infra-red window (10.5 - 12.5 μm) observations and the empirical models, we can estimate the evaporated water every day. The yearly water loss can be determined from the integration of the daily values.

INTRODUCTION

Nasser Lake is the second largest man-made lake in the world, extending from the southern part of Egypt to the northern part of Sudan, about 500 km length, and 7000 km circumference. The level of water oscillating between 147 to 182 meter over the sea level during the *one* year, and from year to year. Nasser Lake is the water bank of Egypt, contains about 180 billion cubic meter from fresh and renewable water. The lake is surrounded by empty flat desert, also the nominal annual insolation is more than 2500 kWh/m^2. The water loss from the lake is one of the national problems, where the evaporated water ranges between 10 to 16 billion cubic meter every year, which request 20 to 30 % of the Egyptian income from Nile water. (see map 1).

Net Radiation is an essential parameter for estimating evaporation from large water sutiaces by energy balance method [1,2]. Net radiation has been measured for the first time over the Nasser Lake for 132 days including warm and cold seasons [3]. Solar energy distribution and moisture estimation over Egypt has been performed for the first time from Meteosat Satellite observations during 1990's [4,5].

The purpose of this study is to derive an empirical relation applicable over the lake to estimate the evaporation using the measured data at ground for atmosphere infrared, air temperature, and cloudiness measured in infrared spectral band by artificial satellite Meteosat.

DATA

<u>Satellite Data</u> :

The Meteosat satellite is stationed in a geostationary orbit at nearly 36.000 km above the equator and the Greenwich meridian (0° N, 0° E). The principle payload of the satellite is a multi spectral radiometer [6]. This provides the basic data of the Meteosat system. The three channel radiometer includes :

- Two identical adjacent visible channel in the 0.4- 1.1 μm spectral band.
- A thermal infra-red (window) channel in the 10.5 -12.5 μm spectral band,
- An infra-red (water vapour) channel in the water vapour absorption band (5.7 -7.1 μm), which can be operated on place of one of the two visible channels.

The set of images in any one half hour period are the 2.5 km resolution visible, and the 5 km for water vapour absorption band (5.7 -7.1 μm).

Every day at L.M.T 11^h, the Meteorological Authority of Egypt at Cairo, receives images from the satellite Meteosat to analyze cloudiness over Egypt and the surrounding countries. One image is in the visible spectral band (O.14 - 1.1 μm), and the other in the thermal infra-red window (10.5 - 12.5 μm). Additionally, a third image in the water vapour absorption band (5.7 -7.1 μm) is received. The brightness of each pixel as seen by the satellite is interpreted as an index of atmospheric opacity. We classified the brightness within five bins (very dark areas are zero, while very bright areas are four), and measured the daily brightness of the cloudiness in the spectral band (10.5 -12.5 μm) for Aswan for the period (1990 - 1992).

Ground Data :

Aswan is located on the north end of Nasser Lake at coordinates (23° 58'N, 32° 48' E). There are a Meteorological ground station for measuring the different component of solar radiation and the other meteorological elements.

The atmospheric infra-red radiation measured at Aswan by Epply precision Infra-red Radiometers.

ANALYSIS AND RESULTS

As a first step we carried out a simple linear regression for the data at Aswan for the period (1990 - 1992), between the incoming long wave radiation for clear skies (R) and σT^4, where σT^4 (mW. cm^{-2}) represent the total infra-red emission by a black-body in all wavelengths at temperature T° K (Stefan law). The correlation coefficient (cc) between R and σT^4 is 0.97 and standard error (se) of estimate is 1.14, and the relative error (re) is 2.9. The regression equations being:

$$R = -22.32 + 1.386\ \sigma T^4 \mathrm{mW / cm^2} \quad \ldots \ldots (1)$$

As a second step, we introduce the effect of the water vapour pressure (e) with temperature to get a preferable result for estimating R in the humid regions.

Elsasser [7] show that, since the spectrum of water vapour is not continuos (i.e. in the water vapour bands, the lines are so far a part from each other that each absorbs or emits independently of the others) but a line spectrum and does not obey an exponential but a square root law of absorption and emission. Hence, we selected $\sqrt{e}$ as a second variable in equation (2).

$$R = -25.312 + 1.550\,\sigma T^4 - 1.093\,\sqrt{e}\,\mathrm{mW/cm^2} \quad \ldots\ldots\ldots \quad (2)$$

where, the multiple correlation coefficient (mcc) is 0.975, and (se) is 1.059, and (re) is 2.7.

As a third step, we introduced the effect of the cloud amount (C) beside the effect of the temperature and water vapour pressure to get a preferable result for estimating R in the cloudy condition, where the cloud cover increases the atmospheric emission, this is a result of that, most clouds radiate as black-bodies at their surface temperature. We have two types of cloudiness, Cg is the mean daily of cloud amount observed from ground, and C_{st} is the mean daily of cloud amount observed by Meteosat Satellite in infra-red band (10.5 - 12.5 μm). The clouds measured in tenths (i.e. $O \leq C \leq I$), and we took the amount of cloud only for simplicity, with ignoring the type and height of each cloud.

It is found that the (cc) between R and Cg is -0.56, the standard deviation is 0.185, and the regression equation being :

$$R = -21.64 + 1.482\,\sigma T^4 - 1.156\,\sqrt{e} - 6.18\,Cg\,\mathrm{mW/cm^2} \quad \ldots\ldots\ldots \quad (3)$$

The cc between Cg and C_{st} for this period (1990 - 1992) is about 0.90, when we use this regression for estimate R value in cloudy days, we find that the accuracy is poor. Hence to clear the effect of cloud in equation (3), we isolate the days which have amount of clouds is equal or greater than 4 Octs from this period are about 100 values and the cc between R and Cg and C_{st} are -0.59 and -0.55 respectively. It is found for the cloudy days the regression being :

$$R = -15.82 + 1.388\,\sigma T^4 - 1.291\,\sqrt{e} - 6.21\,Cg\,\mathrm{mW/cm^2} \quad \ldots\ldots\ldots \quad (4)$$

where the multiple correlation coefficient is 0.986, and the standard error of estimate is 0.78, and the relative error is 2.03.

For the case of clouds measured by Meteosat Satellite C_{st}, the regression being :

$$R = -16.6 + 1.3828\ \sigma T^4 - 1.66\ \sqrt{e} - 2.026\ C_{st} \mathrm{mW/cm^2} \ldots\ldots\ldots\ldots (5)$$

where the multiple correlation coefficient is 0.978, and the standard error of estimate is 0.83, and the relative error is 2.8.

Map (1) : Location of Lake Nasser in Upper Egypt

CONCLUSION

We conclude that : from equation (2) for the clear sky days, and from equation (5) for the cloudy days, we can estimate the water vapour pressure e, then the evaporation over Nasser Lake, from knowing the incoming long wave radiation for skies, and screen temperature T measured at ground stations, and cloudiness Cst from Meteosat observations in infra-red band (10.5 -12.5 μm).

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MULTI-MISSION OPERATION MANAGEMENT OF LEO SATELLITES

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ABSTRACT

Spacecraft Control Centre, ISTRAC supports pre-launch, LEOP and Normal Phase operations of Indian Remote sensing Satellites (IRS) and Stretched Rohini Series Satellites (SROSS) in Low Earth Orbits. Currently five three-axis stabilised polar sun-synchronous IRS satellites and one SROSS satellite in 435 km x 610 km orbit are being supported. Over years ISTRAC has built up the infrastructure, operations environment, trained manpower and management system for carrying out multi-satellite control in a smooth way.

This paper describes the salient features of spacecraft control and operations in terms of computer hardware and control facilities, software system and management system. Special features such as data handling systems, man/machine interfaces, multi-satellite scheduling including payload programming requirements, automation of flight dynamic operations, mechanism of spacecraft contingency handling, reporting and review mechanisms that help in efficient operations are highlighted.

1. INTRODUCTION

ISRO Telemetry, Tracking and Command Network (ISTRAC) provides ground segment support of spacecraft operations and control for remote sensing and science missions. Spacecraft Control Centre (SCC) located at Bangalore supports pre-launch, launch and early orbit phase and normal phase operations of Indian Remote Sensing Satellites (IRS) and Stretched Rohini Series Satellites (SROSS). Currently five three-axis stabilised polar sun-synchronous IRS satellites and one SROSS satellite (435km x 610km orbit) are being supported in a multi-satellite support environment. Table-1 provides the salient features of these missions. Figure-1 shows the functional organisation of the ground segment for mission operations. Mission operations are conducted from SCC, which has the necessary facilities for carrying out satellite health monitoring, analysis and control. For Telemetry, Tracking and Command (TTC) functions, SCC is supported by a network of ground stations in S-band and VHF. SCC computer system with attendant software and displays provides the environment for conducting flight operations and mission analysis. It also supports flight dynamic software for orbit determination, orbit manoeuver planning and attitude computation. Network communication software in conjunction with dedicated communication links provides the connectivity to all the TTC stations and work centres. Scheduling network stations and spacecraft operations including payload operations in a multi-satellite support scenario is an important activity. SCC interfaces very closely with the mission team, spacecraft designers, payload data acquisition and processing teams spread across various work centres of Indian Space Research Organisation.

2. TTC GROUND STATION NETWORK

The radio visibility of the satellite from a ground station depends upon the satellite orbit type. For Low Earth Orbit (LEO) satellites only a short arc segment (pass) of the orbit is visible in one revolution. Five to six passes per day are visible for an equatorial station; six to fourteen passes are visible for a station at higher latitude.

TTC network for LEO missions is selected considering the orbit coverage requirement, orbit determination requirement to collect adequate tracking data from different arcs of the orbits, satellite operations requirement to handle specific sequence of events and contingencies. ISTRAC ground stations at Bangalore, Lucknow and Mauritius along with Medvezji Ozera (Bearslake, Russia) support the TTC functions for IRS & SROSS satellites throughout the mission life. In addition to these stations, during the launch and early orbit phase or initial phase, extended radio visibility of the spacecraft from additional ground stations is required for conducting critical operations such as sun acquisition, earth acquisition, three-axis stabilisation and orbit manoeuvres. Availability of a back-up station support during critical operations is a desirable mission requirement. Therefore, initial phase network for IRS missions is augmented with external agency ground stations at Hartebeeshock/South Africa (CNES), Weilheim/Germany (DLR), Pokerflat/USA (NASA). These stations, also, provide the additional tracking data required to establish the orbit accurately after spacecraft injection. This TTC network with stations at longitudinally and latitudinally separated geographical locations ensures IRS spacecraft visibility in every orbit. All the TTC stations are connected to SCC by satellite communication links operating at 64 Kbps.

2.1 DESCRIPTION OF ISTRAC TTC STATION

The functions performed by S-band TTC Ground Station are:

- House-keeping (Realtime/Playback/Dwell) and star sensor telemetry data reception, recording, conditioning and transmission of data to SCC
- Transmission of commands generated at SCC to the spacecraft
- Tracking the spacecraft, collecting range, doppler and angles data and transmission to SCC

ISTRAC TTC stations are equipped with almost identical systems for TM data reception, tracking and commanding. All stations are provided with transmit-receive antenna of size 10m dia with a G/T of 19.5dB. Antenna can be driven in Azimuth and Elevation by servo system in manual, auto-track, program track and slew modes. An acquisition antenna mounted on the main antenna system with a beam width of 7deg. facilitates initial acquisition of the satellite. All the stations have the capability to receive 3 or 4 TM carriers with necessary recording, PCM decommutation and quick look facilities. Each station is provided with a complete telecommand system of 2KW RF power and precision range and range rate system. Simultaneous transmission of commands and tones over a single uplink carrier is also feasible. Station computers interact with mission computers at SCC for data transfer in realtime. Time and frequency are maintained with GPS timing system and high stable oscillators.

3. SPACECRAFT CONTROL CENTRE

SCC is the central decision making element and is responsible for mission, spacecraft as well as ground facilities operation and control during pre-launch, launch, early orbit and on-orbit phases. The major tasks of the Spacecraft Control Centre are:

- Scheduling of spacecraft operations and execution of orbit and attitude manoeuvres as per mission requirements
- Scheduling and carrying out command operations including payload programming
- Routine house-keeping data processing and health monitoring in realtime
- Spacecraft health data archival and database management
- Spacecraft health analysis and performance evaluation

- Sub-system performance monitoring through trend analysis
- Orbit and attitude determination
- Co-ordination with various network stations, payload data reception stations, National Data Centre (NDC) and other related agencies to realize the above tasks
- Fault detection, isolation and recovery in case of spacecraft emergencies

Control centre facilities, computer systems and software with proper man-machine interfaces (MMI) help the spacecraft controller and operations team ensure flawless operations. MMI provides a user friendly environment to perform spacecraft operations efficiently.

3.1 SCC FACILITIES AND INTERFACES

SCC consists of mission control rooms, mission computers with attendant software and support systems. SCC comprises of several control rooms for conducting mission operations. The Main Control Room (MCR) and Mission Analysis Room (MAR) are used during pre-launch and initial phase operations. For each satellite mission, a Dedicated Mission Control Room (DMCR) is provided to carry out spacecraft operations in normal phase. These control rooms are equipped with monitors and keyboards. These are used for monitoring the spacecraft health from housekeeping telemetry, transmit telecommand blocks to the spacecraft and confirm commands execution onboard the spacecraft, communication link and data flow status from TTC stations. Graphic terminals help to display the plots of chosen spacecraft parameters, mimic display of subsystem status and ground trace of the spacecraft. Printers and plotters are also provided to obtain hard copies. Large screen displays in MAR help to analyse the data and those in DMCR display satellite ground trace, schedules and other relevant information. All these rooms are fitted with multi-channel intercoms, universal and count-down time displays. Close circuit TV and video displays help to monitor activities at different control rooms. MCR houses consoles for the operations and network co-ordinations teams. MAR is used by the mission and spacecraft sub-system designers and has desk top mounted displays to monitor subsystem health and data analysis. Flight dynamics activities are carried out in a separate room with table top mounted terminals, graphic displays, PCs, printers and plotters. Other facilities at SCC include fully furnished conference hall, visitors gallery, VIP room and E-mail/Fax/Photocopying facilities. SCC facilities are powered by a fully redundant UPS system with battery back-up and centralised air-conditioning system.

3.2 COMPUTER CONFIGURATION

Computer systems play a major role in the mission operations for spacecraft control. Figure-2 shows details of computer configuration for multi-spacecraft support. This configuration consists of:

- Dedicated Communication Processors (CPs) for interfacing with ground stations Network (VAX 11/750 systems)
- Realtime Processors (RTPs) for realtime and near realtime processing of individual satellite data (Microvax II & Microvax 3400 systems)
- Flight Dynamics and Analysis Processors (FDAPs) for data archival, orbit and attitude determination and trend analysis (VAX 11/785 and DEC Alpha systems)

The CPs interact with TTC stations using X.25 Level-2 communication protocol for data transfer. CP01 acts as the main system while CP02 is a hot standby. The data received is logged on a mass storage. Simultaneously realtime data is routed to RTPs. The RTPs are connected to CPs via async links for data transfer. Terminals are connected to these systems through Ethernet LAN. RTP and FDAP allocation for multi-mission support is as given below.

	REALTIME		FDAP	
MISSION	PRIMARY	BACKUP	PRIMARY	BACKUP
IRS-1A	RTP01	RTP05/06	FDAP01	FDAP02
IRS-1B	RTP02	RTP06/05	FDAP01	FDAP02
SROSS-C2	RTP02	RTP06/05	FDAP02	FDAP01
IRS-P2	RTP01	RTP06	FDAP02	FDAP01
IRS-1C	RTP03	RTP05/06	FDAP03	FDAP04
IRS-P3	RTP04	RTP05	FDAP03	FDAP04

Data archival is carried out at FDAP-01/02 and the online archival is maintained on mass storage connected to FDAP-01/02 via HSC mass storage servers.

4. SOFTWARE

Software plays an important role in successful multi-satellite operations. Spacecraft operations are conducted with the help of communication handler software, mission software, multi-satellite scheduling and payload programming software and text data manager software.

4.1 COMMUNICATION HANDLER (COM) FOR MULTI-SATELLITE SUPPORT

Communication handler software provides the link for information exchange between the ground stations and the mission software by handling communication line protocols on the one hand and managing interactions with the mission software packages on the other. The main functions of communication handler for multi-satellite support are:

- Acquisition of telemetry, telecommand and tracking data packets on communication channels from various ground stations
- Reception of telecommand messages from the command generation modules and transmitting the same to the ground stations.
- Exchange of station status data and operational text messages between ground station and network software
- Sorting and logging all the above data into independent temporary files for each satellite according to data type, data sub-type and mode of data transfer for archival and further processing.

In addition to the above mentioned mission related functions, COM carries out logging of communication line statistics, interactive display facility and data table management to configure the network and to support multiple satellites.

4.2 MISSION SOFTWARE

Mission software consists of spacecraft health monitoring, analysis and control software (SCHEMACS) and flight dynamics software. These packages are directly related to the processing of all the relevant spacecraft parameters and orbit and attitude parameters.

4.2.1 SCHEMACS

SCHEMACS is the tool for monitoring the health of the spacecraft and perform command functions. Features of SCHEMACS include simultaneous processing of two streams of data, extraction of Flight Dynamics information and processing in Realtime to derive orbital events and sensor dazzle information, presentation of processed health parameters in sub-systemwise alphanumeric pages; graphic display of parameters; integrated graphics for realtime, dwell, phase plane; health analysis events and performance; archival and retrieval of TM, TC and TR data.

SCHEMACS also provides log of events and alarms apart from realtime display of change of status and alarms. Several utilities for sub-system data analysis in off-line are available. SCHEMACS also has facility to generate TC database and sequence of events database.

4.2.2 FLIGHT DYNAMICS SOFTWARE AND AUTOMATION

Operational functions for the flight dynamics software for LEO missions are:

- Pre-processing of tracking data of all network ground stations, data quality checking and feedback of data quality to the tracking stations and orbit determination
- State vector and visibilities generation and transmission to the payload processing centres, network stations as per time line
- Generation of eclipse, ground trace, sensors dazzling by Sun and Moon, Precision yaw sensor update timings and offset commands for spacecraft control operations
- Orbit maintenance manoeuvres scheduling
- Attitude determination for all payload passes using Star sensor/Earth sensor data

Flight dynamics software operations for orbit and attitude computation involve repetitive execution of many programs. These operations are automated by Operations Automation software. This software is interlinked with individual Flight Dynamics software package through a number of command procedures to carry out the defined task. The executive software wakes up periodically and performs the assigned task with proper status messages displayed to the user. Orbit and attitude products are thus generated in an automated way for all the spacecraft missions.

4.2.3 MULTI-SATELLITE SCHEDULING SYSTEM (MSS) SOFTWARE

MSS software is one of the key elements in multi-satellite support and it generates the operations schedules and allocates network resources for different satellites supported at SCC. This software prepares the general schedules of all operational satellites. Satellite specific constraints, ground stations configurations, satellite priorities and priorities of certain payload operations as well as visibility clashes are taken into consideration while making the general schedule in an optimal way. Payload data programming requests are considered and scheduled on best opportunity basis while making the general schedule for TTC operations for the network of ground stations. Pre-assigned priorities and dynamic weighting factors, scheduling curtailed pass are effectively used to maximise support in case of support conflicts.

For a global mission like IRS-1C with multiple payloads viz., PAN, LISS-3 and WiFS, payload programming forms an important part of spacecraft operations. NDC, Hyderabad consolidates the payload programming requests from users and supplies the same to SCC after considering priorities and satellite programming constraints. MSS interfaces with Payload Programming System (PPS) in generating the command and operations schedule.

4.2.4 TEXT MANAGER SOFTWARE

Message transfer between SCC and payload reception ground station, Shadnagar (SAN) as well as SCC and Data Processing Centre Balanagar (BAL) of NRSA without manual intervention is achieved by text manager software. It helps in transmitting the messages in transparent, reliable and user- friendly way. Operational messages between SCC and TTC stations are also transferred using this software.

5. MISSION OPERATIONS MANAGEMENT

ISRO has the advantage of design, development and operations of spacecraft performed by the same agency. LEOP operations are carried out by the mission planning and sub-system designers team along with ISTRAC operations team. Operations management during the normal phase is lead by Operations Director (OD) who works under the guidance of Mission Management Board. He is assisted by Operations Managers in the areas of Spacecraft, TTC Network, Flight Dynamics software, SCHEMACS software, Communication and Scheduling.

TTC stations and SCC work in round-the-clock shifts to carry out scheduled operations. Scheduling and flight dynamics operations are carried out in day-shifts on all seven days a week. Spacecraft Operations are carried out in every shift with shift operations manager as focal point. He is assisted by spacecraft controllers identified one each identified for each operational spacecraft. Pre-launch simulations and training are elaborate activities and during this phase, spacecraft controllers are imparted adequate training on the configuration of the satellite and flight operations procedures.

In case of spacecraft emergency or ground support element failure, real-time updates are required in daily operations schedule. The shift operations manager at SCC interacts with Satellite Operations Manager (SOM) and OD and real-time updates are prepared. In case of spacecraft contingencies, Mission and sub-system experts will be brought into the operations loop. The shift operations manager is authorised by SOM/OD to proceed with contingency recovery procedure. Later an anomaly report is prepared.

5.1 REPORTING AND REVIEW MECHANISMS

Operations reporting and review mechanisms have been established over years and play a major role in successful operations. Daily operations monitoring is carried by operations managers in their respective areas. Daily Operations Review which is an important activity at SCC is conducted at 16:00 IST on all working days and is attended by OD and all Operations Managers and facility representatives, as shown in Figure-3. Weekly operations schedule meeting is conducted on every Tuesday and forecast and confirmed schedules are finalised. Daily operations report and anomaly report, if any, are prepared by shift operations manager and communicated to all concerned. Monthly operations report for all the spacecrafts and Quarterly and Annual sub-system performance reports for individual spacecraft are prepared.

Operations Review Board convened by OD reviews the performance and approves the updated procedures for spacecraft operations. Overall mission operations plans and guidelines are reviewed by Mission Management Board convened by the Mission Director (MD).

6. FUTURE SCENARIO

ISTRAC has been operating multiple satellite missions successfully so far. By 2001 ISTRAC will be supporting 12 IRS satellites at a time. In order to meet the TTC support requirement, all the existing ground stations will be augmented and a ground station in Arctic region is under consideration. This remote station with two satellite support capability will have visibility for all the 14 orbits for all the satellites.

The new plan for computer support beyond 1996 retains the architectural advantages of the existing configuration and will have features such as implementing open systems such as UNIX as O/S & TCP/IP for communication; bridge/routers for inter-connecting SCC to ground station; work stations for all processing and display; improved man/machine interfaces with GUI MOTIF and X-Windows; file servers/Database servers for data management and virtual LANs for connectivity.

In near future, it is planned to build knowledge-based systems for satellite control and operations. These expert systems will help the operator, providing synoptic information of the spacecraft by performing analysis of large quantity of data. These systems will also help the controllers to carry out complex command sequences and control functions with ease.

TABLE-1: SPACECRAFT SUPPORTED AT ISTRAC (JUNE, 1996)

SATELLITE / PARAMETER	IRS-1A	IRS-1B	SROSS-C2	IRS-P2	IRS-1C	IRS-P3
Launch date (dd/mm/yy)	17/03/88	29/08/91	04/05/94	15/10/94	28/12/95	21/03/96
Semimajor axis (Km)	7284.419	7282.190	6899.932	7195.014	7195.089	7195.243
Inclination (Deg)	98.723	99.077	46.035	98.634	98.698	98.794
Eccentricity	0.001974	0.000839	0.012801	0.001182	0.001156	0.001111
Orbital period (Secs)	6194.341	6191.591	5696.523	6080.876	6080.996	6081.177
Perigee height (Km)	891.895	897.985	433.466	808.364	808.626	809.151
Apogee height (Km)	920.652	910.155	610.123	825.374	825.262	825.023
Payloads	LISS-1, LISS-2A,2B	LISS-1, LISS-2A,2B	RPA, GRB	LISS-2A,2B	PAN, WiFS, LISS-3	WiFS, MOS, X-RAY, CBT
Local Time at descending node (hh:mm:ss)	06:27:04	10:30:47	NA	10:30:49	10:30:31	10:34:00

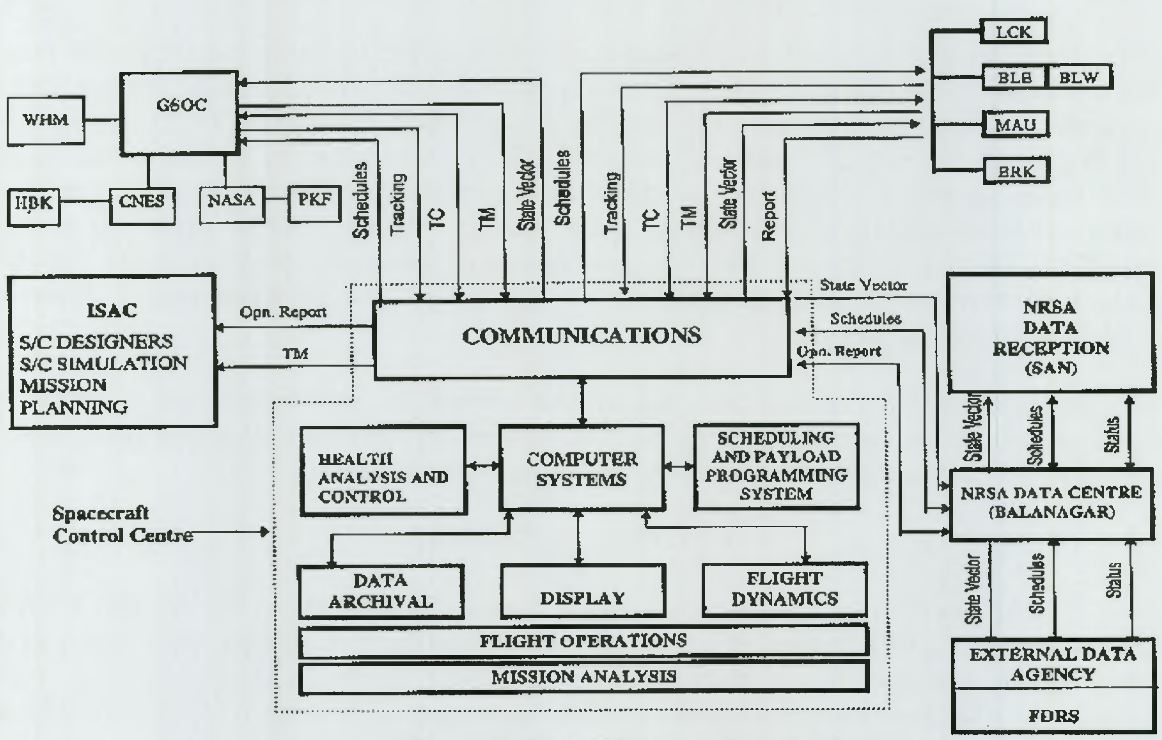

Figure-1: Ground Segment Organisation

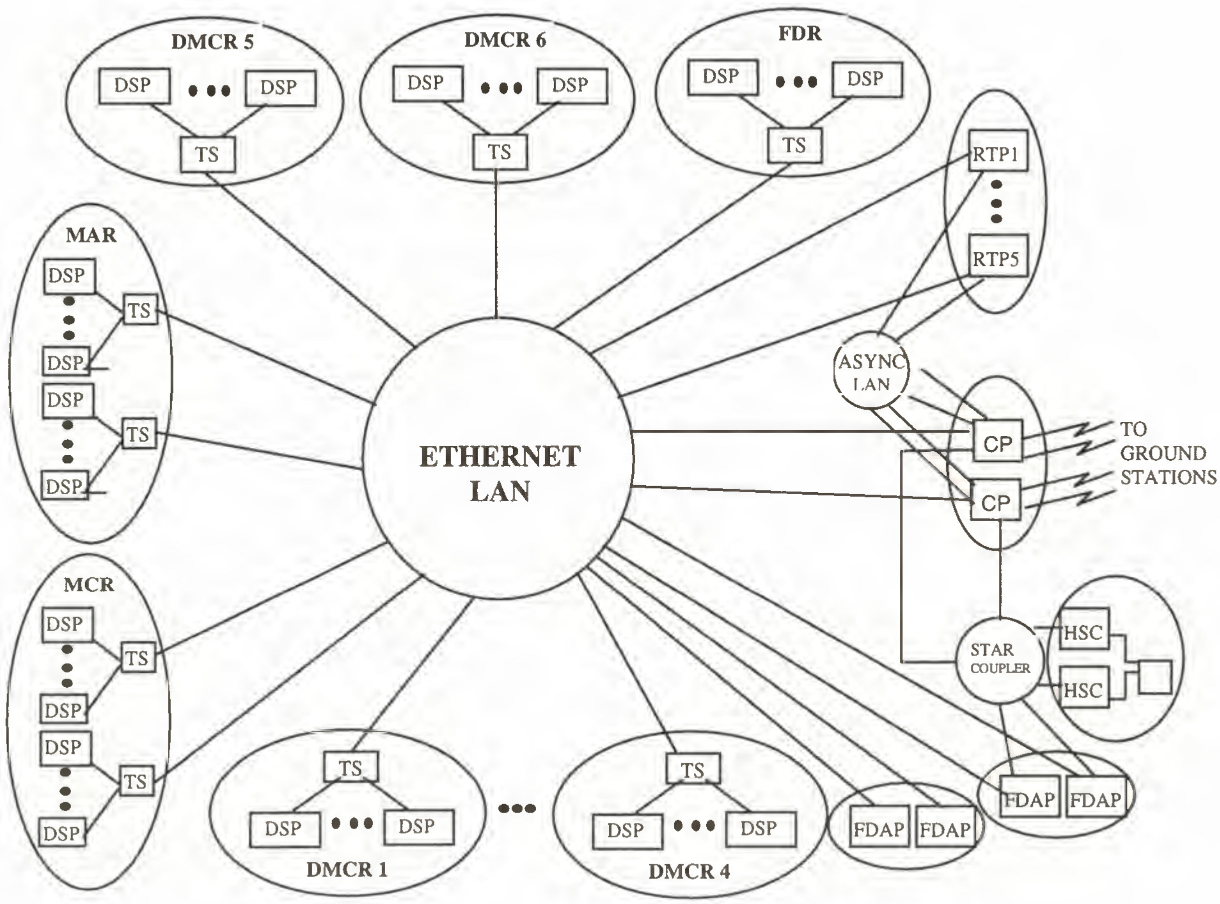

Figure-2: SCC Computer Configuration

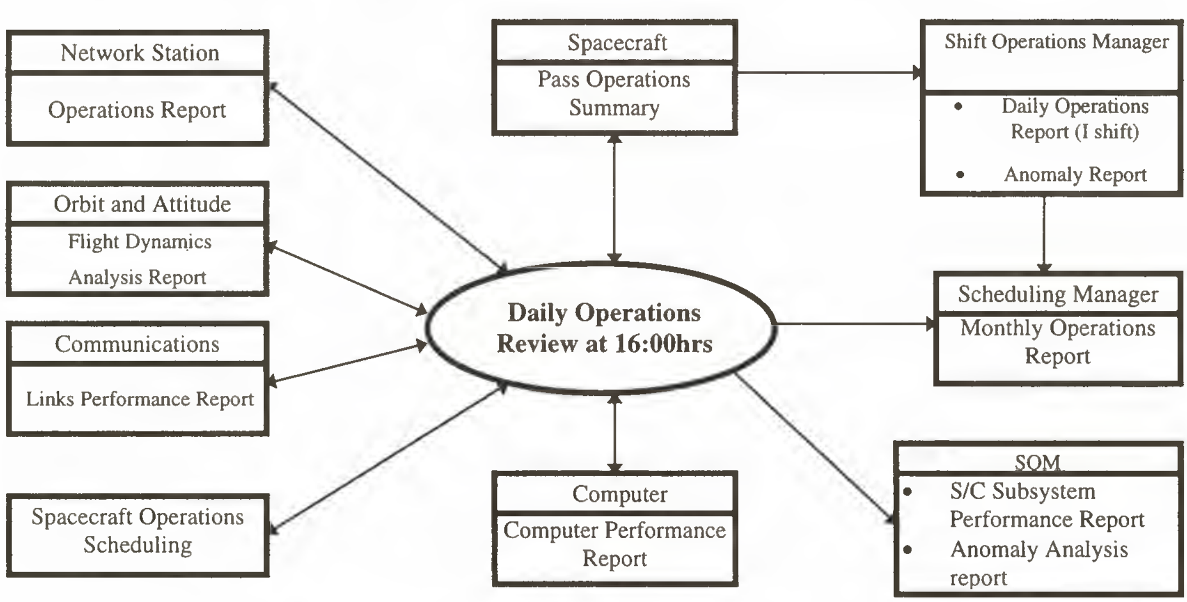

Figure-3: Operations reporting Mechanism

THE EVOLVING EARTH OBSERVING SYSTEM (EOS) MISSION OPERATIONS CONCEPT: THEN AND NOW

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ABSTRACT

The Earth Observing System (EOS) mission, a major component of NASA's "Mission to Planet Earth" program, has undergone many changes since it was officially established in 1990. This paper describes the evolution of the mission from its first conception to what it is today.

Over the past five years, EOS has been "restructured", "rescoped", "rebaselined", and "reshaped". The spacecraft and the ground system concepts have been re-examined and adjusted in response to the need to find better and more cost-effective ways of conducting earth observations while still meeting the goal of providing comprehensive data that scientists can use to determine the extent, causes, and regional consequences of global climate change.

This paper compares the original mission concept (two series of large observatories, each with many instruments) with the current configuration. Some of the significant impacts on the EOS ground system and mission operations are discussed. This paper does not address changes that affect the systems involved with Level 1-4 processing.

1.0 INTRODUCTION

EOS was planned to provide a comprehensive, long term set of observations of the Earth to the Earth science research community. The data will aid in understanding global climate changes caused both naturally and through human interaction. Understanding man's impact on the global environment will allow sound policy decisions to be made to protect our future.

EOS consists of numerous instruments on multiple spacecraft and a distributed ground system. The EOS Data and Information System (EOSDIS) is the major ground system developed to support EOS. The EOSDIS will provide EOS spacecraft command and control, data processing, product generation, and data archival and distribution services for U.S. EOS spacecraft. Data from EOS instruments on other Earth science missions [e.g., Tropical Rainfall Measuring Mission (TRMM)] will also be processed, distributed, and archived in EOSDIS. The EOSDIS will also archive processed data from other designated NASA Earth science missions (e.g., UARS) that are under the broad umbrella of Mission to Planet Earth. The U.S. and various International Partners (IP) [e.g., the European Space Agency (ESA), the National Space Development Agency (NASDA) of Japan, the Ministry of International Trade and Industry (MITI) of Japan, and the Canadian Space Agency (CSA)] participate in and contribute to the international EOS program.

2.0 EOS PROGRAM CHANGES

2.1 ORIGINAL EOS BASELINE

In 1990, the EOS consisted of 30 instruments that had been assigned to fly as three groups: the two EOS observatories, EOS-A and EOS-B; and the set of instruments that would fly as attached payloads on the Space Station Freedom.

EOS-A and EOS-B were termed as "large observatories", each spacecraft consisting of 15 instruments. Each series consisted of three spacecraft that would be launched every five years, for a total observing mission of approximately 18 years.

2.2 RESTRUCTURING

The restructuring process in 1991-92 was directed by the U.S. Congressional Committee on Appropriations for three main reasons: to focus EOS science on the most important problem of global change, i.e., global climate change; to increase mission resilience and flexibility by flying the instruments on multiple smaller platforms rather than a series of large observatories; and to reduce the cost across the board from $17 billion to $11 billion through FY 2000. This resulted in the replacement of the A and B series of large observatories by five series of smaller spacecraft and the launch of the first spacecraft, designated as AM1, advancing to June 1998 (6 months earlier).

2.3 RESCOPING

The restructured of $11 billion for the 1992-2000 timeframe was reduced by the U.S. Congress to $8 billion in October 1992, thus cutting the original budget in half. Despite this rescoping, EOS retained its focus on collecting observations over a 15-year period, but many important measurements were canceled or deferred since EOS was now a "cost driven program". Difficult tradeoffs across the end-to-end system were made to minimize the adverse impact on science objectives. The rescoping resulted in a program with reduced contingency, increased reliance on interagency and international cooperation, and the development of a common spacecraft bus for EOS PM, CHEM, and AM-2/AM-3. Some instruments were expected to be provided by international partners, as well as the spacecraft for the AERO series. The total number of instruments to fly on EOS spacecraft (including international contributions) was reduced to 22, of which 15 would fly before 2003. The launch date of June 1998 for EOS-AM-1 was unchanged.

2.4 REBASELINING

In 1994, GSFC was directed to respond to a 9% budget reduction and still maintain the AM-1 schedule, provide the EOSDIS elements necessary to support AM-1, and prepare a Request for Proposal (RFP) for a common spacecraft for the PM-1 and CHEM-1 spacecraft. The rebaselining process resulted in the following: the AM, PM, and CHEM series were placed on six-year repeat -flight intervals; the Altimetry mission was split into the radar and laser series; the TES instrument was moved from the AM-2 spacecraft to the CHEM-1 spacecraft, thus making it possible to accommodate an advanced Landsat instrument on AM-2; the flights of the SAGE III instrument (which was on the AERO series) on an IP spacecraft (Russian Meteor spacecraft) and on the International Space Station were approved.

Rebaselining brought a new risk category, that is, the intended lifetime design of all EOS instruments is 5 years, while the replacement cycle was changed to 6 years. This means that EOS instruments must operate at least one year longer to provide continuity of observations throughout the 15-year period. Table 1 provides a summary of the U.S. EOS launch dates.

Table 1 - U.S. EOS Launch Schedule

U.S. Earth Observing System (EOS)				
Spacecraft Series	No. of Spacecraft	Launches * (Tentative)	Design Lifetime (Years)	
			Per Spacecraft	Series
AM	3	June 1998, 2004 & 2016	5	15
PM	3	December 2000, 2006 & 2012	5	15
LALT	3	June 2003, 2008 & 2013	5	15
CHEM	3	December 2002, 2008 & 2014	5	15
* Launch dates after AM-1 are for planning purposes. Replacement cycle of six years				

2.5 RESHAPING

In 1995, the National Research Center (NRC) Panel for sustainable development reviewed EOSDIS as part of an overall U.S. Global Change Research Program (USGCRP) and NASA MTPE review. In response to the panel recommendation to GSFC to streamline the EOSDIS components responsible for flight control, data downlink, and initial data processing should be streamlined, an EOS reshape team was formed to determine the most efficient and effective ways to accomplish the streamlining. The team conducted an intensive examination of all mission requirements and "scrubbed" them, as appropriate, without significant degradation of services. The primary result of the reshape study was the formation of an "adaptive downlink" architecture approach (see section 4.2).

The reshape activities in 1995-96 also include an ongoing assessment of the CHEM spacecraft series, looking at potential scenarios for various instrument configurations of one to four instruments (some instruments with proposed redesigns incorporating technology advances to reduce size, power, and mass requirements) with corresponding smaller/lighter spacecraft configurations.

3.0 SPACECRAFT CONFIGURATION CHANGES

The current spacecraft configuration consists of four series of spacecraft, each with a different flight configuration based on scientific measurement objectives. The reconfigured EOS consists of 15 instruments required for global climate change which will be flown on four series of spacecraft: AM, PM, Chemistry (CHEM), and Laser Altimetry (LALT). The Radar ALT and SAGE III instruments will be flown on non-U.S. international partner spacecraft.

The first spacecraft AM1 will be launched on an ATLAS IIAS vehicle. PM, and CHEM are currently slated to fly on medium or small expendable launch vehicles (MELVs or SELVs). NASA is emphasizing "smaller, cheaper, better" implementations of spacecraft. Through the use of advanced technology and reduced design complexity, it is hoped that these missions can be launched faster and at less cost than previously planned, thus accelerating the timetable for obtaining critical data on global climate change.

Other significant changes to the EOS spacecraft center are the onboard science storage and space to ground communications. Onboard data recording and management has been greatly improved by switching from tape based recorders to solid state memory. EOS spacecraft can be commanded to download selected "virtual" buffers which provides the EOS mission operations personnel with increased flexibility and reduces the likelihood of data loss.

The current baseline is for spacecraft after EOS- AM1 to utilize X-band to transmit science data to dedicated EOSDIS ground stations. From the spacecraft design perspective, the elimination of the Ku-band link through the Space Network/Tracking and Data Relay Satellite System (SN/TDRSS) results in the elimination of a steerable High Gain Antenna (HGA), thus reducing spacecraft cost, and weight and power requirements

Table 2 summarizes the major differences between the original and current spacecraft configuration.

Table 2 - Spacecraft/ Configuration (Original vs. Restructured)

CHARACTERISTICS	ORIGINAL CONFIGURATION	RESTRUCTURED CONFIGURATION
Number of Series/Total Number of Spacecraft	2/6	4/12
Orbit/Nodal Crossing Time	EOS-A: 705 km/98.2°, sun-synch, 1:30 PM equatorial EOS-B: 705 km/98.2°, sun synch, 1:30 PM equatorial	EOS AM: 705-km/98.2°, Sun-synch (SS),10:30 AM descending EOS PM: 705-km/98.2°, SS, 1:30 PM asc EOS CHEM:705-km/98.2°,SS,1:45 p.m. asc LALT: 600km(?)/94°, non-sun-synch
Number of Instruments per Spacecraft	EOS A: 15 EOS B: 14-15	EOS AM: 5 EOS PM: 5 EOS CHEM: 4 (under assessment) EOS LALT : 1
Launch Vehicle	Titan IV	EOS AM-1: ATLAS IIAS EOS PM-1 and CHEM-1: (MELV) EOS LALT and subsequent EOS spacecraft: (SELVs, MELVs)
Onboard Data Storage	Tape Recorders	Solid State Recorders
High Rate Space to Ground Communications (for science data)	Ku-band via TDRSS	AM-1: Ku-band via SN/TDRSS w/ X-band back-up to Ground Stations X-band via EOSDIS Grd Stations after AM-1 (Ku-band via SN/TDRSS under study)
Forward Link Data Rate	1 to 100 Kbps	1 to 10 Kbps for AM-1 1 to 2 Kbps for others
Return Link Data Rate Average Data Rate	up to 300 Mbps up to 50 Mbps	up to 150 Mbps up to 20 Mbps
Spacecraft Design	Common design and modularity of subsystem components	One intermediate spacecraft; the rest, medium/smaller spacecraft with increased autonomy

4.0 EOS GROUND SYSTEM CHANGES AND IMPACTS ON MISSION OPERATIONS

Figure 1 provides an overview of the current EOS mission concept. EOS "mission operations" includes the operation of the EOS spacecraft and the ground system components involved with the command and control of the spacecraft and its instruments, the capture and Level 0 processing of the science data transmitted to the ground, and the delivery of the data to the EOS Distributed Active Archive Centers (DAACs). The elements of the EOS ground system to accomplish these tasks include: the EOS Data and Operations System (EDOS); the EOS Backbone network (EBnet); the Flight Operations Segment (FOS) of the EOSDIS Core System (ECS), the ASTER Instrument Control Center (ICC) which is part of the AM-1 ASTER Ground Data System (GDS); and the NASA institutional elements providing support to EOS, namely, the Space Network (TDRSS and the Network Control Center (NCC)), the Deep Space Network (DSN), the

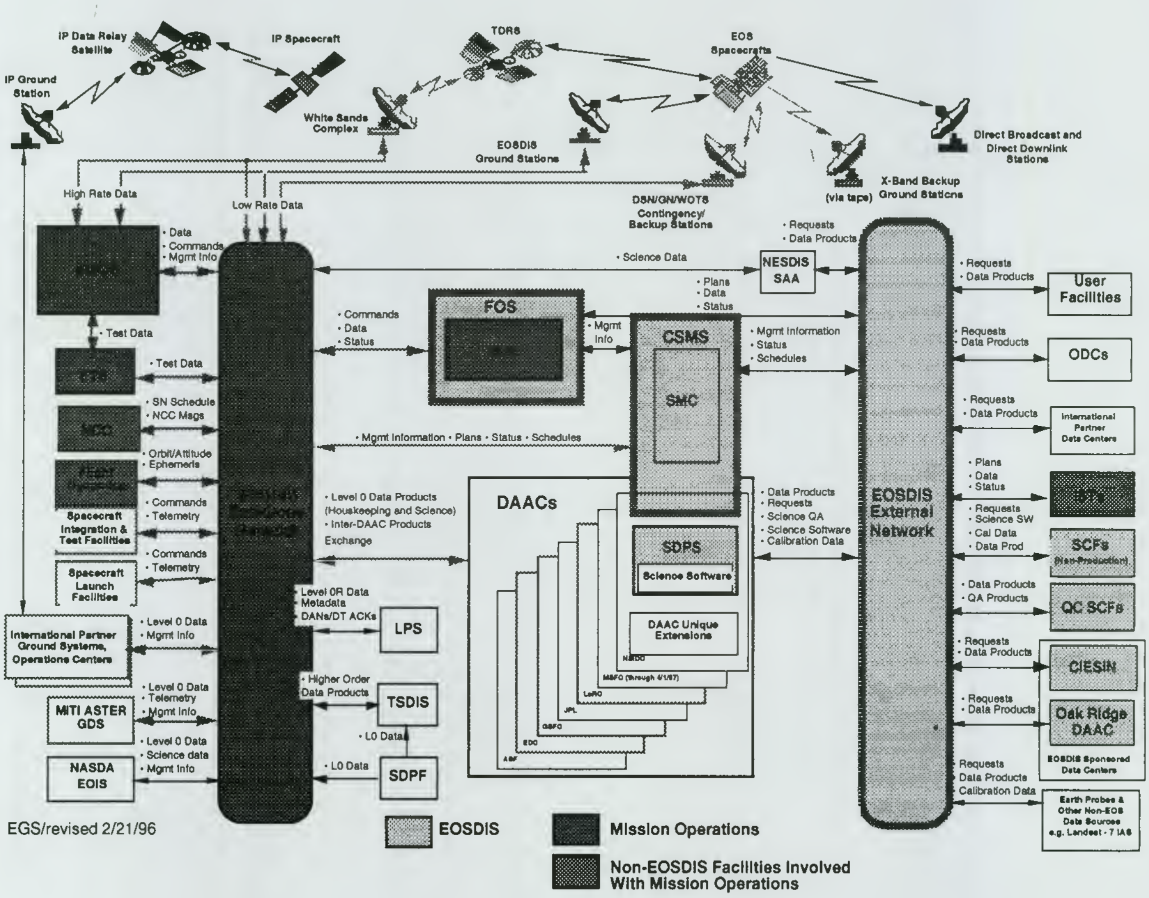

Figure 1 - EOS Mission Concept

Ground Network (GN), the Wallops Orbital Tracking Station (WOTS), the Flight Dynamics Division (FDD), and the NASA Communications (Nascom) system.

There have been a number of significant changes to the EOS ground system "mission operations" components, primarily the EDOS and the EOC. The changes are discussed below as well as their impact on EOS mission operations.

4.1 CHANGES IN THE EOS OPERATIONAL PROFILE

During the 15 year plus operational lifetime of EOS, as many as four spacecraft will simultaneously be performing normal operations. During periods of cross-over operations (3 to 6 months), up to five spacecraft will be on-orbit, all requiring mission operations support, including planning and scheduling, command and control, monitoring for health and safety and spacecraft performance, and data capture/data transport services. In addition, prelaunch operations (e.g., I&T, simulations, ground system compatibility, and operational readiness tests) for successor spacecraft must also be supported.

The EOSDIS is being developed with the potential to expand and evolve as EOS progresses. EDOS, EOC, and Ebnet are designed such that needed enhancements and capabilities can be added and tested with minimal impact to ongoing operations. This includes being able to add capacity (when needed) to support prelaunch operations for successor spacecraft as well as ground system upgrades and maintenance.

4.2 SIGNIFICANT GROUND SYSTEM CHANGES

The adaptive downlink architecture was conceived in response to two drivers. The first was the uncertainty in the science downlink system for EOS follow-on missions. As discussed earlier, the original program called for EOS spacecraft that would utilize the NASA SN/TDRSS for spacecraft-to-ground forward and return link communications for both tracking, telemetry and command (TT&C) and science downlink operations. AM-1 is baselined for TDRSS support. PM-1 and Chem-1 are currently baselined for ground station support, but there is an ongoing study to determine whether TDRSS or ground stations should be used. The second was the EOS reshape in response to the National Research Council recommendation to streamline the EOSDIS components for flight control, data downlink, initial processing and networking.

In order for the EOSDIS development to continue without significant impact when the decision is made, the EOSDIS front-end architecture was reshaped and an adaptive downlink architecture was chosen. This architecture is flexible by nature and results in minimal impact to the ground system should either the TDRSS or ground station approach be implemented. If northern latitude ground stations are chosen for follow-on support., AM-1 will be initially supported using TDRSS and then transition to ground stations in the year 2000.

The reshaped (streamlined) ground system resulted in the following changes:

a. Minimal preprocessing at ground stations and/or White Sands Complex ,

b. Level Zero Processing

   Another significant change brought about by reshape was the redistribution of EDOS functionality to the various EDOS facilities located at GSFC, White Sands, and at the EOSDIS ground station sites. The changes resulted in reducing the processing requirements at White Sands and the ground stations and consolidating the Level zero processing at GSFC. It was originally planned to be at Fairmont, West Virginia and then later moved to White Sands to reduce communications cost. Moving it to Goddard accommodates the data interface from either/both White Sands and the ground stations cost effectively. The redistributing of EDOS functionality eliminated duplicate high rate processing equipment at the remote sites thus reducing both hardware and operational costs.

c. Front End Operations

   Front end operations refers chiefly to the forward and return link processing performed by EDOS and the command and control functions performed at the EOC. The command and control scenario for spacecraft after AM-1 will utilize both TDRSS and the EOSDIS ground stations for S-band uplink and low rate housekeeping data. All EOS spacecraft conform to the Consultative Committee for Space Data Standards (CCSDS) for space to ground communications. As part of the command receipt verification process, the CCSDS Command Operations Protocol-1 (COP-1) will be utilized. Under the original baseline, EDOS handled the physical layer portion of this protocol by applying the acquisition and idle sequences between spacecraft commands prior to uplink. The current architecture simplified the EDOS/EOC command interface by moving the functionality into the EOC.

d. Science Data Recovery and Front End Automation

   Increased automation in front end operations is planned in order to reduce long term operations costs. Automation enhancements in the EOS Operations Center are planned several months after the launch of the AM-1 spacecraft. This will result in reduced/minimal staffing, with a goal of "lights out" operations during the off shifts (night time). The penalty for not staffing during the night shift is increased risk of losing data, i.e., if a downlink contact is missed, there is no one to react to schedule another contact to downlink the data before the data is overwritten on the onboard recorder. This led to the change in the science data requirement. To provide the greatest flexibility, increase automation, and implement a solution which would provide the greatest cost benefit, the requirement for EOS to be capable of delivering "not less than 95% of the all payload-related data to the DAACs and the Level 0 back-up archive during any 2 consecutive orbits" could not be satisfied. To resolve this, the requirement has been changed to read, " EOS shall be capable of delivering not less than 95% of all payload-related data to the DAACs and the Level 0 back-up archive over 16 days".

EDOS and EOC development teams are working jointly to increase automation through transferring operations messages between hardware as opposed to via operations personnel. Event and status messages from EDOS will indicate that EDOS hardware is up and running in the desired mode, and will indicate if a problem has occurred which requires an EOC operator to bring up an EDOS window via a remote terminal interface.

4.3 EXPEDITED SCIENCE DATA SERVICE

One of the major casualties from the rebaselining process in 1994 was the quick-look science data service. Historically, investigators on GSFC missions had been provided quick-look science data (i.e., within an hour of receipt on the ground) to help them monitor and evaluate instrument performance in near real-time during all mission phases. The original EOSDIS baseline provided the capability for delivery of quick-look level zero data within an hour after ground receipt, and higher level (level 1 and above) processed data within three hours of receipt at the science data processing system.

With the rebaselined EOSDIS, the quick-look data service (as traditionally provided) was deleted. To satisfy the investigator's need for near real time data and provide it within the constrained budget, the expedited data service will be provided. This service will provide temporary level zero data sets, called expedited data sets (EDSs) within three hours of ground receipt . The EDSs can be used by investigators to support instrument calibration and/or anomaly investigations prior to the completion of normal production data processing. This service does not restore the original EOSDIS capability to produce higher level (level 1 and above) quick look data products. This service provides only level zero data sets at the Distributed Active Archive Center (DAAC) for access by the investigators, who want to process the data at their own Science Computing Facilities to produce higher level data products.

4.4 NETWORKS CONSOLIDATION

The consolidation of what was known as EOS Communications (Ecom) and the EOSDIS Core System (ECS) Science Network (ESN) into the EOSDIS Backbone network (EBnet) yielded both technical and cost benefits. The EBnet provides wide-area communications circuits and facilities between and among various EOS Ground System (EGS) elements to support mission operations and to transport mission data between EOSDIS elements. EBnet is responsible for transporting spacecraft command, control, and science data worldwide on a continuous basis, 24 hours a day, 7 days a week. Real-time data includes mission-critical data related to the health and safety of on-orbit space systems and raw science telemetry as well as pre-launch testing and launch support. Science information includes data collected from spacecraft instruments and various levels of processed science data including expedited data sets, production data sets, and rate-buffered science data. In addition to providing the wide-area communications through common carrier circuits for internal EOSDIS communications, EBnet serves as the interface to other systems such as Distributed Active Archive Centers (DAACs), users, and the NASA Science Internet (NSI). EBnet also includes exchange Local Area Networks (LANs) which provide communications between the Wide Area Network (WAN) and site-specific LANs.

5.0 NEAR TERM MISSIONS

5.1 EOS-AM1

As of June 30, 1996, the EOS-AM1 launch is two years away. Spacecraft development is on track; instrument deliveries to the spacecraft integration and test facility are scheduled to occur from December 1996 to February 1997. The EOS ground system development is progressing well; the first delivery of hardware and software for the EOS Operations Center will start in August 1996. Capability will be in place to support early testing activities with the spacecraft which begin in November 1996. The first EOC Compatibility Test (ECT) is scheduled for January 1997, followed by ECT 2 in July 1997 and ECT 3 in February 1998. An End-to-End Test and 100 hours of mission simulations will be conducted in March 1998 prior to shipment of the spacecraft to the launch facility at Vandenberg Air Force Base in California. Staffing for the Flight Operations Team (FOT) is underway, with a core team in place by December 1996. The Mission Operations Review (MOR) is scheduled for third week of November 1996.

5.2 EOS-PM1

The spacecraft contract was officially awarded to TRW Systems of Redondo Beach, California in April 1996. Several planning meetings have been held between GSFC and TRW personnel and to address working relationships, documentation, concerns, and lesson learned from other missions. The EOSDIS will be enhanced if needed to accommodate unique requirements for PM-1.

6.0 CONCLUSION

The reshaped EOS mission is progressing well in all areas. EOS is a long term mission which will provide a comprehensive data base on global climate change. The impacts of the restructuring on mission operations concepts have been evaluated; adjustments have been made to accommodate the program changes. Some of the concepts are addressed in this paper. More detail can be found in Reference 3. On-line information is available on the EOS homepage (url: http://eos.nasa.gov), the ESDIS homepage (url: http://spsosun.gsfc.nasa.gov/ESDIShome.html), and the EOS Mission Operations homepage (url: http://esdis.gsfc.nasa.gov/ops).

7.0 ACKNOWLEDGMENTS

This paper includes relevant information on the EOS program contained in various project documentation and presentations. Thanks go to Candace Carlisle and Dan DeVito for providing additional information on the reshaping and adaptive downlink architecture. Special thanks go to Gregg Einfalt for his valuable technical input and help in getting this paper ready.

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A KNOWLEDGE BASED SYSTEM TO SUPPORT THE OPERATOR IN ATV RENDEZVOUS MISSION WITH THE INTERNATIONAL SPACE STATION

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ABSTRACT. Nowadays, rendezvous control requirements exceed the operational capabilities of mission control systems for conventional missions, adding special characteristics and constraints driven by time-limitations on the execution of the various mission phases, the degree of automation placed in the space segment and the safety aspects of manned spaceflight.

This paper describes a prototype flight operator support environment, implementing the concept of a Vehicle Expert Module as defined in earlier studies, that has the potential to be used within the Mission Control System for the Automated Transfer Vehicle (ATV) rendezvous missions.

The prototype has been developed using a commercial real-time Knowledge Based System (KBS) platform, compatible with NASA KBS environment, and is made of object-oriented models of the ATV spacecraft and its mission, and a rule-based diagnostic system, together with a telemetry generator/failure simulator. The prototype is able to support a flight controller of rendezvous missions with synthetic advanced monitoring, safe status checks and evaluation, fault prevention, early diagnosis, fault detection and isolation, fault recovery and resource consumption evaluation.

1. CONSTRAINTS AND CRITICALITY IN RENDEZVOUS MISSIONS

The number of space missions involving rendezvous will increase dramatically with the development of the International Space Station (ISS) and its associated space traffic required to transport up and down crew, consumable and experiments. One of the two major contribution of the European Space Agency to the ISS is the Automated Transfer Vehicle, an unmanned spacecraft, launched by Ariane 5, which has the capacity to carry around 7.5 tons of pressurized and unpressurized payload up to the ISS and to dispose of station waste during its destructive re-entry.

The control requirements for rendezvous vehicles such as ATV exceed the operational capabilities of mission control systems for conventional missions, adding special characteristics and constraints driven by three factors: the time-limitation for the execution of the various mission phases, the degree of automation placed in the space segment and the safety aspects of manned spaceflight.

The limited ATV on-board resources, especially the electrical energy stored in batteries, not recharged by solar panels, give an overall autonomy of 110 hours of free-flying operations, including margins and contingencies.

The on-board automation does not off-load the ground segment tasks and responsibilities; on the contrary, besides nominal monitoring, upload of updated parameters and of authorizations to proceed, the flight control engineers have to be able to react whenever a non nominal situation is taking place, to be aware of what is happening on board and to overrule the on-board Failure Detection, Isolation and Recovery (FDIR) if and when required.

The other critical element is the visiting station, with its crew on board, requiring rigorous safety adherence, including the capability for the astronauts and for the ground to abort the rendezvous and for the vehicle to perform automatic collision avoidance manoeuvres, in case of contingencies.

As a consequence some investigations have been carried out to identify those technologies and methods that could be used in support of the ATV controllers to monitor efficiently the vehicle and to promptly and safely react in case of contingencies.

2. THE VEHICLE EXPERT MODULE (VEM) CONCEPT

During past rendezvous studies [1] the role of the ground has been analyzed and described in the definition of the Ground Operator Assistant System (GOAS), covering aspects related to both spacecraft system control and mission/flight dynamics control. Within the GOAS an innovative module has been conceptually identified and named as Vehicle Expert Module (VEM), where basically all "modus operandi" of the vehicle subsystems are intended to be stored.

Recently this concept has been further analyzed, refined and prototyped, combining software engineering and knowledge engineering in a common life-cycle.

The basic idea of a VEM is to have an on-line expert repository capable to process in real-time the in-coming telemetry and to provide flight control engineers with synthetic information on the health of the spacecraft and on its capability to enter new mission phases. During failures the VEM has to be able to provide active support to the engineers in the troubleshooting process, with the ultimate goal to shorten the necessary steps and recover successfully the mission within the given time-limits.

During troubleshooting, the decision process remains under the control of the engineers, while the VEM will act as decision support system to the experts and to the decision makers.

The VEM concept also takes into account the current trend of Mission Control System (MCS) topology and makes use of model-based representation of the spacecraft component parts and of the mission. Figure 1 represents a synthesis of the knowledge transfer flow identified within the refined VEM concept.

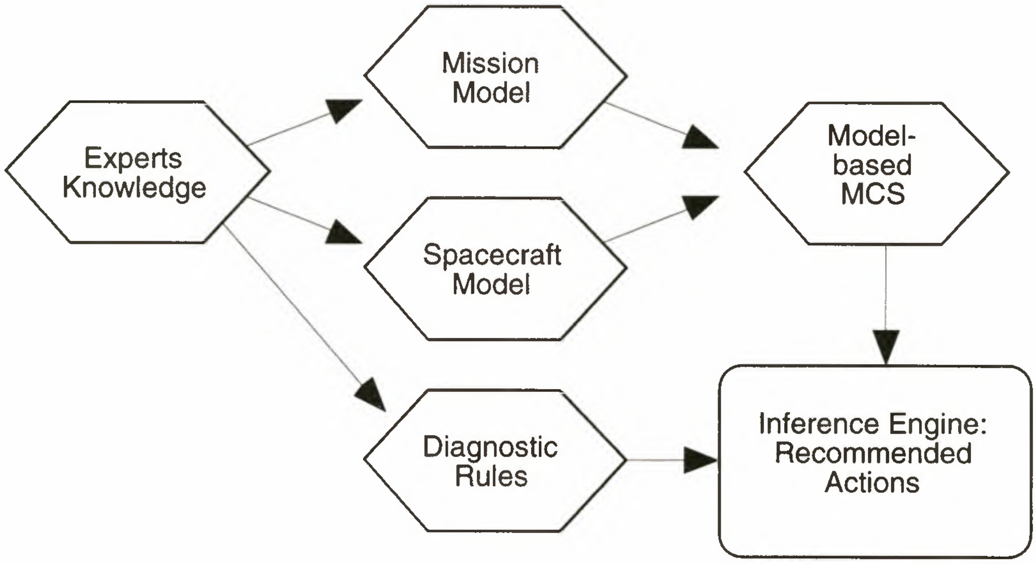

Figure 1 - Knowledge Transfer Process in the VEM concept

The VEM is proposed to be used as an add-on facility to the traditional real-time monitoring system, to provide near real-time diagnostic capability and advanced monitoring features. Following an incremental approach it will be first introduced in support of a limited number of spacecraft subsystems/units and/or for selected payloads.

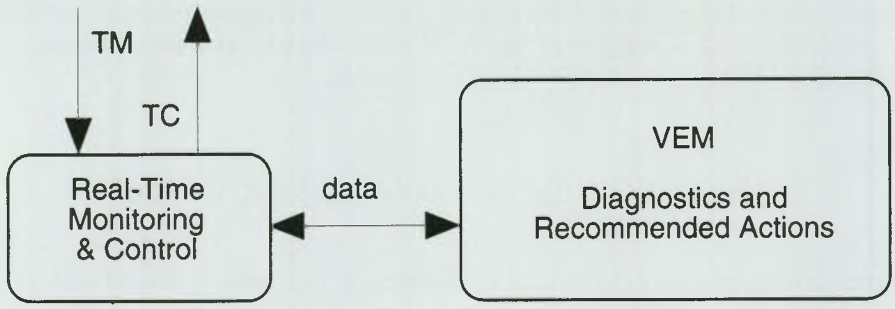

Figure 2 - Complete Monitoring & Control and VEM System

3. AN IMPLEMENTATION APPROACH: RAPID EVOLUTIONARY VEM PROTOTYPING

Today decision support systems and knowledge based systems are quietly entering, at operational level, the control room of manufacturing plants, of electrical power plants, just to mention some cases. Time seems right for the introduction of intelligent monitoring systems in support of space missions control, too.

A limited budget for this prototype was a major constraint for the exploratory activities, driving one to a careful selection of the development strategy and of the most suitable development environment. At the same time it was tried to avoid waste of time and money reinventing the wheel, and to make the development process as smooth and efficient as possible. In addition, Expert Systems (ES) and Artificial Intelligence (AI) have already provided in the past overexpectation and overconfidence, bringing the management to a reduced degree of confidence vis-à-vis AI.

It was decided to use an iterative development process, to balance goal-directed implementation with the ability to respond to unexpected discoveries during the development.

As a first step a Commercial Off-The-Shelf (COTS) real-time development environment was selected. The goal of the first small scale prototyping effort was to stress the tool capabilities required for the VEM, such as real time characteristics and satisfactory rapid development environment features. At that time the tool was already operationally used by INTELSAT in the monitoring and control of their ground stations and communication network. Recently it has been selected for IRIDIUM and by NASA JSC as reference environment for the knowledge based application within the Space Station Control Centre.

The tool was found adequate to perform rapid VEM evolutionary prototyping, making use of its object-oriented, real-time and graphics capabilities.

3.1 THE ATV SUBSYSTEMS MODELLED IN THE VEM

The ATV Object Oriented Model was developed, taking into account these guidelines:

- Develop a sample model of all of the ATV subsystems
- Verify the applicability of the model approach to support the operator in fault detection, isolation and recovery

Having in mind these requirements the following steps have been performed in the modeling process:

- Representation of the ATV physical breakdown. It was implemented modeling the ATV subsystems and units the ATV is composed of, in an object network, as outlined in fig. 3.

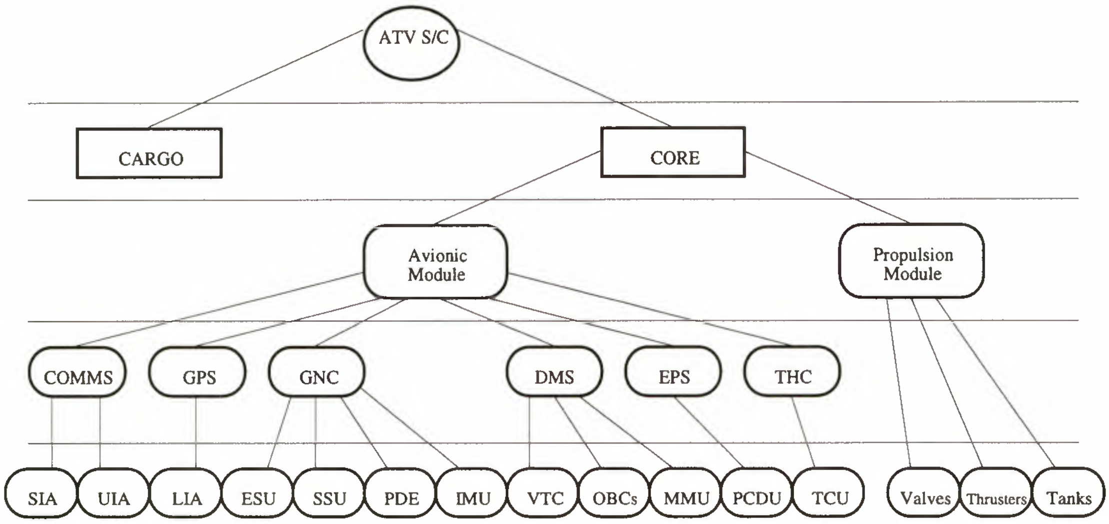

Figure 3 - The ATV Objects Network -

- Representation of the relationships and roles of each unit belonging to the breakdown: for example, the Inertial Measurement Unit (IMU) object as instance of the SENSORS class.
- Definition of the mission: functional breakdown of the ATV Mission, in terms of its operational phases:

- Launch	- Docking	- Departure
- Cruise	- Reboost	- Loitering
- Orbital Transfer	- Stand-by	- Reentry
- Rendezvous	- Check-out	
- Proximity	- Retreat	

  In turn, each phase has been associated with the required subsystem modes and the related units status.
- Representation of the ATV telemetry involved in the execution of the envisaged test cases (as mentioned below) . These telemetry parameters have been modelled as objects: the expected behaviour has been represented both in the form of mathematical law to be followed by the parameter trend, and as checks to be performed on some statistical parameters.
- Representation of the dynamic monitoring knowledge, needed to analyze the incoming simulated telemetry values, to synthesize and derive from them the status of the involved ATV units and to map these states on the screen according to a defined color code.
- Representation of the diagnostic knowledge, needed to dynamically select, on the basis of the current mission status, the units and parameters to be analyzed during the diagnostic process. In addition the knowledge used to explain the inferential process, together with the recovery knowledge have also been modelled.

Outside the ATV Model, a Telemetry Generator Model has been developed in order to provide the application with the required telemetry parameters and to simulate and propagate on these parameters the effects of envisaged faults and/or mission events. The VEM prototype is represented in figure 4.

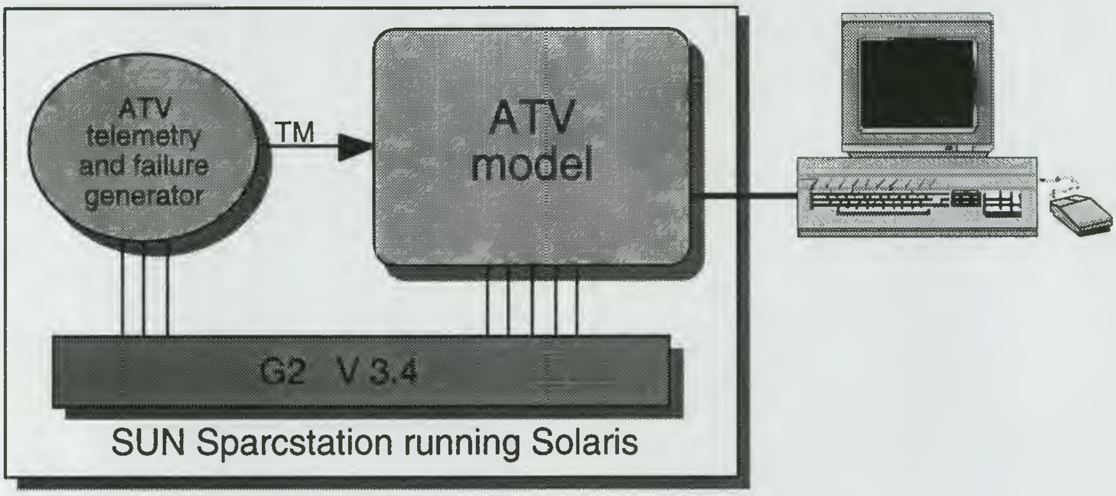

Figure 4 - The VEM Prototype

The fault detection, isolation and recovery process follows a step-by-step approach. Whenever an anomaly is detected the VEM analyzes the incoming parameters and suggests a recovery action. If the operator decide to send the suggested command to the ATV the prototype simulates its effect resulting either in a refinement of the failure analysis, leading to a new recovery action or in a successful fault recovery. At each step the controller can require a detailed explanation of the inferential process. As reported in fig. 5 the VEM provides with the list of facts currently used in the reasoning process, the list of actions already performed and the list of hypothesis considered by the VEM inference engine.

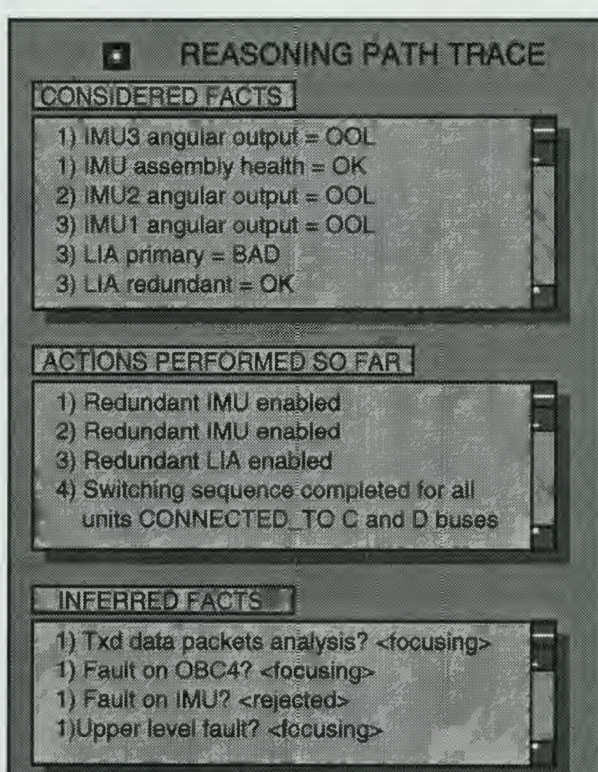

Figure 5 - The VEM Reasoning Path Trace

The VEM is also capable to perform on-board resource monitoring and evaluation, computing dynamic resources consumption profiles, starting from initial nominal budget, modifying the expected consumption when on-board failures and contingency event take place and comparing the expected and actual consumption trends with pre-defined alarm levels.

Two test cases have been developed, stressing different VEM supporting functions.

3.2. THE FIRST TEST CASE

The first modeling case has been designed to test the VEM prototype capabilities in the detection, isolation and recovery of *a multiple failure event occurring in the ATV on-board data handling system*. The scenario is for when the ATV has nearly completed the phasing to the ISS, after the second orbital transfer burn. The goal of this test case is to point out how crucial the VEM potential is when the on-board ATV FDIR functions are not sufficient to solve autonomously the failure.

Focusing on the ATV data handling, the present case involves several ATV avionics subsystems. Although the failure event is mainly built into the Data Management System (DMS), the other subsystems which contribute to characterizing the case are the Electrical Power S/S (EPS), the Guidance Navigation & Control (GNC) S/S, the L-Band Communication S/S.

The case primarily involves the following units:

- 4 On-Board Computers (OBC) and 4 system buses
- 1 Inertial Measurement Unit (IMU) with double-redundancy function
- 1 Battery Module (BM)
- 1 L-band Interface Adapter (LIA) with single-redundancy function

The VEM prototype is expected to monitor and control any event concerning all subsystems and units involved in the test case, thus helping the flight control engineers at least in the following activities:

- Failure diagnosis and recovery
- Failure Propagation Analysis
- Safe Status Check

The VEM provides support through the following operations:

- keep track of S/S, unit, and bus related telemetry
- suggest and perform command unit and bus reconfigurations
- provide information on unit design specifications
- produce real-time simulation of those on-board actions expected to take place during non-visibility periods (e.g. S/S and unit mode transitions)
- request dump of on-board S/W memory areas to inspect events occurred during non-visibility periods.

3.3. THE SECOND TEST CASE

The second modeling case has been designed to test the VEM prototype potential in the *step-by-step detection, isolation and recovery of an on-board failure event affecting the ATV Guidance Navigation & Control (GNC) activities*. The other purpose of this test case was to highlight *the VEM resource evaluation capability* as far as the prediction of failure-induced budget consumption is concerned. The scenario is for when the spacecraft is phasing to the ISS, after the first orbital transfer burn.

This test case involves the ATV avionics subsystems. Although the failure originates in the ATV Thermal Control (THC) System, it actually produces its major effects in the GNC S/S processed operations. Besides THC and GNC, the UHF-Band and L-Band Communication subsystems contribute to characterize the case. The simulated failure involves directly the following units and components present in the S/C avionics architecture:

- GNC Application Software integrated in the On-Board Computer System
- 3 Inertial Measurement Units (IMU)
- 2 UHF-Band Transponder Units (TxRx)
- 3 heater components controlled by the Thermal Control Unit (TCU)
- 1 thermostat component mastered by the TCU
- 1 L-Band Receiver (GPS Rx)

The VEM prototype will be expected to monitor and control all subsystems, units, and components characterizing this test case, thus helping the flight control engineers at least in the following activities:

- Failure Diagnosis and Recovery
- Safe Status Check
- Resource Evaluation

The VEM provides support through the following operations:

- keep track of the subsystems, units, and component part related telemetry
- command unit and power line reconfigurations
- provide information on unit and component design specifications
- request dump of on-board S/W memory areas to inspect events occurred during non-visibility periods
- evaluate budget consumption induced by on-board events, e.g. vehicle manoeuvres and unit performances.

4. ASSESSMENT OF THE PROTOTYPE

The resulting prototype implementation of the Vehicle Expert Module has the following characteristics:

6	ATV Subsystems
300	Telemetry Data
3500	Rules
3000	Objects
1000	Methods

The test cases have been used to validate the models and to prove the VEM benefits provided to the flight control engineers within a mission control centre, as reported below.

- During the monitoring activities, the information contained in the incoming telemetry values are analyzed and synthesized. The spacecraft controllers are provided with a graphic and hierarchical representation of the S/C subsystems which allows mapping and synthesizing the information contained in the telemetry.
- The mission functional losses are acknowledged, identified and represented graphically. In addition these losses are real-time mapped with the states of the physical components needed to execute the related mission phase.
- In a Fault Detection and Isolation context, the operators can be immediately provided with the right sequence of actions to be executed to focus, isolate and recover from the failure(s). The system is able to detect the propagation of the faults on each ATV subsystem and on the

mission phases to be executed. In addition, a step-by-step interactive approach allows progressive reduction of the scope of the analysis, until the fault is isolated.

- In an on-board resource evaluation context, the effects of detected failures on the resource consumption can be predicted, for each mission phase. The VEM is able to trigger alarms and propose reallocation of resources as a consequence of faults.

The VEM approach has several advantages, if compared with the standard approach for the on-ground FDIR:

- all the different types of knowledge required (e.g. operational, spacecraft engineering, etc.) are available at the same time;
- the identification of the recovery actions, being traditionally a time consuming and not straightforward process, is in this way optimized, accelerated and, up to a certain extent, automated;
- the VEM add-on functions (e.g. reasoning path trace, resource evaluation support, etc.) allow the spacecraft controller to analyze the reasons and the facts used in the VEM FDIR process.

In summary a sound use of the VEM capabilities could well provide a contribution to contain *mission operations costs*, especially for long duration or repetitive missions, by reducing the required number of operation positions.

This study led also to the identification of possible additional utilization of a VEM-based application, that may be the subject of future prototyping investigation.

- Training: the spacecraft model approach could be used to train inexperienced users in spacecraft monitoring and control. In addition the skill level can be ascertained, via the tool expert capabilities, and training lessons assembled accordingly;
- Operation Language Interface: the VEM capabilities could be extended to deal with flight procedures assembling, generation, verification, simulation and execution. An intelligent editor/parser would guide the user in the procedure definition while a direct interface with the mission database should allow access to the telecommand/telemetry information needed. Finally advanced checks could be performed against the procedures being assembled through the combined use of mission knowledge and the VEM expert system approach.
- Spacecraft Modeller: the VEM approach could be generalized, in order to allow spacecraft engineers and experts to define a spacecraft architecture together with the diagnostic/recovery knowledge. No expert skill on AI tools and programming would be then required since the tool's man-machine interface guides the user through an interactive process ending with the definition of all the required spacecraft models (mission, physical, etc.) plus the diagnostic rules and meta-rules.

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MISSION OPERATION PREPARATION AND ORGANISATION TO SUPPORT A WIDE FRENCH SCIENTIFIC CONTRIBUTION TO MARS96 PROJECT-

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ABSTRACT. The MARS96 mission to be launched in November 96 is a RUSSIAN project of Mars exploration including a very large international participation (more than 30 experiments for more than 20 participating countries).Additionally of the French contribution management, CNES provides a relay integrated on the US MGS1 spacecraft which should be used for an additional support to the Mars96 mission.
It is the basic task of CNES in the area of the mission preparation and operations organisation to maximise the French scientific return. That must be supported by a clear justification of requirements and constraints from the French side taking into account the system capabilities and the other experiments requirements. This mission preparation work shall be the basis for the actual realisation of operations to adjust the final version of scientific observations program (transmitted eventually to the spacecraft) as function of expected or unexpected mission events.
After the general presentation of the mission and of the French contribution, this paper shall present how this approach has been implemented and the consequence for the architecture and the organisation of the French ground segment. Then this MARS96 experience shall be analysed in conclusion to prepare efficiently for next projects knowing the difficulty and constraints for the operations of such international projects.

1. THE MARS96 MISSION

The MARS96 mission to be launched in November 96 is a RUSSIAN project including an Orbiter and two small stations and two penetrators. On each vehicle there is a very large international participation mainly oriented towards the implementation of scientific experiments (more than 30 experiments for more than 20 participating countries). The orbital module design is inherited from the Phobos spacecraft but among the main structural modifications the solar array size has been increased, two platforms for specifics and more accurate pointing modes requested by some experiments have been added, and the adaptation for the transport and the separation of the landers has been implemented especially. The two pointing platforms have been designed according to two different types of scientific requirements:
- the PAIS platform (2 axes) in order to point mainly the stars both during cruise phase and orbital phase
- the ARGUS platform (3 axes) in order to point specific areas of the planet during the orbital phase.

That leads to a total spacecraft mass (including propellant) of about 6720 kg after separation of the launcher upper stage. A Proton launcher with a fourth upper stage (Block-D) is therefore mandatory to provide the injection on the Mars transfer trajectory. A specific propulsion module is used partly for this injection and for all the manoeuvres up to the realisation of the operational orbit. The small stations must be separated before the arrival and a semi-hard landing is ensured by an aerodynamic braking with an aerothermal shield, a descent phase under a parachute and a landing shocks absorption by air-bags. The penetrators will be separated from a highly elliptical orbit, and an inflatable device ensures the aerodynamic braking to provide a hard landing speed for which the equipments and the penetrators structure has been designed and qualified especially.

The MARS96 mission is under the RKA (Russian Space Agency) leadership. IKI (Space Research Institute of Russian Academy) is responsible for the scientific mission. It ensures the international scientific coordination and provides also a part of the scientific experiments. The prime contractor for the Orbital module (except the two platforms development) and for the spacecraft control centre is NPOL (NPO Lavoshkin) with its design office the Babakine Centre. The PAIS platform has been designed, integrated and tested by IKI, but the development of the ARGUS platform has been directly contracted to VNII Transmach of St Petersburg. The small autonomous stations (SAS) and the penetrators (PN) are respectively under responsibility of IKI and Vernadsky Institute for Geochimy , but the development and the general mechanical design of the vehicle for the Orbiter interface, the entry, descent and landing phase and the integration are under responsibility of NPOL.

The mission was originally more ambitious and complex (with two identical launches in 92 and an additional descent module on each spacecraft) in the Soviet wide program of Mars exploration. At the beginning of the development phase it has been simplified and the present mission was scheduled for 94 followed by another launch in 96 with the descent module. Due to the Russian budget shortages and some technical problems which appeared in 93 and 94 a postponement to November 96 has been unavoidable and the second launch was eventually cancelled. The 96 launch window ballistic consequences and the increase of the spacecraft total mass (particularly attributed to the payload and to the landers), induced adaptation and discussion of the mission profile with the international scientific community and with the participating national agency, several times. This task for optimisation of the mission profile is one of the important activities for the mission preparation which are presented later.

2. FRENCH CONTRIBUTION AND ORGANISATION

The French scientists are involved in most of the disciplines of the mission, by providing either PI (Principal Investigator) instruments or being CoI in international teams like showed in the Table 1 and 2. The corresponding experiments are spread on the different parts of the vehicles and operated during different phases of the mission (see also Table 1 and 2).The French laboratories are responsible for the development of the scientific instruments. A CNES project team has been created to monitor all these developments and to manage the interface with the Russian side. CNES also provides Russia with additional furnitures (data relays, batteries for SAS, components ...) and support services (expertise, measurement and tests facilities, decontamination of landers equipments ...) to the Russian institutes and industries responsible of the project. CNES is responsible of the development of a general ground system (including a communication link between Evpatoria Deep Space station and Moscow). It shall be used to gather, to process and distribute to the laboratories, all the data produced and needed for the scientific exploitation of the mission, and to coordinate all the operations of the French instruments. Moreover CNES provides a relay integrated on the US MGS1 spacecraft to be launched also on November 96, and which shall be utilised like a complementary and back-up facility to locate the landers and transmit the descent and on surface data. Therefore CNES shall be a central node to coordinate the relays operation and their data collection and distribution.

By consequence, inside the CNES project team an important task for the system analysis and the mission preparation must be ensured (a system and operation group has been implemented):
-to coordinate the requirements of scientific PI and their correct implementation through the spacecraft design and the mission definition,
- to ensure the optimal utilisation of the CNES furnitures (in particular for the communication chains), in close relation with the definition of the ground system.

NAME	Sensors	Scientific objective	French Laboratory	Vehicle/ platform	Mission phase
DYMIO	Ions spectro/analyser	Ionosphere, thermal Ions	CETP	Orbiter	Orbital
ELISMA HFMI	HF Antennas & mutual imp. probes	HF Waves, thermal electrons	LPCE	Orbiter	Orbital
ELISMA ULF	3 axes Magnetometer	UBF Waves, solar wind/Planet Interface	CETP, LPCE	Orbiter	Orbital
ELISMA VLFA	FFT Analyser	TBF Waves, plasma & surface	LPCE	Orbiter	Orbital
EVRIS	Stellar photometer	Stellar sismometry and rotation	DESPA LAS	PAIS	Cruise
LILAS-2	Gamma Spectrometer	Cosmic gamma bursts	CESR	Orbiter	Cruise /Orbital
OMEGA	IR and visible spectrometer	Surface & atmosphere components	IAS, DESPA	ARGUS	Orbital
SPICAM-E SPICAM-S	Multi channel spectrometer Photometer	Atmosphere sounding with occultation	SA	PAIS Orbiter	Cruise (calib) Orbital
DESCAM	CCD Camera	Vicinity of landing site imaging, wind	LAS	SAS air-bags	Descent
OPTIMISM MAG	3 axes flux gate Magnetometer	Magnetic sounding, solar wind interaction	IPGP,INSU U.Paris Sud	SAS petals	Descent, On surface
OPTIMISM SISMO	Long period Sismometer	Seismology, Internal structure	IPGP, INSU	SAS	On surface
ODS *	Optical sensor	Atmosphere optical depth	SA	SAS	On surface

Table 1: Experiments with French PI

NAME	Sensors	Scientific objective	PI & French Laboratory	Vehicle/ platform	Mission phase
FONEMA	Ions spectro/analyser	Dynamic of planetary Ions	SSL (G.B), CESR	Orbiter	Orbital
Spicam SOYA **	Photometer	Helio seismology	Obs Crimée, SA,IAS	Orbiter	Cruise
RADIUS-M	Detectors X, e^-, i^+ μ meteorites	Radiations doses	(Ru)	Orbiter	Cruise/orbital
METEGG	P, T,U Wind sensors	Meteorology	FMI, SA	SAS	Descent/ On surface
PANCAM	CCD camera	SAS surface environment	IKI LAS, CNES	SAS	On surface

Table 2: Experiments with associated French laboratories

* ODS is considered like a part of METEGG package of instruments

** SOYA, SPICAM-S, SPICAM-E are integrated by SA in the complete package SPICAM

NOTE- CNES has participated to the antenna measurement, sterilisation of some parts of penetrators and provided components for coding . French scientists shall be associated to penetrator data exploitation.

3. Mission preparation complexity

The definition and organisation of operations to optimise the scientific return of the mission is then a complex task for IKI responsible of scientific payload and NPOL prime contractor of the spacecraft. Of course each PI searches to maximise the observation for his instrument, that is in general contradictory with the spacecraft and ground systems capabilities and with constraints and requirements from the others instruments. Like underlined above, the wide French contribution is coordinated by a CNES project team . Therefore the optimisation of French science return supported if necessary with science guidelines and priorities defined by a Mars science group with a science coordinator, is the basic task of CNES project in the area of the mission preparation and operations organisation. The presentation of a coordinated French request enforces generally the position of French scientists and simplify the optimisation task for IKI because it represents already a synthesis of constraints for a wide part of the payload.

But in any case, it is impossible to gather exhaustively all the constraints and requests and to discuss it with all the international participants of the project. For instance the annual meeting of the international scientific committee (MNS) get together more than one hundred people.

3.1 Mission preparation organisation

3.1.1 Mission preparation logic

In fact the mission preparation work is distributed through implicit or explicit ways at very different levels along the development phase:

- the mechanical interface (place and orientation) which take into account instruments field of view and requirements (thermal, attitude..) for scientific observations are negotiated at the beginning of the project (and formalised in an ICD for CNES interface). That is generally not re discussed during the project and is considered as an input for the mission analysis.
- The main events and main phase of the mission are defined and the nominal phase for science observation are rather imposed. That constitutes the outline of the mission provided in form of a preliminary mission profile.
- For each phase of the mission the corresponding resources and the trajectory and orbit characteristics are refined, generally at a system level.
- The phase of ground segment design in particular the analysis of operational exchanges requirements are oriented through an operational concept which is the basement of the mission scheduling and the corresponding definition of scientific observations.

3.1.2 Mission preparation control

Usually, in particular for a such complex project the mission definition is the result of quasi-permanent iterations between the requirements, the constraints and the facilities (ground and on-board) required for the mission. Along this process some decisions are taken which permit to progress and to go deeply on the mission definition. For a classical European space project these cycles of iteration and decision are controlled by a classical development scheme supported in particular by a plan of reviews at system level and a corresponding definition of the mission analysis and the mission preparation documents to be submitted to these reviews.

In the Russian project, this kind of organisation for the development phase does not appear to the foreign participants. Therefore it was very difficult to understand and to participate really to the mission preparation task. A rough analysis of the Russian style of thinking and working results in the general conclusion that each specialist must maintain a system coherency for his particular tasks but the system knowledge and the mission definition process is concentrated towards the higher hierarchy project level identified like general constructor, chief designer or mission science responsible. A continuous adaptation to this kind of organisation has been needed to ensure the French coordination responsibility as efficient as possible.

3.1.3 Definition of sub-groups and corresponding contribution for the mission preparation

The opportunity or the needs of coordination encountered along the development phase have in general conducted to the creation of specifics working groups. Even if the mission preparation was not the main objective of a sub-group, in general that provides results which widely contributes to the progress of this task. This organisation with separate working groups has really permitted to simplify by an implicit distribution of the optimisation problem in sub-problems. Inside the working groups it was easier to directly support the French interests. The counterpart is obviously that a synthesis and a coordination must be done at a higher level (hierarchical or system level). Several people of the French and Russian projects team and some PI participated to the work of most of the sub-groups, that provided an easier coordination.

The main sub-groups with representatives of French side were:
- The different science subgroups (planetary, plasma, ..) This was organised earlier in the project phase for a better efficiency of the Science committee work. Grouping the PI with common scientific objectives which induces generally the same constraints and requirements for observing a same class of phenomena or objects, provides the definition of common requirements to the system and a general attribution of resources which can be managed inside the sub-group.
- The "objects" subgroups (PAIS, ARGUS, SAS). This is a natural grouping of experiments which used a particular important equipment of the spacecraft (pointing platforms) or a separated vehicle for the mission. The platforms themselves have been implemented to simplify the operation, in the sense that experiments which require very specific pointing zones and precise stabilisation accuracy can realise that without conflict with respect to other experiments which cope with the nominal mode of spacecraft attitude. The definition of the operational coordination exchanges inside these groups (which shall continue to act during the mission) and with respect to the general operational organisation were also defined with these groups.
- The Orbit group. It was created to decide the nominal working orbit for a 94 launch. The postponement to 96 and the total mass increase necessitate to reconstitute this group which has worked to define a new class of optional orbits. But the group also participated to the establishment of the mission profile, because some requirements for the landing conditions of landers and for communication with spacecraft induce constraints on the injection strategy and the working orbit acquisition. It is obvious that this group shall continue to work during the mission realisation to optimise in case of degraded performances or better in case that the development margin (for instance inside the propellant budget) can be used efficiently for improvement of the science return.
- The ballistic and communication working group. Due to the highly eccentric orbit and the injection dispersion, the optimisation of communication with landers was a complex problem. French side providing the relay and contributing to the performance of the link (with compression and protection code) and to the measurement of performances (antenna characteristics, interface and end-to-end tests) widely participates to the creation and tasks of this group.
- The IOPG (International Operation and Planning Group) with CNES, NASA/JPL, IKI and NPOL representatives was created for utilisation of the MBR (Mars Balloon relay) on board the Mars Observer spacecraft. In a sleeping mode after the fatal failure of the spacecraft, it was reactivated after the decision to provide the same type of relay for the MGS1 spacecraft, and to support the utilisation of

this relay for the Mars96 landers.
- The EMC (Electromagnetic compatibility) group is a very specific area of activity. But it is closely linked to the operations by the fact that all operational configuration must be run for the EMC demonstration test and the possible remaining interference conflicts must be taken into account for the operations.
- The ground segment and operations group. This group was created to define the architecture, the interfaces and the operational exchanges between the Russian and the French ground segment. For the mission preparation it acts principally to define the cycles for the scheduling and the realisation of scientific observations requests. But the limitation of the system (Number of TC, TM volume, sequencer programs) was also identified in this group and a preliminary resources attribution had been provided through this group.
- The SPICE/NAIF and navigation group. For the mission it was decided to use the SPICE/NAIF data base and tools developed by JPL. In addition to the needed coordination for the implementation of this common facilities in the different centres, they have contributed by defining and implementing specifics common computation and graphic tools used for the mission analysis tasks. The definition of operational exchange cycles for the navigation and localisation data were also part of the mission preparation for this specific domain.

4. Results for the mission preparation and execution

For a Russian mission (CNES have a long experience of cooperation inside Russian projects), we know that there is very few contractual or technical documents which can notice and synthesise all the results of the mission preparation. The final one which is the nominal flight plan must be provided only 3 months before the launch. In this document do not appear all the constraints and compromises which have been used for the optimisation of this plan. Most of these informations are distributed into the protocols of specific meetings. Therefore it is not easy to keep the memory of the development phase, which in fact mostly transmitted by the people who participate to this phase, and shall continue to work for the mission execution.

Nevertheless, it is important in particular in case of unexpected events to take into account all the implicit and explicit constraints which are relevant for a reliable and quick processing of a new procedure. CNES through the discussion and the results of the above mentioned working groups acquired a knowledge of the system and participated to the mission definition in such a way that it should be capable to react as function of the mission events efficiently to help for an optimal French science return. As far as possible these results were noticed inside CNES or Russian/French or international documents which shall serve like a basic reference for this task. The following paragraphs provide typical and most important examples of this work results.

- Experiments DCI

The Russian side has provided a general specification applicable for all the payloads, which defines the environment and interfaces with the spacecraft and the acceptance tests conditions. That was not considered sufficient by CNES to specify all the interfaces of a particular payload. It was proposed to the Russian side a DCI (Interface Control Document) for each experiment. At least for the Orbiter experiments it was possible to have a common approval with the Russian project responsibles and a configuration management of these documents. For the mission preparation it is usable because it contains the operational constraints for the experiments functioning and the scientific observations. Moreover inside an Annex called "Cyclogrammes de fonctionnement" the different modes of experiment are described with the corresponding resources requirements in term of the different telemetry volumes and power consumption.

- Experiment program type

One of the most constrained resources is the number of commands (TC) which can be loaded for a working interval of the flight plan. For most of experiments these TC are provided through a general Orbiter data handling equipment called PVS. CNES with support of Russian specialist has written a document to notice the functioning characteristics of this equipment to the laboratories. It was required for each experiment to define a "program type" which constitutes the nominal sequence of commands to be sent by the PVS. Then the TC number required for a specific observation is minimised by sending only correction of this "program type", defined in a document provided to the project operation responsible. That should be very useful for operation execution to provide a deterministic sequence for each experiment functioning.

- Mission profile and operational Orbit

We have already noticed that the postponement to 96 created new constraints in particular for the operational Orbit choice. The injection condition and the area and local time for the landers arrival were also subject to trade-off and discussions. That was an important task for the Orbit group and the Small Stations group. To evaluate the impact of an orbit choice on scientific observations, a set of graphs was created and the parameters and diagram forms were commonly agreed between the CNES and NPOL ballistic specialists and the system and science responsibles. Based on an agreed set of initial data the resulting diagrams were compared and validated between CNES and NPOL. Then a table of Orbit options was elaborated by the Orbit group and IKI with each science group can evaluate quickly the different options using the corresponding diagram (In general one diagram is sufficient to evaluate scientific observations opportunity along the mission for a given science group like planetary and plasma groups). The present nominal orbit with a period of 43.05 hours has been fixed by NPOL according to a propellant budget which includes all the necessary margins. During the launch preparation and the manoeuvres realisation if it appears that these margins can be used to change the operational orbit, it should be easy to choice a new orbit among the options with an optimal utilisation of the margins. Additionally, the diagram generation softwares have been added to the tools delivered to the laboratories for the SPICE/NAIF data base utilisation. Then a scientific responsible can elaborate quickly a long term observation plan using these diagrams, and he can see the impact of a constraint modification which are explicitly considered like input parameters. That should be very useful for the final step of mission preparation and along the mission execution. The main characteristics of experiments (like field of view, axis systems ...) used for events previsions are additionally agreed and put in a specific file of the SPICE/NAIF which is accessible by each project participant.

- Communication with landers

Additionally of the choice of the areas and local time for landing (French requested a landing during day for a correct functioning of the DESCAM camera) which impacts the mission profile and the periapsis initial position (discussed in the Orbit group), the elaboration of the landers communication strategy was an important subject for the mission preparation. That was the main task of the ballistic and communication working group. Based on the performance measurements of the Orbiter and landers radio systems a simplified formula for link budget and radio-electrical visibility computation has been agreed. The visibility is very dependant of landers (and by consequence antennas) orientation which is randomly realised but can be measured with internal sensors, and of the high dynamic of range variation on the highly eccentric orbit. Moreover the possible occurrence of first communications is not easily predictable due to high dispersions ($\pm$9 hours on the first orbit period) of the Mars injection manoeuvre. A common method of stochatics computation has been agreed and incorporated in CNES and NPOL software to perform the analysis and a strategy elaboration.

These results have been presented by CNES to the IOPG group to define a common strategy with Mars96 and MGS spacecraft to increase the probability to obtain and to optimise communications as soon as possible after the landing. For the routine phase after MGS aerobraking (to realise a low circular orbit) the relay should be used for complementary or back-up communications with landers.

The software commonly specified and validated for these communication studies shall be useful along the mission to schedule the operations of the relays and for the Orbiter antenna pointing parameters.

After MGS launch, a check-out period of the relay functioning using mainly a Standford university radio-astronomy antenna has been defined with JPL. CNES has initiated and supported a request to use the same facilities for a check-out of the Mars96 communication chain. That shall necessitate a close operation coordination between CNES, JPL and NPOL, but shall help to remove doubt on an important part of the communication chain .in case of communication problems.

- Operational exchanges
Inside Ground segment and operations group, CNES with IKI and NPOL have defined a operational cycle for science observations requests and scheduling and for corresponding TC files delivery. The definition of an agreed formal structure (based on CCSDS recommendations) for these exchanges shall permit to organise and to secure for the creation and management of these files with operational softwares. The result of this work is stated in an operation DCI.
A specific coordination for the experiments using ARGUS and PAIS platforms is needed to define the pointing request of the platforms. The ARGUS and PAIS groups have performed the definition of the corresponding exchanges which shall be also agreed in ARGUS and PAIS operations specifics DCI. These platform groups shall be adapted for operations execution and taking into account like operational entities in the operation organisation.

- Degraded cases
Up to now there are not degraded cases considered at the system level for the flight plan generation. Nevertheless, during the development phase there were concerns about the flight readiness feasibility of the ARGUS platform. A solution without platform with the experiments body-mounted directly on the spacecraft has been evaluated under IKI leadership, and with the CNES support to consider this solution like a prime back-up. In order to maintain at least a minimum of scientific observations with these instruments, it was necessary to orient the whole spacecraft from the nominal inertial attitude towards the Nadir direction. A preliminary study of the modifications for the attitude control system and of the operational impacts of this specific attitude move and pointing was performed by NPOL. This back-up solution was abandoned but the additional attitude control modes was developed and decision to implement it was taken by RKA. It should be used like a back-up degraded case in case of a failure with the platform pointing system. The operation plan shall be completely revised if this mode must be used (about 150 specific attitude sessions at periapsis vicinity can be envisaged).
CNES had performed an analysis of the NPOL study and a synthesis for the French experiment responsibles to evaluate the technical and operational impacts . With IKI a preliminary list of a new set of constraints for all concerned payloads with respect to a non-nominal attitude has been established.
Therefore that should be a useful basis, to be refined according to the actual flight conditions, if such a degraded case must be used.

5. GROUND SEGMENT DEFINITION

The French ground segment and its integration with Russian ground segment have been developed in coherency with the operational concept agreed with the French scientific community and applied for the mission preparation. The scientists have made it clear that priority should be given to rapid data retrieval in France thus enabling them to quickly interpret on-board measurements and thus plan work sessions for subsequent orbits. In general they have asked that special attention be paid to problems to do with exchanges of information between the different partners (Russian centres, laboratories, etc.), and for the centralisation and validation of these exchanges. Figure 1 shows the general organisation of the ground segment for the MARS96 mission

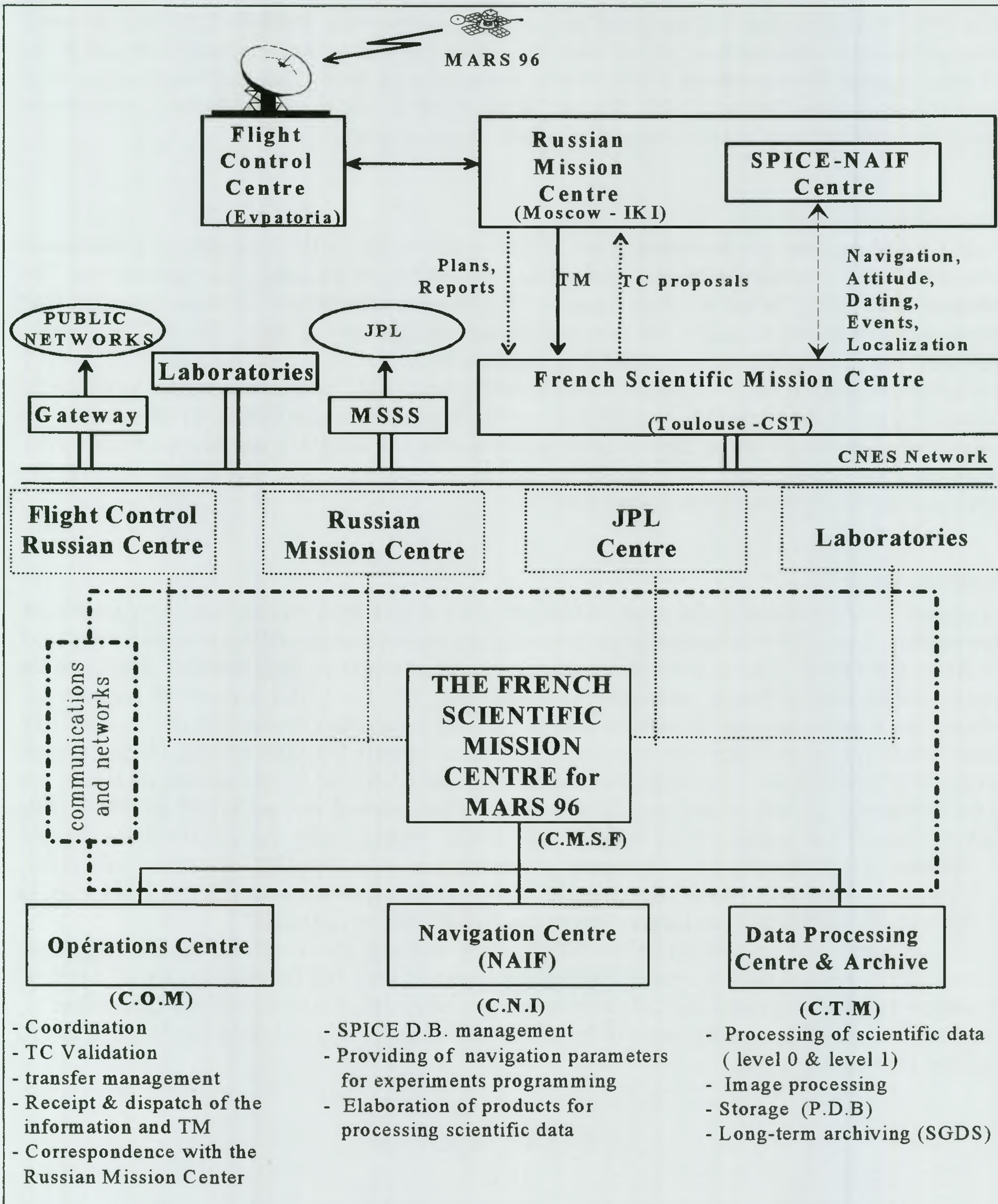

Figure 1: Physical and functional ground segment architecture

The C.M.S.F. will centralise all of the management and processing functions and will be closely interlinked with the Russian mission and control centres and the French laboratories. The flight control centre and the principal receiving station are located in Ukraine (Evpatoria), and the operations should be also coordinated by NPOL from Moscow . The Russian mission centre is in IKI at Moscow, and is linked through the C.M.S.F with nine French laboratories located at different areas in France. The ground segment is connected to JPL control centre for the MGS relay operations and to MSSS (Malin Space Science Systems) to receive the landers data.

Among the entities of the CMSF which are represented on the Figure 1 with an indication of their main functions, the COM shall be the French central node for the operations execution and the only interface point with the Russian segment. Therefore only the functions of this entity are detailed hereafter:

- ***Management of operations data*** : The COM will handle reception, validation, storing and dispatching of all of the operations data exchanged between the Russian mission centre and the French scientists (plans, TC proposals, reports, etc.)
- ***Real-time monitoring of scientific and technological data***: During communications sessions, the COM will handle real-time acquisition of the TM data. A laboratory will be made available at the Toulouse Space Centre for visiting scientific teams wishing to analyse the data with their test and control equipment (GSE), to enable them to possibly modify the short term programming for their experiments. This organisation will enable scientists to conduct flight operations from Toulouse without having to be present in Moscow in the Russian mission centre. However, for critical operations they can benefit of the same functions on a CNES server inside IKI mission centre, thus for routine stages, the experimenters will be able to do all of their control and programming work from their laboratories, since the telemetry, once received and validated, will be immediately dispatched to them.
- ***Off-line dispatching of scientific data***: 24 hours after each communications sessions the COM will recover the real-time TM data corrected by the Russian mission centre. This raw data will be validated and then dispatched to the Processing Centre.
- ***Dispatching of navigation data***: Periodically (once a week) the COM will recover from IKI the updates for the SPICE data base, which, following verification, will be used to update the CNES SPICE data base. The navigation data accessible through the services offered by the CNI will enable scientists to prepare the programming for their experiments.

The ground segment should be qualified by operational exchanges simulation, but also during the 10 months transfer phase which is less demanding in term of data volume transmission and of time criticality for operations coordination. A part of the software (for instance the small stations data processing) shall be coded and validated only after launch for the functions used only after Mars Orbit injection. That shall permit an incremental implementation of this complex system for the operations execution.

6. CONCLUSION

For a successful operation coordination and execution inside a such complex project, the mission preparation phase is very important and must be taken into account along the development phase. All the constraints and informations relevant for the operations should be identified, agreed and noticed like input for the nominal flight plan and to prepare efficient reaction to degraded cases. It was intended to perform this synthesis from the French side, inside a system definition file document. Face to the Russian organisation and working procedures rather different of current European space project that was difficult, and has been adapted. Nevertheless an efficient mission preparation task can be achieved through different working groups which should continue to act during the actual operations. This was possible due the wide scientific French participation and the CNES coordination which permit to present an unified set of requirements and to develop a ground segment coherently with this operational concept. Moreover CNES took benefit of the furniture of general equipments and services (for communication with landers in particular), to participate more closely to the system tasks of the project.

Even if the tendency is to decrease the vehicles size (smaller, cheaper) we are convinced that the solar system exploration should continue with more and more internationalised project and realisation of complex operations. Rosetta mission for instance although it is realised inside more classical European organisation shall present the additional difficulty that the operation actual execution shall be done more than 10 years after development phase. A large French scientists community shall be associated to this project and CNES also participate closely to the Champolion lander definition and communication system with JPL. Then we can expect that the MARS96 experience for mission preparation and operations support organisation should benefit for the next century missions to cope efficiently with the difficulty and constraints on mission organisation imposed by such international projects.

HUYGENS PROBE MISSION OPERATIONS

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Abstract: The Huygens Probe is the ESA contribution to the joint ESA-NASA Cassini/Huygens interplanetary mission aiming at the study of the Saturnian system. The Huygens Probe will fly, as a passenger of Cassini, the NASA spacecraft, to Saturn where it will be released for entry in the atmosphere of Titan, the largest satellite of Saturn. During the controlled descent phase, on-board experiments will execute a complex sequence of measurements to study the chemical and physical properties of this atmosphere, and, in case of impact survival, will collect data to study Titan surface properties. This paper introduces the ground system infrastructure, the procedures and the constraints necessary to operate the Huygens mission safely over its very long duration.

1. INTRODUCTION

The Cassini/Huygens mission will be launched by a TitanIV/Centaur rocket from Cape Canaveral in October 1997, on a journey of 10.7 years duration, which includes a 6.7-year flight time to Saturn after which the Huygens probe will be released into Titan's atmosphere, and a 4-year orbital tour of the planet, its rings, satellites, and magnetosphere.[1,2,3,4,5,6,7] NASA/JPL will control the Cassini Orbiter, whereas ESA/ESOC will control the Huygens Probe. The data exchange with the Probe — Telecommands (TC) and Telemetry (TM) — will be routed via the Cassini Mission Support Area (MSA) at JPL and uses the NASA Deep Space Network (DSN) facilities.

Operations of the Cassini-Huygens missions will be carried out from these two centres working in close liaison. Both spacecraft will be largely operated through pre-programmed time-driven command sequences, either uplinked from the ground or driven by on-board software. The Huygens probe in particular has, after separation from Cassini, no telecommand capability during its mission descent through Titan's atmosphere and the operation of its scientific instruments is then entirely automatic, driven by a combination of triggered and programmable schedules. To ensure the success of the mission all Probe systems are hot redundant and their performances are checked out, up to Probe release, at regular intervals throughout the 7-year cruise to Saturn.

The Cassini-Huygens Ground System is designed to meet all the requirements of operating the combined mission considering a 160 min round-trip light-time (at Cassini-Probe separation), with high reliability and within critical resource budgets over a period of more than ten years. The implementation of this complex system is an on-going effort both at JPL, for the Cassini part, and at ESOC for the Huygens part. It will allow both flight control teams to manage the mission and to cope with its particular constraints and characteristics: especially, those arising from the impossibility to have a real-time-type of interaction with the spacecraft and from the autonomous nature of many of their on-board systems.

2. THE CASSINI MISSION

The primary goal of the Cassini mission is to deliver a combined Saturn Orbiter and a Titan atmospheric probe for scientific research to the Saturnian system. After delivering the probe into the Titan atmosphere and relaying its scientific data to Earth during the first orbit following Saturn orbit insertion, the Orbiter will embark on its 4-year tour to observe the Saturnian ring and satellite system from a variety of phase angles and orbital inclinations.[3] Scientific activities will begin two years before

Saturn Orbit Insertion in June 2004. Before that spacecraft activities will be limited to routine maintenance of the orbiter´s subsystems and payload, probe checkouts, and several radio science gravity wave experiments. Approximately 76 days after orbit insertion, the spacecraft will execute a manoeuvre to raise the orbit periapsis and to target the combined Orbiter and probe for Titan impact. The probe will be released from the Orbiter 21 to 22 days before the first Titan flyby. Two days after probe release, the Orbiter will perform an orbit deflection manoeuvre to place it into a trajectory which flies over the probe landing site. The Orbiter will point its high-gain antenna at the predicted probe entry point on Titan to receive descent telemetry data relayed from the probe and store it redundantly on two solid-state recorders.

3. THE HUYGENS MISSION

During the coast to Titan the probe is essentially dormant, with only a timer running. Shortly before the probe is predicted to enter the atmosphere of Titan (about 3 hours prior to Titan surface touch-down), the timer will initiate a sequence which applies power to the probe subsystems and scientific instruments. The parachute controlled descent of the probe through the atmosphere will be initiated by accelerometers which monitor the deceleration as an indicator of Mach number. Pyrotechnic devices release the front shield and back cover and a pilot parachute pulls out the main parachute. Subsequent events are triggered by a software timer, initiated at the moment of parachute release, T_0. These events include establishment of the radio relay, switching on of further instruments, and replacement of the parachute by a smaller drogue to ensure that the probe reaches the surface of Titan within 150 minutes. The time is constrained by the capacity of the probe's batteries and by the changing geometry of the relay link as the Orbiter continues on its orbit about Saturn.[1]

Critical functions like pyrotechnics, which could endanger the mission if executed prematurely, are protected by an independent hardware timer which is initiated at a higher deceleration value a few seconds before T_0. The instruments use information about time and predicted or measured altitude broadcast to them from the probe command and data management subsystem to control their operations. During checkouts these operations are activated from a simulated T_0, but in the absence of decelerations the arming sequence is not run.[2]

Should the probe survive the impact with the solid or liquid surface, it will continue to transmit data until the batteries are exhausted and this will be recorded by the Orbiter until 30 min after the latest predicted touchdown. Later the Orbiter will be reoriented to transmit the recorded data to Earth and thence to the Huygens Probe Operations Centre (HPOC) at the (ESOC). The probe telemetry data will be retained on-board the Orbiter until successful downlink has been confirmed.

4. CASSINI MISSION OPERATIONS

Due to the long propagation delays expected during most of the Cassini mission (up to 160 minutes round trip light-time), real-time monitoring and control-loop — common to most near-Earth missions — is not feasible. A more suitable approach is that of uplinking at regular intervals — for the Cassini mission every two months — a set of time-tagged commands for subsystems, scientific payload, and the Huygens probe covering all the operational activities that must be performed during that time span. These sets constitute the Sequence Programs which are stored and executed by Cassini's command and data subsystem.

To simplify the mission planning and sequence generation process, the mission will be planned using Operational Modes — i.e., a power and data-rate resource envelope applied to the operational states of the spacecraft subsystems and scientific instruments — and a limited number of “unique” Sequences. The spacecraft will always be controlled through an operational mode, a unique sequence, or a. predefined transition between operational modes.

All probe activities will be designed as “unique” sequences. The probe relay sequence is defined to be a "critical" sequence in order to ensure that even an Orbiter fault condition will not prematurely terminate the relay sequence. The planning and generation of any probe checkout, the probe release and the relay sequences is a co-ordinated effort between Cassini's uplink operations team at NASA´s Jet Propulsion

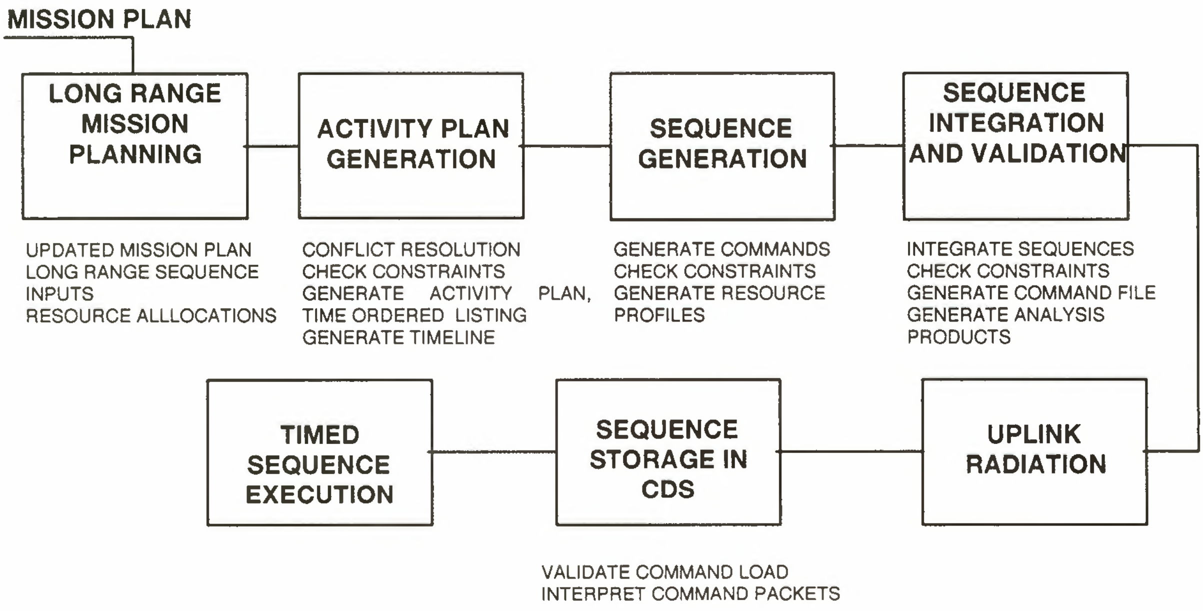

Figure 1: Cassini Uplink planning & generation process

Laboratory (JPL) in Pasadena and the Huygens operations team at ESOC. Figure 1 illustrates the planning process.

Approximately one year prior to launch, the long-range mission planning activities begin, which consist of the analysis and co-ordination necessary to identify the major engineering activities, scientific and probe activities necessary to achieve the mission plan , considering the latest trajectory data, and related ground support activities. Thereafter, for any given probe activity, the long-range mission planning process begins about 8 weeks before the uplink of the sequence containing the probe activity, and takes about 3 weeks to complete. After the mission plan has been updated to include the new activities, an activity plan is produced. During this process, which takes about 2 weeks, all conflicts are resolved and spacecraft activity sequence files are generated which specify the start and stop times of spacecraft activities.

During the sequence generation process, which lasts for about 7 work days, the activity plan serves as a basis for generating activity files at the command level. For a particular probe activity, it will include probe telecommands submitted by Huygens operations personnel and Orbiter commands submitted by Cassini operations personnel. The sequence integration and validation process, which lasts for about 11 work days, integrates all the activity files which have been generated for a particular sequence.

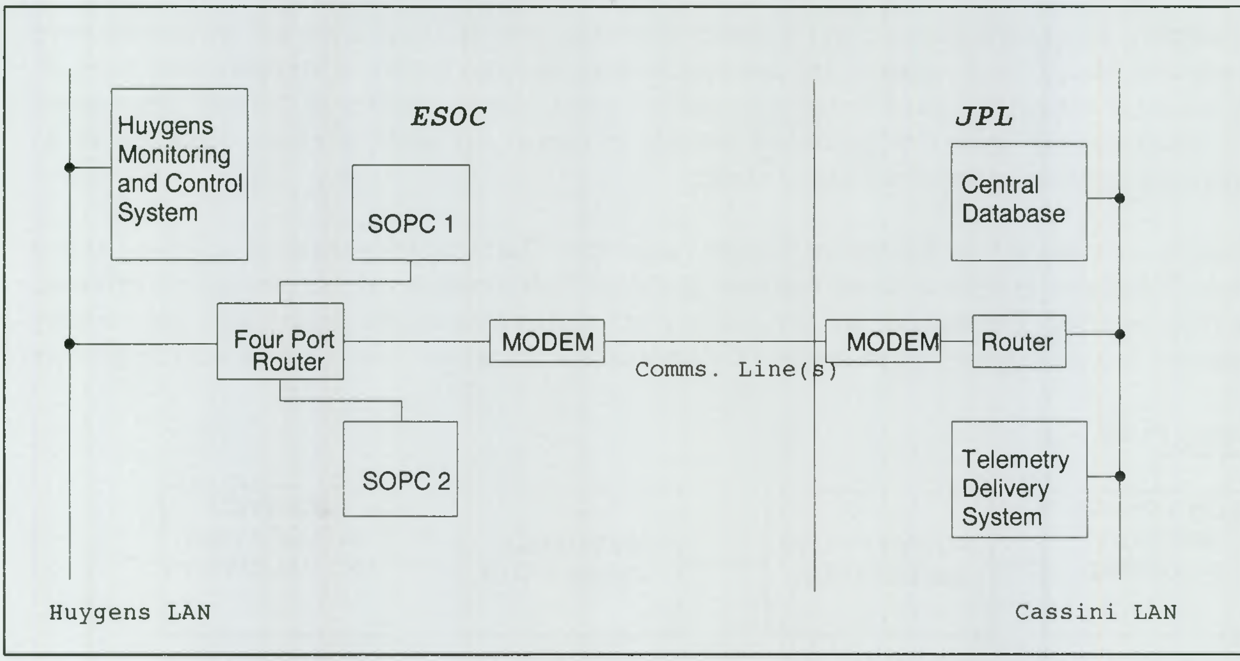

Fig. 2. ESOC-JPL interface

Upon sequence validation and approval, the final Ground Command File is generated and queued at the station and radiated to the spacecraft. Upon uplink validation by the orbiter's command and data subsystem, the sequence programs are registered, and sequence execution is allowed to commence.

The Cassini ground system performs the primary functions of mission planning and navigation, spacecraft command and control, spacecraft data acquisition, information processing and storage, and data distribution and archiving. These functions are performed with the aid of a network of workstations that are interconnected via the Cassini local area networks (LAN). Figure 2 illustrates the interface connection between the facilities at ESOC and the facilities at JPL. A Cassini science operations planning computer workstation (SOPC) is installed at ESOC as a gateway to the Cassini LAN's.

5. HUYGENS PROBE OPERATIONS

During the cruise phase, a full probe check-out will be performed about every six months in order to verify that no probe failures have developed. The checkout data will be analysed by the operations team and the probe scientific calibration or simulated data will be distributed to the instruments principal investigators for their own processing and analysis. Any contingencies arising in a given check-out period will be analysed between check-out periods and any reaction and corrective action will be attempted in the next check-out. Recovery activities will probably involve modifications to the on-board software.

During the Saturn orbit phase, (from June to November 2004) all probe subsystems and instruments will be brought into their final configuration to perform the autonomous descent sequence of operations, during a series of probe check-out periods. Once the probe is released from the Orbiter, telecommanding will be impossible: from this moment on, the probe will follow the automatic sequence of events that drives its activities till the end of mission, which has been programmed in the on-board software.

5.1 THE PROBE OPERATIONS CENTRE

The Huygens mission will be controlled from the Huygens probe operations centre — at ESOC, Darmstadt, Germany; its functional break-down is as follows and is shown in figure 3:

- The **Huygens Monitoring & Control System** this provides the ground data processing facilities and interface support for the proper execution of both the probe operations and the distribution of the mission products to the external users involved;
- The **Science Operations & Planning Computer** the gateway for all operational data exchange between ESOC and JPL;
- The **Science Data Storage & Display** this will be used by the PIs to analyse and display the mission scientific data collected during the Saturn orbit and descent phases;
- The **Mission Planning Support** to define, plan and validate any needed probe operations;
- The operational **Interfaces** with:
    - **JPL**: for the uplink and downlink functions, as well as for overall mission co-ordination;
    - **Principal Investigators Home Institutes** for scientific data distribution and instrument operations commanding inputs;

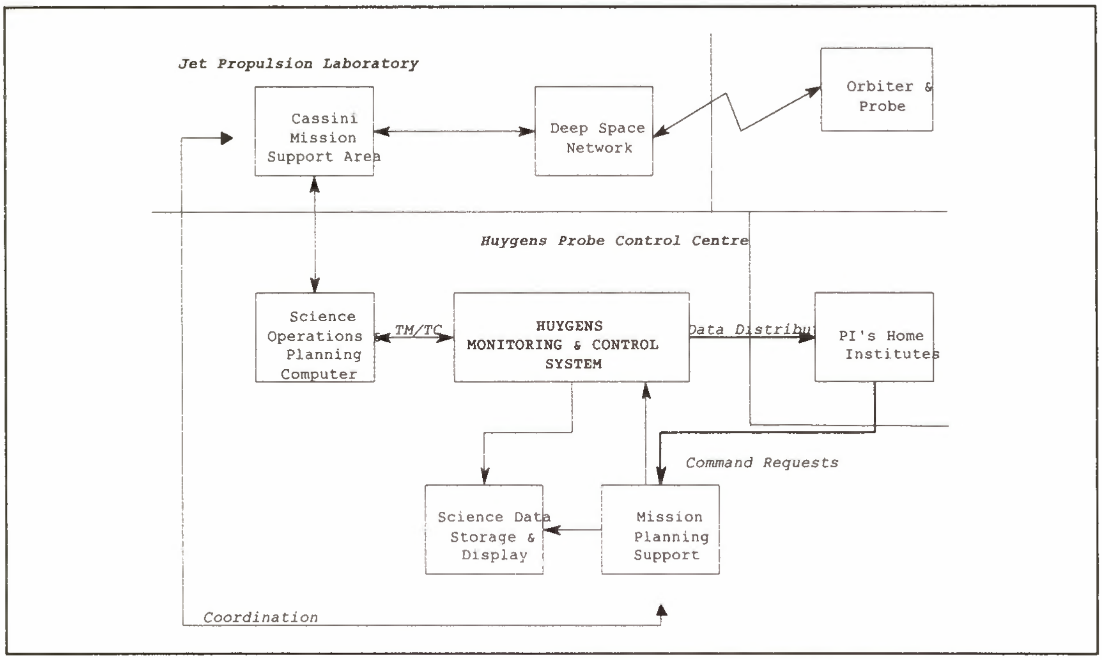

Fig. 3. Overview of HPOC Functionalities

Also part of the Huygens Probe Operations Centre, closely related functionally to the mission planning support, are:

- **The Probe Simulator** to be used as the primary validation tool for operational procedures, as well as for training purposes of the flight control team;
- **The On-board Software Development Environment** to be used to develop/maintain the on-board software and to validate new or modified software at sub-system level, before creating the relevant software update procedures, which will in turn be validated at system level by using the probe Simulator.

6. PROBE OPERATIONS

During the cruise and Saturn orbit phases power for the check-outs is provided by the Orbiter. During these phases, when the probe is controllable from ground by telecommand, carefully designed command sequences will be used, to test the health status of the probe and instruments and to perform either a simulated descent sequence or any special instrument calibrations, as required.

The probe is designed to perform its mission (the descent to Titan) autonomously, with all the activities driven by the on-board software based upon a set of tables pre-defined for producing the "best" mission output in the nominal and failure cases. The Probe checkout is designed to demonstrate that the probe subsystems and instruments are completely fit to support the mission (or otherwise!).

Between the preparation of the commanding sequence for a given check-out and the actual reception and analysis of the telemetry data several months may pass. As mentioned earlier, a finalised probe commanding sequence for a given check-out period will usually be transmitted to JPL two months before its execution time. It may then take up to a week after the check-out execution, before a suitable deep space network pass can be used for downlinking the probe-produced telemetry. All the operational activities must be defined and properly planned with these constraints in mind: the planning and generation of any probe checkout and of the final probe release/data relay sequence is a co-ordinated effort between Cassini and the Huygens operations teams.

Figure 1 illustrates the process for scheduling, generating, validating, and radiating sequence programs to the orbiter's control and data management system which, upon execution, control probe activities.

7. CRUISE PHASE IN-FLIGHT PROBE OPERATIONS

The probe check-out operations sequence can be modified by ESOC as required: it may be routine, or some anomalous behaviour in the probe or instruments may have to be analysed and resolved. In principle, the functional sequence described below applies to all the check-out periods including that for pre-separation, although here there are some extra activities, described below. The preparation activities will define the objectives of the check-out and how to achieve them: this includes any special requests of operations for any instrument, as well as operational activities related to the investigation and solution of possible contingencies arising from onboard anomalies in the probe, probe support equipment or instruments.

To achieve the most efficient use of the check-out periods allocated to the probe in the Cassini Mission plan, the following inputs will be needed at T_{up} - 3 months (**T_{up}** = the time of uplink of the Cassini telecommand sequence):

- **Cassini Mission Planning** this contains the operations plan for the Orbiter around the time of the check-out, and will be needed for co-ordination purposes with JPL.
- **Probe Activity Requests** containing any requests for operations to be performed during the applicable check-out period.
- **Instrument Activity Requests** containing any requests for special operations on the on-board instruments to be performed during the applicable check-out period.

The check-out operations sequence is illustrated below.

- T_{up} - 2.5 months: Based on the data above, a check-out operations plan for the check-out period in question shall be ready. From the check-out operations plan, the relevant command schedules will be produced and validated at the subsystem and system level, including by simulation;
- T_{up} - 2 months: The finalised telecommand schedules will be converted into activity sequence files and made available to the Cassini data processing centre

- JPL will then merge the Huygens activity sequences into an overall Orbiter spacecraft sequence file; this file will be validated by ESOC, for the part relevant to the probe, and a "go/no-go" decision to uplink it will be taken. The generated Huygens probe system telemetry (both probe housekeeping and instruments raw scientific data) will be routed to the Cassini Orbiter, which relays it to the Orbiter Control Centre for archiving.
- As soon as possible, ESOC will access the JPL Cassini data processing centre to retrieve the probe telemetry for subsequent data processing and archiving and distribute the raw scientific/calibration data to the scientists. Verification of the proper reception on-board the probe of the uplinked telecommands and their correct execution can be done at this stage, based on the analysis of the relevant produced telemetry:
- Probe performance evaluation and possible failure recovery analysis will be performed, based on all the available data (including previous checkouts) to evaluate the state of the probe system and to prepare a recovery action for any anomalies that might have arisen.

8. PROBE RELEASE

The **Saturn orbit phase** will require reaction times of the order of days rather than months as for the cruise operations phase. Apart from two standard check-out periods, just after the ring-plane crossing and before the probe release there will be some special tasks to be performed.

The probe has to rely on on-board batteries after release. These are $Li\text{-}SO_2$ primary cells, which must be depassivated by applying a controlled load for a few minutes to each one. This is a critical activity, because of its non reversibility, and should be performed as close as possible to the actual probe separation, in order to minimise the impact on battery capacity. The verification of the success of the operation, on the other hand, has to be performed while the probe is still attached to the Orbiter and commandable from the operations centre. The last probe check-out before release would be too early, and a special operations sequence is foreseen for this activity about one day before release. As a part of the same sequence, the three redundant coast timers will be loaded with the value calculated to ensure that the probe is woken up at the correct time during its descent. Before the probe is released, the content of these timers is monitored on the ground to ensure that they are operating correctly.

A final “GO/NO-GO” decision to release the probe will be taken by ESOC, based on the successful verification of these final operations: in the event of a problem, the release would be aborted and postponed to the orbiter's second flyby of Titan.

The coast phase starts at the separation of the probe from the Orbiter, and ends at the entry into Titans atmosphere at a nominal altitude of 1270 Km; its maximum duration is 22 days. For a detailed description of the entry and descent see Patti (1995)[5].

9. PROBE ON-BOARD SOFTWARE MAINTENANCE

The Huygens on-board software runs in a typical MIL-STD-1750A microprocessor environment and is configured in its operational form before launch. It is composed of the following two parts:

- PROBE ON-BOARD SOFTWARE: the main purpose of the probe on-board software is to execute the Huygens mission according to a pre-defined timeline, collect and format telemetry and, before probe separation, to respond to telecommands. It resides within the probe command and data management subsystem.
- SUPPORT AVIONICS SOFTWARE: the main purpose of the main purpose of the support avionics software is to provide a means of communication between the Orbiter and the probe. It resides within the part of the probe system that remains attached to the Orbiter.

The on-board software has been designed to be reprogrammable; indeed, in case of anomalies, software updates may be required as part of the contingency resolution. A software development facility will be used for the maintenance of the probe software and its validation at subsystem level: its validation at system level is performed by means of the probe simulator which includes hardware emulators for the on-board processors. Once the validation process has been satisfactorily concluded, the software update will be archived and prepared for uplink to the probe; the final step will be its on-board verification by means of analysis of the appropriate telemetry. Instrument software maintenance is done by the relevant principal investigator: ESOC has, however, the responsibility to verify that these updates do not affect the probe at system level and, once this point is cleared, to uplink them to the probe for delivery to the relevant instrument.

After launch, any modifications to the software code will be done by software patching. This process involves loading a patch into EEPROM by telecommand. This stored patch is accessed only at the next power on of the processor, when it is applied to the main RAM.

A new on-board memory image, containing the patch will be generated using the Software Development Environment, and passed to the HMCS where it is used to produce patch commands by comparison of the new image with a reference image of the on-board software. The HMCS provides utilities for the storage, management and configuration control of images, generation of patches and processing of memory dumps (including comparisons with stored images).

10. CONCLUSIONS

The complexity of the control system — in its various aspects of ground system, operational strategies and procedures, as well as operational tools — needed to guarantee safe spacecraft operations and maximum scientific return have been described for the Cassini/Huygens mission. The implementation of this complex system is on-going at JPL, for the Cassini part, and at ESOC for the Huygens part. It will allow both flight control teams to manage the mission and to cope with its particular constraints and characteristics: especially, those arising from the impossibility to have a real-time-type of interaction with the spacecrafts and from the autonomous nature of many of their on-board control systems.

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Track 2 – Ground Segment Engineering & Architecture

Track Manager: E. E. Lijphart (ESA/ESOC)

SPACEOPS96 TRACK 2:REVIEW

Ground Segment Engineering and Architectures

Address at the Closing Plenary Session of 20th September 1996
by

E.E. Lijphart
ESA/ESOC

Ladies and Gentlemen,

Let me commence with expressing my gratitude to all the authors of the papers presented in this technically oriented Track. But I would like to also extend my thanks to all those who have submitted abstracts for this conference.

Selection process, Organisational lessons

Indeed, the competition for selection has been hard; and relatively much harder in this Track, than on average in SpaceOps 96. As can be seen from table 1: Out of 9 Tracks, Track 2 collected more than 25% of all the submissions. And although an unusually large number of papers were finally selected, for the chairing of which I fortunately got the valued support of Mr. F.J. Lehbruner of DLR, one can see that the selection rate is still considerably below the Conference average.

	Track 2	SpaceOps 96
Submissions	98	367
Selected papers	35	210
	36%	57%

Table 1: Submission and selection statistics

The selection criterion, applied to reject such a large number of, in principle, very interesting potential contributions was an adaptation from the Symposium's motto: "Global Operations for the next Century"; it is printed in the Track description as: "Emphasis is on novel concepts and innovation in architectures, technology and methodology".

Applying this filter, we have been able to accomplish the sad task of rejecting more than 60 proposals. But it has become very clear that a strong desire exists to report on Technical Installations which have been implemented and are being used for the support of Space Missions. Whereas we had to reject most of these for this SpaceOps, I would like to formulate the Recommendation to open more than one Track on Engineering and Architectures for the next Conference, e.g.:

- Mission Control Systems; in this the many technical descriptions ("as built") could be allocated, which some authors somewhat loosely consider to be "architectural" descriptions.
- Ground Segment (Advanced) Engineering, which could then concentrate on innovative concepts.

Classification

In a field of technical disciplines, as wide as "Ground Segment Engineering and Architectures", one must expect to have many very different technical subjects addressed. Wishing to compare equal to equal in the selection process, the abstracts were allocated to groups or "Sub-Tracks", as shown in table 2; this provided a suitable means of assessing the merits of papers.

The sequence of presentation was selected accordingly, in order to allow the audience to attend a group of presentations of their particular interest.

Sub-Track	Papers
Overall Ground Support Systems	3
Control Centre (distributed) architectures	7
Control Centre specialised Sub-Systems	3
Networks & networking	6
Ground Stations	5
Engineering & methodology	4
Other (Including 3 papers on user support systems)	7

Table 2: Sub-Tracks and number of papers

In general the presentations were quite valuable in presenting technical solutions and triggering discussions and the interest by the audience was encouraging (except for the Wednesday afternoon speakers, who were deprived of their audience by a simultaneously organised guided tour of DLR).

There were two "no-shows". I find this not only disappointing but quite unacceptable: Authors who are prevented from presenting their paper and cannot find someone else to do so, should at least have the courtesy to inform the Symposium Organisation. It is my opinion, that professionals, who do not consider this most elementary politeness, should be black-listed for any future conference.
But I hasten to say that this does not apply to the two authors who withdrew in good time, allowing me to re-introduce two of the more interesting papers of this Track.

Highlights

In the ten minutes reserved for this survey, it is of course not possible to discuss all of the 33 papers, individually. And although I have tried very hard to draw some simple, general conclusions, the topics and disciplines covered a too wide field and made such a goal futile. I have therefore decided to take it on me to highlight a few papers, which I found particularly interesting, because they break new ground, introduce novel concepts or described technical work of particularly high quality; this without wanting in any way to mark down any of the other highly appreciated contributions.

The text of the papers can all be looked up in the Proceedings and on the WWW, and below I only indicate the aspects of innovation potential, which make them in my mind something above the ordinary.

SO 2.07 by R. Bane and J. Fox presented the prototyping of a "Virtual Mission Operations Centre", in a very promising approach to reconcile automation for routine operations with on call human expertise for exception handling.

SO 2.16 by T. Yamada put forward a proposal for a very straightforward end-to-end Data Management Protocol, as an alternative to the SCPS, which is presently being considered in CCSDS. As we have been explained in this conference (e.g. in SO 8.04) that "Better" is frequently to be interpreted as "Simpler", this alternative approach merits special attention.

SO 2.19 by W. Hell and G. Theis discussed the studies carried out and the class libraries developed in preparation for an implementation of a Service Management System for Ground Stations. This promises and prepares a practical way for End-Users to employ Ground Networks irrespective of ownership; it should be a valuable contribution to "Global Operations for the Next Century".

SO 2.21 by J. Statman, P. Beyer and D. Hardi describe the modifications applied to the DSN in the rescue exercise for the GALILEO mission, after the High Gain Antenna failed to deploy. In their contribution it is described how all registers of optimisation were pulled, resulting in an outstanding technical accomplishment.

And last but not least:

SO 2.26 by B. Anderson on "Trans-global mission architectures" in which she proposes the introduction of a layered mission operations architecture, as an extension of the ISO OSI model. She proposes the simultaneous design and implementation of Space segment and Ground segment in a parallel layered control; which would carry the promise of removing the presently always returning problems of recovering in the Ground segment from the "*faits accomplies*" established in the S/C design.

In addition,

SO 2.25 by D. Boland, D. Weidow and W. Steger does not, in itself, propose any novel technology but merits special mention as a valuable survey paper on the consequences of the Emerging Technologies on systems' implementation of the future. Each single one of the areas of new technology has been treated also elsewhere in this Symposium. But the attempt to extrapolate these developments into future "Rules of Spacecraft Ground Support" give this paper a special visionary quality, which is worthwhile to study. We shall be looking forward to more work from this group.

Cost-effectiveness

I would, at this point have liked to present a small analysis of the so-called "new" trend in software engineering, which is the increased use of COTS. This is also touched upon in the above paper, which points at the alternative of re-use of internally designed products; to which I would like to add that still insufficient long-term experience exist with re-use of OO technology.

In the short context of the present summary, I must restrict myself to warning against "going overboard" with the COTS: Evolution rather than revolution should be preached. The accepted principle, that for complex support functions one tries to procure sufficiently stable packages from commercial vendors, should see a controlled evolution into provision of application functionality through the use of commercial packages; but avoiding revolution of operational support systems, which might lead to e.g. incorporating packages from vendors, which are likely to exist for a brief period, shorter than the design life of the support systems themselves.

Finally, I would like to make a case for an aspect of cost effectiveness, of which we have not heard a lot in this Symposium; except from ESA's Director General, targetting in his opening address the incompatibility of Ground Systems between Agencies:

With the upcoming of small satellites, an increased need for end-to-end communications support will materialise. In this aspect small satellites have a common characteristic: They are **small,** and thus have small power and small transmitters; nevertheless many plans show quite high telemetry data rates. In consequence, they need large antenna systems infrastructure for their communications to the Earth and with many small satellites it is unavoidable that a bottleneck will be created. (At this point I must make an exception for the scheme proposed in SO 4.16, by D. Zillig et. al., in which an extension of TDRS towards Ka band could provide a link to a Spacecraft carrying a 70 W transmitter; this could be a good option, but that class of satellite is not **really** small).

Rather than building new support networks to remove the bottleneck, it should be attempted to utilise the over-capacity which exists in Ground Stations of ESA/ESOC and other Agencies. The basic agreements for such co-operation are presently being coined in Panel 3 of CCSDS, standardising the (automated) ordering and provision of services to external users.

It is my plea that Agencies should much more actively support these activities, not only theoretically, but

- with development of the systems implementing the agreed schemes,
- with the marketing and public relations activities necessary to make the availability of such services known to prospective users,
- with reasonable charging schemes.

I hope that such an international support scheme could become a noticeable contribution to the cost-effectiveness of Global Operations in the Next Century.

I thank you for your attention.

METEOSAT SECOND GENERATION (MSG) GROUND SEGMENT: CONCEPT FOR THE CENTRAL FACILITY

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ABSTRACT. EUMETSAT is engaged in the procurement of ground segment facilities for the second generation of European meteorological satellites (MSG). The Central Facility will provide an integrated environment for the planning, scheduling, control and monitoring of the entire MSG mission: satellites; ground segment; and the primary missions of earth imaging, meteorological product extraction, image and product dissemination, data collection, and image archiving. It will also support the parallel execution of multiple phases of mission operations: operations preparation; validation and training; planning; operations execution; mission analysis; and maintenance and development. Each phase will be supported by automated tools and a human computer interface tailored to the user tasks of that phase. The core MSG mission control element (which supports centralised planning, scheduling, monitoring and control functions) is based on a conceptual view of the MSG system consisting of *control*, *status* and *event* objects. Planned operations are executed through an automated *schedule*, from which control is exercised at three levels: planned *tasks*, scheduled *activities* and discrete *commands* to remote facilities.

1. BACKGROUND AND CONTEXT

1.1 The MSG Programme

The launch of the first Meteosat Second Generation (MSG) satellite is planned for the second half of the year 2000. The MSG System, comprising the satellites together with a new ground segment, will provide an enhanced service to support the following Meteosat missions:

- Earth Imaging (High-Resolution Visible, and H_2O, CO_2 & O_3 absorption bands) with higher spatial resolution and shorter repeat cycle than the first generation system.
- Extraction of derived meteorological and other products.
- Data Collection from surface or airborne Data Collection Platforms (DCPs) with a significantly increased number of regional channels.
- Dissemination via the satellite of processed image data, derived products, and meteorological data from other sources. This will be a fully digital service, with two distinct schemes (HRIT and LRIT) operating at high (1 Mbps) and low (128 kbps) data rates.
- Secondary Payload missions: the Geostationary Earth Radiation Budget (GERB) mission and the Search and Rescue (GEOSAR) mission.
- Archiving and Retrieval of image data and derived products.

1.2 The MSG Ground Segment

Eumetsat is currently embarked on the procurement of a new ground segment to support the MSG System. Definition of the overall ground segment architecture has identified a number of facilities to be procured and integrated by Eumetsat, as illustrated in Figure 1.

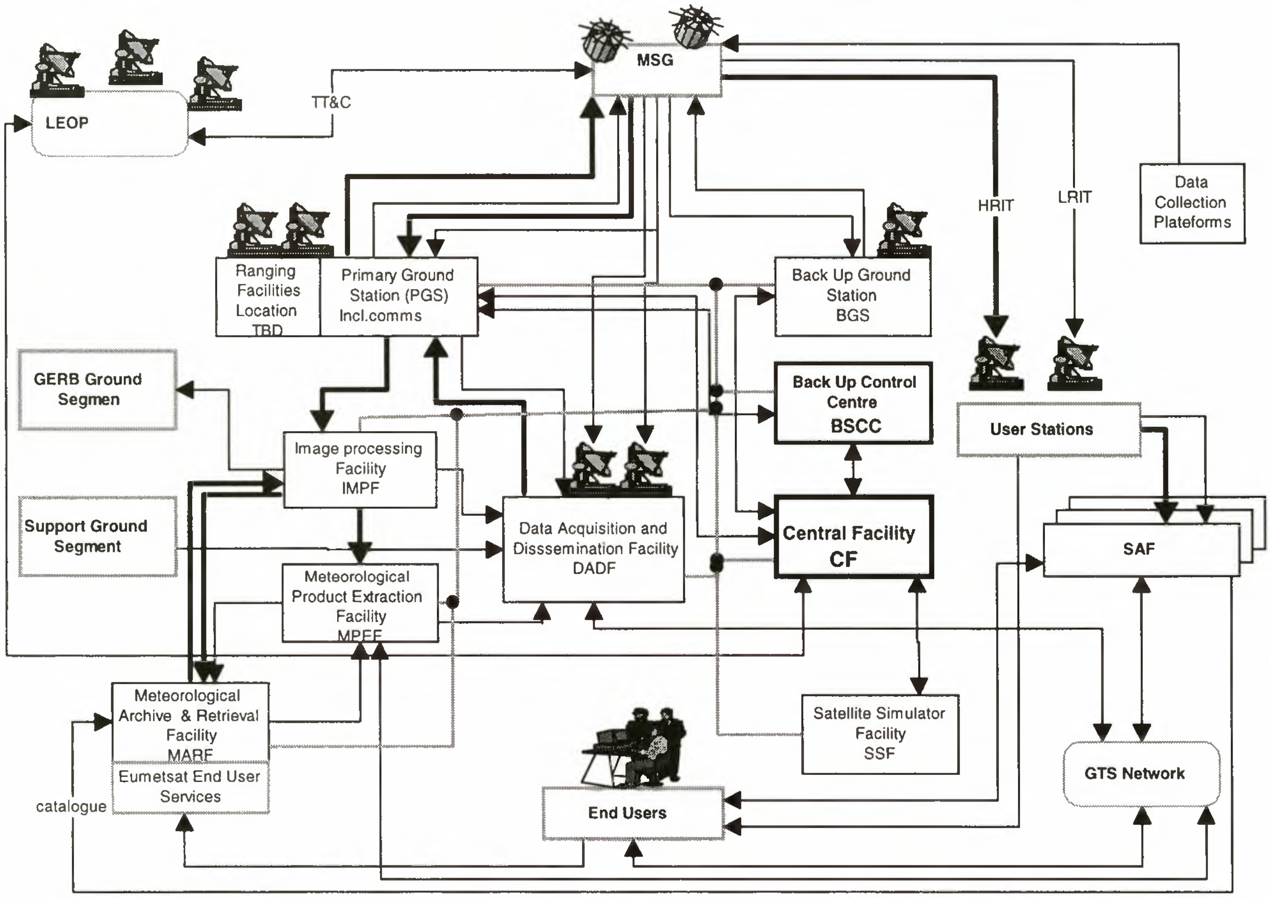

Figure 1: Overall Architecture of the MSG Ground Segment

The facilities to be provided by Eumetsat are as follows:

1. **Central Facility (CF)**: providing support for mission operations, including control of both space and ground segments. The **Back-up Satellite Control Centre (BSCC)** is a component of this facility, located separately to provide site redundancy.
2. **Satellite and Ground Segment Simulator Facility (SSF)**: simulates the behaviour of the satellites and also the ground segment, as seen via the external interfaces of the Central Facility. This will be used to support test, validation and training activities.
3. **Primary Ground Station (PGS)**: provides the primary space to ground interface, supporting satellite TT&C and ranging, Raw Image and GERB data acquisition, DCP Message acquisition, and Dissemination uplink.
4. **Back-up Ground Station (BGS)**: provides site redundancy for the TT&C space to ground interface, in case of unavailability of the PGS.
5. **Ranging Facilities**: provide a distant site from the PGS to support accurate ranging campaigns.
6. **Image Processing Facility (IMPF)**: acquires the raw image and performs pre-processing and rectification; extraction of navigational information; and geometric and radiometric calibration and quality assessment. The rectified image is geo-located and includes quality and status data.
7. **Meteorological Product Extraction Facility (MPEF)**: provides the core functionality of the product extraction mission, for an agreed set of meteorological products. Additional products will

be generated by **Satellite Application Facilities (SAFs)** located at and operated by user organisations.

8. **Data Acquisition and Dissemination Facility (DADF)**: performs the acquisition (and distribution) of DCP data; the formatting and encryption of rectified images and other products as HRIT and LRIT dissemination formats; forwarding of data (including 'foreign' satellite data) for dissemination uplink; and monitoring of dissemination performance.
9. **MSG Archive and Retrieval Facility (MARF)**: provides all functionality related to the archiving and retrieval of images and meteorological products, including end-user services.

The Central Facility will be located within the Mission Control Centre (MCC) at Eumetsat HQ, together with the IMPF, MPEF, DADF, MARF and the Simulator. The PGS and BGS will be located at distinct sites. The Ranging Facilities must be geographically separated from the PGS, but could be co-located with the BGS. The BSCC site will include a copy of the Simulator.

1.3 Central Facility Context

Within the MCC at Eumetsat's Headquarters, the Central Facility will provide an integrated environment for the planning, scheduling, control and monitoring of the entire MSG mission: satellites; ground segment; and the primary missions of earth imaging, meteorological product extraction, image and product dissemination, data collection, and image archiving. It is responsible for routine operation of all other MSG facilities operated by Eumetsat. The Central Facility context is illustrated in Figure 2.

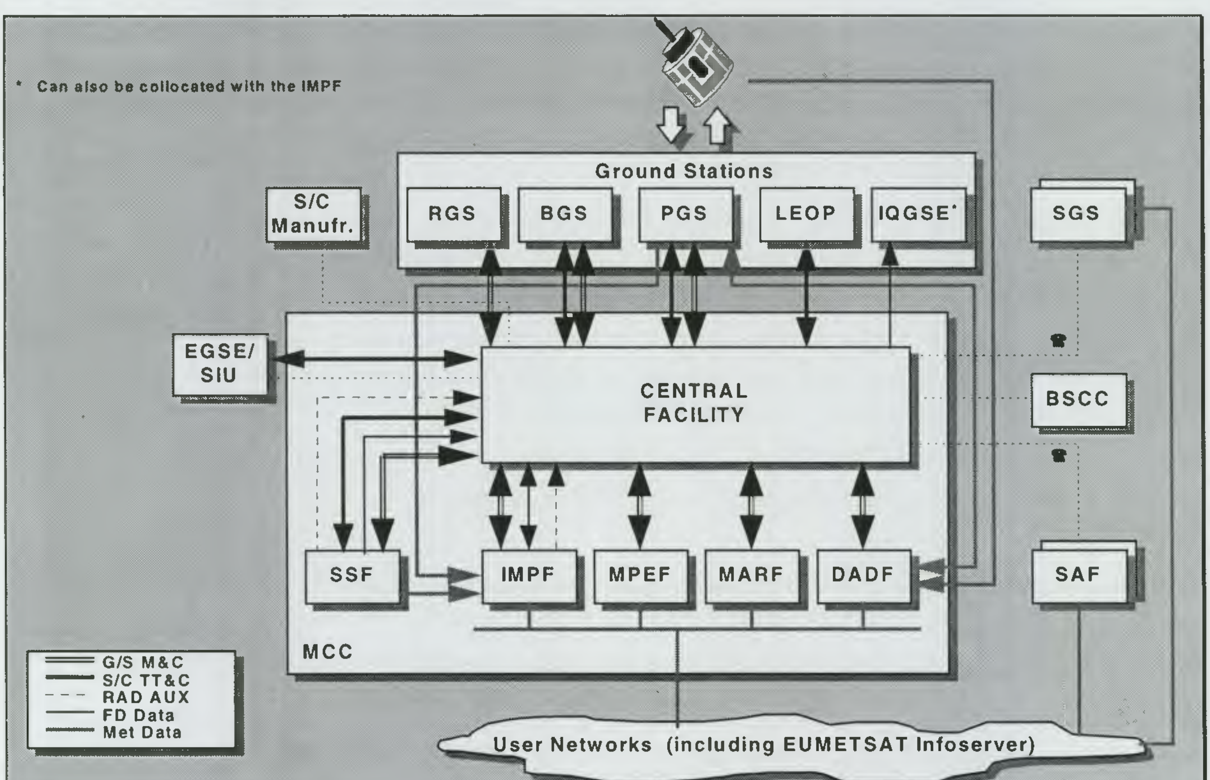

Figure 2: Central Facility Context

The diagram shows additional test and validation interfaces with the satellite check-out (EGSE) equipment, and the Image Quality Ground Support Equipment (IQGSE). Satellite documentation, databases and on-board software will also be received from the spacecraft manufacturer.

2. CENTRAL FACILITY FUNCTION

2.1 Generic Mission Control

The Central Facility forms the hub of the MCC. As such it will provide a single point of control for the entire MSG System (Spacecraft, Ground Segment and Primary Missions), with centralised facilities for preparation, planning, control, monitoring and analysis of mission operations. This includes support for the following activities:

- Centralised Planning of MSG System Operations
- Centralised Execution of Scheduled MSG Space and Ground Segment Activities [Procedures]
- Centralised Commanding of MSG Space and Ground Segment Facilities
- Centralised Monitoring of MSG Space and Ground Segment Facilities
- Centralised Processing of MSG Space and Ground Segment Events [including Alarms]
- Centralised MSG Ground Segment Network Management
- Co-ordination of Spacecraft Ranging and Tracking
- Spacecraft Flight Dynamics
- Operations Preparation (of Operations Plan, Procedures, Databases and on-line Help)
- Configuration Control of Software and Database Versions of MSG Space and Ground Segments
- Operations Data Archiving and Retrieval
- Centralised Performance Reporting and Analysis.

The Central Facility will provide generic mission control functionality, capable of supporting the MSG mission through the following spacecraft operations phases: Operations Preparation; Operations Validation; LEOP Operations; Commissioning; Routine Operations; and De-Commissioning. At any one time, several of these phases may be running in parallel, for different MSG satellites.

The other MSG Ground Segment Facilities will each have local monitoring and control (m&c) capability, but nominally all mission planning and routine m&c will be performed centrally, via the Central Facility.

In order to achieve this, m&c for all facilities, and the communications network, will be managed in the same generic manner. The space-ground interface will follow the ESA Packet Telemetry and Telecommand standards, and also to a large extent the Packet Utilisation Standard (PUS). The m&c interfaces of the ground segment will also be based on exchange of packets. At the most abstract level, each facility will provide Monitor Data and Event Notifications, and respond to Commands.

2.2 Operational Phases

Most discussions of project lifecycles identify an Operations & Maintenance phase. If this is examined in detail, it can be seen that it comprises a continuous iterative cycle of phases, which can exist in parallel throughout the lifetime of the system. A number of Operational Phases can be identified for MSG:

- System Maintenance and Development
- Operations Preparation (Configuration Databases, Procedures and Documentation)
- Validation of Operations (System, Configuration Data and Procedures)

- Training of Operations Personnel
- Planning of Operations
- Execution of Operations
- Analysis of Operations

Each phase has its own specific requirements in terms of functionality, availability, user interface, etc. In the past, it has often been the case that satellite control systems have been designed with primarily the Operations Execution phase in mind. The MSG Central Facility will be required to support all the Operational Phases listed above. Consideration of these phases has had some impact on the decomposition of the Central Facility into *functional elements*, but has also resulted in the identification of a number of physical *environments*, or systems, each supporting one or more operational phases.

2.3 Human-Computer Interaction and the Operations Language

The decomposition of the Central Facility into *functional elements* and *environments* has been driven by the recognition of the existence of a variety of user tasks which require interaction with the system. The Central Facility will provide user interfaces tailored to the requirements of these user tasks. However, it is also recognised that individual users may perform several user tasks. Commonality in the user interface across the facility, and between facilities, is therefore seen as a strong requirement. This is achieved through the specification of a common HCI standard, built upon the concept of generic display types, which define common patterns of interaction with the display as a whole.

Within the Central Facility there are many cases which can be identified, both within configuration databases and during user interaction, where there is a need to specify engineering knowledge which is not purely declarative, but includes complex expressions, derivative, or procedural information. In order to simplify this aspect of an Operations Engineer's interaction with the system, all such information shall be specifiable in a common syntax: the Operations Language.

3. FUNCTIONAL DECOMPOSITION

The Central Facility software is decomposed into *functional elements*, which are distributed and duplicated amongst the environments as necessary. Elements have been identified to support the following functions:

- System Control (Central Facility)
- MSG Control (Space & Ground Segments and Primary Missions)
- Network Management
- Flight Dynamics
- Operations Data Archiving and Retrieval
- Configuration Control
- Operations Preparation
- Performance Reporting and Analysis
- Software Maintenance

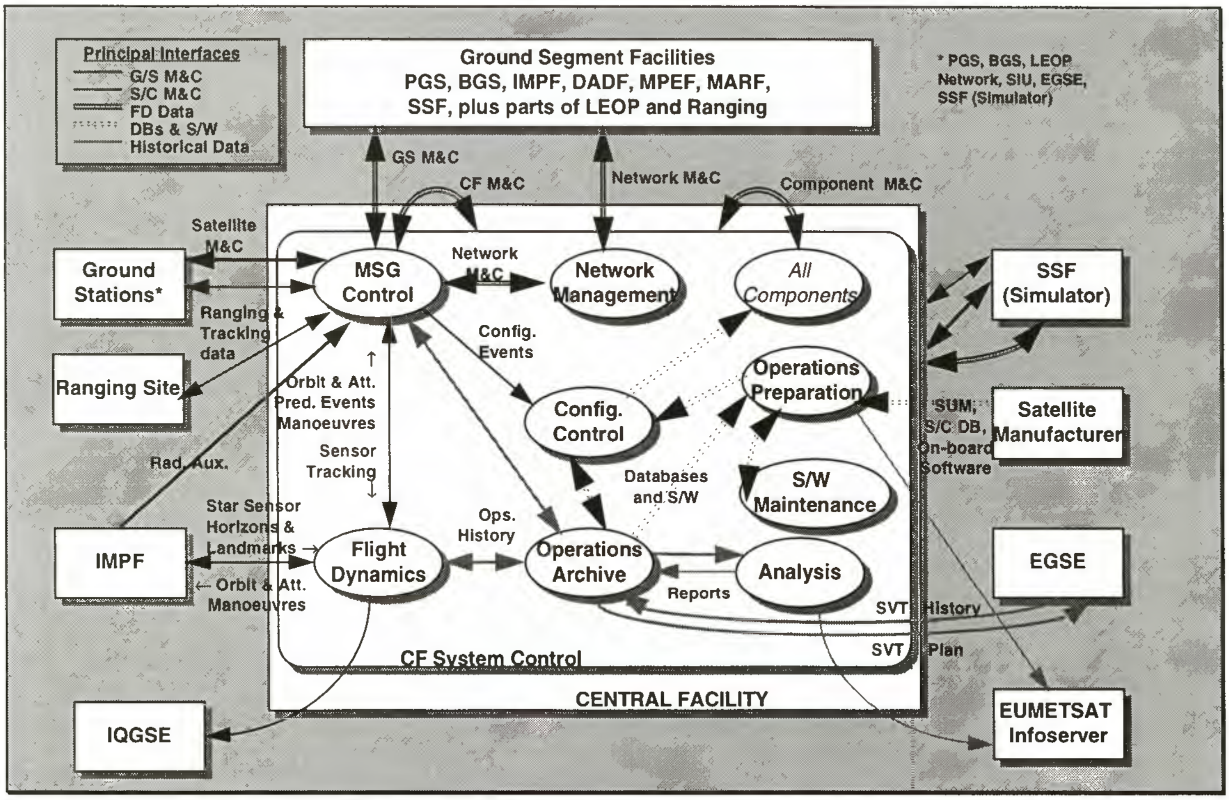

Figure 3: Central Facility Functional Elements

Many functional elements of the Central Facility have counterpart elements within each remotely controlled facility. This results into many commonalities in the functional architecture of all facilities.

4. ENVIRONMENT DECOMPOSITION

Separate environments have been defined to support specific operational phases, or to satisfy the requirements of site redundancy. Fundamentally, three classes of environment are identified:

- **On-Line** environments containing the System Control, real-time aspects of MSG Control, Network Management, Flight Dynamics, Operations Data Archiving and Retrieval and Configuration Control functions.
- **Off-Line** environments containing the Operations Preparation, Planning aspects of MSG Control, and Performance Reporting & Analysis functions. Off-line user interfaces for Flight Dynamics and Configuration Control are also included.
- A **Development** environment providing software maintenance and development facilities for both on-line and off-line environments.

At the MCC Site, there will be two instances of the on-line environment: Operational and Validation & Training. Essentially these satisfy the requirements of the corresponding operational phases. Two instances of the off-line environment satisfy the Operations Preparation, Planning and Analysis phases, and supports the off-line user interfaces for the on-line environments.

At the BSCC Site there will be minimum configurations of both the on-line and off-line environments.

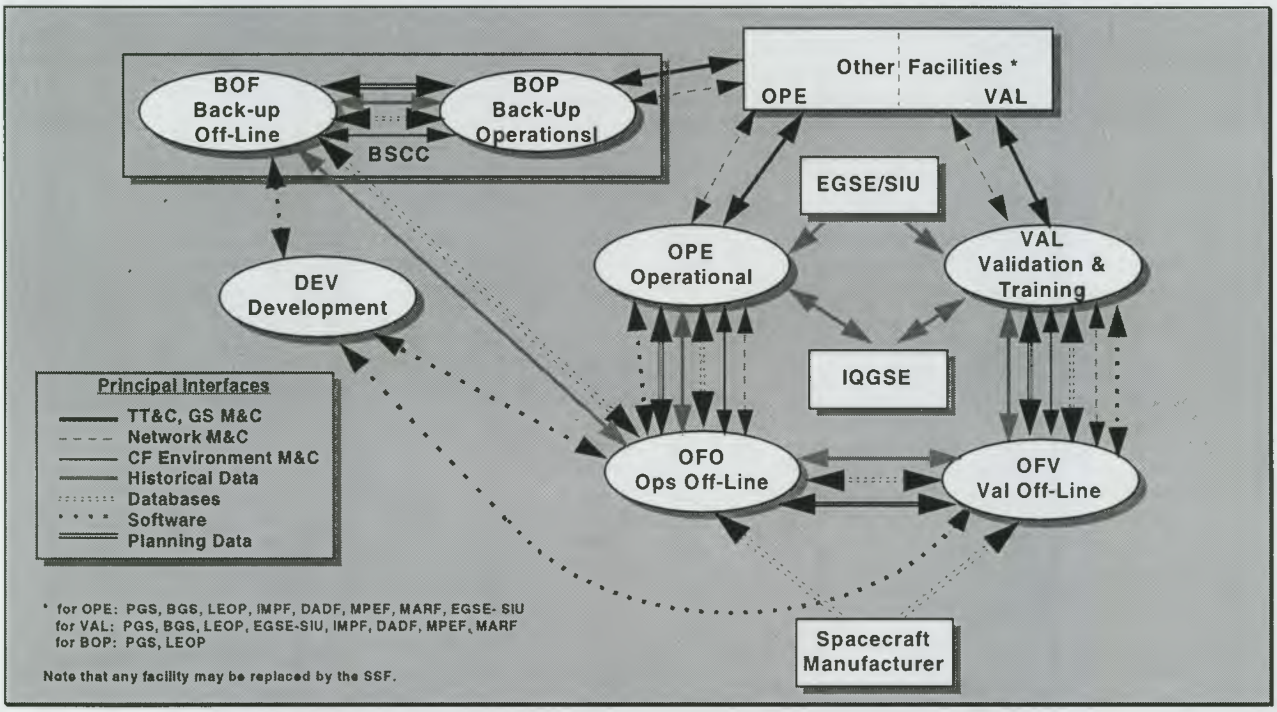

Figure 4: Typical Example of CF Environments Configuration and Interfaces

Each on-line environment will each be capable of supporting the entire MSG System (although in a degraded mode for the Back-up).

The Validation & Training environment will be capable of supporting multiple *system contexts* in parallel. A *system context* defines the timeframe (past, present or future) and set of configuration databases to be applied within the System Control, MSG Control and Flight Dynamics elements. This allows multiple test, validation or training scenarios to be run in parallel using live, recorded or simulated data. Note that the Validation environment will only contain a single instance of the Network Management, Operations Data Archive and Configuration Control elements. The other on-line environments will only support a single *system context* (in the real-time timeframe).

5. MSG CONTROL CONCEPT

The core of the facility will be the MSG Control element, which supports the centralised planning, scheduling, monitoring and control functions. This is based on conceptual view of the MSG system consisting of *control*, *status*, and *event* objects. Planned operations are executed through an automated *schedule*, from which control is exercised at three levels: planned *tasks*, scheduled *activities* and discrete *commands* to remote facilities.

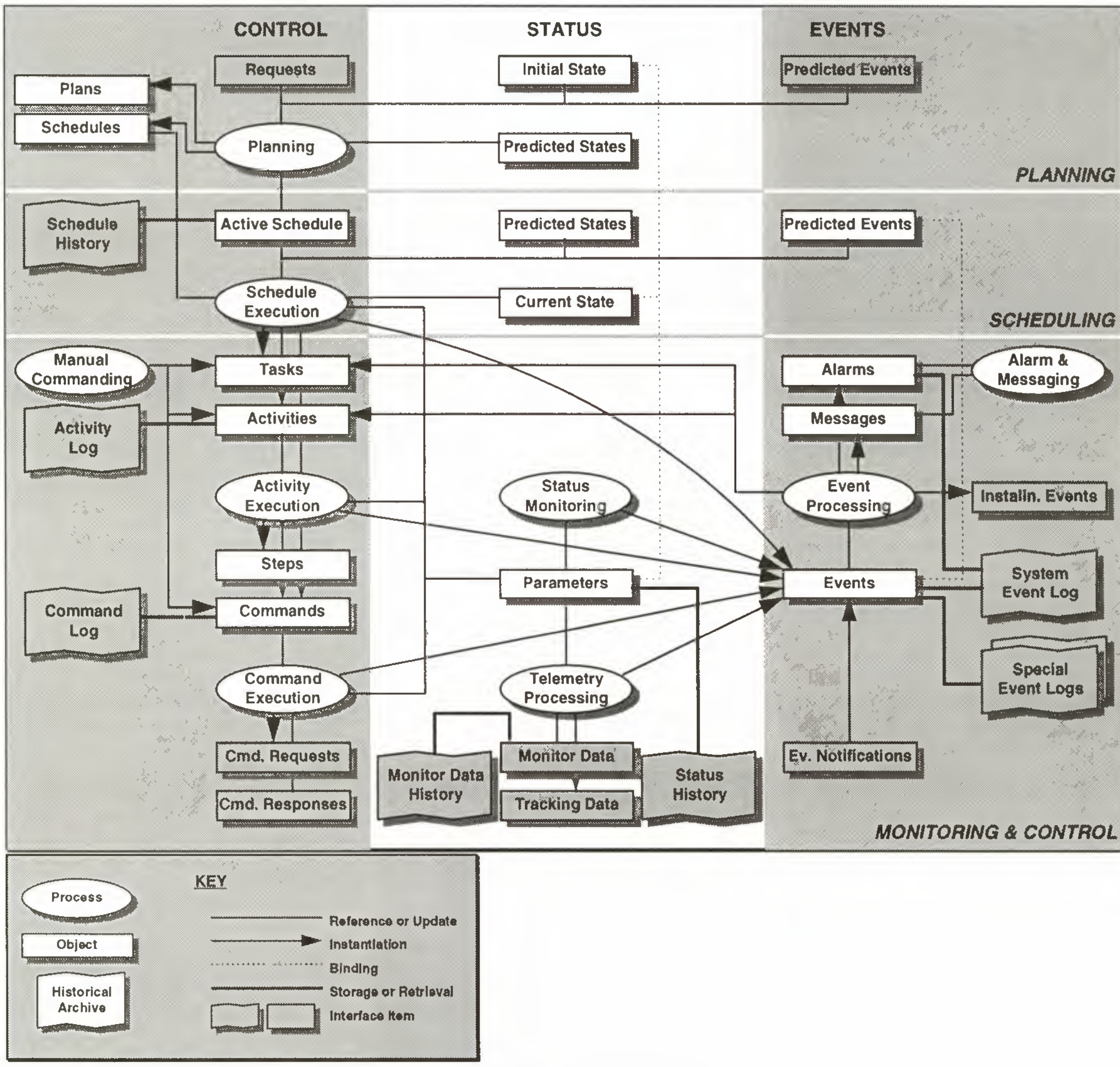

Figure 5: MSG Planning, Monitoring and Control Concept

Figure 5 uses a hybrid representation of both processes and objects to show how closely planning, scheduling, monitoring and control are interrelated. The hybrid nature of the representation means that the diagram should not be interpreted too literally from the viewpoint of any design formalism. The objects in the diagram constitute the context data of the MSG Control element. Each object is a compound structure comprising: static data attributes (eg. description); dynamic data attributes (eg. value, status, validity); and procedural methods (eg. procedure script, derivation expression, verification expression, *constraint* expression, or activity *effect*). All procedural methods associated with the objects in this diagram are specified by operations engineers in the Operations Language. Some objects are persistent, being periodically updated (eg. parameters); others are transitory, being instantiated, existing for a certain lifetime, and then being consigned to history (eg. *tasks*, *activities*, commands, events, and alarms).

Tasks are placed on the plan in response to predicted events (eg. geometric events from Flight Dynamics) and planning requests which may be entered interactively, or automatically by Flight Dynamics (eg. Manoeuvres). *Tasks* correspond to discrete operations, and may act on more than one MSG Facility (Space or Ground). *Tasks* are decomposed into a number of *activities*, which may be automatically executed within a particular *Domain* (Spacecraft or Ground Segment). The placement of *tasks* and *activities* on the scheduled timeline are restricted by a set of *constraints*, which relate *tasks* and *activities* to each other, the execution timeframe, or the status of the MSG System (as represented by an abstracted state vector. This knowledge of *constraints* is not only available at planning time, but is also available to the schedule execution process, to ensure that *constraints* are not violated in real-time. *Activities* also have associated state vector *effects* and predicted durations which can be used during the planning process to predict the evolution of the timeline and state vector and to detect potential constraint violations over the period of the plan. Similarly, this knowledge of *effects* and durations can be used during real-time schedule execution to predict future constraint violations occurring within a limited *schedule horizon*.

The primary control will thus be exercised via the schedule. A dynamic graphical timeline display of the schedule, supporting graphical interaction with the Mission Controller(s) will be a primary tool for monitoring the execution of operations. This will be supported by activity and command level user interfaces, using both text-based and graphical representations of the status of currently executing activities and commands. To support manual commanding, there will still be a command stack interface. Historical control data may be viewed via timeline displays, scrollable logs, or by replaying schedule, activity or command data through the corresponding real-time displays.

The monitoring of status is based on a set of parameters, which are either:

- Direct Parameters received via telemetry
- Memory Parameters containing an image of remote memory or registers, updated either on receipt of memory dump data, or on sending a memory load command.
- Derived Parameters periodically evaluated from other parameters
- Asserted Parameters, explicitly set by the Operator, Activities or Commands

Parameters are subject to checking, both at the individual level, and for the occurrence of compound statuses. Check violations result in the generation of an event. Status data may be viewed through a combination of display formats including tables, spreadsheets, graphs, charts and schematics. The replay of historical data will also be supported with the same display formats.

Events are received directly as notification messages from remote facilities, or generated internally by control and status monitoring processes. The subsequent processing of each event can be configured, and can include: raising an alarm; broadcasting a message; or invoking a contingency *task* or *activity*. Event data may similarly be viewed via timeline displays or scrollable logs, and may be 'replayed'.

It will also be possible to combine control, status and event data in graphical timeline displays, or in a co-ordinated replay session.

Acknowledgment: The authors would like to thank all members of the Central Facility Specification Team for their essential contribution to the detailed definition of the concept presented in this paper.

WORLD-WIDE EXTENSION OF THE JOHNSON SPACE CENTER MISSION CONTROL CENTER

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Lockheed-Martin Space Information Systems, a division of the Lockheed-Martin Corporation, has completed linking the Mission Control Center at the Johnson Space Center in Houston with the Russian Space Agency Control Center in Moscow, to conduct joint operations of space missions.

Performed under the Missions System Contract, Lockheed-Martin worked with the National Aeronautics and Space Administration (NASA) and the Russian Space Agency (RSA) to install and integrate an advanced capability that will enhance data communication and data sharing between the two facilities. In addition, Lockheed-Martin was responsible for training Russian controllers on the new equipment. The entire installation was successfully completed in March, 1996, on schedule, using commercial-off-the-shelf (COTS) products.

This work confirms Lockheed-Martin's commitment to delivering high-performance technology to the global space market. Lockheed-Martin has been working with the foreign participants of the International Space Station since contract inception in December, 1989. Currently the company is in discussions with the Canadians, Europeans, and Japanese to supply them with ground systems for use during the construction and flight of the International Space Station.

REMOTE EXTENSION MOSCOW (REM)

The Remote Extension Moscow (REM), located in the Russian Control Center in Kaliningrad, Russia, a suburb of Moscow, is an extension of the Johnson Space Center's Mission Control Center (JSC-MCC). The REM provides a data link between the U.S. and Russian Mission Control Centers for joint space shuttle and space station operations. With this system, real-time or recorded telemetry data, planning data, and control capabilities can be shared between Houston and Moscow. Operators in Moscow can view the data on displays that are identical to those in use in the JSC-MCC. A file transfer capability for file updates and remote maintenance is also included.

The overall design of the interface consists of a Houston gateway and the REM equipment in Moscow. The following discussion is divided as follows:

1. Houston Remote Gateway Interface Design Concept
2. Moscow REM Design Concept
3. Operations Concept
4. Testing, Installation, and Maintenance.

HOUSTON REMOTE GATEWAY INTERFACE DESIGN CONCEPT

An interface was developed in the Houston JSC Mission Control Center (MCC) to be used as the physical link to the REM in Moscow. The equipment in Houston consists of a server and associated local area network (LAN) and data communications hardware and software connected to the mission control center network. For commonality, the hardware and software used for the gateway are identical to that used in the mission control center. The interface equipment consists of a server, firewall, and two routers. The configuration of this equipment provides not only the data to the external users, but also proper security for the JSC operations environment. (Figure 1)

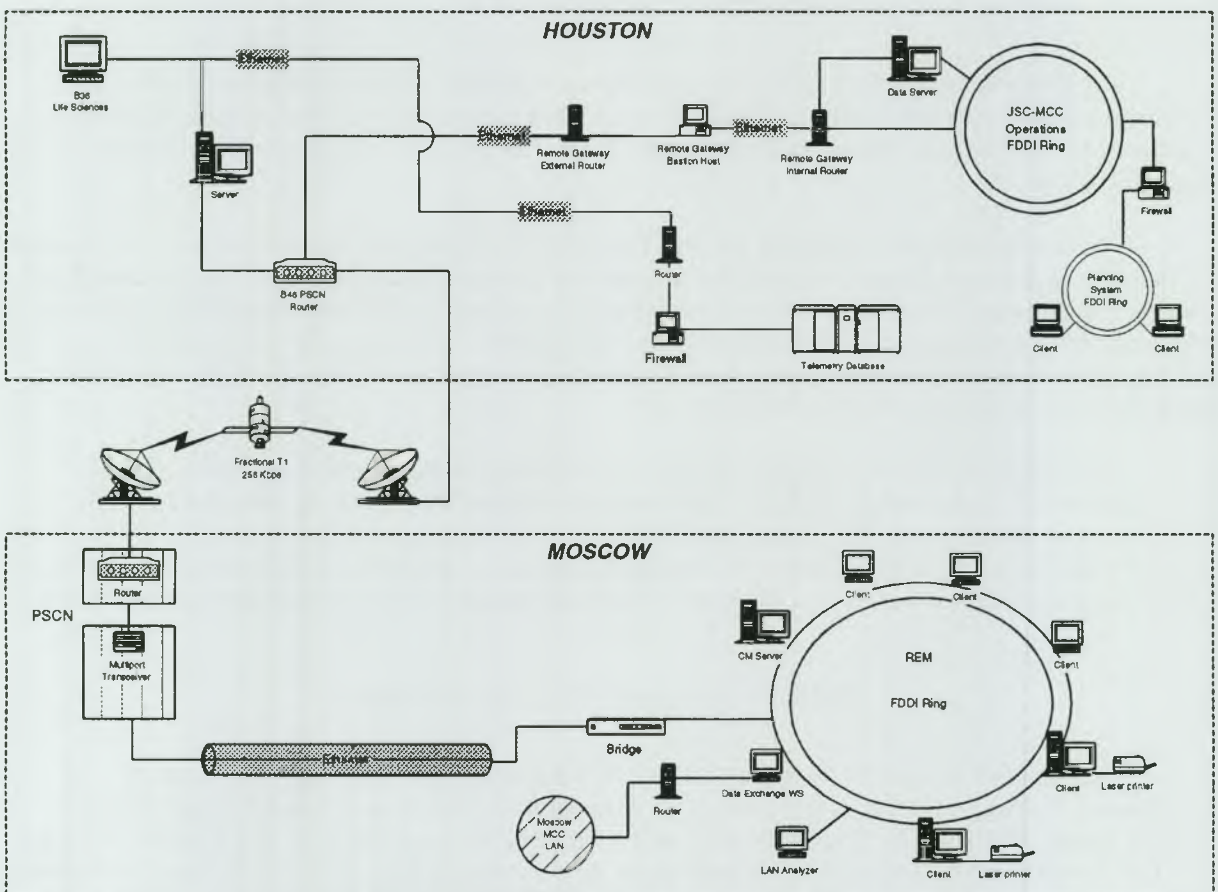

Figure 1. Houston - Moscow Interface

Hardware:

The first item necessary for distribution of data to Moscow was a data server for use as the main gateway interface. For commonality with the workstations in the JSC-MCC, a similar high-end workstation was chosen. This server is connected to the main operations LAN in the Mission Control Center, and can receive all data that is on the network. This allows the flexibility to send to Moscow, or any other external user, any data, (real-time, recorded, simulation, or test) that is available. Conversely, the server can be configured to prevent certain types of data from leaving the control center.

Between the server and the outside world, a firewall was installed. This firewall is a computer utilizing a Unix firewall software product. It is designed to prevent unauthorized entry into the JSC-MCC. As shown in figure 1, the entire firewall consists of the data server, an interior router, an exterior router, and a bastion host. The data server is designed to allow passage of only designated types of data. The interior router allows for packet screening, and source/destination verification. The bastion host is the main proxy application gateway, allowing file transfer and remote login capabilities initiated from JSC. An exterior router provides additional filtering of source, destination, protocol, and port. File transfers are initiated by an authorized user on the JSC-MCC LAN, who initiates a connection to the file transfer proxy on the firewall. This authorized user then performs a file transfer to move files from JSC, through the firewall, to the Moscow clients. The authorized user can get files from Moscow in the same manner, utilizing file transfer and remote login. An additional operations security measure is that file transfer and remote login are enabled only when necessary.

Access to the JSC telemetry data storage and retrieval database is provided via a connection outside of the normal operations environment. This enables external operators to access it without the overhead of JSC operations or the operational environment security measures. A standard JSC software product that provides access to the database is loaded on the REM system in Moscow.

Software:

For commonality with the software in the JSC-MCC, identical operational software is used. When it becomes necessary to update the software in the main JSC Control Center, the gateway interface will be updated as if it were a standard workstation on the JSC LAN. Standard display software is utilized for displaying the telemetry on the remote gateway. These display software products allow the display of plots and tabulations including multi-sample scrolling of data. All main displays are initiated via a display navigator function which is mouse/menu driven. The telemetry displays are used to verify the quality of the data being transmitted to the external user and are identical to the displays loaded on the REM system in Moscow.

Protocol

The protocol chosen for delivery of the telemetry data to Russia is Information Sharing Protocol (ISP). This is a change-only protocol that is widely used in the JSC control center. The advantages of the ISP protocol are assured delivery, based on Transport Control Protocol / Internet Protocol (TCP/IP), and the inexpensive nature of utilizing a product already in use at JSC. The disadvantage of using ISP is the several layers of specific network communication software in both the host and remote locations that must be properly synchronized before data can be sent to the REM. There is a plan to update the external interface protocol in late 1996 to a TCP/IP protocol with industry-standard interfaces. This new approach will minimize the amount of synchronization needed between the remote sites and systems in Houston.

Data Communications:

The data transmission method used is the NASA Program Support Communication Network. This network was already available for transport of data to Russia, as well as other external users. A 256 Kb link is assigned to the REM for bi-directional telemetry data flow. It is anticipated that future deliveries will include a standard, secure, T1 link service.

MOSCOW REM DESIGN CONCEPT

The equipment in Moscow consists of high-end workstations and associated LAN and data communications hardware. The REM hardware and software give the Russian Space Agency fast, reliable, and cost effective equipment for monitoring telemetry information during docking missions between the Space Shuttle and Russian MIR Space Station, or for future Space Station operations. On this system, operators can work in Moscow and receive space shuttle or space station telemetry data from Houston, just as if they were working in the Mission Control Center front room at the Johnson Space Center in Houston.

Hardware:

In Russia, the desire was to store, manage, and establish the software configurations of the client workstations in a single location. Therefore, a configuration management server was needed. For operator use, five client workstations were provided, with either one or two monitors (Figure 1). An additional workstation was needed for use as the interface to the main Moscow Control Center LAN. The LAN utilized for the REM in Moscow is a dual attached FDDI ring. A router is used to interface with the outside network, and another router is used to attached to the Moscow Control Center LAN. This LAN equipment is housed in a single location in an industry standard rack. For maintenance and development purposes, a LAN Analyzer is also provided.

Software:

A subset of the software from the JSC-MCC is utilized in the REM for commonality. The software utilized to display the telemetry consists of the same standard display software in use at JSC. Enhanced security software is included to provide security audit data to the system administrator. This package helps prevent unauthorized access into the REM, and enables the local operators to manage their local security polices and procedures. Real-time software advisories are provided on each operator workstation. Operating system clocks are distributed within the REM locally via a network time protocol service.

Moscow LAN Interface Software:

Lockheed-Martin was given the challenging task of creating a telemetry interface to the Russian Mission Control Center in under 9 months. Lockheed-Martin began by using a document written by a Russian ground system specialist. This document defined a protocol for the transfer of telemetry data inside Consultative Committee for Space Data Systems (CCSDS) packets (Fig 2). Using this protocol as the framework for the software design, Lockheed-Martin took existing MCC-Houston capabilities and created about 25,000 lines of C code to bridge the gap. This bridge consisted of five unique applications:

Parameter Number	Transmit Mode	Parameter Type	Dimension Number	Parameter State	Parameter Time Value	Parameter Value
Bits- 16	4	4	8	4	28	64

Figure 2. Russian Data Packet

1. The first application developed was an X-Motif based reconfiguration tool. This reconfiguration tool was created to allow users to change and/or enter the new parameters they wish to receive from the Moscow LAN. This tool allows changes to be made to the telemetry system in a very quick and easy manner. Reconfiguration of ground systems is an activity that is often underestimated when building any ground based telemetry system. This tool helped minimize the problem.

2. The second unique application developed for the telemetry interface was the CCSDS Packet Repeater. This application has the capability to take a single TCP/IP connection that is receiving CCSDS packets and to make it available to up to 10 clients. This application was also written to log all data being received from the Moscow LAN. Operationally, a single CCSDS TCP/IP telemetry stream from the Moscow LAN is received. The Packet Repeater is then used on the workstations in Moscow to divide that stream into the telemetry applications there, and to route the data back to Houston via the external network. Houston receives and processes the data by having a second Packet Repeater in Houston connect to the first repeater running in Moscow.

3. The third unique application developed reads in the CCSDS telemetry packets from the Moscow LAN and converts the telemetry data contained within to ISP traffic. This turns the Russian telemetry into LAN traffic that the U.S. systems can process and display. It was within this application that the protocol was used to run necessary calibrations on the Russian data. This application made the Russian data available in real-time to flight controller displays.

4. The fourth unique application developed was for non-real-time viewing of the Russian data. This is an X-Motif delogger that has the capability to pick apart the recorded CCSDS packets and provide print-outs (scrollable reports in a window) at the request of the flight controller. In the event a data parameter was not seen, the operator can use this application to go back and get a report of the data.

5. The fifth unique application developed was a Russian Data Emulator. This is a computer program that generates simulated Russian telemetry. This allowed for complete test and check-out of the telemetry system before interfacing with the Moscow LAN. The emulator also has the capability to playback CCSDS packets from a file. In this way, it is possible to do playbacks of the Russian data through the U.S. systems, independent of the Moscow LAN. This application has an X-motif user interface that allows the user to set any Russian parameter to any value.

OPERATIONS CONCEPT

The following is a step-by-step description of the operational concept. The step numbers in the text correspond to the step numbers on figures 3 and 4.

U.S. Space Shuttle Telemetry data sent to Russia. (Figure 3)

1. The ISP symbol dictionary is loaded pre-flight on the JSC Remote Gateway
2. Moscow to Houston fractional T1 communication link is established.
3. REM clients perform the following:
    a. Register with the Network Registration Service to begin communications
    b. Request parameters and supply ISP server on the Houston Remote Gateway with thresholds, filters, callback data, etc.
4. Houston Remote Gateway receives Shuttle telemetry from the JSC-MCC LAN.
5. Houston Remote Gateway recognizes an event.
6. Houston Remote Gateway generates a TCP/IP (ISP) packet. The following is performed:
    a. Packets are output from the Remote Gateway WS.
    b. Packets are sent via a fractional T1 link
7. REM interface receives ISP data.
    a. TCP/IP (ISP) packets are sent to the client that requested to be informed when the parameter/status threshold was exceeded.
8. Client supplies information to applications and services for display.

Russian Telemetry data sent to Houston: (Figure 4)

1. User logs-in and selects activity at the Houston Remote Gateway and REM workstation. Software and configuration files are Network File Service (NFS) mounted.
2. User starts the Russian Packet Processor (RPP) and the REM ISP Server registers with the Moscow Control Center LAN.
3. The Houston ISP Server application on the Remote Gateway registers with the LAN in Houston.
4. Clients connect to the applicable ISP Server.
5. Russian CCSDS packets start arriving from the Moscow Control Center LAN.
    a. Data is converted and delivered to the REM ISP server for display on the Moscow Clients.
6. The CCSDS packets are also sent via the T1 link to Houston.
7. Houston RPP converts data and publishes it to the Houston ISP server for the Houston clients.
    a. If loss of data occurs, the failure is detected by the TCP/IP layer and the RPP attempts to re-establish connection on one minute intervals. Clients remain connected waiting for data.

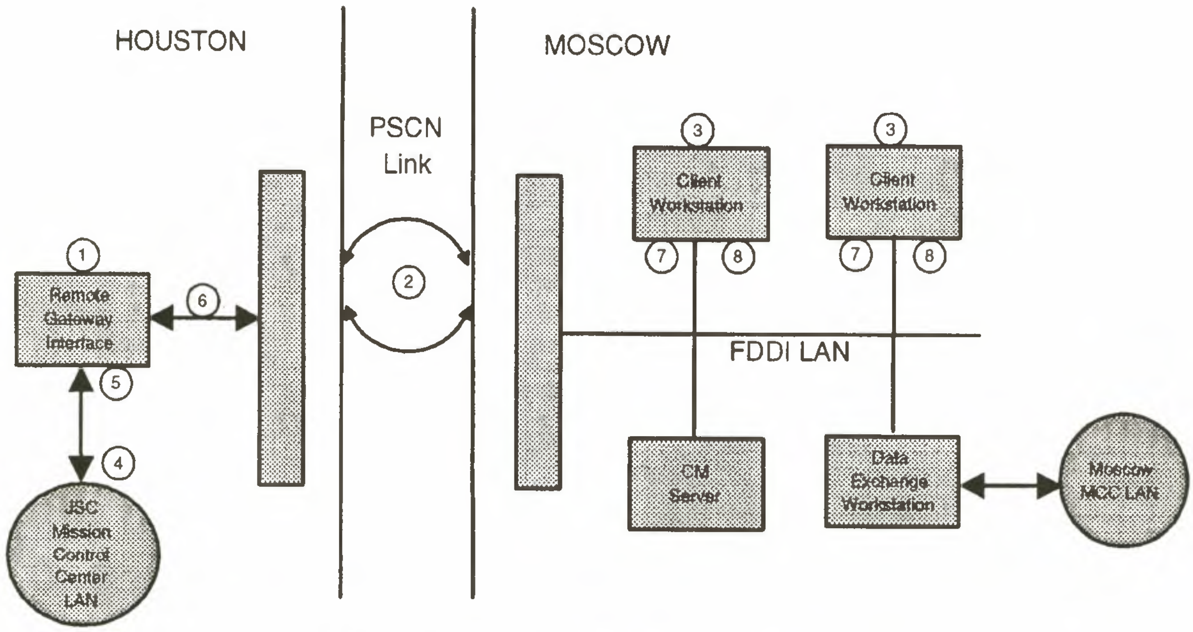

FIG 3. U.S Telemetry Data sent to Moscow

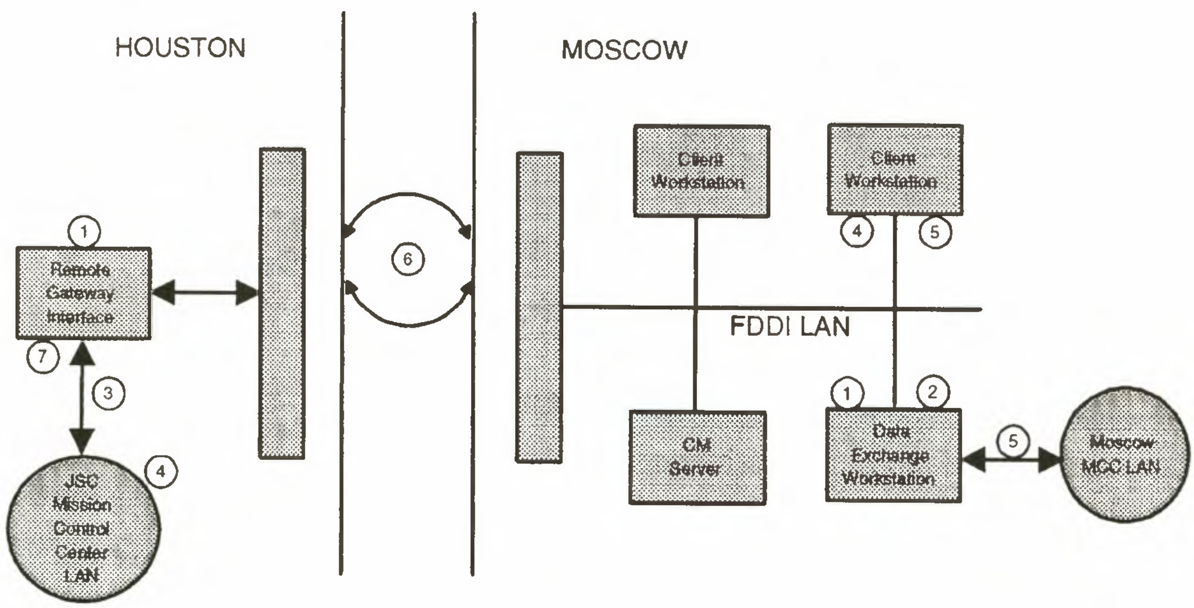

FIG 4. Russian Telemetry Data sent to Houston

TESTING

All testing prior to shipment was done at the main Lockheed-Martin facility in Houston, Tx. Several 220v, 50 Hz generators were utilized to insure all equipment was suited for European power. To more accurately test the system, a T1 link was established from the Lockheed-Martin building in Houston, to the development environment of the JSC-MCC. Therefore, the equipment in the Lockheed-Martin building could realistically simulate the Moscow environment, receiving real-time or recorded data from the JSC-MCC.

INSTALLATION

The REM was installed in Moscow in two phases. The first installation in Moscow occurred in September, 1995. The goal of this installation was to transmit U.S. Shuttle telemetry data to the REM in Moscow. The additional ability to process, distribute, and display real-time Russian Space Vehicle telemetry data in the REM and in Houston, was completed when the second installation occurred in March, 1996. Continuing installations in the late 1996 time-frame will include the ability to distribute the REM telemetry data directly onto the main Moscow LAN, and add a permanent flight planning capability.

MAINTENANCE

In order to provide proper maintenance and configuration control for the system in Russia, it was decided to award a maintenance contract to a single vendor in Moscow for all of the hardware repairs. This enabled Lockheed-Martin to have a single point of contact in Moscow for all maintenance issues. Software maintenance and configuration control is accomplished via a remote login and telnet capability from Houston to Moscow that is available to software developers from the main Lockheed-Martin software development facility in Houston.

THE INMARSAT TT&C GROUND SYSTEM

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ABSTRACT. This paper describes the TT&C ground system used by Inmarsat to control its satellites as it was modified from its earlier stage until its present configuration . After a general introduction on Inmarsat, its space segment and early TT&C ground system the paper concentrates on the modifications required by the third generation satellites and their implementation throughout the final system integration . Finally a short description of current and planned future development is given.

1. BACKGROUND ON INMARSAT

Inmarsat is an international organisation established in 1979 to provide maritime communications via satellite. At present it has 79 member countries and it has gradually expanded its communication services to serve the maritime, land-mobile and aeronautical users on a world-wide basis.

Until the year 1990 the Inmarsat communications had been relayed by specialised satellite transponders operating at L-band and C-band. Those satellites, leased from other organisations and not directly controlled by Inmarsat, can be considered the first generation of the Inmarsat space segment; many of them are still in use today as spares.

The second generation was deployed in the years 1990-92: four dedicated Inmarsat-2 satellites, made by a consortium headed by British Aerospace, were successfully launched and commissioned. The four satellites positioned over the three main ocean regions and the West Atlantic region have been continuously operating satisfactorily, all of them meeting or exceeding their design specifications.

The contract for the third generation of spacecraft was awarded in 1990 to GE Astro (now Lockeed Martin) as prime contractor. Five Inmarsat-3 satellites, which would eventually take over the Inmarsat-2, were ordered, providing greater capacity and improved performance by using spot-beam antennas at L-band. A dedicated transponder at C-band was also included in the Inmarsat-3 design to offer navigation services complementary to the present GPS system. The first Inmarsat-3 was successfully launched and has started the operation in May 1996 over the Indian Ocean Region.

2. INMARSAT-2 TT&C SYSTEM

The ground control system to support Inmarsat-2 satellites was designed and built in the period 1986-89; Inmarsat decided to procure the main elements (equipment, software, services etc.) from different companies, acting as manager, integrator and finally operator of the ground control system. The launch and early orbit operation was contracted out to the French space agency CNES.

The TT&C network comprised four earth stations, a satellite control centre (SCC) and a back-up facility for the control centre. The stations were located in Fucino (Italy), Beijing (China), Santa Paula (USA, California) and Southbury (USA, Connecticut) providing full coverage of the geostationary orbit. Three TT&C antennas in the systems, designated 'multi-function antennas' with dual band feed and higher performance, were also equipped for testing the satellites in orbit (IOT) and monitoring the RF performance in service (CSM).
The SCC was installed at the Inmarsat headquarters in London with back-up at the Fucino earth station.
The local station operators owned and operated under contract with Inmarsat the antennas and associated RF equipment; Inmarsat supplied and owned the baseband, IOT and communication equipment which was maintained and operated by the station operators.
The earth stations and the control centres were connected by a network of leased lines in a redundant configuration with route-diversity. Although several links were of digital type (56 or 64 kb/s), the majority of them was analogue (M.1020) which offered a limited capacity in terms of transmission rate but sufficient to carry the low Inmarsat-2 telemetry rate (320 b/s). All TT&C data traffic was transmitted in packets over the links by the X.25 protocol.

3. INMARSAT-3 TT&C

In preparing for the Inmarsat-3 support, Inmarsat followed the approach adopted with its second generation; in addition, it was decided to conduct the transfer orbit operation from the SCC, using the upgraded network.

Because the TT&C characteristics of the Inmarsat-3 spacecraft are not too dissimilar from the Inmarsat-2, it was recognised that the existing TT&C network could be economically expanded to provide control of the combined Inmarsat constellation.
The same basic architecture was maintained (four TT&C stations with SCC and back-up) and subsystems were to be expanded or upgraded with the following objectives:

- continuous control of a total number of 8 spacecraft positioned in pairs (one of each generation) over the four ocean regions and also support relocation of spacecraft between ocean regions;
- same or better overall system reliability and survivability (global operation not affected by a failure of a station or control centre);
- no interference to the Inmarsat-2 operation during the integration phase and subsequent launch phases;
- minimum time for completing the IOT of each of the new satellites.

In particular, the following were the key technical issues considered for the upgrade and their impact on the system:

- different frequencies used in the uplink and both circular polarisations in the uplink and downlink as shown in figure 1 $\Rightarrow$ modification of the frequency translation and antenna equipment.
- dwell telemetry on a data stream separate from the normal telemetry and modulated on a different RF carrier $\Rightarrow$ additional receivers for dwell telemetry reception.
- telemetry signal with different data format and modulation characteristics (refer to figure 2 for the Inmarsat-3) $\Rightarrow$ dual specifications for the telemetry receivers for sharing equipment.
- more entities to control (spacecraft plus station RF and baseband equipment) $\Rightarrow$ control computer system expansion.

- increased traffic load on the links from the TT&C stations because of more satellites, higher telemetry data rate and more than one stream per spacecraft ⇒ data links with higher throughput.
- transfer orbit operation support ⇒ new orbit and attitude determination programs in the SCC and significant upgrading of the TT&C station equipment used in this operational phase in terms of antenna tracking, telemetry and ranging receiver performance.
- telecommands encrypted by a secure, US Government-approved, algorithm ⇒ interface between the control computer system and encryptor units; also security measures for the encryptors and their set-up.
- handling of emergencies from the SCC during off-duty hours of station personnel ⇒ full remote control of several antenna systems.

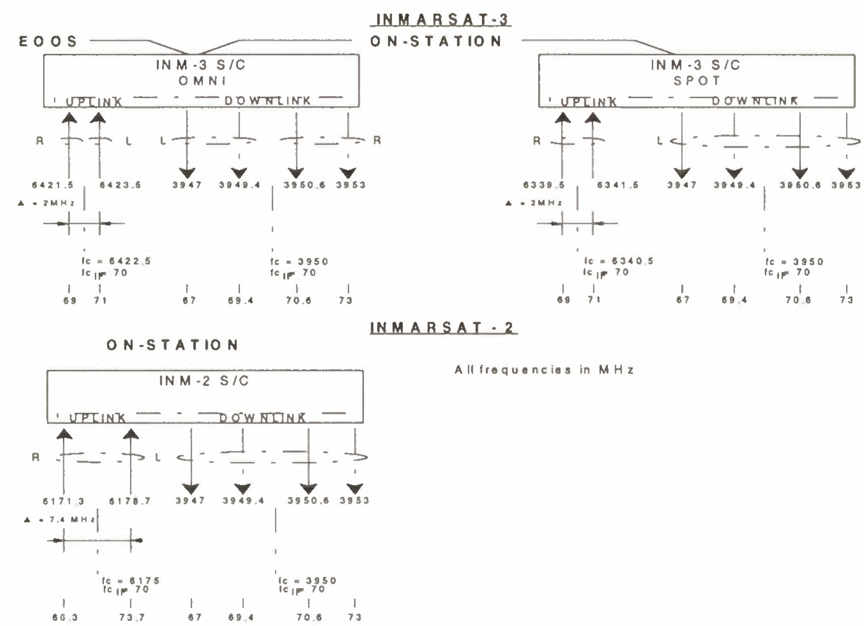
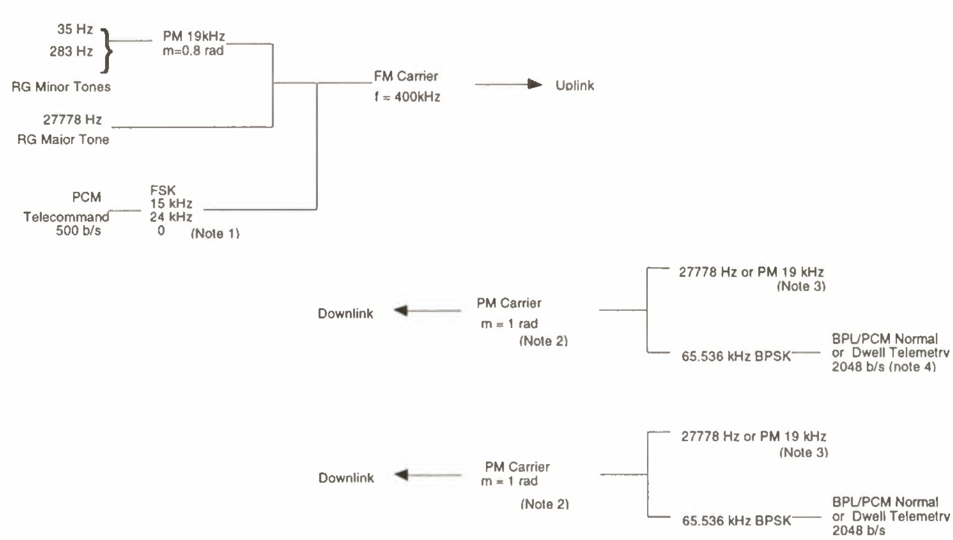


Fig 1: Satellite Modes & TT&C Frequencies



Note (1) : No FSK signal In each half bit interval.

Note (2): m=0.7 rad for each Telemetry and Ranging when simultaneously present.

Note (3) : The PM 19 kHz subcarrier is not further demodulated by the satellite TT&C subsystem.

Note (4) : 320 b/s on 40.96 kHz for Inmarsat-2

Fig 2: TT&C Modulation Schemes Inmarsat-3

The expansion of the control system mainly affected the areas described below.

Communication network
The communication data network was upgraded first; by the time the Inmarsat-3 project began, all the links had been changed to digital type at 64 kb/s and time division multiplexers installed at all nodes providing a flexible and better use of the total available bandwidth. Telephony, for intercom operation, has been accommodated, coded at 9.6 kb/s, on the same links.

Antennas and RF equipment
More antennas were required and if use was to be made of the existing antennas, some upgrade of the frequency capability was necessary. After an open tendering process, the possible scenarios meeting the requirements above were evaluated in terms of overall cost, operation and technical performance and risk associated with the integration. It was decided to retain and expand the sites of Fucino and Beijing and to replace Southbury and Santa Paula with Pennant Point (Canada, Nova Scotia) and Lake Cowichan (Canada, British Columbia) respectively. The new network again provides full coverage of the geostationary orbit as indicated in figure 3.
The stations use antennas of between 8 and 15 m in diameter (G/T of 28 to 34 dB/K and maximum EIRP of 82 to 90 dBW at C-band).

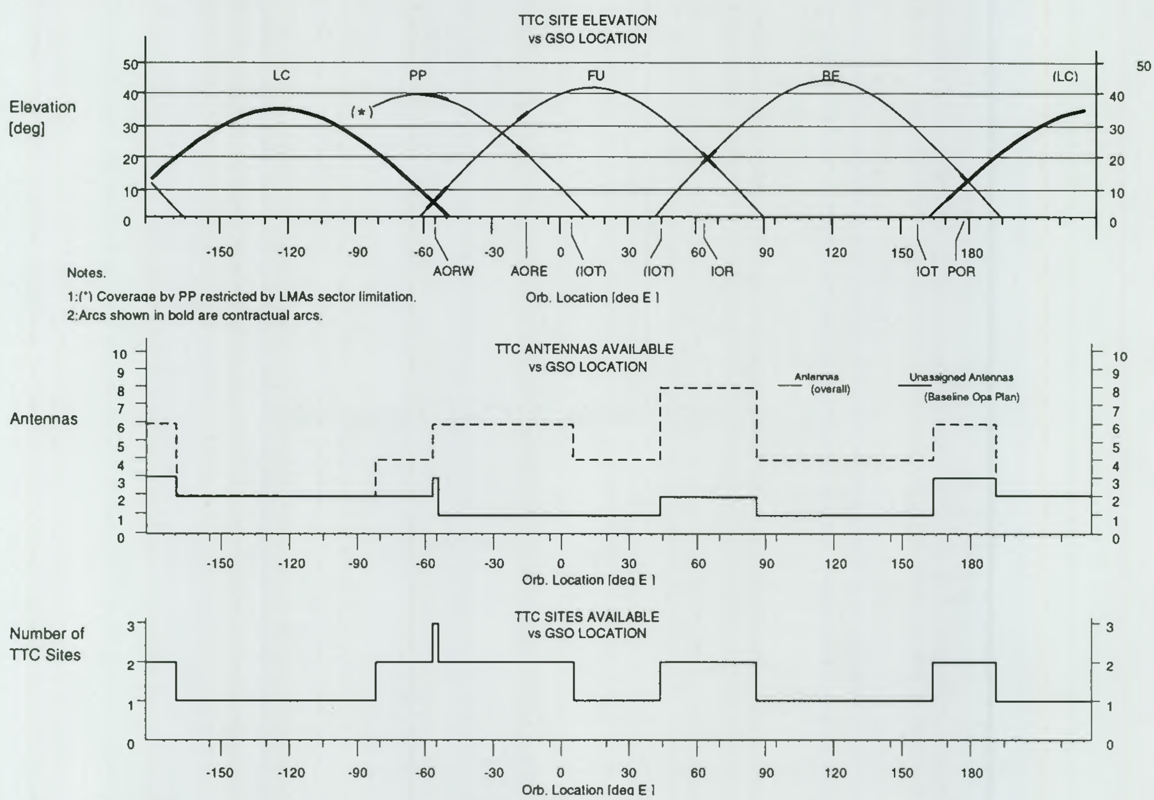


Fig 3: Ground Segment Orbital Visibility

Baseband equipment
New equipment was necessary to handle the different modulation and data format characteristics of the telemetry signals. Advantage was taken by the availability of DSP-based receivers that allowed telemetry of different characteristics to be processed by the same hardware by downloading appropriate software. Instead of operating two different sets of baseband equipment it was decided to use eventually only the new equipment, in an augmented

configuration, for operating both generation spacecraft. After the integration phase the old equipment was removed from the system.

<u>IOT equipment</u>
The basic IOT system was retained in terms of test instruments, but it has been necessary to upgrade mainly the control computer, peripherals and programs in order to achieve a faster execution of the tests and facilitate the analysis of the results. Of the three existing systems those at Fucino and Beijing were upgraded while the system at Southbury was dismantled and used as spare.

<u>Control centre computer system</u>
The existing hardware was upgraded to provide more capacity and extensive new software was written in-house to cover the new requirements (eg dwell telemetry, telecommand encryption support etc.). The number of entities to be controlled was reduced by merging the remote station RF and baseband equipment data by a new front-end processor located at the SCC. A new system for orbit and attitude determination was also developed in-house to be used during the early and on-station orbit phases. In the ancillary subsystems area, the storage/data archive system based on magnetic tapes was changed to an optical discs system

To ensure a smooth transition between the old Inmarsat-2-only system and the augmented system, for several months an interim network was operated as shown in figure 4. During this period, the new equipment was being checked and integrated on-site; at the same time the back-up centre was moved from the Fucino station to the UK near London. The final configuration , shown in figure 5, was established at the end of 1995.

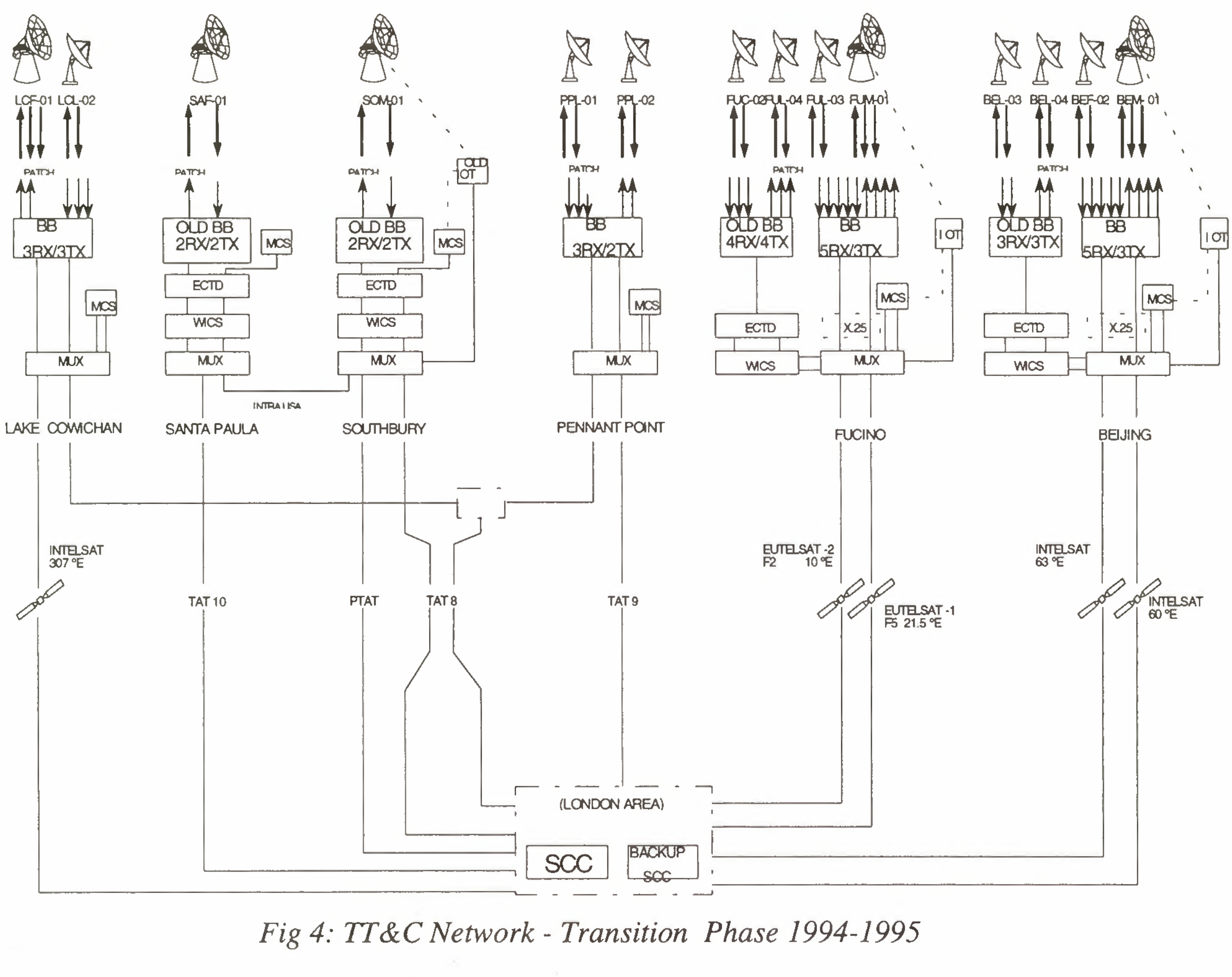


Fig 4: TT&C Network - Transition Phase 1994-1995

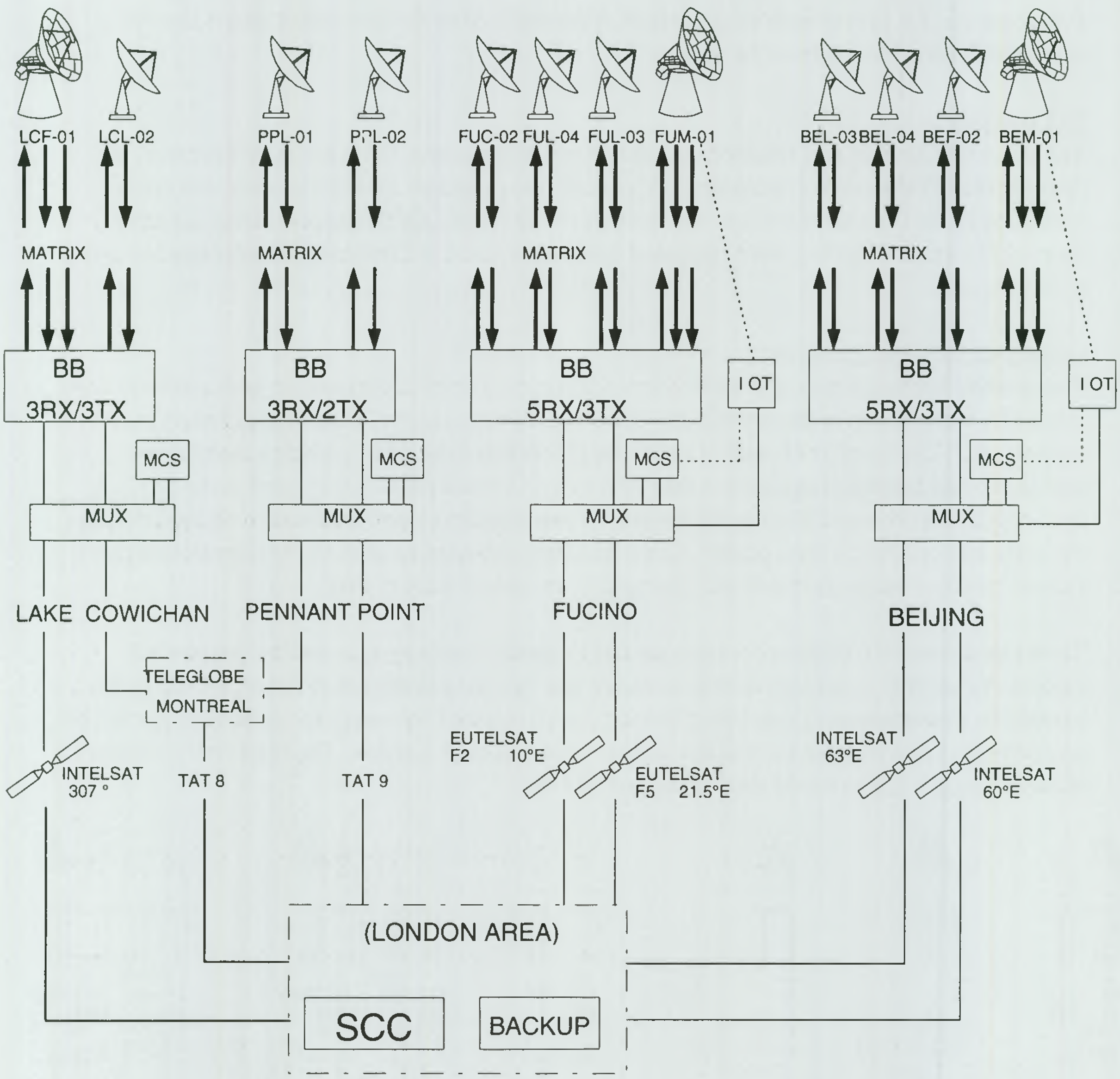


Fig 5: TT&C Network Final Configuration

3. IMPLEMENTATION AND TEST

To meet the tight schedule for completion of the system a Programme Office was established to co-ordinate the various works and activities in the different areas. While the subsystems at the remote sites (antennas and RF equipment, baseband and IOT) were contracted out, most of the work related to the control centres was done in-house with help of external consultants.

Considerable efforts were spent in developing the interface control documents (ICDs): with so many contractors (external and internal) involved in the system it was necessary to maintain tight control of the interfaces. Overall control of the system specifications and configuration was exercised by a Configuration Control Board.

Each subsystem was first tested by the supplier in factory and after installation as part of the acceptance tests in a stand-alone configuration. The various interfaces and their operation were then checked before proceeding to the final system test. The tests had to be carefully planned in conjunction with the ongoing Inmarsat-2 operations in order to avoid mutual interference.

The test tools which have been used in the test and integration phases are described below.

Compatibility test set
A set of baseband equipment to be installed at the spacecraft manufacturer plant. It is used during the checks of compatibility between the spacecraft TT&C subsystem and the ground control software. It is also used at the launch sites for final check-out. It was supplied under the main contract for the baseband equipment.
Dynamic spacecraft simulator
A software program simulating the whole spacecraft installed at the SCC to check the ground control software; used mainly to test the ground control software and for the preparation of control procedures and their validation. It was produced by the spacecraft manufacturer.
'Suitcase' spacecraft TT&C simulator
A transportable equipment simulating the spacecraft TT&C subsystem. It was used at the TT&C station for validating the RF and baseband equipment. Only one unit was produced by the spacecraft manufacturer and it was shipped to the sites as required.
Spacecraft telemetry simulators
Simple generators of spacecraft telemetry data (repeating patterns) built in each of the baseband subsystems. Their use is mainly for checking the telemetry units during maintenance but they were also useful during final tests to load the system with telemetry data.

The objective of the final system test was mainly to demonstrate that the system could handle normal or contingency scenarios without disruption. In this phase telemetry data from real satellites (Inmarsat-2) and simulators were used to load the network while exercising multiple operations.

The evolution of the Inmarsat TT&C system is presented in figure 6.

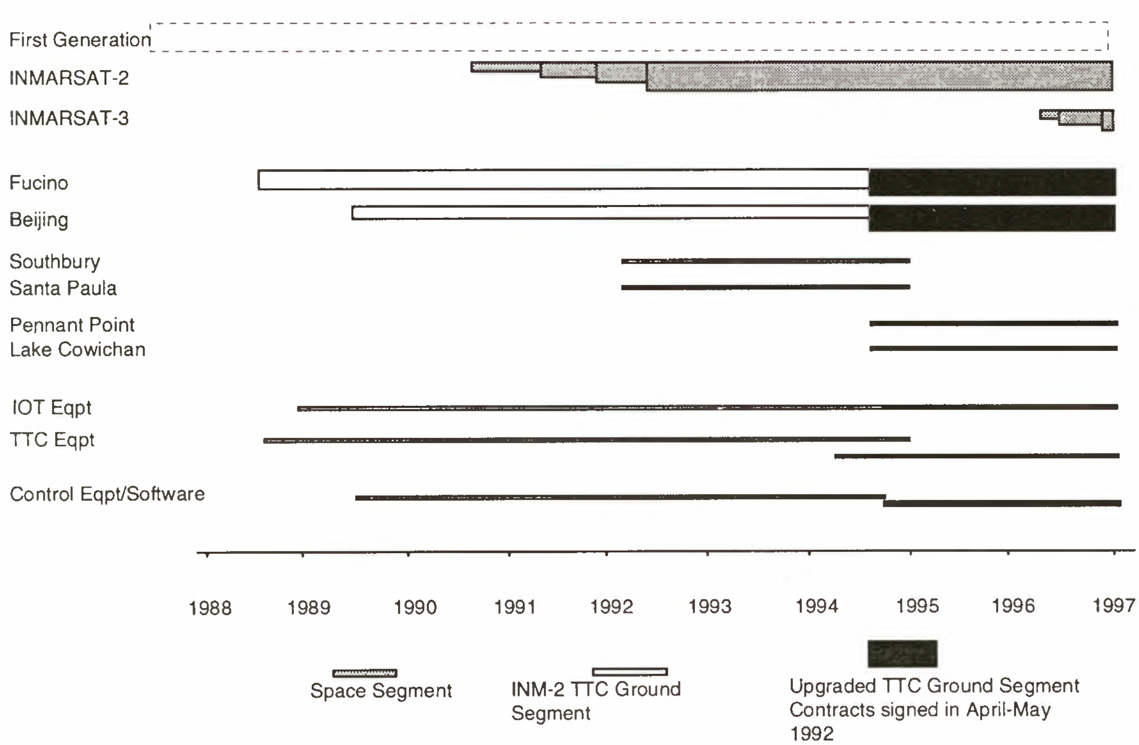


Fig 6: Inmarsat TT&C Ground System Evolution 1988 - 1997

4. CURRENT AND FUTURE DEVELOPMENTS

With the new TT&C ground system in place and operating well, the focus is now on preparing for the remaining Inmarsat-3 launches and economically improving the operation.

Expert System

As the workload on the SCC was going to increase due to more new satellites being put in service, it was decided to have many routine-type operations performed on the Inmarsat-2 handled by an 'expert system'. In this way the SCC personnel have more time to dedicate to the familiarisation with the new spacecraft and concentrate on the critical manoeuvres. After evaluating several commercial products, one was selected and tailored to the Inmarsat needs. The expert system, connected to the main ground control computer, started its operation early this year and more new processes are being developed and added to it. It is planned to have eventually all Inmarsat satellite control routine operations run by this system.

Maintenance

In general, Inmarsat is trying to rationalise the maintenance required by all the different subsystems in operation. As a planning and management tool in this area a program (FRACAS) has been procured to replace the previous Anomaly Reporting Tool (ART). FRACAS will offer a better monitoring of the system reliability and O&M activities.

Fifth Inmarsat-3

There is a possibility that the fifth Inmarsat-3 satellite will be deployed in orbit and there will be nine satellites to control. Some modifications and expansion of the system might be required, depending also on the chosen orbital location of this spacecraft.

Data communications network

As the world-wide telecommunications services evolve, more efficient and less expensive ways of connecting the stations and control centres may become available. Among the various systems under consideration are VSATs, frame-relay packet networks either Inmarsat-owned or contracted out.

MMS GENERIC CONTROL CENTRE FOR TELECOMMUNICATION SATELLITES

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ABSTRACT. During the early 90's, MMS has developed the satellite control centres for HISPASAT and TELECOM 2. Since then, a strong effort has been made in order to improve this product by using an incremental process of development. MMS can now offer a turnkey system for the EUROSTAR satellites including a customised control centre (CSC), a full set of software tools (OPSware) and a flight dynamics package (COSMIC). All the products are operational in the Multi-Mission Control Centre located in MMS Toulouse, France. A new step forward will be made on this development leading to a UNIX based system for the EUROSTAR 3000 platform.

AN INCREMENTAL PROCESS

The development of the MMS Satellite Control Centres (SCC) is based on the idea that the same EUROSTAR platform being used for the various MMS telecommunication satellites, the same SCC can also be used. This has been done for the first time during the development of the Telecom2 SCC which is based on the Hispasat SCC. The main modifications are a new design of the MMI to provide a more user friendly interface in french and a different interface with the mission control centre.

The next step was to provide MMS with a mean to ensure the in-orbit follow-on of the delivered satellites as well as the LEOP operations. The modifications being quite important and the users' needs evolving with the acquired experience, an incremental development process was chosen. This consist in development phases of 6 months maximum performed by a small development team (4 persons maximum). Each phase is splitted into 4 steps:

a) identification of few requirements by the users. These requirements are expressed at high level and detailed during discussions with the developers team.
b) a proposal of implementation at preliminary design level is made by the developers. This propositional is discussed with the users in order to find the best ROI.
c) development of the agreed implementation. A strong interaction between users and developers is still important during this step. It allows to adapt the implementation to the difficulties encountered.
d) validation of the new functionalities. An overall validation to detect potential side-effects and regressions is also performed.

This incremental process has allowed a quick realisation of a SCC fully adapted to the end-users needs. The resulting product is called CSC for Customer Support Center.

An other key point is the high reactivity of the development team. In case of urgent need, the development team has been able to develop light upgrades with a high added value in a few days e.g. the automatic launch of a predefined list of trend analysis at a predefined time with a given frequency. The reactivity in case of anomaly was also a priority.

ARCHITECTURE

The main characteristics of the CSC architecture are the following :

- Distributed architecture on Alpha workstations and servers. This architecture is highly customizable, e.g. it allows to add as many workstations as necessary.
- The OS is OpenVMS
- Communication over Ethernet
- X11/Motif MMI
- Redundancy of the servers allowing the shortest loss of critical functions. Typically less than 5 mn on Telecom2 SCC to a few seconds on Worldstar SCC. The data are replicated using disk mirroring techniques.

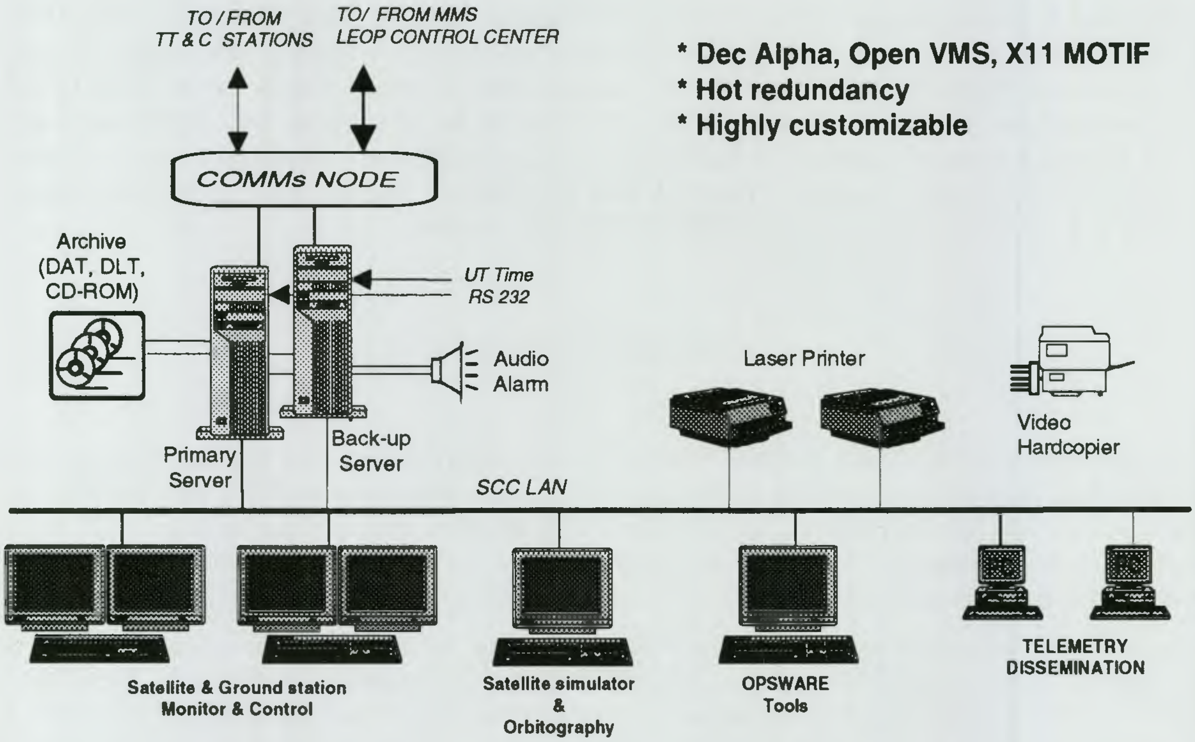

FIGURE 1: Typical CSC architecture

ENHANCEMENTS

In addition to the classical TM/TC/RNG functions, the current version of the CSC provides :

- A configurable number of satellites and operator positions. This is defined during installation of the software on the operational configuration. The available modules of a given CSC may be defined using a licensing system.
- A multiprotocol telemetry and telecommand capability allowing to manage PSS45-46 (CNES, EUTELSAT, INTELSAT) and CCSDS protocols.
- Full compatibility with the software satellite simulator which runs on one of the CSC workstations.
- Flight dynamic package, called COSMIC, for collocated satellites which is operational at the Hispasat control centre.

Dissemination on PCs

A major evolution of the CSC is the capability to access to the main SW functions from a desktop PC or any X terminal linked to the server via an ETHERNET Network. This is a very cheap way to increase the number of stations in a control centre. All the real-time and off-line functions are available except critical actions such as:

- communication ports configuration
- Database update
- monitoring configuration change
- telecommand sending

It is then possible to visualise real-time or replay telemetry and to perform off-line analyses. The MMI is exactly the same from a PC or a workstation. The operator can get the result file of the analyses locally on its PC and process it with any spreadsheet software (EXCEL™, LOTUS™...).

Three new features have been developed for the X-terminals :

- A local database dedicated to the terminals (displays and analysis database)
- A copy of the TC page in order to monitor the on-going operations
- The list of subscribers of this dissemination service is managed from a controllers workstation. It is possible to enable or inhibit each subscriber.

The system is based on X11 emulation. Then, it does not need any specific software for an X station and just an X emulator for PC (e.g. eXceed™ for Windows).

OPSWARE TOOLS

The OPSware approach

Usually a control centre provides basic software functions to support the fundamental tasks related to satellite operations. However, in many programmes there is a need to develop advanced software functions to partly automate some tasks in order to improve reliability and efficiency in the context of reduced operations budgets. A new generation of operations assistance tools is now emerging, and it will deeply affects the performances and the economics of space operations.

In particular, MMS has been developing for several years the OPSware concept, and the associated generic tools, to support space operations. These tools are now used operationally in various contexts, and they constitute a commercial offer.

The OPSware tools are the synthesis of numerous software projects for operations support, conducted by MMS in the last ten years in close cooperation with end-users, in the following areas:

- Mission preparation (database and documents)
- Mission planning
- Real time assistance to the operator and operations automation
- Operator training

The approach taken in OPSware, was to identify from all the applications developed by MMS in these areas, a consistent set of well defined generic tasks that can be supported thanks to reusable software components providing intelligent assistance.

Available OPSware components

The OPSware components that are available today cover the following tasks:

- preparing and verifying control procedures: **OPSat,**
- preparing operational documentation (including the Operations Requirements Handbook) and navigating within this documentation: **DOCsat**
- generating schedules of LEOP and routine activities: **Timeline**
- automating operations execution: **OPSexecuter** & **TimelineExecuter**
- analysing satellite health & performances and generating reports: **SAT-Analyst**

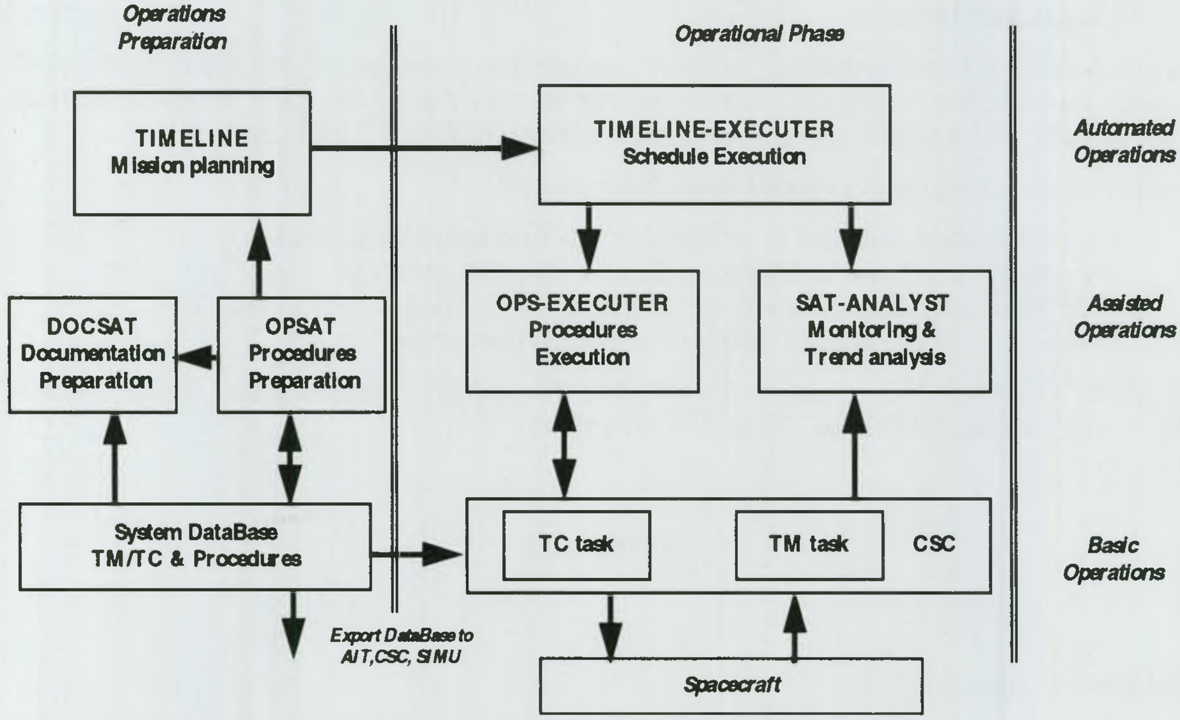

FIGURE 2: OPSware tools concept showing the role of each component in the satellite life cycle

Most of these OPSware components have been integrated in Mission and Control Centres. The leading systems are the Customer Support Centre (CSC) developed by MMS for communication satellites and the SPOT4 Satellite Control Centre. OPSware tools are being extended in the frame of the development of MMS new telecom platform (EUROSTAR 3000).

Here is an overview of the available OPSware components for supporting operations:

Toll and Projects	Main functions	Main features
TIMELINE MMSC, Nilesat, Astra	Mission Planning : generates schedules of activities (Housekeeping, Ground Segment, Instrument) and detailed timelines.	Graphic editor. Generic interface with Flight Dynamics and Procedures Database. Runs on UNIX platforms. Portable C++ code.
OPSat Telecom 2, Hispasat, Soho, Helios1/Spot4, Hotbird, Worldstar, Nilesat, Orion, Astra	Flight Procedures preparation: procedure creation, verification and formatting. Based on a formal operations language.	Runs on UNIX platforms.
OPSexecuter MMSC, Nilesat, Worldstar, Astra	Operations Automation based on automatic (or step by step) execution of timelines and procedures. Based on formal procedures representation (i.e. procedures generated with OPSsat).	Provides a high level view and a detailed view of timelines/ procedures under execution. Operator can get back in the loop at any time. Portable C++ code. Runs on UNIX and Open VMS.
DOCsat Hispasat, Hotbird, Nilesat, Worldstar,Astra	Documentation management (production and navigation). Can be used to access the FOP, the SUM, the Satellite DB...	Supports many standards for documentation (Frame, SGML, Word, HTML). Runs on UNIX platforms.
SAT-Analyst (Telecom 2, Hispasat,, MIR, Ariane)	Component for Satellite Trend Analysis and Performance Evaluation	Supports interactive and automated analyses, automatic report generation (with plots). UNIX and VMS platforms

Key features of the OPSware components include:

- **functional complementary and inter-operability of the tools**: the OPSware tools address complementary types of users tasks. Each tool can be used as a stand-alone element, but can also communicate or exchange data with other elements of OPSware. These requirements tend to make some common concepts emerge, such as formalized operations procedures, and to derive consistent "functional chains" such as procedures preparation / timelines preparation / procedures and timelines automated execution.
- **complementary with conventional space operations and data processing systems**: similarly, the OPSware tools are designed to be complementary to the functionalities of Satellite Control Centres and other Ground Segment facilities, and to be easily implementable on top of those systems.
- **software genericity**: an important effort has been made to derive, from specific applications, generic tools or generic kernels which can be reused to implement new applications in a very efficient way. This allowed for instance to develop the OPSMAKER (procedures preparation) and X-ANALYST (data analysis) kernels, now used in several application areas.
- **use of standards**: tools are built on top of standard basic software (Unix, X Window, ORACLE, FrameMaker...), using standard programming languages (C and C++).

MMSC MULTI-MISSION SUPPORT CENTER

MMS is used to support EUROSTAR customers for the in orbit phase. This support starts by the delivery of a complete and fully validated operational documentation and associated operation support tools as described before, but includes also the provision of very attractive operation services. From 1989 MMS has been largely involved in all LEOP services of EUROSTAR satellites (10 successful LEOP up today). Based on this experience which covers also Network assembly and flight dynamics activities, MMS can perform LEOP services tailored to customer requirements (NILESAT, ASTRA).

Mission preparation is performed in less than 12 months using a MMS in house multimission facility called MMSC for Multi-mission support centre.

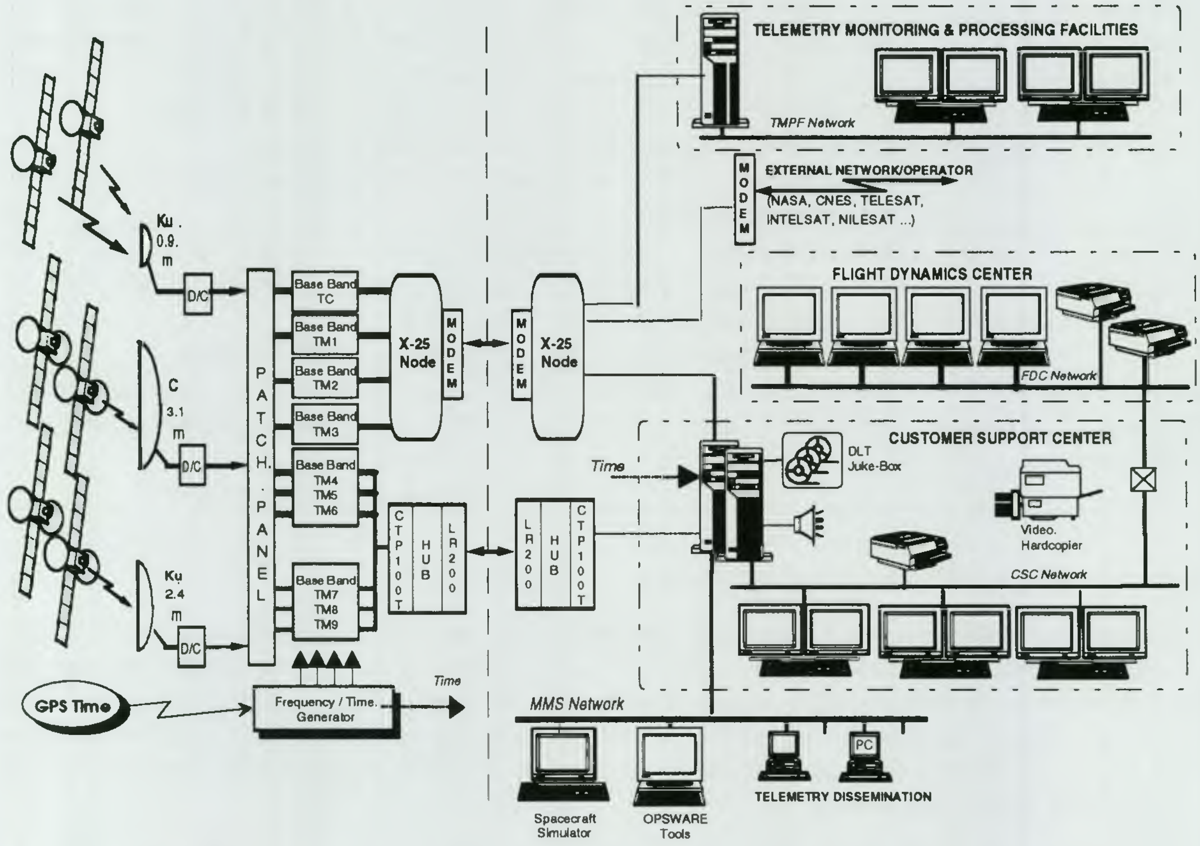

FIGURE 3: Architecture of the Multi-Mission Support Centre in MMS Toulouse

The MMSC major functions are :

- real time monitoring and commanding of 20 satellites based on CSC software
- off line analysis/replay, trend analysis, report, using SAT-Analyst
- training and simulation of EUROSTAR LEOP and On-station operations.
- telemetry dissemination on MMS Network (for quick engineering support)
- back-up satellite control centre (TC capability)
- Orbitography support for LEOP and On-station
- Automated operations thanks to OPSware tools

The components of the MMSC in Toulouse are :

- 3.1 m C band antenna
- 2.4 m Ku band antenna
- 0.9 m Ku band antenna
- Baseband equipment including 9 TM processors and 1 TC processor
- Satellite control centre (CSC)
- EUROSTAR satellite simulator
- full set of OPSware tools: OPSat, DOCsat, SAT-Analyst and OPSexecuter
- communications node to external Network (CNES, NASA, LEOP stations,...)
- Flight Dynamics Centre (MERCATOR)

The MMSC can be used for various activities according to customer requirements :

mission preparation, validation and training of customer operational staff : The MMSC is equipped with the OPSat and DOCSat tool as presented before as well as with the EUROSTAR dynamic satellite simulator. This allows to perform an easy and early validation of Flight Control procedures during the satellite design phase. In addition Customers can be trained using theses flight control procedures with the CSC which is equivalent (functionally and as far as Man Machine Interface is concerned) to the Satellite Control Centre which will be delivered at Customer site. **LEOP**

for operation team and specialist team : the Mission Centre MMSC facilities have been used during HISPASAT Leop for satellite specialist monitoring : allowing to have quick answer to in orbit unforeseen behaviour. The MMSC was also able to be used a back-up site in case of main centre at ARGANDA (SPAIN) unavailability.

MMSC will perform NILESAT (November 97) and ASTRA (September 98) LEOP operations.

back-up control centre : as example the MMSC was used as a back up control centre for HISPASAT during 9 months and MMS was able to take full responsibility of satellite operations in less than 2 hours notices.

The availability at MMS of EUROSTAR operation experts guarantee that the satellite will be operated safely until the recovery of nominal conditions of customer ground control centre.

in orbit support to customer : for satellite health assessment and mission optimisation. A team of more than 50 highly expertised engineers is available to perform systematic satellite health assessment and provide support to real time operations if anomaly occurred.

Thanks to CSC capabilities, the satellite telemetry, real time or off line is available on specialist desk top PCs as well as SAT-Analyst, OPSat and DOCsat functions through MMS Company Network.

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Today, 5 CSC are used in operational environment, controlling 6 satellites in orbit and having performed 4 LEOP. In addition, 8 contracts are currently under development:

	Company	Centres	On-Station S/C	LEOP
April 92	HISPASAT	Primary Centre, Arganda ,Spain. Back-up Centre, Madrid ,Spain.	Hispasat 1A,B	Hispasat 1A,B
Oct 93	CNES	Primary Centre, Toulouse ,France. Back-up Centre, France.	Telecom 2 A, B, C, D	Telecom 2 C, D
May 94	MMS	Multi-Mission Support Centre, Toulouse, France.	Hispasat 1A, B TC2 A,B,C,D	Nilesat F1 Astra 2B
4Q 96	MMS	LEOP Centre in Stevenage, England.		ST-1
4Q 96	ALCATEL	Primary Centre, Toulouse, France.	Worldstar 1,2,3	
Sept 97	ERTU	Primary Centre, Cairo, Egypt Back-up Centre, Alexandria, Egypt.	Nilesat F1	
4Q 97	ST ITA	Primary Centre in Singapore Primary Centre, Taipei, Taiwan	ST-1	
1Q 98	ASTRA	Primary Centre, Bedzorf, Luxembourg Back-up Centre, Bedzorf, Luxembourg	Astra 2B	

The success of the CSC is due to the possible customisation of the software, the well-suited interface with the OPSware tools and the fact that each CSC is delivered as a turn-key system « ready to operate » including a fully validated TM/TC and procedures database.

TOWARD NEXT GENERATION

To develop the next generation of MMS SCC, the same incremental development process will be used in order to follow as much as possible the evolution of the users needs. This will allow to keep on offering to our customers a mean perfectly adapted to our satellites.

An other direction will be the introduction of up to date technologies. The rationale is to be able to connect the SCC with commercial tools, to facilitate the evolutions of the product, to allow portability on any platform, to reduce maintenance costs...

The technologies proposed are WindowsNT, UNIX, middlewares, frameworks, Object Oriented design and languages, cots...

Furthermore, the commonality with the Electrical Ground System Equipments used during Assembly, Integration and Test of the satellites will allow a cost reduction. It will also allow a validation of the SCC with the real satellite before the beginning of the Operational Qualification.

Finaly, the OPSware tools will be further integrated with the SCC, allowing a high reduction of the operations costs.

SPOT2/3 SCC REFURFISH, FIRST STEP TOWARDS A FULL GENERIC SCC

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ABSTRACT. The « Spot2/3 SCC refurbish » project development has been recently completed. It included an important reuse of several parts of the UNIX based Spot4/Helios 1 SCC. The development has been carried out with the objective of a maximum genericity for the new functions and with the constraint of a short planning. This paper gives an overview of the key features of the development and the main functions of the system, highlighting the steps towards a SCC generic product line.

1 OVERVIEW

The Spot2/3 SCC is a component of the Spot2/3 Operational Control Center (OCC) which CNES decided to refurbish in early 1995. This new OCC comprises :

- the Management Center, in charge of off-line functions : orbit manoeuvres management, on-board software and configuration management, payload instrument resources management and programming,

- the Satellite Monitoring Center, in charge of long-term data archiving and of satellite technological monitoring ,

- the On-Board Ground Interface Generator (french acronym: GIBS), which centralises and manages all the data connected with the satellite and feeds all the other sub-systems of the OCC,

- the Satellite Control Center (SCC) , which performs the operations required in real time or near real time: preparation of pass, reception of housekeeping telemetry, monitoring and display of processed parameters, localisation measurements collection, telecommand transmission, short term telemetry data archiving and analysis.

MMS was charged by CNES to develop the GIBS and the SCC.

The hardware equipment for both sub-systems is a set of Hewlett-Packard 9000 computers running HP-UX.

The development was started on June 95 and completed on June 96. This short time for development process was a strong constraint and has been possible thanks to an important reuse of the Spot4/ Helios1 SCC software.

2 FUNCTIONAL ARCHITECTURE OF THE SCC

Provided functions

The main functions performed are in relation to the satellite over pass:

In advance of pass:

commands plan preparation by collecting, checking and sheduling the telecommands issued by the Management Center , according to the daily pass prevision.

During the pass:

reception of the housekeeping telemetry,

monitoring and display of processed parameters,

localisation measurements collection,

telecommand transmission.

Short-term post processing:

generation of supplies for the Management Center and the Satellite Monitoring Center(e. g. Logbook of Commands) ,

raw or physical telemetry displaying ,

execution of telemetry analysis programs for technological monitoring of the satellite.

Hardware architecture

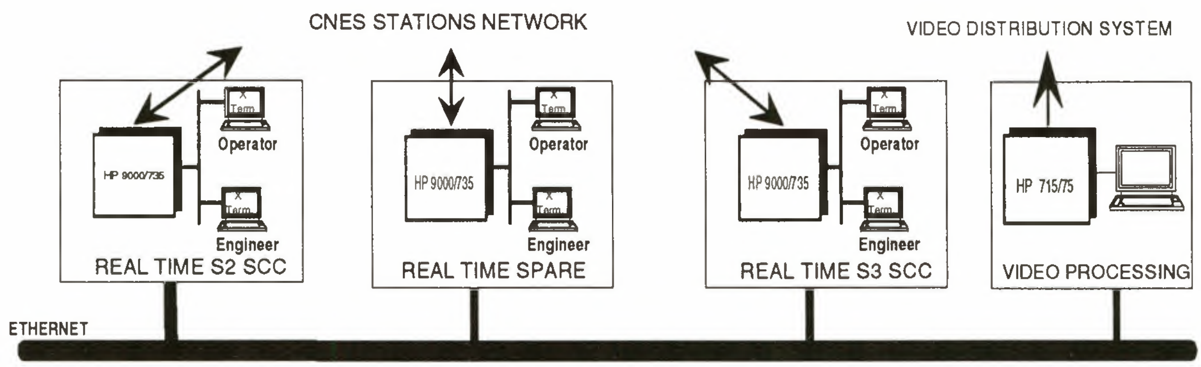

figure 1: Spot2/3 SCC hardware architecture

The SCC is distributed over several workstations interconnected through an ETHERNET bus.

Each satellite is assigned a dedicated Control Center mainly composed of:

- a HP computer (9000 serie, running HP-UX and OSF-MOTIF)
- a X terminal meant to operator tasks (telecommand sending in particular),
- a X terminal for engineer , allowing synoptics visualisation.

The spare Control Center ensures a cold redundancy of both Spot2 and Spot3 SCC's for routine operations and a hot redundancy of one satellite for critical phases (manoeuvres...).

The Video Processing unit ensures the dispatching of displayed data to remote X-terminals located in the operation control rooms. It also supports the GIBS sub-system and the associated ORACLE RDB tools (see hereafter).

Software architecture

The software components are spread over three layers:

- the UNIX layer comprises the operating system and the OSF-MOTIF product.
- the Kernel ans Services Layer (KSL) provides various basic services and utilities:

. inter process and inter computer communication, time management, file management,

. logbook management, hardware and software configuration control,

. agenda and procedures management: work schedule definition, automatic execution of applications, recovery steps on failure occurrence.

- the Application layer is composed of all the programs which fulfill the operational functions of the Control Center (TM processing, TC processing...).

The software design aims at offering a maximum of independence with respect to satellite characteristics and flexibility with regard to future adaptations:

- the data related to the On-Board/Ground interface are derived from an ORACLE Data Base managed by the GIBS,

- the relations between the TM processing and downstream process (e.g. synoptics displaying) are based on standardised producer/consumer protocol, allowing for a new process being easily added.

The development process

The reuse of the Spot4/Helios1 SCC software was a target justified by both economic and planning reasons. It has been carried out fully for the Kernel and Services Layer, for the MMI and Synoptics Management functions and partly for the TM processing, the TC processing and the Pass Preparation.

Another important helpful inheritance from Spot4/Helios1 have been the development methods and environment , especially:

- conception methods (« abstract machines »),

- testing environment (unit testing, integration & validation testing)

- installation procedures.

The development of Spot2/ 3 SCC project has lead to take into account a new criteria for each software module: commonality/specificity with respect of the Spot4/Helios1. The configuration management process has dealt with this need, using the CMF tool.

The software specifically developed for Spot2/3 represents around 50% of the entire software volume. It mainly consists in:

- Data Base Management (GIBS),

- Telemetry Processing,

- Post Processing Data Evaluation.

These domains are discussed hereafter.

4 The specific evolutions of the Spot2/3 SCC

On Board Ground Interface Generator (GIBS)

This sub-system of the Spot2/3 OCC aims at collecting, organising and managing in a single information structure all the data connected to the On Board/ Ground interface or to ground processing.

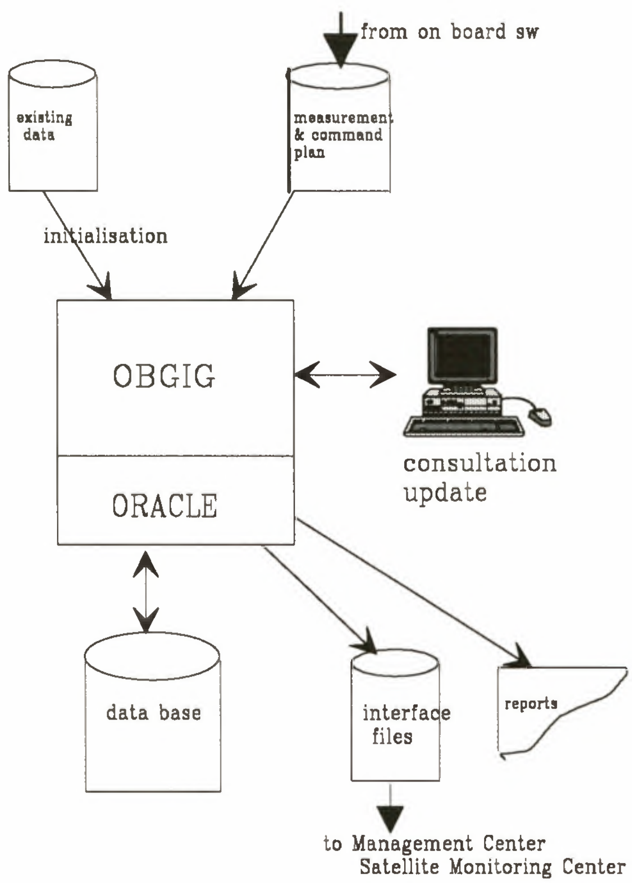

figure 2: the GIBS functional interfaces

On the former Spot2/3 OCC, these data were scattered over several heterogeneous files and one of the functions of the GIBS is the recovery of the existing data for initialisation of the database.

In addition, GIBS provides the following:

- periodic update of the database from an external supply consisting in a Measurement and Command Plan

- coherency check of the database content,

- interface files generation towards other sub-systems of the OCC,

- consultation, update of the database content through transactions or SQLPLUS tool,

- report generation.

The GIBS has been based on the RDB ORACLE, version 7.

The conceptual model has identified the following entities:

telecommand, on board parameter, on board monitoring, ground parameter, ground processing, on board software description, ground housekeeping .

From the conceptual model, a table structure has been derived: this process has been highly supported by the use of automatic generator Database Design Wizard provided by ORACLE package DESIGNER 2000. This tool has also been useful for automatic generation of forms, reports and checks.

The first feedbacks of the users show a great satisfaction with the reached performances and the easy to use interface. This concept of an OCC data base has shown its great advantages, data reference uniqueness, flexibility, for a minimum development cost.

Telemetry Processing

The Spot2/3 telemetry, unlike the Spot4/Helios1, features several formats (real time, survival, report,...) , different w.r.t. size and structure. This specificity has lead to deeply adapt the telemetry processing.

The evolutions have been carried out with the objectives of genericity (as far as possible) and of reusability for the new generation Spot5/ Helios2 satellites.

Such as to reach these goals, the telemetry processing has been organised as an automaton.

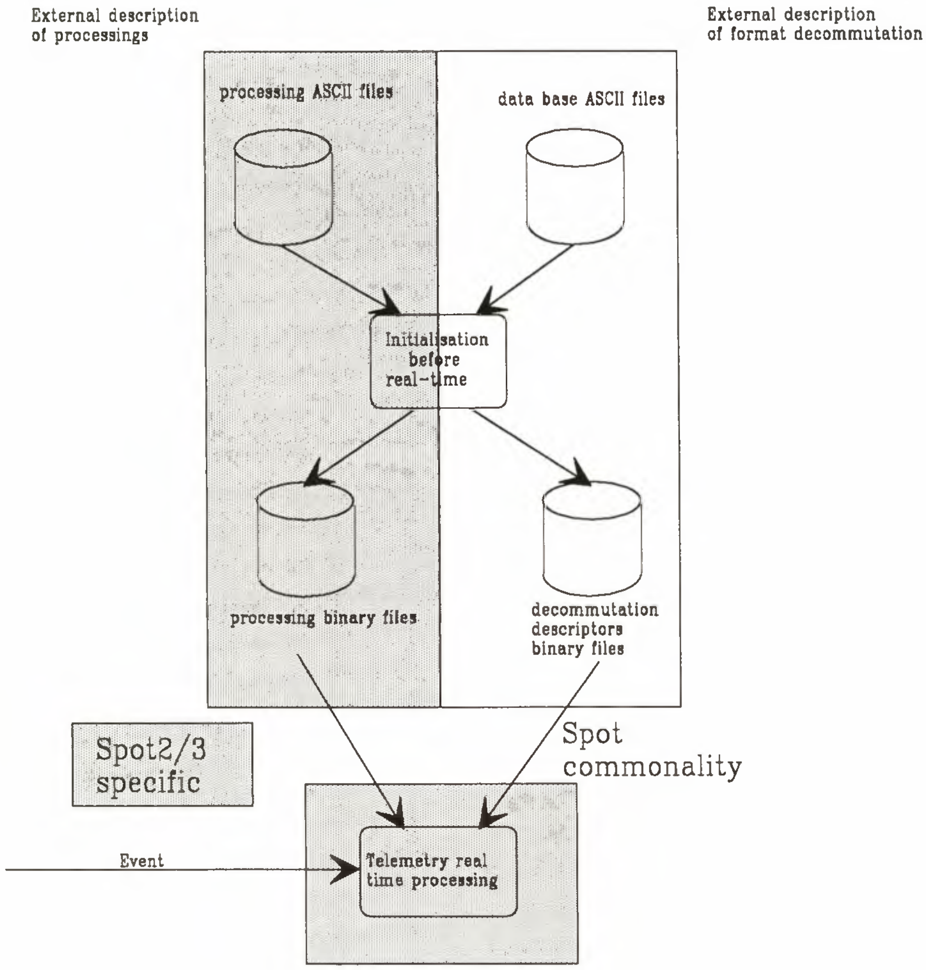

figure 3: the Spot2/ 3 automaton principle

On EVENT occurrence (beginning of pass, telemetry line ...): performance of ACTIONS linked to the EVENT.

One ACTION is characterised by:

- a function (mandatory)

- a function activation condition (optional)

- a decommutation descriptor (optional).

This design approach, by clearly identifying actions and events, has highly improved the Telemetry processing adaptability and maintenability. In particular, new formats of telemetry should be handled, without notable difficulty.

Post Processing Data Evaluation

This domain concerns the post pass operations performed on archived raw telemetry, either systemetically or on demand, meant to short-term technological monitoring of the satellite.

The initial step for these operations is the production of « physical telemetry » i.e. a file containing the telemetry expressed in engineering values. This has been achieved using the Replay service of the real time Telemetry Processing

Various processings can be performed on the physical telemetry.

A generic processing has been defined enabling monitoring, statistics calculations, tabular editions, graphic display Y(t) or Y(x).

Besides, specific technological processings dedicated to specialised areas like propulsion, AOCS, payload optical instrument ... , have been developed.

The generic and the specific processings have been coded using the command language of the COTS product PV-WAVE from Visual Numerics. In order to reduce the development time and to increase the standardisation , a set of library routine have been provided (e.g. retrieving the physical values of a given parameter, plotting a Y(t) curve...).

5 CONCLUSIONS

The Spot2/3 project has enabled to experience several concepts on a real size system:

- the reusability of the Spot4/Helios1 SCC has been demonstrated. Around 50% of the software has been reused, resulting in a large planning gain.

- the genericity target has been carried out as much as possible: the GIBS mission data-base, the Temetry Processing and the Post Processing Data Evaluation may constitute a basis for future SPOT5/ HELIOS2 SCC.

Furthermore, the integration of reusable products during the exploitation phase of a system, has proved the fruitfulness of the step by step convergence approach towards « a generic » SCC.

THE DESIGN AND IMPLEMENTATION OF THE VMOC PROTOTYPE

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ABSTRACT. In response to the pressures to reduce the cost of mission operations, the Data Systems Technology Division (Code 520) of the Mission Operations and Data Systems Directorate at NASA Goddard Space Flight Center has been developing a new operations concept called the Virtual Missions Operations Center (VMOC). The VMOC concept calls for a system that provides flexible distributed support for mission operations, in which routine tasks are automated, and dynamically configured teams act as on-demand support personnel to aid or take control of the system as needed. This paper focuses on the tools being used to develop the VMOC, in particular the G2/IMT expert system and Lotus Notes. It describes why the tools were selected, how those tools are used in designing the VMOC, lessons learned from working with those tools, and a brief discussion of the future role of those tools as the VMOC matures.

1. INTRODUCTION

Today, operations make up a considerable proportion of the life cycle cost of spacecraft. Space operations are expensive, in part, because current mission operations centers require dedicated facilities and continuous monitoring by human operators. To address these problems, a new paradigm for spacecraft operations, called the Virtual Missions Operations Center (VMOC), has been developed under the sponsorship of NASA Goddard Space Flight Center in Greenbelt, MD, USA.

In the VMOC, spacecraft management will be conducted by dynamically configured teams. The team members will act as on-demand supervisors at any time in any place. The supervisory tasks will take advantage of increased automation that would allow for the implementation of a proactive management-by-exception paradigm [1]. During routine operations, standard process monitoring and management tasks will be performed autonomously using advanced automation, expert systems, and software agents. However, when a potential critical fault or emergency is detected, workgroup computing tools allow the dynamic creation of a response team by identifying and adding the most appropriate personnel and resources from remote locations.

To accomplish the goals of the VMOC and build the necessary tools, the VMOC system utilizes both commercial off-the-shelf (COTS) and custom-developed software. The key applications being used to implement the VMOC are:

- G2™ [2] and Intelligent Mission Toolkit™ (IMT) [3] -- an expert system shell and extensions for automated spacecraft monitoring and command and control.
- Lotus Notes™ [4] -- groupware for workflow automation, automated form filling and management, on-line documentation, threaded communications, and built-in distributed paging and phone-based interfaces.

The remainder of this paper focuses on the VMOC development team's experiences with these tools. A brief overview of the tools' capabilities is presented. This is followed by a discussion of how the

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tools are used within the VMOC, the lessons learned from using those tools, and the future role of those tools in the development effort.

2. DESIGNING WITH G2 AND IMT

Automation of routine spacecraft monitoring and maintenance is an important part of the VMOC concept. Expert systems are a mature technology well suited to the implementation of monitoring and control systems. Many vendors sell expert system development tools (called "shells"). For the VMOC prototype, we chose such a COTS expert system shell. This allowed the purchase of a basic automation framework so that the development effort could be concentrated on adding distributed capabilities to the underlying functionality. G2/IMT, from Gensym Corporation, was chosen as the platform for the VMOC prototype primarily because of a G2 capability called TeleWindows™, which allows multiple users to see and interact with a single running inference engine. This capability is critical to the VMOC concept of remote expert collaboration.

2.1. G2

G2 is a "kitchen-sink" philosophy expert system shell. It allows system development using procedures, rules, objects, fuzzy logic, and graphics; all its features are well integrated. All development is done within G2 using its proprietary tools (editor/GUI/debugger). G2 runs under Unix, VMS, Windows NT, or MacOS. G2 developed systems are portable across platforms with no source changes.

2.2 IMT

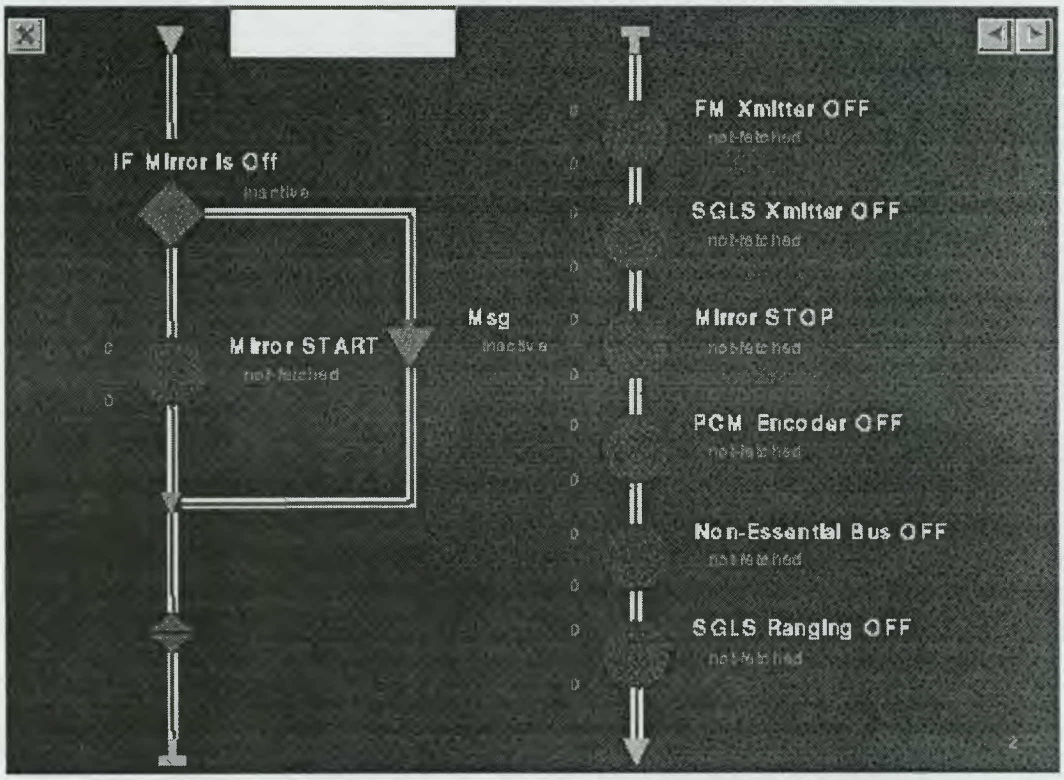

Figure 1. IMT graphical pass plan

Intelligent Mission Toolkit (IMT) is a spacecraft commanding and monitoring system built on top of G2 by Storm Integration. IMT has a graphical object-oriented spacecraft commanding system. Each pass plan step is an object; steps can represent simple operations (send one spacecraft command) or complex ones (run an expert system rulebase). Pass plans are built by taking objects and connecting them together into diagrams that look and function like flow charts (Figure 1). A completed pass plan has an object-and-link structure that can be easily traversed and manipulated by other G2 code, so plan analysis is straightforward. IMT supports the Loral 500 front end processor for command transmission and telemetry. Mappings between commands and bit-string encodings are stored in a Sybase database.

2.3. VMOC EXTENSIONS TO G2/IMT

In implementing the VMOC prototype, we extended the standard IMT shell by added more automation in pass plan execution as well as gateways to allow the system to react to events outside of spacecraft telemetry.

Specifically we added:

- Pass plan queuing -- structures where pass plans can be queued to wait for future events like acquisition of spacecraft signal or availability of a resource. Storm Integration has since added a similar feature to IMT.

- Pass plan analysis -- a facility for stepping through pass plans, noting arbitrary features, and processing them accordingly.

- Email gateway -- a facility that allows IMT to send and receive email; appropriately formatted incoming mail can trigger events within IMT.

- Data structures -- prototype representations of experts, areas of expertise, and mappings between them and detectable spacecraft problems.

3. DESIGNING WITH LOTUS NOTES

In analyzing current operation centers, it became clear that to maintain the same level of performance as conventional operations centers while drastically reducing the number of staff, the VMOC needs more than an expert system. Additional software is needed to facilitate the routine non-real-time MOC activities (e.g., pass planning as well as fault management activities, like anomaly resolution). What makes designing a system to support these features such a challenge is the fact that the system will support a team that is now distributed both in place, as well as in time. Additionally, the team members will no longer have frequent interaction with the system, because most of the team will only be utilized as on-call personnel.

These design requirements lead to the decision to include a groupware system as the infrastructure or glue for the VMOC operation concept. Groupware refers to the computer facilities for groups, usually small, or organizations that enables or supports them in electronically achieving their shared goals. Typically, groupware supports one or more of the following components:

* Communication -- the ability to transmit and receive information (e.g., electronic discussion and video conferencing)
* Collaboration -- the sharing of information to reach a common goal (e.g., workflow management and scheduling)
* Coordination -- the support and management of group work and tools (e.g., message & document databases and meeting facilitation)

Because the design team wanted to utilize COTS products wherever possible, Lotus Notes was chosen as the groupware tool. Though not currently used in the command and control community, it is the de facto standard for groupware in the business community. Lotus Notes is a client/server groupware package with the core capabilities to build custom applications, send and receive messages (email), access multiple mixed document databases, and provide workflow automation. Additionally, there are a large number of third-party tools that increase Notes' functionality, including Internet (World Wide Web) access and publishing, video conferencing, paging, and telephony access.

For the VMOC effort, Notes is being used as the "glue" for the overall system. It provides the underlying capabilities for the distributed team to work together. Notes databases are being developed for:

* Remote communication (e.g., paging)
* On-line documentation (e.g., spacecraft notebook)
* Automated reporting and logging (e.g., spacecraft anomaly reports)
* Information dissemination (e.g., via the World Wide Web through Notes' Domino™ Web Server [5])

4. SAMPLE SCENARIO

Currently, the development effort is focusing on the fault detection, isolation, and recovery (FDIR) aspect of mission operations. The following scenario provides a high-level workflow of how the VMOC software would operate for a standard automated pass in which an anomaly is detected.

4.1 PRE-PASS AND ON-PASS PROCESSING

First, during pre-pass, a pass plan is submitted to the G2/IMT expert system, possibly via email, and queued for future execution. G2/IMT analyzes the submitted plan and recognizes and negotiates for any special resources it may require (e.g., real-time expert human monitoring or additional computers for processing). When all needed resources for the pass are allocated, the analyzed plan is released for execution at its requested time. While the plan is executing, the expert system monitors telemetry for anomalous data.

4.2. FDIR

The basic workflow for the VMOC FDIR process is shown in Figure 2. When the expert system identifies an anomaly, it will email Notes with a message (through an SMTP gateway) that contains the event information, such as the type of fault, time identified, and pass number. By using the email delivery mechanism, the Notes part of VMOC can communicate with G2/IMT or any other expert system that can generate an email message (e.g., via SendMail).

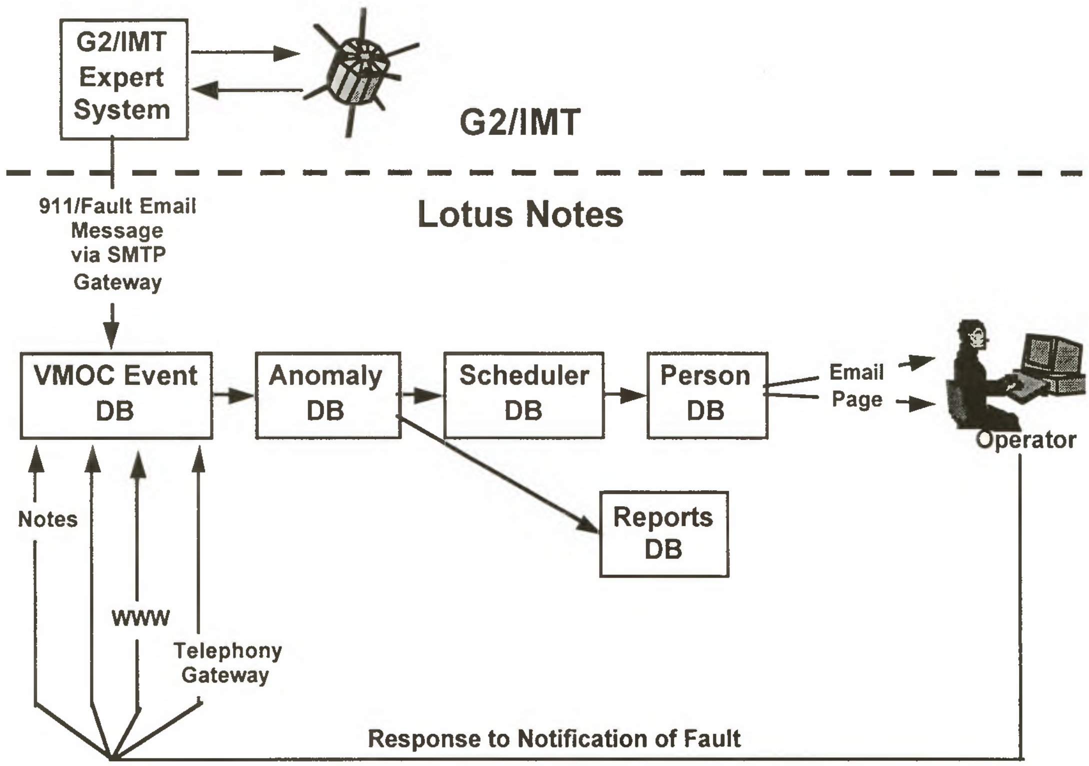

Figure 2. Basic VMOC workflow for supporting FDIR

Once Notes receives the email message indicating a fault, a Notes agent parses the text message and stores that information in a form under a unique event ID in the *Event* database. Also on that same form are tracking and notification information, including the person (people) notified, the method of notification, the time of notification, that person's response to the notification (e.g., acknowledged, contact next most qualified person, etc.).

The agent then uses that Anomaly ID code from the email message to look up the appropriate alert notifications based on the data in the *Anomaly* database. That anomaly database contains a unique record for each known type of anomaly, a text description of the problem, the associated security level, and notification information. The notification data include the types of people to contact (e.g., operator or engineer), the priority of contacting them (e.g., emergency or standard), and the alert message to be sent.

Once the agent reads in the type of people to notify, it will open the *Scheduler* database to get the names of the team members who are on-call at that time. After collecting the names, the agent will search through the *Person* database to collect the appropriate contact media (e.g., pager) and contact numbers (e.g., pager service and PIN numbers). It will then contact the team members via the appropriate gateways (either pager or SMTP for email).

Another agent will then begin monitoring to see if the on-call team members login to the Notes database to acknowledge their notifications. If there is no acknowledgment within a specified period of time (as defined in the *Anomaly* database), there will be a roll-over notification sent to another person. This roll-over will continue until somebody replies to their alert notification.

Once he/she receives an alert notification, the team member can access the *Event* database through a local Notes client, email, a web browser (via Domino with using the Secure Sockets Layer (SSL), a security protocol), or a telephone using a third-party product called MailSpeakIt™ [6].

MailSpeakIt is a tool that provides remote and mobile users access to their Lotus databases via a touch tone telephone. MailSpeakIt utilizes electronic mail, speech, and telephony server technology to enable users to read, create and send Lotus Notes and electronic messages with both text and/or recorded voice mail messages and attachments. It also allows users full control of their databases. Along with using Notes, the experts can then communicate with the VMOC and each other via TeleWindows to diagnose the fault.

5. LESSONS LEARNED

5.1. G2/IMT

When the VMOC project started back in 1994, G2/IMT was a good choice as a platform because of its support for multiple display clients from one inference engine and its spacecraft-specific focus. Its non-standard GUI was seen as a small drawback compared to its other features, but its full-featured development environment was seen as an advantage for prototyping despite its complexity. Since then, other alternative platforms have become available, both within NASA and commercially. Two of the most interesting ones are ALTAIR™ and GenSAA/Genie. This has led to a reevaluation of using G2/IMT as the expert system for the VMOC project. Recently the VMOC developers have done a study comparing these three systems as potential future platforms for VMOC [7].

ALTAIR is a spacecraft commanding and monitoring system from ALTAIR Aerospace that is based on Talarian's RTworks™ family of software tools [8]. It can do VMOC-style networking from its RTworks base, and its state-based modeling looks like an intelligent tool that can be maintained by engineers and operators instead of computer scientists. This is an important consideration when moving from prototype to deployment.

Generic Spacecraft Analyst Assistant (GenSAA) [9] is under development by Code 520 of NASA at Goddard as a tool to make it easier for flight operations team (FOT) personnel to generate intelligent telemetry displays. GenSAA essentially connects the CLIPS rule engine to spacecraft telemetry via TPOCC (The Transportable Payload Operations Control Center), and lets users drive GUI widgets from the rule engine. Since the start of VMOC, GenSAA has added Generic Inferential Executor (Genie), a system that lets the rule engine do commanding and monitoring. GenSAA/Genie has recently added socket-based access to the rule engine to provide the necessary infrastructure to support VMOC-style networking.

5.2. LOTUS NOTES

To date we have found Lotus Notes to have tremendous potential for supporting highly automated space operations. Notes' built-in scripting language and agents allow for easy creation of workflows. Also, the ease of integration with alternative communications devices (e.g., pagers) makes fault notification fairly straightforward to implement. Once the FDIR component is complete, the role of Notes will be greatly expanded. Notes will be used in all aspects of mission operations, from providing a web-based front-end for principal investigators to requesting data collection for post-pass administrative functions. In fact, there are plans to try to use Notes throughout the spacecraft life cycle by facilitating design activities via databases for design documentation and operators' manuals. This concept should help reduce the cost of a mission by increasing the continuity of the program.

However, there have been, and still are, significant obstacles to overcome. In particular, Notes has no built-in capability to support agent triggering actions at a resolution of less than one half hour. This initially prevented us from easily building the hierarchic roll-over paging scheme. Lotus claims this feature will be changed in future releases on Notes. Until then, we are experimenting with a more complex mechanism of utilizing multiple agents that work together at fixed time intervals. If this does not work, API-level programming will be required. However, this would somewhat reduce the advantage of using a COTS product.

Also, we have found, like many others who are just beginning to use Notes for complex tasks, it is worthwhile to use an experienced Notes consultant to assist in designing the overall architecture, in selecting and interfacing with the right third-party tools, and in developing critical or unusual functionality. Lotus Notes is so unlike traditional database design that it takes time for in-house developers to become trained in Notes and to develop a sufficient level of proficiency. It is during this ramp-up time when an experienced Notes developer is most useful.

6. CONCLUSION

The VMOC prototyping effort is continuing today. Once the core infrastructure elements are completed, the goal is to team with operational missions in order to test the VMOC software in an operational environment and hopefully to validate many of its operational concepts. Lessons learned will be used to reevaluate tool selection, optional concepts, and software and user interface designs. From there, it is envisioned that the VMOC software would be iteratively designed and the technology transferred to the operational community.

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THE ARCHITECTURAL DESIGN OF THE ATV CONTROL CENTRE : RESULTS OF THE PHASE B STUDY

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ABSTRACT. The Automated Transfer Vehicle (ATV) is an unmanned, autonomous satellite that will provide infrastructure service to the International Space Station Alpha (ISSA). ATV services include consumables and cargo delivery, Space Station refuelling and reboosting, Columbus Orbital Facility (COF) delivery for attachment to ISSA, and ISSA waste disposal via destructive athmospheric re-entry. The ATV Control Centre (ATV-CC) will provide support to the ATV during all mission phases, along with coordination and authority transfer between the centres involved in the different mission phases. The complexity of the ATV System Infrastructure poses many requirements on the ATV-CC architecture. The aim of this paper is to present the results of the phase B study, where a preliminary architecture of the ATV-CC has been defined. The paper will provide an overview of the ATV mission and the requirements and constraints of the ATV-CC. Then, the different steps for deriving the ATV-CC architecture will be presented. Finally, the paper will present the resulting ATV-CC architectural design and its compliance with the mission requirements.

This study has been commissioned by ESA to an industrial consortium under the prime leadership of DASA. TRASYS was responsible in this consortium for the study of the ATV-GS. Dataspazio, as a subcontractor to Trasys, was responsible for the study of the Flight Dynamics component of the ATV-CC.

1. THE ATV MISSION AND SYSTEM.

The services provided by the ATV to the space station largely depend on the Design Reference Mission (DRM). The ATV will support the following DRM's :

- DRM1B : unpressurised cargo delivery to the US side of ISSA. The ATV approaches ISSA from below, is grappled ("berthed") by a robotic arm and relocated. Cargo unloading is performed via the robot arm.
- DRM4 : pressurised and unpressurised cargo delivery to the Russian side of ISSA, refuelling and reboosting of ISSA to a higher orbit. The ATV approaches ISSA from behind and docks automatically.
- DRM5 : delivery of Columbus Orbital Facility (COF) to the US Side of ISSA.

Unloaded cargo will be replaced by ISSA waste. The ATV will dispose of this waste by destructive re-entry in the atmosphere. The ATV mission is subdivided in different phases : Launch, Phasing, Rendez-Vous, Attached Operations (max. 6 months), Retreat, Departure, Loitering and Re-entry.

The ATV Ground Segment (ATV-GS) will consist of dedicated ATV support centres and Ground Support Equipment and Facilities, such as (see figure 1) :

- The Ariane 5 Launch Control Centre at the Centre Spatial Guyanais with adequate Electrical, Mechanical and Fluid Ground Support Equipment (EGSE, MGSE and FGSE),
- The ATV Control Centre, provides the liaison with ISSA and its control centres, DRS, the launch authorities and is responsible for mission preparation, planning, control, evaluation and archiving,

- The DRS centre (in case DRS is unavailable, two TDRSS satellites will be used),
- The Interconnect Ground Subnetwork (IGS), providing the Ground Communications Infrastructure,
- The Space Station Control Centre in Houston (SSCC-H),
- The Space Station Control Centre in Moscow (SSCC-M).

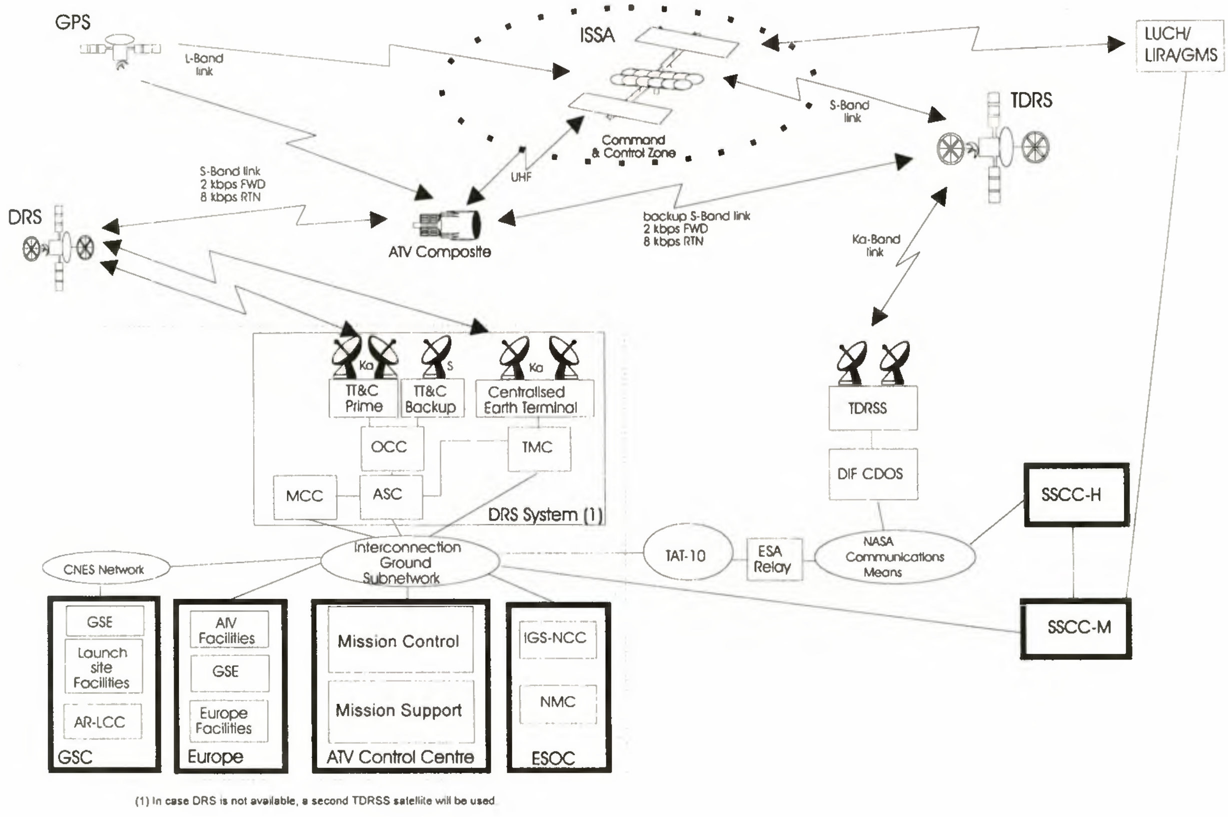

Figure 1 : the ATV Ground Segment

The ATV, having a high degree of in-flight autonomy, is commanded by high-level command sequences stored on-board. The ATV activities are planned on-ground and the resulting commands are time-tagged. The control authority (i.e. the authority to take decisions) over the ATV will remain at the ATV-CC until entering the approach ellipsoid around ISSA. In the approach ellipsoid, the control authority is transferred to the Space Station Control Centre (SSCC) in Houston. The command authority (i.e. the authority to send commands to the ATV) always resides at the ATV-CC. When the ATV is in the approach ellipsoid around ISSA, the space station crew has limited control authority over the ATV. This limited authority includes commands such as “stop”, “hold position”, “withdraw”. In addition, any planning/replanning activity remains under ATV-CC responsibility, as well as the identification and resolution of those mission and safety critical faults which cannot be solved autonomously on-board.

2. DESIGN DRIVERS FOR THE ATV-CC

The implementation of the ATV-CC will be based on the satisfactory fulfillment of mission constraints and system requirements. The main mission constraints concern the system lifetime since the ATV System shall be usable for a minimum of 15 years and the system shall be capable to support one mission per year nominally, and two missions per year as a maximum.

Therefore the ATV-CC shall be designed and developed in order to generate a complete and flexible system, which can be used for each of the planned DRM's. This implies that the ATV-CC and its infrastructure will be maintained between missions.

In general, between each mission, changes to the ATV-CC design may be necessary due to the needs of future missions and lessons learned from the previous ones. These changes will generate "delta-activities" which allow to identify those parts which need to be configured for the new mission, e.g. the common parts as well as the mission specific parts. The ATV-CC architecture shall be able to provide the modularity and flexibility level in order to cope with different mission scenarios in efficient ways. This implies that the ATV-CC shall be able to fulfill the mission goals of a cost effective and reliable resupply of the ISSA, with ISSA cargo and trash disposal in a safe way.

The drivers considered for the ATV-CC architecture mainly address engineering constraints to be taken into account as recommendations for the ATV-CC development. During the phase B Study the following aspects have been analysed :

Operational Factors, which include those activities which characterise the ATV mission, e.g. autonomous operations concept, strategies for rendez-vous, transfer of authority and coordination with both ISSA and the other centres of the Ground Segment. These activities require that the ATV-CC be responsible for the oversight of all the ATV vehicle functions, including responsibility for aborts driven by the ATV system, troubleshooting and detailed system management.

Reliability Requirements, which are important drivers for the identification and evaluation of risks associated with mission technical success and safety, since they affect the engineering design activities. This implies that whenever the potential for catastrophic or critical hazardous consequences or major consequences exists as a result of the design or operations of the ATV-CC, the design shall meet the following failure tolerance requirements :

- no single failure or operator error shall have major, critical, or catastrophic consequences:
- no combination of:
    a. two failures
    b. two operator errors
    c. one failure and one operator error

shall have catastrophic hazardous consequences.

The failure tolerance requirement will be different for safety critical functions (2 failure tolerant) and reliability critical functions (1 failure tolerant)

Automated Tools, whose utilisation has to be envisaged for operating the ATV during both nominal and contingency procedures, in order to minimise human action, and for failure diagnosis, in order to reduce the risk of human errors. The concept of automation shall apply to the ATV-CC wherever possible. However, for safety reasons, override control should be provided for each automatic operation task.

Security Concepts, which consists in defining a security policy including procedures that apply to protect the system and the data integrity. The objective is to prevent the risk of non-trusted users to access the system using communication infrastructures. Therefore it is recommended to define a set of strategies for the management of users' access, e.g. to allow the interaction with the ATV-CC only via a set of predefined User Profiles, each having a set of functions and passwords associated with it.

Human Computer Interface (HCI), which consists in a standardised approach for all the interactive tasks foreseen in the ATV-CC. In fact the HCI functions belong to a set of General Functions (such as

Data Handling, Logistic Services, etc.) that will be available to all the ATV-CC facilities. The HCI concept which describes how the ATV-CC will be accessed by users, shall take advantage of modern technology, ranging from powerful workstations and high resolution displays to an intensive use of WIMP's (Windows, Icons, Menus, Pull-down) interaction techniques. In order to provide a user-friendly and intuitive approach, the HCI shall be based on X-Window application, also to benefit from having multiple applications running in parallel on separate windows on the workstation screen. The use of the HCI (e.g. visual aids, alarms, colours) shall be consistent and homogeneous throughout all the ATV-CC facilities. This concept implies for example the definition of the ATV-CC error standard for reporting all error messages; the definition of alarm classes, to categorise alarms on the basis of both impact severity and operator responsiveness criticality; and the choice of colours which could be configurable for each mission, apart from those used for alarms and warnings.

Missionisation, which addresses the definition of the needs and procedures to prepare the ATV-CC before each mission, by checking that any part of the ATV-CC is properly configured. This concept is mainly related to the preparation of the ATV-CC in view of different missions. In fact the main problems for such a complex system having the aim to control different missions concern how to harmonise different mission set-up by ensuring that proper parameters are provided to any mission. Obviously, this aspect enhances the need to identify mission configuration related parameters, by selecting a representative and significant set of data, which allow to unambiguously initialise the ATV-CC before any mission.

This requirement is even more stringent if we consider the activities to be charged to the ATV-CC when supporting simultaneously two different missions that are run in parallel. Indeed, the ATV-CC may support at the same time the preparation phase of two missions or support the preparation of one mission and the execution of another mission. In this last case, the ATV-CC means are advised not to be the same for both missions, as continuous operational control of the mission in its execution phase should have priority to the mission in its preparation phase, obvious reasons being the ISSA man-rated aspects.

Maintenance, which consists of a set of strategies able to guarantee that any modification (e.g. system upgrade, error) occurring during the mission will not hinder the ATV-CC operational life-cycle. Maintenance aspects are of key relevance for those systems like the ATV-CC which are expected to be operated for more than 10 years. Though maintenance has to play a key role in the design of the ATV-CC, several cautions need to be considered in order to minimise the impact of maintenance activities on mission operations, in fact the availability requirements of the ATV-CC shall be fully met during the execution of maintenance activities. In addition the ATV-CC architectural design shall be based on a modular approach, in order to allow to update/install only individual parts of the ATV-CC.

3. FUNCTIONAL ANALYSIS OF THE ATV-CC

After identifying mission constraints and system requirements, the study proceeded with the definition of the functional architecture of the ATV-CC to establish basic functions and related interfaces. This functional analysis, based on the formalism of the Structured Analysis Design Technique (SADT), leads to a hierarchical description of the required functions, their inputs, outputs, controls and mechanisms. This analysis was performed both for the ATV-GS (high level) and for the ATV-CC (lower level). The functional analysis was then formally consolidated in the requirements specification, both for ATV-GS as for the ATV-CC.

The resulting functional components or "building blocks" serve as the basis for the architectural design, which is described in chapter 4 of this paper.

The ATV-CC functions can be divided into two main categories : Mission Control functions and Mission Support functions. Mission Control functions are involved in the evolution of the mission itself. This means that they directly influence the mission operations progress or the system performance. Mission Support functions on the other hand provide support to the Mission Control functions.

Mission Control Functions include:

- Mission Preparation and Planning: this function is responsible for every aspect of mission analysis, mission planning, preparation and timeline execution.
- Mission Operations & Performance: this function is responsible for control of the overall mission performance and operations progress.
- ATV Composite Monitoring & Control: this function monitors the ATV TM and composes and updates the TC's. It also includes On-board Software Maintenance
- Flight Dynamics: this function supports the ATV orbit determination, rendez-vous strategy analyses, ATV position determination and prediction, fuel consumption.
- ATV Ground Segment Monitoring & Control: this function is responsible for the correct functioning of the ATV-CC and the ground communications links

Mission Support Functions include:

- Data Handling: this function is responsible for the collection ,storage, retrieval and distribution of all mission data and for the maintenance of the mission databases.
- Simulation and Training: this function provides adequate simulation models and training tools.
- Test, Qualification & Validation: this function is responsible for testing, qualification and validation of all the means and the plans that are developed, modified, updated or adapted for a specific mission. For the first mission, tests range from ATV-CC internal qualification tests to Joint Integrated Tests, where the complete ATV system will be tested. For recurrent missions, only the changed components and plans will undergo testing.
- General Support: this function provides specific support, such as engineering and logistic support (i.e. specialist support from industry), administration and maintenance support for the ATV-CC. It also manages the general utilities functions which will be used by all the ATV-CC subsystems, such as HCI, Communication Services,Time Reference, Audio/Video means.

4. ARCHITECTURAL DESIGN OF THE ATV-CC

The design of the ATV-CC Architecture has been based on the translation of the functional components resulting from the functional analysis into a set of HW/SW subsystems to which ATV-CC functions have been allocated. This further step also included two basic constraints:

- Maximum re-use of existing facilities
- ATV-CC Failure Tolerant design

Re-use of existing means and analysis of ESOC and GSOC as candidates for the ATV-CC

The customer's requirements of cost reduction through maximum re-use of existing facilities was accomplished by means of an analysis of ESOC and GSOC both as candidates for the location of the ATV-CC and as sources of available tools/means for mission operations and control. This analysis mappped GSOC and ESOC features against the functional components of the ATV-CC. The following conclusions have been derived:

- The strength of ESOC is in the development of tools for mission support. Indeed, as the operations centre for the ESA missions, ESOC has supported the development of a large number of tools based on a homogeneous approach, with a strict application of safety and reliability requirements and easily extendible and adaptable to other missions and projects. The most important tools include :

- SCOS II (Spacecraft Control and Operations System), ESA's system for satellite operations, with full support of the spacecraft controller.
- ORATOS (Orbit and Attitude Operations System), ESA's flight dynamics support tool, providing an adaptable platform containing (on the application level) libraries, facilities for orbit determination, etc. and shells for implementation of mission specific algorithms;
- GOAS (Ground Operator Assistant System), a tool for operator support during rendez-vous, and further developments such as a Vehicle Expert Module (VEM) of ATV in G2. This tool can act as an extension of ORATOS;
- SIMSAT+, ESA's general purpose simulation environment for operations support both during mission preparation and mission execution phases.
- ARPKSIM+, a Eurosim based simulator developed in the scope of the ATV Rendez-Vous Predevelopment Kernel (ARP-K) project to support the verification and validation of Rendez-Vous and Docking procedures;
- IGS developments for communications between the elements of the ATV-CC. IGS combines existing infrastructure (OPSNET, S-band Stations, communication control, ...) with experience from other missions (IML, Atlas, Euromir).

- GSOC has a large experience in different missions, such as geostationary satellite positioning, satellite operations, scientific missions comprising a multitude of users distributed over a large geographical area, ... GSOC provides control room infrastructure, operations expertise, and hardware/software infrastructure fo flight dynamics, satellite control, simulation, ... GSOC is also responsible for the development of E-POCC as a control centre for the Columbus Orbital Facility (COF-CC). E-POCC will support the following functions:
  - the Communications & Infrastructure Subsystem,
  - the Data Processing Subsystem,
  - the Archive & Retrieval Subsystem,
  - the Mission Planning and Navigation Subsystem,
  - the Ground Operations Subsystem,
  - the Training, Qualification and Validation Subsystem ,
  - the Electronics Operations Support System.

  The E-POCC architecture can be tailored towards the specific needs of the ATV-CC.

RAMS Analyses of the ATV-CC

In order to obtain the required failure tolerance, a failure modes and effect analysis of the different ATV-CC functions was performed. This resulted in the identification of the effect of failures on the ATV-CC and the ATV system as a whole. The severity of the effect is reflected in the required failure tolerance. This had the following effect on the ATV-CC architecture (see figure 2):

- for the Mission Control function, failure tolerance requires the Mission Operations and Control workstation and the ATV Monitoring and Control workstations to be 2 FT. This is achieved by taking over the critical functions of a failed workstation on another workstation, thus ensuring operations continuity. A cold stand-by workstation is then configured from the central database on the Fault Tolerant Server. This server and associated database is internally FT, e.g. via the use of a RAID (Redundant Array of Inexpensive Disks) level 5 database architecture or via data mirroring. This way, the same cold standby workstations can be used for the whole ATV-CC.
- Failure Tolerance against human errors can be achieved by performing commanding in 3 steps (for a 2 FT system). A telecommand will be prepared by the Spacecraft Controller or the Spacecraft Operations Engineer. It is then passed to the Spacecraft Operations Manager for approval. Finally, it is send to the Flight Operations Director. After his or her approval, the TC is then uplinked to the ATV.
- The failure tolerance of the LAN's can be foreseen e.g. by using Fiber Data Digital Interface LAN's (FDDI), which are internally 1 FT. This ensures a 2 FT architecture for the OPS LAN and a 1 FT architecture for the General Purpose LAN.

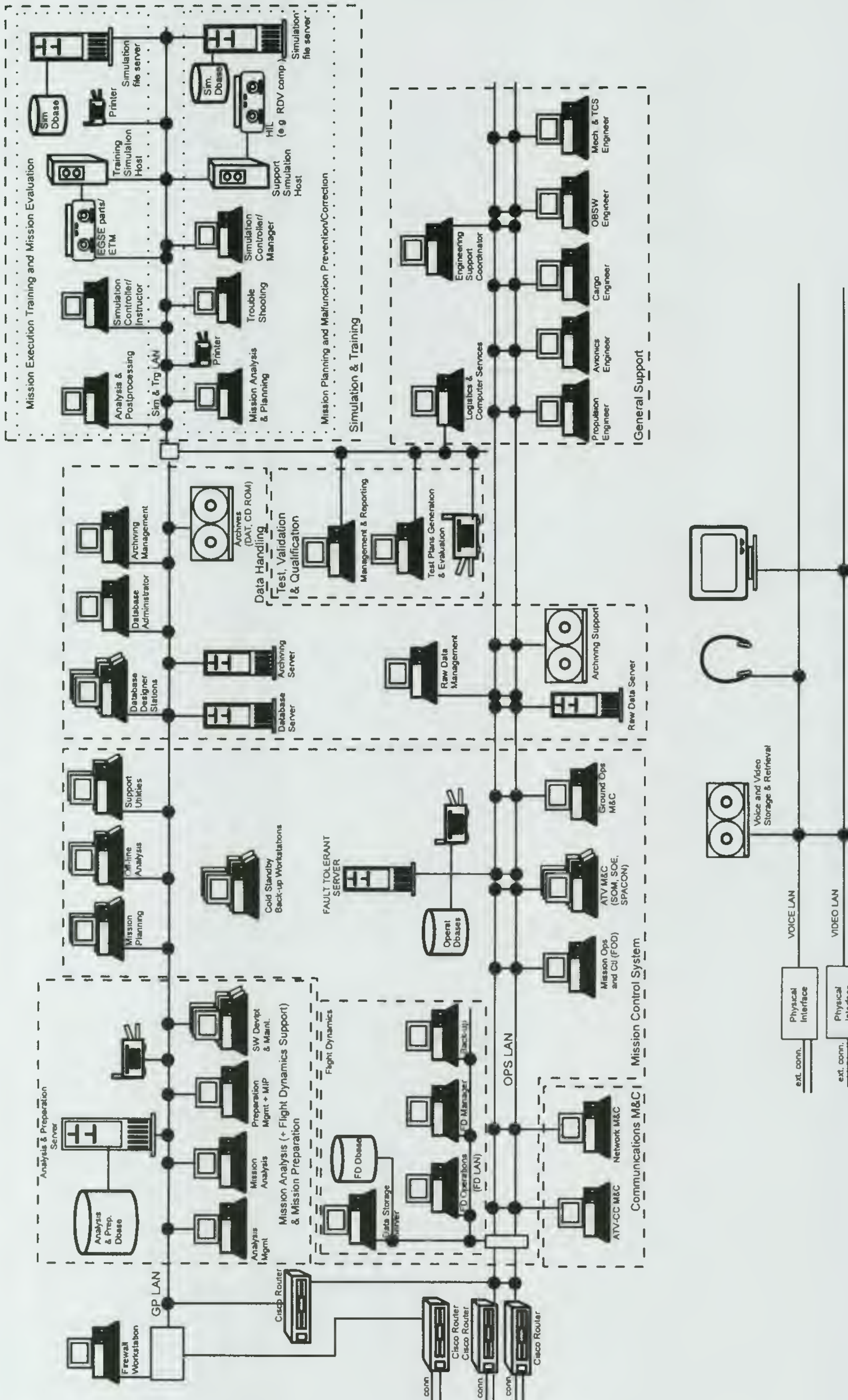

Figure 2: ATV-CC Architecture

The RAMS analysis provided reliability and availability calculations which satisfy the relevant requirements. The RAMS analysis also addresses those safety aspects which involve the ATV-CC. Hazardous events which concern debris creation, damage to public and private property, do not fall under the direct ATV-CC responsibility. However, the ATV-CC should foresee the appropriate strategies to minimise risks and side effects during the mission, from launch to de-orbit and re-entry, by choosing proper trajectories and fall-out zones in unpopulated or desert areas. In particular it is requested to monitor ATV trajectories during re-entry to estimate ATV or debris impact zone. Especially for the first mission, this information may help to validate the prediction models and to provide early warnings in case of large deviations from the predicted re-entry trajectories. This implies that the ATV-CC should be connected to the existing ground tracking systems.

The previous steps led to the development of the ATV-CC architecture. This architecture is built around the following components :

- Internal Network :
    - Redundant On-Line LAN
    - Redundant General Purpose LAN (GP LAN)
- Workstations :
    - use of a data distributed architecture with the following properties:
        - data distributed system and not processing distributed, with workstations dedicated to specific tasks and interconnected via LAN's for communication.
        - process data exchange between different workstations.
    - provide the ATV controller with interactive displays (sophisticated MMI)
    - Use of automated tools (such as expert systems) for operating the ATV is another alternative that reduces the required staffing, the human interaction and the risk of human failure.

Figure 2 presents the resulting ATV-CC architecture.

5. CONCLUSIONS.

This paper discussed the results of the phase B study to design a control centre for the ATV. The conclusions of this study are the following:

- The ATV-CC is designed to fulfill a large number of requirements of different nature. It is built around a flexible and modular architecture, enabling it to be adapted during its expected lifetime of 15 years;
- The ATV-CC makes re-use of a large number of existing tools, thus avoidung duplicate efforts and incorporating proven technology;
- The ATV-CC is designed to cope with a highly autonomous spacecraft, able to treat hard real-time replanning requests;
- The state-of-the-art of the technology at the time of ATV-CC development being unknown, and due to the ever changing concepts and requirements, evolutions in the ATV-CC architecture are still possible.

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The role of Centralization in a Distributed Architecture: The SCOS II Experience

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ABSTRACT. This Paper describes the experience acquired during the design and implementation of SCOS II, a new infrastructure for spacecraft control. In particular, it focuses on how distribution and centralization of services and resources have been used to meet the performance and reliability requirements essential in an operational environment. The paper discusses the problems encountered and the possible solutions, explaining how SCOS II has adopted centralised or decentralised approach according to the situation.

1 INTRODUCTION AND CONTEXT

SCOS II, (Spacecraft Control System II) is ESOC's new spacecraft control infrastructure (See [2], [3], [4]). It is being built to address some of the problems existing with current systems. In particular the following key points have been addressed:

- easy mission customizing and extension;
- vendor independence,
- improved performance;
- improved functionality.

SCOS-II makes use of the following techniques to achieve these objectives:

- object-oriented technology to support better reuse (See [1]);
- C++ as implementation language for efficient code;
- widely adopted standards, like Unix System V Release 4, X11, POSIX, IP protocols to improve vendor independence;
- client-server paradigm.

The implementation is based on the client-server paradigm, where server processes provide services to the network as a whole (e.g. spacecraft database server, data archive server). In this respect SCOS II is a distributed system, but with some system functions (i.e commanding) centralised on a specific node.
Telemetry data is broadcast over the network by the data server, and permanently stored by a central mission archive on disk, so that it can be requested again. A local caching mechanism available at each user workstation, gives efficient and fast distribution of telemetry data to local applications, minimizing access to the mission archiver and network load. Telemetry data is always processed on a central node by the master telemetry processor to allow the user to *monitor* the spacecraft behaviour. The master telemetry processor is responsible for generation of system events (i.e alarms) and synthetic (i.e. derived) data. Access to

system services is performed by local applications whenever some central information is required to accomplish the current task. Telemetry can be processed either in real time or in retrieval mode by secondary telemetry processors available at each user workstation. A display facility based on advanced man machine interface is available on any client workstation to display the result of the real time processing or to access already processed data.

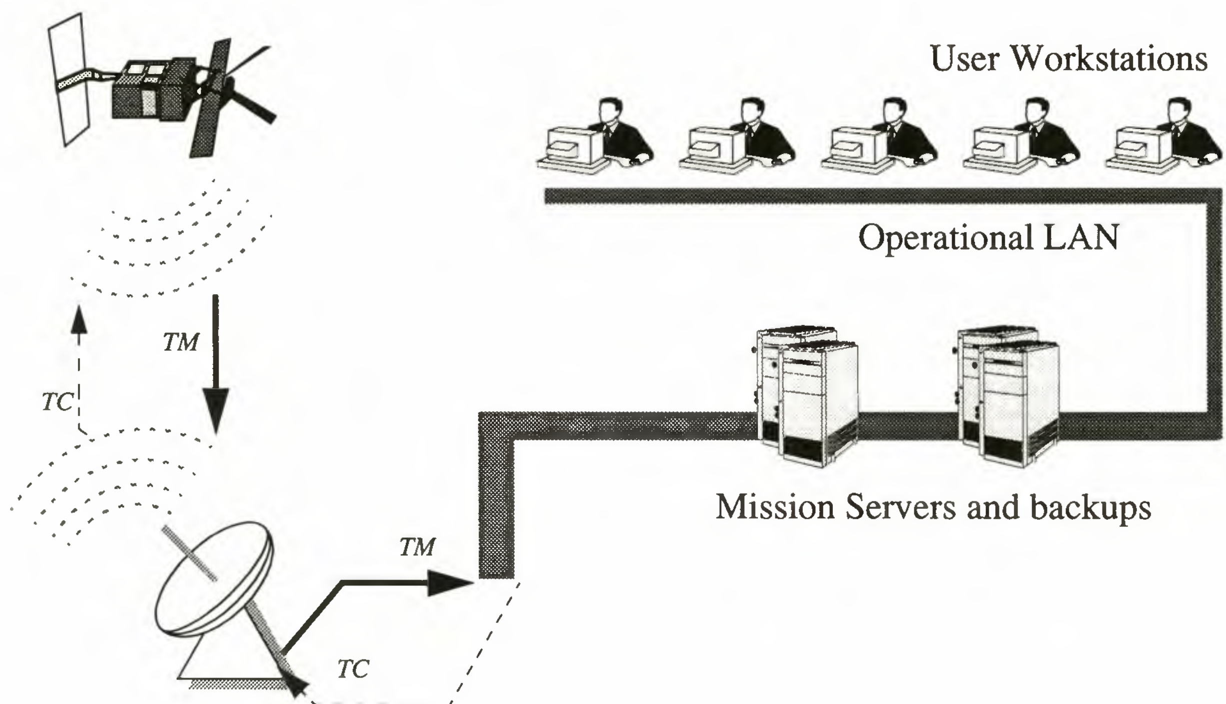
SCOS II provides an integrated telecommand chain to allow the operator to *command* the spacecraft and to *verify* the effects of the commanding activity making use of the telemetry chain. The mission database provides all the information required by the system to work, like definition of displays, limits, telecommands, calibration curves, etc., and allows mission configuration without requiring any change to the system source code.

In this scenario the client server paradigm allows to assign system responsibilities to certain nodes according to the requirements of the mission and to distribute system functions to more than one workstations or to combined them on the same machine. The client server paradigm offers great flexibility: the system can run on a single workstation ("SCOS in a box") where all clients and servers are co-located or in a bigger configuration where services are distributed among the different workstations.

More than one year of integration and system test has resulted in the definition of a few typical reference configurations where functionality is allocated to dedicated nodes of the system to match the required system performance and reliability requirements.

A typical SCOS II configuration is shown in Figure-1.

Figure-1 A typical SCOS II Mission Configuration



2 CENTRALIZATION VERSUS DISTRIBUTION

A system component is *centralized* when its elemental components (i.e Unix processes) are physically co-located on one unique physical node of the network It may act as a server accepting service request from clients, or merely perform a defined task. Sometimes, for security reasons, there is a need for more than one of these processes to be running. In these cases of on-line redundancy one process will be qualified prime and the other back-up. Mechanisms to detect failures of the prime and switch to the back-up have to be provided. In some circumstances centralised components can be cloned locally on other nodes. In this case they are called *replicated.* The reference clone is called *the master*, and this provides the services of that component to the rest of the system. Any other clone is *local* and no remote access is provided. Access to the services provided by a *local* process are restricted to local client applications.

A system component is *distributed* when it is available on the network and its elemental components (i.e Unix processes) are physically distributed on different nodes. It may act as a server accepting service request from clients, or merely perform a defined task.

From a client application point of view the fact that a resource or service is *distributed* or *centralised* is irrelevant. The client will access the resource or the service via a dedicated interface which hides the details of the implementation and the location of the server. On the contrary the implementation might be rather different due to the constrains imposed by the problem domain. Distributed process can be easily centralised via configuration; the opposite is not always possible.

Location of services and resources is one of the more difficult aspects of system design, and in particular when a system is complex like a mission control system, a general approach cannot be formulated. It is very difficult to find a *"rule of the thumb"* for determining if a system component has to be centralised, or distributed. In practice, we have adopted a pragmatic approach, in which the decision to make a service centralized or distributed is made on the basis the of constrains applicable to that service.

It was almost immediately evident that the initial goal of avoiding *single points of failures at any cost* had to be relaxed. In some of the most complicated cases we found that the best approach is in fact a compromise, and where the complexity of the problem domain was already very high we decided against introducing additional complexity just for the sake of having a *pure* distributed system.

A typical example of this is the commanding kernel, which must be fully reliable, and for a mission with reduced spacecraft contact, it must dispatch and deliver commands very quickly. In this case spreading responsibility across several nodes, requires additional coordination between components and does not bring much value in terms of functionality. The SCOS II commanding kernel is in fact *centralised.*

On the other hand commanding functionality must be available at any user workstation and therefore commanding sources (e.g. manual commanding and command scheduler) together with monitoring and history displays are typical examples of *local* services. The commanding system as a whole, i.e the commanding kernel and commanding sources is on the other hands *distributed.*

2.1 ADVANTAGES, DISADVANTAGES AND CONTRAINS

Advantages and disadvantages of one solution in respect to another are very often related to the particular design problem and they will be discussed in the following sections, but our experience has confirmed the following:

- *Centralization* reduces the complexity of the design in many cases, allowing components to take advantage of simpler and faster communication mechanisms (e.g. shared memory, file system)
- A *centralized* solution can not be always converted into a distributed solution.
- *Centralization* implies restarting only the node where the service is located in the event of a crash.
- *Centralization* implies that the service or resource is fully lost in the event of a crash. Should that be an unacceptable situation, a strong back-up strategy has to be implemented for major system components.
- *Distribution* allows more flexibility.
- *A distributed* solution can usually be centralised, simply via configuration.
- *Distribution* implies more CPU cycles available to the system component, but this does not always imply better performance.
- *Replication* (e.g. secondary Telemetry processor) implies:
    - high availability of services;
    - less resources available to local client applications (i.e CPU, disk space, etc. are shared);
    - system scalability;
    - data management overhead due to the duplication of data.

Constraints dictated by the type of application that the system must support and the availability of resources

play an import role and influence the system design. In our case the major constraints are the network bandwidth and the volume of data to be distributed, processed and archived. Traffic due to inter-system communication also plays a role and has influenced the design.
The above constraints has driven the design in the following directions:

- distribution of data must be efficient and therefore broadcast has been selected as default data distribution mechanism;
- application should find frequently used data locally, minimising requests to the mission archive;
- traffic due to the X11 applications is not negligible so local X servers are used for all MMI components;

In addition it is essential in a monitoring and control system that any information on which any operational decision might be taken is reliable. As a consequence some of the components need to act as a reference for the whole system and are therefore *centralised.* Best candidates for centralization are system components like master telemetry processor and the commanding kernel; the uniqueness of such system components ensures that there is no duplication of referenced data, keeps the architecture quite simple, and does not compromise the overall system scalability, allowing secondary telemetry processors and commanding sources to run anywhere.

3 SYSTEM COMPONENTS

Each of the components in the control system has been designed to be centralized or distributed depending on the constraints, both of performances and reliability, the component shall support. In some cases both options have been chosen; for example the telemetry processor, where the output of a master server is used as reference for taking operational decisions and archived, has been complemented by adding a local secondary telemetry processor on each node, where many displays can be run either in real time or in retrieval mode without impacting the overall system performance. This represents an example of replicated component.

3.1 MISSION DATA SERVER

Telemetry data is received from the ground station interface by a mission data server. This performs checks on the quality of the received data units and distributes the data for filing and processing. Backup data servers may be provided for critical mission phases. The sample mission data server included in the distribution is a centralised system component and is very simple. A complex mission data server may be required to support re-distribution of telemetry to other systems (i.e principal investigator), and a distributed implementation might be required. This system component has always been a mission specific software element in the past and this assumption is still valid today.

3.2 MISSION DATA BASE SERVER

The Mission data base is a typical area, whereby functions can be both local and centralized. A centralized data base server ensure consistency of the data across the network for all operational tasks and any change in the operational database, performed and coordinated by an authorized personal, is notified to all running operational tasks. To avoid unnecessary load on the data base server however, data base changes are first performed and then tested locally before to be transferred to the operational central data base server. In such a test mode, an application invokes a local service instead of the centralized one. Performance achieved locally have been quantified to be better, and therefore for missions where the database access time is an hard constraint a local solution can be adopted. The drawback of a local solution is that the required data base files need to be duplicated on all the nodes, and consistency between copies need to be guaranteed by the data base files distribution procedure. A mixed approach is also possible, but none of the supported missions has used it yet.

3.3 MISSION ARCHIVER

The mission archiver is responsible for storing all data received and generated during the mission lifetime. This is mainly, telemetry (received and synthetic), telecommands, monitoring events (e.g. out of limits) and system events (user log-in, change of database etc.). All data are available for future retrieval. A centralized server ensures reliability and integrity of the stored data. However, this design imposes performance constraints, if retrievals are only performed using the services of the central server. Scalability in fact cannot be guaranteed if applications have the freedom of directly starting any number of retrievals. To avoid such a situation, and also to allow performance oriented algorithm to be used, requested data are retrieved in bursts, and cached locally on the client machines for further processing. The size of the cache and the bursts are configurable items, so that nodes can be configured to better satisfy application needs. Locally cached data will be replaced using a Last Recently Used policy, so that frequently used data will be usually supplied directly to client application without going back to the archive server.

3.4 TELEMETRY PROCESSORS

The telemetry processor is one of the key component, providing information used as input to several operational processes of the mission control system and responsible for monitoring violation of critical conditions and limit checking. Such responsibility imposes:

- a *centralized* approach with a strong redundancy and recovery mechanism to cope with failures. The outcome of the prime master telemetry processor is first archived then made available to applications who need to take operational decisions (i.e the Commanding System, Alarm Handling).
- a *local* approach not impacting on the server. It gives the flexibility to validate database changes, check the outcome of the prime telemetry processor task, run many telemetry displays in parallel, and process retrieved telemetry using different time bases.

3.5 COMMANDING SYSTEM

The commanding system provides commanding facilities to the user via *local* dedicated applications like the manual stack or command scheduler. These applications are known as commanding sources, because they generate commands to be sent to the spacecraft. More than one commanding source can be active at any point in time, and they can be started from any user workstation. The initial validation is performed under the responsibility of the local command source who will access either information kept in the mission data base or derived by the telemetry processing. Once the commands have passed the initial validation they are then dispatched to the *central* command handler, which will take responsibility for further processing. Commands can be un-dispatched by the source if required. It is responsibility of the *central* command handler to produce a consolidated stream of command execution requests by multiplexing commands coming from different sources. Priorities, constraints, and verification of conditions are checked by the *central* command handler that is responsible for sending to the mission archiver all released and executed commands with their various validation and verification attributes. It also keeps *local* commanding sources up to date with the current status of the execution.

The validation and verification process is done in tight cooperation with the master telemetry processor: telemetry values are used to validate and verify commands, and limit checking, performed by the master telemetry processor, is enabled/ disabled according to the expected status of the command activity verification parameters.

3.6 ALARM AND EVENT HANDLING

Different types of alarms and events coexist in the mission control system and therefore a mixed approach is used:

- Events used to take operational decisions, are generated for processing and archive by centralized process, guaranteeing the uniqueness of events across the network. For instance, parameter values out-of-limits reported by the prime master telemetry processor, confirmation of the execution of a command reported by the prime command handler or the submission of a new operational database by the centralized database server. Events of an operational nature may represent alarm condition so they are broadcasted to a local alarm handler on each workstation. Since only one user is qualified to acknowledge a particular alarm, only one alarm handler raises an alarm for a given event.

- Important events generated by independent tasks, such as user log-in into the system or local database modification, are also archived. These events are not network wide, but related to a specific node/process.
- Administrative events (secondary telemetry processing output, local data processing computation) might be archived on request. The ability to control the generation and archiving of such events is required to control the load imposed on the mission archiver.

3.7 DISPLAYS

Displays are a typical example of local applications. They are usually CPU intensive due to the high number of graphics operation required to keep the information presented on the screen up to date. They introduce network traffic if the X11 protocol is exported on a different node. The approach taken for displays is to have the display applications running on the same node as the X11 server, so that network bandwidth is preserved.

3.8 OFF LINE TASKS

Off-line task (long term retrieval analysis task) are by nature local. They can be started anywhere on the network, but all will require resources from the server to get access to the requested data. The priority of these tasks is low compared to that of operational tasks. The control of the resource allocation is then performed by the server itself, who might decide to satisfy, delay, or deny the data delivery on a case by case basis.

4 THE ROLE OF THE MIDDLEWARE

The experience in early prototyping phase, showed that a badly design client server architecture might lead to severe performances problems and particular attention has to be paid to make the distribution of data reliable and fast to minimize network load introduced by application making retrievals and by unnecessary client server interactions. The implication is that the middleware has to provide flexible retrieval algorithms, efficient communication protocols (See [5]), together with suitable application program interfaces required to minimize communication overhead, and context switches between clients and servers. Design patterns and C++ programming idioms (See [6], [7], [8]) have been very useful in helping to get the design of critical components right in the first place, especially when reliability and performance were an hard constrains. On the client side, if the delivery and processing speed of data is inadequate or the time spent waiting for request completion is excessive, the application response is not adequate and the overall performance of the system is compromised.

A fast and reliable middleware plays a fundamental role in avoiding these kind of problems, and all the techniques used to minimize network load, unnecessary processing, etc. have been very useful in helping to achieve the required performance, but as explained in next section this is not always enough.

4.1 PERFORMANCE ASPECTS

Experience has shown that a good middleware is a key point for the success but alone it does not guarantee that required system performance can be achieved in all possible configuration. An inadequate configuration, whereby clients and server are located on two different physical workstation, can be validated in principle but could fail during load tests. It came clear that the performance aspects considering peak operational condition had an impact on the architecture itself, implying that for specific critical tasks, system components and clients themselves have to be located on the same physical workstation. In turn, this requires the middleware to be designed to provide high performance in both contexts, of task spread across several physical machine across the network, or located on the same physical hardware.

4.2 RELIABILITY ASPECTS

Reliability of critical data like processed telemetry, dispatched telecommands is a key issue in an operational environment. Two major aspects must be considered:

- *the need to ensure that no critical data is lost* implies that the middleware must handle all the possible error conditions efficiently and in addition must support hot redundancy, i.e. two duplicated tasks with a mechanism for switching from the prime to the backup.
- *the uniqueness of the data* implies that in the case of telemetry that one telemetry processor is made the reference (master).

The retained solution is here a trade-off: Two (at least) identical tasks are located on different node on the network, but only the results of the master are considered. Moreover, the result of the back-up is not distributed on the network, but only potentially available, in order not to impact on system load.

5 CONCLUSION

When considering the optimization of the system configuration, it becomes clear that resource constraints dictate that servers very often are co-located or combined. For example, a possible system configuration is to locate the mission data server and the archive server on the same machine so that the bulk of the data to be archived is efficiently distributed to the archiver without loading the network. Locating the commanding kernel on the same machine together with the uplinker (usually a mission specific system components) improve system performance.

Taken to its logical conclusion, we arrive at the concept of mission servers. These could be few high performance machines providing core system functions, principally:

- data distribution;
- archiving;
- master telemetry processing;
- command handling;
- database management.

As an additional benefit, with the server processes running on the mission servers, the requirements of the client (or user) workstations are usually less demanding, reducing the overall cost of the system hardware.

SCOSII is being experienced with various missions. The very different nature of these missions (a deep space probe - Huygens, a telecommunication satellite - MARECS, a meteorological satellite - MTP) is best to validate the concept of distribution / centralization against different type of mission constrains. Each of these has a configuration best adapted to their need, by considering their own constrains, and has proved that the concept of distribution / centralization can be successfully applied.

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DISTRIBUTED MIDDLEWARE FOR FUTURE GROUND SEGMENT ARCHITECTURES

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ABSTRACT. The architectures of spatial ground segment are inherently distributed. The overall architecture considers computing centers linked to one or more Wide Area Networks. Each center groups computers connected to a Local Area Network (Ethernet,...). The kind of information transferred can vary according to the nature of communications (LAN, WAN).

If the architectures are mostly distributed, it is not always true with applications. They are often designed as centralized. And this results in the cooperation of centralized applications running on a distributed architecture.

This paper will focus on the impact of new distributed middleware (CORBA, OSF/DCE, ONC+, ISIS, JAVA...) in the design of future architecture. After introducing these technologies and some overall concepts (Client/Server model, Distributed Object model, Virtual Computer, Naming,...), the presentation will explain how these technologies can contribute to improve performance, standardization, security, architecture independence, fault tolerance, efficiency, scalability and PC integration to our current and future architectures.

The paper will end with the demonstration of a prototype of a Distributed Oriented Object Control Center. This prototype implements functionalities close to those of a classical control center (telemetry acquisition, parameters visualization, computing, control and monitoring, logbook, off-line tools,...). Built with distributed technologies (CORBA, ISIS, JAVA), this prototype allowed us to test their contributions in a spatial environment.

1. OVERALL APPROACH

The motivation behind our work is the growing importance of distributed computing environments. First of all, a state-of-the-art review of distributed systems was made so as to reveal the main underlying concepts. We then determined what innovative contributions could be made to the design and development of our space computing applications by such distribution concepts. Once these contributions were clearly identified, it was decided to validate them by applying them to the development of a prototype representative of a distributed space application.

2. STATE-OF-THE-ART REVIEW

There are many definitions of distributed systems. We chose the following one: "A distributed system is a system whose behavior is determined by algorithms specifically designed to take into account and use several processing places".

Client/Server Model: The customer/server model is certainly the most widespread concept in the literature dealing with distributed architectures. The server defines services it makes available to the client. The client can access the server only through the set of services (functions) the server has decided to export. The server can serve several clients. The best technic to implement a client/server model is the RPC (Remote Procedure Call).

Distributed Object Model: This model is very close to a client/server model in the way that the client invokes a method (object operation) of a distributed object. Concepts like client, server and services remain true in this model.

The Virtual Computer: Another concept highlighted in the state-of-the-art review is that of the virtual computer. This approach allows the hardware architecture to be masked to an application in order to give it the impression that it is being run on a centralized system.

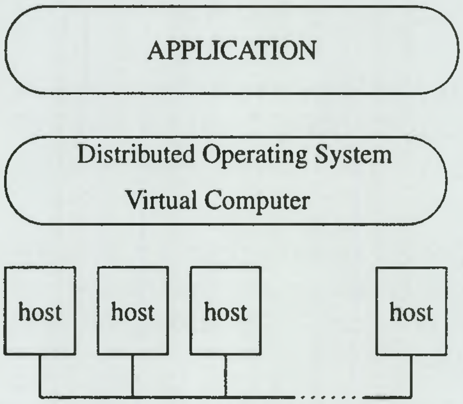

Fig 1: Virtual Computer

The virtual computer concept is closely linked with the concept of transparency. Several transparency levels are defined in the ANSA project:

- access-to-object transparency: an object (such as a file) may be accessed (i.e. opened, read, deleted etc.) in the same way whether locally or remotely. An example of a system offering access-to-file transparency is the NFS (Network File System). However, a real distributed system must provide this transparency for all the objects it manages (not only files, but also peripherals, processes, memory etc.).
- location transparency: a user or an application need not worry about the location of the objects he/it is handling. The NFS also offers this type of transparency: nothing in the filenames indicates the location of these objects.
- concurrency transparency: several users or applications may share a remote object without being aware of it.
- replication transparency: some objects are replicated without the application being aware of it. This is very useful for implementing hardware fault tolerance techniques by process replication.
- failure transparency: the occurrence of faults is masked to applications, or at least the work in progress is completed.
- migration transparency: objects can migrate from one computer to another without the application being aware of it.
- performance management transparency: the system can reconfigure itself dynamically in order to improve performance in a transparent manner.
- scaling transparency: the system or applications can change the execution scale (e.g.: increased number of computers in a network) without having to change the algorithms.

The implementation of the different transparency levels can be used to define a real distributed operating system based on the concept of a virtual computer. Most Industry or Research products provide both access and location transparency. Some provide even more, but at this point in time, none of the systems investigated are able to provide all the different kinds of transparency mentioned above.

Process groups: This concept can be found in many of the systems investigated. A process group, as its name indicates, groups together several different processes. Its advantage is that all the processes belonging to the same group receive the same messages.

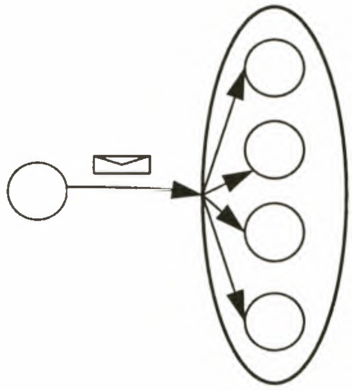

Fig 2: Process Groups

With this concept, message broadcast and above all fault tolerance can easily be implemented by replicating the same processes on different sites.

3. SOME DISTRIBUTED TECHNOLOGIES

CORBA (Common Object Request Broker Architecture) is a specification from the OMG (Object Management Group). The aim of CORBA is to provide a standard distributed object model to computer industry. The CORBA architecture is based on a software bus, named ORB (Object Request Broker).

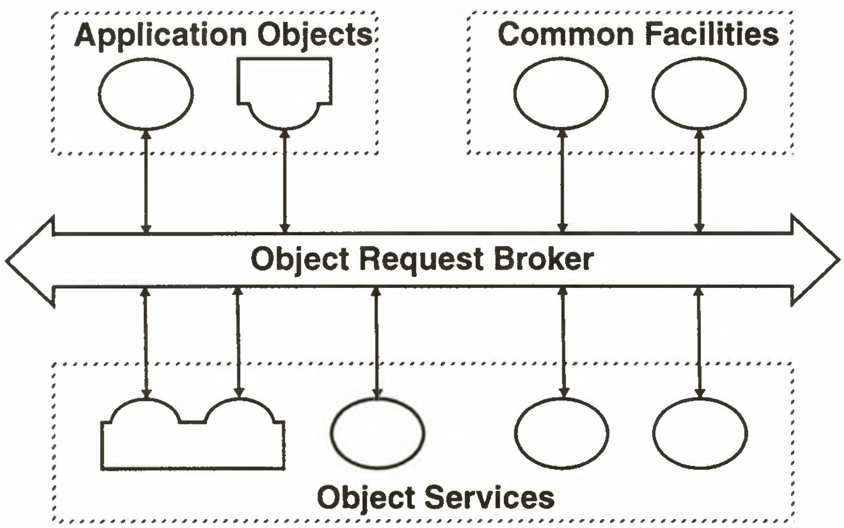

Fig 3: CORBA architecture

This bus is responsible for communications between applications. Many implementations of CORBA standard exist. We have chosen to use the IONA ORB named Orbix.

ISIS is a toolkit (tools and C API) allowing the development of fault tolerant distributed applications. The main concept is the process group. In order to provide an Object Oriented interface to ISIS, IONA and Stratus have together developed a fault tolerant ORB based on Isis technology. This means that interfaces are CORBA-like but implementation is based on ISIS. So Orbix+Isis is the first and the only fault tolerant ORB CORBA.

DCE (for Distributed Computing Environment) is an OSF standard. DCE provides some interesting features like naming, RPC, synchronisation of computers and a powerful distributed file system. DCE seems to be very adapted to geographically distributed applications with security constraints. In fact, security is based on Kerberos protocols allowing authentication, secure communications and authorization. The main DCE drawbacks are its cost, performances and a non object oriented API (Application Programming Interface).

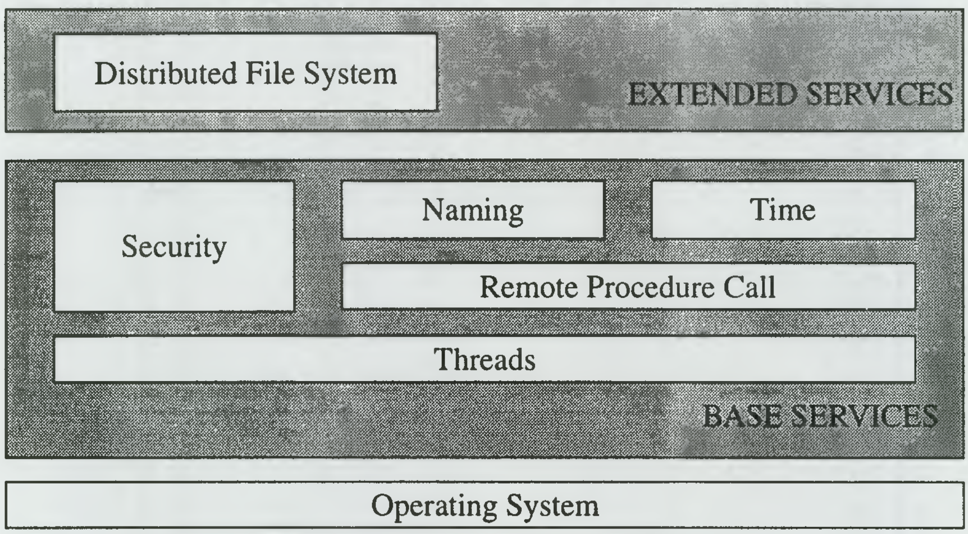

Fig 4: DCE Software Architecture

Introduced in 1995 by SUN, **JAVA** is an object oriented language close to C++ functionalities but easier to use. JAVA offers a powerful language with base classes, a portability approach (UNIX, WINDOWS, MAC) and an integration to WWW allowing users to communicate with JAVA applications via a browser JAVA compliant. JAVA can be considered as a distributed middleware in the way that the code of JAVA programs can be transferred from the Web server (httpd) to be executed on the client computer.

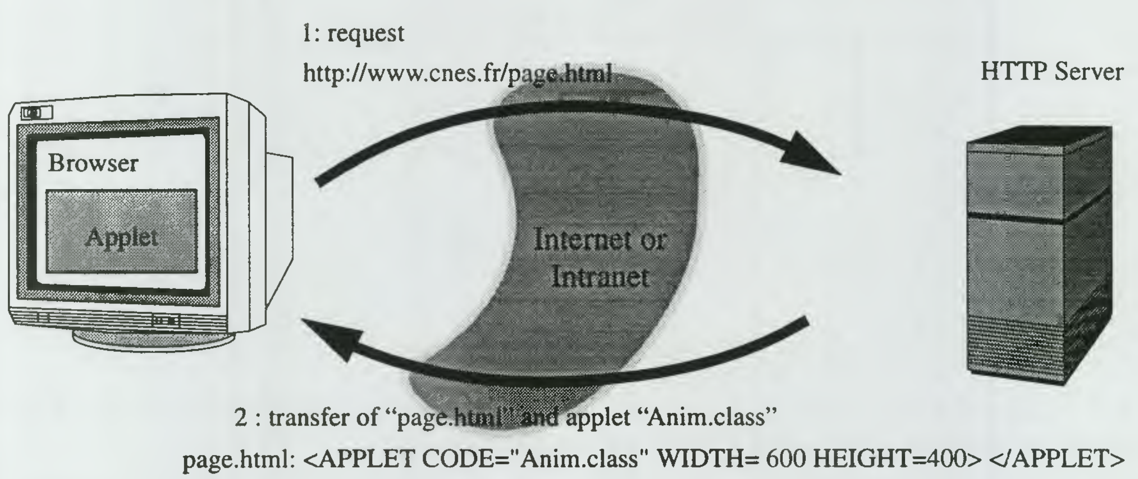

Fig 5: Applets JAVA and WWW

4. THE CONTRIBUTION OF THE CONCEPTS AND TECHNOLOGIES

Adapting the architecture to the application: When building a spacecraft control center, the manufacturer and hardware architecture are both selected at the outset of the project, before software development begins. Sometimes, however, software development can last several years (1 to 5).

One never knows before the application's validation if the hardware architecture will be efficient enough to run the application. If it is not efficient enough, the current configuration either has to be upgraded (through extra memory, CPU board, additional disks etc.), or the software code has to be optimized. If the power of the CPU board cannot be upgraded, one or more extra computers have to be added, requiring a change in the architecture, and therefore a change in the application code.

Using a distributed system implementing the concept of a virtual computer enables the architecture's distribution to be masked to the application. Thus, it is quite possible on integration to redistribute application components over another distributed architecture while maintaining its performance standards (addition of a computer) and without having to change the application code.

Keeping one step ahead of architecture obsolescence: Owing to the current developments in data processing technologies, the price/performance ratio of computers is constantly decreasing such that the architecture selected at the beginning of the project is technically superseded by the end, and the resulting price/performance ratio is very poor. The project investment cost may appear to be relatively high compared with the architecture's real value at the time of validation. Furthermore, there may be a better architecture/manufacturer pair at the time of the application's validation.

One solution consists in choosing the target architecture after the application has been developed. Firstly, this requires the use of a standard (Unix) operating system in order to be independent of the manufacturer. If this system implements the virtual computer concept, the application also becomes independent of the architecture. However, this poses many problems: firstly, if no architecture is chosen, on which computers will the application be developed? This problem can be solved by buying "low-quality" workstations which will be used exclusively for development work. Secondly, is it really possible to do without the specific characteristics of a project (communication protocols, fault tolerance etc.) which often determine the choice of architecture at the outset of the project?

Simplifying the development of distributed applications: The design and development of a distributed application is quite complex: using tools such as TCP/IP sockets is not easy, and the final development of a distributed application may even be distinctly difficult (error reproducibility difficulties, no final development tools etc.).

The development of distributed applications can be simplified using the CORBA-based distributed object model. CORBA provides interface description languages and generators which allow the developer to concentrate exclusively on the development of server's objects and customer invocation of methods without worrying about network communication. The server's objects interfaces are clearly defined and, as a result, their final development becomes easier.

Tolerating hardware faults: Hardware fault tolerance acts as a brake upon distribution. It has a direct effect on both the architecture's design (redundant computers) and development (reconfiguration scenarios, failure processing etc.).

In some applications the problem is solved by:

- using fault-tolerant computers.
- replicating computers so as to be able to reinitiate the application on the redundant computers.

The solution based on fault-tolerant computers may be deemed expensive. Computer replication may be inappropriate as it requires that the application should be stopped and then reinitiated on another machine with the same hardware configuration.

Fault tolerance problems can be solved efficiently - and without having to buy specific computers - with a distributed system implementing the process groups on replicated computers. Indeed, as the processes are replicated on distinct computers, the failure of a single computer does not affect the application's operation.

5. THE PROTOTYPE

The objective of the prototype's development was the practical validation of the aforementioned concepts, namely the concepts of virtual computer, distributed object model and process groups.

Thus, the prototype was designed:

- to be independent of hardware architecture. It is hoped that our application will be able to run on one, two or "x" number of computers without having to resort to recompilation. It was therefore decided to develop and validate our distributed application on a single computer before testing it on a distributed architecture.
- to be independent of the manufacturer by using Unix standards (portability).
- to tolerate computer hardware failures without affecting the application's operation.
- to integrate PC computers (with JAVA) for low cost end-user displays.

It was decided to put the previous concepts into practice in an application typical of the space environment, and building a prototype inspired by spacecraft control centers appeared a judicious idea.

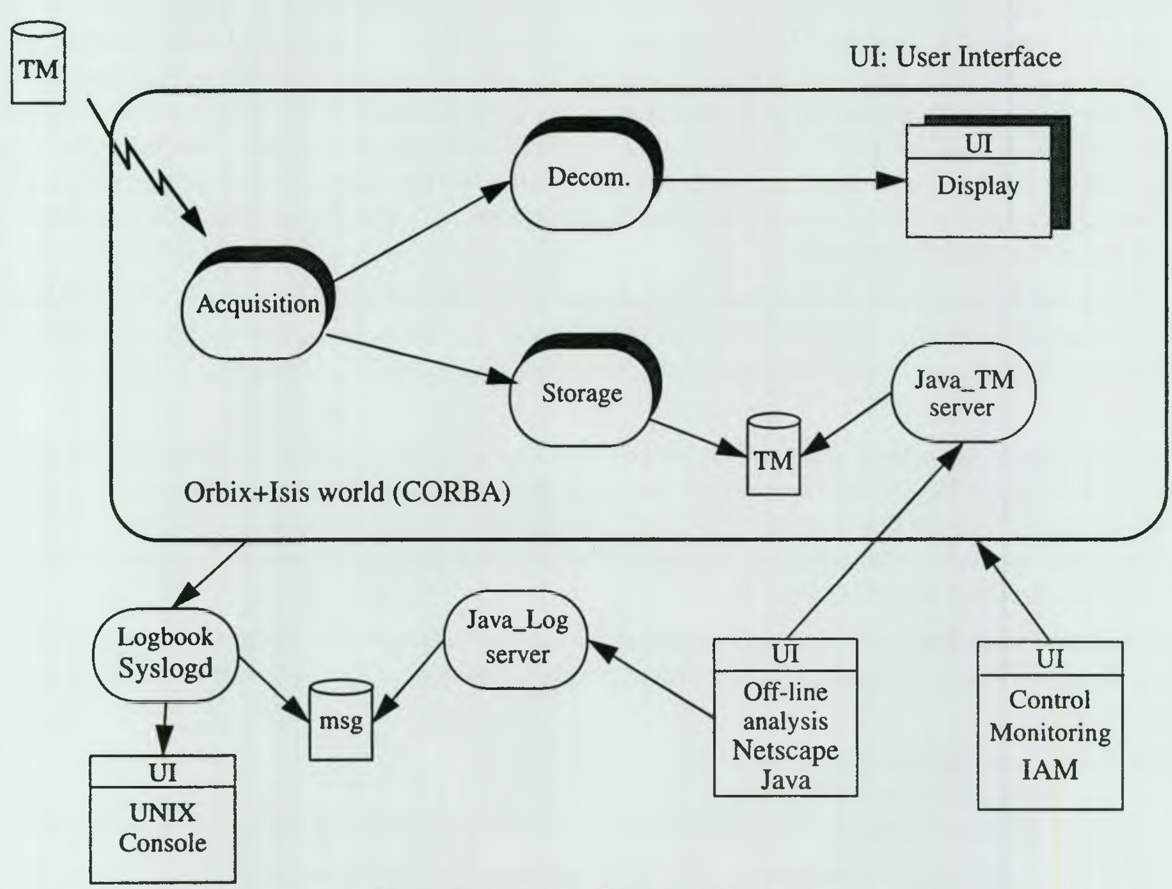

Fig 6: Prototype software architecture

The following functions were chosen:

- Telemetry acquisition and decommutation,
- Real-time telemetry monitoring,
- Control and monitoring of the distributed application,
- Real-time logbook,
- Off-line analysis of the logbook,
- Off-line telemetry processing.

The prototype have been realized by Cap Gemini company. Its environment consists of:

- the C++ language for modular software development.
- the JAVA language for developing some graphical interfaces integrated to Web browser JAVA compatible.
- the Orbix+Isis product from Iona and Stratus companies. This product is a Corba ORB implementing the process group concept.
- an ORB-like for JAVA applications allowing JAVA "applets" to communicate with CORBA servers. This JAVA/ORB is a freeware from SunSoft: ROJ (Remote Object for Java).
- the IAM (Isis Availability Manager) product from Stratus/Isis company. IAM allows to control a distributed application (stop, start, sensors, triggers, rules, faults detection...).
- the OSF/Motif system for multiwindowing combined with a graphic interface generator.
- the UNIX Syslog facility for logging messages.
- a UNIX system complying with POSIX and X/OPEN standards, to be independent of the manufacturer. Whilst our application is intended to be developed on a SUN/SOLARIS workstation, the target architecture will actually comprise DEC, HP and SUN UNIX computers.

6. CONCLUSION

This research project is now completed. Results are positives and we hope that future developments in spacecraft control centers will integrate distribution concepts so as to be able to develop space applications which are flexible, upgradeable, hardware fault tolerant and above all independent of hardware architecture.

NETWORK TECHNOLOGY FOR COF AND ATV OPERATIONS

FROM EARLY UTILIZATION TO FULL IMPLEMENTATION

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ABSTRACT. The Interconnection Ground Subnetwork (IGS) will provide the communications infrastructure to support operations of the Columbus Orbital Facility (COF) and the Automated Transfer Vehicle (ATV). This Network will interconnect all European sites for operations and experiment support and provide the operational links and services to NASA and Russian sites. This paper describes the design principles and the strategy for the IGS implementation. The initial preparation phase is characterized by the use of the IGS testbed network in supporting precursor telescience missions. On the basis of the experience gained in these pilot scenarios the paper will then introduce the strategy of considering the technological evolution in the realization of the final communications architecture, with a particular emphasis on the cost-efficiency aspects.

1. INTRODUCTION

The Interconnection Ground Subnetwork will constitute the ground network infrastructure to provide the communications services for the distributed ground facilities involved in operations of the Columbus Orbital Facility (COF), which is the European part of the International Space Station, and of the Automated Transfer Vehicle (ATV). In the preparation phase, a prototype implementation of the IGS, called IGS-Testbed, has been set up, and has successfully supported precursor scenarios of European tele-science mission operations during International Spacelab and MIR missions.

This article starts with a description of the target architecture for the fully deployed network and its services. Then the present achievements will be presented which support the proof of concept. It will then elaborate the trends of developments in communications in the rapidly changing technology environment while focusing on those topics which are relevant to COF and ATV project requirements. To secure easy migration capability a consistent strategy has to be followed. This will ensure that also in implementations for early utilization future carrier tariff reductions and performance implications will be taken into considerations such that minimum adaptations will be needed while following the technological evolution.

2. THE TARGET SCENARIO FOR COF AND ATV REMOTE OPERATIONS

The communications architecture to support Columbus and ATV operations and remote science operations is depicted in figure 1. The main facilities in Europe are the control center for COF and ATV, the ESA Astronaut Center (EAC), the User Support and Operations Centers (USOC), and the engineering support facilities for COF and ATV. The connectivity and provision of operational services between the dispersed sites in Europe and the operational centers of NASA and in Russia will also be provided by the IGS. This network will be operated from a dedicated Network Management Facility (NMF) located at the European Space Operations Center (ESOC) in Darmstadt.

The anticipated scientific experiments in COF and the SSF and the expected consequences for future manned space exploration resulted in an evolution of perspectives since the days of Spacelab development and various new factors need to be taken into consideration: the demand to support remote system and science operations from Europe over a period of over 10 years has introduced new terms of requirements, the technological evolution in the field of communications is extremely progressive, and new developing tariff structures will lead to cost optimizations by mapping of communication requirement service profiles to the appropriate technical implementation concepts.

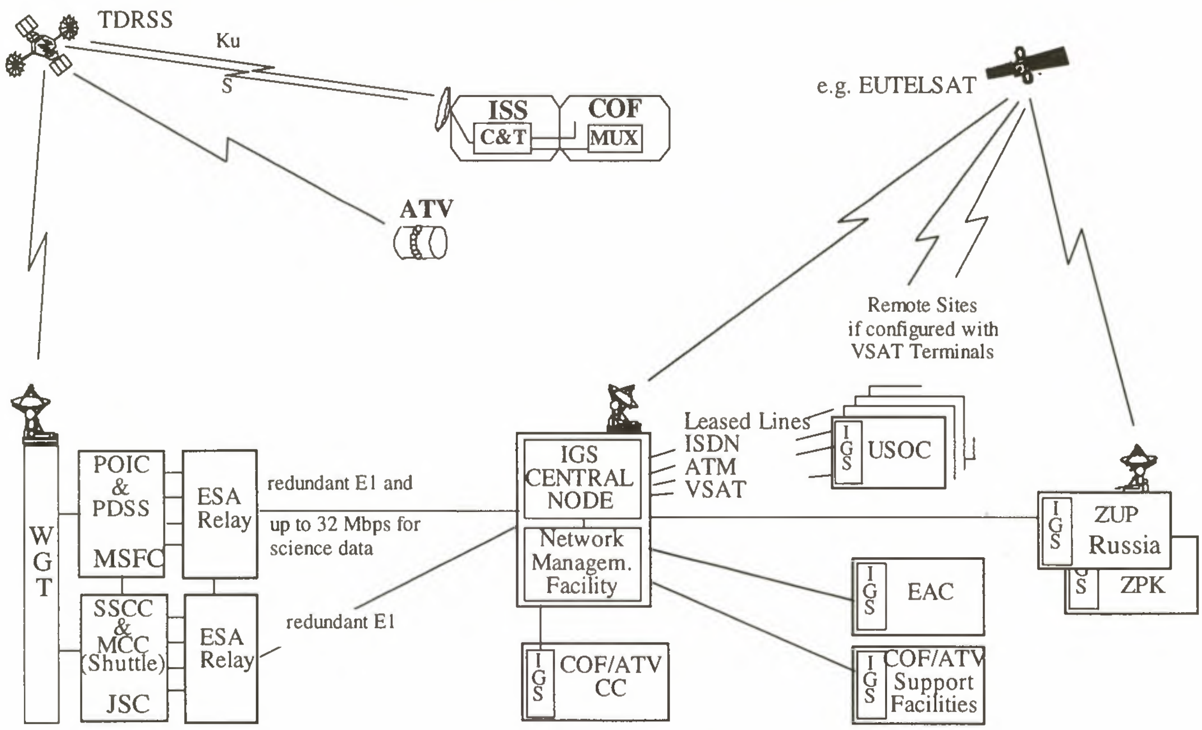

Figure 1 - Columbus and ATV Communications Scenario

The IGS will support a broad spectrum of communication services, ranging from typical data distribution services for telemetry, telecommanding and mission management information access, to new high speed data applications for science, multimedia applications like video conferencing/multicasting, and voice conferencing for operations coordination. For remote science operations the enhancement of the scientific return is achieved by enabling the principal investigators (PI) to conduct those experiments from their home laboratories, where dedicated expertise and processing facilities are available. While the communications support for system operations will have to respond to very high availability, reliability, safety, and security requirements, for experiment operations in addition large bandwidth and possibly very bursty data traffic will have to be supported.

Figure 1 also depicts the trans-Atlantic links between the NASA sites and the IGS central node at ESA/ESOC. While the communications bandwidth demand for system operations is comparatively low (~ 2 Mbps) and constant, the experiment data flow from MSFC can be very dynamic (up to 32 Mbps). It is essential that the costly bandwidth between NASA and the European sites can be shared and redundant information transmission will be omitted, e.g. on-board video is transmitted once to the central node in Europe and multicasted from there. Services with high availability and reliability requirements will be supported via leased lines (core network) with on-demand backup resources in case of line failures. Experiment data with more dynamically changing bandwidth requirements will make use of technologies which allow economic bandwidth adaptation to data rate peaks. This can be accomplished today by on-demand aggregates of ISDN channels and in the near future by Asynchronous Transfer Mode Technology (ATM). Similar considerations apply for the data transport within Europe. Here in addition satellite based multi- and broadcasting services using VSAT terminals can play an important role.

The implementation of IGS will take place in three phases:

- Testbed activities to investigate technical feasibility, applicability of new standards (CCSDS), and to validate the concept during the support of precursor missions,
- The early utilization phase in which by initial operational IGS implementations first ATV and COF related communication functions can be provided,
- The final phase when the network is fully deployed.

Although all installations will be completed in the third phase the connectivities and link resources will vary as they will be continuously be adjusted to changing of experimenter requirements.

3. STATUS OF THE PRECURSOR IGS AND MISSION SUPPORT

In the initial phase in 1992 the testbed activities at ESOC focused on validation of CCSDS standards and compatibility tests with NASA. With the successful completion of these studies the next aim was to prove the design concepts for the IGS and gain experience and feedback from a real implementation in a distributed environment. The initially sheer test network was turned into an experimental pre-operational infrastructure interconnecting various European facilities. The setup, in different configurations and including different sites, supported a number of Spacelab missions (ATLAS-2/3, IML-2) [1], the EUROMIR-95 mission with a duration of 6 month until the recent Spacelab mission LMS.

The important lesson learned from conducting the different missions supports as independent fixed-budget projects, came from the analysis of the planned and actually incurred costs, which identified the dominance of connectivity cost versus the hardware cost [2]. E.g. for a Spacelab mission support, lasting typically 6 months including preparation and test phases, more than half of the overall cost was constituted by the connection charges. This led to the refinement of the cost estimation process prior to a mission, based on the planned mission timeline and on the selection of the most appropriate connectivity technology for each service and each user site.

Besides the provision of leased line interfaces all nodes now are equipped with ISDN inverse multiplexers which allow on-demand connectivity with aggregated bandwidth of multiples of 64 kbps up to 2 Mbps. The cost efficiency of this connectivity combination was confirmed during the precursor missions based on the following principles:

- Test and mission simulations require relatively short active periods separated by longer intervals where no communication support is required. This phase is best supported by on-demand services.
- For the last system test and the mission proper leased lines provide higher availability compared to ISDN for voice loops and data connectivity, while ISDN remains for backup capability and supports on-demand video dissemination or conferencing.
- The EUROMIR-95 mission also included VSAT terminals which supported scheduled video transmission from the space station and video conferences. This concept is considered to become cost efficient for future video broadcasting services.

These principles were applied in the support of science teleoperations during the recent Spacelab LMS mission (20.06.96 - 07.07.96). At any time of the project the status of the accumulated connectivity charges were visible so it was ensured that the calculated cost envelope was not exceeded. The communications scenario of the LMS mission is depicted in figure 2.

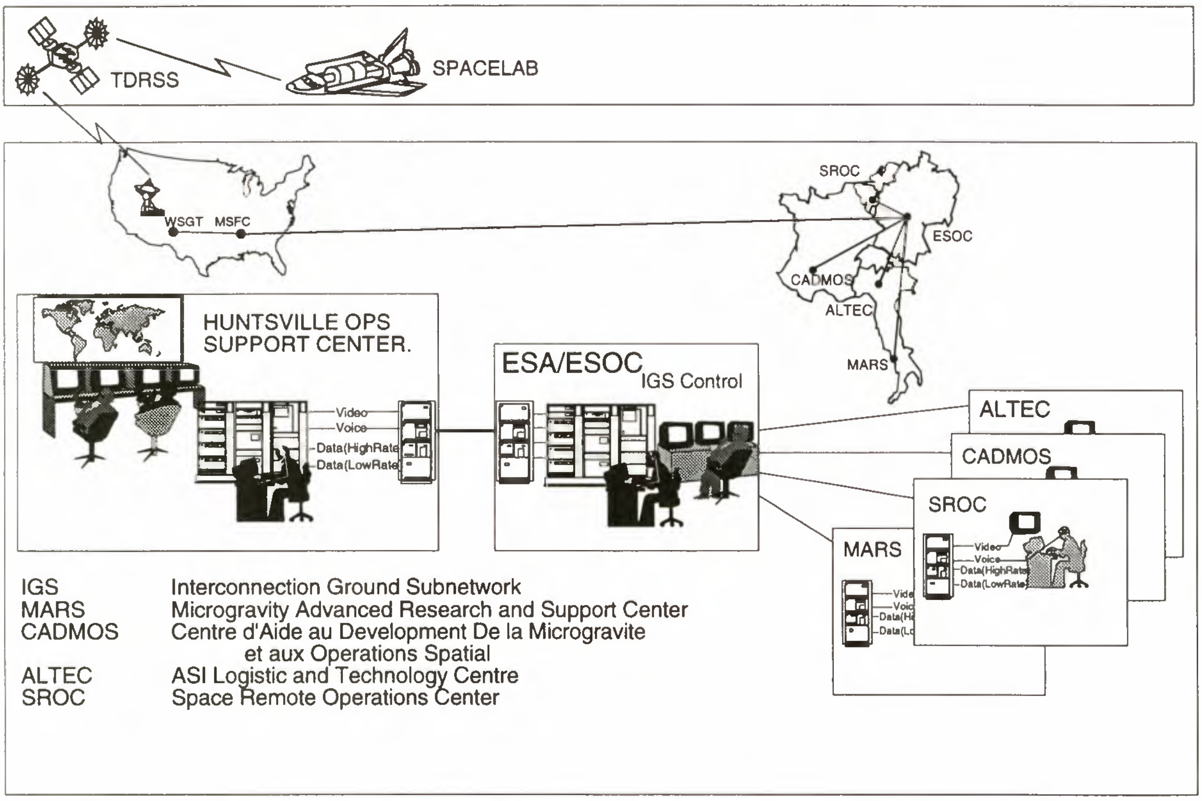

Figure 2 - The IGS-Testbed setup in support of Spacelab Mission LMS

The IGS-Testbed uses state of the art equipment and is based to the maximum extent possible on commercial off-the-shelf technology, to minimize procurement costs and implementation time. Hybrid switching nodes support both packet and circuit switching, which interconnect the various end and intermediate systems like video codecs, multi-protocol routers, voice conferencing units, to provide the end-to-end services.

Figure 3 depicts the current locations of IGS testbed nodes. Additional to the IGS testbed nodes in Europe two nodes, representing precursor ESA relays at JSC and MSFC, provide end-to-end services between the NASA sites and the European IGS sites. Currently the ESOC-MSFC link is supported by corporate network bearer services while the JSC-ESOC link is established based on ISDN technology.

Particular emphasis has been put on the development of an integrated platform for the network management of the whole IGS, with the target of an operational system requiring dedicated expertise only at a central location and minimum support at the remote sites. Since the various systems come with different management interfaces, often non-standard, this would have lead to a collection of management applications in the network control area, with the effect of preventing the operators from having a complete view of the network, and introducing very complex troubleshooting procedures.

The network management platform chosen was based on an expert system customized to interface and manage the various systems according to the particular needs of the remote operations support scenario. Due to the heterogeneity of the network management interfaces, the customization effort was substantial, revealing the criticality of a proper choice of the network management interfaces and standards.

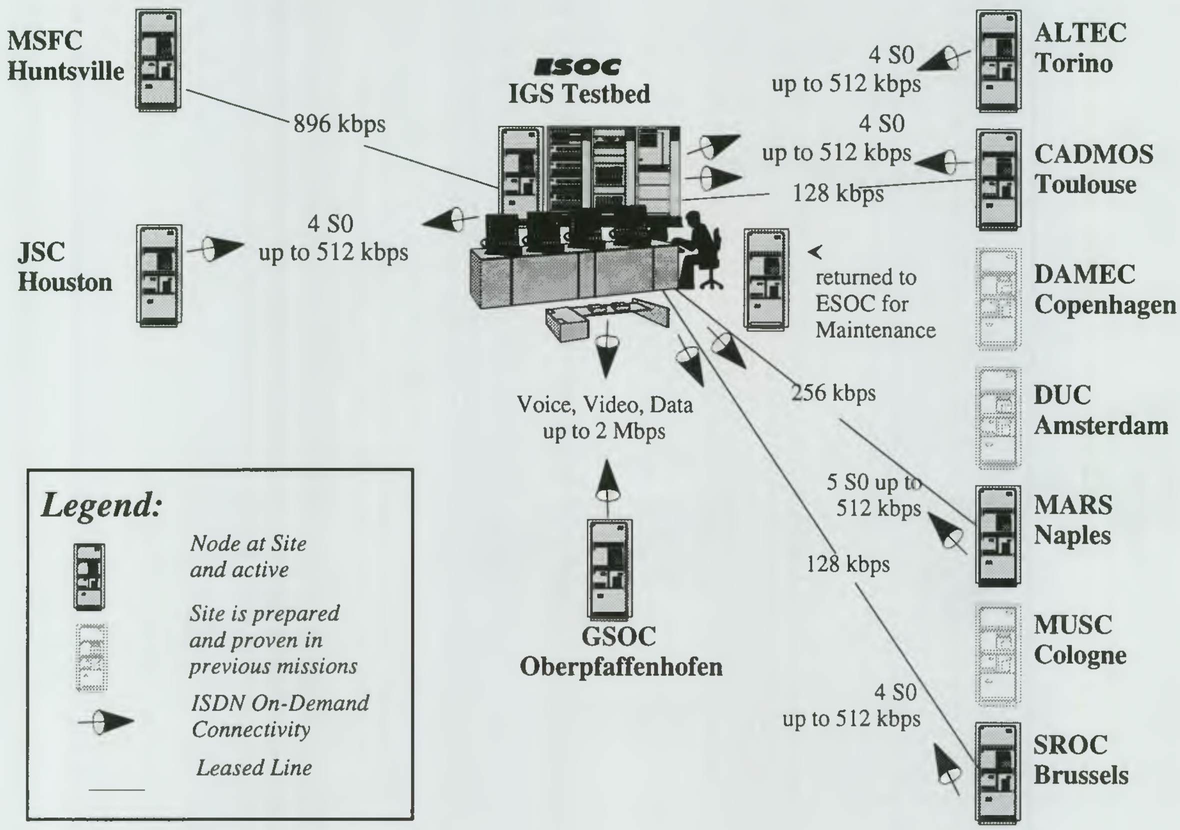

Figure 3 IGS installations and available Services

4. IGS ARCHITECTURE RESPONDING TO COMMUNICATIONS EVOLUTION

For the migration to the final IGS implementation, new requirements will have to be considered and upcoming technologies will be exploited, adapting the design principles validated in the testbed to the evolving scenario. The design will focus mainly on two directions: the selection of optimum network technologies and connectivity resources and the definition of an integrated network management architecture.

4.1 ATM Network Architecture and Services

The IGS will certainly exploit the benefits of the ATM, with the objective to combine the various IGS services into a single network technology. Figure 4 depicts a preliminary scenario on the utilization for the IGS of ATM-based on-demand connectivity, which is expected to be available in public B-ISDN networks by the time frame of the Columbus utilization.

In this scenario, the IGS network has a star topology, with a central node located at ESOC, and two relay nodes at NASA MSFC and JSC locations. Other nodes are located at European operation facilities, user, support and industrial sites.

The IGS nodes are based on ATM "edge" switches or access concentrators, whose function is to collect the IGS traffic, perform IGS traffic routing and interface to the connectivity resources, both permanent or on-demand.

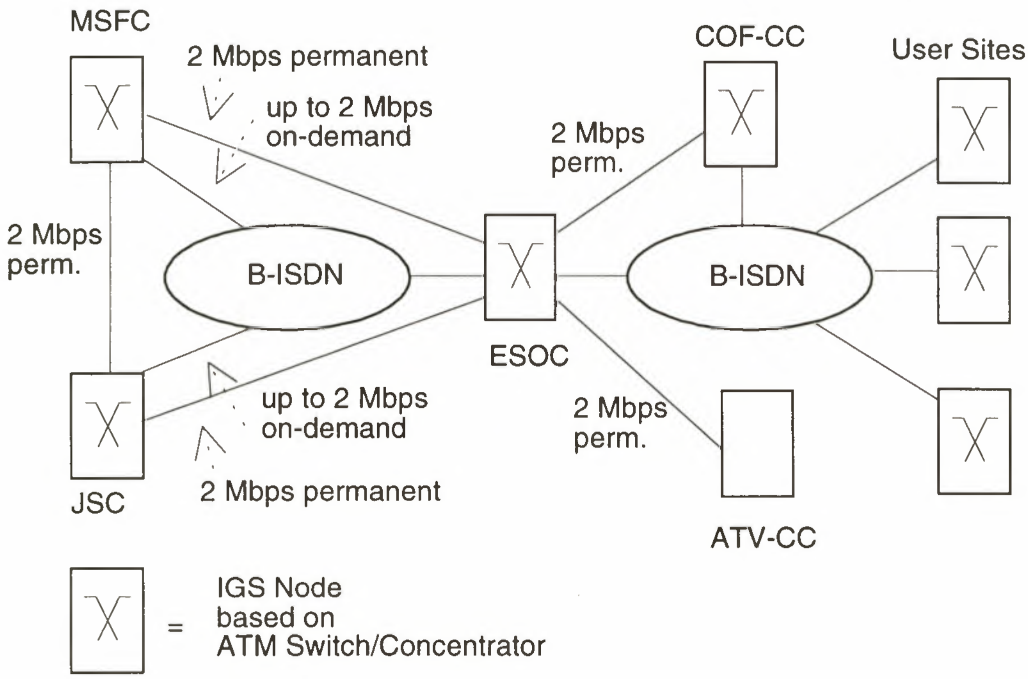

Figure 4 - ATM-based IGS Implementation

The basic concept is that permanent connectivity is implemented only for those services requiring the most stringent availability figures or for those services whose utilization patterns justify this choice from an economic point of view. The permanent connectivity can be based on traditional leased lines, also via satellite, or by dedicated resources on the public ATM infrastructure. The usage of ATM also on fixed-bandwidth connectivity is justified by the inherent optimization offered by the statistical multiplexing nature of ATM. The on-demand resources are represented by switched ATM connections realized over the public infrastructure. These connections can carry the IGS traffic with bursty or time-variable nature, and also constitute a back-up of the permanent connectivity.

ATM networks will include sophisticated traffic and congestion control capabilities, which are currently the subject of ongoing research and standardization effort. The aim is to maximize the overall network utilization for the network operator and to offer to the network user the possibility to choose among different network services characterized by different Quality of Service (QoS) parameters and different tariffs. The complexity originates from the fact that the range of services to be supported has extremely different requirements, from real-time delay-sensitive services, like isochronous video and voice, to typical bursty data applications.

It is important that the end applications which will be developed to support the Columbus scenario and the IGS communications architecture will take into consideration the new ATM services and capabilities, because their proper usage will lead to considerable savings both in the case of IGS constituting a “private” ATM network infrastructure (better resource utilization) and in the case of IGS using “public” ATM connectivity services (better tariffs' exploitation).

Table 1 shows a potential mapping of IGS applications and communication services into the ATM bearer services and QoS classes as currently defined by the ITU-T and the ATM Forum [3] [4].

The ATM Layer QoS is defined by a set of parameters, such as the ATM cell transfer delay (CTD) and cell delay variation (CDV), cell loss ratio (CLR), etc. Currently, the ATM Forum has defined five service categories, that are distinguished by the manner in which the QoS parameters are applied [4].

These categories are intended to accommodate a broad range of requirements of the applications and performance characteristics of the network, from real-time traffic with (ideally) zero cell loss to non-real-time traffic with unspecified performance. The QoS categories correspond to typical ATM supported services as indicated in table 1.

When a user requests a new ATM connection, the traffic characteristics in both directions of that connection must be specified, by selecting a QoS class and indicating the values of some traffic parameters and descriptors, like the Peak Cell Rate (PCR), the Cell Delay Variation Tolerance (CDVT), the Sustainable Cell Rate (SCR) and the Maximum Burst Size (MBS). If the network can commit the resources necessary to support that traffic description, it accepts the connection, thus forming a "traffic contract" with the user.

It is anticipated that the ATM services will provide different tariff structures, depending on the selected QoS classes and traffic parameters. The IGS applications and protocols will have to be designed in order to make an appropriate usage of the different services and capabilities offered, with the final objective of a cost-efficient architecture that meets the performance and reliability requirements of the end applications.

Concerning the tariffs, it can be expected that constant bit rate services will maintain a tariff concept somehow similar to present on-demand switched services like ISDN, and the usage charges will depend on the connection time of day, duration, data rate and distance. Instead, the variable bit rate services will offer new tariffing schemes, based more on the actual volume of data injected by the user into the network. Constant bit rate services should be used only by highly sensitive applications like high definition real-time experiment video, while other typical circuit applications of today, as video and voice conferencing will most likely be supported by the ATM real-time variable bit rate service.

The greatest cost-saving effects will come by a proper selection and dimensioning of the variable bit rate data services. An example of data service which can be based on variable bit rate ATM data service is the frame relay service, where the charging, apart from other fixed costs, mainly depends on the Committed Information Rate (CIR), which is the actual transfer rate that the network commits to support, after negotiation with the user. The user can inject more data in excess of the CIR but this can be subject to discarding in case of congestion. A similar tariffing concept can be envisaged for a pure ATM VBR data service, by using the notion of Sustained Cell Rate (SCR).

On-line real-time telemetry and telecommanding applications can make an efficient use of the VBR data services, by proper sizing of the CIR or SCR with respect to the actual minimum required throughput, and by exploiting the available network capacity to inject, at no-extra cost, bursts of data in excess of it.

Particularly interesting from the point of view of cost-optimization for the transfer of non-critical off-line experiment data are the emerging Available Bit Rate (ABR) services and "best-effort" or Unspecified Bit Rate (UBR) services. The Available Bit Rate (ABR) services are characterized by the fact that there is a minimum cell rate (MCR) agreed (or for frame relay CIR=min) but the user can make use of potential available capacity in the network by interpreting the congestion information originated by the network. This available capacity would then be used by the user virtually at no extra cost, under the condition that the network could discard the data in order to satisfy the committed information rate of other users, however notifying the ABR user via congestion indication that it should reduce its injected data rate. The "best-effort" or UBR service ensures no performance objective and is intended for users that can cope with cell losses and adapt to time-variable resources; in exchange, a very low charging can be expected, which could be interesting for off-line data retrieval or other non-critical Intranet applications.

<table>
<tr><th>IGS Applications and Services</th><th>Constant bit rate video and audio</th><th>Interactive Video, Audio Conferencing</th><th>High Speed Real-Time Telemetry, Telecommand</th><th>On-Line exp. data, Mission Planning Data</th><th>Off-line data retrieval, “Intranet” services</th></tr>
<tr><td>Potential Protocol Architecture (examples)</td><td>MPEG (CBR) video, H.320/H.261 video, CBR voice conferencing</td><td>future VBR video (MPEG-2 over ATM) and audio coding schemes</td><td>High Speed Transport Protocol over Frame Relay or direct ATM</td><td>TCP/IP/ATM, TCP/IP/SMDS /ATM
new TP/ATM</td><td>TCP/IP/ATM</td></tr>
<tr><td>Service Supported by ATM network</td><td>Circuit Emulation</td><td>Variable bit rate audio and video</td><td>Variable Bit Rate Data Transfer</td><td>Available Bit Rate Data Transfer</td><td>Best Effort Data Transfer</td></tr>
<tr><td>ATM Layer Service (QoS) Category</td><td>CBR</td><td>rt-VBR</td><td>nrt-VBR</td><td>ABR</td><td>UBR</td></tr>
<tr><td>QoS Parameters</td><td colspan="2">peak_to_peak CDV, maxCTD, CLR</td><td>CLR</td><td>CLR (network specific)</td><td>none</td></tr>
<tr><td>Traffic Contract</td><td>PCR, CDVT</td><td colspan="2">PCR, CDVT, SCR, MBS</td><td>PCR, CDVT, MCR</td><td>PCR, CDVT</td></tr>
<tr><td>Potential Tariffing Scheme

Cost = I+M+V

I = Inst. charge
M = monthly fixed charge
V =variable charge</td><td>M = f (access speed, distance)

V = f(connect time of day, duration, data rate)</td><td colspan="3">M= f (access speed, distance)

V= f (connect time of day, duration, data rate)
or
f (negotiated sustainable icell rate)
or
f (injected data volume)</td><td>F= inst. charge + monthly charge

V = f (PCR) (low tariffing)</td></tr>
<tr><td>Tariff Examples (preliminary information)</td><td>M= f (access speed, distance to first switch)

V= f (connect time of day, duration, data rate class)</td><td>V = f(SCR)</td><td colspan="2">FR: V = f (CIR, distance)

FR ABR-like: CIR=min, V=f(CIRmin)

SMDS:
M = (access speed, fixed volume)
V = f (volume of additional injected data)

ATM nrt-VBR: V = f(SCR)

ATM ABR service: V = f(MCR)</td><td>V= low fixed rate</td></tr>
</table>

Table 1 - IGS Applications, ATM Services and expected Tariff Schemes

It is important to underline that only the applications capable to correctly interpret and react to the congestion avoidance information and mechanisms available in the ATM network will actually profit from these new service types. Since the required functions are located in the transport layer in the end systems and there is currently no standardization consensus, there could be the need to go ahead with solutions designed to suit the particular ESA applications.

Similarly with what has been done in the initial IGS testbed, a new experimental augmentation of the IGS testbed, based on ATM technology, is being prepared at ESOC in cooperation with the research center of a telecommunications provider.

4.2 Integrated Network Management

The experience gained with the IGS-TB in supporting the Columbus precursor missions has clearly indicated the importance of an integrated management architecture for the IGS. The objective is to achieve a centralized network management of the distributed IGS elements which is interacting with the operations control facilities to implement efficiently the communication services according to the mission timeline, and is representing for the IGS users a single point of contact for troubleshooting and service requests, minimizing the communications expertise required at the remote sites.

Figure 5 depicts a potential realization of an integrated network management scenario for the IGS. The Network Management architecture is based on a two-level hierarchical approach, which relies on the concepts of Element Management Systems (EMS) and Integrated Management System (IMS).

The Element Management Systems are the specific management systems of the main interconnected systems which compose the IGS: the video and voice conferencing systems, the Telemetry and Telecommand Systems and the Wide Area Network, which is intended as the core networking infrastructure based on switching and routing systems. It is possible that some management functionality will be grouped on a single system, but it is undoubted that a number of different management systems will exist, simply because it will not be economical to replicate all their specific functions and capabilities on another platform.

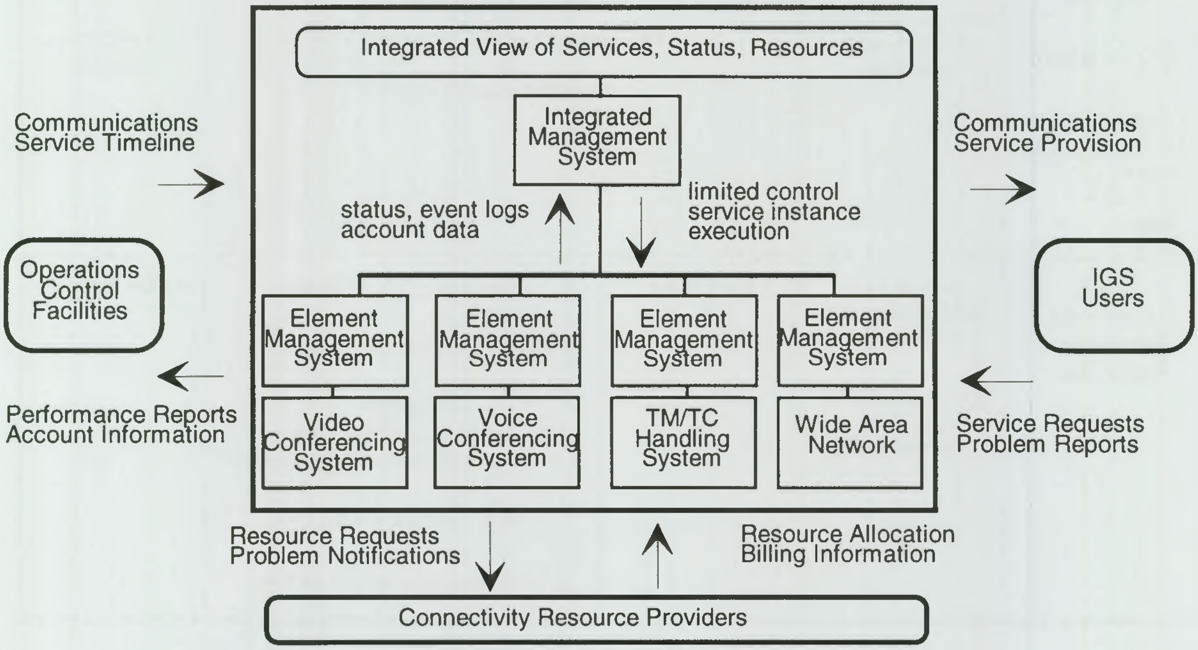

Figure 5 - IGS Network Management Architecture

The Integrated Management System has the task to integrate the capabilities of the Element Management Systems in order to provide a unified management view of the IGS.

While the EMSs are responsible for the complete management operations on the corresponding systems, the IMS collects monitoring information from them and interprets it to offer to the operators an end-to-end view of the status and the performance of the services provided and of the resources used. Also, some control functions will be exercised by the IMS, especially those related to the automatic execution of communications "service instances" which are derived from the communications service timeline generated by the operations control facilities.

The Element Management Systems will be provided by the manufacturer or developer of the respective systems. Their provision of standard interoperable interfaces based on CMIS/CMIP or SNMP protocols and services is a critical requirement, because the Integrated Management System will be based on a commercial-off-the-shelf platform implementing those standards. Should this requirement not be satisfied, the Integrated Management System must also render possible the development of custom agent functions to interface to still existing non-standard Element Management Systems.

5. CONCLUSIONS

The definition of an overall communications architecture for the support of remote operations and telescience operations requires careful analysis of the requirements of the new applications involved, which are new with respect to the traditional spacecraft support applications. The direct support of early precursor missions with a testbed implementation has given ESA the chance to gather this knowledge and to identify the critical technical and cost aspects. During these precursor missions also the validity of the concept was confirmed and the broad acceptance of the IGS users is attributed to the demonstrated increased science return. For the near future, it is important that the evolution of communication technologies and services is closely followed and reflected into the final design phase, in order to achieve a cost-optimum implementation.

ACKNOWLEDGEMENTS

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EUROMIR 95 GROUND SEGMENT DESIGN AND IMPLEMENTATION

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ABSTRACT. The EUROMIR 95 mission was the European Space Agency's (ESA) longest manned mission to-date and because of this a decentralised operations concept was developed to allow users to remain at their home bases rather than spending long periods at a central control centre. Due to the resulting large number of involved centres supporting the EUROMIR 95 mission, taken together with the decentralised operations concept, a complex ground segment had to be defined and implemented. Two further constraints were influential in the definition and implementation of the ground segment. Firstly, only 6 months were available for the complete definition, implementation and testing, and secondly the ground segment implementation should use existing systems/equipment as far as possible to limit the implementation costs. This paper describes the definition process and the resulting ground segment, details the advantages and disadvantages which resulted from the mixed communications system design, describes the experience gained during the implementation and test process and the finally touches on the experience gained during course of the EUROMIR 95 mission. Furthermore, the paper goes on to make recommendations for the definition and implementation of ground segments for future manned missions.

1. DESIGN APPROACH

The complete ground segment for the EUROMIR 95 mission had to be defined, implemented and tested within a very tight schedule. According to the overall project schedule approximately 6 months only were available for all the above activities. Not only was the schedule tight, but also due to the decentralised nature of the mission operations and the large number of participating sites, a complex ground communications network with a high degree of flexibility needed to be implemented.

The definition was complicated by the fact that only top level user requirements were provided by the project at the beginning of the design phase. Therefore, the requirements for the implementation were largely defined by DLR and the European Space Operations Center (ESOC) based on experience from previous missions. These requirements were then iterated with the project through discussions which preceded the project's approval of the defined Ground Network Infrastructure (GNI). However, it should be noted that the requirements on the data handling side remained fluid throughout the complete design, implementation and test phase. This was primarily due to a lack of agreement/system implementation with/by the Russian Control Centre (ZUP) and National Aeronautics and Space Administration (NASA). Naturally, this led to problems implementing a final system within the defined implementation schedule, with the consequence that the final data handling system was available to support neither the initial test activities nor the two Operation Simulations.

The following gives an overview of the major user requirements influencing the GNI definition:

- MIR video, Air-to-Ground (A/G) audio and downlink data to be transmitted from ZUP to SCOPE
- Data distribution from SCOPE to the user sites
- Nine sites to be provided with an audio conferencing capability through the use of remote keysets connected to the GSOC Voice Intercom System (VIS); Space Remote Operations Center (SROC),

Center for Assistance to Development for Microgravity Operations in Space (CADMOS), Agenzia Spaziale Italiana (ASI) Logistic Technology Engineering Centre (ALTEC), Danish Medical Center (DAMEC), European Astronaut Centre (EAC), Microgravity User Support Center (MUSC) with two keysets, European Space Research and Technology Centre (ESTEC) with three keysets, ZUP and ESOC

- The remaining sites to be able to connect into the GSOC VIS via a telephone connection; the so-called Public Switched Telephone Network (PSTN) Interface
- Nine sites to be provided with the capability to receive video on demand and to participate in video conferences; ESTEC, EAC, MUSC, SROC, CADMOS, ALTEC, DAMEC, ESOC and ZUP
- The World Wide Web (WWW) to be used for the dissemination of planning information and together with the Internet for the submission of electronic mission planning and data replay requests

Given the above constraints and to provide a cost effective ground segment, an analysis was first performed to identify what systems/equipment were already available and which of these could be utilised to support the mission and meet the user requirements. The resulting GNI definition was therefore based heavily on the further utilisation of the existing ESA communications infrastructure, Direct Inter-establishment Communications in Europe (DICE) and the Interconnection Ground Subnetwork (IGS), on the existing German Space Operations Center (GSOC)-ZUP satellite link and on the infrastructure available at the System for the Control of the Operations of Payloads for EUROMIR (SCOPE). In this way the need for procurement of new equipment was kept to a minimum, and was generally restricted to the procurement of extensions to the existing equipment, i.e. IGS Node or DICE station. As such the technical risk was correspondingly kept to a minimum. However, certain modifications to the above systems were unavoidable to meet the specific needs of the EUROMIR 95 project.

2. RESULTING GNI DEFINITION

Based on the requirements given above and respecting all constraints the following EUROMIR 95 GNI operational definition resulted, see also Figure 1 on page 3:

- GSOC-ZUP link to provide the nominal data and A/G audio connection to the ZUP, to support the operation of the ZUP remote keyset, and to provide a telephone/fax connection. Additionally, the DLR earth stations in ZUP and SCOPE were utilised to provide a backup video capability
- IGS to provide an on-demand voice and video conferencing capability for SROC, CADMOS, ALTEC and DAMEC. Additionally, the IGS was required to support the prime data distribution to ALTEC and CADMOS and a backup route to the other two sites, and in combination with ESANET to support the operational fax (X.25) to Moscow and all ESA sites
- DICE stations at ZUP, SCOPE, ESTEC and at the EAC shared with MUSC to provide a four way video conferencing capability, the prime means for video distribution from the ZUP, and a limited data distribution and Internet access capability, including backup telemetry data transport from ZUP to SCOPE. Additionally DICE provided the capability for data exchange between the various sites, including a backup fax capability
- A mixture of leased lines and ISDN, based on a cost optimisation, for providing the communication lines between the SCOPE and the DICE sites for connection of the remote keysets
- Internet (including the DLR WIN and ESA ESANET networks) to provide the prime means of data distribution to all EUROMIR 95 sites, with the exception of ALTEC and CADMOS (due to security restrictions at these sites)
- SCOPE infrastructure systems, VIS, Video System and Data Handling Systems to support the reception, archiving, processing, display and distribution (as required) of mission data (video, audio and digital)

- ZUP Systems; DICE system, GSOC interface computers and ground station, PABX and remote keyset providing a support infrastructure to the MOST team and interfacing to the ZUP systems

As stated above the GNI could only be implemented within the tight schedule through the use of existing systems, and this led to a very flexible system with many backup possibilities. However, this approach also had a negative side. As can be seen from Figure 1, the GNI was comprised of a mixture of networks each with its own network management. There was no central network management and due to the interfaces between the various networks it was not always possible to identify exactly where a problem lay. Furthermore, due to the highly decentralised manner of the EUROMIR 95 operations and the mixed communications systems this also led to very complex troubleshooting. The experience showed that in the areas where good monitoring information was available, particularly if this information was centrally available, then the troubleshooting tasks were relatively straightforward. In areas where very limited or no monitoring information was available, or where several systems interacted without a centralised monitoring capability, then the troubleshooting proved to be a much more difficult and often time consuming activity. For future missions a centralised monitoring and control capability for all systems similar to that provided within the IGS should be ensured to ease the troubleshooting/management of the overall GNI.

Another consequence was that EUTELSAT became a single point of failure for the ZUP-SCOPE link (both the GSOC-ZUP and DICE links went via this route). As an example of the implication both the DICE and GSOC-ZUP links were affected by unauthorised transmissions occupying the same frequencies.

(Please note that modifications made during the course of the mission are also shown here).

Figure 1. Overview of the EUROMIR 95 Ground Network Infrastructure

3. GNI IMPLEMENTATION AND TESTING

This section describes the general approach taken and experience gained during the implementation and testing phase. Due to the limited time available for the implementation and the proportionally long procurement duration for various new items, the implementation schedule had to be developed around the procurement schedule. That is to say that the implementation of certain systems was dependent on the delivery of procurement items, whereas other implementation/integration activities could be performed without the need for procurement items. These activities were naturally scheduled appropriately.

Additionally, wherever possible the integration and test activities were scheduled in a way to minimise the required travel, and to reduce the travel costs, e.g. the integration and testing of keysets at a remote site coincided with the upgrade or delivery of an IGS node to that site. In this way the two activities could be performed by the same persons during a single visit.

The following major implementation/integration activities were required:
- Integration and upgrade of IGS Nodes
- New DICE systems at SCOPE and ESTEC
- Upgrading of the GSOC systems at ZUP
- Keyset implementations at ESTEC, SROC, ALTEC, ESOC, MUSC, EAC, ZUP, DAMEC and CADMOS
- Implementation of the necessary communications links (leased lines and ISDN connections)
- Implementation of PSTN-VIS interface system
- Implementation of EUROMIR 95 Data Handling System at SCOPE
- Implementation of EUROMIR 95 WWW/Request Handling system

Very few major problems were experienced during the implementation due to the use of known standard equipment/systems, and the implementation proceeded more or less according to the schedule (minor discrepancies are covered later). As such it can be stated that the implementation went very smoothly, at a system level, despite the tight budget/time scales involved. This was a direct result of the low risk approach taken to the design and implementation of the GNI, i.e. the use of existing equipment/systems and experienced personnel.

The test concept defined for EUROMIR 95 was based on four different levels of testing:
- Component level tests for all new or modified items
- SCOPE functional tests covering all SCOPE EUROMIR 95 systems
- SCOPE to remote site interface & functional tests covering all tests between the SCOPE and one site for all interfaces (data, voice and video)
- End-to-end tests involving all sites

Once again the test program was conducted with relatively few problems. However, the following major points can be noted w.r.t. the test activities from a system point of view:
- The test activities had to be scheduled based on a staggered availability of systems/sites in order for them to be completed within the available time
- The test activities could not always be carried out according to the schedule due to the incomplete implementation status of some systems (in particular the Data Handling System (DHS))
- End-to-end testing could not be fully carried out according to the overall test schedule due to the unavailability of the DHS. However, these tests could be successfully performed later prior to the launch

4. DETAILED IMPLEMENTATION AND TESTING EXPERIENCE

This section describes in more detail the experience gained during the implementation and testing of the various components of the GNI and covers the SCOPE, ZUP, USOC, ESOC and network implementations.

The definition for the EUROMIR 95 SCOPE was based as far as possible on the use of the existing GSOC systems with only minor modification/re-configuration. One of the required modifications was needed in order to interface the SCOPE voice, video and data systems with DICE and IGS, which due to the flexibility of these systems could be done without significant system modifications. The following covers the experience gained during the implementation and testing of the SCOPE systems:

- DHS
  The DHS for EUROMIR 95 was comprised of a Data Transfer System (DTS), data processing software on the GSOC I/F machines in the ZUP and data processing software at the SCOPE.
  The DHS, and in particular the DTS, proved to be difficult due to changing and partially missing requirements. Not only was it difficult to reach an agreement with NASA and ZUP w.r.t. to the respective interfaces, but also to obtain the required information from the user sites necessary to implement their data delivery. In particular:
  - ZUP requested a CCSDS format for experiment and housekeeping data transfer, but did not initially implement it
  - the NASA system was not completed until after the EUROMIR 95 launch due to the late launch of Spektr

  The above problems resulted in the DTS not being able to be implemented according to the overall implementation schedule and therefore the DTS was not able to fully support the end-to-end tests and simulations.
- VIS
  The GSOC VIS is a flexible, multi-mission system and therefore the needs of the EUROMIR 95 mission could be largely accommodated by standard re-configurations. However, to support the large number of remote users, new rate and terminal adapters (for interfacing to the PTT) were required to be procured and subsequently the remote keyset strings had to be integrated and tested. Also due to the additional delay over the satellite link to the ZUP a software upgrade in the ZUP rate adapters was required.
- PSTN I/F System
  The PSTN I/F system allowing outside users to connect into the VIS system from a normal telephone was a new implementation and the requirements matured as the design progressed and the operational implementation was assessed. The original requirement was for a single telephone connection to A/G, which then evolved into one connection with talk access and four additional ones in monitor only mode. This finally ended up as eight connections all with selectable talk/listen to practically all EUROMIR 95 loops. These changing requirements naturally impacted the design, leading to the necessity for rapid design changes.
  During the testing of this interface it became clear that the talk access must be restricted to a maximum of three external callers in order to provide acceptable audio quality
- WWW/Request Handling System
  In the original GNI design only an EUROMIR 95 WWW Home Page for public relations and general information purposes was foreseen. However, during the design and implementation phase a desire for a less paper intensive means of operational information distribution and requests handling was raised by the Project. The expanded use of the WWW was suggested and DLR agreed to investigate this. The result of the investigation was a prototype system, which was gradually refined during the simulation and test activities. Some modifications to the system were also required during the mission to handle unforeseen complications. However, these modifications could be implemented without impacting the nominal use of the system.

- DICE installation
  A number of problems arose which could only be resolved later through Software (S/W) upgrades to various components. Additionally, the implementor was not aware of the concept for the use of the DICE at SCOPE, in particular of the interfaces to SCOPE VIS and Video Systems. Finally, the period of one week for the installation and training of the DICE station was too short. Particularly when taking into account the number of staff that were required to be trained. Either more time should have be allocated to the training or the training should have been performed with a smaller, more selective group. These 'trainees' would then have been responsible for performing the training for the others.
- IGS installation
  This was performed relatively smoothly without any notable problems.
- Fax service
  A X.25 fax service was provided by connecting between the SCOPE and other EUROMIR sites via a combination of IGS and ESANET, and this required substantial troubleshooting over a period of several weeks between GSOC, IGS and ESANET before the cause of the problem could be tracked down and resolved
- Interfacing of DICE and IGS with SCOPE VIS, Video and Data Handling Systems
  In general the above was performed without major problems, with the exception of the connection of the IGS and DICE video systems. Synchronisation problems between the DICE and IGS video codecs were experienced requiring the additional installation of Time Base Correctors (TBCs) between the two codecs
- SCOPE Configuration
  To best meet the needs of the EUROMIR 95 mission, the EUROMIR 95 control room, the DICE video conference room and the mission management room were correspondingly configured. This included the procurement and installation of PCs, fax machines, video printers and direct telephone lines. Furthermore, to support the operation of DICE and IGS, a video selection panel and audio selection switch were installed in the DICE room, allowing control over the outgoing video and incoming audio to be possible. All implementations/installations were performed without notable problems.

The implementation and testing of equipment in the ZUP was on the other hand a very difficult process due to the complications given below:

- The transport of equipment to the ZUP is extremely difficult due to customs' delays in Russia. In general to overcome this all equipment was sent via ESTEC in co-operation with RSC Energia. However, ad-hoc deliveries due to unforeseen problems or equipment failures were subject to the normal customs' delays, unless hand-carried to Russia. Two recommendations can be derived from this experience. Firstly, that all systems to be implemented in ZUP should be rigorously tested in Europe before delivery to Russian, in as realistic an environment as possible. Secondly, extensive spare parts/support equipment should be delivered with each system to avoid, wherever possible, the necessity to ship additional equipment later at short notice
- When equipment installed in ZUP did not perform as expected during test activities, it was often very difficult to perform the troubleshooting remotely. Once again it must be stressed that extensive advance testing is required on equipment to be installed in Russia and that whenever possible ESA/DLR support should be available at ZUP during important test periods. An alternative would be to train up Russian technicians to provide the necessary troubleshooting support.
- During the implementation and test phase it was often difficult to obtain adequate support in the ZUP. This was particularly evident for the testing of the DTS. It is recommended that travel to Russia is foreseen to accommodate the implementation of equipment in the ZUP and that extensive testing is scheduled during that period. Naturally the duration of the stay must correspond with the support to both activities. It should also be considered whether a permanently staffed position in ZUP is not essential.

- It was never possible to properly test the NASA interface prior to the mission since the equipment on-board was not fully tested. However, when the NASA on-board data handling system (MIPS) data was finally available it was clear that NASA had implemented a completely different interface to that which was agreed with DLR. (It should be noted that NASA reverted to the DLR agreed interface very quickly after the problem was raised by DLR). Investigation revealed that EAC had also at a working level reached an agreement with the NASA implementor for a different interface. It is important that there is only one interface partner for each interface and that this should be established and agreed by the project and known to all other team members.

A summary of specific USOC implementation and test experience with respect to SCOPE interfaces is provided below:

- The DTS implementation and testing was complicated due to the lack of appropriate inputs from many of the user sites, despite repeated requests for this information. Some of the information provided by the users had to be revised. In the case of ALTEC and CADMOS due to security restrictions at these sites a different implementation (via IGS instead of Internet) was necessary for data access.
- The testing of the video and audio systems at the remote sites often resulted in echo requiring an optimisation of the audio set-up. In some cases equipment was required to be changed in order to provide an acceptable audio configuration (e.g. ALTEC and IGS Control where Push-To-Talk microphones had to be installed to replace the initially available microphones).
- At the IGS sites the remote keyset implementation was handled as part of the IGS implementation. No significant problems were experienced with this approach. For the DICE sites the remote keysets and supporting equipment were sent to the sites pre-configured and tested and only requiring connection to the appropriate PTT interface. During the mission problems were experienced with the ESTEC implementation and therefore it must be questioned whether this approach (installation of keyset string performed by remote site itself) was correct. However, a remote monitoring capability of this equipment if it had been available would have allowed a quick identification and rectification of this problem
- Problems were experienced with the ESTEC DICE installation. Matra Marconi Space (MMS), suppliers of the RF equipment, needed to re-visit ESTEC to perform troubleshooting. However, even during the mission problems with this installation were experienced in the form of regular transmission dropouts (typically 5-20 seconds).

With regard to the network implementations, including the central IGS implementation at ESOC, there were generally no significant problems with the exception of the following. During the initial ISDN implementation at the various IGS sites there were often problems due to insufficient network resources being allocated by the local PTTs. It was often difficult to establish the required number of B channels, and as a result the local PTTs were required to perform upgrades to ensure the availability of the full number of B channels when required. However, once the PTTs had performed their upgrade the required number of B channels was generally available when required.

5. RECOMMENDATIONS

The recommendations given here are based on the experience gained during the EUROMIR 95 mission and are sometimes specific to this type of mission, whereas other are more generally applicable. Some recommendations have already been given in earlier sections of this paper and will not be repeated here.

The data distribution method employed for EUROMIR 95 was to deliver the data from the SCOPE to the USOCs using File Transfer Protocol (FTP) either via the Internet or the IGS. However, due to the limited availability of the IGS due to the chosen ISDN on-demand nature of this service and to occasional problems with the Internet this concept is no longer considered to be ideal. It would be recommended instead that the mission data be placed on a DLR FTP server and collected from the users by the users as required. A listing of the available data could be placed on the WWW for users to view.

For future missions due to the added complications of implementing, testing and maintaining systems in the ZUP the following recommendations would be made:

- All systems to be implemented in ZUP should be rigorously tested before delivery to Russia
- Redundancy should be provided for all ZUP systems to allow operations to be performed without interruption whilst the cause of failures are isolated and resolved
- Extensive spare parts/support equipment should be delivered with each system to avoid as much as possible the necessity to ship equipment at short notice
- A set number of trips to the ZUP for troubleshooting/maintenance should be planned in for long duration missions or alternatively a permanently manned position should be established at the ZUP (possibly a trained Russian technician)

The necessity for the above is dependent on the level of reliability and availability required of the ZUP systems, which for EUROMIR 95 were not clearly defined. It is important for future missions that reliability and availability requirements are clearly defined prior to the system design.

It stated in the GNI definition a mixture of leased line and ISDN was used for the connection of the remote keysets at the DICE sites. Based on the initial usage predictions the use of ISDN was in virtually all cases less expensive. However, during the mission it became clear that the usage of the remote keysets was more intense than foreseen pre-mission. As a result a switch between ISDN and a leased line was made for one of the ESTEC remote keysets. It would be recommended that a cost trade-off for all communication lines between ISDN and leased be performed to identify the most cost effective solution for each, but this must be based on realistic usage estimates.

One aspect that hasn't been covered in this paper to date is the issue of support to Public Relation (PR) events. For EUROMIR 95 substantial additional support was required to define, implement and test non-nominal system configurations that were needed to meet the event requirements. This resulted from the fact that no requirements for PR support were available during the design phase of the GNI. For future projects it should be ensured that PR is considered early in the design phase and that the required PR configurations be engineered into the system from the beginning and only these configurations be offered for PR support.

6. CONCLUSION

To summarise it must be stressed here once again that the flexibility expected of the EUROMIR 95 ground segment could only be achieved by utilising existing infrastructure and an experienced team, especially when taking into account the very short period available for the design, implementation and testing of the ground segment. The resulting mixture of different existing network components (DICE, IGS, GSOC-ZUP link, ISDN, Internet) turned out to be flexible and cost effective for this mission, and generally the network operations ran smoothly. However, where problems arose the troubleshooting was often difficult and time consuming due to the lack of monitoring information at the SCOPE for some systems, and due to the mixed nature of the network with interfaces between different systems. For future projects with similar constraints as to EUROMIR 95, such an approach using existing systems should be employed. However, for the International Space Station Alpha (ISSA) a consistent network approach should be adopted with centralised network management..

Direct Video and Data Transmission from the MIR Space Station to Germany (BDD)

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Abstract:

In the frame of the MIR mission-96, a direct Satellite link from the MIR Space station to the German GSOC in Oberpfaffenhofen is currently being tested. It is intended, to achieve simultaneous real-time transmissions (i.e. Video and Audio Information, On-board experiment data, and telecommands) using Russian Relais-Satellites (SDRN). The bidirectional information exchange between MIR and the ground control station is being controlled and supervised by intelligent front-ends, which is located on board MIR and also at GSOC.

This technology experiment should contribute to the extension and improvement of the currently existing communication with MIR. Furthermore, it was the intention to test available Russian satellite infrastructure under real mission conditions and to implement all necessities for the economical realization of technology experiments on MIR in the future.

Key words: *Satellite transmission, real-time communication, data transmission, video transmission, SDRN, Relais-satellites, front-end, GSOC.*

Introduction and scientific objectives:

On the manned Russian MIR space station a special Relais-satellite and data network (SDRN) has been used for many years for TV-broadcasting, which consists of several space and ground segments. Unfortunately, the SDRN has in fact never been used within the MIR-programme to fulfill scientific tasks.

The reason for this, is largely that neither the existence nor the uses of the SDRN was ever known to the scientists, and its technical characteristics have never been published by the Russians until now. Consequently communication options were very limited to simple downlinks, voice contacts, UHF radio and information exchange by telex used within the experimental programmes which have been run so far. Real-time communication between the ground station and MIR and vice versa was therefore impossible.

The scientific objectives of the BDD experiment can be summarized as follows:

1. Implementation of all necessary techical and organisational requirements on board MIR as well as on the ground in order to realize efficient bidirectional communication;

2. First achievement of real-time communication directly from Germany to MIR without passing through Russian territory;

3. Testing of new methods and new technologies regarding their implementation in the future;

4. Control of selected MIR-96 experiments from GSOC by using BDD-hardware, and finally

5. Proof of the fact that available Russian satellite technologies are appropriate for use in space communication and as a result, can provide interesting and economical alternative solutions.

Technical Equipment

Recognizing the fact that Russian standard satellite technology is already available on board MIR, this can be improved by connecting additional, modern communication technology.

Therefore the technical BDD-equipment consists of the following:

- Add-on communication assembly and
- additional equipment, such as interface-cables, to connect the Communication Assembly.

The communication assembly contains the high-tech communication electronics (encoder/decoder) to feed digital data into an analog-modulated TV-signal, which is then transferred to the satellite transmission equipment via the relevant interfaces. The Teletext inserter-receiver which is used for the data exchange permits a maximum transmission rate of 29 Kbytes / sec.

External users, who are involved in the data exchange, can be connected using the following interfaces: ETHERNET, RS232 and RS422/RS485. Furthermore, the interface-ports BNC, AUI and UTP are available for the connection of external video equipment. The System-Camcorder which is being used for the MIR-96 mission can also be run via these interfaces.

An overview of the communication assembly's signal structure is illustrated in Fig. 1.

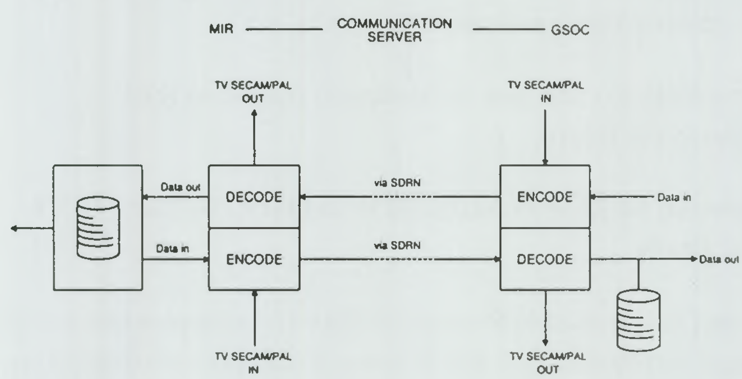

Fig. 1: Signal structure of the communication assembly MIR-GSOC

A communication via SDRN to the MIR-space station is possible, due to the fact that an appropriate satellite ground station exists at GSOC. The ground station has a 4.5m parabolic-antenna and is suitable for all special functions of SDRN communication.

The most important technical data of the GSOC ground station are:

Antenna:	4.5m, Cassegrain-feed
Polarization:	circular, Tx: LHC, Rx: RHC
Frequency range:	Tx: 14.0-14.65 GHz, Rx: 10.5-11.7 GHz
Antenna gain:	54.5 dBi at 14.5 GHz/52 dBi at 11 GHz
3 dB Antenna Pattern:	0.3 grd at 14.5 GHz/0.36 grd at 11 GHz
Antenna tracking:	manual, step-tracking, program-tracking
Reception quality:	30.0 dB/K min. at 11.0 GHz

EIRP (transmission):	75 dBW at 14.5 GHz
Input/output:	Video: FBAS, 1 Vss
Modulation/demodulation:	Video: FM-Secam/Audio: FM-Subcarrier

For communication in the MIR-96 program, the SDRN satellite will be used in the orbital position 16 deg W. A schematic illustration of the satellite can be seen in Fig. 2.

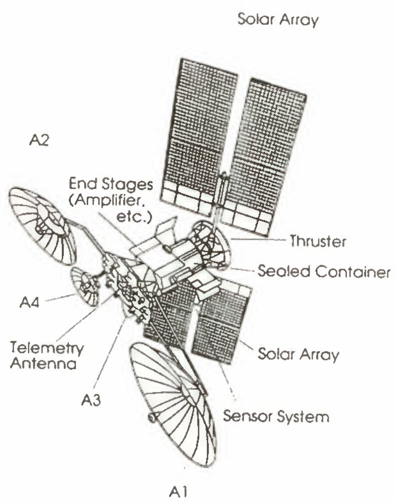

Fig. 2: SDRN-Spacecraft LOUTCH

Experimental procedure

The BDD experimental procedure is carried out in two steps:

1st Step: Operation and test of the used equipment and verification of the communication principles under real mission conditions according to a fixed procedure.

2nd Step: Use of the on-board communication assembly in connection with the relevant MIR-96 experiment hardware.
In this case it is supposed that the experiment has been set up for the use of BDD-hardware (data exchange and recognition of received telecommands).

The communication MIR - LOUTCH - GSOC is organized according to Fig. 3.

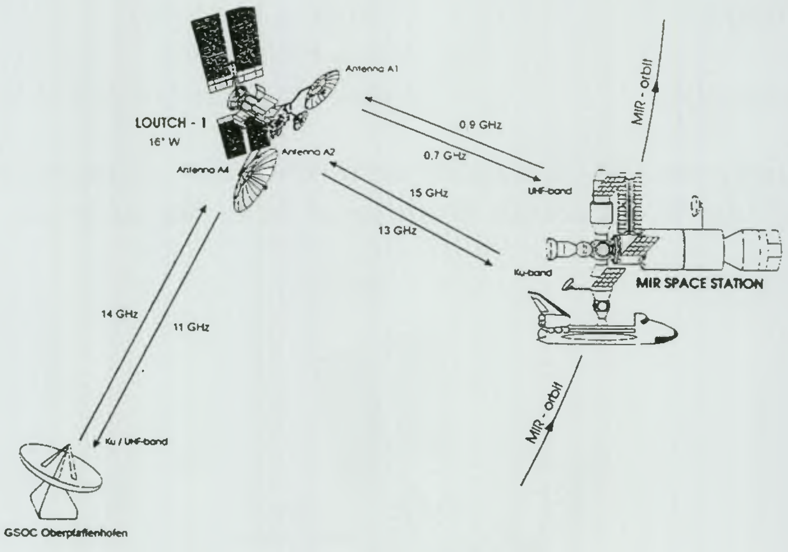

Fig. 3: Communication scheme MIR - LOUTCH - GSOC

For the establishment of communication links to the MIR space station following facts and operational steps should be considered:

Firstly: During the MIR-orbit, which takes approx. 90 min., the space station is visible for approx. 43 min., by using the SDRN satellite in the position 16 deg W. Consequently, the experiment duration is limited to this visibility time. An extension of this time is possible as long as a second or third satellite has been included in the transmission scheme, however, this has not been planned for MIR-96.

Secondly: The MIR-station represents a mobile object, and for a permanent link an antenna-tracking is required. The link quality depends largely on said antenna-tracking.

Thirdly: The SDRN-satellite antenna A2 (see fig. 2) throws a spot beam to the earth surface, which will cover the Russian mission control centre TSUP, in the nominal case. Due to the fact that the antenna beam only has a radius of approx. 800 km, the German mission control centre GSOC cannot be covered. To allow direct communication between MIR and GSOC despite this fact, the satellite antenna A2 will have to be moved.

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Kayser-Threde, Munich

List of Abbreviations

BDD - Betriebstechnik Deutschland Direkt
GSOC - German Space Operation Centre
SDRN - Satellite Data Relay Network
UHF - Ultra High Frequency

NASA'S NEXT GENERATION TRACKING AND DATA RELAY SATELLITE SYSTEM (TDRSS) - LAUNCH AND OPERATIONAL GROUND SEGMENT ARCHITECTURE

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ABSTRACT. The next generation of TDRSS Spacecraft (H,I, and J) are being developed for NASA by Hughes Space and Communications Group (HSC), for user support into the 21st century. HSC will also provide the modifications to the White Sands TDRSS Ground Terminals (WSC) required for the enhanced user support, control of the TDRS H,I,J, and support for transfer orbit operations while preserving compatibility with the present generation of TDRS spacecraft. This paper describes the new TDRS H,I,J capabilities, contrasting them with the existing TDRS and describes the architecture of the modified WSC and the new ground terminal in Guam to close the "Zone of Exclusion". Additionally, this paper describes the unique architecture for the control centers, data flows and operations for the launch, transfer orbit and on-orbit testing leading to NASA on-orbit acceptance of the TDRS H,I,J.

1. BACKGROUND - THE SPACE NETWORK (SN)

The major elements of the SN are shown in Figure 1. The White Sands Complex (WSC) includes the White Sands Ground Terminal Upgrade (WSGTU/Cacique) and the Second TDRSS Ground Terminal(STGT/Danzante) which provide forward, return, and tracking services to user spacecraft via the TDRS constellation. Project Operations Control Centers (POCCs) request services via the Network Control Center (NCC) and receive and transmit their user spacecraft data via NASA Communications (NASCOM). The NCC provides schedule requests, acquisition data, and real-

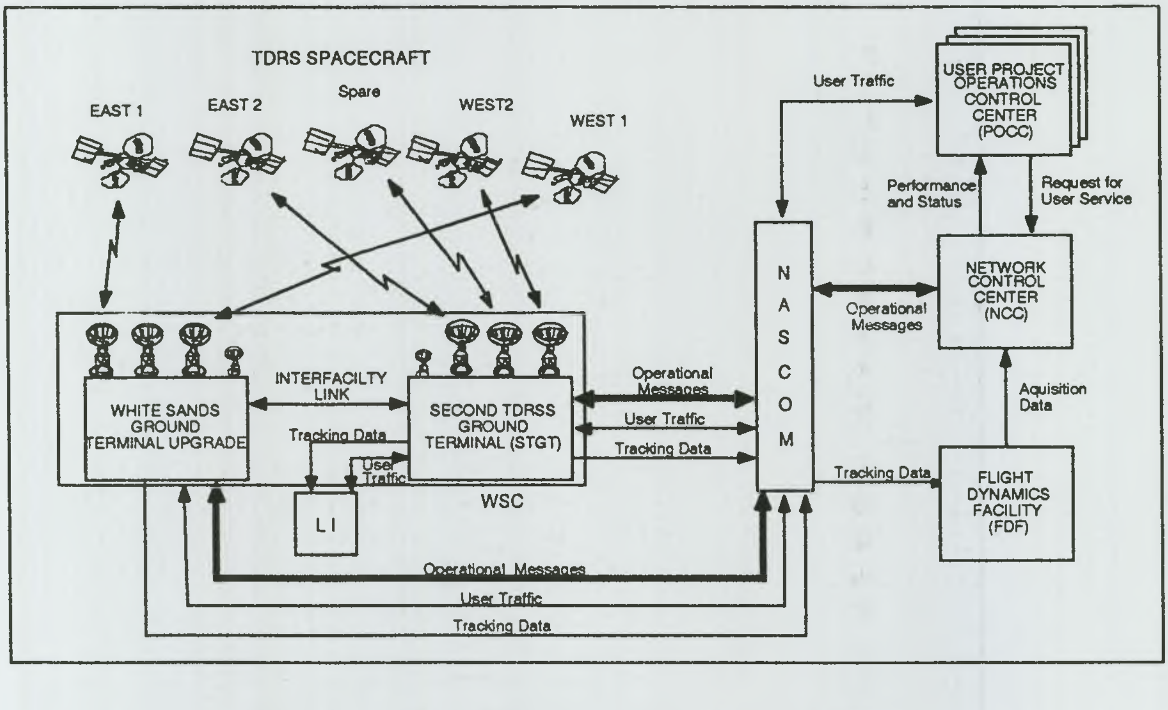


Figure 1 - The NASA Space Network with the WSC

time user spacecraft configuration control messages to the WSC via NASCOM. The Flight Dynamics Facility (FDF) processes user and TDRS tracking data and provides acquisition data to the NCC. The user services provided by the WSC will be enhanced by the addition of TDRS H,I,J to the constellation.

2. ENHANCED CAPABILITIES OF THE TDRS H,I,J

The TDRS H,I,J will provide enhancement of the Multiple Access (MA) system, addition of a Ka-band user space to space link (SSL), and an Expanded Elliptical Field of View (EEFOV) for the Single Access (SA) Antenna services. A comparison of the TDRS H,I,J vs. the TDRS A-G services at the WSC is shown in Figure 2.

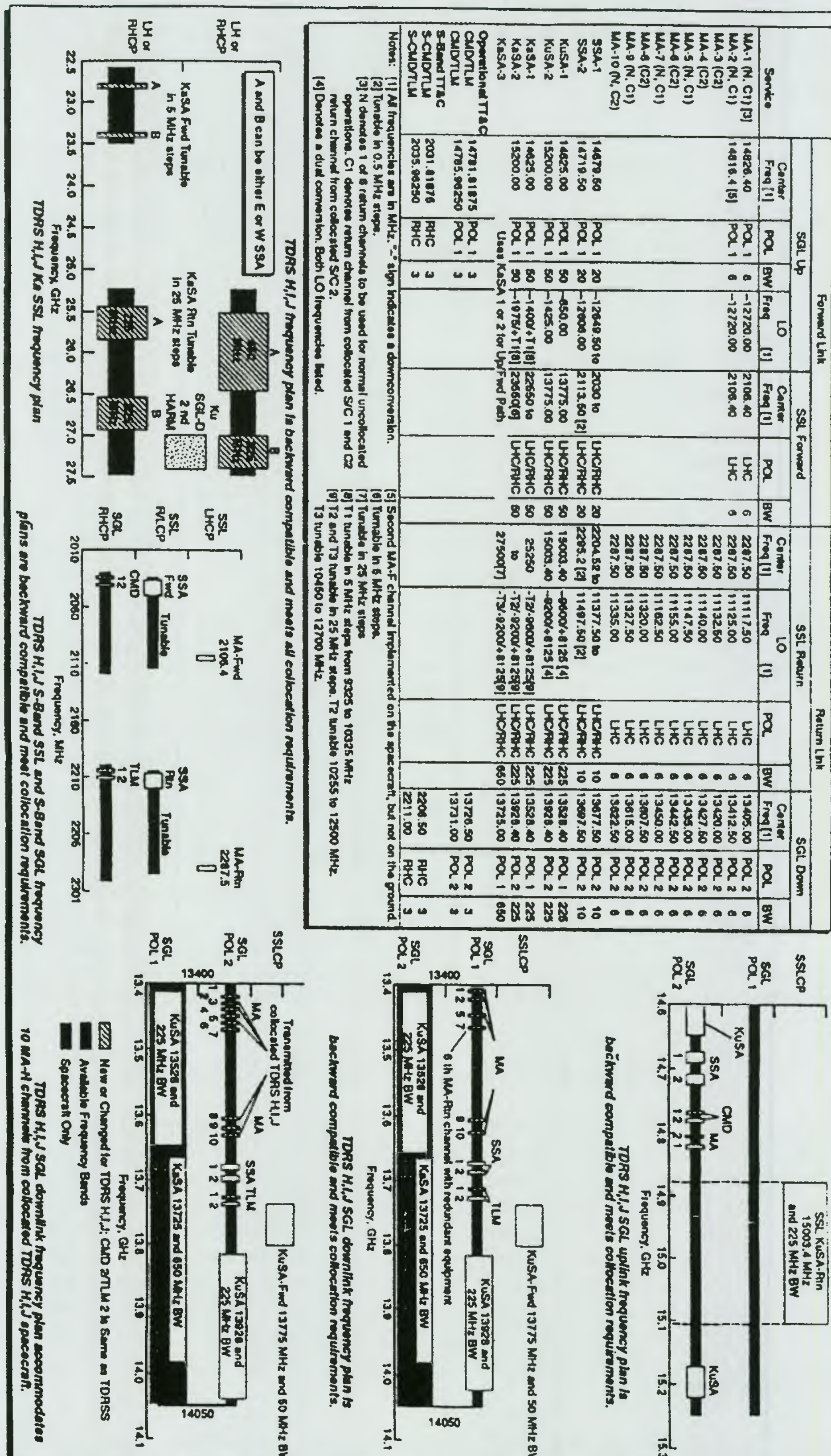
SERVICE			WSC TDRS A-G CAPABILITIES	WSC TDRS H,I,J CAPABILITIES
SINGLE ACCESS	S-Band	FORWARD	300 kbps	300 kbps
		RETURN	6 Mbps	6 Mbps
	Ku-Band	FORWARD	25 Mbps	25 Mbps
		RETURN	300 Mbps	300 Mbps
	Ka-Band	FORWARD	———	25 Mbps
		RETURN	———	300 Mbps/800 Mbps (1)
	NUMBER OF LINKS		2 SSA/TDRS; 12 SSA/WSC 2 KuSA/TDRS; 12 KuSA/WSC	2 SSA/TDRS; 12 SSA/WSC 2 KuSA/TDRS; 12 KuSA/WSC 2 KaSA/TDRS; 8 KaSA/WSC (2)
MULTIPLE ACCESS		FORWARD	1/TDRS @ 10kbps 4/WSC	2/TDRS (3) @ 300 kbps 4/WSC
		RETURN	5/TDRS @ 100kbps 20/WSC	5/TDRS @ 3Mbps 20/WSC
USER TRACKING			Range, 1&2 way Doppler	Range, 1&2 way Doppler (No Ka band Tracking)

(1) Spacecraft Only; (2) Ku or Ka; (3) 1/TDRS at WSC; (4) For User data Configurations, see Users Guide (STDN 101 Rev 7)

Figure 2 - WSC Capabilities Comparison (4)

The TDRS H,I,J S-band MA system (called SMA) will implement on-board beamforming using separate forward and return phased array antenna (36 elements for return and 15 elements for forward). Up to six return (SMAR) beams and two forward (SMAF) beams will be formed using user ephemeris data uplinked from WSC. (TDRS A-G utilize 30 element phased arrays for one forward and five return beams, with return beamforming performed on the ground.) The center frequencies of the SMAR channels, which have a 6.0MHz Bandwidth (BW), are selectable and occupy the same Space to Ground Link (SGL) spectrum as the 30 elements of the TDRS A-G. The TDRS H,I,J design has largely preserved the TDRS A-G SGL frequency plan in order to maintain compatibility (see Figure 3). The maximum data rates are 3Mbps for SMAR and 300 kbps for SMAF. TDRS A-G data rates are 100 kbps and 10kps.. Range and Doppler tracking are provided for SMA users.

The Ka-band SSL is an entirely new TDRSS service. The forward link band is 22.55 to 23.55 GHz, tunable in 5MHz steps, with a bandwidth of 50 MHz and data rates up to 25Mbps. The return link band is 25.25 to 27.50 GHz tunable in 25 MHz steps, with a bandwidth of 225 MHz and data rates up to 300 Mbps. A 650 MHz BW with data rates up to 800 Mbps is available on the TDRS H,I,J spacecraft, but is not planned to be supported by the WSC at this time. No tracking services are provided at Ka-Band. Ka-band services use the same SGL frequency bands as the Ku-band, except the 650 MHz BW (see Figure 3). Ka-band services (with the exception of the return



Service	Forward Link: SGL Up Center Freq [1]	SGL Up POL	SGL Up BW	SGL Up LO Freq [1]	SSL Forward Center Freq [1]	SSL Forward POL	SSL Forward BW	Return Link: SSL Return Center Freq [1]	SSL Return LO Freq [1]	SSL Return POL	SSL Return BW	SGL Down Center Freq [1]	SGL Down POL	SGL Down BW
MA-1 (N, C1) [3]	14826.40	POL 1	6	-12720.00	2106.40	LHC	6	2287.50	11117.50	LHC	6	13405.00	POL 2	6
MA-2 (N, C1)	14816.4 [5]	POL 1	6	-12720.00	2106.40	LHC	6	2287.50	11125.00	LHC	6	13412.50	POL 2	6
MA-3 (C2)								2287.50	11132.50	LHC	6	13420.00	POL 2	6
MA-4 (C2)								2287.50	11140.00	LHC	6	13427.50	POL 2	6
MA-5 (N, C1)								2287.50	11147.50	LHC	6	13435.00	POL 2	6
MA-6 (C2)								2287.50	11155.00	LHC	6	13442.50	POL 2	6
MA-7 (N, C1)								2287.50	11162.50	LHC	6	13450.00	POL 2	6
MA-8 (C2)								2287.50	11320.00	LHC	6	13607.50	POL 2	6
MA-9 (N, C1)								2287.50	11327.50	LHC	6	13615.00	POL 2	6
MA-10 (N, C2)								2287.50	11335.00	LHC	6	13622.50	POL 2	6
SSA-1	14679.50	POL 1	20	-12649.50 to	2030 to	LHC/RHC	20	2204.52 to	11377.50 to	LHC/RHC	10	13677.50	POL 2	10
SSA-2	14719.50	POL 1	20	-12606.00	2113.50 [2]	LHC/RHC	20	2295.2 [2]	11497.50 [2]	LHC/RHC	10	13697.50	POL 2	10
KuSA-1	14625.00	POL 1	50	-850.00	13775.00	LHC/RHC	50	15003.40	-9600/+8125 [4]	LHC/RHC	225	13528.40	POL 1	225
KuSA-2	15200.00	POL 1	50	-1425.00	13775.00	LHC/RHC	50	15003.40	-9200/+8125 [4]	LHC/RHC	225	13928.40	POL 2	225
KaSA-1	14625.00	POL 1	50	-1400/+T1[8]	22550 to	LHC/RHC	50	25250	-T2/-9600/+8125[9]	LHC/RHC	225	13528.40	POL 1	225
KaSA-2	15200.00	POL 1	50	-1975/+T1[8]	23550[6]	LHC/RHC	50	to	-T2/-9200/+8125[9]	LHC/RHC	225	13928.40	POL 2	225
KaSA-3	Uses KaSA 1 or 2 for Up/Fwd Path							27500[7]	-T3/-9200/+8125[9]	LHC/RHC	650	13725.00	POL 1	650
Operational TT&C														
CMD/TLM	14781.81875	POL 1	3									13726.50	POL 2	3
CMD/TLM	14785.96250	POL 1	3									13731.00	POL 2	3
S-Band TT&C														
S-CMD/TLM	2031.81875	RHC	3									2206.50	RHC	3
S-CMD/TLM	2035.96250	RHC	3									2211.00	RHC	3

Notes: [1] All frequencies are in MHz. "-" sign indicates a downconversion.
[2] Tunable in 0.5 MHz steps.
[3] N denotes 1 of 6 return channels to be used for normal uncollocated operations. C1 denotes return channel from collocated S/C 1 and C2 return channel from collocated S/C 2.
[4] Denotes a dual conversion. Both LO frequencies listed.
[5] Second MA-F channel implemented on the spacecraft, but not on the ground.
[6] Tunable in 5 MHz steps.
[7] Tunable in 25 MHz steps.
[8] T1 tunable in 5 MHz steps from 9325 to 10325 MHz.
[9] T2 and T3 tunable in 25 MHz steps. T2 tunable 10255 to 12500 MHz. T3 tunable 10450 to 12700 MHz.

Figure 3 - TDRS H,I,J Frequency Plan

center frequencies recommendation) will be compatible with the "Recommendations for International Space Network Ka-Band Interoperability, Rev 1., 1 June 1995."

TDRS H,I,J will have an EEFOV for the SA Antenna (SSA) of 77.0 degrees (outboard) by 22.5 degrees (inboard) East/West and ±31.0 degrees North/South. There are some restrictions on autotrack acquisition and user services during thruster firings when operating beyond 22.5 degrees East/West. TDRS A-G has a ±22.5 degree E/W by ±31.0 degree N/S field of view.

Although the TDRS H,I,J mission and operations vary greatly from commercial communication satellites, HSC has been able to incorporate many autonomous features of the HSC HS-601 product line into the TDRS H,I,J design. The additional autonomy will significantly lessen the workload on the WSC Flight Operations Specialists in the maintenance of spacecraft health. A major feature of the autonomy is the automated momentum management performed on-board the spacecraft. By the use of "solar sailing", operators will be able to eliminate thruster firings to control Roll/Yaw momentum, versus a firing every fourth day for TDRS A-G. Eclipse power management operations can also be handled autonomously on-board the spacecraft. The spacecraft design allows all autonomous features to be performed by the ground if needed.

A robust, layered approach to fault detection and protection protects the spacecraft from anomalies. The spacecraft control processor is capable of replacing failed units to preserve the ongoing service with minimal data interruption, while maintaining spacecraft health and safety. The final layer of safehold places the spacecraft in a power and thermal safe state to allow ground personnel the opportunity to resolve an anomaly.

The TDRS antenna pointing algorithms will also be performed on-board the spacecraft. The WSC will provide user ephemeris polynomial coefficients to the spacecraft, from which the spacecraft control processor will compute the antenna pointing commands to support the planned service. This alleviates the need to step the antennas with real-time commanding from the WSC.

3. GROUND SEGMENT ARCHITECTURE

Within the WSC, unique equipment chains (called Space Ground Link Terminals (SGLTs)), are dedicated to a single TDRS for the provision of user services and the control, health, and safety of a TDRS. A block diagram of an SGLT is shown in Figure 4. There are three SGLTs at each of the WSC ground terminals. HSC will modify the hardware and software of two SGLTs at each of the terminals (total of four modified SGLTs) for user support via the TDRS H,I,J. The modifications must retain compatibility with the TDRS A-G series of spacecraft. The significant modifications to the SGLTs are to the MA service chains and MA user services support (USS) software to accommodate the new SMA services and to the K-band Tracking, Telemetry, & Command (TT&C) equipment and software for control of the TDRS H,I,J.

A block diagram of the MA equipment with shaded areas showing the modification for SMA is shown in Figure 5. The existing Integrated Receivers (IRs) which are currently used for MA user support will be shared for SMA support (TDRS A-G provides only MA and TDRS H,I,J will provide only SMA support.) The IRs, under control of the MA USS ADPE, provide carrier and PN code acquisition and tracking, demodulation, bit/symbol synchronization, deinterleaving (as required), convolutional decoding, range and Doppler tracking, and operational status to the ADPE. For MA return (MAR) services the IRs receive inputs from the ground beamforming equipment. Modifications for the SMA include an RF switch to bypass the beamformer, a power divider to route RF energy to five frequency agile downconverters and a switch to route the downconverter outputs to the IRs. The new downconverters downconvert the five SMAR channels (formed on-board TDRS H,I,J) to a 370 MHz IF for input to the IRs. Since the signal structures for the SMAR are the same as for S-Band SA, for which the IRs are also used, no modifications to the IRs will be required. No modifications for the SMAF equipment are required to accommodate the increased data rates. Modifications to the MA USS ADPE software will be required to configure and control the new switching, the frequency agile downconverters, the IRs for the new SMAR data structures and to provide MA or SMA support.

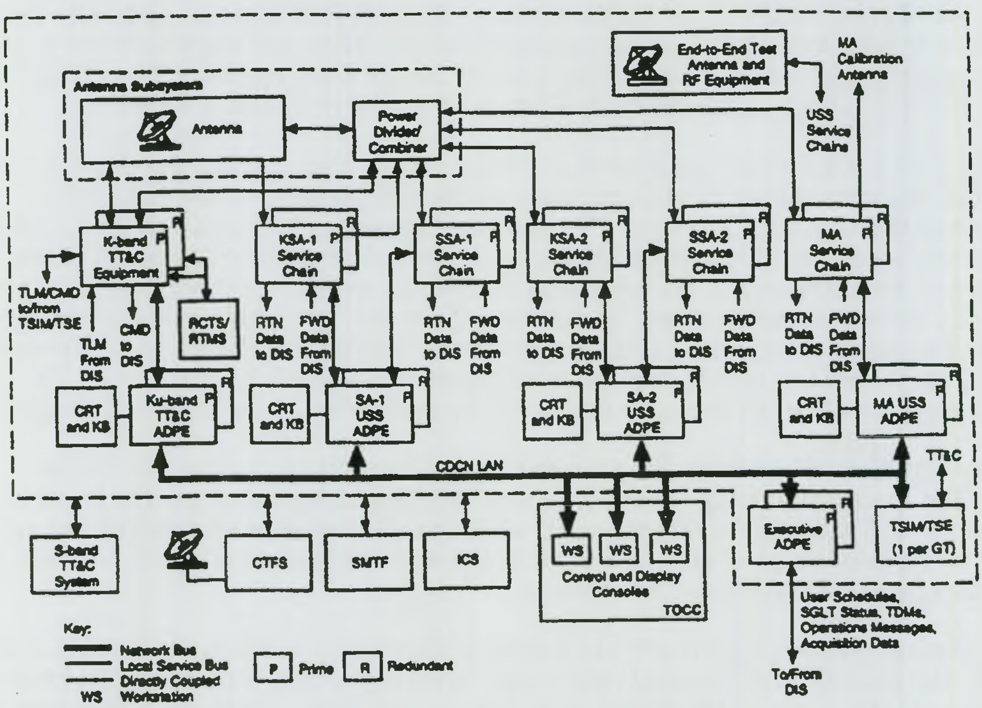


Figure 4 - SGLT Reference Architecture

The TT&C equipment requires two modifications. One is the addition of a new TDRS H,I,J command encoder with interfaces to the TT&C ADPE and command modulator. TDRS H,I,J telemetry, although different from the TDRS A-G, will use the existing receiver and programmable frame synchronizer. The second modification is for the generation of a second new command frequency to be used when two TDRSs are collocated in a single orbital slot. The TT&C software for processing command and telemetry data and control of the TDRS H,I,J is entirely unique and a separate TT&C program will therefore be developed. The new program will run on the existing TT&C ADPE platform. Existing software for LAN communications, peripheral I/O, application process intercommunication, TDRS orbit determination, and TDRS and user ephemeris generation will be reused.

Since the new Ka-Band SSL service uses existing SGL frequency bands and has no new data structures or data rates, no SGLT modifications are required for this new service. Minor software modifications will be required to accommodate changes in the scheduling and operations control messages from the NCC. In order to utilize the 650Mhz BW with 800 Mbps, a new High Data Rate Receiver and Bit Synchronizer would be required.

4. GUAM-ZONE OF EXCLUSION (ZOE) CLOSURE

The current TDRS constellation, with the WSC as the only ground station, leaves an area over the Indian Ocean without low Earth orbit user support (i.e. a ZOE). Limited closure of the ZOE is currently accomplished by a remote ground station in Australia for S-band services. By the beginning of the next century, the ground segment architecture will be changed to allow an SGLT located at a ground terminal in Guam to be operated remotely out of WSC. By placing the SGLT in Guam, the SN will be able to close the ZOE fully for all current capabilities. Emergency S-Band support will be available through the Deep Space Network (DSN) in Canberra.

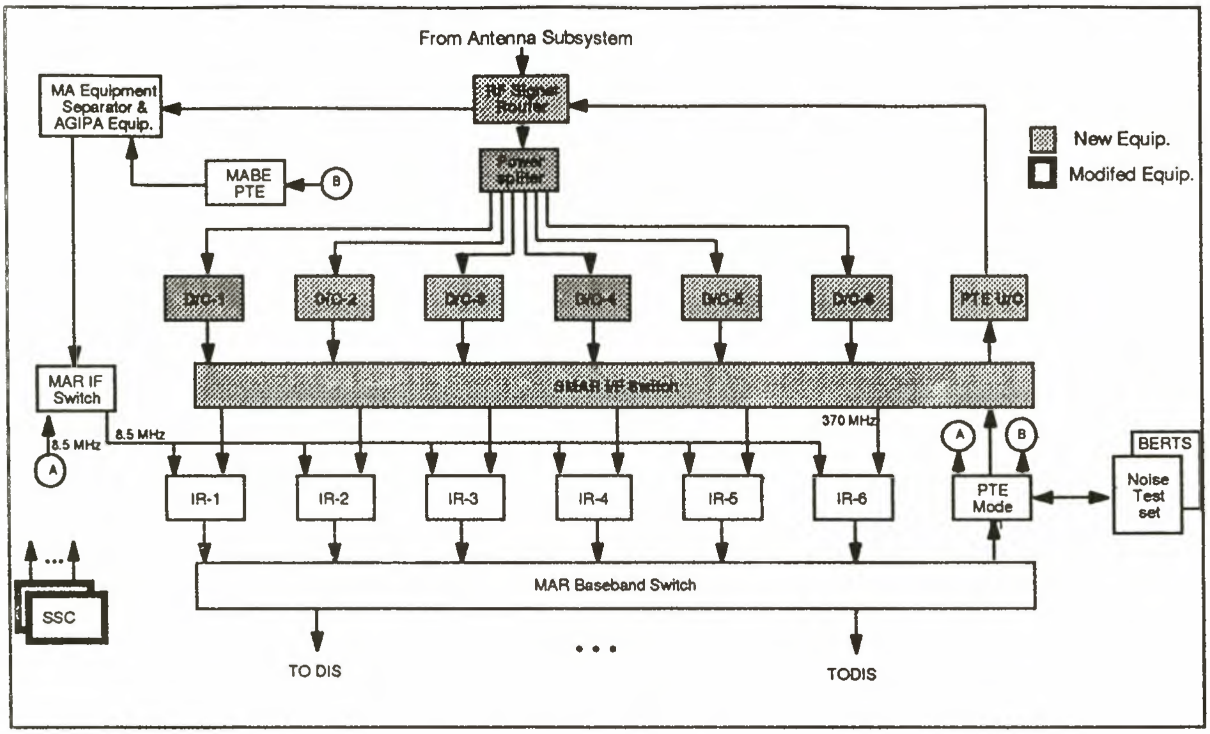


Figure 5 - SMAR Hardware Block Diagram

5. TDRS HIJ LAUNCH/CHECKOUT ARCHITECTURE

NASA is buying the TDRS H,I,J system from HSC with a Fixed Price contract, with the final delivery to NASA on-orbit. To have the greatest chance of delivering a fully functioning spacecraft to NASA, HSC has chosen to perform as much of the early orbit operations as possible using the HSC Mission Control Center (MCC) in El Segundo, California. This choice leads to an unusual network plan to support the launch and early orbit phases of the TDRS H,I,J mission.

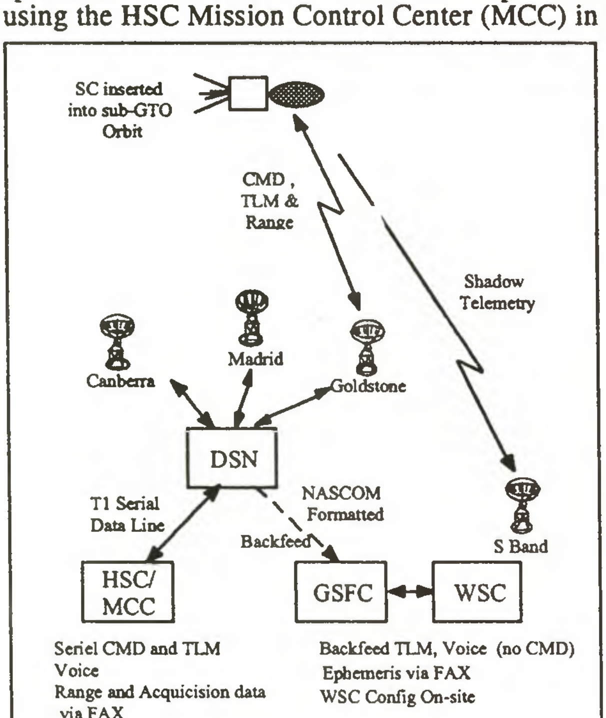


Figure 6a - Transfer Orbit Network Architecture

The TDRS H,I,J mission plan is to have a ten day transfer orbit with an on-orbit checkout period of approximately two months. Control of the spacecraft during all early orbit checkout originates at the MCC. As shown in Figure 6a, The MCC connects to DSN "26m subnet" at JPL, and also has a dedicated serial line connecting to a WSC antenna. TDRS H,I,J telemetry is at S-band during transfer orbit, requiring that the DSN be used instead of commercially available ground stations. The DSN will be used to support the transfer orbit phase of the mission, and is used in emergency situations for TDRS support throughout the spacecraft life. The DSN network is a multi-user resource, which will be different from the dedicated stations usually associated with HSC commercial launches.

The use of the WSC as a "remote" site for early Geosynchronous Orbit (GEO) operations and checkout is a new capability for the SN. The WSC has always been the only originator of TDRS commands, and has always been a standalone station without the capability to accept an external command source (although capable of using "off site" antennas from the DSN). By incorporating the capability for MCC commanding, HSC is increasing the operational flexibility of the SN while maintaining heritage for Software, Procedures, and Experience developed by the MCC for the critical early mission phases. The architecture for this approach is presented in Figure 6b. Some challenges of this approach are the new interfaces that need to be developed to transport the commands into the WSC and get the telemetry back to the MCC and GSFC.

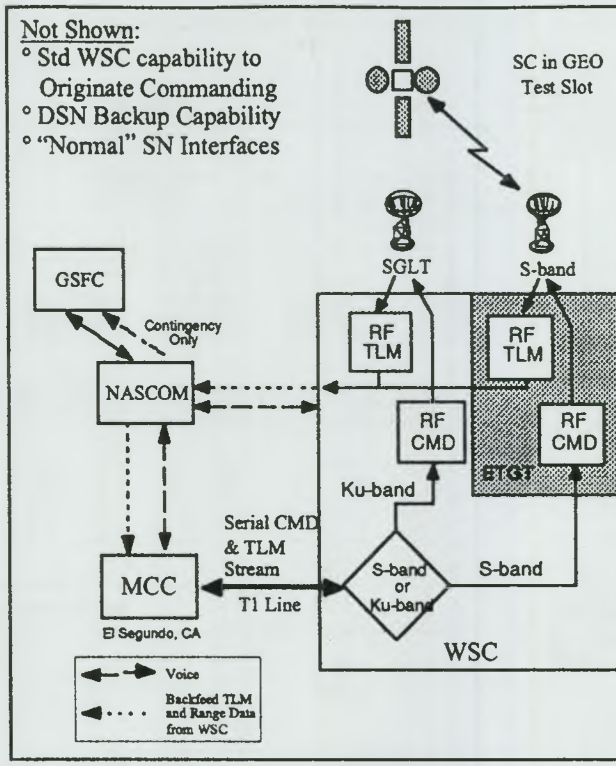


Figure 6b - On Orbit Test Network Architecture

6. SPECIAL USERS

In recent years, the SN has been supporting users outside the standard description of Low Earth Orbit (LEO) spacecraft. Additional "classes" of TDRS customers have been identified, including Launch Vehicles, Sub-orbital, and Stationary users.

TDRS has demonstrated the capability to support Launch Vehicles by augmenting the fleet of ARIA telemetry gathering aircraft that had supported the U.S. launch vehicles for many years. TDRS currently supports Space Shuttle, Titan/Centaur, and Atlas/Centaur launches from KSC. Initiatives are underway to support Titan/IUS, Delta, Pegasus, EELV, Minuteman, and Sea Launch vehicles. Discussions are underway to provide Range Safety telemetry for the Eastern and Western Ranges through the SN in order to take advantage of the continuous coverage offered by TDRS. TDRS launch support coverage of non-U.S. launches is considered a viable future capability. With the addition of the EEFOV on TDRS H,I,J, TDRS will be even more capable and support transfer orbit and other missions out to geosynchronous altitudes.

TDRSS has been able to support spacecraft without TDRSS Compatible Transponders. TDRS provided launch support of the Polar spacecraft during the Delta/Polar launch in February 1996. The IR locked onto the CW signal to provide differential tracking data to the FDF. The differential Doppler provided from TDRS-East, -West, and Spare enabled FDF to provide and accurate orbit determination of the Polar spacecraft. The successful tests and demonstrations of the Integrated Receiver to provide support for the non-TDRS compatible SGLS transmitters by locking onto the PSK sub-carrier, has led TDRSS to sign up to provide operational support for the TOMS-EP launch currently scheduled for June 1996. TDRS will provide the 1 Kbps telemetry data off of the PSK subcarrier to the TOMS-EP project along with differential tracking data to the FDF.

TDRS also supports high and low data rate users mobile who are not at orbital altitudes. Examples are the STARLink Project (aircraft), the Long Duration Balloon Project (LDBP), and Unmanned Aerial Vehicles (UAVs) for high altitude research. The STARLink Project will use the TDRSS and NASCOM to relay voice and data communications between the STARLink ER-2 aircraft and the user POCC located at NASA Ames Research Center. STARLink will utilize the TDRS KuSA forward and return links for scientific data and communications. Both the LDBP and the UAV project will use a "balloon class" transponder and omni antenna for TDRS communications (with the UAV at higher power for a higher data rate capability). These missions can utilize both MA and SSA service (S-Band only) for forward and return links. UAVs may in the future employ High Gain directional antennas to increase data rates.

Earth based (Stationary) users can also take advantage of TDRS. The SN has supported remote land based researchers (such as in Antarctica) that commercial satellites do not cover. The researchers are able to communicate data and receive results that before had to be carried by magnetic tape on ships and aircraft. The ground equipment necessary for this link is portable, and consists of a laptop computer, a GPS receiver, and a TDRSS transmitter (known as PORTCOM). The National Oceanographic and Atmospheric Administration (NOAA) is studying using PORTCOM thru the TDRS MA system to communicate with roughly one hundred remote buoys monitoring oceanic conditions. Each buoy would transmit data for a few minutes each hour at low data rates with the capability for commanding on rare occasions.

The TDRS H,I,J will be able to fully support the new International Space Station. The increased capabilities will make it possible to support the Station at K band while simultaneously supporting a Shuttle at S-Band, on the same SA Antenna.

The TDRS community is dedicated to making the SN easier to access for all potential users. Two initiatives are currently underway to enable of smaller spacecraft to take advantage of TDRS capabilities in the future. The first is the development of a fourth generation TDRSS transponder which has similar weight, power, and data rate capabilities as current GN transponders. The major obstacle to small spacecraft utilization of TDRS is the cost, size and power required by current TDRS transponders. The fourth generation transponder would bridge the gap allowing the smaller users to use TDRS without effecting spacecraft design any more than using ground terminals would. The second is the development of "Demand Access" which will allow customers to access the MA forward and return services without prior scheduling. By deleting the overhead and operational complexity associated with MA service scheduling, users will get rapid and reliable access to TDRSS. Users will be accommodated on a First In First Out priority system. By implementing these initiatives, the TDRS system will be able to meet the needs of the user community which is headed towards smaller, less expensive space systems.

THE CLUSTER SCIENCE DATA SYSTEM NETWORK

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ABSTRACT: The ground segment for the Cluster mission features a Cluster Science Data System (CSDS). For the interconnection of the Joint Science Operations Centre (JSOC) and Data Centres (DCs) to Cluster Data Distribution System (CDDS), a communications network was needed which could meet the relevant requirements for availability, throughput and transit delay. CSDSNet has been implemented as a LAN-LAN interconnect system based on the Internet Protocol (IP) Suite. It has a dedicated IP address space and includes gateways into the worldwide Internet, to national Internet service providers at JSOC and at the DCs, and into the corporate IP network of ESA. Its infrastructure consists of IP routers interconnected via a frame relay (FR) network. The permanent virtual circuits (PVCs) and their committed information rates (CIRs) have been sized to the needs of CSDS traffic. On-demand backup links are available for critical connections. The overall infrastructure and its operations are provided by a pan-European network service provider. This paper will expand on the requirements and the network design. It also deals with the split of responsibilities between the Agency and the supplier in various life cycle phases of the system. It describes and evaluates the CSDSNet service, including aspects of performance and network management. This covers the period from initial implementation in early 1995 until May 1996.

1. CSDSNET REQUIREMENTS AND PLANNING

1.1 TOPOLOGY

The concept of the overall Cluster Science Data System is described in [1]. The CSDS dedicated communications network is CSDSNet. The network nodes are located at the Joint Science Operations Centre (JSOC) at RAL, UK, at the mission operations centre ESOC, Darmstadt, at the project site ESTEC, Noordwijk, and at the national data centres (DCs). These exist in UK (at RAL, Didcot), France (CFC at CNES, Toulouse), Germany (previously MPI at Berlin, now MPAe at Garching), Sweden (KTH at Stockholm), Austria (IWF at Graz), Hungary (KFKI at Budapest). A USDC exists at GSFC, Maryland (with direct link to RAL).

These sites were determined by the CSDS Traffic Model Task Group, which provided a basic input to network design. The task group also dealt with the communications requirements in terms of experiments/tasks to be supported, the required data service types, traffic source and destination needs, and bandwidth requirements between sites [2]. In addition, the group addressed aspects of network transit delay and of quality of service, given that data transfers related to instrument commanding need a higher quality of service (time constraints, transmission errors, availability) than transfers for the CSDS scientific data exchange (e.g. summary plots).

1.2 NETWORK SERVICES

Network services needed throughout the entire mission concern three major types of applications:

I) Data Disposition System (DDS): retrieval of quick-look raw science, housekeeping and auxiliary data kept at ESOC;
ii)Command Request (CR): submittal of command requests to the Operations Control Centre at ESOC;
iii) Data centre Exchange (DE): electronic data exchange of scientifically processed data between the individual CSDS national Data Centres.

In addition, communications for spacecraft Assembly Integration and Verification (AIV) was needed at an early stage. AIV support was given via temporary enhancements of the Agency's own Intranet. The connections were provided as on-demand links from a hub at ESOC over the German public Integrated Digital Services Network (ISDN).

The mapping of the requirements to the design of a network and its specific communications services was the subject of [3]. The following table is a basic overview of all CSDS functional network requirements.

	Name	Location	Experiment	Data Service Type [1)]			
				DDS	CR	DE	AIV
	JSOC	Rutherford, Didcot (UK)	Science Operations	X / HM	X	X	
CSDS DATA CENTRES	UK-DC	Rutherford, Didcot (UK)	DWP, FGM, PEACE	X	x	X	X
	CFC	CNES, Toulouse (F)	CIS, STAFF, WHISPER, WBD	X	x	X	X
	GCDC	MPAe, Garching(FRG)	RAPID, EDI	X	x	X	X
	SDC	KTH, Stockholm (S)	EFW	X	x	X	X
	ACDC	IWF, Graz (A)	ASPOC	X	x	X	X
	HDC	KFKI, Budapest (H)	Orbit Data	X		X	
	US-DC	GSFC, Maryland (US)	US node (WBD)	X	x	X	
	ESOC	Darmstadt (FRG)	Control Centre	X	X		X
	ESRIN	Frascati (I)	Catalogue			x	
	ESTEC	Noordwijk (NL)	Project	X		X	X
	Dornier	Friedrichshafen (FRG)	Integration site				X
	IABG	Ottobrunn (FRG)	Integration site				X

[1)] DDS = Data Disposition System, CR = Command Request, DE = Data Exchange (including catalogue access), AIV = Assembly Integration and Verification (only pre-launch); HM = Health Monitoring, X = main traffic, x = to JSOC

Table 1.- Functional Requirements Summary

An early and natural decision was made to use one single protocol suite, namely the TCP/IP suite, which has become the de-facto standard in local-area and wide-area data internetworking.

1.3 CAPACITY AND QUALITY OF SERVICE

Associated with the services listed in Table 1 are particular data volumes. To size the required communications resources, the volume averages were translated into data rates, using the following assumptions:

I) Data transfers take place on average 8 hrs/day, 5 days/week;

ii) An estimated overhead factor of 50% above network user application data rates;

iii) The network has to offer high throughput reserve. Hence, the available bandwidth per connection shall be at least twice as high as the average data exchange rate requirement.

This results in bandwidth figures as specified in Table 2.

to \ from	ESOC	RAL	IWF	CNES	MPAe	KFKI	KTH	GSFC	Total in (kbit/s)
ESOC		4.2	0.0	0.0	0.0	0.0	0.0	0.0	**4.2**
RAL	55.2		1.0	8.8	4.0	0.6	2.2	0.0	**71.8**
IWF	3.4	4.8		8.8	4.0	0.6	2.2	0.0	**23.8**
CNES	41.4	4.8	1.0		4.0	0.6	2.2	0.0	**54.0**
MPAe	12.0	3.6	0.0	3.6		0.6	2.2	0.0	**22.0**
KFKI	4.2	4.8	1.0	8.8	4.0		2.2	0.0	**25.0**
KTH	9.0	4.8	1.0	8.8	4.0	0.6		0.0	**28.2**
GSFC	0.0	21.4	0.0	0.0	0.0	0.0	0.0		**21.4**
ESTEC	0.0	3.6	1.8	1.8	1.8	1.8	1.8	0.0	**12.6**
ESRIN	0.5	1.5	1.5	1.5	1.5	1.5	1.5	0.0	**9.0**
Total out (kbit/s)	**125.2**	**53.5**	**7.3**	**42.1**	**23.3**	**6.3**	**14.3**	**0.0**	

Table 2.- Transmission Bandwidth Requirements [kbit/s]

In addition to the bandwidth requirements listed above, CSDSNet has to meet for each data service type a set of Quality of Service (QOS) parameters:

The rationale for this is that the Data Disposition System is sensitive to backlogs which could build up during phases of network congestion or down-time, and which could make quick-look data "outdated". Therefore, adequate throughput reserve is built into the design. - The Command Requests service requires the highest overall QOS, particularly in terms of availability, reserve for retransmissions, and operational support. - For Data Centre Exchange the most critical QOS parameters are availability and throughput. The others are medium. -Assessment of the above QOS parameter sets leads to the conclusion that CSDSNet must offer in particular high availability and guaranteed throughput.

2. ARCHITECTURE AND DESIGN

The CSDSNet architecture is a Wide Area Network (WAN) interconnecting Local Area Networks (LANs). At each CSDS site, the end-systems are connected to a dedicated Ethernet LAN segment, to which only CSDS hosts and routers are attached. The LAN-interconnect service provides logical end-to-end connectivity to the hosts, allowing them to run various network applications.

This interface also provides a clear demarcation line between the areas of responsibility of ESA and of the DC. In-service diagnostics are possible on that interface, thereby contributing to ease of operation of CSDSNet.

2.1 ADDRESSING, ROUTING AND SECURITY

According to the CSDS Announcement of Opportunity, the routing of national traffic, such as institutes connecting to a DC, is not a CSDSNet task; it falls within the responsibility of the national DCs. The interface between the CSDS network and the DCs has been explicitly taken into account in implementing CSDSNet.

However, CSDSNet cannot be seen in total isolation, independent of any "non-CSDS" network. On the contrary, CSDS communications for the general science community must allow the use of services of the public Internet. Apart from the data throughput and bandwidth requirements mentioned so far, the design of CSDSNet also had to take into account connectivity and security requirements, both within CSDSNet and at its borders. Those of are reflected in the actual network topology and in router configuration details and will be commented further below.

As can be easily interpreted from Figure 1, CSDSNet must be carefully and compatibly embedded in a system of networks known as the Internet. It must however be a dedicated communications resource with a controlled utilization. In particular CSDSNet is not a general transit network. Therefore it was best to configure it as a self-contained network. It has its own IP addressing space with its own routing policy. In view of the foreseeable number and distribution of interfaces and hosts requiring a CSDSNet address, a "Class-C" address was obtained from the Internet regulatory body in Europe (RIPE). The allocation of this Class C address which is a range of 254 allocatable addresses from RIPE ensures the smooth co-existence of CSDSNet with the Internet.

The integration of the CSDSNet with the DC site networks was determined by the conditions of the existing public Internet connectivity of the site. CSDSNet distinguishes two types of Data Centres, a Type 1 DC is seen from any national Internet as a system on *peer* level. A Type 2 DC however is merely *part* of the national Internet of the country where it is located; it is not a peer network when seen by another national network. To take these design constraints adequately into account was and is extremely important for the consistency and stability of CSDSNet routing in conjunction with its gateways.

A further complicating factor was the request for CSDSNet to be used as a project specific transit network by certain national PI's who needed to access the CDDS host at ESOC. Their original method of accessing CDDS was via the Internet's system of international gateways. These however proved to be unreliable and had low throughput characteristics which made CDDS access impractical via this method. CSDSNet was adapted to allow the PI to route traffic to the CSDS router at the national data centre which would selectively allow only the PI traffic for CDDS into CSDSNet thereby bypassing the bottlenecks in the Internet.

Connectivity between the DC s and JSOC, into the ESA institutes is implemented by means of a dual gateway between CSDSNet and the Agency's private Intranet, which is known as ESINet. Gateway sites between CSDSNet and ESINet are at ESOC and ESTEC.

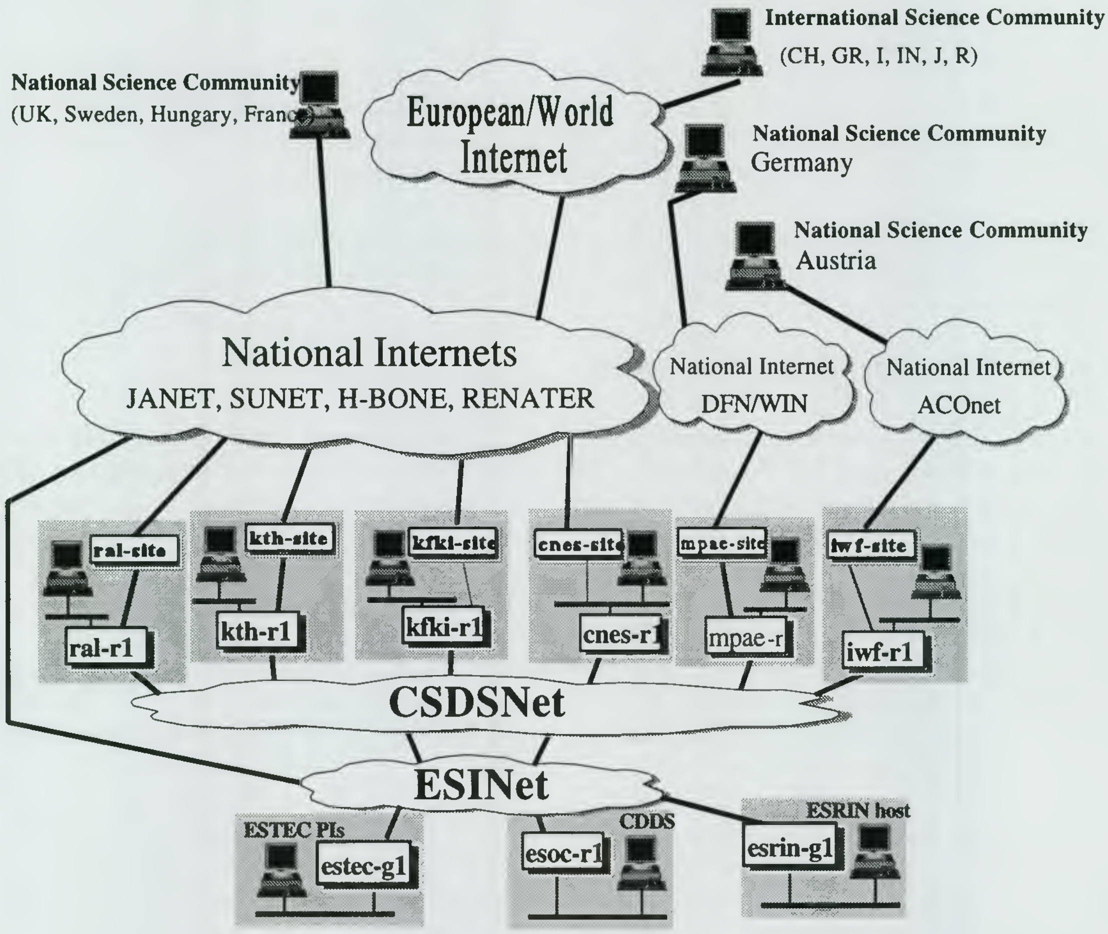

Figure 1.- CSDSNet and Connections to other Networks

CSDSNet achieves its complex balance of selectively allowing certain traffic flow while disallow others by use of a routing policy. This policy determines the traffic that is eligible to be carried through CSDSNet. When a candidate packet arrives at a CSDSNet interface, the router checks that the packet matches the routing policy and if so forwards it towards its ultimate destination. If it does not (which would be unusual) the packet is discarded. This has the added advantage of offering a basic security to CSDSNet connected hosts. CSDSNet does NOT carry out any further security checking of the packet or user data. As the CSDS hosts will be accessible from the public Internet, it is the responsibility of the DCs to ensure that they are adequately protected by whatever means they feel appropriate. The routers in the CSDSNet themselves are protected from unauthorised access by the use of access-lists of authorised hosts and passwords on the management interfaces.

2.2 INFRASTRUCTURE AND TRANSMISSION CAPACITY

The standard connection method between CSDSNet routers and the interconnecting WAN is Frame Relay. (FR). FR is a highly efficient and flexible protocol that provides a means for statistically multiplexing many logical data conversations over a single physical transmission link. These logical data conversations are known as Permanent Virtual Circuits (PVCs).

The Wide Area Network (WAN) configuration supporting CSDS is schematically depicted in Figure 2.

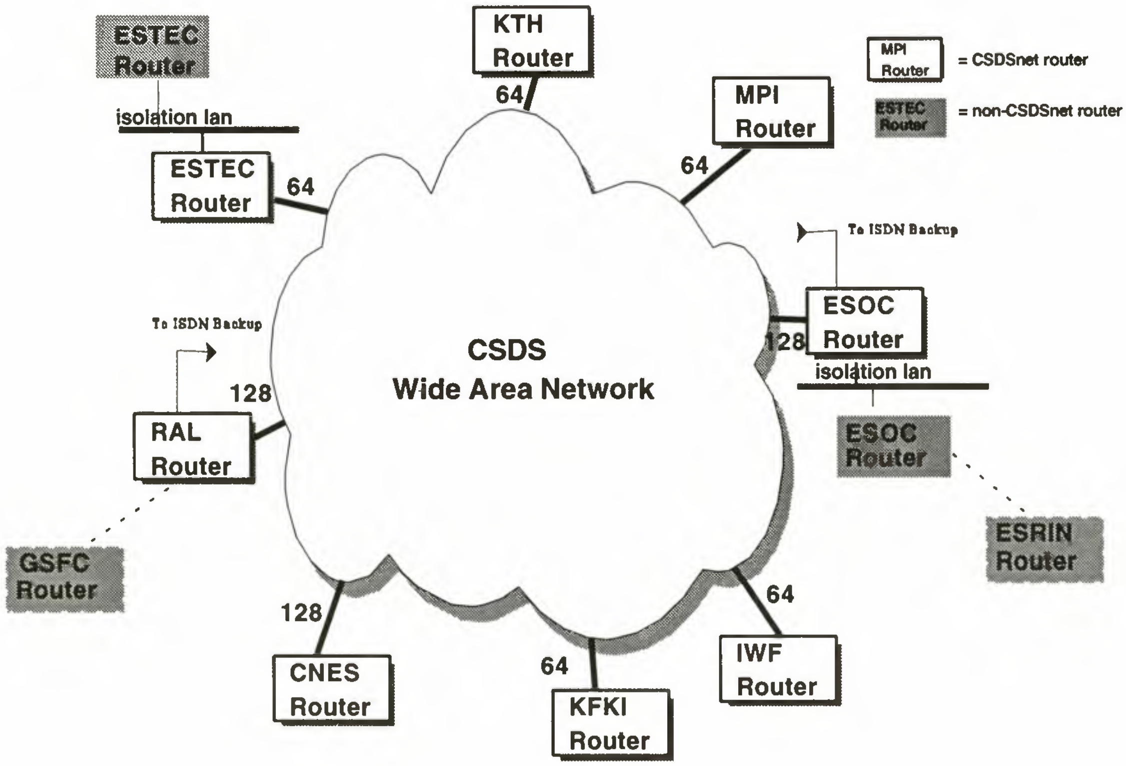

Figure 2.- CSDS WAN Configuration

The physical bit rate required for each WAN PVC connection has been derived from Table 2. Since carriers do not supply leased lines at random bit rates, the actual access links to be implemented shall have a bit rate rounded up to the next higher standard value. This leads to the capacities depicted in Figure 2 for the CSDS routers' WAN access links.

The FR network acts as one logical IP network across which all routers are directly attached, i.e. one logical hop away from each other. The actual connections shall be made by means of PVCs, between each pair of routers, resulting in a full mesh of connectivity. In order to guarantee the required throughput on the F/R network, a mechanism known as Committed Information Rate (CIR) is used. A CIR is a minimum "contract" or share of the bandwidth that the PVC will always get regardless of the demand that other PVCs are placing on the network being traversed. For CSDSNet a CIR value is allocated to each PVC, in each direction. The standard CIRs is 16 kbit per second with the exception of ESOC to RAL and ESOC to CNES where the CIR is 48 kbit per second.

3. NETWORK IMPLEMENTATION

Given the scope of the requirements an early decision was made to utilise the services of an external organisation for the actual implementation and day to day running of CSDSNet. This was achieved without ESA losing visibility or control of the network design or other related tasks in which ESA has a legitimate interest. In fact, there have been three distinct phases in the life of CSDSNet to date. The initial requirements gathering, design and specification phase, the implementation phase and the operations phase. Throughout all three phases the communications unit of the ESA Computer and Networks Operations Department has retained key CSDSNet design responsibilities including

- planning and design of CSDSNet on network level,
- technical specification of the network to the service supplier
- specification of router configurations for all parameters governing the addressing and routing as supported on the LAN interfaces,
- specification, supervision and sign-off of equipment and network acceptance testing,
- data centre site testing (in collaboration with the DCs)
- specification and commissioning of connectivity to DC LANs and national Internet links (in collaboration with DCs and national Internets)

A further key activity that ESOC fulfilled was the development of procedures to be adhered to by all parties for the successful smooth running of CSDSNet. These procedures cover such areas as scheduled changes to the network, requests for new services, and how to diagnose problems should they occur. These are documented in [4].

The CSDS WAN service is provided by a single telecommunications supplier. This service consisted of the installation and maintenance of CSDS routers at the DCs, provision of the FR network and the access circuits into the DCs. The service also consists of the management and operations of the overall network, including regular availability and utilization reporting. Since readiness of CSDSNet (on schedule in June 1995), the network has been operated routinely. The current role of ESOC is supervision and quality assurance of the service and first diagnostics as application, host, or network fault in case of problems. To support this, ESOC has read access to the supplier's network management information. ESOC also acts as single contact to the network provider and engineers router modifications as need arises.

4. NETWORK PERFORMANCE

4.1 COMMUNICATIONS SERVICE LEVEL

Under the contract with the supplier, certain service level commitments for CSDSNet have to be met and are defined in a Service Level Agreement (SLA). These are availability of permanent FR PVCs within CSDSNet, throughput, and network transit delay. Availability is defined end to end and thus includes the core network, access circuits and site equipment up to the LAN port. It is measured for each frame relay circuit individually and averaged over a month. Each DC has multiple frame relay services. Examples are RAL to ESOC, RAL to CNES, RAL to MPAe and so on. There are 81 connection in total. The minimum contracted availability for any connection is 98.8%. For connections serving the JSOC and the CDDS site, i.e. RAL and ESOC, it is 99.4%. To ensure this target can also be met in case of access circuit outages, JSOC and ESOC can also connect to the core network via an automatic ISDN dial up on demand. Availability is reported by the supplier on a monthly basis.

Throughput and transit delay targets must also continually be met. These were benchmarked with dedicated test equipment during acceptance testing. Should the network behaviour as perceived by the users deviate from this, the supplier has to verify the network elements in question by quantitative tests. Throughput has to be in line with the committed information rates. For transit delay, the SLA foresees to maintain a defined average over a 4 hour validation period for a specific packet size.

During 1995, frame relay was not available in Austria and Hungary. Therefore these sites were originally integrated into CSDSNet via X.25, for which no tight delay warranty is possible. In early 1996, however, these sites were migrated to frame relay. There have been no violations of the transit delay SLA.

Reports on availability for 1996 up to June show the following: in February an outage occurred where the SLA was not met for 8 of the virtual circuits. This was due to access circuit problems. During all other times, the SLA was fulfilled. Apart from these exceptions: 99.55% on three PVCs in January, 99.92% on 8 PVCs in May, the actual availability was 99.99% or 100%

4.2 USER EXPERIENCE

Following the commissioning of connectivity to DC LANs, CSDSNet was handed to its users. CSDSNet has been proven to meet the requirements placed on it in the system validation tests and this was formally confirmed at the Ground Segment Readiness Review. Subsequent revalidation activities carried out throughout 1996 have also proved that CSDSNet meets its specification.

5. SUMMARY AND CONCLUSION

CSDSNet has been implemented as a mission dedicated Intranet with its own routing, access and usage policy. Architecture and design follow a clear concept. An important element of this concept is uniformity of transmission protocol, equipment and interconnecting technology. The core network uses a bandwidth efficient statistical multiplexing technique. There is a well defined interface to the participating institutions and to the user community outside CSDSNet itself.

The external components of the CSDSNet service are provided by a world-wide operating provider of telecommunications services. This ensures that the service infrastructure is consistent for all of CSDSNet. The network uses resources which are committed by the supplier to an un-compromised support of a larger user base. Therefore CSDSNet achieves a very high availability. - CSDSNet was ready on schedule and it has been proven that the requirements are fulfilled, in particular throughput and availability.

The CSDSNet design offers high flexibility. For example, the German DC was moved on very short notice from Berlin to Garching by introducing a local access circuit from Garching to a frame relay switching hub at Munich. CSDSNet is also a scalable network. Committed information rates can be varied within a wide range by the supplier without loss of service to the users.

CSDSNet could have been implemented on a spectrum of different solutions, ranging from pure usage of public Internet (with an extreme risk of low performance) to using a totally private infrastructure end to end. A project specific Intranet as described in this paper yields the best balance of performance and cost. In this respect CSDSNet is in fact a model for mission product internetworks. It is hoped that there will soon be a revised Cluster mission and a new opportunity for the Cluster scientific community to benefit from CSDSNet.

ACKNOWLEDGEMENTS

As became apparent from the paper, the creation of CSDSNet had various phases, ranging from system and architectural design over detailed design work to implementation by the network provider and the data centres, including the integration of CSDSNet with institutional and public networks. The contributions of Walter Dillen and especially Ray Hunter, who both left ESOC in the summer 1995, to the work in all these phases are gratefully acknowledged.

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A DATA MANAGEMENT PROTOCOL FOR SPACE MISSION OPERATIONS

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ABSTRACT: This paper proposes a method of data management for space mission operations. This method, which is called the Packet Management Protocol (PMP), uses the CCSDS Recommendations for Packet Telemetry and Telecommand as its base, and the Protocol Data Unit used for transferring user data is the CCSDS Packet. PMP monitors and controls transfer of Packets and manages storage of Packets using a network management protocol (or a messaging protocol). Thus PMP (1) provides information on Packets being transferred between nodes and Packets stored at nodes, (2) performs reliable delivery of Packets (not only realtime delivery but also store and forward delivery), and (3) manages stored Packets from remote nodes.

1. INTRODUCTION

Most space missions of today adopt Packet Telemetry and Packet Telecommand Recommendations [1-4] developed by the Consultative Committee for Space Data Systems (CCSDS) for communications between spacecraft and ground segments. These Recommendations meet the requirements of current space missions for flexible and efficient transfer of various data over space links. Space missions of the future, however, will require many functions for data transfer and handling that the current CCSDS Recommendations do not provide.

First, the CCSDS Recommendation for telecommand [4] specifies a protocol for automatic retransmission of frames for guaranteeing correct transfer of command frames to the command decoder of a spacecraft, but it does not necessarily guarantee delivery of command Packets to their final destinations (i.e. payloads or instruments onboard the spacecraft). As for telemetry, CCSDS does not have any method for performing complete delivery of data. Future space missions, however, require a method for complete end-to-end delivery of Packets because high-level data used by future spacecraft will be sensitive to loss. Second, CCSDS has not defined a method for managing transfer of Packets. A method for monitoring and controlling transfer of CCSDS Packets such as the SNMP (Simple Network Management Protocol) used in the Internet will be beneficial to space mission operations of the future. Further, Packets are often stored at various places, such as central data handling systems of spacecraft, ground stations and some control centers, for delivery to next or final destinations at later times. This mode of delivery is called store and forward delivery. A method for managing Packets which are stored at such nodes will be beneficial, too.

Reliable transfer of data can generally be achieved with a transport protocol such as TCP or a file transfer protocol such as FTP. However, these protocols cannot be applied to space operations directly because the environment for which these protocols were developed is different from the environment of space operations. Firstly the physical characteristics of space-to-ground links (e.g. bit error rate and propagation delay) are very different from those of terrestrial high-speed data links, and secondly these protocols were developed for realtime transfer between end nodes and do not work for store and forward delivery. To solve some of these problems, a set of protocols called SCPS (Space Communications Protocol Standards) are being developed by a US group [5]. These protocols are based on TCP/IP but some modifications have been made to adapt TCP/IP to the space environment. The concept of SCPS, however, differs from that of Packet Telemetry/Telecommand in that the former is a byte oriented protocol whereas the latter is a record oriented protocol. Most space data can be regarded as series of records, and a record is usually transferred in a Packet if the CCSDS Packet Telemetry or Telecommand Recommendation is used. If SCPS is used, however, users have to define another data structure in the application layer for representing records. Therefore, to implement SCPS, many modifications have to be made to the current packet-based space data systems.

This paper proposes a completely different solution to the above problems, which is called the Packet Management Protocol (PMP). This protocol uses the current CCSDS Packet Telemetry/Telecommand Recommendations as its base, and tries to meet the requirements of future space missions described above by adding some capability to Packet Telemetry/Telecommand. What is needed to implement PMP is only adding a simple mechanism for network management to the current packet-based space data systems.

2. NETWORK MODEL

In this Section, a network model necessary for defining the Packet Management Protocol (PMP) is introduced. This model consists of a definition of Nodes which process Packets and a definition of a structure of protocol layers.

2.1 NODE TYPES

In this network model, CCSDS Packets are processed by two types of nodes: i.e. End Nodes and Packet Nodes. An End Node is located at an end of a data path, and generates and/or consumes user data inside CCSDS Packets. A Packet Node is an intermediate node located in the middle of a data path, and routes CCSDS Packets to the next Packet Node or receiving End Node. If necessary, a Packet Node stores CCSDS Packets and deliver them at later times (store and forward delivery). Packet Nodes do not process user data contained in the Packets. They only look at the Primary and Secondary Headers of each Packet. On spacecraft, payloads and instruments are End Nodes, while central data handling systems onboard spacecraft play the role of Packet Nodes. On the ground, control centers and payload operations centers are End Nodes, and ground stations act as Packet Nodes. If a control center further delivers data to payload operations centers, it plays the role of a Packet Node as well.

A set of similar links which interconnect Nodes is called a subnetwork. An onboard network, a space-to-ground link, a ground network are examples of subnetworks. Any two Nodes which exchange CCSDS Packets with each other are connected via a single subnetwork.

2.2 LAYER STRUCTURE

In this network model, protocols are classified into three categories: i.e. Application Layers, the Packet Layer, and Subnetwork Layers (see Figure 1). The Applications Layers are a set of layers which deals with the user data area of CCSDS Packets, and reside only in End Nodes. The Packet Layer sends, relays and receives CCSDS Packets using PMP, and resides in both End Nodes and Packet Nodes. At Packet Nodes where Packets are stored, the storage of Packets is managed by the Packet Layer. The Subnetwork Layers move Packets from a Node to another Node through a subnetwork.

Please note that these layers do not necessarily correspond to particular layers of the Open Systems Interconnection Reference Model (OSI-RM) defined by the ISO. These layers are defined based on their relative relation to the Packet Layer which handles CCSDS Packets. The Subnetwork Layers can differ from subnetwork to subnetwork and have any number of layers. For example, only the Physical and Link Layers are usually used for moving CCSDS Packets over space-to-ground links, while four layers (from

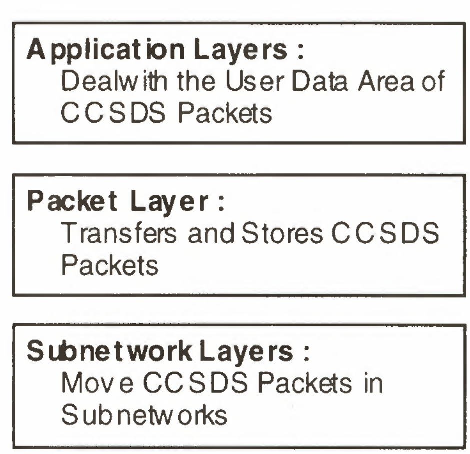

Figure 1: Layer Structure

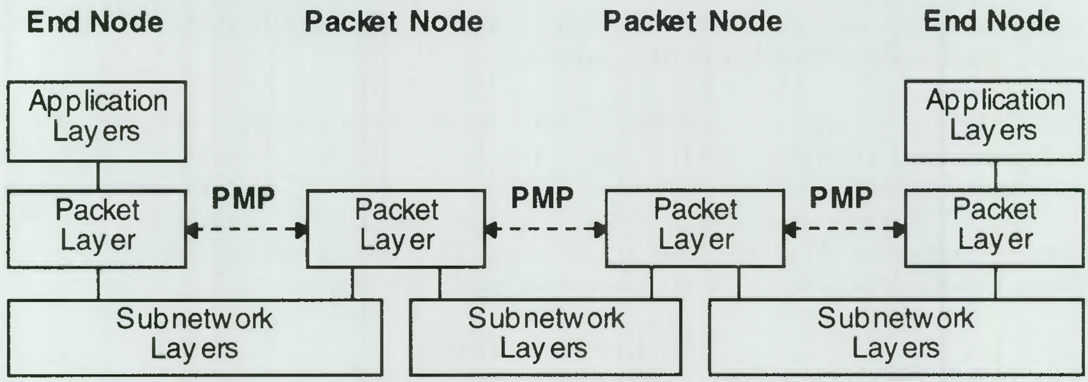

Figure 2: Layer Structure of an End-to-End Data Path

Physical to Transport) are typically used for moving CCSDS Packets in ground networks.

An example of the layer structure of an end-to-end data path is shown in Figure 2. This structure is the same as the structure of the Path Service defined by the AOS Recommendation of CCSDS [2]. PMP is basically used between two adjacent Nodes of a data path at the Packet Layer.

3. COMPONENTS OF PACKET MANAGEMENT PROTOCOL (PMP)

3.1 BASIC CONCEPT

PMP is a set of techniques for transferring and managing space data rather than a single communications protocol. PMP consists of the CCSDS Packet Telemetry/Telecommand Recommendations and a standard network management protocol (or a standard messaging protocol) with the Management Information Base defined for PMP (see Figure 3). The unique feature of PMP is that reliable transfer of data (including retransmission control) and management of stored data are realized with a network management protocol. Network management protocols were not originally developed for controlling data transfer, but in PMP a network management protocol is utilized to provide a mechanism for out-of-band control of data transfer. PMP can be applied to both telemetry and telecommand Packets.

3.2 DATA STRUCTURE

The Protocol Data Unit (PDU) of PMP for transferring user data is the CCSDS Packet. The format of the CCSDS Packet is shown in Figure 4. Each CCSDS Packet is identified by a Path ID and a Packet Sequence Count. The Path ID defines a logical data path through which the packet traverse the entire network. Associated with each Path are one source End Node, one (or multiple) destination End Node(s), and some intermediate Packet Nodes which relay Packets. A Path ID

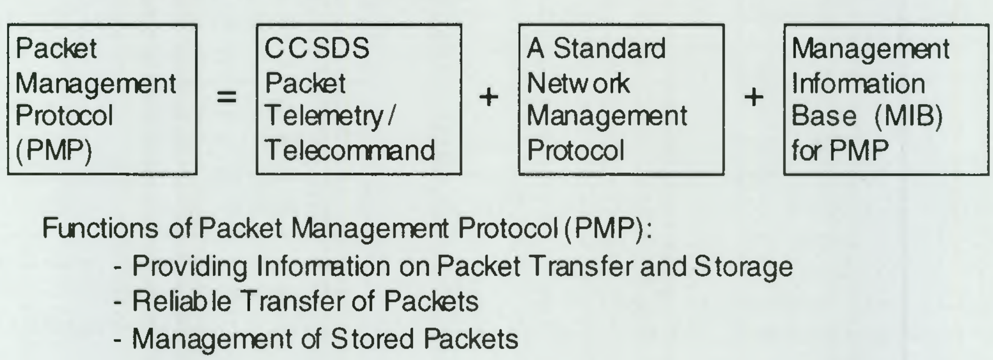

Figure 3: Concept of Packet Management Protocol

Primary Header							Sec. Header		User Data
Version No.	Type	Sec. Hdr. Flag	APID	Seq. Flags	Packet Seq. Count	Packet Length	Stream ID	Other Infor-mation	

Figure 4: Format of CCSDS Packet

consists of an Application ID (APID) and a Spacecraft ID (SCID). The APID is contained in the Primary Header of each Packet, while the SCID is not. It is assumed here that the SCID is conveyed from a Node to its next Node along with each Packet using a function of the underlying subnetwork (e.g. with the header of the frame containing the Packet or as ancillary data to the Packet).

In addition to the CCSDS Packet, PMP uses another data unit called the Packet Stream. A Packet Stream is defined as a sequence of consecutive CCSDS Packets with a Path ID, and it can consist of a finite or infinite number of Packets. The first and last Packets of each Packet Stream are marked with the Sequence Flags in the Primary Header. Each Packet Stream is identified by a Stream ID. The Stream ID is contained in the Secondary Header of each Packet. The last Packet of a finite Packet Stream contains in its Secondary Header the total number of Packets belonging to that Packet Stream. With these methods, completeness of a Packet Stream can be examined with only the Headers of the Packet Stream. A Packet Stream serves as a unit for on-line Packet transfer session as well as a unit for storing Packets. In the latter case, a Packet Stream corresponds to a file.

3.3 MANAGEMENT AND MIB

Transfer of Packets is controlled with a network management protocol (or a standard messaging protocol) and a Management Information Base (MIB). Any standard network management protocol can be used as the network management protocol for PMP. One of the candidates is the Simple Network Management Protocol (SNMP) developed for the management of the Internet. Each Node (End Node or Packet Node) has a MIB defined for PMP. The MIB for PMP contains a set of managed objects shown in Table 1 for each Path which the Node is sending out, and a set of managed objects shown in Table 2 for each Path which the Node is receiving. If the Node is sending Packets of a Path to multiple Nodes, a set of managed objects is maintained for each receiving Node. These managed objects represent the status of the protocol machine of PMP at that Node for each sending or receiving Path. Although these managed objects only reflect the status of transfer between two adjacent Nodes, complete end-to-end delivery of a Packet Stream can be assured because the completeness of a Packet Stream can be verified with the Packet Stream itself (see Section 3.2), which is transferred from the source End Node to the destination End Node unchanged.

Table 1: Managed Objects for a Sending Path

Managed Objects	Read/ Write
Spacecraft ID (SCID)	R
Appl. Process ID (APID)	R
Next Node ID	R/W
Session Status	R/W
Transfer Mode	R/W
Stream ID	R
Next Packet to be Sent	R
Total No. of Packets Sent	R
Next Packet to be Received	R/W
Window Size	R/W
Time-Out Value	R/W
Max. No. of Retransmissions	R/W
Priority	R/W

If a Packet Node stores Packets, the Node has in its MIB a set of managed objects shown in Table 3 for each stored Packet Stream. Managed objects for stored Packet Streams provide directory information for the data which the Node has stored.

Managed objects in the MIB are monitored and/or set by other Nodes with the selected network management protocol. The value of a managed object with attribute *Read* can be monitored by other Nodes, and the value of a managed object with attribute *Write* can be set by other authorized Nodes. Messages of the network management protocol are sent in CCSDS Packets with special Path IDs reserved for management messages. Messages for inquiring the status of multiple Paths and/or setting values for multiple Paths can be sent in a single CCSDS Packet. In principle, these management messages can be exchanged between any two Nodes defined in Section 2 provided that a management Path is defined for the two Nodes. But usually management messages for a Path are exchanged between two adjacent Nodes comprising the Path. How the MIB is used for reliable transfer of Packets and management of stored Packets is explained in Sections 4 and 5, respectively.

Some functions of PMP overlap with some functions of the Space Link Extension (SLE) services being defined by CCSDS [6], which provide services for extending space-to-ground links to some other locations on the ground. The differences between the two is that (1) the SLE services are used only between two ground Nodes while PMP is used for end-to-end data paths including both space and ground Nodes, and (2) the SLE services handle any data structure of the CCSDS Recommendations while PMP only deals with CCSDS Packets. Since PMP can be realized with multiple implementation methods (e.g. different network management protocols in different subnetworks), PMP can utilize functions of the SLE services to realize its own functions. Therefore, PMP and SLE are not mutually exclusive protocols. In this paper, PMP is only concerned with transfer of CCSDS Packets because it is assumed here that the Packet is the data unit that has to be managed throughout the network. However, the same principle can be applied to CCSDS Frames in case the management of Frames is necessary.

Table 2: Managed Objects for a Receiving Path

Managed Objects	Read/ Write
Spacecraft ID (SCID)	R
Appl. Process ID (APID)	R
Previous Node ID	R/W
Session Status	R/W
Transfer Mode	R/W
Stream ID	R
Next Packet to be Received	R
Total No. of Packets Received	R
Priority	R/W

Table 3: Managed Objects for a Stored Packet Stream

Managed Objects	Read/ Write
Spacecraft ID (SCID)	R
Appl. Process ID (APID)	R
Stream ID	R
Storage Status	R/W
Sequence Count of First Packet	R
Total No. of Packets	R
Complete Stream or Not	R
Reception Time of First Packet	R
Reception Time of Last Packet	R
Time Before Erasing	R/W

4. RELIABLE TRANSFER OF PACKETS WITH PMP

PMP realizes reliable transfer of CCSDS Packets in much the same way as TCP does. The biggest difference is that PMP sends control information through the MIB with a network management protocol in a different connection from the connection for user data, whereas TCP sends control information with the same data structure as used for user data in the same connection. Nodes sending and/or receiving CCSDS Packets using PMP monitor and set the values of relevant managed objects as necessary while sending and/or receiving Packets.

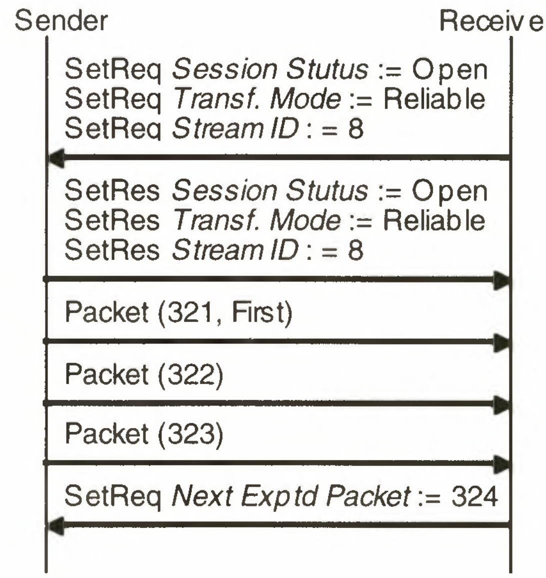

Figure 5: Example of Message Sequence

Functions for reliable transfer are realized with managed objects (MOs) as follows. Establishment of a data transfer session is done by setting the value of the MO *Session Status* to *Open*. Either the sender or receiver can request session establishment. The receiver can check what the sender is receiving from the upper Nodes by monitoring the values of MOs for receiving Paths at the sender before requesting session establishment. Either the sender or receiver can specify the mode of transfer by setting the value of the MO *Transfer Mode*. The MO *Transfer Mode* has one of the following three values: *Reliable*, *Best Effort* or *Unreliable*. Either the sender or receiver can specify the Stream ID of the Packet Stream to be transferred by setting the value of the MO *Stream ID*. In the reliable transfer mode, a transfer session starts from the first Packet of a Stream unless the receiver specifies from which Packet it wants to receive by setting the value of the MO *Next Packet to be Sent*.

Once a Packet transfer session has started, the receiving Node periodically sets the value of the MO *Next Packet to be Received* for acknowledgment of reception unless the transfer mode is *Unreliable*. If the sender does not receive an acknowledgment of a Packet it sent within the value of the MO *Time-Out Value* from the transmission time of the Packet, it retransmits the Packet. If the sender has already retransmitted the Packet the number of times specified by the value of the MO *Max. Number of Retransmissions*, it aborts the session if the transfer mode is *Reliable* or it continues to transmit remaining Packets if the transfer mode is *Best Effort*. The number of outstanding Packets is limited by the value of the MO *Window Size*, which can be set by the receiver for controlling the flow of Packets. A session can be closed by either Node by setting the value of the MO *Session Status* to *Close*.

The configuration of a Path can be controlled by an authorized Node by setting the values of the MOs *Next Node ID* and *Previous Node ID*. Managed objects for error reporting and performance monitoring are not included in the tables of managed objects in this paper, but such managed objects can be added if necessary.

An example of a sequence of management messages and Packets are shown in Figure 5. In this example, the receiver of Packets initiates a session for a Packet Stream of a Path with Stream ID=8. In this figure, only management messages for that Path is shown, but a Node can send management messages for multiple Paths simultaneously in a single management Packet. Therefore, the overhead of management messages is not so large as it seems.

5. MANAGEMENT OF STORED PACKETS WITH PMP

A Packet Node stores received Packets if the bandwidth of the outgoing links is not sufficient or if the Node is to serve as a data server for users. For example, a central data handling system onboard a spacecraft stores telemetry Packets received from payloads while the spacecraft is not visible from any ground station. A ground station or control center may store received Packets for distributing them to users at convenient times. The managed objects for stored Packets shown in

Table 3, which have to be maintained at Nodes with data storage, are used for providing receivers of Packets with directory information of Packets which the Node has stored or is storing, and for managing the data storage.

A Node (End Node or Packet Node called Node A) which desires to receive Packets stored at another Packet Node (called Node B) can check what Packets are stored at Node B by examining the values of managed objects of Node B. If Node A locates the Packets which it desires to receive at Node B, Node A can request transfer of the Packets from Node B with the procedures described in Section 4. A Node authorized to manage the storage of another Node can remotely manage the storage by setting the values of appropriate managed objects for stored Packets. For example, Node A can specify which Paths or Packet Streams should be stored at Node B by setting the value of the MO *Storage Status* of Node B. Also, Node A can specify the time at which Node B can erase data for each stored Packet Stream by setting the value of the MO *Time to Live* of Node B.

6. CONCLUSIONS

This paper proposed a method of data management for space mission operations called Packet Management Protocol (PMP). PMP extends the CCSDS Packet Telemetry/Telecommand Recommendations by adding a method for managing Packets. With simple operations with managed objects, users can send or receive CCSDS Packets reliably, locate Packets they want to receive, and manage storage of Packets. PMP works for both realtime delivery and store and forward delivery. Improving the efficiency of data transfer with the selective repeat technique or other techniques is a theme for further study. Hopefully, this protocol will be prototyped in one of our missions at the beginning of the next century.

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INTERPRETATION OF SATELLITE TELEMETRY DATA UNDER ADVERSE CONDITIONS

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ABSTRACT. To control and effectively monitor the health of the satellite, telemetry data is essential. Onboard parameters are generally sampled much more often than the minimum Nyquist rate. Nominally enough link margin is provided to obtain a very low bit error rate. If for some reasons the bit error rate were to worsen considerably, wrong interpretation may result in conventional processing schemes. A method is proposed to handle such cases which works by overlaying telemetry frames based on ground receive time and majority voting for recovery of selected bits. It is shown that limited amount of information can be extracted successfully even under conditions of poor link margin. The emphasis is on a direct assessment of health and estimation of the behaviour of the satellite in a gross manner. For example, it would help to resolve whether the attitude is stable or lost. Depending on the criticality of the mission such a data processing assumes importance. Yet another contingency is when onboard telemetry is intermittent and a contiguous segment of data is less than a full telemetry frame. Processing schemes then have to rely on correlation of the received data with expected sequences in the normal frame. The processing is in near-real-time and uses pattern recognition. Cross checking with any other related parameter is one of the guiding factors to improve the confidence level in the data interpretation. These schemes are implemented using commercially available expert system tools on a workstation. The efficacy of the methods is demonstrated on simulated noisy data as well as on data of actual satellites under abnormal conditions.

1. INTRODUCTION

One of the main functions of the mission control centre is to monitor the telemetry data from the satellite in order to ensure the healthy functioning of the subsystems. Depending upon the orbit in which the satellite is placed, the availability of this data may or may not be continuous. For near-earth satellites the availability of telemetry data is dictated by radio visibility over the network stations. For satellites placed in geostationary orbit, on the other hand, there is an uninterrupted availability of telemetry. The telemetry system multiplexes several analogue, digital and status parameters into a suitably formatted stream. For geostationary communication satellites the data rate is usually low, of the order of 1 kbps. This data is modulated on to an RF carrier which is received on the ground, demodulated, bit-synchronised, frame-synchronised, sub-frame identified, word/bit values extracted and converted into engineering units for further processing and display. The information thus provided is useful not only for control of the satellite in real time but also for a detailed analysis leading to useful inputs to the subsystem engineers for design validation / improvement.

Though the conventional telemetry acquisition schemes ensure high quality for the data, it would lead to rejection of useful data when the link is poor or when there are frequent interruptions in the telemetry. Even under such adverse conditions, it is necessary to utilise the data as even a few bits of data can provide a vital clue which will help in recovering a satellite in distress. For interpreting data under such circumstances, unconventional methods are called for. It may be necessary to revise the targets in terms of number of parameters and accepting delays in response and fuzziness in the decisions. Efforts must be aimed towards a direct assessment of health, without having to know the value of each and every parameter.

This paper deals with the interpretation of telemetry under two different abnormal situations namely - (i) significant deterioration of link quality and (ii) reception of short bursts of telemetry data. Section 2 presents an analysis of typical telemetry data and identifies subsidiary sync sequences that would help in interpreting telemetry data under abnormal conditions. Section 3 presents details of the typical contingency scenario. Section 4 deals with short bursts of data and methods for extracting useful information from them. Section 5 considers the case of noisy data and how it is possible to derive some information out of it. Section 6 gives an approach in terms of the processing modules needed in such cases. Though these schemes are generally mission-specific, the ideas presented herein can form the basis for developing suitable modules for the specific contingency that may arise. Section 7 summarises the important ideas presented in this paper.

2. SALIENT FEATURES OF TYPICAL TELEMETRY DATA

Telemetry, Tracking & Command (TT&C) subsystem of a satellite interfaces with the mission support ground segment for carrying out satellite control operations. The telemetry subsystem centralises the encoding of information from all the onboard subsystems and transmits them as a composite signal for house-keeping/health monitoring on ground. The health of all the subsystems of the spacecraft is monitored continuously onboard and sent to the ground. Fast varying parameters are monitored in every frame whereas slowly varying parameters are monitored once in a master frame. Under normal circumstances many of the parameters are highly over-sampled. In the case of geostationary satellites the thermal parameters, for example, generally vary with the period of one day, but are sampled once in a few seconds. Then there are parameters like the telemetry calibration voltages that are expected to remain constant throughout the mission life. These data, nevertheless, are to be monitored continuously in order to identify an anomalous condition which can suddenly develop on the spacecraft. In order to accommodate parameters requiring different sampling frequencies, the telemetry data is structured into a master frame consisting of a fixed number of sub-frames. Each sub-frame has a constant frame-synchronisation code. Generally, only the data sandwiched between two valid frame-sync codes are accepted for processing. The received data on ground after demodulation are fed to a bit synchroniser which extracts the data and clock from it. This is followed by frame-synchronisation, that is, assembling the data into frames. The output of the frame-synchroniser can be fed to the mission computer through a serial/parallel interface or directly to the network. The computer can then identify the sub-frame and word number so that the values of the parameters can be extracted. For analogue or digital parameters the engineering unit value can be obtained and from status parameters the current status of the satellite can be derived. Some of the processing could be conditional such as momentum wheel speed would be calculated only when the wheel is on. Based on the values of the parameters, limit checks and alarm conditions are derived. The telemetry data is also useful for confirmation of the commands transmitted from the ground. Display forms an important part of health monitoring as the processed parameters need to be presented in a convenient form for the user to assess the health of the spacecraft quickly.

As a typical example, the specifications of INSAT-2 telemetry subsystem are shown in Table 1.

Frame Format	128 words / frame
Word Format	8 bits/word
Bit rate	1 kbps
Frame sync code	24 bits
Sub-frames per master frame	8
Format	Stored program
Modulation	PCM/PSK/PM
No. of analogue parameters	375
No. of status parameters	390

Table 1. Typical specifications of telemetry subsystem.

Because of the importance of the information provided by the telemetry channel, the system is designed with sufficient operating margin. Under normal conditions the RF link margin would be several tens of dB. This leads to a reception of each and every frame of data at the control centre without error. There is, of course, a large amount of redundancy in the data. Very few parameters vary from frame to frame; and if they do (such as the attitude data), they vary so fast that there is hardly any necessity for knowing the specific value. However, as high as 84% of the bits in the master frame do not change under normal conditions. This is so because of unused words, used-up parameters (like deployment status), slowly varying parameters (like temperatures), constant values (like the most significant bits of onboard time), restricted operational range within the allotted wider range (like the wheel speeds), etc. Figure 1 shows the statistics of varying bits out of 8192 bits of the master frame. The data span includes a segment where the satellite lost its attitude lock, during which time the percentage of varying bits rose from 5% level to 8% level. Figure 2 presents the details of how the varying bits are distributed in the different subframes for the same span of data as in Figure 1. It is true that the varying bits alone carry significant information; but the presence of the invariant bits can be turned to our advantage to provide some form of a sign-post in the wilderness of noisy or short-segment data.

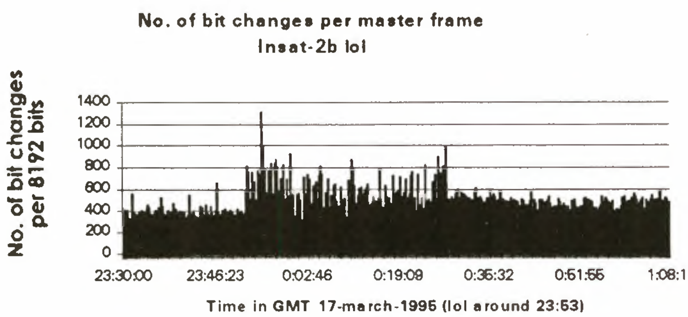
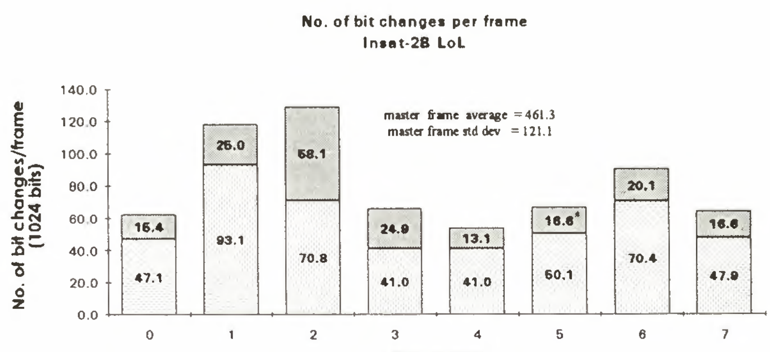


Figure 1. The statistics of varying bits out of 8192 bits of the master frame.

Figure 2. Distribution of varying bits in the different subframes.



Numbers indicate average and standard deviation

3. POSSIBLE CONTINGENCY SCENARIOS

There are several conceivable situations in which the telemetry data received may become unsuitable for conventional processing. The simplest case would be when the link margins are affected. For example, whenever the geometry is such that the ground station, satellite and sun are collinear, there is a sharp increase in the noise floor and this may impair the reception of telemetry. Such sun outages occur for a few minutes on a few days in a year for the geostationary satellite. The other way in which the link margin can get affected is by the reduction of onboard EIRP may be because of an anomaly in the onboard transmitter or may be because of a change in orientation resulting in a decrease in the gain of the onboard antenna in the direction of the ground station. Such instances, though rare, have occurred in several missions.

Yet another contingency can arise when the satellite is in a tumbling mode and the power generation is intermittent and batteries are fully discharged. It is then possible that the onboard telemetry becomes unpowered. Depending on the body rates and the sun geometry, it is conceivable that power is generated for short durations, restarting the telemetry transmission every now and then. This will result in small segments of data being received. If the segment length is less than a telemetry frame, this data is bound to be rejected by the conventional telemetry acquisition system. When the satellite is in such an emergency it becomes all the more important to receive the bits of data and interpret them to whatever extent possible. Methods have been evolved at the Master Control Facility, Hassan which controls INSAT series of geostationary satellites, to log such small stretches of data directly even on a PC. In such cases the loss of data can be minimised by increasing the loop bandwidth setting on the bit synchroniser. The clock and data that are output from the bit synchroniser are acquired using a special but simple hardware. The bytes of data received are stored in the

4. HANDLING BURST DATA

First we consider the case where the link is good, but the transmission is intermittent. When the data is not continuous each burst of data must be processed independently to identify where it belongs. This is because the onboard telemetry system is reset every time it is unpowered thereby losing onboard time reference. The basic scheme of acquiring the burst is as spelt out in the previous section. The bits thus acquired need to be recognised for their position in the standard telemetry frame. If the number of bits in the segment is more than the number of bits constituting a frame (1024 bits in the case of INSAT), it is expected that the frame sync code will appear somewhere in the data. By sliding the frame sync pattern and correlating with the data, the position of the frame sync pattern can be fixed up. If this process is successful, the entire set of data on either side of the frame sync code can be interpreted as the sub-frame ID will also be available in the contiguous set of bits constituting that segment. If the number of bits in the segment is less it is still worthwhile to look for the frame sync code followed by sub-frame ID; if sync code is found, the interpretation is straight forward. If one is unsuccessful in identifying the frame sync code, the only alternative is to look for known patterns. The invariant bits of the master frame provide subsidiary sync sequences (SSS) which play an important role in positioning the bits into the frame thereby facilitating their interpretation.

In order to appreciate the usefulness of SSS under the said circumstances, statistics were collected on INSAT-2A satellite regarding their length distribution, their position in the frame and relative separation between the adjacent sequences. Figure 3, 4 and 5 present the statistics obtained by analysing 90 hours of INSAT-2A, INSAT-2B and INSAT-2C data collected at one hour interval.

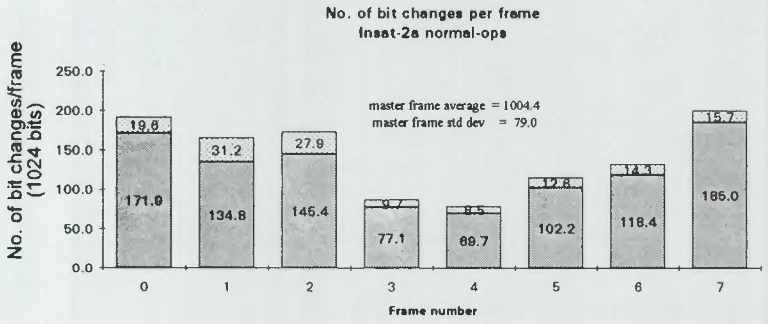


Figure 3. Statistics obtained by analysing 90 hours of INSAT-2A data.

Nos. indicate average and standard deviation : 90 hours data sampled at 1 hour interval

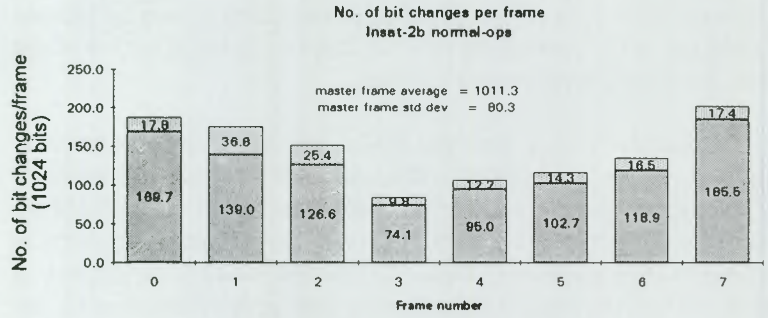


Figure 4. Statistics obtained by analysing 90 hours of INSAT-2B data.

Nos. indicate average and standard deviation : 90 hours data sampled at 1 hour interval

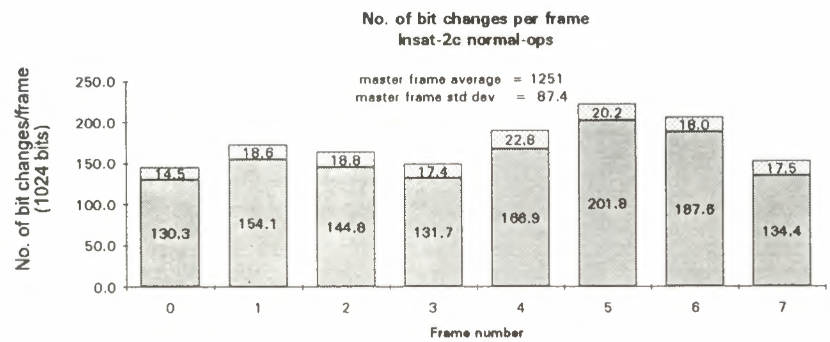


Figure 5. Statistics obtained by analysing 90 hours of INSAT-2C data.

Nos. indicate average and standard deviation : 90 hours data sampled at 1 hour interval

The longest unchanging sequences are of the order of 48 bits whereas typical length of the SSS is around 21 bits. There are a few lengthier sequences with all zeros, but these are not considered for template matching. SSS are fairly evenly distributed within the telemetry master frame. The selection of suitable sequences for bit fixing is governed by a number of criteria such as the length of the sequence, the position of the sequence (for example, closeness to an important parameter) separation from the nearest SSS, and how orthogonal one sequence is with respect to another.

Frame #	Word:Start bit	Bit Length	Pattern
0	003:0	24	000010010000000000000000
	049:0	16	1011000101001001
	054:0	16	0011101100000000
	064:0	07	1100100
	112:0	21	110011101110110011001
	119:0	08	11010010
	123:3	07	0100011
1	003:0	24	000010010000000000000001
	112:0	21	000000000000000000000
	119:0	08	00000000
	123:3	08	00100000
2	003:0	24	000010010000000000000010
	126:0	15	101111111011111
3	003:0	24	000010010000000000000011
	088:3	08	00000000
	091:5	08	00000000
	095:3	09	000000000
4	003:0	24	000010010000000000000100
	049:0	26	10110001010010011000010001
	055:0	08	00000000
	066:3	11	00101001110
	102:0	12	100000000110
	105:0	13	0000000001010
5	003:0	24	000010010000000000000101
	049:0	26	10110001010010011000010010
	054:0	16	1011101100000000
	064:0	11	10000000000
	070:0	48	000000000000000000000000000100100100000000000000
	082:0	16	1000000000000100
6	003:0	24	000010010000000000000110
	049:0	26	10110001010010011000010010
	053:6	19	0000111011000000010
7	003:0	24	000010010000000000000111
	049:0	26	10110001010010011000010010
	053:7	26	00101110110000000011001000
	060:0	32	11001010010000000000000100000001

Table 3: Statistics obtained by analysing 72 hours of INSAT-2A data.

The overall approach in such cases is correlation of SSS with the received burst. It is possible that no match is found, which will happen if the burst does not contain sufficient amount of invariant data. On the other hand, the burst may correlate with more than one SSS, which can happen particularly when the length of the burst is small. Under these circumstances, it becomes necessary to look for correlation with other SSS at known separation from the matched one. It is sometimes possible that one SSS can be a subset of another that can result in a false match. To avoid this condition, it is preferable to match the received data with different SSS, in the decreasing order of their lengths.

As brought out in the previous section, some of the bits that do not change in the normal phase of operations would do so under abnormal conditions. It is hence necessary to generate the templates as appropriate for the current phase of operations. It is reiterated that the invariant bits do not carry information and to that extent they are overheads. But under the circumstances under consideration, these help us position the varying bits in the telemetry frame. If there are too few invariant bits in the telemetry frame, it may not be possible to get a proper fix, especially for short bursts of data.

The presentation of the data under these conditions poses its own challenges. The identified parameters can be presented in a tabular form. For smoothly varying data, it is possible to use interpolation techniques and represent their variation graphically. It is also important to classify the parameters as critical or important and concentrate the efforts on getting good estimates of their values. For instance, when INSAT-1C was in such an emergency, it became necessary to monitor certain sun sensor values and hence two long fixed sequences on either side of this telemetry word were selected as templates.

5. INTERPRETATION OF NOISY DATA

When the link quality degrades as specified by the ratio of carrier power to noise power spectral density, the bit error rate would increase. Under this condition, a bit synchroniser must be configured with the shortest loop bandwidth available. When the bit error rate becomes as large as 10^{-3} or worse, it becomes impossible to look for data sandwiched between two valid frame sync codes. Increasing the number of allowed errors in frame sync code would not also be the right solution as this could lead to some crucial bits of data being wrongly received and interpreted. (For example, the bit showing earth presence can erroneously be showing loss of earth). Under these conditions, it becomes necessary to make certain compromises on accuracy, number of parameters being monitored, and time of availability of the values of the parameters. The emphasis will be on the direct assessment of health. Wherever possible, corroborative evidences must be sought for confirming any anomalous condition.

The overall approach in handling such data is based on the realisation that the onboard telemetry system is perfectly normal and once a correct frame sync code is identified, the subsequent data can be framed based on the ground receive time. For obtaining the frame sync at the first place, it is required to segment the data into those of one frame length (1024 bits for INSAT). Taking three successive such segments one looks for the frame sync pattern after majority voting at the bit level. If it is unsuccessful, the number of successive segments taken up for majority voting can be increased from 3 to 5, later to 7 and so on. Once the frame sync is located, the data is stacked by the word number in the telemetry frame. Removal of wild points is by majority voting at the bit level. For main frame words the folding of data is in lengths of the main frame, whereas for master frame words the folding is corresponding to the master frame length. Care must be taken to pre-process some of the words prior to the majority voting (for example, some parameters which carry the data in 2's complement or grey code etc.). It is obvious that the majority voting which has to be carried out in a sliding manner will result in delayed availability of the values of the parameter, but will enhance its utility as it has been better confirmed. Depending on the circumstances, one can resort to an improvement in the certainty factors by model-based reasoning which will be highly specific to the mission as well as the type of contingency a satellite is placed in.

6. SOFTWARE ORGANISATION

The telemetry module is organised to collect the data in the data store and do the frame sync part in the computer system rather than in the frame sync unit. This telemetry acquisition model therefore has the flexibility to take any number of templates for 'frame sync'. After acquiring the data, the bit stream is taken out from the data store by the bit-fixer module to locate the bit in the master frame buffer with a proper time tag. Based on the number of collected words, the longest available SSS is taken for pattern matching. In case of failure, the next longest SSS is used. After the bit / word is fixed, the data is passed on to the engineering unit conversion module and display module. Disk logging is carried out based on the availability of data optimising the storage requirements.

For the case of noisy data, continuous error checking is done to quantify the noise level. Once it crosses the threshold the processing module, based on bit level integration is automatically invoked. Even when this is operative, it is possible to keep track of the bit error rate by counting the number of errors in the known segments of invariant data.

7. SUMMARY AND CONCLUSIONS

The conventional processing schemes adopted for telemetry are robust and reliable. However, on rare occasions one can get into contingencies where the data is so corrupted or so scarce that meaningful interpretation of the same will call for new schemes. These schemes will have revised goals and must necessarily trade-off some of the features of conventional processing. Two such cases have been considered in this paper. The case where the link deteriorates making the telemetry stream quite noisy can be handled by stacking the frames by the correct word number and bit number and using majority voting to remove erroneous data. On the other hand, if the telemetry data is interrupted frequently onboard, the timing reference is lost which calls for interpreting short stretches of data. Some of these bursts can even be less than a frame in length. In spite of this limitation, some useful information can be extracted if one uses the off-line analysis of the telemetry frames identifying the subsidiary sync sequences which can be selectively used to locate a few of the important telemetry words. Both these schemes are amenable to software development using an expert system shell.

ACKNOWLEDGEMENT

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ORATOS - DEVELOPMENT, OPERATION AND FUTURE EVOLUTION

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ABSTRACT. ORATOS is ESA's multi-Flight Dynamics support system. The initial goal of ORATOS development - the move away from a mainframe to a distributed computing environment with modern graphical facilities - has been achieved. New goals for future evolution aim at new mission operations requirements and cost reduction. New requirements are placed on the Flight Dynamics System (FDS) by future missions like ROSETTA and COBRA/SAMBA. Cost reductions will be achieved by increasing automation and further reduction of complexity within the Flight Dynamics system. This paper analyses cost factors and shows how to achieve further cost reduction under the given constraints and lists new developments inside ORATOS to fulfil the new requirements.

1. INTRODUCTION

Flight Dynamics support tasks at the European Space Operations Centre ESOC are:

- orbit determination, prediction and control
- spacecraft attitude determination and control
- AOCS monitoring
- AOCS calibration
- mission planning

ESOC will during the near future support primarily the following mission types:

- geostationary satellites (LEOP) - MTP
- Earth observation missions - ENVISAT
- observatories - XMM, INTEGRAL, FIRST
- general science - ROSETTA, COBRA/SAMBA

The Orbit Attitude Operations System ORATOS is ESA's Flight Dynamics operations system for the support of all future missions. The ORATOS hardware comprises a network of UNIX workstations (SUN/Solaris) which are divided in development and operational platforms. The first time ORATOS proved its operational fitness was during operation preparation and the launch and early orbit phase (LEOP) of ERS-2 in April 1995. Since then it is used operationally for ERS-1, ERS-2, ISO, CLUSTER and ITALSAT-F2 (LEOP) and will be used for all future missions.

ORATOS provides an infrastructure which contains tools and facilities to implement and operate Flight Dynamics systems for all different mission types. Two mission types comprise currently series of missions with largely similar support requirements: Earth observation missions (ERS-1, ERS-2, ENVISAT) and observatories (ISO, XMM, INTEGRAL, FIRST).

2. ORATOS' HISTORY AND DEVELOPMENT

ORATOS development started with one explicit goal: the move away from mainframe-based computer systems to networked UNIX workstations. This requirement was driven by the increasing operations costs of mainframe systems. A second major change to the Flight Dynamics systems at ESOC was the move from alphanumerical input to graphical user interfaces (GUI) for application control. This requirement was implied by the move to workstations which use GUIs as their native user interface. The third area of change addressed chaining and automatic scheduling of Flight Dynamics application software execution. Development in this area started - to some extent - already on the mainframe-based system and could easily be extended using built-in elements of the UNIX operating system.

ORATOS was designed and implemented as a Flight Dynamics operations support system. Its software architecture is divided in three layers:

- The "Operating System Layer" which contains the basic operating System (today Solaris 2.4) and low level (3rd party) tools for graphical user interfaces, data management and interprocess communications.
- The "Support Layer" which provides high-level tools and services in the areas of communications and data dissemination, man-machine interfaces and systems management. It is the foundation customised for the implementation and operation of the Flight Dynamics applications.
- The "Applications Layer" which houses the different Flight Dynamics applications together with standard facilities (e.g. for orbit determination), shells (e.g. for AOCS monitoring) and libraries.

Details on the design of ORATOS are available in [2].

The next steps in ORATOS development will be taken to cover new mission requirements and the need for further cost reduction.

3. NEW TOOLS FOR NEW REQUIREMENTS

ESA's cometary rendez-vous mission ROSETTA requires optical navigation in the proximity of a comet. This is a domain which has never been covered by any ESA mission before. Optical sensors will be used to determine ROSETTA's trajectory relative to the target comet as well as physical dynamical properties of the comet nucleus. This operational concept requires new advanced graphics facilities fro the FDS.

XMM and the observatory missions after it (INTEGRAL and FIRST) require parts of the FDS to be used by non-Flight Dynamics experts. Attitude determination and trim manoeuvres will be performed on-line by the SPACON. New steps need to be taken to support this part of the routine operations of the Flight Dynamics systems for these missions.

Today there is no need identified to make changes to the ORATOS hardware concept other than the usual maintenance and occasional upgrades. The same applies to the Operating System Layer: low-level tools will be replaced when they are phased out and new versions of commercial software packages may replace the current versions.

In the Support Layer a number of new tools are required. They will deal mainly with advanced graphics and automation support. In the area of graphics new viewers will be developed to visualise star catalogues, ground tracks and spherical geometry. Tools for image processing will be applied to support optical navigation for ROSETTA. The domain of operations automation will be augmented by tools to support the implementation of inter-application interfaces, automatic request handlers and monitors to provide visibility of automatic processes.

The main areas of extension in the Applications Layer will be the generalisation of the mission planning support tools for all observatory missions, optical navigation support and new shells in the area of command generation and AOCS calibration.

4. COST FACTORS

To identify starting points for cost reduction one has to first break down the development and operation of Flight Dynamics systems into cost factors. The following cost factors can be identified:

- computer and network hardware
- commercial off-the-shelf (COTS) software
- mission studies and early design (A)
- development of dedicated software and configuration of infrastructure facilities (B)
- testing and verification of FDS (C)
- team training and verification of operations concepts and operations support for critical phase, e.g. LEOP (D)
- operations support for commissioning phase (E)
- operations support for routine phase (F)

The costs for commercial software and hardware do not contribute significantly to the support costs. Manpower is of largest influence to the total support cost.

Figure 1 shows the manpower profile estimated for ENVISAT Flight Dynamics support. Figure 2 shows the same for XMM. Although of different nature both projects show similar profiles.

Figure 1. Manpower profile for ENVISAT

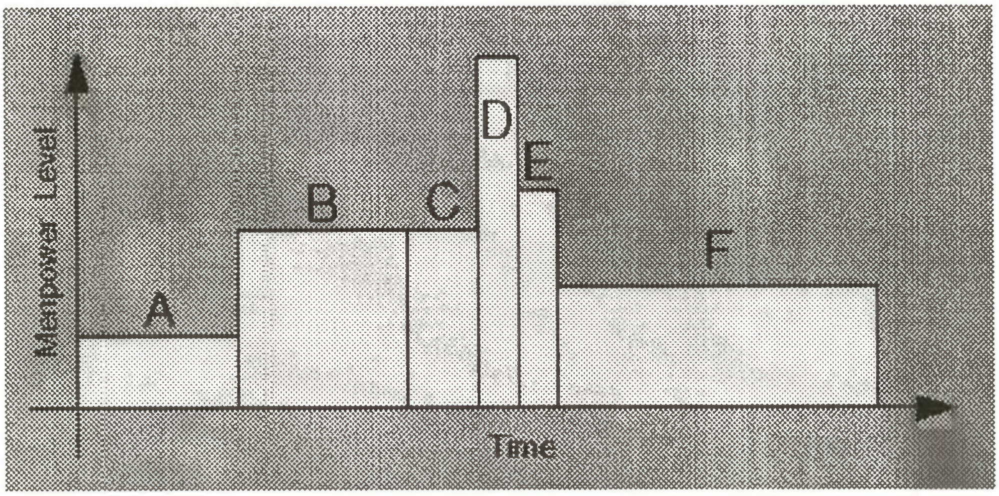
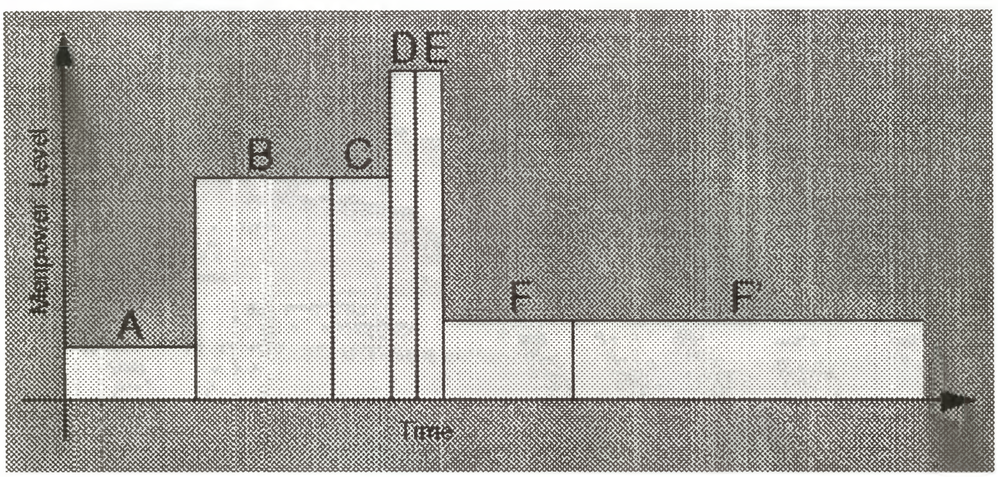


Figure 2. Manpower profile for XMM



A closer look shows the coupling between the areas. The initial studies and early preparatory work is usually carried out by a very small team. This area is correspondingly small and its size depends largely on how much innovation is required for the project at hand. Both examples - XMM and ENVISAT - are follow-up missions. For missions like ROSETTA which require innovation in many different areas the amount of effort required is significantly higher.

The effort required for development of dedicated software and configuration of infrastructure facilities (B) and testing and verification of FDS (C) reflect mainly the level of complexity of both the Flight Dynamics support tasks - which is mission dependent - and system. Follow-up missions require significantly less development effort owing to the re-use of software from the predecessor missions.

The European space programme has achieved a level of matureness that the number of possible *new* mission types is very small today. Therefore the likelihood of a new mission being part of a mission type which was conducted before is very high. Today ESOC is in the fortunate situation where two major series of missions have to be supported: Earth observation and observatories. By designing the FDS with re-use in mind allows for a considerable reduction of the development effort.

The amount of manpower required for the team training and verification of operations concepts and operations support for critical phase, e.g. LEOP (D) is basically proportional to team size and duration. The team size depends on the number of Flight Dynamics support tasks which have to be done in parallel (taking into account the coverage of contingencies). The duration of the preparations and operations phase is driven by the complexity of the operation of the system and the overall mission operations concept.

The effort required for the operations support for commissioning phase (E) follows the same rules as for LEOP - scaled by the involvement of Flight Dynamics in this phase.

While LEOP and commissioning phase require for short periods the maximum team size the operations support for routine phase (F) is supported by a reduced team for a long period.

5. EXISTING MEASURES FOR COST OPTIMISATION

A system designed for space operations has to provide a high level of reliability and must be save to operate. This is an overriding constraint when attempting to reduce support costs.

[1] describes existing methods to optimise costs for Flight Dynamics operations support. In an environment where costs are already highly optimised on the organisational level it is difficult to further reduce support costs.

Using the principles of "end-to-end responsibility" and the "true effort costing" work is organised to reduce the costs to a minimum. By not having development and maintenance, and operations teams dedicated to a certain project software development but assigning maintenance and operations tasks to the same person the work necessary can be distributed in a flexible manner. Extra staffing required for short periods, e.g the support of critical operations for a certain project (e.g. LEOP), are covered by adding developers from other (later) projects with a fraction of their time to the team. This explains why the manning level for testing and verification of FDS (C) is usually lower than the one for team training and verification of operations concepts and operations support for critical phase, e.g. LEOP (D). The same applies for operations support for routine phase (F). Here support tasks are infrequently carried out by people who are primarily working on other projects.

6. OPTIONS FOR FURTHER COST REDUCTION

Cost reduction in some areas can be achieved by shortening periods and/or reducing team sizes. The amount of effort required for studies and the duration of LEOP, commissioning and routine operations phases depend on the nature of the project and lie outside of our control.

Obvious measures to reduce Flight Dynamics operations costs are reduction of team size as well as reduction of complexity of the system and operations concept. To the reduction of team sizes there is a hard limit: the minimum number of positions in a team cannot be less than the number of tasks which have to be done in parallel. The minimum team size results from the minimum number of positions and requirements for shift work or redundancy.

The complexity of the FDS and the operations concept are the primary cost factors during the development and test phase. Complexity of the FDS development decreases with the amount of software re-use. ORATOS contains facilities, e.g. orbit determination, prediction and control packages like LEOPOLD, which represent almost complete sub-systems for certain mission types. Shells - like the AOCS monitoring shell - provide standardised frameworks and software module libraries which enable the move of complexity of sub-systems from mission dedicated software down to a common infrastructure. These are the existing tools which ORATOS provides already now to reduce costs.

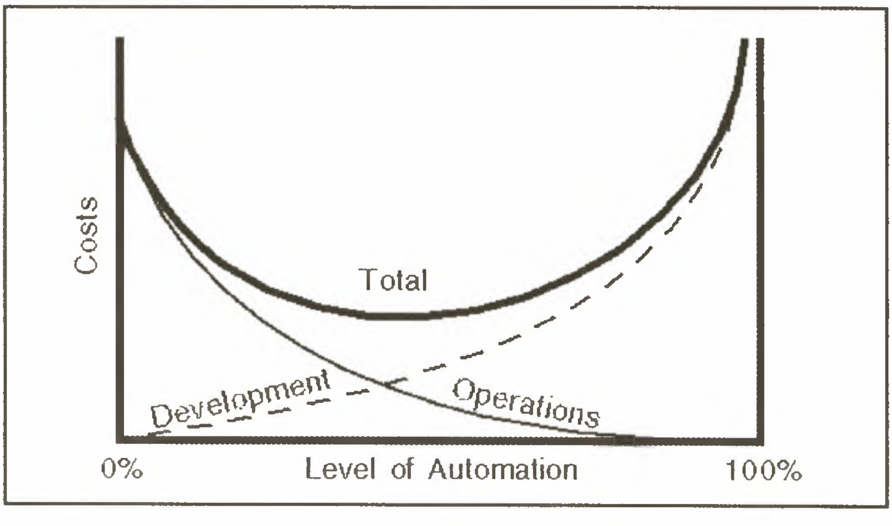
Cost drivers are controllable to different degrees. While limited influence can be taken on S/C and mission complexity, by early involvement of FD in mission and systems analysis (e.g. GIOTTO, ROSETTA), the breakdown of tasks within the FDS can be use to optimise costs.

The ORATOS shells guide the developer towards a clean architecture by providing a generic architecture. In particular interfaces inside the AOCS monitoring system are covered and optimised inside the AOCS monitoring shell. The same approach as with the AOCS monitoring shell can be taken for the overall FDS design. Following an analysis of existing systems a generic architecture can be defined for systems which are sufficiently similar to optimise the interfaces and sub-divisions. The implementation of a system following this architecture may be aided by software tools.

The task breakdown inside the FDS controls the complexity of the FDS and the operations concept. Interfaces between the different Flight Dynamics sub-systems - traditionally orbit, attitude, manoeuvre - drive the complexity of the operations concept and thereby the manpower level required for testing and verification of FDS (C), team training and verification of operations concepts and operations support for critical phase, e.g. LEOP (D) and operations support for commissioning phase (E) as well as the duration of testing and verification of FDS (C). Software tools can improve the implementation of these interfaces to reduce complexity. This "glue" between the sub-systems adds on the other hand to the development and testing effort and thereby to the size of box B.

For the current mission series - Earth observation and observatories - the cost for software development is reduced for the sum of missions by a design which favours re-use.

Figure 3. Total cost as function of level of automation



The same is true for the balance between manual and automatic operational tasks. Simplification of operations (i.e. operations cost) has to be paid for by increased development and testing effort, as shown in Figure 3. One can see from the trends shown in the graph that development costs grow over proportional with increasing automation. The operations costs decrease from the level where no automation is provided down to the level of process monitoring and contingency recovery. The operations costs grow proportionally with the number of repetitions - inside a single mission or across a number of missions in a series. The optimum is somewhere in the middle between fully manual and fully automatic operations. The optimum shifts towards higher degree of automation for tasks which are repeated frequently.

The goal of the simplification of system operation is to replace operator procedures by chaining of tasks. Higher integration of applications up to operations automation may be applied to reduce workload during LEOP operations and preparations, commissioning and routine phase. Simplification during routine phases reduces the operational effort for long periods with usually many repetitions. Simplification during LEOP and commissioning phase may bring the manning level even closer to the absolute minimum. This minimum is constraint by the number of tasks which need to be done in parallel.

One secondary effect of operations simplification is to shift the emphasis from system operations to “Flight Dynamics” and spacecraft aspects of mission support.

Although outside the scope of the FDS the spacecraft and mission design may be done in a way that it does *not* require 24 hour support. This would immediately reduce the team sizes.

7. CONCLUSION

The next phase of development will bring a continuing evolutionary augmentation of ORATOS. The mid-term goals are to consolidate and exploit the current status and invest in additions to the system facilities to be ready for the next missions and their new requirements and to simplify operations and thereby reduce costs.

8. REFERENCES

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A SERVICE MANAGEMENT SYSTEM FOR ESTRACK

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Abstract: The ESTRACK Service Management System (ESMS) is a new asset of the ESA Tracking and Data Acquisition Network (ESTRACK) which facilitates the provision of ground station services to computerized applications in mission operation facilities. It allows mission managers to order ground station services in a one-stop-shopping fashion at a single interfacing point, the ESMS. In this paper we explore the "management of ground station services" meaning the planned provision of ground station capabilities in a multi mission environment where ground stations must be shared. Particular attention is given to the mapping of service provision requests onto the resources which are available from ground station equipment. After a brief introduction to motivation and framework for this undertaking, we describe the essential information structures and outline the functional architecture taking into account the current development stage of a prototype. The paper concludes with an outline of the implementation approach chosen for the ESMS.

MOTIVATION

Future space mission scenarios of the major Space Agencies indicate a trend towards multiple simultaneous missions which operate a relatively large number of small satellites under tight budget constraints. Ground infrastructures must respond to these demands and offer an attractive range of services and flexible provision schedules at low cost.

In view of this situation and in consideration of the CCSDS Recommendations for the spacelink, CCSDS Panel 3 defines standardised ground station services and related management capabilities which allow to coordinate the services of ground infrastructures of several Agencies for the needs of a mission. Considering the progress which has been achieved in this standardisation work, the speed and automation of telecommunication and the new programming techniques it should be possible - if not economically mandatory - to automate activities which up to very recently could only be performed with human circumspection and intelligence. In ESTRACK the monitoring and commanding facilities for ground stations have reached a satisfying level of automation, whereas the preparation of mission support schedules, their verification and execution monitoring lags behind; to large portions these activities are performed manually with only marginal computerized support, such as spreadsheets, word processors, electronic forms and facsimile transmission. Taking into account the experiences which the ESTRACK Scheduling Office gained during so many years of "manual" service management , the ESTRACK Service Management System (ESMS) project embarks on applying new technologies in this field.

OBJECTIVES AND ENVIRONMENT

The ESMS is a new asset of the ESA Tracking Network (ESTRACK). It is positioned between mission operation organisations and ESTRACK ground stations.

The ESMS allows mission managers to order standardised ground station services (and their inherent telecommunication support) in a one-stop-shopping fashion at a single interface point. It will accelerate the preparation of ground stations for contacts with spacecraft and ensure the timely provision of their service capabilities and of the necessary interfaces for computerized end user applications in mission operation facilities.

The domain of the ESMS is comprised of service capabilities which are offered by the various ESTRACK ground stations and by the telecommunication capabilities offered by OPSNET, ESA's telecommunication network for the support of mission operations. The responsible entity managers advertise to ESMS the service capabilities which they keep ready in their domain; once advertised, they commit themselves to establish these capabilities with the performance attributes specified and maintain them for the duration indicated.

Figure 1 shows the position of ESMS in respect to mission organisations and its relationships with the other constituents of ESTRACK and with OPSNET in a snapshot of a hypothetical mission scenario.

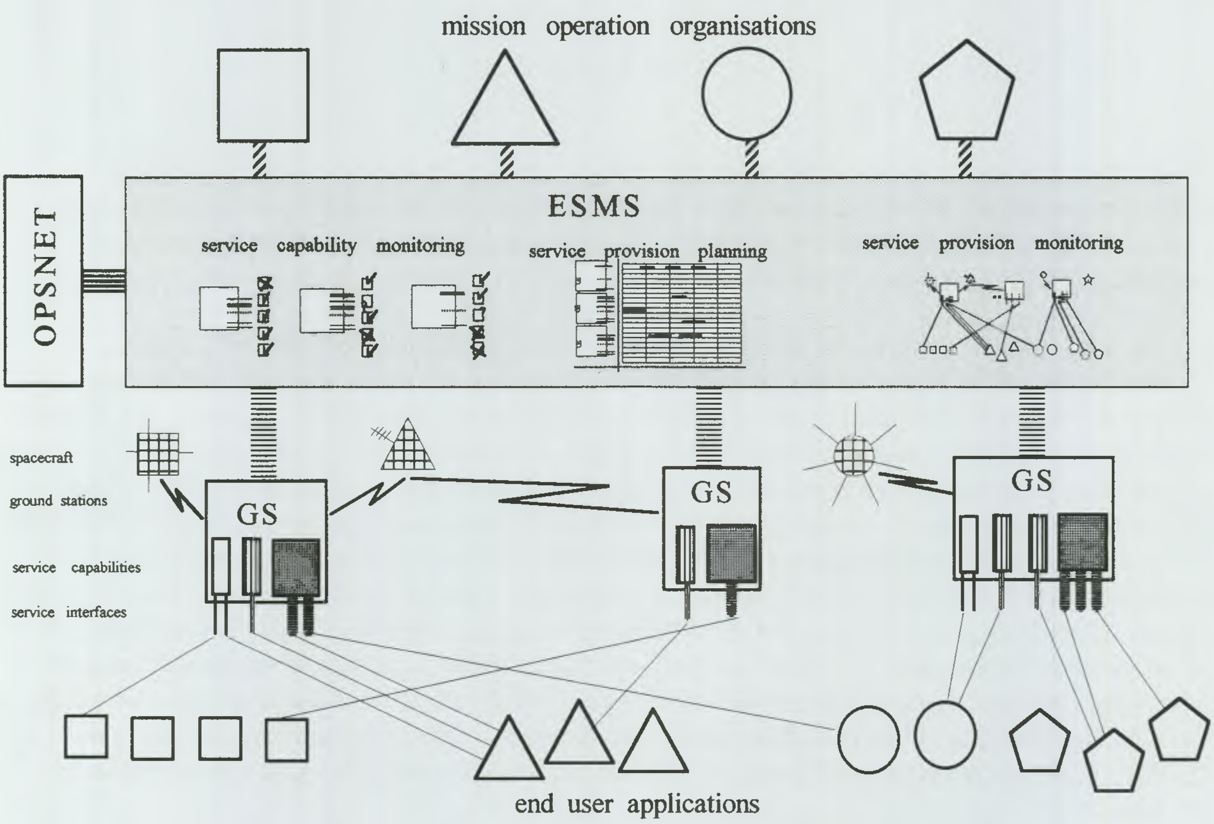

Figure 1: the ESTRACK Service Management System and its environment

The framework for ESMS operations is determined by the following obligatory requirements:

- serve missions of ESA and of other space agencies which apply the CCSDS Recommendations for Space Link Extension Services
- simplify interaction between mission organisations and ESTRACK by means of standardised information structures which conform to the Reference Model for Space Link Extension Services [CCSDS 1]and to the related management scheme [CCSDS 2]
- apply a deterministic strategy for treating incoming service provision requests. Depending of mission requirements on their mutual coordination, the strategies may range from simple first-come-first-served to strategies which respect relative mission priorities which change with mission phases.
- trade the service capabilities of ESTRACK ground station against the service requirements of space missions
- achieve a high utilization factor of ground stations by simultaneous provision of services to multiple missions at a given ground station
- prevent resource conflicts in ground stations by careful planning and scheduling of service provisions
- inform the mission managers concerned about conflicts detected and solicit an adequate modification of their respective service requests
- provide synoptic information about the health status of each ground station and about its current utilization by means of regular inspection of ground station information
- reduce ESTRACK operation cost by achieving a high degree of automation for routine tasks in the field of ground station scheduling.

INFORMATION STRUCTURES

For support of a space mission, the management of an individual ground station must have the following information available: the characteristics of the spacecraft, the prediction of its orbit and the service provision schedule. With this information and by means of its monitoring and commanding facilities, the ground station is then able to configure its resources for the services demanded, to come in contact with the spacecraft and to keep the ground station in the appropriate operational condition as long as end users are allowed to use its services.

The ESMS is responsible for the preparation of schedules for service provision which on one hand satisfy the need of the mission organisation and, on the other hand, can be provided with the resources available from ESTRACK. Consequently, the ESMS must extract utilization information from the requests of the mission organisations and it must obtain resource information from each ground station.

The mission operations organisation establishes the overall mission operations plan in incremental segments, each of them being valid for a limited future. Such a segment implicitly determines the pending needs of end user applications for access to ground station services. The intended coverage of the spacecraft's orbit may require the coordinated use of ground stations from several space agencies. Therefore the mission organisation must derive request packages which specify the service provision requirements for each one of these networks. Such service request packages are the driving information structure for the ESMS. An entry in such a package identifies a ground station service and the options chosen, the time and duration when it shall be provided and whether the service shall be backed up at the same or at another ground station. Eventually, the ESMS completes the service request package and adds to each entry the respective interface assignments and the credentials which an end user application must present when it accesses the service capability. In ESTRACK, today, the interlocutor for such requests is the Scheduling Office, in future the ESTRACK Service Management System will take on this role.

For the ESMS prototype, the service provision requests have a structure which captures the information needed by today's ESA groundstations; for the future it is expected that CCSDS Panel 3 prevents the proliferation of provider specific forms for service requests and soon publishes a recommendation for content and structure of request packages for standardised "CCSDS Space Link Extension" services [CCSDS 2]. An important restriction of the prototype is that the scope of a service request package is limited still to a single groundstation. In future, the target ESMS shall allow to formulate service request packages without considering the actual groundstations and leave the task of their optimal selection to ESMS if missions take that option.

Besides the service requests, the ESMS needs from the mission organisation spacecraft characteristics and orbit predictions: The spacecraft characteristics - radiometric parameters and the possible spacelink configurations - are specified by the project organisation during the development of the spacecraft. They are needed in order to verify that the capabilities of a ground station can be tuned to the parameters of the spacecraft. Orbit predictions depend on the actual launch trajectory and on disturbances of the past orbits of the flying spacecraft, therefore - throughout the duration of the mission - they are regularly updated by the orbit determination function of the mission operations organisation. Orbit information describes visibility of the spacecraft from ground stations and the duration of the respective passes; hence, it constrains the selection of groundstations for spacecraft coverage and governs the scheduling of the capabilities at a ground station.

For service provision planning, the utilization oriented information which have been outlined above are not sufficient; they must be complemented with resource oriented information:

The central concept applied in service planning is "service capability". This abstraction is necessary because different makes of ground station equipment can be configured in different ways but nevertheless offer services which are identical in terms of data product, interface behaviour and quality-of-service. Consequently, a service capability is the class of all equipment configurations which are able to provide a specific type of ground station service. Without this notion it would not be possible to relief the ESMS from knowing all possible configurations by which ground stations may possibly support a service. In general a ground station offers service capabilities for a variety of service types e.g. telecommanding, ranging measurements, recording, etc; for a given service type, it may even offer a number capabilities which can be booked and operated independently (e.g. a ground station may feature three "chains" each representing a telecommand service capability). For the ESMS, a service capability is the unit of planning and booking, for the ground station manager it is the unit of configuration and, when a service provision schedule comes to execution, it is the unit of activation and deactivation. For the translation of service provision requests into bookings of service capabilities, the ESMS needs for each service a "service characteristics table"; such a table identifies the service (and for all its optional variants) the precisely corresponding service capability and the necessary parameter values for its "fine tuning". The service characteristics table must equally capture dependencies between services in the sense that the activation or deactivation of a given service capability can be performed only after another service capability has been successfully activated or deactivated.

For the actual booking of service capabilities the ESMS must be aware of related constraints. Therefore, each ground station manager must advertise the service capabilities which have been configured on site, he/she must forecast their availability in the foreseeable future and must report about their current health status'.

In addition to the resource information from groundstations, ESMS needs similar information from the telecommunication network. This aspect has not yet been investigated in depth but it is foreseen to incorporate suitable capabilities into the target ESMS.

When the ESMS tries to reconcile service requests with the capabilities available it may discover that appropriate capabilities do not exist or are already booked for other missions. In this case it will notify the mission managers concerned with a rejection notification or with a conflict notification. In the latter case it would identify the service requests which cause the conflict, the missions concerned and the detailed reason for the conflict and forward this information to the mission managers concerned as a basis for subsequent negotiations. The target ESMS may be able to "attach" to the conflict notification a suggestion for modifications of the service provision requests.

In respect to a ground station, the main product of the ESMS is the set of consolidated mission specific service provision schedules. The service provision schedule is the main management instrument of the ESMS. It is a collection of time tagged calls to standardised service provision procedures. Each call has its parameters set according to the specific requirements derived from the corresponding service provision request. These service procedures are tailored individually per ground station and exploit the monitoring and commanding features of the equipment which is available on site in a particular configuration. Upon their invocation, they "tune" the service capability according to the parameters of the call and according to complementary information which they take from the applicable spacecraft characteristics table.

Each ground station management - i.e. the monitoring and commanding application which has been tailored for a given ground station - informs the ESMS about the execution of each service provision schedule. This is achieved by means of standardised ground station journals and by updating selected ground station parameters. A ground station journal is a file with an excerpt from the master log of that ground station. For a journal, the ESMS may select from a set of standardised filters and apply it to the master log in order to reduce the comprehensive information therein to the needs of the monitoring function for service provisioning. For more urgent information, ESMS has access to predefined standardised lists of ground station parameters which contain their most recent value. Such monitored variable lists can be delivered on demand, in periodic intervals or upon the change of one of its values. The target ESMS may be provided with additional alarms and event notifications which the ground station could issue upon the occurrence of important events such as space link acquisition or of unexpected incidents like breakdown of a service capability or resource locking conflicts between service procedures.

Ground station journals and the parameter lists are needed in order to keep the ESTRACK status display up to date. Excerpts from them are entered into the standardised reports for mission managers. These reports indicate to them the progress of the "execution" of their service request package. Additional reports will notify them when problems with a service provision are encountered. The target ESMS may have capabilities to derive accounting information from the ground station reports and the journals.

The ESMS keeps a log of events which are of importance for itself; such a log will record e.g. reception of a service provision request, begin and completion of related ESMS internal processing steps, downloading of a service provision schedule, major actions of the ESMS operator, occurrence of internal alarms and the occurrence of important ground station events. The ESMS logs will be available to the ESMS operator for inspection and archiving.

FUNCTIONS AND INTERFACES

The activities of the ESMS can be organised into a few groups of closely related tasks or functional areas. In order to establish the basis for the service management, the ESMS must cover the following "core" functions:

- **ground station monitoring**: ensures that at any time the status of the service capabilities of each ground station and of OPSNET are known at a central location and are available for service planning, for the coordination of diagnostic and recovery actions and for general information for the ESTRACK operators and customers.
- **service request processing**: covers all aspects of interaction with mission planning systems in respect to ordering ESTRACK services. It includes planning of their provision under consideration of availability of ESTRACK resources and of competition with other missions.
- **service provision scheduling**: transforms consolidated service orders into ground station specific schedules, ensures their timely transmission to ground stations, monitors their execution and reports to customers about progress and problems which concern their respective service order.

These core functions are prerequisite for a number of "foreground" functions such as:

- helpdesk for ESTRACK customers
- support of fault detection, diagnosis and recovery from capability failures in groundstations and telecommunication network
- support of security management for access to ground stations.
- accounting for provision and use of ground station and telecommunication services

Further, ESMS staff shall draw from their operations experience and actively foster the evolution of ESTRACK by performing "background" functions such as:

- competitive service offering and customer acquisition
- elaboration of upgrading strategies for ground station capabilities in response to the demands of forthcoming space missions and technological advances
- design and development of innovative ESTRACK services.

Initially, the ESMS prototype will cover the ground station monitoring function and include only very rudimentary elements of the other two core functions; incrementally, the prototype will be extended with more elaborate core functions. A ESMS generation which could be deployed in ESTRACK shall cover the core functional areas to their full extent and in addition selected foreground functions which are required for the support of the then prevailing mission scenarios.

All ESMS activities are governed by the arrival of a service request package from a mission organisations via the interface between the ESMS and the originating mission planning system. The package is verified in respect to syntactical correctness and the service provision requests contained therein are isolated and subject to individual processing. Each request must be verified in respect to its feasibility with the groundstation resources available and in respect to its conflict potential with previously submitted service provision requests from parallel missions. This means that ESMS must search for a free service capability which satisfies all aspects of the service provision request; in particular, the service capability must be located at a ground station which is in contact with the spacecraft during the due time. Whereas the initial ESMS will employ a rather simple search strategy, the target ESMS shall, without further involvement of the mission organisation, select the most suitable groundstation (or a combination of ground stations) considering spacecraft constraints like its orbit and ESTRACK constraints like available service capabilities and communication lines (throughput, reliability, cost) between ground stations and end user applications. Further extension may optimise the planning e.g. in respect backup of the prime capability, minimal communication cost and maximum ground station utilization rate.

When the searching was in vain, several cases must be considered: (1) if the service requested is not offered by ESTRACK: then the ESMS must reject the request; (2) if all suitable service capabilities are already booked by missions then the ESMS must identify the conflicting service provision requests respectively their origination mission managers, inform them about the conflict in all detail and solicit a modification of their service requests; (3) if suitable service capabilities would be available if they had not been scheduled for maintenance then the ESMS operator negotiates with the responsible ground station manager with the aim to resolve the blocking. If these negotiations fail, the ESMS must reject the service provision request.

Once each individual service provision request from a package has proven feasible and is not involved in a conflict, it is provisionally "booked" for the demanding mission. If all service provision request of a given service request package could be booked, the ESMS commits the so far provisional bookings and derives a detailed service provision schedule for each ground station which eventually will support this package. From then on the package is frozen and is considered as a contract binding both, the mission organisation as well as ESTRACK. It is under investigation whether the ESMS could tolerate modification of the information in the package still during the freeze period.

Sufficient time ahead of the due time for its execution, a service provision schedule must be downloaded as a datafile to the responsible managing entity: for ground stations the recipient is the station operator, for OPSNET the recipient is the network manager.

Based on the time tags of the service procedure calls, the service provision schedule is executed: this means that the groundstation management - the monitoring and commanding application in cooperation with the ground station operator - will activate and deactivate individual service capabilities as required.

In respect to a service provision schedule in execution, the ESMS stays in a monitoring role: it collects information about the current execution status and keeps the originating mission organisation informed about the progress by reporting the regular events as well as notifying about occurrence of unexpected incidents. Future extensions of the ESMS may allow a more active role and could perform recovery actions in certain cases of outage or degradation. The ESMS could automatically activate a backup service capability at another groundstation e.g. when the prime capability is degraded to an unsatisfying quality-of-service or if communication outage does not allow to operate the prime service interface.

IMPLEMENTATION APPROACH

The development of ESMS is conceived in an incremental fashion. For the production of the initial ESMS prototype (ground station monitoring function) a number of libraries which have been developed within the Station Computer project will be reused. The subsequent prototyping activities take the ESMS prototype and extend it with capabilities - i.e. object libraries - for the functional aspect which they investigate. The so extended ESMS prototype is then ready for reuse and for further functional extensions. The first operationally deployed ESMS will be built on the basis of the latest extension of the prototype. The additional effort for the completion opf the prototype includes the development of capabilities which have not yet been provided, the refinement of object classes and application tailoring for the support of the standardised information structures (e.g. in the prototype, a schedule object class may not allow to add an entry, but the standardised schedule object would allow such operation). Later, additional "foreground" ESMS functions and appropriate support for its "evolutionary" functions will incrementally be added to the operationally deployed version of the ESMS just in the same way as the ESMS prototype has been upgraded before.

The ESMS software is designed and developed with object oriented methods including Rumbough's OMT method as available from the StP toolset, C++, commercial object libraries (X-Windows, sphinx/grinx). Whereas the prototype does not need an object oriented database management system, later extensions of the ESMS may benefit from such a tool; in this case ONTOS would be the prime candidate.

The external interfaces of the ESMS are implemented by means of standardised commercial products: protocols of the OSI telecommunication stack, ASN.1 tools, CMIS/CMIP and FTP (or FTAM) for file transfers.

CONCLUSION

The growing financial pressure (cheaper, better, faster) on space agencies is expected to lead to more, but smaller missions. Their cost effective operations depend on the availability of standardised ground support services which do not need costly custom developments in the ground segment. The definition of such services and of their pertinent management is pursued by CCSDS and eventually will enable space agencies to offer standardised ground support services and uniform management interactions to their client missions.

Dependable provision of such services and safe sharing of the ground station resources needs computerized assistance. Such a system shall schedule service provisions according to the requests submitted by the managers of the client missions and plan the allocation of the network resources such that potential access conflicts can be prevented. Service provisions will be monitored and related reports will be made available to client missions.

With the ESMS project, ESA has embarked on the development of such a management system for its ground station network. A prototype will be implemented re-using components which have been developed for a ground station management system. This prototype will be incrementally extended with specific functions. The detailed implementation schedule largely depends on when the pertinent CCSDS recommendations become sufficiently stable.

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CCSDS 910.4-R-2, March 1996 (Blue Book issue under preparation)

[CCSDS 2] Space Link Extension: Service Management Specification
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Draft Recommendation X.901 | ISO/IEC 10746, July 1994

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END-TO-END VALIDATION OF THE PACKET TC AND TM SERVICES

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ABSTRACT. ESA provides support for the launch, early orbiting and operational phase of a spacecraft mission utilizing a network of ground stations (GS) and a mission specific Operational Control Center (OCC). Within the Ground Station a "Telemetry System" performs the digital processing of space link data for the return link while the Telecommand Encoder provides the link between the ground data network and the front-end Intermediate Frequency part for the forward link.

This paper describes how the Telecommand and Telemetry Systems, together with other dedicated test units, e.g. the FARM Emulator and OCC Simulator(s), allow end-to-end validation of the Packet Telecommand and Telemetry Services and enables exercising and detailed checking of the Space Link Extension Services provided by the TC and TM Systems.

The connection of such environment to a system hosting the on-board chips for Packet Telemetry Encoding and Packet Telecommand Decoding, renders possible a complete validation of the TC/TM Services with respect to the ESA approved devices. On-board applications can also be validated. This set-up also supports conformance testing of "foreign" telecommand decoders.

1. INTRODUCTION

Figure 1 shows the simplified diagram of an ESA Ground Station where the Monitor and Control (M&C) system centralizes the information on the different subsystems into the Station Computer. Within the Ground Station a "Telemetry System" performs the digital processing of space link data for the Return Link. Today, ESA have implemented two systems: the Return-Link Protocol Handling System (R-PHS) and the Telemetry Processor (TMP). Although different with respect to the Hardware and Software Architecture as well as performance and configurability features, the two systems are based on common concepts and offer the same services. For the Forward Link, the Packet Telecommand Encoder (TCE) fully implements the Packet TC Standard that provides for reports on TC transfer (i.e. delivery to the spacecraft) as opposed to the reporting on TC transmission provided by the PCM standard.

Both types of systems have of course been designed to satisfy the immediate needs but also keeping in mind the idea of Cross Support Services that today are finally becoming a CCSDS Standard [CCSDS-SLE] to increase the level of inter-operability among Agencies.

2. THE RETURN LINK SYSTEMS

For the Return Link signal, the *Telemetry System* connects the front-end Intermediate Frequency part of a Ground Station with the X.25 based terrestrial communication network. It considers also the Forward Link but only as far as extraction (and forwarding to the TCE) of the Command Link Control Word (CLCW) from the Return Link is concerned.

In the Return Link demodulated symbols are received from the IF subsystem and are converted to data units requested by the user. These data units can be forwarded, in the same sequence as they were received, to the user applying either of two types of quality of service:

- <u>timeliness</u>, i.e. data are immediately processed and forwarded to the user discarding older data whenever, due to bandwidth limitations on the terrestrial communication network, a too large backlog is accumulated,
- <u>completeness</u>, i.e. data are forwarded to the user as fast as possible, but applying full flow control (via the so called Immediate Data Access - IDA - service that also allows to retrieve telemetry previously stored by the Telemetry System).

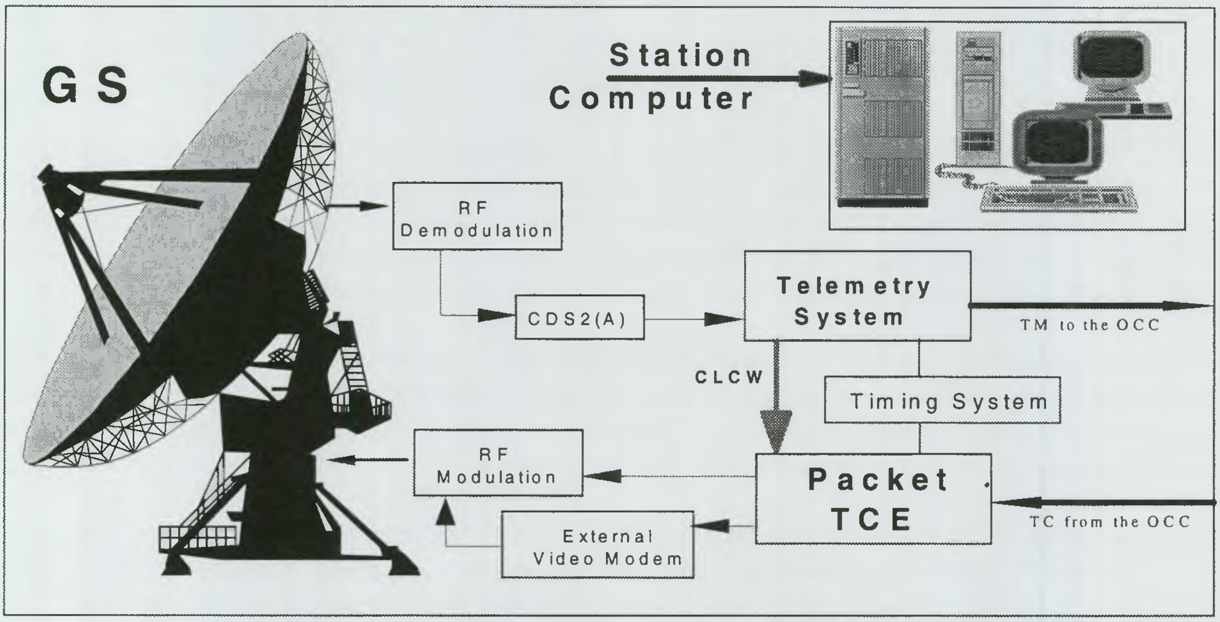

Figure 1. The ESA Ground Station (simplified diagram)

All the received data units are delivered to the user together with their annotation (for Transfer Frames or Source Packets). The main annotations are:

1. the ground reception time;
2. the data quality indication stating whether the data unit was received complete and error free (e.g. Reed-Solomon decoding error, etc.);
3. the data sequence quality indication stating whether preceding data units have been lost;
4. a specific diagnostic code inserted by the ESA decoding system;
5. the time calibration packet annotation for performing time calibration according to the ESA Standard [ESA-TM];
6. the incomplete source packet annotation for a TM Source Packet only partially reconstructed.

The Telemetry Systems can support the following telemetry standards used for spacecraft operation: Packet Telemetry, Pulse Code Modulation (PCM) Telemetry and (partially) Advanced Orbiting System (AOS) Telemetry. However only the first two are presently used by ESA. Configuration of position and size of specific data fields within the space link Protocol Data Units is also supported to accommodate also missions which deviate from the fixed formats defined in the telemetry standard.

Data Storage includes the storage of Transfer Frames and Source Packets received during an on-going acquisition. In nominal setup of the Telemetry System, data are stored at VC level for frame and at Application Id lever for Packets. During data storage, directory information on the data being stored is built. It may be used afterwards for Telemetry retrieval as well as (partial/complete) Telemetry deletion and to provide catalogue information on the stored data to an external user.

Any stored Sequences of Data Units is described by attributes, which comprise Start & End Acquisition Time, together with the number of data units in the sequence. At VC level and for Packets also the relevant Start & End Counters are recorded. When applicable, Start & End Source Packet Time are also part of the sequence's attributes.

Data Retrieval is requested via the IDA service provider or may be caused by maintenance actions. In addition, the catalogue information on the stored data, built during acquisition, can be retrieved by the user to know in advance the amount of stored data and then to request retrieval only of the subset of data units in which he is presently interested.

The communication between the OCC and the Telemetry System, is based on the Telecommunication Protocol Profile shown in Table 1.

OSI Layer	Entity	
	Control Channel	**Data Channel**
Common ASE	Common Management Information Service Entity (CMISE) (ISO/IEC 9595)	
Common ASE	Remote Operations Service Element (ROSE) (ISO/IEC 9072-1)	
Common ASE	ACSE, kernel functional unit (ISO/IEC 8649)	
Presentation	OSI Presentation, kernel functional unit (ISO 8072)	
Session	OSI Session, with full duplex functional unit (ISO 8326)	
Transport	OSI Transport Class 2 (ISO 8072)	
Network	OSI X.25	
Data Link	OSI LAPB	
Physical	OSI X.21	

Table 1: Telecommunication Protocol Profiles

Special data channel synchronization flags are used as a mechanism to synchronize the data flows on the control and data channels, e.g. to mark when a new data flow of data units starts on the data channel after a new selection has been requested on the control channel. Protocols for both channels have been described, and then implemented, by using a state machine approach [EIPD] while ASN.1 (Abstract Syntax Notation One, X.208) has been used to define the Application Protocol Data Units (APDUs).

The separate Control and Data channels have been defined to take into account the quite different requirements in terms of throughput: very limited (but requiring a fast reaction) for the control channel and very high for the data channel where the overhead introduced by a full protocol stack with the related encoding could have been not acceptable. In addition this choice leaves open other future possibility like e.g. the use of a separate network for bulk data transfer (e.g. ATM) or to use multiple links to form a single data channel.

The service provision is performed by the Telemetry System according to the following two concepts: Selection Criteria, and Start & End Criteria (only as far as the IDA Service is concerned).

The Selection Criteria allow the user to select one of the following types of Data Streams:

- Space Link Channel Data Stream, i.e. all the Transfer Frames (including the Reed-Solomon Check Symbols, if they are available at the Telemetry System) received by the system will be forwarded to the user;
- Master Channel Data Stream, i.e. the "good" Transfer Frames identified by a given Master Channel Identifier (MCID, consisting of Version Number and Spacecraft Identifier);
- Virtual Channel Data Stream, i.e. the "good" Transfer Frames identified by a given Global Virtual Channel Identifier (GVCID, consisting of MCID and Virtual Channel Identifier);

- MC Header Data Stream, i.e. only the Primary Headers and the (optional) Secondary Headers of the Transfer Frames identified by a given MCID;
- VC Header Data Stream, i.e. only the Primary Headers and the (optional) Secondary Headers of the Transfer Frames identified by a given GVCID;
- VC Data Unit Zone Data Stream, i.e. only the Data Fields of the Transfer Frames identified by a given GVCID;
- MC Operational Field Data Stream, i.e. only the Operational Control Fields (OCF, containing the CLCW) of the Transfer Frames identified by a given MCID;
- VC Operational Field Data Stream, i.e. only the Operational Control Fields of the Transfer Frames identified by a given GVCID;
- Source Packets Data Stream, i.e. reconstructed Source Packets identified by (a set of) Application Identifier(s) on a given GVCID;
- Time Calibration Data Stream, i.e. reconstructed Time Calibration Source Packets (according to the ESA Standard);
- Bad Frames Data Stream, i.e. . all the "bad" Transfer Frames received on one SL Channel.

For AOS the following types of Data Streams are supported: Space Link Channel, Master Channel, Virtual Channel, VCDU Data Unit Zone, MC Operational Field, VC Operational Field, Path Packets and Bad Frames.

Since it is intended to provide CCSDS compliant Space Link Extension Services, these Data Streams may be subject to modifications when the related CCSDS Recommendations are finalized.

When the IDA Service is used, the user is also allowed to specify Start & End Criteria, thus defining an interval such as:

- start and end ground reception time;
- start ground reception time and a given number of data units;
- the VC counter (or the Source Packet Counter) of the first data unit after a given ground reception time and a given number of data units;
- start and end Source Packet time;
- start Source Packet time and a given number of data units.

The R-PHS, whose principle architecture is shown in Figure 2, consists of several sub-units, whose hardware is based on VME bus with (mainly) standard Motorola boards, interconnected via a dual ring FDDI LAN for fast data exchange. The Sub System Manager (SSM) and Data Network Interface (DNI) functions of the R-PHS execute on a UNIX System which provides for sufficient performance and allows to use proven off-the-shelf packages for the implementation of the OSI protocol stack and the GUI. Time critical tasks are executed under pSOS+ on dedicated real time CPUs. The application has been written in ANSI `C`.

The R-PHS is mainly based on the concept of Functional Processing Chain (FPC), i.e. a sequence of functionally specialized units where each provides a specific functionality. In the R-PHS one of these functionally specialized units is called Functional Unit (FU).

The following Functional Units (apart from FUs used for testing) have been defined in the R-PHS:

- the CDS2A, Concatenated Decoder/Encoder System 2A, (or the older CDS2) implementing the frame synchronization, extraction and decoding functions;
- the Return Link Data Processor (RLDP) implementing the Telemetry demultiplexing;
- the Return Link File Store (RLFS) implementing the Telemetry storing and retrieval;
- the Data Network Interface (DNI) implementing the interface with the OCC(s);

- the Sub System Manager (SSM) implementing overall R-PHS management and interfacing to the Station Computer.

The CDS2(A) already existed and was not part of the R-PHS development, however a future enhancement will connect it to the FDDI LAN for better performances.

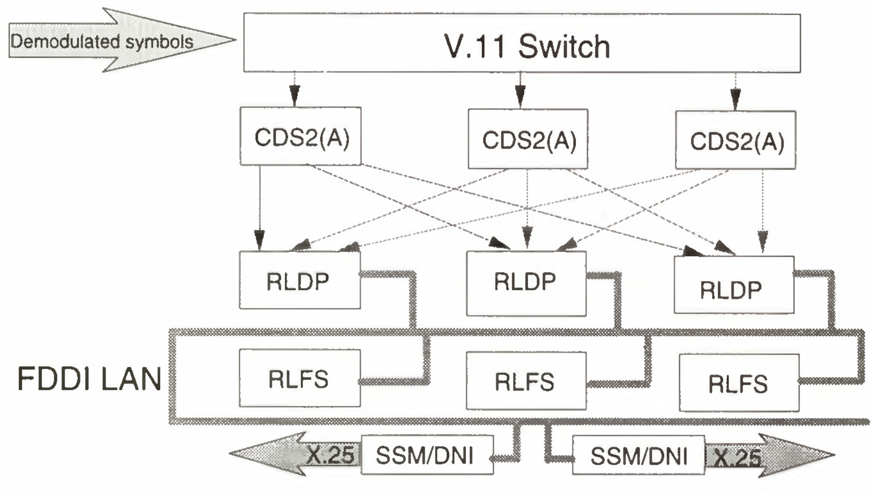

Figure 2. R-PHS Architecture

In the R-PHS these Functional Processing Chains have been defined for operational use:

- Data Acquisition and Storage (DAS), i.e. CDS2 & RLDP & RLFS (no connection to an OCC);
- Data Acquisition and Delivery (DAD), i.e. CDS2 & RLDP & DNI (no storage);
- IDA Data Delivery (IDD), i.e. RLFS & DNI.

Several FPCs of various type can be concurrently active within the R-PHS to ensure the best service provision either for redundancy reasons or for multiple users needs.

The Functional Units are interconnected by means of establishing the appropriate virtual circuits on the FDDI LAN, as required for the provision of the requested service. Since several (at least 2) functional units of a given type form part of the R-PHS and since FPCs, i.e. the interconnections, can be established in a flexible manner without requiring a complex switching gear, a high level of availability is achieved. This is considered a major asset of the R-PHS.

The *TMP* is based on a Sun SparcStation20 running SunOS. For system evolution and in order to provide better real time characteristics, migration to the Solaris 2.x Operating System is planned. The Application software has been written in ANSI `C` with an Object based approach. Although much smaller than the R-PHS, it fully supports, in terms of demultiplexing, storing and delivery, the services defined for Telemetry Data Streams using the same Protocol as the R-PHS. In this way the user does not need to be aware of which system he is presently connecting to.

Telemetry simulation facilities are also supported within the R-PHS and TMP in form of dedicated hardware and software facilities.

3. THE FORWARD LINK SYSTEM

The Packet TCE, provides the link between the ground data network and the Intermediate Frequency (IF) part of the Ground Station subsystem for the forward link signal. The TCE hardware is based on a VME bus rack with (mainly) standard Motorola boards. It was developed using a VMEexec real-time multi-processor support package and a UNIX System V based development environment. Time critical tasks are executed under pSOS+ on dedicated real time CPU's. The application has been written in "ANSI C".

The TCE offers to an OCC, i.e. to its operational user, the following services:

- those defined in [CCSDS-COP], implemented according to [ESA-TC], i.e.:
    - the Sequence Controlled Service (AD Service) for TC Packets (with and without authentication: this is seen in [ESA-TC] as two distinct services);
    - the Expedited Service (BD Service) for TC Data Units.

  In addition some features of [CCSDS-TC] not included in [ESA-TC] are supported.
- the so called Physical Layer Interface Service (PLIS) for CLTUs and non packet TC Data Units.

It is noteworthy that the three types of services mentioned above (i.e. including PLIS) match (3 of the 4) Forward Telecommand Space Link Extension Transfer Services that are under definition by [CCSDS-SLE] in the context of the cross support between ground-based entities.

The TCE implements the TC layers defined in [ESA-TC] up to and including the Segmentation Layer and via the Packet Protocol Handler (PPH) it handles incoming OCC requests and internal M&C. The Packetization layer is not implemented in the TCE but in the OCC connecting to the TCE.

The TCE-OCC Communications are based on CMIS/CMIP (Common Management Information Service/Protocol) on top of the ISO OSI layered architecture (see Table 1).

Although the feature operationally is not yet exploited, particular attention has been put on the multi-user capability. Several users will be allowed to concurrently access the spacecraft for performing separate tasks, as would be the case in telescience. In order to ensure safety of the spacecraft, two distinct types of TCE users have been defined. The Primary OCC, typically the "bus" controller, has unrestricted access to the spacecraft, while a Secondary OCC, typically a payload controller, is only allowed to obtain the Sequence Controlled service for a particular subset of spacecraft destination (i.e. a subset of Application ID's within a given Virtual Channel) s. The TCE can support parallel TC sessions with a Primary OCC and up to three Secondary OCCs. The Primary OCC is able to:

- perform FOP management activities (e.g. use of FOP Directives);
- use the Expedited Service;
- define the set of currently available TC Virtual Channels (VC's);
- define and control the multiplexing scheme (e.g. give priority to one of the four supported TC VC's [1] and/or to selected Multiplexer Access Points, MAPs);
- take complete control of the TCE by interrupting Secondary OCCs TC Sessions.

The TCE Transfer Layer provides the two mentioned packet services (AD and BD) in three different modes: in *'ESA mode'* the AD Service will be terminated automatically by the TCE before BD Service can start; in *'CCSDS mode with priority'* the BD request will be served as soon as possible, being inserted at the top of the AD queue; in *'CCSDS mode without priority'* the BD request is inserted at the tail of the AD queue.

4. THE FARM EMULATOR

A dedicated simulation unit, i.e. the *FARM Emulator*, has been developed for the TCE overall system and performance tests. It:

- provides a Video Modem Emulator;
- implements the Physical Layer protocol to interface with the Coding Layer of the TC Decoder;
- enables testing of the Frame Operation Procedure scheme by manipulation of the CLCW and by generation of CLTU error conditions;

---

[1] Currently [ESA-TC] does not foresee commanding to several VC's at the same time. Typical on-board implementation foresees a nominal TCD and a redundant one associated to different VC Ids.

- provides a Frame Acceptance Reporting Loop possibility via an output to an external Telemetry Frame Generator;
- includes a TC Decoder;
- provides a Software emulated TC Decoder ;
- provides a Man-Machine-Interface (MMI) for display of CLCW, FAR, AU-Status, Video Modem Emulator Control signals, TC Segments and for configuration and control of the FARM Emulator itself.

The TC Decoder Board is directly derived from the flight model for the ARTEMIS On-Board Computer Unit and implements the Coding and the Transfer Layer and the Segmentation Layer MAP interface functions of the Packet Telecommand Protocol as specified in [ESA-TC] and in [ESA-TCD] with the minor limitations listed in Appendix C of [ESA-TCD].

5. THE OCC SIMULATOR

The *(OSI)-OCC Simulator* has been used for testing the OSI communication interface and the server functions in the TCE and in the Telemetry Systems. Multiple associations with the TM/TC Systems can be simultaneously used by executing distinct instances of the simulator. The OCC Simulator provides the possibility of transmitting predefined Application Protocol Data Units (APDUs) to the TM/TC System, over the TCE-OCC X.25 interface, and to expect/receive (and store) APDUs from them.

6. VALIDATION IN THE TCE PROJECT

The above mentioned units formed most of the Validation Environment for the TCE project. Figure 3 illustrates the typical FOP (Short Loop) Validation Context where, the TCE being the unit under test, TC Requests were forwarded by the OCC, and correct encoding into CLTUs, as well as correct implementation of the FOP State Table, was verified via local (i.e. on TCE local MMI and log files) and remote (i.e. on TC Responses) analysis. The FARM Emulator allows to test various behaviors, thanks to the possibility of manipulating the CLCW and of injecting errors.

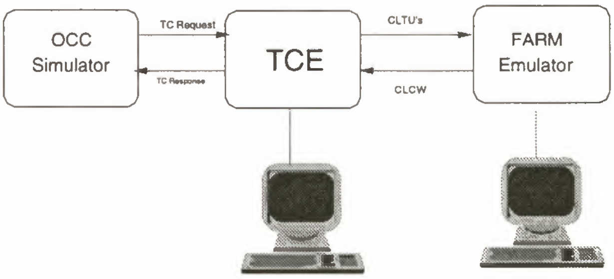

Figure 3. TCE-FOP Validation Context.

Figure 3 is also referenced as Short Loop being the minimum possibility for creating a closed end-to-end validation loop. However thank to the additional external interfaces provided either directly by the TC Decoder board (i.e. the MAP interfaces) or by the FARM Emulator as integrated unit, other test configurations have been conceived, for verification and validation of the on-board elements of the TM and TC chains, the TCE being in this case one element of the test bed.

6. VALIDATION OF TC DATA SINKS

With respect to the validation of Telecommand Data Sinks, i.e. the on-board applications, various possibilities can be envisaged. Taking into account the four de-multiplexed MAP outputs that are directly available on the TC Decoder board of the FARM Emulator, the simple connection of the TC Data Sinks under test to these output ports gives the configuration shown in Figure 4.

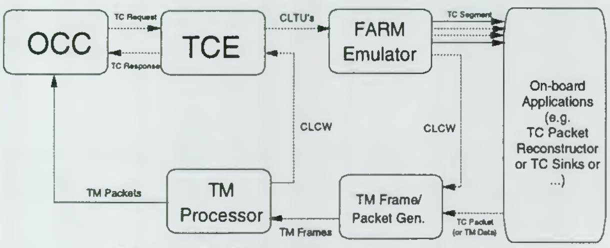

Figure 5. Validation Long Loop.

Appropriate use of the OCC Simulator gives the possibility of verifying the impact of multiplexing, retransmission, OCC interaction (as it may be the case for telescience applications), problems on ground etc. according to the exact behavior of the underlying Telecommand chain.

However, considering that, in addition to the four MAP outputs, the FARM Emulator provides also, at the External Frame Generator output, all the control and data passing through the TC Decoder board, longer validation loops can be identified according to the future configuration shown in Figure 5.

The Generator of Telemetry Frames or Packets will be a system capable to format the TM flow as required by the Telemetry Processor system. The On-board Applications in turn represents a more complex system of TC Data Sinks (as well as TM Data Sources) as illustrated in Figure 6. The element added to the four Telecommand Data Sinks is a unit which is supposed to be able to coordinate those applications in order to produce data to be inserted into the telemetry flow (e.g. by simply inserting the received TC Packet into the Telemetry for comparison purposes or producing "TM responses" consistent with the received TCs), so emulating the behavior of the on-board TM encoding system. This would allow to close completely the loop started by the OCC Simulator.

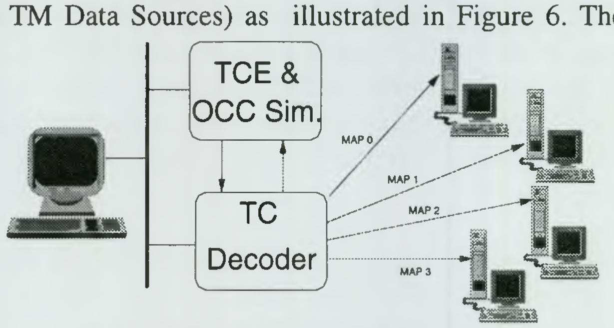

Figure 4. Validation of TC Data Sinks.

7. VALIDATION OF ESA TC/TM SERVICES

The connection of this ground segment environment (i.e. OCC + TCE + TM System) to a system hosting the on-board chips for Packet Telemetry Encoding (Virtual Channel Assembler, VCA, and Virtual Channel Multiplexer, VCM) and Packet Telecommand Decoding (PTD), renders possible a complete validation of the TC/TM Services with respect to these ESA official devices [ESA-FES].

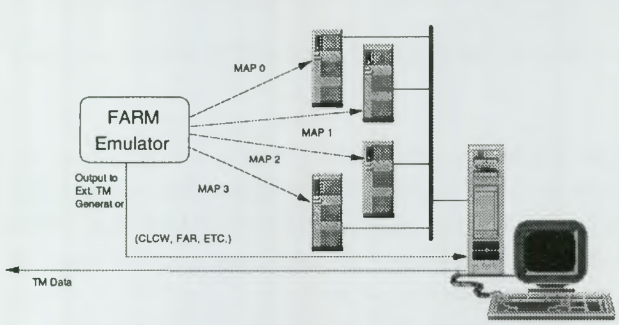

Figure 6. TC Data Sinks in Long Loop.

In fact the PTFG/PTDEC (Packet Telemetry Frame Generator/Packet Telecommand DECoder) board, including also a Reed-Solomon/convolutional Encoder, provides a very representative replica of the (first part of the) on-board segment allowing effective testing for normal operation as well as for robustness check. In addition such a board can be easily connected to an additional Data Sink/Generator, similar to that one shown in Figure 6, for complete end-to-end validation of the Packet TC and TM Services closing the loop in the Application Layer and not only at CLCW level.

8. VALIDATION OF TC DECODERS

As already mentioned, ESA shows interest in the area of cross support to missions of other space agencies. Therefore, in case ESA is required to support - by means of its Ground Stations - a spacecraft implementing Packet Telecommand but using a non-ESA TC Decoder, the need arises of validating such decoder.

This is achieved by inserting the non-ESA decoder board into the validation loop. Figure 7 shows a possible validation context where the TCE is still used as CLTUs source. In this case however, it also uses the options provided by the Physical Layer Interface Service so that a wider range of CLTUs contents and sequences can be forwarded to the decoder under test.

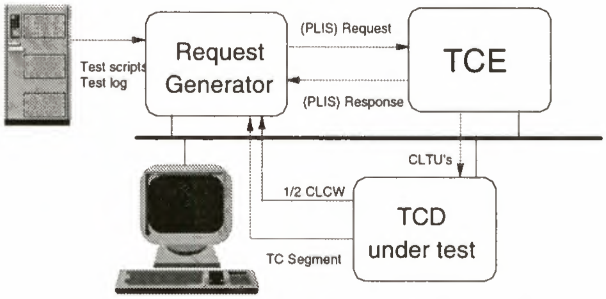

Figure 7. TC Decoder Validation Context.

In such case the Request Generator cannot simply be an OCC Simulator accessing the [CCSDS-COP] services but, in order to test all the decoder features, it shall include additional characteristics in order to be able to generate all the possible output configurations for CLTUs and to evaluate the data processed by the decoder itself, i.e. it shall access the PLIS.

REFERENCES

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[CCSDS-CH] Telecommand Part 1 Channel Service, CCSDS 201.0-B-1, January 1987
[CCSDS-COP] Telecommand Part 2.1 Command Operation Procedures, CCSDS 202.1-B-1, October 1991
[CCSDS-DM] Telecommand Part 3 Data Management Service, CCSDS 203.0-B-1, January 1987
[CCSDS-DR] Telecommand Part 2 Data Routing Service, CCSDS 202.0-B-2, November 1992
[CCSDS-TC] CCSDS 200 to 203 (see this list)
[CCSDS-SLE] Space Link Extension Cross Support Reference Model, CCSDS 910.4-R-2, March 1996
[EIPD] TMP4 and R-PHS External Interfaces and Protocols, PH-ID-CRI-0001, Issue 3.0 960308
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[ESA-PCM] ESA PCM Telecommand Standard, TTC-A-01, Issue 1, Apr. 1978
[ESA-TC] ESA Packet Telecommand Standard, PSS-04-107, Issue 2, April 1992
[ESA-TCD] ESA Telecommand Decoder Specification, PSS-04-151, Issue 1, September 1993
[ESA-TM] ESA Packet Telemetry Standard, PSS-04-106, Issue 1, January 1988 [2]
[ESA-SWE] ESA Software Engineering Standard, PSS-05-0, Issue 2, February 1991
[RPHS-DOC] R-PHS Project documentation (produced according to [ESA-SWE])
[TCE-DOC] TCE Project documentation (produced according to [ESA-SWE])
[TMP-DOC] TMP Project documentation

[2] It must be said that, after CCSDS and ESA decision of deleting segmentation of TM Source Packets, a new issue of this standard is expected soon.

AUTOMATED OPERATIONS FOR GALILEO COMMUNICATIONS

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Abstract

After the Galileo High Gain Antenna (HGA) failed to deploy in 1991, the Jet Propulsion Laboratory (JPL) faced the challenge of implementing a science-rich mission with a Low-Gain Antenna (LGA), at data rates that were almost four orders of magnitude less than originally planned. To accomplish this, JPL completely redesigned the downlink to maximize the data return and increase its reliability, requiring the implementation of dramatic changes both in the Galileo on-board software and in the Deep Space Network (DSN). Key features of the new link include data compression, antenna arraying, recording and reprocessing of telemetry, suppressed carrier tracking, and highly efficient error-correcting coding, resulting in an effective data return that is approximately two orders of magnitude above that that would have been feasible with the LGA had the changes not been implemented (see Figure 1 below). In particular, JPL has developed and deployed a new DSN Galileo Telemetry (DGT) subsystem at the three DSN sites: Goldstone, USA, Tidbinbilla, Australia, and Madrid, Spain. To maximize the data return, the DGT parameters (data rate, tracking loop bandwidths, array configuration) are continuously adjusted and the link operates on a very-narrow margin. Because the operation will continue for almost two years, 24-hours-per-day, the DGT is designed as an automated system that continuously monitors and adjusts its operational parameters and environment in response to either pre-loaded sequences or changes in internal state, with minimal operator intervention. The single-antenna DGTs have been deployed at the DSN sites and the follow-on array DGTs will be deployed shortly. In addition to the Galileo support, these automated DGTs are suitable to provide ground support for other low rate missions.

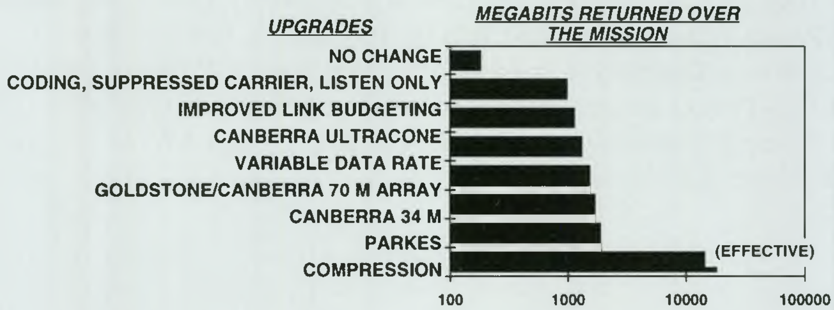

Figure 1 - Galileo Data Volume - With and Without the Changes in the Link

1. INTRODUCTION

[1] The work reported in this article was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

The Galileo Spacecraft was launched in October 1989 on a difficult VEEGA (Venus-Earth-Earth-Gravity-Assist) trajectory shown in Figure 2. The mission's communications were based on the use of an X-band, 4.8-m high-gain antenna (HGA), with backup from two S-band, low-gain antennas (LGA). In April 1991 Galileo was commanded to deploy the HGA but the deployment failed due to mechanical problems. The Jet Propulsion Laboratory (JPL) faced then the challenge of implementing a science-rich mission with a LGA at data rates that were almost four orders of magnitude (!) less than originally planned for the HGA-supported mission. To accomplish this, JPL completely redesigned the downlink to maximize the data return and increase its reliability, requiring the implementation of dramatic changes both in the Galileo on-board software and in the Deep Space Network (DSN). Key features of the new link include data compression, antenna arraying, recording and reprocessing of telemetry, suppressed carrier tracking, and highly efficient error-correcting coding, resulting in an effective data return that is approximately two orders of magnitude above that that would have been feasible with the LGA had the changes not been implemented. In Section 2, we present the new DSN Galileo Telemetry (DGT) subsystem that JPL has developed and deployed to address this challenge. In Section 3 we discuss the operational challenges and how automation was introduced to overcome them. In Section 4, we highlight a key lesson learned from the DGT development. The DGT has been routinely supporting Galileo since May 23, 1996, with extremely high reliability and minimal operator intervention.

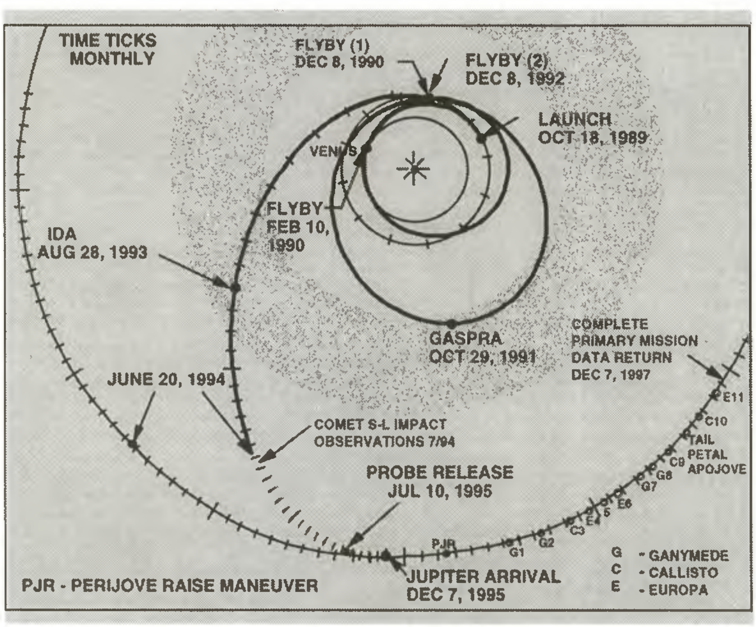

Figure 2 - The Galileo VEEGA Trajectory

2. THE DSCC GALILEO TELEMETRY (DGT) SUBSYSTEM

To address the Galileo challenge, JPL developed and installed DGT equipment [1] at the three DSN sites: Goldstone, USA, Tidbinbilla, Australia, and Madrid, Spain. The DSN configuration with the DGT is shown in Figure 3. Key features of the DGT are:

1. The DGT is a self-contained telemetry recovery unit. It receives an IF signal and produces decoded data frames - all signal processing is internal to the DGT.

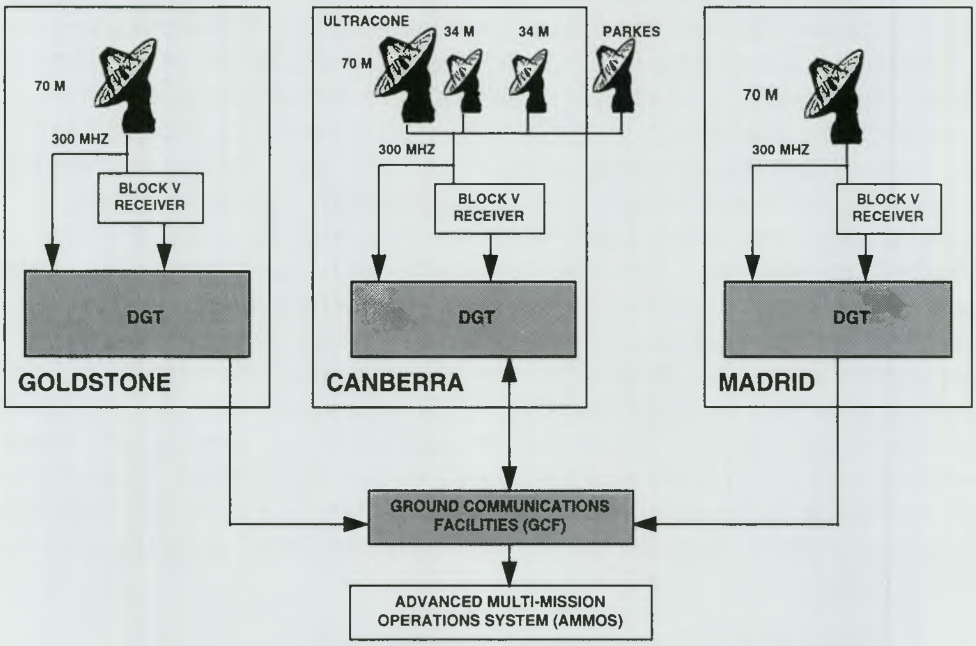

Figure 3 - DSN Configuration with DGT

2. An IF arraying capability is provided. This allows the DGT to combine the IF signal from multiple antennas, effectively adding the G/T (the ratio of antenna gain to system noise temperature) of the individual antennas with minimal loss in the combining process. For Galileo, the DGT combines the signal from two 70-m antenna at Goldstone and Canberra, two 34-m antennas at Canberra, and a 64-m radio-telescope at Parkes Australia.

3. An IF recording capability is incorporated, enabling recovery of telemetry at a later time, if the initial recovery is unsuccessful due to equipment failures or sub-optimal setup. Note that IF recording requires no “locking” thus it provides a full record of the received signals for the full duration that the antenna points to the spacecraft.

4. Superior error-correcting coding is included. The decoding uses frame detection in the symbol domain, a (14,1/4) convolutional decoder, and a 4-redundancy Reed Solomon decoder, all implemented in software. The decoder is fully programmable and can be easily adopted to other missions.

5. Data delivery from the DGT to the project is provided using commercial “guaranteed delivery” protocol, including TCP/IP for block transfers and FTP for file transfer.

The DGT implementation relies heavily on the use of high-speed SUN workstations, performing the function of demodulation, decoding, and arraying. Only the front-end portions of the DGT, and its test signal generator, use custom hardware.

3. OPERATIONS CHALLENGES - HOW THEY WERE ADDRESSED

Even with the link improvements described above, the maximum data rate from Galileo is no more than 160 BPS. To maximize the data return, the Galileo telecommunications link was set to operate on a very-narrow margin and the DGT parameters (data rate, tracking loop bandwidths, array configuration) need to be continuously adjusted. Because the mission operations will continue for almost two years, 24-hours-per-day, the DGT had to be designed as an automated system that continuously monitors and adjusts its operational parameters and environment in response to either pre-loaded sequences or changes in internal state, with minimal operator intervention. This resulted in radical departures from routine mission operations.

Let us highlight a specific example of the difference between Galileo operations and routine spacecraft operations. During a tracking pass, as a spacecraft ascends from the horizon to maximum elevation and then descends back to the horizon, the received Signal-to-Noise-Ratio (SNR) varies as shown in Figure 4 (squares and triangle symbols), primarily due to changes in the System Noise Temperature (SNT). The variation can be as much as 2 dB, a significant G/T gain for deep space missions, and a mission could vary the data rate during the pass to take advantage of the higher mid-pass SNR. In practice, most missions forego this potential benefit either to avoid the loss-of-lock associated with a data rate change or to maintain simple planning and operations. For the Galileo mission we have selected to adjust the downlink data rate to maximize the data return, as shown in Figure 4, resulting in an increase of approximately 1.0 dB (26%) in the data return for the mission.

And the data rate adjustment is accomplished without any operator intervention! - the process is fully automated. At the planning stage, the data rate is increased almost as soon as the link margin permits it, and decreased as soon as required. The DGT then automatically adjusts its tracking parameters to "cruise" through the data rate change without any loss of telemetry. The data rate transitions and their timing were selected so that the whole process is automated.

Another example for the innovative operations approach employed in the DGT implementation is the concept of "post-pass processing". Telemetry equipment is designed to process data in real-time, with minimal or no buffering. How does such equipment respond to unforeseen changes in the signal level, stability, or timing? The designers of the telecommunications link usually provide a "statistically-acceptable" solution. At JPL, the practice is to compute or derive the standard deviations of the "losses" in the link, convert them to dB loss, sum them and define the result as the standard deviation of the link, σ_L, expressed in dB. Then a link margin, typically $2\sigma_L$, is added to the link, reducing the downlink data rate. Factors such as limited signal stability are accommodated through wider tracking loops, further reducing the achievable data rate. The only practical way to pare down some of these data losses is to continuously adjust the downlink data rate based on residuals from real-time tracking, a process that is operationally cumbersome. The result is a link design that is very robust and very conservative - its driving philosophy is "there is no second chance to recover the telemetry".

In contrast, the DGT allows a second chance (and a third, and a fourth...) to recover the telemetry. The DGT operates in two stages: "real-time processing (RTP)" and "post-pass processing (PPP)", as shown in Figure 5. During the pass, the DGT operates in the RTP mode: the tracking parameters are set at moderately-conservative values with a goal of recovering at least 90% of the telemetry. This "real-time" data is useful in determining the latest state of the spacecraft but is not comprehensive enough to recover science data. After the pass is complete, the DGT switches to the PPP mode and attempts to recover the remaining 10% of telemetry. During this fully-automatic stage, the DGT zeroes in on the missing data and adjust the processing parameters (e.g. loop bandwidths) repeatedly to recover the missing data. The algorithms are quite sophisticated, including processing forward and backward in time, and are selected automatically from a tool-box, according to their probability of success. PPP ends when the pre-determined time-limit has arrived, with a default of 4 hours.

Actual Data Rate With and Without Parkes

Achievable And Actual Telecom Performance -- C10 Orbit

Date	Diplexer	Ranging	Range (AU)	JEP (degrees)	Jupiter Temp (K)	SEP (degrees)	Scin Degradation (dB)	Achiev Data Return In 24 Hours (Mbits)	Step Data Return In 24 Hours (Mbits)	% of Achieve	Data Return with 15 Minute Minimum Restrict	% Loss due to 15 Minute Minimum	Cone Angle
10/7/97	Off	Off	4.56	0.11	2.68	118.43	0.00	6.66	5.68	85.4%	5.68	0.0%	4.0°

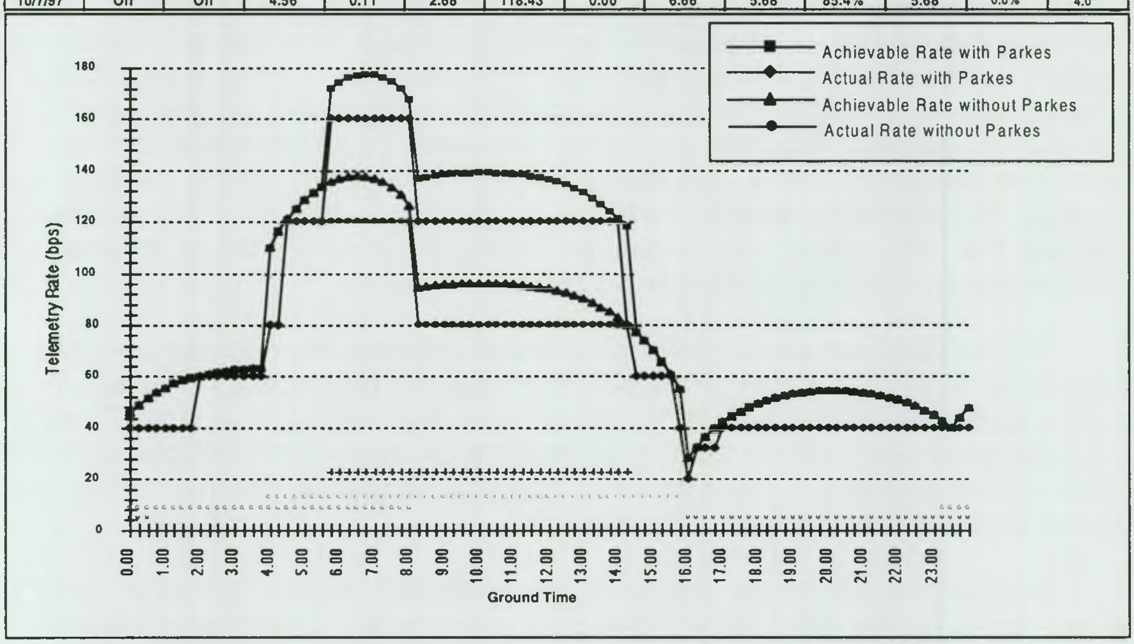

Figure 4 - Effect of Changing the Data Rate During a Pass

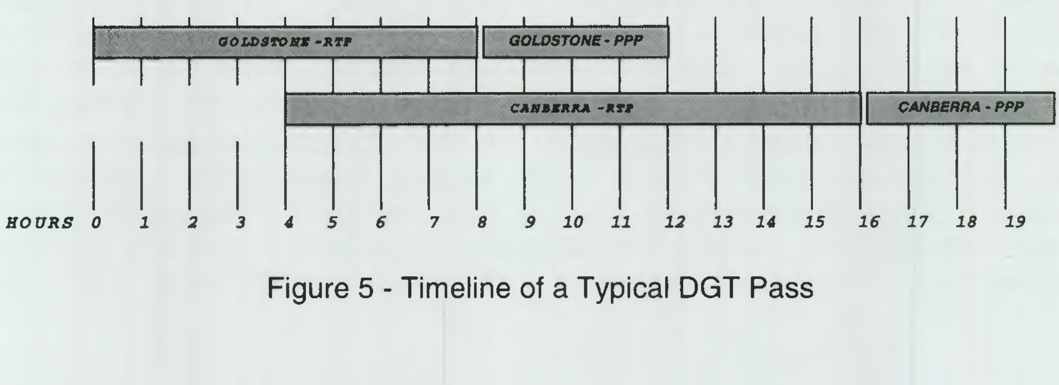

Figure 5 - Timeline of a Typical DGT Pass

These two examples highlight the fact that the DGT establishes a new balance between the sophistication of processing and automation. In a typical pass, the operators are required to conduct a minimal number of steps prior to the pass and perform no steps during the pass. Nevertheless, through automation the DGT is able to "tweak" its operations to maximize the data return for the mission.

4. LESSONS-LEARNED

The single largest factor in the successful emergence of the DGT as an operational system is the involvement of the Operations Organization and staff from the early stages of the development. Even though the DGT emerged from the confluence of the Galileo antenna anomaly and the maturation of a significant R&D program, it could not have turned into a successful operational system without the involvement of the operations teams at the three DSN sites as well as at JPL and Pasadena. To accomplish this, at the outset of the project, both an operational concept and an operational scenario were developed jointly by the implementation and operations staffs, well before the DGT configuration and design were solidified. Then, the operations staff participated in recommending, reviewing, and sometimes designing (e.g. man-machine interfaces). Levels of automation and maintenance were jointly established. Thus when the implementation was completed, the DGT reflected the operational experience developed over many years and missions. We see this successful transfer to operations in the surprisingly low number of phone calls and other requests for help from the operations staff.

5. CONCLUSIONS

As these words are written, the JPL approach to recovering from the Galileo HGA anomaly is proving its success by delivering spectacular pictures and discoveries from Ganymede, the first target of a 2-year tour of the Jupiter system. What was four years ago a risky conversion of R&D technology into an operational system, calculated risk as it may be, is paying off with handsome science return, and without an overdue loading on the operational infrastructure.

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ESA's DEEP SPACE AND NEAR EARTH GROUND STATIONS FOR THE NEXT CENTURY

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ABSTRACT. The sharing of the S-band (2 GHz) between new ESA missions and more than 350 already flying vehicles is proving more and more difficult if not impossible. Beside the inter-service sharing, additional coordination is required with the Mobile and the Fixed Service that have co-primary ITU allocation status with the Space Services.
Therefore, ESA is taking steps towards the use of X-band uplinks (7 GHz) for Near Earth and Deep Space missions along with X-band (8 GHz) and Ka-band (32 GHz) downlinks, the latter being exclusively allocated to Deep Space probes. On top of the frequency clearance, an additional advantage in moving up in frequency is given by the increasing antenna gain which makes it possible to transmit and receive higher data rates for typical Near Earth orbiters or to support farther away Deep Space missions.
The higher atmospheric attenuation of Ka-band frequencies can be mitigated by flying on-board RAM that can be dumped to the Earth when weather conditions are more favorable and/or by employing site diversity and arraying techniques. Arraying techniques are also the way to extend the distances currently supported by the ESA network of 15-m S/S and S/X-band network without having to build larger and therefore more expensive and more difficult to operate and maintain antennas. Compatibility and cross-support with partner agencies like NASA already moving towards higher frequency bands are also key issues on ESA's mind.
As far as the back-end is concerned, new equipment like an all-digital receiver and modem are being conceived along with the subsystems required to support the new frequency bands.
The present paper describes the various activities that ESA is carrying out within the European industries with the aim of providing a ground network meeting the requirements of the next Century.

I. INTRODUCTION

The European Space Agency has been conducting spacecraft operations through its ESTRACK network in UHF for the last 20 years. ESTRACK essentially consists of a network of 15-m antennas, suitable for near-Earth, geostationary, Highly Elliptic Orbit and Deep Space missions. The frequency bands used for these purposes have been in S band, 2025-2120 MHz for the uplink and 2200-2300 MHz for the downlink. Only for the scientific data return of Deep Space missions (whose height is more than 2 million kilometers) a downlink frequency in X band (8400-8450) has normally been selected along with a pair of up and down link frequencies in S-band.

Today there are more than 300 satellites registered by the International Telecommunication Union (ITU) operating in the uplink S-band and more than 350 satellites operating in the downlink S-band. Besides, as of the ITU World Administrative Radio Conference of 1992 (WARC-92), the Space Operation and Space Research Services in the S band have to share the spectrum with the Mobile Service and with new types of the Fixed Service, all having co-primary allocation status. This has increased tremendously the burden on the Agency's Frequency Management office in the effort of trying to assign the required frequencies to new missions via several step of worldwide coordination. Exchanging predicts of RFI events with other operators has become part of everyday's mission planning.

The search for new frequency bands in cooperation with ESA partner agencies like NASA has therefore been initiated. A good candidate frequency plan for future Deep Space missions is X-band uplinks (7145-7190 MHz) coupled with simultaneous X-band (8400-8450 MHz) and Ka-band (31.8-32.3 GHz) downlinks. For other missions, X-band up (7190-7235 MHz) and (8450-8500 MHz) down links are under consideration.

ESA is currently studying the possibility to add X-band transmission and Ka-band reception to some of its TT&C antennas, already operating in S/S or S/S/X bands. Alternatively, a refurbishment of the same antennas for the new X and Ka bands can be considered.

On top of the modification of current antenna apertures, several other items like cryogenically cooled HEMT front-ends, antenna arraying techniques, all digital IF modems and more powerful decoders are under study or development for next century's ground stations.

II. THE FREQUENCY BAND ISSUE

Deep Space missions are characterized by the extremely weak received signal levels and operate with very low margins (less than 1 dB) making any RFI intolerable. To improve reception, coherency between up and down links via fixed transponder turn-around ratios is normally utilized. Dual frequency downlinks (S and X band simultaneously) are also used to counter ionospheric delay and achieve better orbit determination accuracy.

Although only a few of the missions are in the Deep Space category, the frequency bands allocated to this service are adjacent to the non-Deep Space allocation and are shared with the Mobile and Fixed Services. Therefore, the powerful uplinks necessary to command and range distant spacecraft are likely to create coordination problems around the Earth station. For instance, reception of telemetry from the ESA Ulysses probe at Canberra (Australia) has not been licensed yet due to the required (coherency) S-band uplink whose noise floor is feared to spread into the adjacent television distribution system (point-to-multipoint distribution.)

The ITU has allocated up to 500 MHz of spectrum to exclusive Deep Space service in the Space-to-Earth direction from 31.8 to 32.3 GHz (Ka-band.) This band can be coupled with uplinks in the X band for coherent operations.

The use of these bands has several advantages, like providing an interference free reception band, providing a large downlink bandwidth suitable for higher rate transmissions as required by future more challenging missions or for wideband VLBI experiments, providing virtually negligible ionospheric effects and faster recovery from solar corona effects, providing larger directional antenna gains thereby permitting either increased data rates or support to farther away distances.

The only disadvantage of moving so high up in frequency is the increase in the atmospheric loss (rain, etc.) However, the nature of Deep Space missions and the availability of on-board solid state recorders with sufficient storage capacity along with re-transmission protocols make it possible to specify relatively low weather availability figures (95% or lower) for which the atmospheric attenuation is not of concern.

Preliminary link budgets for the Rosetta mission (comet nucleus sampler) have shown that the existing 15-m antenna network upgraded to X/Ka capabilities can support the mission as far as 6.25 Astronomical Units (AU) from Earth as well as a new 30-m S/X-band antenna would do. Since NASA is also moving to X/Ka-band for its future Deep Space missions (New Millennium) and cross-support between the Agencies is normally foreseen, the bread-boarding of a new on-board transponder has been initiated by ESA/ESTEC whereas ESA/ESOC has started to study the upgrading of the current 15-m antennas.

For non-Deep Space missions, called Near Earth missions in ESA terminology, the use of the X-band for up and down links is encouraged. Although the uplink allocation is subject to article 14 of the ITU Radio Regulations, the coordination area is reduced in size with respect to the 2-GHz case by the frequency ratio squared. As most of the spacecraft in this category operate with omni-directional antennas, there is no link budget advantage associated with this move to higher frequencies. The increase in atmospheric loss in the uplink is not a problem due to the normally high margins of the uplinks whereas the effect on the downlinks is more than compensated by the reduced interference scenario.

For special missions like the Moon Orbiter (MORO) this interference free reception band makes it conceivable using X-band Masers in place of HEMTs in order to increase the telemetry data rate by fully exploiting the advantage of the lower MASER noise temperature.

III. THE NEW FRONT-END

Fig. 1 shows the two antenna types available in ESTRACK. Tab. 1 summarizes their present main technical characteristics.

For each structure, three options have been studied:

- the possibility of adding X/Ka capabilities to the existing ones, resulting in a 5-band design (S/S/X/X/Ka);
- the possibility of removing the present capabilities, resulting in a 2-band design (X/Ka), suitable for new missions;
- the possibility of removing S-band capabilities only, resulting in a 3-band design (X/X/Ka).

Each of such alternatives has a different impact on ESA programmatic, on the structure to be refurbished and on the expected design results. For cost reasons, a common design shall be considered.

As a general issue, the added upgrading should not reduce performance of the present system. On the other side, the new bands service should fulfill the requirements listed in Tab. 2. The various frequency bands should be served simultaneously (concepts such as feed rotation, adaptation of antennas depending on the running missions, should therefore be avoided).

III.1 THE APERTURE DESIGN

The main technological issue to be considered when refurbishing existing antennas is the design of the aperture. As can be seen in fig. 1, the two available reflector configurations are quite different: one is a standard Cassegrain (fig. 1a)), the second is a near field Cassegrain antenna (fig. 1b)). To obtain the requested performance, illumination efficiencies around 80% should be obtained. This would in turn require similar illumination patterns on the main reflector for all bands.

Several illumination concepts have been considered, involving the displacement of the radiating elements (one or more feeds, dichroic surfaces or dichroic subreflector) and the transformation of the near field Cassegrain concept into a standard Cassegrain. Transformation of antennas into beam waveguide concept has not been taken into account, since it would involve a redesign of the existing pedestals.

Analysis shows that the near field Cassegrain concept is not suitable for multifrequency applications. In fact, it is rather difficult to integrate several radiating elements, providing similar radiation characteristics and keeping the phase centre at the same position. The guided concept shown in fig. 1b) is inherently narrow band. Moving some radiating elements on the primary focus would require a dichroic surface (dichroic subreflector or dichroic plane between the subreflector and the secondary focus). However the required illumination angle would be too large, for any reasonable dichroic design.
The design has then been finalized for the concept shown in fig. 1a), since it has been shown that the existing near field Cassegrain antennas can be mechanically retrofitted to such concept. The illumination concept has been studied for the following alternatives:

- multi frequency feed placed in the secondary focus;
- two feeds (one in primary focus, the other in secondary focus) separated by a dichroic subreflector;
- as the above case, feeds separated by a plane dichroic surface;
- cluster of feeds arranged around the secondary focus.

For all of them the possibility of including the three required frequency bands has been taken into account, being always possible to descope some of them at a later stage. Principles of these geometries are shown in fig. 2 a-d).

The preferable way of extending the capabilities of the existing antennas would be to replace the present feed (placed in the secondary focus) by a combined S/S/X/X/Ka one. This would ease the accommodation of RF equipment and would make installation simpler. However, as explained later, a single corrugated feed covering the five frequency bands and providing the required illumination efficiency at the same time implies big dimensions. The overall length would be considerably more than the present one, pushing the phase centre towards the subreflector. This would in turn require a larger flare angle and induce a higher secondary blockage. Such a structure would be feasible if a loss on illumination efficiency of about 0.2

dB could be acceptable. In case S-band is not required, a X/Ka band could be easily accommodated in the secondary focus. Its dimensions would avoid all the above mentioned problems.

Fig. 2 b) shows the configuration where the S/X (or X only) feed is placed in the secondary focus, whereas the Ka-band feed is located in the primary focus, behind a dichroic subreflector. Such subreflector should reflect S and X bands and be transparent at Ka-band, with lens capabilities. From the figure it can be seen that the incident angle of the rays coming from the Ka-band feed varies from 0 to 70 degrees, leading to a very high transmission loss, near the edges of the subreflector, for any of the known dichroic structures. For this reason such an approach has not been further evaluated.

The principle of an antenna with plane dichroic reflector, placed in the mid point between the primary and the secondary focus, is shown in fig. 2c). In this case the dichroic shall reflect at Ka-band and transmit at S and X. For such a configuration an incidence angle limited to 24 degrees is needed.

The arrangement shown in fig. 2d) has also been studied. Such a solution is not recommended for a 15 m antenna. due to the limited space available around the secondary focus.

Calculations have been performed for both antennas, to verify the possibility to use proper shaping of main and subreflector. This would optimize the illumination efficiency. The available adjustment ranges for panels displacements have been taken into account. The simulations have shown that such a possibility exists, for both cases. In practice efficiencies higher that 80% are obtainable.

III.2 THE FEED DESIGN

As seen in the previous section, the basic two alternatives are:

- a 3-band feed located in the secondary focus;
- S/X feed in the secondary focus, dichroic plate and Ka-band feed in the primary focus.

The two alternatives are briefly assessed here. It has to be taken into account that a dual frequency (S/X band) feed already exists and is currently installed in the antennas of fig. 1a). It is a corrugated feed with dielectric rod for the X-band radiation (reception only).

The design of a 3-band feed, including autotracking for the 3 receive bands, is quite challenging. To get some data on the feasibility of such a device, some basic investigations have been performed. Estimations on the expected performance and development costs could be derived.

The following cases have been studied:

- combined S/X/Ka-band corrugated horn;
- combined S/X-band corrugated horn with dielectric Ka-band radiating rod.

The high level design of a 3 band corrugated feed is depicted in fig. 3a). There are two basic degrees of freedom in the design of such horn: the groove structure used to create a proper boundary condition for the hybrid modes to propagate and the flare angle together with the final aperture size, to obtain the desired pattern.

A groove depth that is multiple of the 3 required operating frequencies can be found, so that the boundary condition to support the proper fast wave can be easily met. Concerning the flare angle, the following has to be considered. As a horn with constant flare angle becomes larger, the radiation patter becomes narrower. In practice, after a certain limit, additional size does not make pattern narrower any longer, because of the increasing phase error over the aperture, so the flare angle alone determines the final pattern shape and width.

A trade-off can be conducted between groove depth and flare angle, so that a sufficiently large aperture can be designed, to get approximately equal patterns for all required frequencies. A semi-flare angle in the region between 27 and 32 degrees is necessary. From this angle, the overall feed length and the position of the secondary focus can be assessed. Because of the relatively large aperture, the use of a profiled horn is not recommended. Fig.

2a) shows a possible final location of the phase centre and consequently of flare angle choice for such a feed. The figure clearly shows that the feed would be nearer to the subreflector than the present feed, creating more severe blockage problems, specially at S-band.

A basic problem stems on the excitation of the various bands in the feed. Difference signals, needed for autotrack, are also needed, for 3 bands. Fig. 3b) shows a possible solution: several slots of different dimensions are required, to generate the appropriate signals at S and X band; a waveguide network combines the signals in order to generate the required signals. Ka band signals are conventionally collected at the throat of the feed.

The second possibility is shown in fig. 4. If the shape and dimensions of the dielectric rod are properly chosen, its radiation characteristics are approximately the same as the X-band section. The essential advantage with respect to the structure of fig. 3b is the decoupling of Ka band from the other bands. The considerations and limitations on radiation and blockage performance remain unchanged.

The third case (S/X feed in the secondary focus, dichroic plate and Ka-band feed in the primary focus) has been shown already in fig. 2c). This case seems to be the most promising, since it should not suffer of any illumination or blockage problems (at least no more that for the existing system), it would re-use existing design and it would leave complete freedom on the design of the Ka band section. On the other hand the insertion of a dichroic surface would lead to higher RF losses (estimated losses are: 0.15 dB at S-band, 0.3 dB at X-band, 0.1 dB at Ka-band). Appropriate structures, supporting the dichroic reflector, should generate negligible blockage, since they are outside the illumination area of the subreflector.

As a conclusion, the last solution is the preferred one, in case all the bands shall be supported by the same antenna.

III.3 SERVO SYSTEM AND STRUCTURE; AUTOTRACK AND POINTING PERFORMANCE

Surface accuracy of about 0.3 mm RMS has been considered reasonable for all the specified frequency bands. The relevant efficiency would be around 90% for Ka band.

Concerning antenna structure, it has to be noted that antennas shown in fig. 1 have quite different mechanical structure. The one shown in fig. 1a) has been designed as a general purpose antenna, suitable for fast movement and consequently with a relatively light structure (backing structure: aluminum and steel), whereas the antenna in fig. 1b) is quite stiff (backing structure: steel) and not suitable for fast movements. Tracking and pointing budgets, for the specified wind speed and gusts (wind speed: 50 km/h, gusts up to 75 km/h) show that the antenna of fig. 1a) should be modified in several parts, in order to perform as the one of fig. 1b). As a reference, the expected performance of antenna of fig. 1b) is given in tab. 3.

III.4 OTHER TECHNOLOGICAL ASPECTS

The addition of X-band transmit capabilities should not create any technological problem. Solid State Power Amplifiers (SSPAs) exist already on the market, or can be easily derived from the commercial C-band units, covering the required range of RF power (around 300 W CW).

Some problems exist in producing cooled HEMT-based LNAs in the Ka band, covering the specified noise temperature (about 25 Kelvin degrees). Temperature around 40 degrees seem to be more affordable, taking into account present industry standards. In case Ka-band feed is placed in the primary focus, the liquid Helium needed for cooling shall be pumped along the subreflector supports, leading to possible integration and heat isolation problems.

III.5 OVERALL RESULTS

Tab. 3 resumes the expected performances of the two antennas. Of the three refurbishment cases considered, only the most complicated one (S/S/X/X/Ka) is shown as it represents the worst case from a performance point of view. One can see that most of the study specifications (tab. 1 and 2) can be met. Exceptions are the autotrack and pointing accuracy where further studies are required to define suitable servo systems for Ka-band.

IV. THE NEW BACK-END

Most of the equipment in the back-end of today's ESA stations are state-of-the-art subsystems compatible with the inter agency support requirements set forth by the Consultative Committee for Space Data Systems (CCSDS) recommendations and by the ESA standards.

The current trend of replacing all possible analog equipment with its digital counterpart will be carried forward with the phasing out of the old analog carrier (phase) demodulators and modulators by a currently under development IF modem. The new IF modem will also include the telecommand modulator and the telemetry demodulator(s) and will be fully programmable thus minimizing the number of different subsystems deployed in the network. Fast acquisition techniques based on the Fast Fourier Transform (FFT) method will be used instead of the conventional phase lock loop (PLL) sweeps thereby reducing both the acquisition time and the likelihood of locking onto unwanted signals (spurious and/or RFI.)
In an effort to support farther away missions (Rosetta will reach 6.25 AU, about six times the distance of its predecessor GIOTTO), the standard downlink convolutional encoding (R=1/2, k=7) is being considered for telecommand uplinks.
Although not yet fully studied and therefore not yet included in the list of codes for inter-Agency support, the Turbo codes have been shown to have such a performance (within 0.9 dB from the Shannon limit) that they will certainly become the new standard. The achievable coding gain will probably require new symbol synchronizers to handle the extremely low symbol signal-to-noise ratio.

For accurate orbit determination of Rosetta at 6.25 AU the current Cesium-beam frequency standard is not deemed to have the required long term stability and will be replaced by a Hydrogen maser already tested with the Ulysses mission in 1996.

A new series of low phase noise up and down converters just breadboarded will also be deployed in the years to come (phased replacement) as dictated by mission requirements and budgetary constraints.

Finally, for contingency and emergency operations requiring reception via spacecraft Low Gain and Medium Gain Antennas (LGA/MGA) as opposed to the nominal High Gain Antennas (HGA) or to further increase the telemetry data rate via the HGA, the fully digital demodulation scheme adopted lends itself quite easily to antenna arraying techniques like Full Bandwidth Combining thereby not requiring back-up support from larger antenna apertures like the NASA 70-m network. An activity encompassing the trade off of the various possibilities, the bread-boarding of the selected combination technique(s) and a series of field demonstration tests has been put forward in the list of possible activities to be selected by the Agency and/or its member countries.

V. CONCLUSIONS

A move to higher frequency bands like X/Ka-bands for Deep Space missions and X/X for Near Earth missions is envisaged in the near future. The possibilities of refurbishing the present ESTRACK stations to cover old and new frequency bands have been studied and a preferred configuration has been outlined

On top of the equipment required for these frequency bands, other very high performance subsystems like advanced digital receivers and decoders are being developed for the ESA stations of the next century.

Tab. 1 - Present antennas main characteristics

	S-band Transmit	S-band Receive	X-band Receive
frequency MHz	2025-2120	2200-2300	8400-8500
polarization	RHCP or LHCP	RHCP and LHCP	RHCP and LHCP
cross polarization dB	-25	-25	-25
sidelobes	ITU App. 29	ITU App. 29	ITU App. 29
antenna gain dBi	47.2	49.1	60.3
EIRP dBW	72-80	-	-
G/T @zenith dB/K	-	29.5	39.1
Rx/Tx isolation dB	100	100	-
autotrack accuracy dB	-	0.1	< 1
pointing accuracy dB	0.05	0.05	0.5
azimuth range deg	0 to 720		
max azimuth speed	0.3, 3, 5, 15 deg/s, depending on the antenna		
max azimuth accel.	0.3, 1.5, 3, 7.5 deg/s^2, depending on the antenna		
elevation range deg	-2 to 92		
max elevation speed	0.3, 3, 5 deg/s, depending on the antenna		
max elevation accel.	0.3, 3 deg/s^2		

Tab. 2 - New antenna requirements

	X-band Transmit	Ka-band Receive
frequency MHz	7145-7235	31800-32300
polarization	RHCP or LHCP	RHCP and LHCP
cross polarization dB	-25	-25
sidelobes	ITU App. 29	ITU App. 29
antenna efficiency	> 65%	> 50%
EIRP dBW	82	-
G/T dB/K	-	50.6@30deg elevation
Rx/Tx isolation dB	90	-
autotrack accuracy	-	TBD
pointing accuracy	< 1 dB	TBD

Tab. 3 - Final results

	S-band Transmit	S-band Receive	X-band Receive	X-band Transmit	Ka-band Receive
frequency MHz	2025-2120	2200-2300	8400-8500	7145-7235	31800-32300
polarization	RHCP or LHCP	RHCP and LHCP	RHCP and LHCP	RHCP or LHCP	RHCP and LHCP
cross polarization dB	-25	-25	-25	-25	-25
sidelobes	ITU App. 29	ITU App. 29	ITU App. 29	ITU App. 29	ITU App. 29
antenna gain dBi	47.2	48.2	59.3	56.8	71.3
EIRP dBW	80.0	-	-	81.6	-
G/T @zenith dB/K	-	28.0	37.5	-	50.2@30deg elevation
Rx/Tx isolation	100	100	90	90	-
autotrack accuracy	-	0.1	<1	-	2.5
pointing accuracy	0.05	0.05	0.5	0.5	4.3

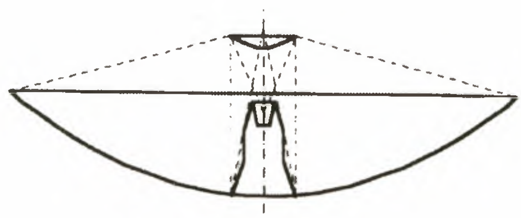

Figure 1a - ESA Standard Cassegrain Antenna Configuration

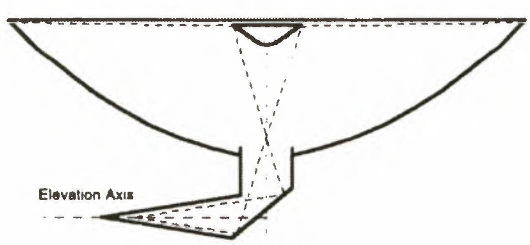

Figure 1b - ESA Standard Near-Field Cassegrain Antenna Configuration

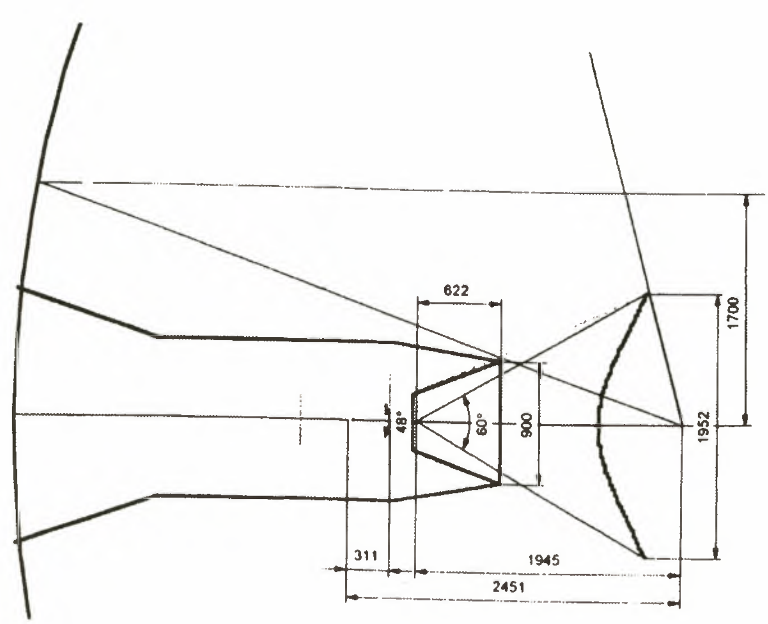

Figure 2a - Multi-Frequency Feed Placed in the Secondary Focus

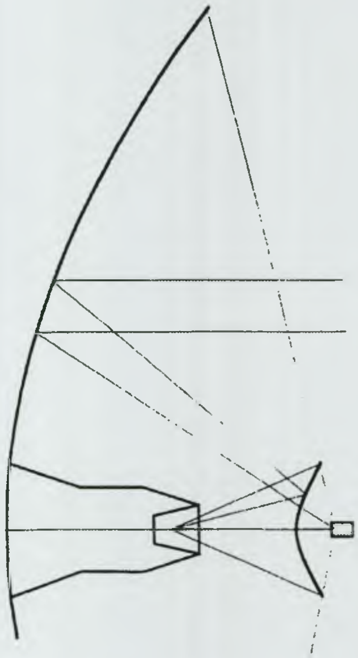

Figure 2b - Cassegrain Antenna with Dichroic Subreflector

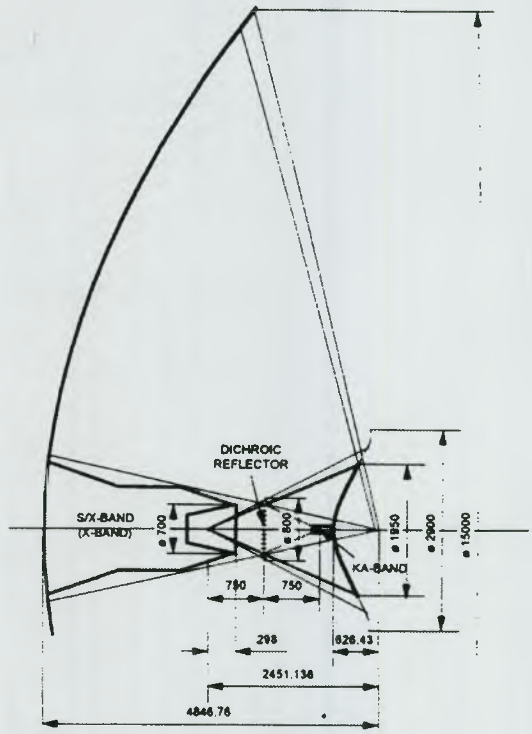

Figure 2c - Cassegrain Antenna with Plane Dichroic Reflector

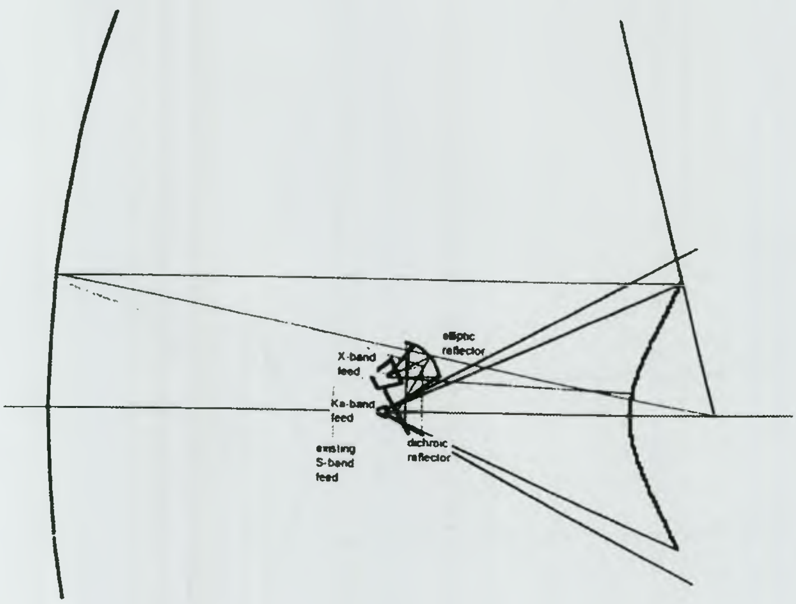

Figure 2d - Cassegrain Antenna with Feeds Placed Around the Secondary Focus

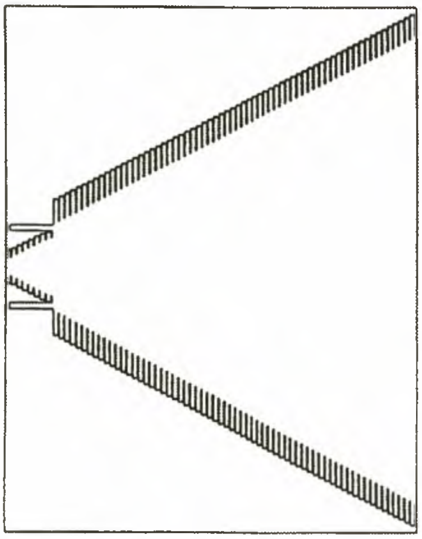

Figure 3a - Multi-Frequency Horn

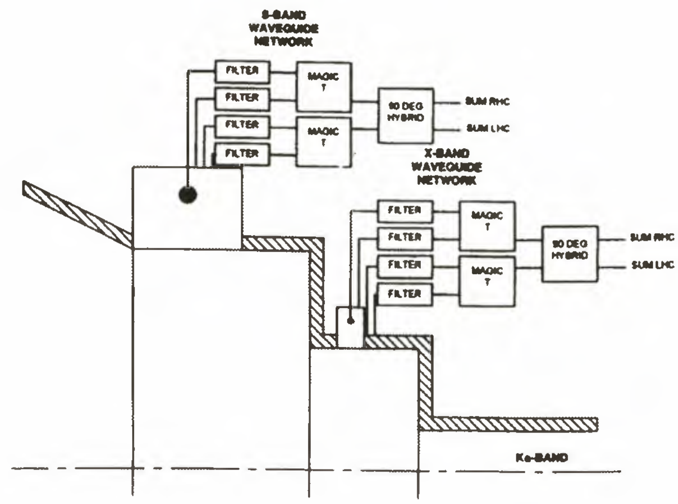

Figure 3b - Principle of S/X/Ka-band Feeding Section

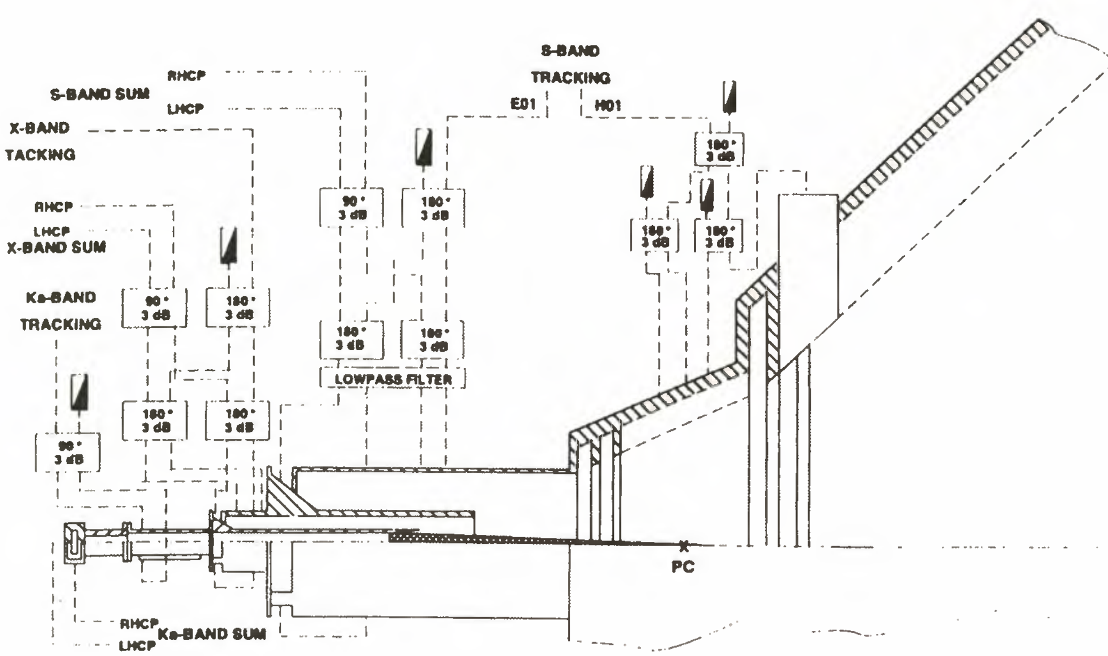

Figure 4 - Corrugated S/X-band Feed Combined with Ka-band Dielectric Rod

MODELLING OF GROUND STATIONS FOR CONFIGURAGBLE MONITORING AND CONTROL

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ABSTRACT. Monitoring and control of ground stations is required on the level of individual subsystems, on the level of a ground station and on the level of the complete ground station network. While the requirements on monitoring and control differ on each of these levels with respect to the level of detail and the level of abstraction, the equipment monitored and controlled is the same and must be presented in a consistent manner. The paper provides a summary of the modelling approach developed at ESOC for this purpose in the recent years. Following an analysis of the M&C information that must be processed and a general presentation of the model it describes how the model is used on different layers of the M&C system, concentrating on the station management layer. The paper concludes with an overview on the "Ground Station Tailoring System" (GSTS) currently in development. GSTS will allow station engineers to build a model of the station and its operation in an object oriented DBMS from which the configuration of all M&C systems is derived.

INTRODUCTION

With evolving technology monitoring and control (M&C) of ground stations has to meet new requirements, characterised by an ever growing amount of data to be handled and increasing demands for automation and more sophisticated operator interfaces. Especially support of low orbiting spacecraft with short passes and the requirement to operate stations primarily via a remote operator position have drastically changed the role of the monitoring and control function from a "nice to have" extension to a mission critical element of a ground station. Higher levels of automation require the M&C system to be fine tuned to the specific station design and to the operational procedures imposed by the missions a ground station shall support. On the other hand economic conditions ask for standard solutions which allow re-use of existing systems.

The conclusion is that the M&C system should be configurable such that the station engineer is able to build a fine tuned application from pre-fabricated building blocks. On a high level such a system could be compared with a spread-sheet which allows to build highly specialised applications based on the combination of rather abstract building blocks such as fields and formulas. A prerequisite for such a system is a generic modelling scheme which allows to describe the structure and operation of a station and its subsystems, their presentation to the human operator and the interfaces between elements of the monitoring and control system.

The architecture of the ESA station M&C system is shown in figure 1. A station is structured into subsystems each of which implements a well defined subset of the functionality. Each subsystem consists of a set of subsystem units which are monitored and controlled by a subsystem controller. The subsystem controllers currently available are:

- the Front End Controller (FEC) for the antenna and front end RF equipment;
- the controller for the Telecommand Encoder (TCE)
- the controller for the Return Link Protocol Handling System (RPHS)
- the Monitor and Control Module (MCM) which acts as a proxy for equipment which is not (yet) integrated into a subsystem.

On the station level monitoring and control is performed by a system called the "Station Computer" (STC) due to historical reasons. This system provides the interface for the station operator on

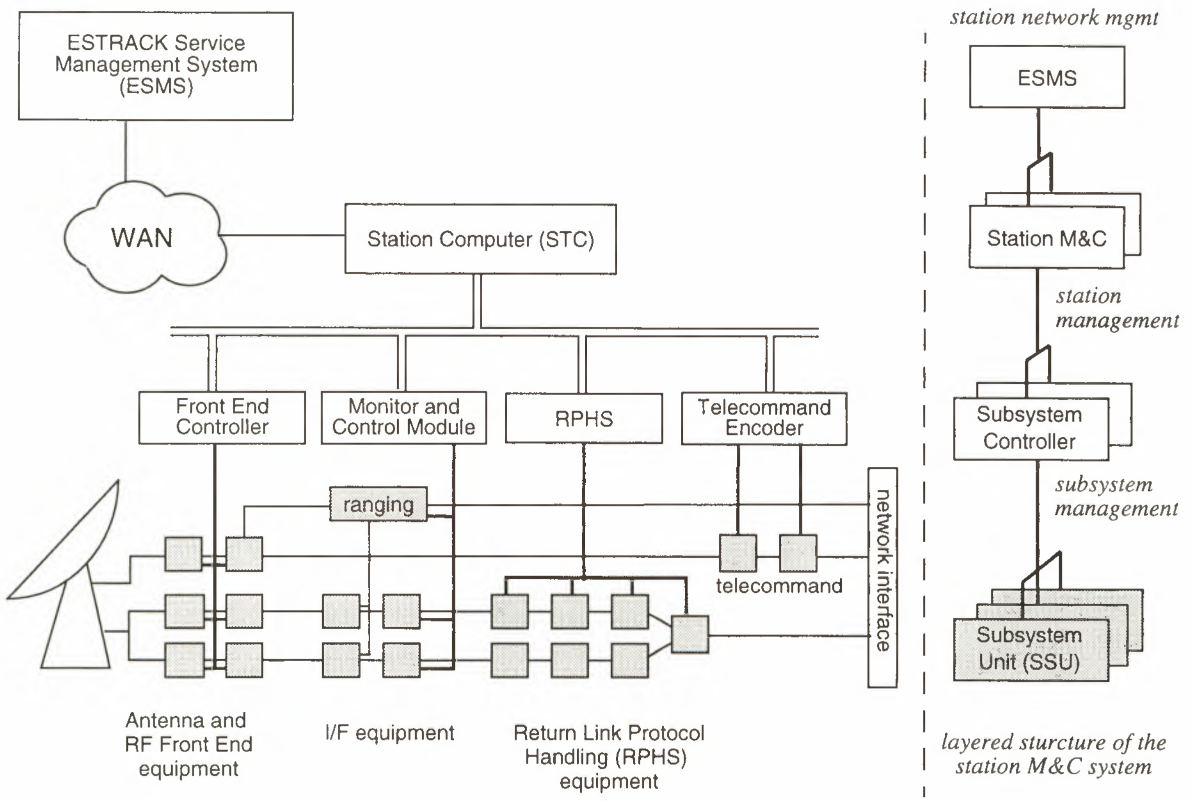

Figure 1. Schematic view of a ground station from a management perspective (left side) compared to the generic structure of the ESA ground station monitoring and control system.

one or more operator workstations which can be located on the station or at a remote site and connected to the "STC server" via a wide area network. All equipment specific interfaces are exclusively handled by the subsystem controllers; the STC M&C application is built on top of a standardised interface to the subsystem controllers based on the OSI Common Management Information Service (CMIS) and a standard Ethernet LAN. It is described in [M&C] and [YD96]. The projected ESTRACK Service Management System (ESMS) described in [WH96] implements the highest management layer.

In contrast to many other M&C applications which have to deal with a moderate number of different types and a vast number of instances, the station M&C system has to handle a large number of different types of equipment and a small number of instances per type, often only one, or two in case of redundancy. This fact severely limits re-use of a hand crafted implementation for every type. The degree of difference between various types also limits the effect of the standard "object oriented approach" by which common functionality is implemented in base classes from which implementations of real world entities are derived. Because of these constraints, a different modelling approach had to be found.

Following the principles of OSI network management (OSI/NM), this approach uses the basic object model, by which any **object** can be described by

- an **identification** which distinguishes an object from other objects,
- **attributes** which capture the characteristics and state of an object,
- **operations** that can be requested from the object, and
- **events** that can be issued spontaneously by the object.

Each of these elements is described in form of one or more **elementary object-classes** with a well defined and fixed set of attributes, operations, and events. In contrast to OSI/NM the description of real systems is achieved by combining **instances** of these classes according to **building rules**, instead of defining new classes for real systems.

For communication between different M&C components, the elementary classes and the building rules form that part of the common knowledge that has to be built into the software of the cooperating systems. Sets of instances structured according to the building rules and describing real systems are stored to a **configuration database** which is read and processed by the software. Instances which must be handled by more than one M&C component are present in the database of each component that needs to handle it.[1] Customising the M&C system means to create and modify these databases.

SUBSYSTEM MANAGEMENT LAYER

Individual attributes of a real system are specified by the class "**variable**". A variable has a **value** attribute. To limit the complexity of the resulting models, the possible **types** of the value have been constrained to a small set which includes the basic data types (boolean, integer, float) as well as enumeration types, text strings, octet strings, and time.

In a M&C system, the value of a variable may actually not be known, e.g. because the communication link to the monitored device is not available. A value may also be undefined under certain circumstances, e.g. because a measurement device only delivers a valid reading when high voltage is switched on. Hence a variable has a second attribute, which defines the current state of the value as being valid, unknown, undefined, or in error. The two attributes "value" and "value state" fully describe the dynamic state of a variable and have to be updated across system boundaries. Further static attributes define its identifier,, the type of its value, alarm limits, engineering units, allowed value range for control, etc.

A variable instance may or may not be controllable. If an instance is controllable, the class provides the operation to set the value.

1. In OSI/NM terms the configuration database contains both the "Management Information Base" (MIB) and the structure of the "Management Information Tree" (MIT). This implies that all objects are predefined and creation of previously unknown objects across the interface cannot be supported.

Variables are contained in a **variable list**, with a distinct identifier. This class provides basic means to describe aggregates of variables.

A **subsystem unit** (SSU), generally a hardware unit, is described by a class which can contain variable lists and other objects referred to later in this section. Beside its identifier, the SSU has three attributes, defining its operational state (setup, operational, inoperable), its administrative state (in service, in maintenance, absent), and its control mode (local, remote)

A frequent operation performed on equipment is to set the values of configuration parameters. This operation is already covered by the variable class. More complex operations which can be started, stopped, and aborted are defined by the class "**task**". A task can be started with an optional set of **arguments**, which are defined in the same manner as variables, except that their value is always valid and does not change spontaneously. The task defines an identifier, a state attribute indicating whether it is idle, busy, terminating, or unrunnable and a completion condition which reports the result of the last run. The actual operation which is performed by a task is not specified by the model. This is defined by the subsystem that defines the task instance.

The complete subsystem is an instance of the class "**subsystem**", which is similar to a subsystem unit, but can contain instances of SSUs. It also defines the communication parameters for the M&C interface.

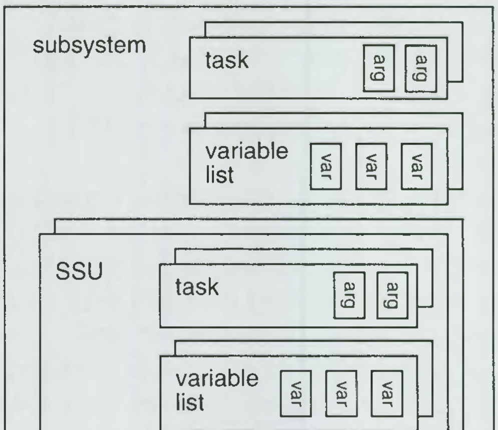

Figure 2. Structure of a subsystem model (simplified)

A schematic view of a subsystem model is shown in figure 2. Further elements of the model, not described in this paper[2] include:

- a function block to specify functional units
- event handlers to define closed loop control
- classes to define subsystem logging
- classes to define subsystem to subsystem communication

The **identification** of instances within a subsystem model follows the "distinguished name" known form OSI network management, with the initial restriction that the full name must be unique. Identifiers, therefore, take the form known from file systems in Unix or MS-DOS.

The subsystem model describes the equipment "as implemented" and in a manner which must cope with all possible uses. In a given installation only a subset of the information may be required for station level monitoring and control.

Therefore, the interface is described in a separate model, which directly specifies the managed objects seen on the CMIS interface. According to the CMIS standard the instances of these managed object classes form the Management Information Tree (MIT) which is available on the subsystem controller (the CMIS agent) and the STC M&C application (the CMIS manager). The interface cannot add any new definitions, but it can omit any element from the implementation part. In addition, the interface does not contain variable lists but groups variables as convenient for monitoring, via **Monitored Variable Lists** (MVL), and for control, via **Controlled Variable Lists** (CVL).

MVLs can be transmitted in a cyclic manner, whenever a variable changes, or only on request.. The type of transfer can be changed dynamically by the STC. When transmitted "on change" only the modified variables are transferred. This feature is also used to inform the STC of **spontaneous events** occuring on the subsystem. CVLs can be used to program a complete table or to set individual parameters only. The grouping of variables in MVLs and CVLs can thus be used to optimise the traffic on the M&C interface.

2. A more detailed description including the M&C interface can be found in [YD96]

STATION MANAGEMENT LAYER

The task of the station management layer is to present the complete station and provide means to control the complete station in a form suitable for operations. This implies that the STC M&C application must be able to adapt to the specific station design and especially to the needs of the missions that are supported by a station. It must particularly

- provide a context sensitive alarming scheme;
- derive condensed high level information from the data delivered by subsystems;
- present functional elements such as a "processing chain" by combination of information from various subsystems;
- combine subsystem monitoring and control with spacecraft specific information;
- provide means to implement procedures to configure the complete station before a spacecraft pass, change configurations, initiate subsystem activities, etc.;
- support schedules which initiate and control pass operations in a timely manner.

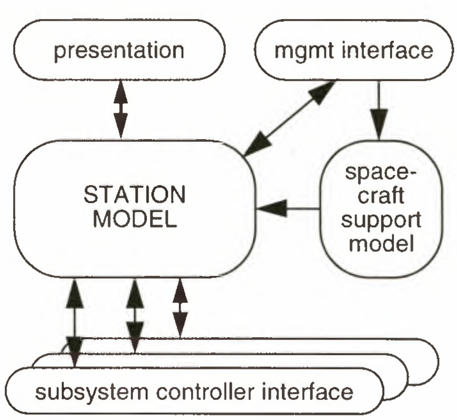

Figure 3. Structure of the STC M&C application (simplified)

For the purpose of the current discussion the structure of the STC M&C application can be presented as shown in figure 3. It contains a subsystem controller interface model for every subsystem in the station, a spacecraft support model, and a station model which provides a combined view of the complete station. The station model in turn is used by the presentation layer which supports the operator interface and can be accessed by higher level management entities, namely the ESMS.

The construction of the station model follows the same principles as described for the subsystem model. The essential difference is how dynamic attributes and operations of elementary classes are defined. In the subsystem dynamic attributes, such as the value of a variable, are determined by what the equipment delivers, and the actual task performed by an operation is defined by the implementation of the real equipment. In the station model the value of every dynamic attribute is specified by an "**algorithm**", an instance of a special class which defines how the value shall be determined. Operations on objects are specified by "**procedures**", instances of a class that allows to define sequences of elementary functions executed within a user defined flow control

Both algorithms and procedures are specified in an application oriented high-level language, the "**Station Tailoring Language**" (STL). STL source code is compiled into a format that can be stored to the configuration data base, loaded, and processed during operation of the system. The variables in STL are attributes of objects in the station model, the actions in STL are procedures or operations on objects in the station model.

Algorithms are expressions that return a result of a specific data type. The operands are either variables received from a subsystem or attributes of objects in the station model. They provide all arithmetic, logical and bit-manipulation operators; built in functions provide trigonometrical calculations, data conversion etc., such that virtually any form of data processing can be implemented as long as it does not have any side effects. An example for an algorithm specification is shown in figure 4.

A procedure can be viewed as a user written program which is executed by the STC M&C application. STL supports all standard flow control features and provides means to:

- specify input arguments including their representation on the MMI;
- request setting of variables and other operations on objects in the subsystem interface;
- verify conditions in the station model using logical expressions;
- call sub-procedures
- issue messages to the logging system and alerts to the operator.

Access to functions provided by the software of the STC M&C application is provided through "system calls", which gives the procedure programmer full control of the system and allows to implement more time critical or processing intensive functionality in software when needed.

Use of procedures is not limited to operations on individual objects in the station model. Procedures can be defined independent from such objects and can be used to configure a station for support of a given mission, for specific tests, or any other purpose.

```
-- algorithm for a parameter
-- value which reads in a
-- variable and applies an offset
-- defined by another parameter

  MVAR(FEC/TRRX/FRQ.VAL) +
    STN/CONF/P12.VAL;

-- algorithm for an alarm on a
-- PLL of a receiver which
-- checks whether a spacecraft is
-- being tracked.

  select
    %ALARM when
       $.VAL = %NOT_LOCKED and
       FEC/TRK.VAL = TRUE;
    %OK when
       ($.VAL = %LOCKED and
        FEC/TRK.VAL = TRUE) or
       ($.VAL = %NOT_LOCKED and
       FEC/TRK.VAL = FALSE);
    %WARNING otherwise
  endselect;
```

Figure 4. Examples for Algorithms

The basic element of the station model is a "**parameter**" which describes one monitored and/or controlled variable. It is similar to a variable in the subsystem model but provides the following enhancements: The value of a parameter is defined by an algorithm which can simply copy the value of a SS-variable, combine it with values of other parameters, or derive the values from any combination of attributes of other instances in the station model. A parameter also defines an optional alarm attribute the value of which is also defined by an algorithm, providing the same flexibility as for the parameter value. Parameters are able to issue a "value change report" and an "alarm change report" which are entered to the station log. Operations on a parameter include features to enable or disable monitoring, alarm monitoring, generation of reports and to acknowledge alarms. If the parameter is controllable an operation to set its value is specified using a procedure.

The station model includes a set of container classes which allow for simple parameter grouping, definition of functional units and description of **devices**. The device class models a hardware unit in the station and is capable of describing both a subsystem and a subsystem unit. Further, more specialised classes are available, a description of which is beyond the scope of this report.

The **event management** scheme of the STC M&C application is a straight forward extension of the station model. An event condition is specified as an algorithm with a boolean result and evaluated whenever one of the operands of the algorithm changes. When the result differs from the last evaluation, the event is considered to have occurred and one or more procedures are executed, which have been specified as event actions. The occurrence of an event is logged using a configurable log message. Events can be enabled and disabled during operations.

The construction of the station model includes definition of its **presentation** on the operator workstations.

The first level presentation consists of a set of diagrams. Objects presented on the diagram make reference to the objects in the station model. The dynamics of these diagram objects, i.e. visibility, colour, etc. is again defined using algorithms which provides a maximum of flexibility. Popup menus can be attached to diagram objects, and procedure requests attached to each menu item, which enables the operator to control the station primarily via the station diagrams. Due to the fact that procedures have access to system functionality procedures can be defined which display sub-diagrams or more detailed displays.

The second level of the presentation consists of tabular displays which list individual equipment parameters, displaying their values and the alarm state, if applicable. As for diagram objects a menu is attached to every parameter from which the operations on that parameter can be invoked.

Procedures not attached to individual objects are invoked via a main menu, which is constructed by definition of tree structured sub-menus and by attaching procedure requests to each leaf menu item. The operator interface to enter arguments to procedures is automatically constructed from the specification of the input arguments in the STL code.

SPACECRAFT SUPPORT AND SCHEDULES

A spacecraft is a special class in the station meta model. It is associated with an entry in the spacecraft support model containing

- a set of spacecraft specific parameters for equipment setup (frequency, modulation, space-link parameters, etc.) referred to as the "Spacecraft Characteristics Table" (SCCT);
- one or more files with orbit prediction data;
- schedules for station operation derived from the spacecraft schedule.

Orbit prediction data and schedules are downloaded from ESMS or directly from a control centre; the spacecraft characteristics are currently specified as part of the station model.

A station model can contain several spacecraft objects. The "currently supported spacecraft" can be assigned to the complete station or to individual subsystems if a station supports more than one spacecraft concurrently. Procedures can reference the SCCT of the currently supported spacecraft via a special STL construct, which allows to write generic equipment set-up procedures independent of the specific spacecraft parameters.

Schedules are supported by a specific STL statement that can be used in procedures:

```
AT <time expression> DO .. DONE;
```

The <time expression> is an algorithm which results in an absolute time and can take procedure arguments as an input. When an AT statement is encountered the system evaluates the algorithm and then waits for the resulting time. At that time the statements in the block are executed. If the time is in the past, the block is skipped.

This feature allows to design and implement schedule templates for specific tasks of the station, such as pre-pass setup, start of pass operations, configuration for telecommand sessions, post-pass operations, etc. The schedule downloaded to the station consists of a list of procedure requests which invoke such schedule templates, passing the required start-time as a procedure argument. As schedule templates are procedures, they can also be invoked via the operator interface, if necessary.

NOTES ON THE IMPLEMENTATION

Development of suitable software to interactively construct the station model and especially to process the model during operation with sufficient performance is a non trivial task. It has become possible through a strictly object-oriented design, use of an object oriented programming language (C++), and use of an object oriented database management system (ONTOS).

All elementary classes of the station model are implemented by one or more C++ classes and instances are stored into the OODBMS including the references between these instances. The STC M&C application reads these objects from the database into memory; processing is performed by calling the "member functions" implemented by the associated C++ classes. This technique also provides the means to effectively process algorithms and procedures. C++ classes are provided for individual operators and instructions. An algorithm or a procedure is constructed as a tree of "operator-instances" and/or "instruction-instances" which can be stored to the database. These object structures can be directly executed by calling the appropriate member functions of the C++ classes without the need for a special interpreter.

The design also makes sure that calculations are only done when really necessary. The STC M&C application is fully event driven and data are recalculated, transmitted, and displayed only when the input really changes.

CUSTOMISING THE M&C SYSTEM

Definition of a consistent model for the description of station equipment and M&C interfaces has allowed to design a system which will enable the station engineer to specify the station model and the operational procedures as required by the specific station design and the mission to be supported. The process of customising a system is traditionally referred to as "tailoring". Hence this system is called the "**Ground Station Tailoring System**" (GSTS). Its role is illustrated in figure 5.

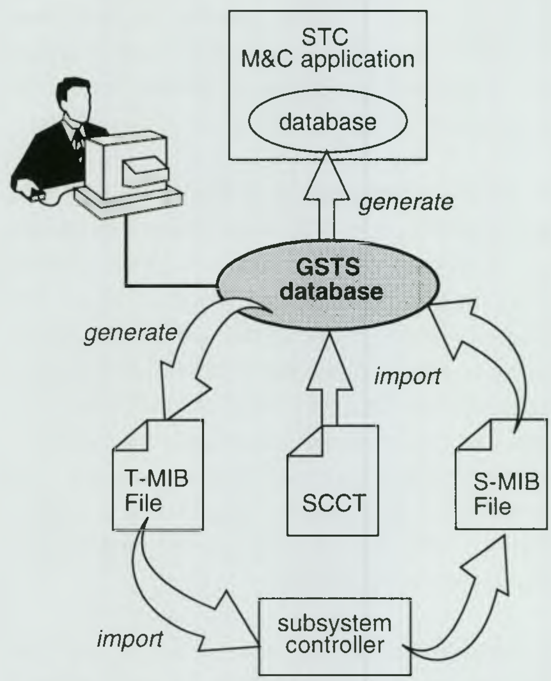

Figure 5. The Ground Station Tailoring System

Input to the tailoring process are the subsystem models. These are made available by the subsystem manufacturer as a text file describing the model in a special data description language. This file is referred to as the "System MIB File"[3]. In some cases the S-MIB file is generated directly from the subsystem database. These MIB files are parsed by GSTS and imported into its database. GSTS is also able to parse and import SCCT files.

The station engineer can now construct the station model and its presentation as described in the previous sections. If required, he can modify the sub-

3. MIB stands for "Management Information Base", a term adopted from OSI/NM

system interface definition and apply limited changes to the subsystem model with respect to the representation on the local MMI. For this task GSTS provides a graphical user interface and extensive support to check user input, trace dependencies between definitions and verify consistency of the model. This is possible, as GSTS stores all definitions as objects and references between objects in an object oriented data base.

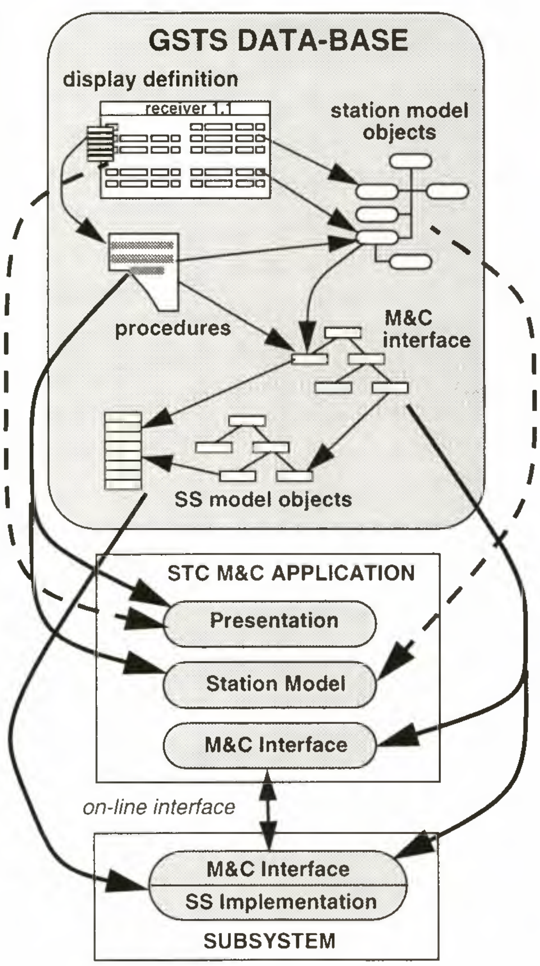

Figure 6. References between elements of the complete model within the GSTS database allow checking of consistency and subsequently generation of configuration data for all systems from a consolidated and validated source.

When the complete model has been verified to be correct and consistent, GSTS generates the database used operationally by the STC M&C application and a "Tailored MIB File" for every subsystem in the station. The T-MIB files are read by the subsystem controllers at start-up and imported into the local configuration database.

STATUS AND EXPERIENCES

Development of the subsystem controllers mentioned in this paper is completed. A beta-test version of the STC M&C application is being finalised and will be handed over to ESOC in the near future. Deployment of the complete M&C system is foreseen in the next year. GSTS is currently in development and is expected to be available for the deployment activities in an initial version.

The modelling approach has been applied for all of these systems and has been found appropriate. Initial work on the ESMS prototype has shown, that it will allow to re-use most of the software developed for the STC for ESMS, as the station meta-model is general enough to describe and present a station and station capabilities within the context of ESMS. In its current form the model exhibits limitations when information structures with a varying number of members have to be described, as is the case in a general definition of a space link protocol profile. This is due to the fact, that the value attribute of variables has been constrained to simple data types. To handle these cases specialised classes will have to be added, once CCSDS standards have become sufficiently stable.

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The results presented in this paper originate from a team effort to which many engineers within ESOC and from industry have contributed. Outstanding contributions have been provided by Y.Doat, G.Theis and W.Hell from ESOC/SCED. Special thanks go to the Cray development teams of the FEC, MCM, STC, and GSTS projects who have brought these ideas to reality.

MAXIMUM ADPE APPROACH FOR A HIGH RATE CCSDS RETURN LINK PROCESSING SYSTEM

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ABSTRACT. The EDOS (Earth Observing System Data and Operations System) program is a multi-mission level zero data processing and distribution system for the Earth Observing System (EOS) satellites and is based on the Consultative Committee for Space Data Systems (CCSDS) protocols. One of the greatest technical challenges for EDOS was to develop and demonstrate a proof-of-concept 150 Mbps CCSDS return link processing capability to support the first EDOS delivery--a time frame of only 13 months from the start of the contract. Although an approach to 150 Mbps return link processing based primarily on general purpose automated data processing equipment (ADPE) had never been demonstrated, the EDOS team believed that the most cost effective solution to this high performance and schedule-aggressive challenge was to make maximum use of existing, general purpose ADPE, and minimize the use of custom hardware. This paper discusses how this technical challenge was successfully met by the EDOS team, and presents key design decisions and performance benchmark results.

Section 1 provides a brief overview of the EDOS functions and the CCSDS services that EDOS provides. Section 2 presents the high rate return link architecture. Details of the high rate return link architecture components that are implemented in developed hardware and the general purpose APDE are presented in sections 3 and 4, respectively.

1. INTRODUCTION

EDOS provides return link and forward link processing services for the EOS missions, beginning with the AM-1 satellite to be launched in 1998. The basic processing performed by EDOS removes space-to-ground communications artifacts from the return link data and delivers the data to customers, and converts the internet protocols to space communications protocols for forward link data. Figure 1 shows the functional architecture of the EDOS system.

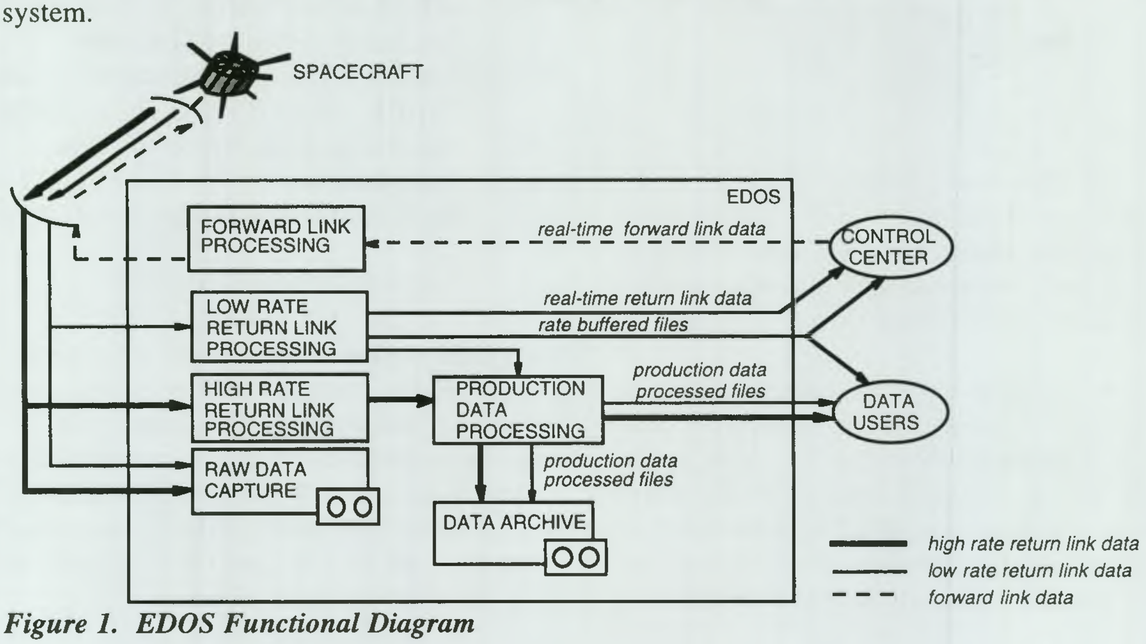

Figure 1. EDOS Functional Diagram

Figure 1 shows that return link data received from the spacecraft are captured as raw, unprocessed data on tape (Raw Data Capture function), and processed by the low rate and high rate Return Link Processing functions. The low rate return link data contain spacecraft health and safety data, and are forwarded in real time to the control center following CCSDS processing. The high rate return link data contains the instrument sensor data; this data undergoes path service processing and is sorted by unique application process identification (APID) and stored in files. These files are then transferred to the control center or data users as rate buffered data, or forwarded to the Production Data Processing function for further processing.

The Production Data Processing function receives multiple packet files from multiple spacecraft contact sessions and merges them into a single data set. The data are ordered by packet sequence number, duplicate data are removed, and missing data are filled with fill packets. The resulting production data sets are delivered to the customer via electronic file transfer or tape. All production data sets are stored by EDOS on archive tape by the Data Archive function.

The Forward Link Processing function receives command link telecommand units from the control center, logs the data, and converts the internet protocol packets into a serial data stream which is then forwarded to the spacecraft.

EDOS Function	Description	Applicable CCSDS Services	Performance Requirements
Raw Data Capture Function	• Store incoming CADUs on tape		• 150 Mbps for high rate channels • Up to 512 kbps for low rate channels
High Rate Return Link Function	• Frame sync • RS decoding • Virtual channel sorting • Packet extraction • Write data to files for each VCID/APID	• Physical channel services (Grade 2 and 3) • Virtual channel service • Path service	• 150 Mbps physical stream • 68,000 packets per second
Low Rate Return Link Function	• Frame sync • RS decoding • Virtual channel sorting • Packet extraction • Deliver data to control center • Write data to files for each VCID/APID	• Physical channel services (Grade 2 and 3) • Virtual channel service • CLCW service • Path service	• 100 bps to 512 kbps • 750 msec delay for real time data
Production Data Processing Function	• Merge APID contact files into data sets • Remove redundant packets • Fill missing packets		• Average aggregate rate of 27.3 Mbps • Up to 24 hours per single data set • Deliver files at 68 Mbps
Data Archive Function	• Write data sets to tape manage tape archive		• Store 200 GB/day on tape
Forward Link Processing Function	• Receive commands • Authenticate source • Serialize data	• Physical layer processing	• Up to 10 kbps • 350 msec latency

Figure 2. EDOS Services and Performance Requirements

Figure 2 presents the applicable CCSDS services and provides the associated performance requirements for each of the EDOS functions described above. The EDOS return link processing function is based on the Advanced Orbiting System (AOS) CCSDS specification and provides both Grade 2 and Grade 3 services. EDOS processing is data driven in that it uses descriptive information contained within the data elements to perform the data processing. The only a priori information required to set up processing is the channel access data unit (CADU) related processing parameters (e.g., frame size, grade of service), and the mapping of what customer-selected services apply to which virtual channels and APIDs. Prior knowledge of packet sizes, or whether or not an individual packet channel will be active in a particular contact, are not needed for EDOS to accomplish return link processing.

Figure 2 shows that the highest performance requirements are associated with the high rate return link function, and these high performance requirements presented the greatest technical challenge for the EDOS project. The remainder of this paper describes in detail the innovative solutions that the EDOS program employed to develop a working end-to-end prototype of the high rate return link function in a 13 month time span.

2. SYSTEM DESIGN

In order to minimize the life cycle cost, development risks, and development schedule for the EDOS return link processing components, three major principles were followed:

- adopt a common approach to high and low rate processing
- minimize the use of developed hardware / maximize the use of general purpose computer equipment and commercial off the shelf (COTS) products
- use industry accepted standards and technologies

The benefit of adopting a common approach to high and low rate processing is that it allows reusability of developed components, reducing the development cost and schedule, and the cost of maintaining and evolving the system. For the return link processing function, the key challenge to achieve this principle is to design a system responsive to the different performance requirements for high and low rate return link channels. The factors driving the high rate processing design include high packet throughput rate and large data volume; the factor driving the low rate processing design is the low (750 msec) throughput latency.

When compared to the use of custom developed hardware and software, using general purpose computer equipment and COTS software provides a mitigation of technical and schedule risks. Software written for a general purpose computer has a much faster product development cycle than developing custom hardware and application specific integrated circuits (ASICs). Rapid prototyping is easier using software on a general purpose computer, and any errors can be quickly corrected. In custom hardware, prototyping is a much longer process (e.g., developing limited runs of custom chips and boards), and fixing mistakes can be very costly, especially in the later stages of the testing phase. Also, using general purpose computers allowed EDOS to make use of the wealth of expertise from the major equipment vendors (e.g., Silicon Graphics, IBM, Digital Equipment), and the product benchmark results and documentation, to achieve a rapid understanding of the details of the components to be used for the return link processing system.

The benefit of using industry accepted standards and technologies allows the system to be more cost effective in the development and life cycle phases. In the development phase, using industry accepted standards and technologies which are vendor-neutral (as opposed to vendor-specific or proprietary technologies) allows one to select the particular product with the lowest cost from a wide selection of similar products that all meet the same interface. During the sustaining engineering phases of the system, industry accepted, widely used standards are typically longer lived, have continued support, and if they do change will likely have industry supplied upgrade paths--all of which lead to a generally lower maintenance costs.

EDOS employed each of the three principles discussed above to derive the system design for the return link. The resulting return link architecture is presented in Figure 3.

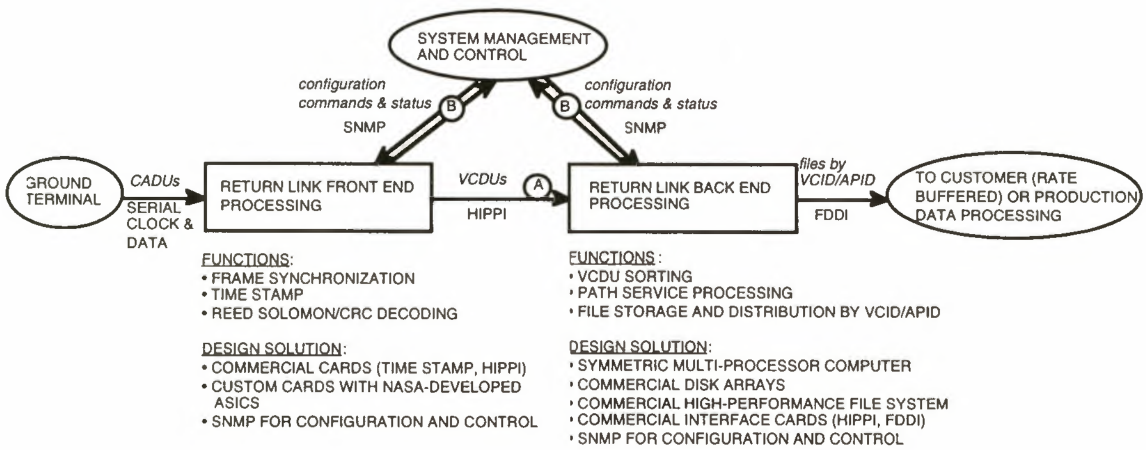

Figure 3. High Rate Return Link Architecture

Figure 3 shows that the EDOS return link processing thread is architected into two major components: return link front end processing, and return link back end processing.

The front end processing component includes those functions that cannot be implemented in a general purpose computer: frame synchronization and Reed-Solomon decoding. These processing-intensive functions use specialized algorithms that require multiple calculations on each bit of data; an implementation on current general purpose CPUs can only perform these functions at rates close to 10 Mbps--not the required 150 Mbps for high rate return link processing.

The back end processing component performs processing functions which can be effectively hosted on a general purpose, high performance multiprocessor computer. These functions include virtual channel and path service processing and data distribution. Several innovative techniques were employed in the algorithm to process the data at 150 Mbps using the symmetric multiprocessing architecture; these are discussed in detail in Section 4.

There are two primary internal interfaces for each return link architecture component: the interface between the front end and back end components to exchange the return link VCDUs (interface A in Figure 3), and the interface between the return link processing components and the management interface to pass statistics and control information (interface B in Figure 3.) The interface between the return link front end and back end needs to be based on a standard supported by both VME component vendors (in order to be integrated into the front end subsystem) and by high performance computer vendors (in order to be integrated into the back end computer). The interface also must support data rates of at least 150 Mbps, employ minimal processing overhead, and be an industry-accepted standard. The only interface that met all of these criteria was the High Performance Parallel Interface (HiPPI). HiPPI is supported by most of the high performance computer vendors and is also available as VME cards for integration into the front end. HiPPI, which supports rates of up to 800 Mbps, has an extremely low processing overhead, as the standard was designed for computer to peripheral data exchanges.

The interface between the management and control function to the return link front end and back end components (interface B) was also selected using the engineering principles that were discussed above. A common approach for both front end and back end components was desired, and one that was based on industry standard protocols to allow the integration of a COTS management framework (e.g., IBM NetView or HP OpenView). The protocol selected was the simple network management protocol (SNMP). This protocol, which is the industry standard for managing network devices, was used by EDOS to manage both the custom developed hardware components (return link front end), the ADPE components (return link back end), and the CCSDS-specific processing services. This solution allows an integrated approach for system computer human interface (CHI) development--a single CHI can display all hardware and software status and control and event logging. Extending the

SNMP standard (which was developed for internet communication management) to monitor CCSDS services is a quite natural extension. Managing a CCSDS communications service, which require collection and display of frame-level statistic (e.g., # frames/sec, # frames/virtual channel, # frames that failed decoding) is conceptually no different than managing the internet service that the standard SNMP monitors and configures. Both protocols are communications protocols that can map to the International Standard Organization (ISO) seven layer communication model.

The following sections describe in greater detail the design of the EDOS return link processing function.

3. DEVELOPED HARDWARE COMPONENT (FRONT END)

As stated previously, the fundamental approach employed to meet the 13 month demonstration schedule was to limit the functions implemented in custom hardware to only those which couldn't meet the 150 Mbps processing rates when implemented in software running on a general purpose computer. The frame synchronization and Reed-Solomon decoding functions are the only two functions that must be implemented in custom hardware to meet 150 Mbps throughput rates. These two functions are performed by the Return Link Front End component using a combination of custom developed cards and COTS cards.

The first design decision for the front end component was to select a data bus technology. (The data bus exchanges data and control between the COTS and custom processing cards of the return link front end component.) To minimize development risk, a VME64 bus was selected because of its maturity and high data throughput rates. Also, several vendors supply off-the-shelf VME64 interface chips for integration onto the custom boards.

Figure 4 shows the resulting return link front end detailed design. It consists of three COTS processor cards: a Master Controller card for overall control, a Time Reference Decoder card for external time source translation, and a HiPPI Interface card with an ethernet daughter board for high rate and low rate data outputs, -- and two custom developed cards: a Reed Solomon card and a Frame Sync card, -- all interconnected by the VME64 bus.

3.1 COTS CARDS

The Master Controller card provides overall control of the return link front end component, translating commands received from the EDOS system management and control function to individual card-level control signals. It is implemented with a Motorola MVME162 product (a 68040 based general purpose single board computer with ethernet and SCSI interfaces.) VxWorks provides the real time operating system for the Master Controller card and was selected because of its UNIX-based development environment, mature networking package, and the availability of a COTS SNMP interface. The Master Controller card does not processes any return link data, so the total VME traffic from this card amounts to less than 1% of bus utilization.

The Time Reference Decoder card is implemented with the Odetics TPRO-VME product. This card was chosen because, in addition to having IRIG-B input capability, it has an option of formatting and outputting time via a VME J2 connector that is normally user configurable in VME specifications. This option is important because the time signal is constantly being distributed to other cards, and it is not desirable to have the associated data volume contend for the available VME bandwidth with control, status, and return link mission data.

The HiPPI Interface card transfers the return link data to the return link back end component and is implemented using the Myriad Logic HIPPI-830 product.

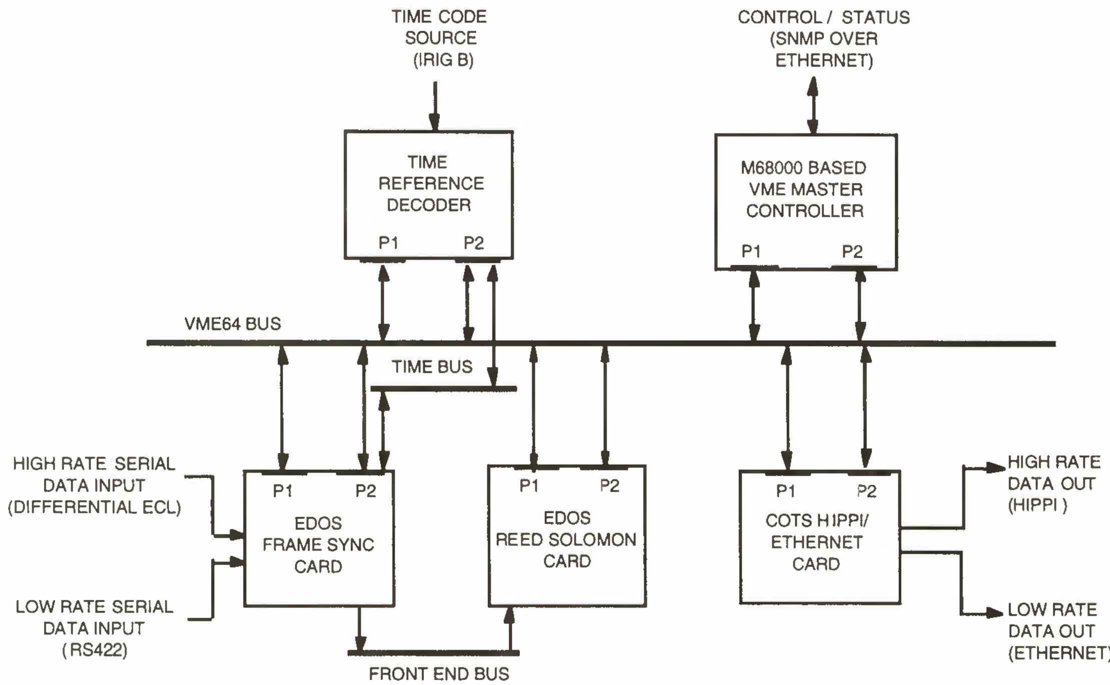

Figure 4. Return Link Front End Design

3.1 CUSTOM CARDS

The frame synchronization card is a 6U VME card capable of performing data processing at 150 Mbps. The card was design to perform all CCSDS recommendations related to frame synchronization functions. The four primary functions allocated to this card are frame synchronization, CRC checking, pseudo random noise (PN) removal, and frame time stamping. The statistics that are collected by this card during data processing include synchronization status and the numbers of frames received, frames with cyclic redundancy check errors, frames with bit slip, and frames with false polarity.

After the CADUs are synchronized by the Frame Synchronization card, they are transferred into Reed-Solomon card through a front end parallel bus. The Reed-Solomon card is also a 6U VME card with master and slave data transfer capability over the VME64 bus. A Reed-Solomon ASIC performs error correction based on CCSDS frame [RS (255,223)] or frame header [RS (10,6)] codes. After the decoding is complete, an EDOS-specific status header is updated based on decoding information derived from the error correction process and the data are moved into a memory buffer. The buffer is configurable from the size of a single frame to 512 Kbytes; the configuration is selected based on real time delay requirements and VME to HiPPI transfers efficiency. When a transfer into the memory is complete, the Reed-Solomon card issues the interrupt on VME bus and the HiPPI Interface card responds by initiating the direct memory transfer to its own memory and then on to the Return Link Back End component.

Because there were no COTS cards available to EDOS that perform 150 Mbps CCSDS processing when the EDOS project began, one of the greatest technical challenges associated with the return link front end development effort was the selection and implementation of necessary components for building the custom cards.

The Frame Synchronization card is implemented with a serial correlator chip and frame synchronization controller chip. Although there are several commercial suppliers of correlator chips for data rates up to 35 Mbps, the only chips capable of operating at 150 Mbps were ones previously developed by NASA/GSFC. Through the NASA technology transfer vehicle, the frame synchronization controller was available from a foundry and was used by EDOS. However, the serial correlator ASIC was obsolete; it was previously implemented in an emitter coupled logic (ECL) gate array that was no longer supported by an ASIC foundry, and there were not enough components in stock to support the EDOS program and have an ample supply for spares. There were two alternatives to the EDOS project for implementing the serial correlator chip: develop a new chip using a modern ASIC technology, or use field programmable gate arrays (FPGA) technology to implement a 4 bit parallel correlator with only simple glue logic implemented in ECL.

The drawback of developing a new ASIC chip is that it takes a considerable amount of time to design the chip and then start a fabrication run at a chip foundry. There is always the risk that the chips from the initial run do not work properly, and the process of design and fabrication must occur over again. And this process is usually only cost effective for a large quantity of chips. The FPGA approach eliminates these risks. Since a foundry is not required to implement an FPGA component, but is instead "programmed" at the site, the time to develop, test, and refine the component is much less. The FPGA approach for the developing the correlator chip was an important decision that allowed the return link front end development effort meet the 13 month schedule.

The Reed-Solomon card makes use of existing ASIC components that were developed by NASA/GSFC and made available as part of NASA technology transfer program.

4. ADPE COMPONENT (BACK END)

The challenge in constructing the return link back end component was to develop an algorithm that effectively used the symmetric multiprocessor architecture found in modern high performance computers. Figure 5 shows the resulting algorithm. The circles represent the actual software processes; the squares represent the CPUs that host the specific processes.

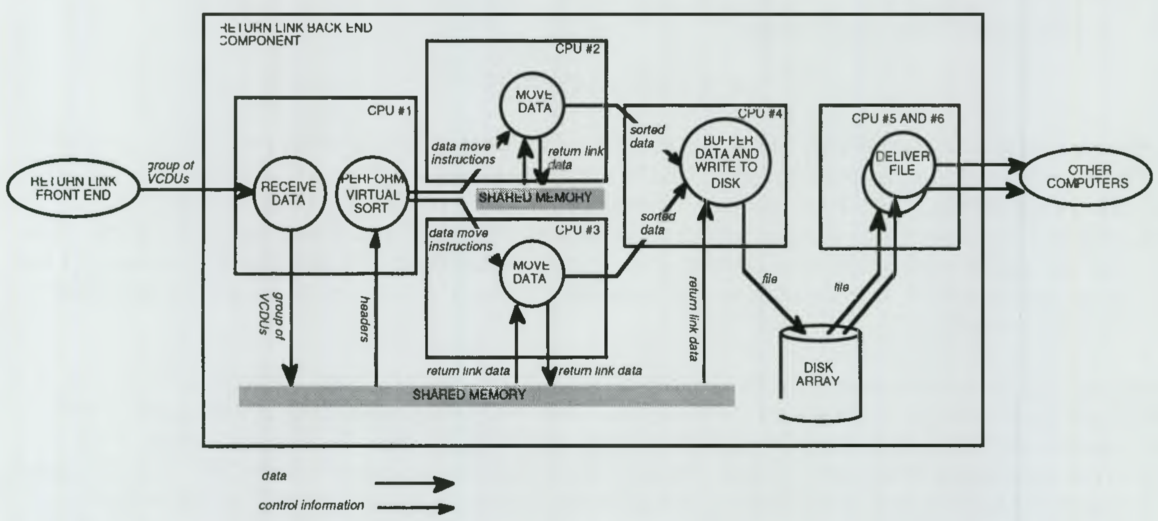

Figure 5. Return Link Back End Software Architecture

The Receive Data process receives a group of VCDUs from the return link front end hardware via the HiPPI interface and stores the data into the computer shared memory. The Perform Virtual Sort process processes the group of VCDUs by extracting just enough information from each VCDU to perform the VCDU and path service processing; this information includes the VCDU header and multiplexing protocol data unit (M_PDU) header. (For virtual channels undergoing path service processing, this process also extracts the packet headers.) The Perform Virtual Sort process then analyzes the headers and creates a set of instructions on how to sort the data, but no data are moved by this process. In addition, some quality and accounting information is appended to each data frame (VCDU or packet) in an EDOS service header. The information for the EDOS service header is written to another location in shared memory, and instructions for eventual placement in the front of each packet are added into the data move instructions.

The data move instructions are then split into two segments and passed to multiple Move Data processes. These processes take the byte-level data move instructions and move each data segment into one of the VCDU or packet buffers (there is one buffer for each unique virtual channel or packet channel). The Buffer Data process manages these data buffers and writes the data to disk whenever a 3 MByte write block is accumulated. Multiple processes are needed to achieve the 150 Mbps rate, as the Data Move process is CPU intensive.

Following the end of the spacecraft contact session, the Deliver File processes use the ftp protocol to distribute the collected data to the customer (rate buffered service) or to higher level of EDOS processing (production data processing service.) Each concurrent ftp session requires a separate Deliver File process; multiple concurrent processes execute on two CPUs to achieve the 68 Mbps requirement.

The algorithm described above has several features that allow it to achieve extremely high data throughput rates. One feature is that data copies within the computer are minimized. Benchmarking results show that data copies (movement from one area of memory to another) consumes more CPU resource than any other processing function. Sustaining a return link rate of 150 Mbps requires a tremendous amount of data moving through the computer, and each copy adds another 300 Mbps of data to the shared memory bus (150 Mbps for the read, and another 150 Mbps for the write). The algorithm minimizes data movement by operating just on the headers of the VCDUs and packets, making use of the CCSDS fixed VCDU size for a given physical channel to easily extract all of the headers in a group of VCDUs. The algorithm uses just one copy (performed by the Move Data processes) during return link processing.

Another efficient feature of the algorithm it is that it operates on large data groups rather than individual frames. The Receive Data, Perform Virtual Sort, and Move Data processes all operate on a group of VCDUs that have been buffered by the return link front end component. This group of VCDUs is a tunable parameter; benchmarking activities have determined that a size of 0.5 MB (about 500 VCDUs for 8160 bits/VCDU size) works well with the amount of secondary cache in the SGI Challenge XL. Data are also buffered by the Buffer Data and Write to Disk processes. The Silicon Graphics XFS file system and the disk array architecture give much better performance when the data for a disk write is in a large buffer (on the order of a formatted disk block) rather than the size of a single VCDU or packet. By buffering the data into 3 MByte blocks before making a write request, we were able to reduce the number of SCSI controllers, and the cost, of the disk array subsystem.

Figures 6 shows the hardware configuration used in the benchmarking system. Figures 7 and 8 provide actual benchmark results.

Component	Vendor, Model
Computer Chassis	Silicon Graphics Inc., Challenge XL
CPU specification	MIPS R4400, 200 MHz
Number of CPUs	6 CPUs
RAM	512 MB
Disk Array	Ciprico, 3 SCSI-2 arrays of 17 GB each (51 GB of array)

Figure 6. Return Link Back End Hardware Configuration

Figure 7 shows the percent CPU utilization for the Receive Data and Perform Virtual Sort processes (CPU #1), and the Move Data processes (average of CPU #2 and CPU #3) as a function of packet rate. For this benchmark, the data rate was fixed at 150 Mbps; the packet rate was varied by making the average packet size smaller or larger. Figure 8 shows the same utilization but as a function of data rate, with a constant packet rate of 19 kpackets/sec maintained for each measurement.

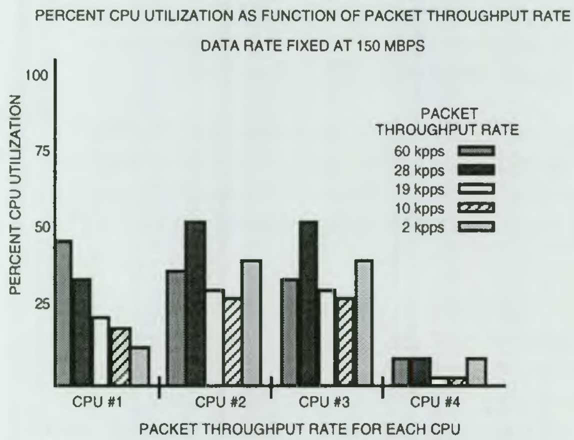

Figure 7. Sensitivity of Return Link Back End to Packet Throughput Rate

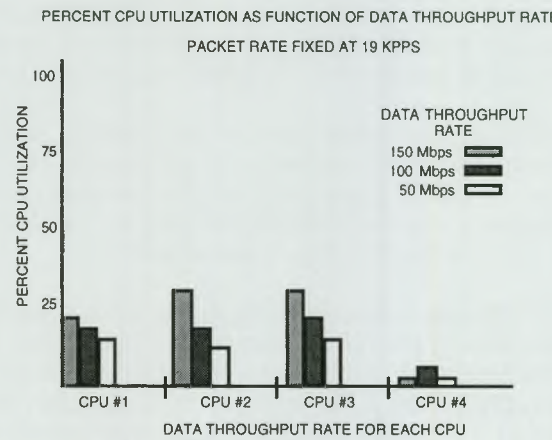

Figure 8. Sensitivity of Return Link Back End to Data Rate

The key result demonstrated by the benchmarks is that the Perform Virtual Sort process (CPU #1) is most sensitive to the packet data throughput rate, while the Move Data process (CPU #2 and CPU #3) is most sensitive to total throughput rate. This is because the Perform Virtual Sort executes a fixed number of CPU instructions per each VCDU or packet, while the Move Data processes are independent of the CCSDS protocol constructs and execute a fixed number of CPU instructions per each computer word (64 bits).

The benchmark results also show that the EDOS return link algorithm effectively splits the processing between the available CPUs. No CPU is more than 55% utilized, and the processing is equally split between CPUs #1, #2, and #3. (Note that the processing allocated to CPU #4, which on the average is no more than 10% utilized, cannot exist on one of the other CPUs. This is because the Buffer Data and Write to Disk process, which resides on CPU #4, consumes sufficient resources when it writes the 3 MByte data block to the disk array so as to interfere with the real time nature of the Perform Virtual Sort and Move Data processes.) To achieve higher rates, additional Data Move processes can be added to the system. Benchmarks using the 4-CPU configuration have demonstrated over 350 Mbps path service processing and over 200 kpackets/sec. For lower throughput rates, the processes can be hosted on fewer number of CPUs. In fact, for the EDOS low rate processing string, the same algorithm is hosted on a SGI uniprocessor computer and can achieve rates of up to 3 Mbps.

5. CONCLUSION

This paper provides an approach for selecting a high performance data processing system architecture that minimizes development cost and schedule risk. The major tenet of the approach is to implement the majority of functionality on general purpose computers, and only the absolutely necessary portion in developed hardware. For a high rate return link telemetry processing system such as EDOS, an approach based on general purpose computers has become feasible only in the last few years with the availability of high performance multiprocessors, disk arrays, interface cards, and file systems. A custom hardware approach may still be preferred if the application requires the production of hundreds of units, but for limited unit applications the maximum ADPE approach provides the most cost effective solution.

As a last example of our approach to implement functionality in general purpose computers, the EDOS program has plans to replace the custom developed low rate front end with developed software hosted on a general purpose workstation and a COTS serial interface card in a future EDOS configuration. All functions currently performed in the low rate return link front end will be performed on workstation. This will provide the EDOS program with further savings in acquisition and sustaining engineering costs.

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HOW EMERGING TECHNOLOGIES ARE CHANGING THE RULES OF SPACECRAFT GROUND SUPPORT

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ABSTRACT. As part of its effort to develop the Flight Dynamics Distributed System (FDDS), the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) Flight Dynamics Division (FDD) has established a program to continually monitor developments in computer and software technologies and to assess their significance for building and operating spacecraft ground data systems. This paper reviews five technological trends in the computing industry and explores their significance for the spacecraft ground support industry. The paper provides examples from our experience in the GSFC FDD of how each of these technologies has already affected the FDD's way of doing business, and extrapolates their likely impact on future ground systems and operations.

1. INTRODUCTION

Technological innovations change the ways in which people organize and carry out work, sometimes in fundamental and unexpected ways. In recent years the spacecraft ground support industry, like many others, has been altered by rapid technological change. Advances in computing power, software development techniques, high-end flight qualified microprocessors, and other technologies will continue to revolutionize the ways in which ground support organizations do business. To remain economically viable, these organizations must be able to quickly adapt to and take advantage of new technologies.

How can we anticipate the consequences of technological change? Hammer and Champy (1993) recommend casting the question in terms of "rules." They ask, what are the technological breakthroughs that are enabling the greatest change, or disrupting the status quo, in a given industry? Which old rules are they breaking, and what are the new rules that seem to be emerging in their place?

In this paper, we use this technique to examine five aspects of computing technology that we find to be the most significant drivers of change in the development of ground data systems. Our observations arise from recent experience at the GSFC FDD, and from studies the FDD has conducted to support the next generation of flight dynamics software. We present an assessment of how we expect these technologies to change the development of space ground systems in the future, and how these changes will affect support organizations. We also extrapolate our results from the flight dynamics domain to the broader ground data systems community.

2. FIVE TECHNOLOGIES THAT ARE CHANGING THE RULES OF SPACECRAFT GROUND SUPPORT

Table 1 summarizes the five technologies we examine in this paper and our observations on how they are changing the rules of spacecraft ground support. Additional information on the how advances in these technologies have utilized in the FDD's ground support systems may be found at the FDD web site, http://fdd.gsfc.nasa.gov/FMET_FDDS.html.

Table 1. Five Technologies That Are Changing the Rules of Ground Support

Technology	Type of Change
Computing Hardware	Computing power continues to get cheaper and more portable
Distributed Object Computing	Interoperable software can be distributed as desired
Internet	Commercial networks can support ground data systems cheaply
Automation	Systems are optimized for autonomy, not human intervention
Software Development	Development power is shifting toward integrators and end users

1. Computing Hardware Technology

According to a recent review article (Patterson, 1995), microprocessor performance will double every 18 months through the turn of the century. With the time between inception and launch of some spacecraft today targeted at 12 to 18 months, a ground system project could see an order of magnitude improvement in computing capacity during its lifetime. Related technologies such as storage and high-bandwidth communications (wire, optical, and wireless) are likely to keep pace.

Old rule: Ground system computing hardware is big and expensive.—In the past, options for delivering the performance necessary for spacecraft ground support were limited to mainframe computers and dedicated communications networks. Only institutions such as multimission centers or long-term project organizations could afford to buy and operate these. This technical reality and the existence of these organizations in turn drove the partitioning of requirements and the design of support systems.

New rule: Ground system computing hardware is portable and cheap.—Spacecraft ground support systems still require high-performance computing hardware and high-speed networks, but such equipment is available from many vendors and is very inexpensive by historical standards. Workstations, computer servers, and file servers can host an entire ground system and are within the means of a small project. This makes great cost savings possible, but requires changing the established patterns of partitioning requirements among institutions. Ultimately all computing support for the mission could be consolidated into a single environment, conceivably on a desktop computer or even on the vehicle itself.

Experiences at GSFC: There has been a pronounced shift from mainframe computing to network computing in recent years. At GSFC, the effects have been a blurring of the boundaries of subsystems (command and control, science data processing, flight dynamics) requiring the reengineering of support organizations. Such reengineering could potentially result in missions that could fly without direct NASA involvement after launch (Macie and Denzler, 1995). The organizations that traditionally built and operated the elements of ground support systems are becoming centers of expertise, system integrators, or "vendors" of ground system components.

Expectations for the future: A continuation of this trend could result in a redefinition of the spacecraft ground support system itself. The placement of hardened commercial processors on the spacecraft (as opposed to NASA/DoD developed processors such as NSSC and MIL-STD 1750A) opens the prospect of moving routine ground system functions on board. We can probably expect the equivalent of today's most powerful workstations to be aboard spacecraft in a few years. On the ground, the trend is from mainframes to workstations and from workstations to PCs, with PCs expected to be as powerful as today's workstations and fully interoperable with the next generation of workstations. The end result is a redistribution of functionality made possible by distributed computing power. The power will be brought directly to the hands of the end user, or placed on the spacecraft itself.

While the initial cost of workstations is much lower than that of mainframes, mainframes stay in service longer. Workstations may have to be replaced every 2 to 3 years to keep up with the needs of commercial software (increasingly important to ground support systems, as discussed under point 5 below). Little incentive exists for the software marketplace to support outdated equipment. If project budgets cannot accommodate this reality, ground systems will have to live with outdated and unsupported versions of software to keep the mission going.

2. Distributed Object Computing Technology

Distributed Object Computing represents the junction of three leading-edge technologies: distributed computing, client-server architectures, and object orientation.

Distributed computing offers a way to achieve the maximum benefit from investment in computing platforms, by allowing applications to execute wherever the available resources and circumstances dictate. However, distributed computing introduces many communication, coordination, and administrative problems.

Client/server architectures are the most widespread approach to implementing distributed systems. The earliest version of client/server was the 2-tier model, in which a client program on a workstation or personal computer accessed a server hosting a database. Three-tier architectures add a middle "application server" layer. This increases flexibility, but adds complexity.

Object orientation is a strategy that promotes the development and reuse of highly integrated, self-contained software objects (for example, a C++ object or class library). This approach can produce robust, maintainable software, that can quickly be assembled into applications. However, the capability to distribute objects across a network has to date been very limited.

Distributed object computing is the emergence of object orientation into the distributed computing environment, and the use of object-oriented techniques in turn to manage the complexities of that environment. Industry standards such as the Common Object Request Broker Architecture (CORBA) and supporting tools promote vendor and language neutrality. The field is developing rapidly as languages such as Java are introduced to take full advantage of distributed computing hardware.

Old rule: Ground system elements must be centralized in facilities.—Because distributed systems were expensive to build and manage, major ground system elements were centralized within dedicated or institutional support facilities. Choices of hardware, vendor, and language placed bounds around the system elements. Distributable software objects simply did not exist.

New rule: Ground system elements can be centralized or decentralized as desired.—Ground systems can be built from interacting objects distributed across platforms. Distributed objects allow centralized implementations (i.e., reuse) but decentralized operations. The system can be distributed across a loosely coupled network of physical resources. The ground support "facility" as such is not necessary. Systems can be either centralized or decentralized as desired, and can be constructed from modules built by different vendors using different languages.

Experiences at GSFC: The basic elements of distributed object computing are being incorporated into the design of FDDS. Client/server architecture is being introduced as mainframe applications are migrated to a distributed environment. Object orientation has proved beneficial in achieving high reuse; the Generalized Support System (GSS) is an FDD initiative that provides a class library of reusable flight dynamics functionality. However, actually distributing objects across platforms has proved elusive. Experiments in applying CORBA to GSS show that it is easier to use CORBA to tie large application programs together than to apply the model to an existing class library structure. Also, industry support for CORBA products and tools is still relatively limited.

Expectations for the future: Within 5 years, we expect that distributed object computing will mature and will have profound effects on the development of ground systems. Market forces will drive vendors to adopt industry standards and provide compatible products. The standard that gains acceptance may be CORBA or a competing approach such as Microsoft's OLE/COM, but *some* standard will become prevalent. By enabling software written in different languages and running on different platforms to interact, the technology will tend to further decentralize operations. It will also increase the need for software components that are packaged for reuse.

3. *Internet: Connectivity That Is Global and Public*

Spacecraft ground systems have always required global connectivity to support tracking data collection and widely dispersed teams of principal investigators. A generation ago this implied a dedicated communications infrastructure. When the Internet (essentially "cheap and easy" TCP/IP) matured and gained a large customer base, the economics of global connectivity changed. Although it took decades for this technology to reach the point of explosive growth, from an outside perspective it is as if the Internet suddenly burst on the scene as a potential replacement for the much more expensive solutions of the past.

Old rule: Dedicated, closed communications networks are required for ground systems.—Sharing data across geographical distances was expensive and required a specialized communication infrastructure (closed networks: special lines, protocols, and organizations).

New rule: Commercial, open communications networks can support ground systems.—Today, sharing not only data but functionality across geographical distances is increasingly easy and inexpensive using the worldwide hardware and software communications infrastructure. Existing infrastructure can sometimes be bypassed, replacing a traditional segment of ground support systems. A "facility" need not be contained in a building or even a geographical region.

Experiences at GSFC: Since July 1995, the FDD has operated a product center on the world-wide web (http://fdd.gsfc.nasa.gov/FDD_products.html) that makes selected institutional products accessible to customers. The use of this product center has steadily expanded, and provides FDD with a very cost-effective alternative to more traditional means of product distribution. A flight dynamics process center is the next logical step and is now being investigated. By coupling Internet technology with the technologies of distributed object computing (Java, CORBA), this will allow the distribution of not just data, but functionality as well.

Expectations for the future: Businesses are now using the Internet for mission-critical applications. Ground system use will grow in this direction as well. Problems such as availability and security, which restrict the use of the Internet in critical applications, will be solved through commercially available products that apply technologies such as digital signaturing. While dedicated lines will always be needed for some purposes, such as spacecraft commanding, economics will hold these to a minimum. Market forces will make user-friendly tools for building web interfaces cheap and widely available. The overall trend is toward the use of commercially available solutions, not specialized solutions for a particular organization or even the ground support industry. These developments make large-scale distributed systems economically feasible, but they do not reduce the engineering problem. They provide are more options and design possibilities that must be sorted out.

4. *Automation Technology*

The technologies discussed up to this point—more powerful hardware, and tools for distributing data and processing—can be viewed as placing more power in the hands of the user of the system.

Another trend in the spacecraft ground support industry seems to be *replacing* the user: lights-out automation. Of course, humans are still the end users of *any* system (otherwise no need would exist for the system). Automation removes intermediate layers of users by relieving humans of routine tasks. The catch is that the definition of "routine" changes as technology changes.

Old rule: Ground system design should make user interaction easy.—Operating ground systems was labor intensive and required skilled personnel. As a result, system development emphasized highly interactive, user-friendly interfaces. This trend accelerated as the windowing systems and bit-mapped graphics brought Graphical User Interfaces (GUIs) into the mainstream. Organizations allocated large portions of their budgets to building or acquiring user interface tools and the expertise to use them.

New rule: Ground system design should make user interaction unnecessary.—Humans are still the ultimate users, but technology has made routine many of the intermediate operator roles traditionally associated with ground support systems. In place of extensive interactive applications, software is being trusted to "run itself."

Experiences at GSFC: Over the years, the FDD invested in increasingly sophisticated successive generations of homegrown user interface systems. The operational emphasis was on allowing as much interaction as possible, so as to enable intervention in every conceivable contingency. The user interface systems embodied highly specific capabilities based on past needs. The result may indeed have been high-quality operations, but at a large development cost and operating budget. Today much of the user interface capability in these systems is rarely exercised. Tools for automation existed for years in FDD systems, but they were not emphasized until the motive came with increased workload and decreased budget. Our experience with commercial flight dynamics software indicates the same forces at work. Many commercial products emphasize "glitz" and provide sophisticated user interfaces and user capabilities. Automation capabilities are only now being addressed as customers demand them.

Expectations for the future: Flight dynamics software will be increasingly subject to automation. Applications that require high levels of interaction will exist, but they will be primarily in the mission and maneuver planning domains. Eventually the techniques of expert systems, artificial intelligence, and case-based reasoning will come into play here as well. The challenge is to retain the human expertise to intervene where and when necessary. The more automation is relied on, and the less human expertise is available, the bigger the stakes if something goes wrong.

5. *Software Development Technology*

Over the past decade, two trends have dominated software development. These trends may be termed *software process* and *software development tools*. The former emphasizes the disciplined application of methodology to reduce rework and create more maintainable systems, while the latter emphasizes "power tools" that enable rapid application development. At times the contention of the two camps borders on religious warfare, but they are really complementary developments. Process emphasizes long-term savings while development tools focus on short-term savings.

In the specialized market of space ground support systems, a third trend developed recently. Technical and economic forces have spurred the growth of an industry that provides commercial off-the-shelf (COTS) hardware and software products that address the specific needs of ground support. While commercial products such as database systems and network technologies have long been used for building ground systems, the new wave of COTS products provide functionality of the type that formerly required custom development (e.g., orbit determination and maneuver planning). Some vendors even offer complete ground system solutions off the shelf, to be customized for the needs of the mission.

Old rule: Software developers build and maintain custom ground support systems.—Historically, ground support software was tailored to exacting requirements by professional software developers. This was a labor-intensive process. Increased productivity was achieved only through software process improvements and software reuse within an institutional framework. Only by building and maintaining their own software could ground support organizations meet their needs.

New rule: End user programmers integrate ground systems using commercially available components and tools.—Advances in software engineering are putting more power in the hands of what has been called the "end user programmer." Traditional development tools (compilers, linkers, debuggers) are giving way to more powerful tools such as configurable component libraries, Fourth Generation Languages (4GLs) and visual programming kits. The end-user programmer is the generalist who uses these tools to build relatively complex systems. One estimate (Boehm et al., 1995) is that by 2005 the United States will have 55 million end-user programmers, compared to about 2.75 million of the more traditional software development jobs. Depending on mission complexity, the end-user programmer of a ground system element could be an operator or a principal investigator.

Experiences at GSFC: Twenty years ago, ground support software for flight dynamics at GSFC was built by people who were specialists in flight dynamics (trained in physics, mathematics, engineering) but generalists in terms of role (analysis, development, operations). As software systems became more complex and expensive, it became cost-effective to employ software specialists (trained in computer science) as developers, who worked from detailed functional specifications prepared by analysts. Now, technology and market developments are causing the pendulum to swing back toward the former model. The FDD has restructured the way it supports projects, and "developer" is just another role on the integrated mission support team.

The FDD formerly relied almost exclusively on custom software solutions. The Division's Software Engineering Laboratory (SEL) pioneered the "experience factory" approach to developing and packaging process improvements, which led to significant increases in reuse and productivity over the years. However, the focus was always on software development within the organization. Recently, the FDD has learned that it also has much to gain by participating in the software marketplace. Not only does it pay to use COTS products, it is also beneficial to treat in-house legacy software as "marketable" government-off-the-shelf (GOTS) products.

Ground system development in the FDD today exhibits three themes: (1) A class library such as the GSS provides a flexible framework for assembling lower-level, generalized components, provided the component library is populated and the system is built within the framework. In the attitude domain of flight dynamics, the GSS has achieved reuse levels as high as 92 to 98 percent. (2) A commercial development environment achieves lower costs by making code generation easy. The FDD has used Matlab, a mathematically oriented development and run-time environment from The MathWorks, Inc. By providing packaged functions and a user interface for building and running programs, Matlab reduces the need for software expertise on the part of system developers, allowing FDD analysts to directly create operational software. It does not necessarily lead to a buildup of software components engineered for reuse. (3) Package (COTS and GOTS) integration achieves high reuse, provided one is satisfied with the capabilities of the existing packages and a loosely integrated system. In the generation of mission support systems currently under development at the FDD, COTS or GOTS products are the norm, and custom development represents a minority of the work.

An example is the Division's support for Landsat-7. Of the flight dynamics requirements for the Landsat-7 mission, approximately 60 percent will be met by COTS products, 35 percent by GOTS products supplied by the FDD, and only 5 percent by new development (percentages derived from tables in Lorah et al., 1996). COTS solutions are used for orbit determination, orbit planning products, and maneuver planning. GOTS products are used for attitude support. The system also takes advantage of both the GSS and Matlab.

Ground system COTS products and powerful development tools do not obviate the need for continuing software process improvements. Rather, new processes and methodologies that are appropriate to the technology and marketplace are needed, and these in turn demand organizational culture changes. Table 2 summarizes the "Package Based Methodology" now in use at the FDD (Software Engineering Laboratory) and some observations on the culture changes that are needed to make it work.

Table 2. Software Development Process Changes and Culture Changes at the FDD

Process and Methodology Changes	Culture Changes
• Development becomes more package integration than code implementation • New activities are required of the organization (e.g., product evaluation, licensing cost analysis, vendor awareness, maintenance of vendor relations) • Some old activities take on heightened relevance (e.g., architecture definition, trade-off studies, requirements analysis) • Some old activities are de-emphasized or ended (e.g., coding, unit testing, maintenance) • Processes have to be revised to fit changing technologies and marketplace forces (e.g., Package-Based Development)	• Discourage custom software development • Place more emphasis on cost/benefit of using available COTS, less on deriving new software-unique requirements • Be aware of the marketplace (the market is the first place to look) • Do not compete with US industry, but rather enable US industry by transferring technology, establishing need, encouraging participation, and using products • Participate in the marketplace (be more "extroverted" in making needs/wishes known to vendors) • Collaborate with vendors to build/modify commercial products

Expectations for the future: The technologies discussed here only relieve part of the development burden. They do not lessen system engineering and integration needs, but within an appropriate process, they can radically change the economics of software development. Still, COTS products, development tools, and configurable libraries have yet to form a clear framework for ground system development. Available COTS packages are not designed for easy integrability with one another or distribution across networked resources, except to some extent within a single vendor's suite of products. Until vendors adopt industry standards such as CORBA that promote plug-and-play compatibility, integrating ground support systems will continue to require a high level of specialized engineering skill, and overall system maintenance may still be difficult and expensive. Finally, the ability of the space ground support industry to support an ongoing thriving market with many vendors and many customers remains to be demonstrated.

3. CONCLUSIONS

Technical advances are placing more power in the hands of the end user. Cheaper computing power, access to the Internet, software development tools, and the availability of COTS software are giving end users more power to build and operate ground systems. This permits faster and cheaper development, but only if requirements are partitioned to realize the cost savings. There is a blurring of established roles and system boundaries as organizations are pressured to reduce or eliminate the middle layers of ground systems. As this happens, there is also a danger that new technologies will be applied without a clear architecture in mind, and long-range benefits, such as system maintainability and reusability across missions, will be sacrificed.

Therefore, *engineering discipline is more critical than ever* to creating ground support systems. The more options that are available, the more choices that have to be made. The spacecraft and all its support functions (on ground and on board) must be treated as an overall system aimed at providing maximum benefit to the mission, and the solution that works best for one mission may be inappropriate for another. Simply adopting COTS solutions or new development tools cannot eliminate the need for good system design and good development processes. Excessive cost and schedule delays are more often due to unmanaged processes than to failures of technology.

Economic effectiveness through appropriate use of technology is the challenge facing organizations that build ground system elements. It is critical for the health of the space industry that we take full advantage of emerging public and commercial technologies and do not stay rooted in a "special case, custom system" mindset. Organizational culture change is an inevitable consequence. The established role of the ground system development organization is likely to change to that of center of expertise, integrator, or vendor, and software development and maintenance will be elevated to a more industry-wide level through commercial organizations. But all organizations, whether project, institution, or vendor, need to continually assess and assimilate new technologies and invest resources to this end.

Automation of ground systems brings fundamental changes for both development and operations. Development strategies oriented toward highly interactive systems (e.g., graphical user interfaces) need to be replaced by strategies for building and verifying more autonomous systems. Automation is not just a way to cut costs, but a way to gain efficiency and apply human abilities toward larger problems. Trained, experienced, enthusiastic people are an investment that is more important to an organization than any process or technology can be. Thus, the operations person whose routine duties have been automated may become the end-user programmer who helps configure ground systems. The software developer who no longer builds system components may be the member of the mission support team who specializes in the integration of COTS products.

In conclusion, it is always useful to remind ourselves that technology does not solve problems. It just provides people tools for solving problems, and the solutions may introduce new problems. As we apply new technologies to ground system development, we must understand where using them has really made the job simpler, versus where we have simply hidden complexity or shifted it to another place.

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TRANS-GLOBAL MISSION ARCHITECTURES

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ABSTRACT. Operations includes the utilization of both space and ground resources to achieve mission objectives. Architectures of the future must also apply to both space and ground components to create a mission architecture. In reality the "global" view will become too small! The next generation will make the spacecraft a node on a distributed system, expanding the scope of missions beyond the merely global. Design, development and operation of the spacecraft and operations to a single operational concept derived from the mission objectives will create a virtual presence of the investigator on the spacecraft and instruments.

I. EVOLUTION OF PLANETARY MISSION OPERATIONS

In the early days of space exploration, the cost of missions was driven largely by the spacecraft development cost. Mission operations costs were driven by the high cost of computing resource in the form of mainframe computers. Electronic communications, like the software for a mission was complex and costly, developed as a custom implementation specifically for each new mission. There were few missions, widely separated in time, with new mission operations systems created for each mission to optimize the return from the spacecraft. Mission operations teams tended to be centrally located near the computers in an operations center. Command and control of the spacecraft was accomplished only from this center, where the coordination of science and engineering demands on the spacecraft and instruments occurred during a long-duration series of reviews. Inclusion of science and engineering experts from remote locations and other countries was severely hampered by long time delays in exchange of information. Scientists not located near the center were likely to experience long delays in the delivery of the data from their instruments. During major mission events, scientists would relocate temporarily to the operations center.

Large numbers of people were involved in the daily monitoring of the spacecraft, in dealing with anomalies, and in offsetting any deficiencies in operational response of the spacecraft. The use of such innovative and dedicated people was effective in obtaining maximum use of the expensive spacecraft resource, but the cost was high. As missions increased in length for planetary exploration, the mission operations costs over the life of the mission often exceeded the cost of development.

The evolution in the 1980's of lower cost high-performance compute power and affordable high-bandwidth communications dramatically expanded the partnering involved in large missions. The inclusion of geographically distributed teams as an integral element of mission operations was enabled by the integrated distributed information systems and the client-server architectures. Both local and remote engineering and science elements became active participants in daily mission operations. In addition to the electronic transmission of data, mission such as Magellan in the 1980's operated successfully with a team of engineers provided at the spacecraft contractor site in Denver linked electronically to the mission control center in Pasadena and using replicated hardware and software. For Mars Observer project, Science Operations Planning Center (SOPC) systems were remotely located at science investigator home locations to allow noninteractive commands to be prepared and electronically delivered for automatic integration into the spacecraft command sequence. The inclusion of science investigators as integral members of mission operations reduced overhead in operations and provided more timely response to investigation requirements. New missions of the 1990's such as Cassini and the Mars Surveyor series take advantage of the remote integrated teams with smaller and fewer mission operations teams in highly challenging science missions. Even traditional missions such as Voyager and Galileo have adapted their mode of operations "on the fly" during their MO&DA periods to provide added online data access and delivery for their user community while reducing the cost of operations. Missions now routinely employ university, industry, and government agency expertise from all parts of the country, and from around the world. The extent of this involvement in planetary mission development and operations is illustrated in figure 1, "Global Involvement in Planetary Missions in the 1990's". In addition, the advent and widespread use of the Internet allows the neartime sharing of mission status, results and products not only with the small number of scientists closely aligned with the mission, but with the broader community of investigators and indeed with primary and secondary educational institutions and with the general public. The interest and satisfaction generated by this access is indicated by more than 2 million visits to the Galileo pages during the period from Jupiter orbit insertion through Ganymede encounter. To facilitate access, graphical and text-based user interfaces are provided.

Figure 1. "Global Involvement in Planetary Missions in the 1990's"

II. MODULARITY AND RE-USE IN GROUND DATA SYSTEMS

Broader and more distributed involvement in mission operations, however, did not change the number of people involved in mission operations or reduce the cost. Software standards, high level languages and relatively low cost high-performance engineering workstations decreased the cost of mission operations development. Additional software required for the management of increasingly complex spacecraft has often more than offset the savings. Software and people replaced hardware as the dominant cost in both development and operations of space missions. The next major step in reducing the mission operations development cost was the reuse of software applications. The efficacy of this approach is enhanced by the use of space data system standards and by a modular architecture with common interfaces among functional elements. Use of standard operating systems and platform-independent implementation allows the re-use of major software developments such as navigation and planning software on new hardware platforms for new missions and for replacement of aging systems during the operational life of long-flight missions such as Voyager. There is typically a somewhat higher cost for the initial development of re-useable systems, called multimission systems at JPL, but experience has shown the "break even" point for multimission systems to be at less than two missions. The effort to apply re-useable systems to new missions varies from table definitions for typical telemetry functions to the addition of models for new mission components for sequence validation and analysis functions. The modularity of the multimission system allows the integration of re-used elements and project-unique elements to create a project's mission operations system. This flexibility allows a common set of multimission software to yield 95% of the ground data system for the large Cassini mission, but also to provide 95% of the support for the small Mars Pathfinder mission at less than 20% of the normal development cost for such a mission. Capability-driven design based on the availability of ground systems for both spacecraft development and operations and concurrent design trades between spacecraft and ground systems have evolved as the preferred method to reduce development costs for the mission system as an entity. In addition to the modularity of the domain applications unique to mission operations, a layering of support functions with the operational environment has been employed, as illustrated in figure 2, "Layered Architectures in Multimission Operations Systems".

The layering of the application functions is a direct extension of the concept employed in the ISO communications model. Support and application functions and their interfaces are standardized. Changes currently underway will extend the multimission system by deploying existing software modules in a "plug and play" architecture to allow selection of needed functions, all with common external and internal interfaces and formats, and to allow the easy integration of new functions from technology development, industry and commercial sources, or from any collaborating partner in mission operations. In operation, all functions required for any mission functions will be accessible from a single workstation, local, remote or mobile. The combination of formatting, presentation and tools will allow a single person to operate many functions as a "system" expert and to access detailed tools within the domain expertise without the need for extensive training in tools. The integration of public institutions into mission operations is quite feasible for some missions, providing not just feedback, but active participation of the expanded communities of scientists as well as the ultimate customers, the taxpaying public. The combination of modularity and layering of the functions used in multimission re-useable ground systems has allowed the use of commercial systems for in the supporting layer for functions including data management, graphical user interfaces and platform environment management functions. An increasing commonality between communications, military and scientific satellites has also promoted the availability of commercial, easily configured systems for some telemetry acquisition and command functions. Interoperability and commonality of distributed systems utilizing standards and standard architectures will make possible the flexible and even dynamic integration of NASA, industry, university and DoD resources in the fulfillment of mission objectives. The extensive re-use of software does much to reduce the development and software maintenance costs for mission operations. It does not, however, directly reduce the staffing costs for operations, now a major limiting factor in the affordability of space exploration. Interoperability offers one possible solution to further reductions. The other potential solution now practiced is the use of automation and autonomy.

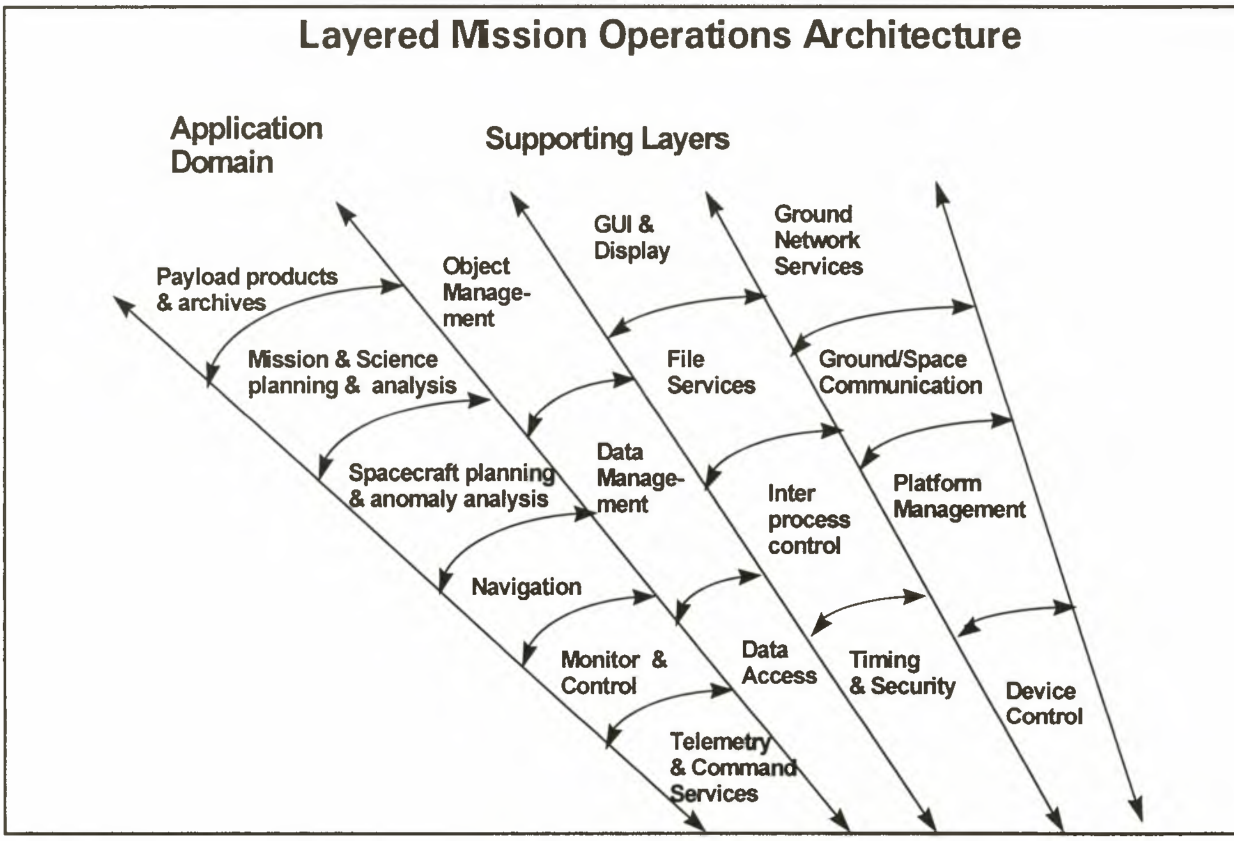

Figure 2, "Layered Architectures in Multimission Operations Systems"

III. AUTOMATION AND AUTONOMY

As noted earlier, the cost of people has become the dominant factor in mission operations. Long-duration mission typical of planetary exploration combined to produce very high operations costs. Automation through specialized software, while costly to develop and test, became a necessity for affordable missions. The trend and demand is to reduce or eliminate operations for routine functions, and to focus human operations attention to events and anomalies of the mission including calibration, spacecraft emergencies, and the ultimate adventure of unmanned exploration, the science observation and discovery. Automated software can scan telemetry for static or trend anomalies, or apply data mining techniques to identify derived events. Analysis tools, sometimes using artificial intelligence and fuzzy logic are employed today in ground-based systems to aid the analysis of identified events and determine or recommend corrective actions. The safety of the spacecraft and its observations with less human attention has been the subject of concern. As planetary exploration moved beyond the inner planets, however, the increase in round-trip light time from a few minutes to hours precluded the early practice of real-time commanding. To avert fatal damage to spacecraft before ground operators could intervene, autonomy was introduced into control computers on planetary spacecraft to "safe" the spacecraft from irreparable damage while awaiting human intervention. Reliance on the safety of the spacecraft has encourage the development of operational concepts which emphasize prime shift only operations rather than round-the-clock "real-time" monitor and control of the spacecraft. The use of autonomy on board the spacecraft is now being developed to enable functions which require more immediate response than a remote human can provide, for example direct orbit insertion or landing and movement on remote bodies. Onboard autonomy can also be used to orient the spacecraft and instrument for scientific observations. Optical navigation with ground and spacecraft elements was used for Galileo. The use of autonomous maneuver and navigation for future spacecraft will allow longer periods between human intervention. The evolution to smaller spacecraft with more flight opportunities overstresses the capacity of the Deep Space Network (DSN). Longer periods between contacts decreases the loading demands on the DSN. Greater ability for the spacecraft to self-monitor, and self-plan is also required during the longer periods between attention. Additional techniques are under development to reduce demand for routine scheduling of ground tracking . Early uses of onboard autonomy, however, created additional workloads for operations. The concept of spacecraft "operability" was introduced. The design of spacecraft for operability and for effective use of existing capabilities requires the participation of both spacecraft/instrument and mission operations engineers with science and mission planners from the very beginning of mission concept development.

IV. TRANS-GLOBAL MISSION ARCHITECTURE

The experience in layering of system functions and re-useable components which has proven itself in the ground system world can now be applied to the spacecraft flight control software and avionics as well. As the mission information system is designed and implemented, the spacecraft with its autonomy and control functions becomes a node on the end-to-end information system. The mission operations system now encompasses both space and ground components, meriting the name "trans-global mission architecture". Figure 3, "Trans-global Mission Architecture", shows this extension of the layered re-useable mission operations architecture to create an open ground/space operations system. The service layer provides a support environment for spacecraft functions, which in turn act a support layer for instruments. The open standards, as in previous experience, will allow the use of one of a set of alternative components for each function, selected to meet the needs of different classes of missions. Unique components required for specific needs such as deep space may be combined with functions such telemetry management common among communications satellites, earth explorers and planetary explorers to reduce the cost and the time delays in implementation.

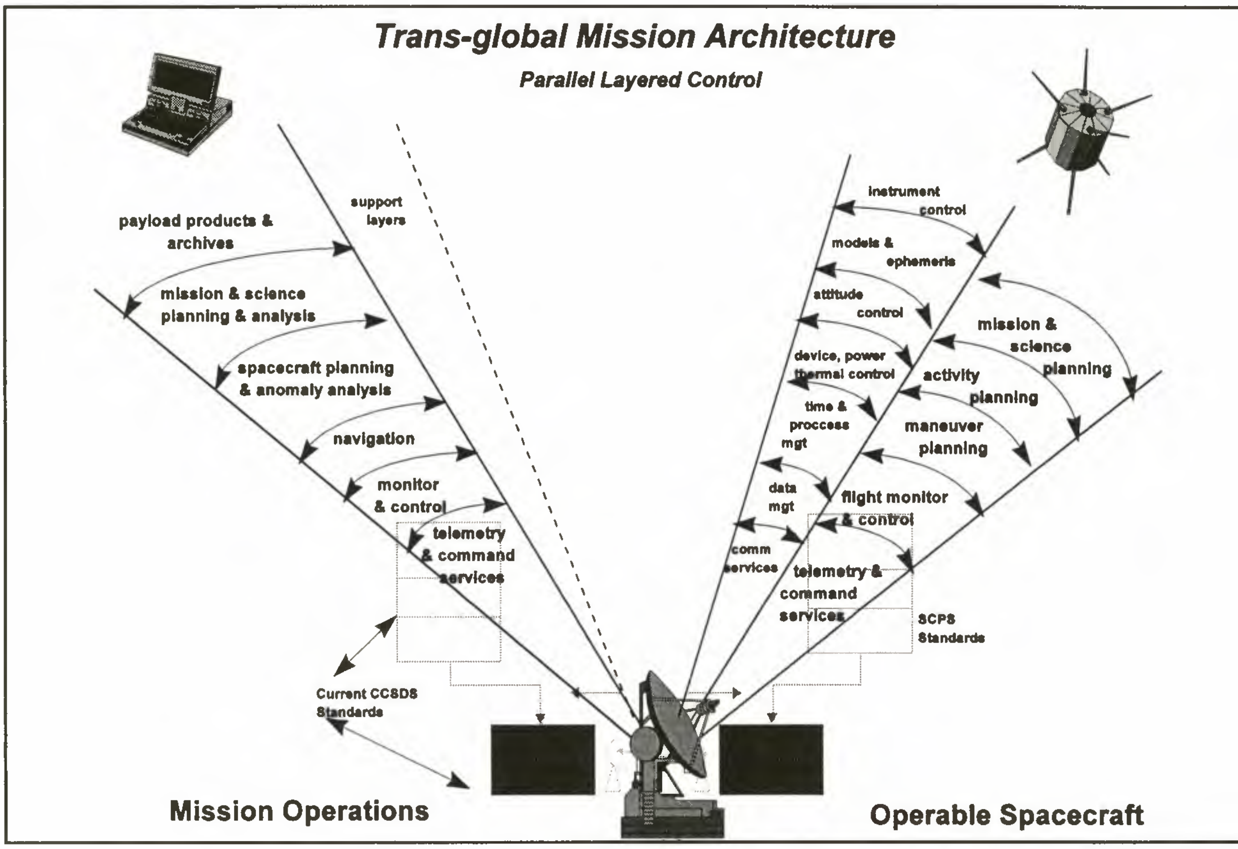

Figure 3, "Trans-global Mission Architecture"

A standardized mission architecture with parallel layering of peer space and ground functions will include interfaces and control to facilitate "plug and play" selection and integration of old and new technology components from disparate sources into varied, affordable and exciting mission systems. The mission architecture provides the "rules" for the structure into which elements will be integrated as operational concepts and technical feasibility dictate. Each layer now includes both a ground and a space component to accomplish together a major function such as navigation or maneuver planning. Functions are implemented to allow ground validation within an operational environment, and for transition of control between ground and flight systems. The optical navigation technology developed over the past decade and employed heavily for Galileo as a ground-controlled function with space components provided the basis for the autonomous optical navigation of the New Millennium program and the DS-1 flight. This example can be employed for the application of science planning, instrument analysis, and automated monitoring expertise to globally remote operation on planetary spacecraft of the late 1990's leading to a period of exploration with operable robust spacecraft requiring minimum routine care from ground-based operations controllers. The smaller spacecraft of the next generation with fewer instruments will both enable more flights, and for some investigations require more than one spacecraft. The investment in multimission trans-global architectures will be repaid in multiple flights.

Before the end-to-end mission architectures can be put into operation extensions are already appearing. The use of information system concepts in the development of the trans-global architecture can be extended to the "server" concept for groups of spacecraft operating to a single set of objectives, reducing the need to replicate the full control and support environment on each spacecraft. Server spacecraft may provide command and control, data management, communications and navigation for a tightly coupled set of spacecraft as in interferometry, or for a more loosely coupled set of spacecraft providing time, space, and instrumentation separation in the observation of a target of interest. Again, the ground-validation of technologies and the application of mature information system concepts will speed the time and reduce the complexity of validating new systems for flight. The next century will see the flight of not just autonomous spacecraft, but of autonomous systems which report back to earth-based operations rather than being minutely controlled from the ground.

V. CONCURRENT MISSION ENGINEERING WITH TRANS-GLOBAL ARCHITECTURES

Using the definition of mission operations as the application of space and ground resources, including people, to meet mission science objectives gains perspective on the scope of the work involved. The mission concept development then expands the mission objectives into an operational concept of what space and ground functions are to be performed, where people and automation are to be applied, and how the components function together as a mission information system to produce scientific observations and products. This concurrent engineering of the mission and of its mission information system produce a viable product for the tightly constrained budgets and schedules of the new classes of missions. Experienced designers have known for decades that this trade is beneficial, but the threat of mission cancellation for violating "caps" on life cycle costs has made the need imperative. Use of project design centers is a start in this process. The tools and capabilities available in the design centers must be expanded to improve the results.

During the concept development, planning tools represent the mission design and the mission components. Trades are made among the design options and mission components based on cost, availability, performance and schedule to produce a viable mission concept. Using a "click-and-play" system with model-based representations of existing and proposed components can greatly enhance the fidelity of the exercise. The attributes associated with each model include performance, cost, and environment to allow the visualization of the mission execution from the concept phase. The mission model then carries the expected operational behavior of the mission system forward during the "selling" phase of the mission and into the design and execution phases. Some research is expanding the option of using models as alternatives to detailed requirements for the test and validation of delivered products. The models may also be used as a management tool for performing end-to-end life cycle cost and performance trades during the execution of the mission, averting past experience of allowing underperformance in development of spacecraft and instruments as an underestimated impact on mission operations.

The use of a layered mission architecture with large stores of re-useable components allows a quick instantiation of the mission concept model in mission testbeds. Actual mission software can be configured quickly using an institutional knowledge base comprised of multimission components. The layered concept allows the development of needed layers for the initial testing of spacecraft breadboards and hardware in a rapid mission prototyping development mode. New technology or components from diverse sources can be readily validated for their operational readiness. This provides an excellent path for the introduction and transfer of new technology. Once validated, the technology is immediately accessible to mission concept builders. Layers not required in early phases are "stubbed out" or represented by simulations. Using this approach, the full set of multimission operational analysis tools are available to support the development of spacecraft systems, and any added analysis or calibration tools developed for specific flight components are integrated into the developing operational systems in a continuing integration process rather than at a per-launch massive exercise of integration and test.. The end-to-end system thus evolves from a simple, but mathematically proper subset of the full mission system into an incremental set of enhanced capabilities through a continuous testing and integration process until all operational functions are present and performing. An end-to-end mission testbed is provided as a distributed system with all re-useable system functions, models for known hardware components, and interfaces for breadboards, brassboards and actual hardware components to facilitate the rapid prototyping process. As the mission concept development reaches maturity in the development phase, separate copies are separated from the generic multimission testbed to become the neophyte new mission system. This process was first employed very successfully for the Mars Pathfinder mission and is now the model for how even faster, better, cheaper and even more innovative and exciting missions can be achieved.

VI. CONCLUSIONS

The architectures, testbeds and new methodologies enable a new period of exciting space exploration by offering innovative missions at a fraction of the cost inherent in older technologies. The "plug and play" replacement enables the continued grown and insertion of new technology rather than the continued use of a limited and limiting set of options. The adoption of standard architectures for the trans-global end-to-end mission information system is essential to containing the cost and risk of space missions while inserting the new technologies which expand our explorations. Global partners should work together to share in the development of the trans-global architecture and to realize both the saving and the rewards of the new period of exploration.

MULTIMISSION SOFTWARE REUSE IN AN ENVIRONMENT OF LARGE PARADIGM SHIFTS

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ABSTRACT. Since the beginning of NASA space flights, each center has been tasked with providing a Ground Data System capable of supporting its flight projects. These ground systems once included only the capability to send single commands and to capture very rudimentary telemetry streams. As the spacecraft capabilities expanded, ground systems requirements have grown to support them. Today's Ground Data Systems not only provide for the simple command and telemetry control of earlier vintage systems, but provide significant increases in uplink and downlink processing capabilities.

The New Millennium Project (NMP) has been tasked as the "technology testbed" for NASA missions of the 21st Century. In this role, NMP has been tasked with demonstrating both spacecraft and ground system technologies. Included in these new technology demonstrations will be spacecraft autonomy with its associated on-board spacecraft sequencing. This paradigm shift from detailed ground sequencing to a "goal" oriented planning approach will effectively move a set of "ground elements" to the spacecraft.

How will the elements of the established JPL ground system support this new paradigm? What GDS changes are required to address these new requirements? Is the ground system architecture capable of supporting these needs?

Although this paper will discuss work in process to meet this new paradigm for the DS-1 (Deep Space-1) NMP mission, benefits of software reuse and code inheritance in satisfying NMP's stringent short development schedule and project development costs will be presented.

How will these systems support the spacecraft changes of the future? What changes in approach or new technologies will be required to support these future spacecraft needs?

1. BACKGROUND

Since the beginning of space flight, each NASA center has been challenged with providing a Ground Data System (GDS) capable of supporting its respective flight projects. The large time gap between missions (typically several years) and the technology advancements which have occurred during this gap have compelled a quantum jump in the GDS capabilities to take place between missions. This has resulted in the too common practice of "re-inventing the Ground Data System" with each project.

This problem has been compounded by scientific demands for increased spacecraft capabilities resulting in increased spacecraft operational complexity and its associated operation costs. The availability of improved computer hardware and its increased performance have led to a potential solution to the increased complexity, in spite of the redesign and/or re-engineering which would be required to transport the software to the new platforms and computer system architectures.

In the early 1980's, with the aging of JPL's mini-computer based telemetry sub-system, it became apparent that a new system would be required to support the next decade's requirements. Consistent with this realization and with the availability of powerful UNIX workstations, it became apparent that a new approach to JPL's software development process should be pursued, to transform the "mini or mainframe, and closed" architecture into the new modern "distributed workstation, client-server, and open" architecture. This proposal was accepted by NASA and thus the Multimission Ground Data System (MGDS) was born. At its inception in 1985, JPL's MGDS was referred to as the Spacecraft Flight Operations Center or SFOC.

The original capabilities of the MGDS used by Magellan in 1988 included only telemetry data processing, spacecraft data monitor and display capabilities, and data transport from the Deep Space Network into a Central Data Base. The additional functional capabilities of science processing, commanding and sequencing were added as were several specific navigation functions including NAIF/SPICE, ephemeris generation, gravity modeling and optical navigation in time to support the Mars Observer Project in 1992. The final major addition to the MGDS will be the addition of mission planning, spacecraft simulation and spacecraft analysis capabilities.

Within the original development guidelines, support was only planned for the three then extant missions consisting of Magellan, Voyager and Galileo and the three then future missions Mars Observer, Ulysses, and Cassini. Subsequently, the additional two missions to Mars, Mars Pathfinder and Mars Global Surveyor, are now using it to meet their ground data system needs. Future Mars missions, Mars'98, Mars'01, Mars'03 as well as Stardust and SIRTF are on track to use significant elements of these tools also.

2. MULTIMISSION GROUND DATA SYSTEM OVERVIEW

Studies performed at JPL have identified a series of standard services common to all planetary flight missions. These standard services are illustrated in the stylized drawing of Figure 1.

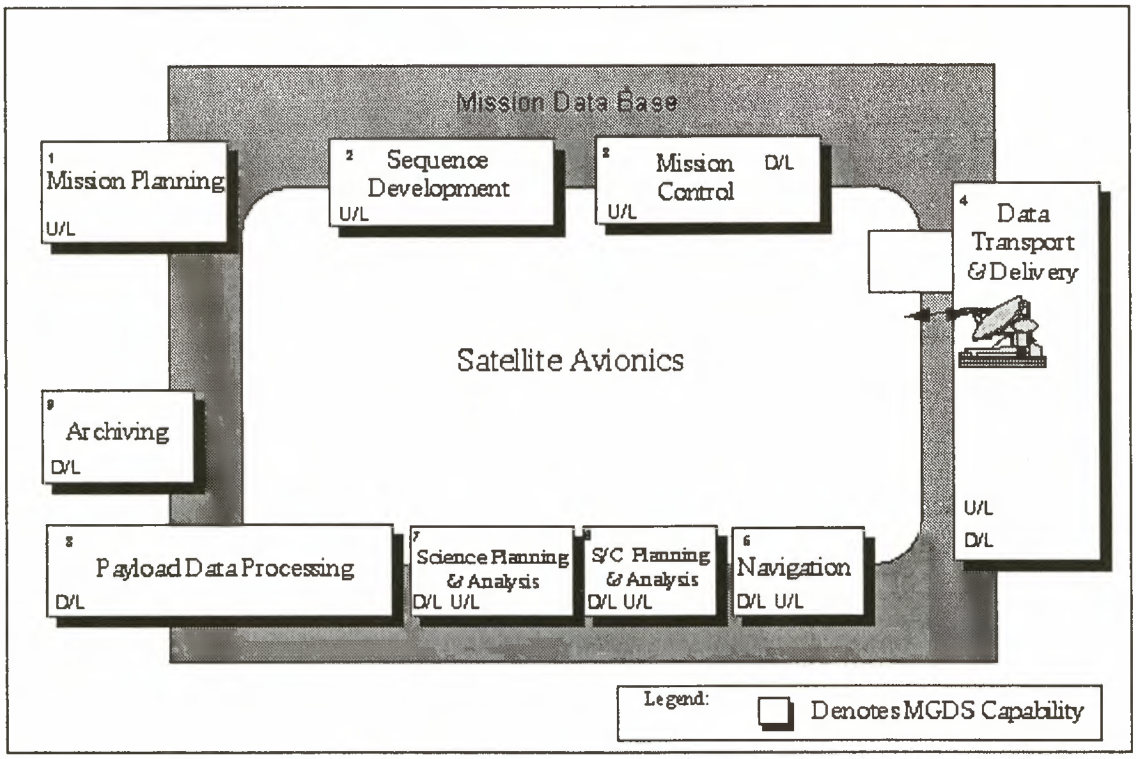

Figure 1—Nine Primary Functions of a Mission Operation System

The way that these services are combined in any given flight project organization is a function of the complexity of that particular mission as well as the individual management style of its project management. However, each of these operational services is required and will be present in one form or other. An enumeration of these functions is provided to show syntax for the MGDS. These services are as follows:

2.1 PLANNING and ANALYSIS Services

- **Mission Planning**. Responsible for all areas of flight planning. This consists of two phases, 1) the pre-flight activity responsible for development of an overall plan for conducting the mission including development of spacecraft trajectories, data acquisition strategy, resource allocations, etc., usually called the Mission Plan development. 2) the post-launch activity responsible for assessing adherence to the mission plan due to unforeseen mission events and for the updating of the mission re-plan, as required.

- **Science Planning and Analysis**. Responsible for supporting the Principal Investigator or Science Team planning of science instrument observations as well as the assessment of instrument health and performance. Science instrument observation planning includes determination of instrument parameters for specific observations as well as conflict resolution between science requests.

- **Spacecraft Planning and Analysis**. Responsible for the maintenance, health, safety, and repair of the spacecraft. This includes supporting all uplink and downlink activities required to monitor, calibrate, and evaluate the performance of the spacecraft and it's subsystems.

- **Navigation.** Responsible for delivery of the spacecraft to its target(s), including planning and gathering of radiometric data, determining and validating the spacecraft flight path, and designing and verifying spacecraft and/or science maneuvers.

2. SPACECRAFT CONTROL Services

- **Sequence Development**. Responsible for integrating all uplink activity requests from science, spacecraft, and navigation planning elements. This integrated set of requests is then expanded and constraint checked by this service to ensure a conflict-free sequence for commanding the spacecraft and instrument, including maneuvers, data acquisition and data transmission to the ground.

- **Mission Control**. Responsible for the real-time controlling, monitoring, and operating of the ground and flight system including monitoring of spacecraft and instrument health and safety, ground system health and performance, as well as controlling and release of commands to and receipt of telemetry from the spacecraft.

2.3 SPACECRAFT DATA HANDLING Services

- **Data Transport and Delivery**. Responsible for transport of data to and from the spacecraft via the DSN, and for delivery of data through out the ground system. Included in this service is the Central Data Base for both archival and easy access to/for uplink and downlink data. Supports acquisition and decoding (if necessary) of telemetry returned from the spacecraft including separation of data into science instrument and engineering data sets, as well as delivery of said data to users for higher level processing.

- **Science Data Processing**. Responsible for the extraction of instrument data from telemetry stream, conversion of science instrument data into physical units and construction of instrument data records for higher level processing. Preparation of data for archiving.

- **Archiving.** Responsible for planning and providing long-term storage of mission science, spacecraft engineering, navigation and other ancillary data. Produces the actual archival data records.

With the evolution of the MGDS, each of these service areas has or is being addressed with the provision of a significant software capability. The final areas now being addressed are Mission Planning, Spacecraft Simulation and Spacecraft Analysis. With the delivery of these capabilities, a comprehensive baseline will exist in support of all areas of the Mission Operation Service suite described above.

3. NEW MISSION CONCEPT

How will this system support the changes in either spacecraft and/or operation approaches of the future? What changes in approach or new technology needs will be required to support these future missions? At present, two changes in paradigm have presented themselves. The first, spacecraft size and associated complexity was ushered in with NASA's announced Discovery and

MedLite missions. The second change, is that ushered in with the New Millennium missions. Both of these will be addressed below.

3.1 NEW SMALL DISCOVERY CLASS MISSIONS

Because these tools were developed in an environment of large class missions i.e. Voyager, Galileo, and Cassini, first perception might be that these tools would not be applicable to missions which did not fit this mold. Mars Pathfinder, NASA's 2nd Discovery Mission, disproved this by its development organization being able to take the elements of the MGDS and produce a basic ground system within only a few months as demonstrated in Figure 2 rather than the normal two or three years experienced by non-MGDS supported missions.

MARS PATHFINDER MGSO BASE	BASE C CODE	C CODE ADDED	C CODE REMOVED	BASE TABLE	TABLE	GENERATED TABLES	TOTAL	*TIME
EEIS PHASE 0	497,399	1,331	1,578	68,737	5,216	8,394	579,499	1 mo
EEIS PHASE 1	104,235	100	0	3,490	300	0	108,125	4 mo
EEIS PHASE 2	681,601	12,064	0	0	2,191	0	695,856	6 mo
TOTALS	1,283,235	13,495	1,578	72,227	7,707	8,394	1,383,480	

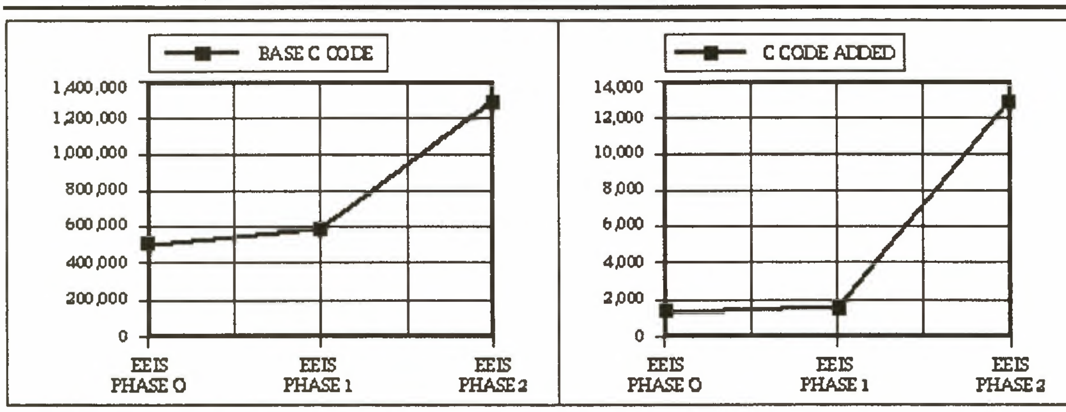

Figure 2—Mars Pathfinder GDS Time to Delivery Using MGDS Inheritance

Figure 3 illustrates the Mars Pathfinder Ground Data System in its launch configuration simplified for purpose of presentation. Elements inherited from the MGDS are annotated by shading as noted.

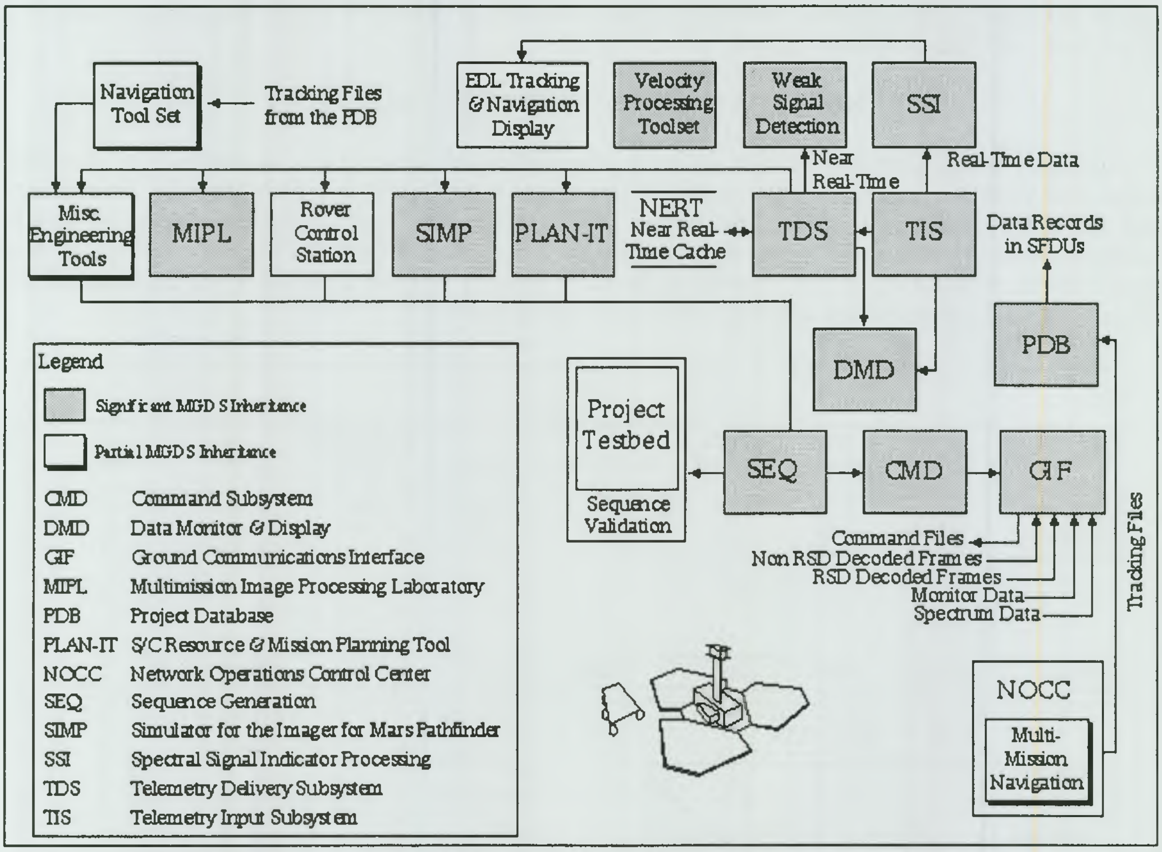

Figure 3—Mars Pathfinder Ground Data System Launch Configuration

Figure 4 illustrates the percentage of inherited MGDS code for the current suite of JPL missions including the Mars Pathfinder Mission.

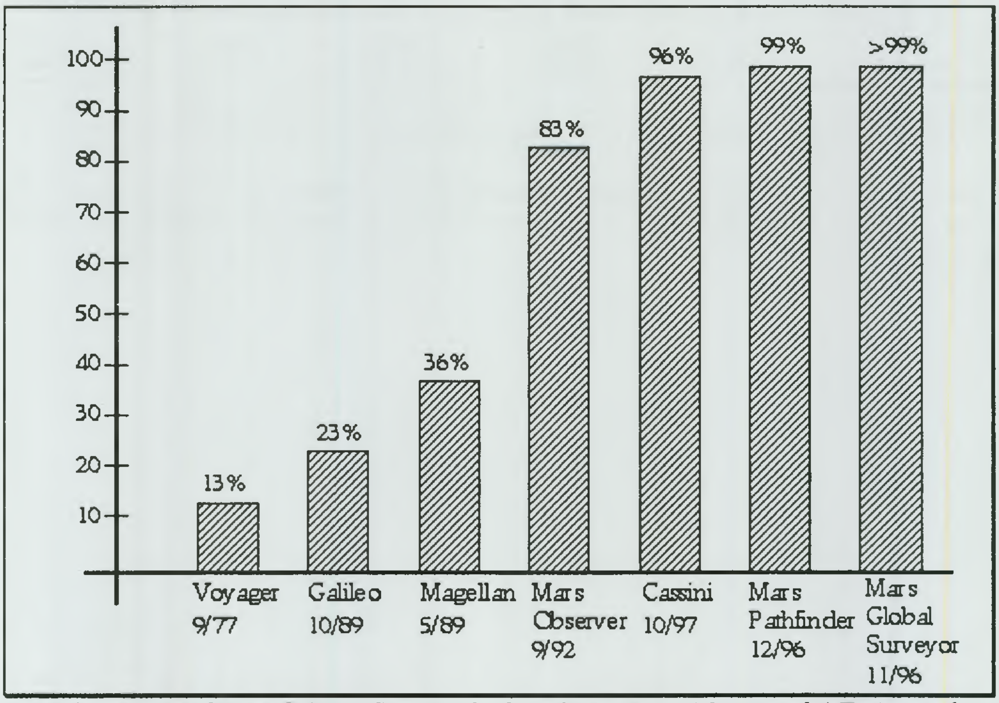

Figure 4—Multimission Ground Data System Code Inheritance (Measured / Estimated at Launch)

Size Study Results: SIZE THEREFORE HAS NOT PROVEN A DELIMITER in using the MGDS to meet mission objectives!

3.2 NEW MISSIONS OF LARGE PARADIGM SHIFTS

What about missions wherein the structure of their operations is a dramatic departure from the "standard JPL approach"? Missions where ground/spacecraft concepts have undergone significant change from those under which the MGDS was developed?

Space science missions that NASA envisions for the 21st Century will use new technologies which are needed to enable frequent launches of cost constrained, highly capable, low-mass spacecraft with highly focused science objectives. In 1995, NASA approved the New Millennium Program (NMP) with its primary objective being the development of a "technology testbed" to help enable these future missions by developing and validating some of the key technologies they will need. Beginning in 1998 with one to two launches per year being anticipated, NMP will flight validate some of the high risk technologies that will help enable these future missions. The first of these missions is a deep space mission, currently known as DS-1 (Deep Space-1). At present, thirteen technologies have been selected for DS-1 although future de-scope gates are expected to reduce this number further. Included in these are several spacecraft autonomy demonstrations including Autonomous Remote Agent, Autonomous Navigation and Beacon Mode Operations each of which will change the standard way JPL flies spacecraft by moving ground functions to the spacecraft. Each of these technologies is targeted at the reduction of operation costs by decreasing the ground support required for missions of the 21st Century. This new approach, the movement of ground functions to the spacecraft is a significant change in paradigm.

How will the elements of the established JPL ground system support this new paradigm? What GDS changes are required to address these new requirements? Is the ground system architecture capable of supporting these needs?

Although the DS-1 development is only nine months into its development cycle, significant MOS and GDS planning has already taken place. Figure 5 illustrates the NMP GDS as presented at the Ground Segment Interim Design Concurrence Review on 22 May 1996. The MGDS elements of the DS-1 GDS are highlighted by cross-hatching. Present estimates of software inheritance were not available at this writing although estimates in the high 90% are anticipated.

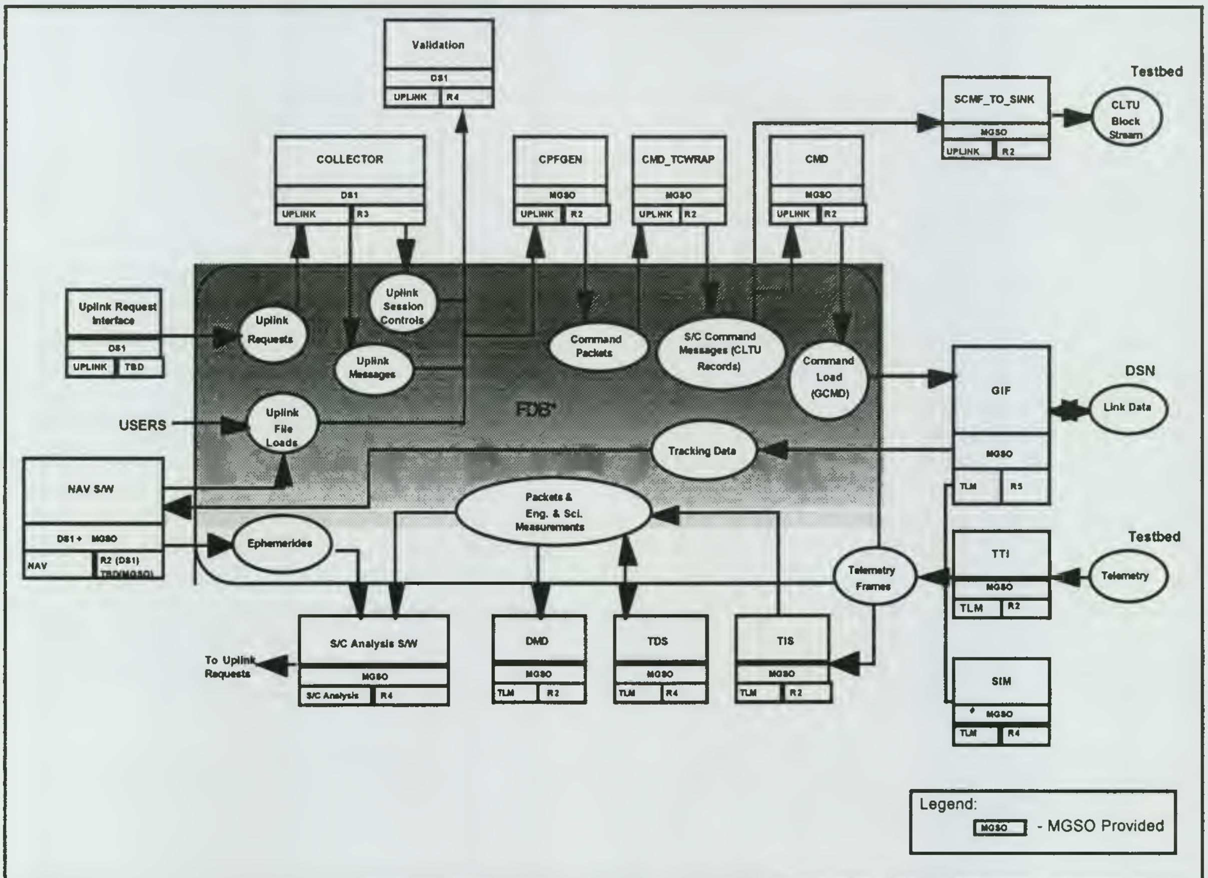

Figure 5—Proposed New Millennium DS-1 Project Ground Data System

Note that of the DS-1 elements only two are not cross-hatched as being provided by the MGDS. These DS-1 project unique tools perform the following functions:

- **Collector Tool**. The interface between the project and the MGSO uplink elements, providing the information necessary to interface with the standard uplink capabilities of the MGDS.

- **Validator Tool**. Performs many technology validation functions for DS-1 including the ground execution of the autonomous flight software, the Remote Agent, while providing a timeline visualization for the operations staff of the effects of the planning.

DS-1 Study Results: 1) Downlink elements appear to have a direct inheritance even for missions which demonstrate significant departures from present operations concepts. 2) Uplink Elements though inheritable, have required changes to the MGDS, though second order in nature.

4. CONCLUSIONS

JPL's Multimission Ground Data System has evolved since its inception in 1985 to include extensive uplink and downlink capabilities. Missions outside its development environment appear capable of realizing the benefits of the MGDS even in the face of large paradigm changes. Although this paper has discussed work in process to meet the new paradigm being driven by the DS-1 NMP mission, every indication is that the basic structure and design of the MGDS continues to be available to assist missions of the future in meeting their ground data system requirements within budget and schedule constraints.

5. ACKNOWLEDGEMENTS

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6. ACRONYMS/GLOSSARY

MGDS Multimission Ground Data System: Data system comprised of the multimission contingent of flight operations ground support software

GDS Ground Data System: Typically a project unique ground data system as adapted for a particular project.

7. REFERENCES

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IMACCS: A PROGRESS REPORT ON NASA/GSFC'S COTS-BASED GROUND DATA SYSTEMS, AND THEIR EXTENSION INTO NEW DOMAINS

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ABSTRACT. The Integrated Monitoring, Analysis, and Control COTS System (IMACCS), a system providing real time satellite command and telemetry support, orbit and attitude determination, events prediction, and data trending, was implemented in 90 days at NASA Goddard Space Flight Center (GSFC) in 1995. This paper describes upgrades made to the original commercial, off-the-shelf (COTS)-based prototype. These upgrades include automation capability and spacecraft Integration and Testing (I&T) capability. A further extension to the prototype is the establishment of a direct RF interface to a spacecraft. As with the original prototype, all of these enhancements required lower staffing levels and reduced schedules compared to custom system development approaches. The team's approach to system development, including taking advantage of COTS and legacy software, is also described.

1. INTRODUCTION

Traditionally, ground data systems for NASA missions were built and integrated entirely by civil servants and contractors. Institutions at NASA centers performed system development and missions operations. Motivated by the desire to aggressively advance space science goals despite shrinking budgets, NASA's approach to all aspects of missions has changed, including ground data systems. Today, missions are conceived and flown in response to Announcements of Opportunity that make the Principal Investigator (PI) responsible for the allocation of funds. The PI can choose to get support wherever he perceives the best value and as a result, NASA centers must compete with each other and non-NASA institutions to provide satellite ground data systems.

At NASA's Goddard Space Flight Center (GSFC), the Mission Operations and Data Systems Directorate (MO&DSD) is charged with building and operating ground systems. Faced with the competitive challenge, MO&DSD sought to reengineer its business and initiated the RENAISSANCE project to lead the way. At its inception in 1993, RENAISSANCE had a modest goal: build an operational ground system in less than 1 year for less than $5 million. Initial studies by the RENAISSANCE team led to an architecture based on reusable building blocks, garnered from GSFC's legacy systems where possible and built to be reusable (Stottlemyer *et al.*, 1993). This approach was called the RENAISSANCE first generation architecture. Shortly thereafter, NASA Director Goldin's exhortation to "faster, better, cheaper" was taken to imply far more substantial changes. The RENAISSANCE team responded with a second architecture that allowed for extensive use of COTS hardware and software (Stottlemyer *et al.*, 1996).

Indeed, in recent years, commercial off-the-shelf (COTS) hardware and software for satellite applications has evolved considerably. COTS tools now surpass the functionality of many custom-built systems and system components. The Eagle testbed, an outgrowth of the CIGSS (CSC Integrated Ground Support System) COTS and legacy system integration project of Computer Sciences Corporation (CSC) provides the experience base for CSC's COTS integration work (Werking and Kulp, 1993; Pendley *et al.*, June 1994). Several other testbed projects, including the United States Air Force's (USAF) Center for Research Support (CERES) (Montfort, 1995), the International Maritime Satellite (INMARSAT) consortium, and the USAF Phillips Laboratory (Crowley, 1995) have produced successful prototypes using COTS components. The Extreme Ultraviolet Explorer (EUVE) Science Operations Center (SOC) at the University of California at Berkeley (Malina, 1994) has adapted a COTS-based system to automate science instrument operations, resulting in significant cost reductions.

2. IMACCS 90 DAY PROJECT—A REVIEW

In 1995 CSC, building on its COTS integration experience, proposed that NASA Goddard's RENAISSANCE team build a COTS-based prototype to demonstrate that significant cost reductions were possible. The Integrated Monitoring, Analysis, and Control COTS System (IMACCS), had the following goals: integrate a set of COTS tools, connect them to live tracking and telemetry data, and reproduce the functions of an operational ground system (Bracken *et al.*, 1995). The target mission for IMACCS was the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) mission , one of the spacecraft in GSFC's Small Explorer (SMEX) series. SAMPEX is a low earth orbiting satellite in its fourth year of operational support. IMACCS was designed to replicate the current real time command and telemetry flight and off-line support for SAMPEX. A time limit of 90 days was imposed, and indeed, proved to be sufficient.

A simplified block diagram of IMACCS is shown below in Figure 1. The COTS hardware and software have capabilities that exceed SAMPEX operations requirements. One tool, the Altair Mission Control System (AMCS), used on IMACCS for command and telemetry, shows substantial promise for automating data monitoring and commanding. CSC, through its Eagle testbed had prior experience with the AMCS and was familiar with its capacity to perform automated operational support. The AMCS provides automation through finite state modeling and state transitions (Wheal, 1993). State modeling and state transitions proved to be easy to implement, and a set of initial state models was built. Other features and capabilities of the IMACCS prototype are detailed in Bracken *et al.* (1995).

A key characteristic of the initial IMACCS project was the speed with which it was implemented, being fully functional 90 days after project start. This rapid turnaround on the original implementation has been repeated for all of the extensions described in this paper. For both new system development and major enhancement, being able to complete major system lifecycle phases on this timescale of 3 months or less is essential for future ground systems that must be delivered on reduced budgets and schedules.

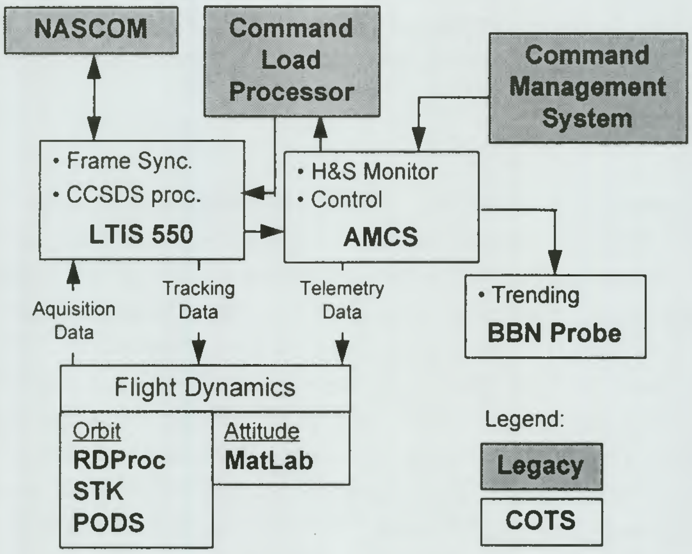

Figure 1. The IMACCS prototype contains six COTS software tools and three legacy tools.

IMACCS prototypes do not cover the entire traditional waterfall lifecycle. The major phases of this lifecycle for ground system development are shown in Table 1. The phases shown in this table are typical of standard methodologies used by NASA, DoD, and other major institutions. Development of the

LIFECYCLE PHASE	PRINCIPAL ACTIVITIES
Requirements Development	Determine what the system is required to do and analyze requirements for completeness, feasibility, testability, etc.
Requirements Analysis	Determine system functionality and allocate functionality to high level components.
Design	Allocate functions to low-level components in detail and specify interfaces in detail.
Implementation	Construct components and integrate into the system.
Testing	Verify that the system meets its requirements.
Operational Deployment	Install system for operations and integrate with existing systems.
Operations and Maintenance	Support system as it used operationally.

Table 1. Major phases of traditional waterfall development lifecycle.

original

IMACCS prototype and its extensions corresponds to the design phase through the testing phase. Because these prototypes have been built in parallel with existing systems (or systems under development), they have started from existing, and therefore stable, requirements. Similarly, because the prototypes can be evaluated against operational systems in most cases, the testing needed to establish their full requirements compliance is less than that required for a new system. Nevertheless, the IMACCS lifecycle of 90 days (or less) for this subset of the traditional lifecycle is still very favorable compared to the 12 to 24 month periods that have been typical of the more traditional approach.

Another element of the IMACCS approach to system development and integration is to make maximum use of COTS products, freeware such as PERL and EXPECT, and other existing software tools. These tools are used intact, with no modifications, and communicate through simple interfaces such as files to the maximum extent possible. The maximum advantage accrues in the design and implementation phases, because there is little detailed design at the subroutine level and similarly minimal code to develop. We expect that fully testing such a system will take about the same amount of effort as for a traditional system, as the full set of requirements must be verified. We also think that reduced effort for the two requirements phases is likely, because the use of existing tools makes prototyping rapid enough to affect requirements development and analysis decisions.

The tools used in IMACCS do not require extensive training to use, and enable a user to directly implement a system function. The benefit of rapid development has been realized by tools that enable experts in the spacecraft and operations domains to adapt the tools to their needs without the intervention of experts from the software domain. User-intuitive interfaces enable spacecraft and operations engineers, unfamiliar with the tool, to rapidly customize the software. With appropriate COTS tools, individuals can easily develop mastery of several packages, thus facilitating their integration.

Another factor in the rapid implementation of the IMACCS prototypes is the use of a small, highly-empowered team of NASA civil servants and CSC engineers that has working relationships with the COTS product vendors. Team members worked in close proximity and a high degree of cooperation. Rapid progress, enhanced by visible results from graphical interfaces of the available tools, accelerated the development pace.

3. IMACCS EXTENSIONS

Analysis of IMACCS operational functions (Pendley *et al.*, November 1994) showed that although IMACCS satisfied telemetry and tracking data processing, commanding, mission planning, archiving and trending, and orbit and attitude determination functions, a number of other mission operations functions were not addressed. Furthermore, automation in the first prototype was restricted to real time data monitoring. The next step for IMACCS was to prove that a COTS-based architecture could expand both functionality and automation. Construction of the initial set of state models showed that the AMCS had substantial capability not only to automate operator functions, but also to implement to highly autonomous systems. Methods to automate off-line functions, such as orbit determination, events computation, and acquisition data generation, have also been discovered. The IMACCS team also investigated COTS alternatives to the NASCOM serial telemetry and command interface between the antenna and the system. A COTS RF link, connected directly to a test antenna at GSFC, was implemented and integrated with the IMACCS system. Finally, IMACCS was extended to perform spacecraft integration and test (I&T) functions.

Automation Our basic approach to automation was to take advantage of the capabilities available in the products or ensembles of products that constituted IMACCS. Working closely with the SAMPEX flight operations team, the IMACCS team developed five categories of operations activities:

- Data monitoring
- Routine pass activities

- Known contingencies
- Emergencies
- Product generation

The IMACCS team automated data monitoring, routine pass activities, known contingencies, and emergencies with the state modeling capability of the AMCS. These four activities are driven by real time telemetry, and their automation is detailed in Klein *et al.* (1996). For non-real time product generation, we needed a way to script the execution of interactive, Xwindows-based programs, like Satellite Tool Kit (STK) from Analytical Graphics. Our approach was to utilize a record-and-replay test tool, Xrunner from Mercury Systems (Lin *et al.*, 1996).

Radio Frequency Interface The original IMACCS received tracking and telemetry data from, and sent commands to, SAMPEX through ground antennas located at Wallops Island, Va.; Goldstone, Ca.; Madrid, Spain; and Canberra, Australia. These stations communicate through the NASA Communications Network (NASCOM) serial data interfaces for both downlink and uplink. IMACCS used the Loral Test and Information Systems LTIS550 front end to receive and transmit data via NASCOM.

Driven by the interest of some flight projects to control all their resources, and by the success of IMACCS, MO&DSD sponsored integration of COTS RF equipment with the IMACCS prototype (Butler, 1996). This system is shown in Figure 2. It utilizes a 4.3 meter dish at the Greenbelt test facility and a receiver being developed by Stanford Telecommunications, Inc. under the under the sponsorship of Goddard Space Flight Center. The multi-functional, Software-Programmable Advanced Receiver (SPAR) (Zillig *et al.*, 1995), couples advanced charge-coupled device (CCD) technology (developed by MIT/Lincoln Laboratory with NASA sponsorship) and digital signal processor (DSP) algorithms. For the RF interface test with IMACCS, only the receiver portion was used. The complete IF-to-baseband data receiver comprises three standard 220 millimeter, 6U VME cards: the IF module, CCD module, and DSP module. Communications and control connectivity between each of the modules and a local PC controller is achieved using a 5 MBPS industrial ARCNET local area network standard.

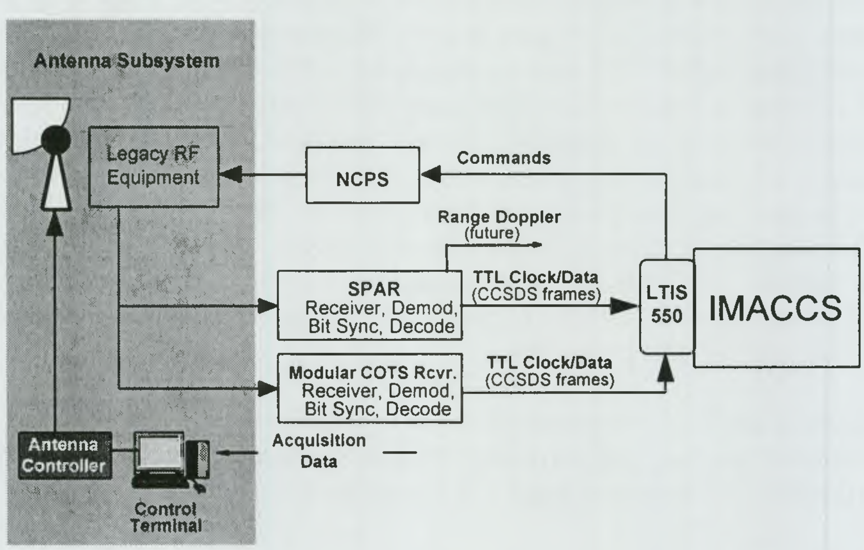

Figure 2. The COTS-based RF interface to IMACCS contained two separate receivers.

The IF module accepts RF input from 370 to 500 MHz (selected for application both at NASA's White Sands and GN ground stations) and at an input power level between -75 and -15 dBm. The resultant signal was passed to the LTIS front end, bypassing NASCOM altogether. The IMACCS/RF system took SAMPEX passes and tracked the spacecraft while monitoring states and telemetry. Other COTS products are available and could have been used in this prototype, as has been demonstrated by JPL. The integration demonstrated the feasibility of a complete, end-to-end COTS-based system and generated excitement and interest among demonstration audiences.

Integration and Test (I&T) Spacecraft I&T system functionality substantially overlaps operational ground system functionality, making it likely that a single system can be tailored to perform both roles. GSFC's RENAISSANCE team compared I&T requirements with those of operational systems, and found this overlap in areas such as data packing and unpacking, EU conversion, limit checking, and command and telemetry database ingestion. They also found that I&T systems differ by requiring frequent database updates and bit level data displays and command construction. I&T systems also derive little benefit from automation of monitoring or commanding.

We identify three systems in the lifecycle: the Spacecraft Component Test System (SCTS), the I&T System, and the Operational Ground Data System (GDS). The SCTS is a collection of tools that evolve as satellite components are developed. The I&T system is used to integrate and test the components into the complete spacecraft. The GDS is used to fly the satellite. As each system hands off to the next in the lifecycle, the information developed in the previous phase must be passed along. Traditionally these hand-offs have required that the three lifecycle systems need to read some database representation of the device parameters or have them input manually, and restructure the information for local use.

The IMACCS team approached this expanded requirement set with the same COTS-based architecture used in earlier prototypes. We borrowed a lab spare piece of hardware from the X-ray Timing Explorer (XTE) mission and reproduced the functionality of the Proportional Counter Array (PCA) Ground Support Equipment using LabVIEW, a graphical instrument driver package made by National Instruments. As with the original IMACCS, integration engineers, familiar (if only slightly) with the problem but not at all with programming built the SCTS in a matter of weeks. Even at that, a substantial portion of that time was spent learning how to interact with the 1553-standard avionics interface. Using the same LabVIEW interface to support the integration of the PCA with the rest of the hardware, the new prototype populates the telemetry and command database, scripts test scenarios, and attaches to a CORBA based network to get data from a variety of data interfaces (the LTIS550, IP sockets, and direct 1553 connection). The operational system reverses the database operation and uses its information to decommutate and convert the data. The obvious advantage to a consistent architecture is that information can be passed along from one phase to another without manual intervention or reformatting. Moreover, the end users at all points along the lifecycle are using similar, if not identical, interfaces to interact with the same spacecraft object.

This architecture evolves smoothly from SCTS through I&T to GDS and bypasses the inefficiencies and risks of data restructuring. IMACCS/I&T differs slightly from the original IMACCS. It is based on PC platforms under Windows NT, because SCTS tools should be on platforms used by spacecraft engineers. The IMACCS team is in the process of implementing a CORBA interface to make the network seem transparent to all users regardless of platform. This extension of IMACCS demonstrates that the benefits of a common architecture now extend from component testing to end of life.

4. CONCLUSION

In the past, satellite missions required costly, custom-built systems because each new mission advanced the state of spaceflight art. Near the end of the fourth decade of spaceflight many more satellites are flown, and the domain of knowledge needed to operate these vehicles is better bounded, allowing development of general purpose tools and economies of scale. These tools are available as the kinds of COTS hardware and software used in IMACCS. The use of COTS-based ground systems will expand as the need for low cost, easily used and automated systems continues to increase. Future missions must be flown economically, which requires that all phases in the mission life cycle must be considered for development cost reduction and operational enhancement. Future extensions of IMACCS will address all phases of the spacecraft lifecycle, from system concept to end of life (from design to debris).

Within GSFC there are efforts being made to support these causes. The Landsat 7 mission is now pursuing the use of state modeling to support the automation efforts of the ground system using COTS tools validated on IMACCS and its extensions. NASA Goddard has also accepted a proposal to replace the current Upper Atmosphere Research Satellite (UARS) control center with a COTS-based system. The use of automation will be the responsibility of the flight operations team. This team, with support from the members of the IMACCS team will develop the state models to support the monitoring of the UARS satellite and develop the pre-pass planning scripts that will be used to automate routine commanding of the UARS satellite.

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THE GATEWAY FOR THE BRAZILIAN PILOT COMMUNICATION SYSTEM USING LEO SATELLITES

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ABSTRACT. This paper presents an overview of the SCD3 system[1], a Brazilian effort toward a communication system using a small Low Earth Orbit satellite, and the Gateway Station design proposed for the system. A pilot voice communication system employing Code Division Multiple Access (CDMA) is considered in the SCD3 mission to validate such communication concepts. Message communication services and propagation characteristics measurements over the Equatorial region are also included in the system. The SCD3 system is composed by the SCD3 satellite with its onboard communication payload, by a set of voice and message user terminals and by a Gateway Station. The Gateway Station has the capability to transmit and receive four simultaneous beams with independent Doppler correction and channel power control. The functionalities and performance characteristics of the Gateway Station are presented and discussed in detail.

1. INTRODUCTION

New voice and data communication systems are being proposed and developed worldwide using satellite constellations. The SCD3 system is a Brazilian effort toward a communication system using a small Low Earth Orbit satellite to implement voice and data communication capabilities in the Brazilian equatorial region.

The concept basic to the SCD3 system design is the use of simple bent pipe repeaters with multibeam array antennas in the L and S bands (Terminal to satellite link), and C band for the feeder link (Gateway to satellite link), a set of voice and message remote terminals transmitting and receiving directly to or from the satellite, and a Gateway Station that provides the feeder links and all ground processing facilities like CDMA access strategy, Doppler compensation, beam-to-beam handoff, power control, user access control and interface with the PSTN.

The following items present an overview of the SCD3 system including the main requirements of the pilot voice communication system, message communication service, and propagation characteristics and background noise level measurements. The Gateway Station main requirements as well as its architecture are presented in detail.

2. SCD3 SYSTEM DESCRIPTION

2.1 - THE COMMUNICATION SYSTEM CONCEPTS AND REQUIREMENTS

The communication concepts used in the SCD3 System, among others, are: a) use of bent pipe repeaters, with no onboard processing for voice or message communication; b) complex functions allocated to the Gateway Station. A PSTN user can access a remote voice or message terminal via the Gateway, that provides all facilities related to processing, routing, access control and billing functions; c) use of one equatorial LEO satellite at 1100 km altitude covering the latitude range of 5°N to 15°S; d) use of phased array for the L and S bands, each antenna providing four beams; e) use of spread spectrum modulation and digital techniques related to CDMA; f) voice and message remote terminals communicating directly to the satellite.

1-The SCD3 system is funded by the Brazilian Space Agency - AEB, contract 004/95.

2.2 - PILOT VOICE COMMUNICATION

The experimental voice communication system is composed by the SCD3 communication payload, a set of portable voice terminals and a Gateway station. This system aims to evaluate the performance as affected by the fading, interference and multipath environment, as well as the technological issues related to: onboard active antennas in orbit; spread spectrum modulation and CDMA (Code Division Multiple Access); error correcting codes; pseudo noise sequence selection and synchronization; transmitted power control; diversity reception; beam-to-beam hand-off; Doppler effect correction; voice coding methods (vocoder). In addition, the Pilot Voice communication system provides an infrastructure for field testing by other LEO satellite systems.

As all terminal transmissions are in the same L band frequency slot, and all satellite transmissions to the terminals are in the same S band frequency slot, spatial separation and CDMA are used. The spatial separation is provided by the multiple beams antennas that transmit to and receive from the user terminals. C band transmission from the satellite to the Gateway station uses Frequency Division Multiplexing, mapping L band signals in a beam into a C band slot. Gateway generated signals transmitted to the satellite in the C Band are mapped into four S Band beams.

The voice communication system performance goals are summarized as follows: a) BER better than 10^{-3} for a 4800 bit/s data rate; b) Mean Opinion Score (MOS) better than 3.4. The Vocoder algorithm produces the specified MOS voice quality in the presence of 0.1% random uncorrected bit errors; c) one-way voice processing delay no greater than 100 ms.

2.3 - MESSAGE COMMUNICATION SERVICE

The Message Communication Service receives messages from, or send messages to, remote terminals located in the Equatorial Region. These terminals transmit messages, via the satellite communication payload, to the Gateway station. If required, the Gateway station stores messages for further retransmission to a destination terminal. The received messages are filed in the Gateway station for PSTN users access. The system has an interface with commercial communication networks to allow terminal message exchange via phone or Internet. The Message Communication has a BER better than 10^{-6} for a 1200 bit/s in the outbound link and 2400 bit/s in the inbound link. Each terminal is interrogated at least once in every pass, i.e. every two hours, with message length of up to 1024 bytes. An example of system overall characteristics and the message communication service link analysis are presented in Tables 1 and 2.

2.4 - PROPAGATION CHARACTERISTICS AND BACKGROUND NOISE LEVEL MEASUREMENTS

The following measurements are planned: S band fading, C band fading, L band fading, and L band background noise as seen by the satellite over all the equatorial region. The measurements are based on the transmissions of S and C band beacons, which are measured at the ground by a special terminal and by the Gateway Station. The fading and noise level measurements have the following performance goals: a) data acquisition rate for L and S band fading measurement greater than 1000 samples/s; b) propagation measurement errors smaller than 2 dB; c) L and S band fading measurements in the latitude region from 5°N to 15°S, and with terminal elevation angle down to 5°; d) L band background noise level measured in the 1610 MHz to 1626.5 MHz band, covering the same latitude region; e) acquisition rate of the background noise level by the onboard computer greater than 1 sample/min.

TABLE 1 - SCD3 SYSTEM OVERALL CHARACTERISTICS

Satellite altitude	1100	km		Gateway elevation angle	15,0	deg
Terminal-satellite frequency	1,616	GHz		Satellite-gateway angle	55,5	deg
Satellite-gateway frequency	5,069	GHz		Satellite-Gateway Range	2588,0	km
Gateway-satellite frequency	6,844	GHz		Gateway Antenna Diameter	4,0	m
Satellite-terminal frequency	2,490	GHz		Gateway TX Antenna Gain	46,6	dBi
Number of beams	4			Gateway RX Antenna Gain	44,7	dBi
Number of Msg. Channels per beam	5			GW effective noise temperature	175,0	K
Data signal bit rate	1200	b/s		Satellite C band TX and RX antenna gain	3,0	dBi
Encoded signal rate (Viterbi k=7, r=1/2)	2400	b/s		Satellite L and S antenna array minimum gain	7,0	dBi
Required Eb/No	5,2	dB		Satellite L and S antenna array maximum gain	15,0	dBi
Chip Rate	1,25	Mbit/s		Satellite C band noise temperature	375,0	K
Terminal RX antenna gain	4,0	dBi		Satellite L band noise temperature	375,0	K
Terminal TX antenna gain	4,0	dBi		Satellite S band Saturated TX Power (W)	2,0	W
Terminal effective noise temperature	285,0	K		Satellite C band Saturated TX Power (W)	2,5	W

TABLE 2 - INBOUND AND OUTBOUND LINK ANALYSIS FOR THE MESSAGE COMMUNICATION SUBSYSTEM

OUTBOUND LINK				INBOUND LINK		
Terminal Elevation Angle (deg)	30,0	45,0		Terminal Elevation Angle	30,0	45,0
Satellite-Terminal Range (km)	1852,0	1455,1		Terminal/Satellite Range	1852,0	1455,1
Gateway Transmit Power per Channel (mW)	500,0	500,0		Terminal Transmit Power per Channel (mW)	1000,0	1000,0
Line Loss (dB)	0,5	0,5		Terminal Line Loss	0,5	0,5
Gateway EIRP per Channel (dBW)	43,0	43,0		Terminal Transmitted EIRP per Channel	4,5	4,5
Uplink Path and Misc. Losses (dB)	-178,4	-178,4		Uplink Path and Miscellaneous Losses (dB)	-162,5	-160,4
Satellite RX Power Level per Channel (dBW)	-132,9	-132,9		RX Power Level per Channel (dBW)	-152,0	-149,9
Satellite Noise Density (dBW/Hz)	-202,9	-202,9		Satellite Noise Density (dBW/Hz)	-202,9	-202,9
Uplink C/No Thermal (dB Hz)	70,0	70,0		Uplink C/No Thermal (dB Hz)	50,9	53,0
Satellite S band Saturated TX Power (W)	2,0	2,0		Satellite C band Saturated TX Power (W)	2,5	2,5
Satellite Output Backoff (dB)	2,0	2,0		Output Backoff (dB)	2,5	2,5
Satellite TX Power per Channel (dBW)	-6,0	-6,0		Satellite Power per Channel (dBW)	-5,5	-5,5
S band Satellite EIRP per Channel (dBW)	0,5	0,5		Satellite C band EIRP per Channel (dBW)	-3,0	-3,0
Downlink Path and Misc. Losses (dB)	-166,2	-164,1		Downlink Path and Misc. Losses (dB)	-175,3	-175,3
Terminal RX Power Level per Channel (dBW)	-162,2	-160,1		Gateway RX Power Level per Channel (dBW)	-134,1	-134,1
Terminal Noise Density (dBW/Hz)	-204,1	-204,1		Gateway Noise Density (dBW/Hz)	-206,2	-206,2
Downlink C/No Thermal (dB.Hz)	41,9	44,0		Downlink C/No Thermal (dB.Hz)	72,0	72,0
Code Noise Density @ Terminal (dBW/Hz)	-216,2	-216,2		Code Noise Density @ Gateway (dBW/Hz)	-188,1	-188,1
Terminal RX Code Noise C/No (dB.Hz)	54,0	56,1		Gateway RX Code Noise C/No (dB.Hz)	45,2	45,2
Outbound Link C/No (dB.Hz)	41,6	43,7		Inbound Link C/No (dB.Hz)	44,1	44,5
Terminal Received Eb/No (dB)	10,8	12,9		Gateway RX Eb/No (dB)	13,3	13,7
UT Matched Filter and Dem. Losses (dB)	1,0	1,0		Gateway Mat. Filter and Dem. Losses (dB)	1,0	1,0
Required Eb/No (dB)	5,2	5,2		Required Eb/No (dB)	5,2	5,2
Outbound Margin (dB)	3,6	5,7		Inbound Margin (dB)	6,1	6,5

2.5 - SYSTEM OVERVIEW

Figure 1 presents an overview of the SCD3 system.

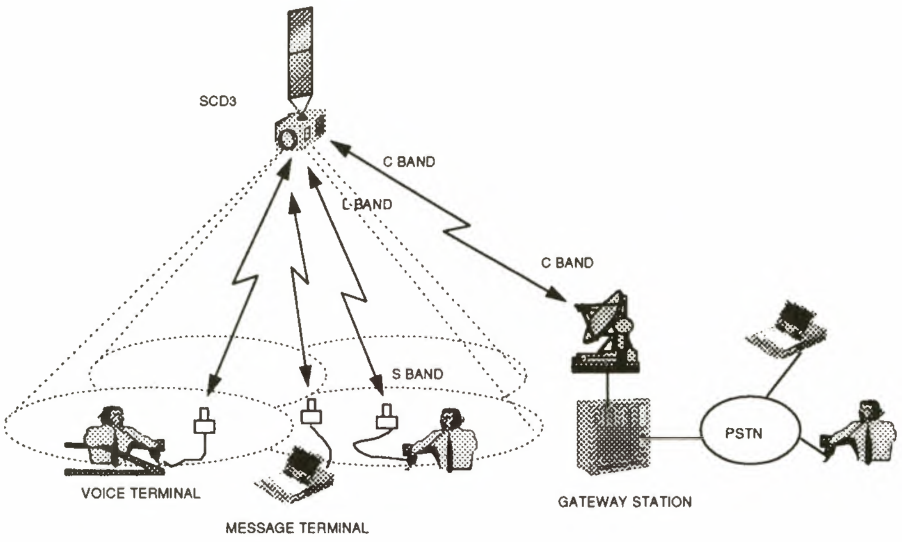

Figure 1: SCD3 system overview

The SCD3 space segment is composed by a three axis stabilized satellite, with 180 Kg weight and 185 W generated power, flying in an equatorial orbit of 1100 km altitude with a 2 hours period. Due to the SCD3 satellite design constraints, four beams are provided by phased array antennas in the L and S bands. Each beam can deliver up to 2 W in the S Band and 2.5 W in the C band.

The SCD3 Ground Segment comprises: a) the Satellite Control Center, located in São José dos Campos; b) three TT&C Stations, one of which portable, the fixed ones located at Cuiabá and Alcântara; c) the RECDAS Data Communication Network, which provides the data communication links between the Ground Stations, the Mission and Satellite Control centers and the Gateway Station; d) a Gateway Station with RF subsystem, voice baseband channel processing, message communication and propagation characteristics measurements; e) a set of voice and message terminals; f) a Data Collection Mission Center, located in Cachoeira Paulista, which receives, processes, stores and distributes the Data Collection Platform (DCP) messages; g) a number of small UHF Receiving Stations, which acquire DCP messages directly from the satellite, for storage and further processing according to the user application requirements.

3. GATEWAY STATION ARCHITECTURE

The Gateway Station is composed by the Gateway RF Subsystem (GRFS), the Voice Communication Subsystem (VCS), the Message Communication Subsystem (MCS) and the Propagation Measurement Subsystem (PMS). The Gateway Station has facilities to accept other baseband subsystems and experiments which may be defined and included in the future. The interface between the Gateway RF Subsystem and the baseband subsystems (VCS, MCS and PMS) is performed at 70 MHz IF frequency. Figure 2 presents the Gateway Station components and main interfaces.

The C Band uplink communication provided by the Gateway RF Subsystem is in the 6825 to 7025 MHz range. The C Band downlink is in the 5050 to 5250 MHz range. The Gateway RF Subsystem can transmit and receive up to four FDM C Band carriers with 12 MHz bandwidth, both in the uplink and downlink.

To permit system user access to the public telephone system, the Voice Communication Subsystem (VCS) and Message Communication Subsystem (MCS) are connected to the Public Service Telephone Network.
The Gateway RF Subsystem are interfaced to the Satellite Control Center via an X.25 data packet communication network. Through this interface the GRFS sends the station monitoring data to the

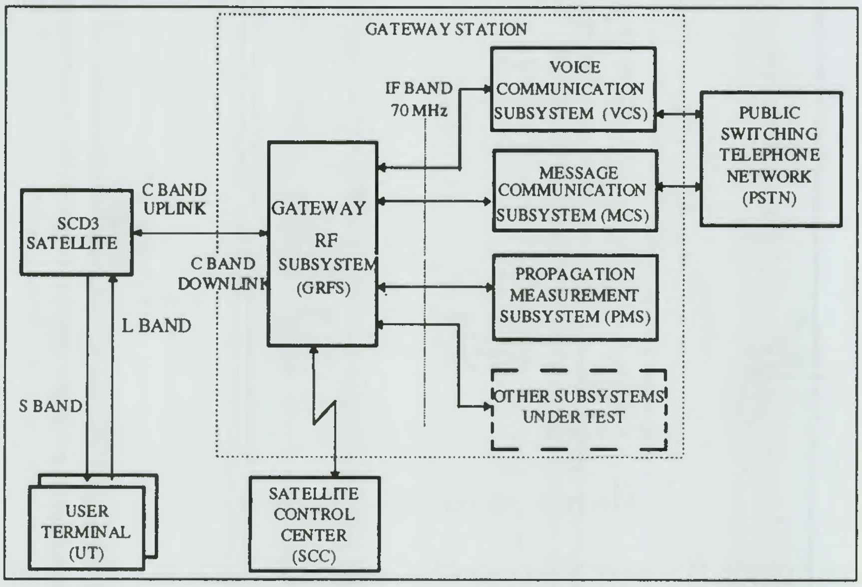

Figure 2: The Gateway Station Components and Main Interfaces

Satellite Control Center and receives the orbital elements for antenna pointing, uplink and downlink Doppler frequency corrections and station configuration and control parameters. By means of the interface with the Satellite Control Center and with the Station Monitoring and Control Computer the Gateway can be operated in an automatic mode.

The Gateway Station has a transportable infrastructure which houses all subsystems. The pedestal which houses antenna positioning and tracking mechanism, reflector and front-end equipments is mounted on a mobile base so that a concrete foundation is not necessary for its installation.

3.1 - GATEWAY RF SUBSYSTEM

Figure 3 presents a simplified block diagram of the Gateway RF Subsystem (GRFS), where its main components and interfaces are shown. Besides the C Band RF equipments related to down conversion to IF and up conversion from IF, the GRFS has the following facilities: Time and Frequency reference generation, Gateway Station Monitoring and Control, Data Communication with the SCC, Antenna Control, and Calibration and Test execution. Some of the main front end characteristics of the GRFS subsystem are summarized on Table 3.

Table 3: GRFS main characteristics	
Antenna diameter	< 4.2 m
Antenna gain (transmission)	≥ 44 dBi
High Power Amplifier (HPA)	solid state, linear, class A
HPA output power	> 50 W
EIRP	> 60 dBW @ HPA power of 50W
Channel transmission power control range	20 dB in steps of 1 dB
Polarization	LHC with 1.0 dB axial ratio
Figure of Merit (G/T) of the antenna	≥ 25 dB/K @ 10°EL and 23°C temperature
Frequency control for Doppler compensation	>±150kHz, step 1Hz to 1kHz, phase continuous

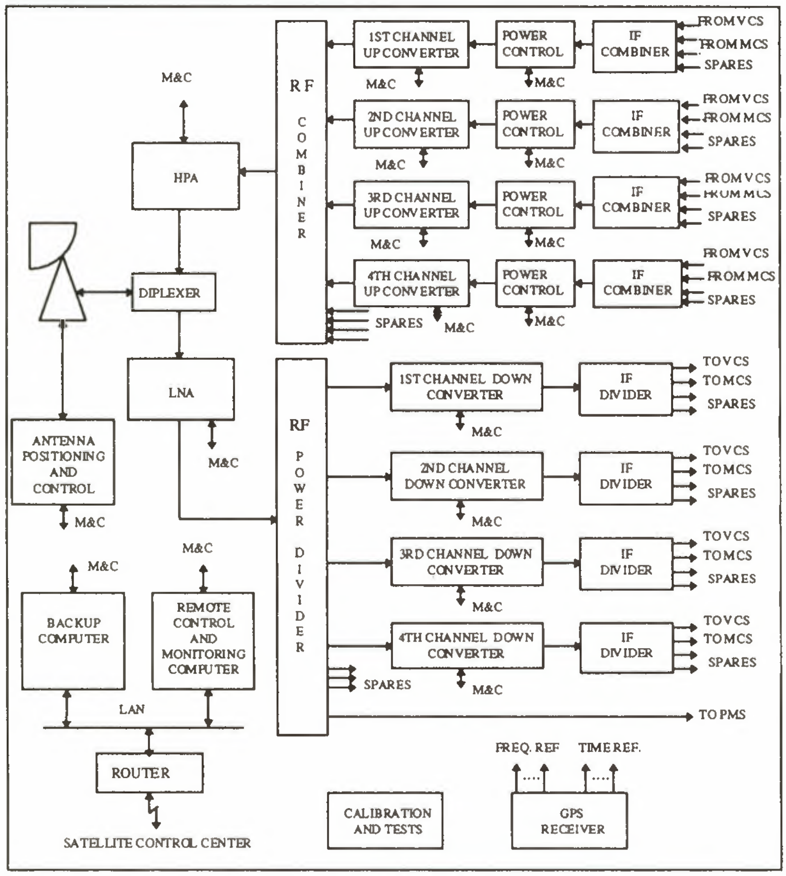

Figure 3: Gateway RF Subsystem (GRFS) simplified block diagram

In the transmission chain there are a set of four IF power combiners, IF power control and channel up converters which are associated to each one the four up link spread carriers, in such a way that each up link carrier frequency can be tuned in all the transmission band with its power independently adjusted. The 70MHz IF signals inputs received from the baseband subsystems are combined in the IF Power Combiners and power level controlled to compensate the free space loss variations to maintain the Satellite C/S Band repeater power output constant. The outputs of the power control units are converted to the C Band up link frequencies by the channel up-converters.

The outputs of the channel up-converters are combined in the RF Power Combiner and transmitted to the satellite. The channel up converter local oscillators use an agile synthesizer with frequency control and sweep capabilities, real time programmed via the Remote Control and Monitoring Computer, in order to compensate continuously the Doppler effect both in the C Band uplink and in the center of the S Band downlink beams. The RF Power Combiner has provisions to accept four additional carriers in the future.

The receive chain has capabilities to receive 4 simultaneous FDM carriers in the C Band. After being detected, amplified and down converted to an appropriate frequency, the received signals are sent to one of the four channel down converters. Each down converter can be tuned in all the reception band. The carrier down converter output is sent to the IF Power Divider which provides the 70 MHz IF outputs to the baseband subsystems. Similar to the transmission chain, the receive chain has a set of 4 down converters and IF Power Dividers associated with one of the received C Band spread carriers. The local oscillators of the carrier down converter use an agile synthesizer with real time programmed frequency sweep capabilities, via the Remote Control and Monitoring Computer, in order to compensate continuously the Doppler effect both in the center of the L Band uplink beams and in the C Band downlink.

The Time and Frequency Unit basically consists of a GPS receiver and is responsible for generating and distributing the time and frequency reference signals to other subsystems.

The Monitoring and Control Unit, based upon an IBM-PC, performs the periodic monitoring of the Gateway Station subsystems status with a period not greater than 4 seconds. The transmitted power control to compensate the satellite range is included in the Monitor and Control functions, as well as the frequency sweep in order to continuously compensate the Doppler effects in the link. The control function permits the complete automatic operation of the station, without the need for local operator intervention.

The Antenna Positioning and Control Unit can operate in the manual positioning, programmed positioning (antenna pointing data provided by the Monitoring and Control Computer) and autotrack modes. For autotrack mode a C band beacon is transmitted by the SDC3 satellite.

The Calibration and Test Unit provides all the necessary tools to execute all the tests and calibrations required to put the Gateway Station in operational state, including, transmission and reception chain functional tests, pointing alignments, test and calibration of autotrack and many other.

3.2 - MESSAGE COMMUNICATION SUBSYSTEM

The Message Communication Subsystem simplified block diagram is shown in the figure 4.

An interrogation protocol and strategy for the service channel ensures that MCS receives at least one message every two hours from each UT. Messages can be transmitted to the UT through the service channel in the interrogation period. The service channels processors, one for each beam, perform the data encoding for error correction, carrier phase modulation with the encoded data and the pseudo noise (PN) sequence, and up conversion to the 70 MHz IF Band. To each beam is attributed an individual PN sequence with low cross correlation.

The MCS will initially have the capability to process up to 5 simultaneous CDMA message channels per beam. One emergency channel per beam is available to permit communications in special conditions such as alarm and loss of contact during the normal polling process. Considering a message length of 1024 bytes and a data bit rate of 2400 bits/s the system has a potential capacity to receive 3000 UT messages in each satellite pass. The traffic message processor performs the 70 MHz IF down conversion, PN code acquisition and tracking, phase demodulation, bit synchronization and data decoding. In the traffic message channels the CDMA is implemented using Gold Sequences.

3.3 - VOICE COMMUNICATION SUBSYSTEM

The Voice Communication Subsystem simplified block diagram is shown in Figure 5.

In the outbound link a pilot channel is used for each beam. The pilot channel is employed by the UT to establish chip and bit timing, to perform residual Doppler shift compensation and to execute the outbound power control. All channels within a particular beam, including the pilot channel, share a common PN mask. The CDMA is implemented using a set of Walsh codes. The outbound traffic channel processors perform data encoding for error correction, carrier phase modulation with the coded data and the pseudo noise (PN) sequence, outbound channel power control and up conversion to the 70 MHz IF Band.

In the inbound link the CDMA is implemented using a set of Gold codes. The inbound traffic channel processor performs the 70 MHz IF down conversion, PN Gold code acquisition and tracking, phase demodulation, In the outbound link a pilot channel is used for each beam. The pilot channel is employed by the UT to establish chip and bit timing, to perform residual Doppler shift compensation and to execute bit synchronization and data decoding. For UT system log-on and call request an access channel is available in each beam of the inbound link. The access channel uses random access method.

All signal routing, including UT to UT or UT to PSTN, is executed under control of the Voice Control Computer. Channel and code allocation and channel power control are done under command of the Voice Control Computer. A line interface with voice codification and decodification is responsible for the connection with the PSTN.

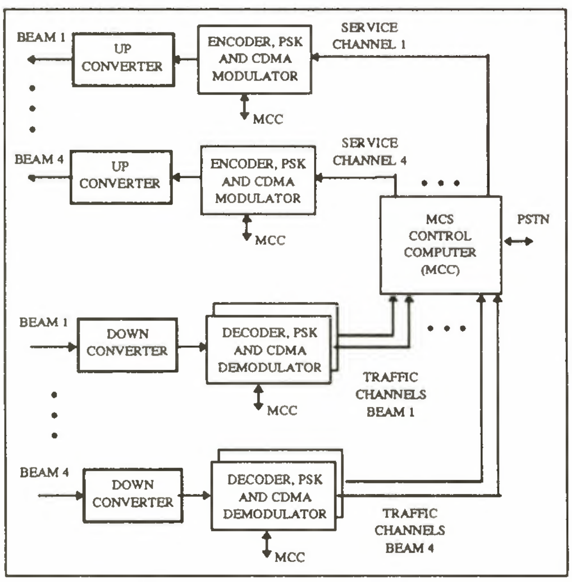

Figure 4: Message Communication Subsystem simplified block diagram

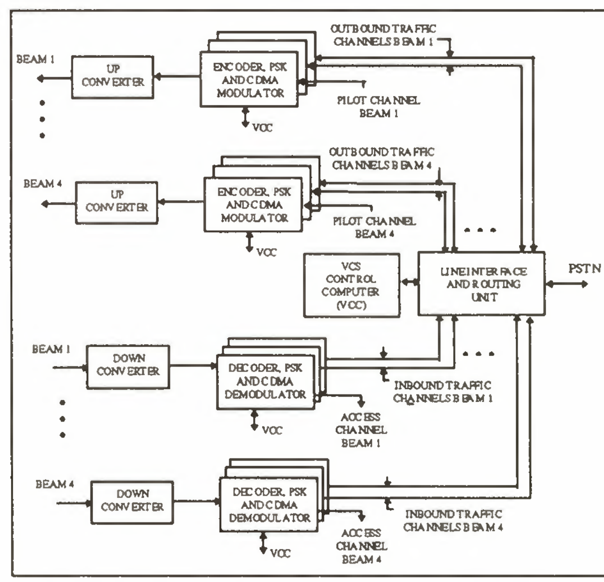

Figure 5: Voice Communication Subsystem simplified block diagram

3.4 - PROPAGATION MEASUREMENT SUBSYSTEM

The Propagation Measurement Subsystem (PMS) uses a phase locked loop receiver, with a narrow IF bandwidth and coherent AGC, and a data acquisition unit with high sample rate. The measurements are time tagged and stored for further processing and analysis.

4. CONCLUSION

A general description of the SCD3 system and the Gateway Station is presented, with emphasis on the pilot voice and message communication service. The Gateway Station assumes an important role in the mission in terms of the pilot voice communication and the message communication service.

The present design of the Gateway Station takes into account the needs for flexible operation whereby key communication concepts can be tested or evaluated in the field, not only by INPE but also by other interested organizations.

The whole system is specified and bidding is in process, some subsystems being under revision to take into account compatibility requirements. The planned launcher is the VLS, a Brazilian launcher under development by the IAE (Instituto de Atividades Espaciais). The present schedule foresees the conclusion of the SCD3 satellite as well as the Ground Segment by the end of 1998.

THE MINI PRESSURIZED LOGISTICS MODULE TECHNICAL SUPPORT CENTER (MTSC)

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ABSTRACT

In the frame of the bi-lateral cooperation between the Governments of USA and Italy (and between NASA and ASI at the Agency level), Italy will provide the ISSA Program with a Mini Pressurized Logistics Module (MPLM) fleet. These MPLM's will perform a regular ground-orbit-ground service for the logistic support of ISSA.
The vehicle design requirements are ten years of operations and twenty-five missions for each of the three delivered MPLM's. In order to maintain the fleet readily available for the missions a large effort will be spent in preparatory and support ground activities such as flight segment maintenance, mission analytical integration, post-flight assessment and prediction of subsystem/equipment performances, etc.
NASA and ASI agreed that an MPLM technical support organization should be established in Italy to ensure continuity in the application of the know-how gained by the Italian Industry during the development phase (currently on-going).
The MPLM Technical Support will be a major component of the ASI Logistics & Technological Engineering Center (ALTEC), located in Torino, Italy, a short distance off the premises of Alenia, the MPLM Industrial Prime Contractor. This ALTEC section supporting the MPLM operations is called the MPLM Technical Support Center (MTSC) and will host four major application functions:
- Integrated Logistics Support Function (ILSF)
- Engineering Support Function (ESF)
- Sustaining Engineering Function (SEF)
- Training Function (TF).

The MTSC will be fully operational from the first MPLM mission (in 1998) and support the MPLM Program throughout its life-cycle. This paper will detail the functions of the MTSC and present the current implementation status and plans.

1.0 INTRODUCTION.

This paper describes the functions and the architecture of the ASI MTSC that will support the MPLM operations ever since the start of the phase E operations.
Three top-level MTSC function classes have been defined:
- Management operations, for the local coordination and integration of the MTSC services (this function classically includes Management and Administration, PA/Safety, Configuration Control and Project Control)
- General Services operations, for the maintenance of the MTSC facilities, building security, documentation services and other support services
- Technical operations, which may be broken down in the following functions:
  - the Integrated Logistic Support (ILSF), for the timely identification of re-supply/maintenance requirements, acquisition of related flight and ground equipment and storage/maintenance of the assigned equipment inventory
  - the Engineering Support (ESF), where the engineering capability to support the MPLM fleet flight and ground operations will reside
  - the Sustaining Engineering (SEF), capable to follow through the evolutionary growth of the MPLM systems in accordance with the ISSA program needs

- the Training Function (TF), for the certification of the MTSC staff as well as the support to the training of the NASA MPLM flight and ground operations crews.

The four technical sub-functions will closely co-operate and share several interfaces in order to maximize the operational effectiveness of the MTSC as a whole.

2.0 MPLM OPERATIONS AND GROUND SEGMENT OVERVIEW

After delivery to the Kennedy Space Center, processing at the SSPF, launch (on the NSTS) and transfer to ISSA the MPLM will be berthed to a station node by the Remote Manipulator System (RMS). The MPLM will next be activated, checked-out and then set up for manned operations. Before return to ground in the same NSTS mission the MPLM will be prepared for return and re-installed in the NSTS cargo bay by the RMS.

After the post landing activities the MPLM will be "turned around" and configured for the next mission. This phase includes the exchange of degraded flight systems as well as the necessary maintenance, refurbishment and repair activities.

The MPLM ground segment will include:

- the JSC, Houston, Texas, the MCC for the NSTS/MPLM missions
- the KSC, Florida, performing all MPLM SSPF processing for both passive and active flights
- the MTSC, located at the premises of the ASI ALTEC, Torino, Italy. The MTSC will also have de-centralised legacies at the KSC and the JSC.

The MTSC will be the MPLM-dedicated support center and will work with the KSC resident team for off-line operations and with the JSC for the mission operations activities.

3.0 MTSC FUNCTIONAL OVERVIEW

3.0.1 INTEGRATED LOGISTICS SUPPORT FUNCTION (ILSF)

The MTSC Integrated Logistics Support (ILS) provides for long term integrated logistics support to the MPLM's and the associated ground support elements, by providing the following services:

- Logistics Engineering (LSA, RLA, RCMA and Logistics Life Cycle Cost (LLCC))
- support to the organizational level maintenance and performance of depot level maintenance
- execution of provisioning analyses, procurement, warehousing, inventory management
- generation of updated manuals and documentation for MPLM logistics support
- coordination, planning and execution of the MPLM off-line related activities.

The ILSF activities will be suitably located, i.e.:

- the MTSC in Torino is the site for all the off-line activities that do not directly influence the MPLM ground cycle. This includes e.g. depot level maintenance (when not assigned to the equipment Suppliers), second line spares storage, inventory management, technical documentation maintenance and update, ILS database maintenance, ILS analyses, etc.
- the KSC is the main location for all the on-line and organizational level maintenance support activities.

3.0.2 ENGINEERING SUPPORT FUNCTION (ESF)

The MTSC ESF will support pre-launch, on-orbit, post-landing and turnaround phases to perform flight and ground segment analyses, as required, e.g.:

- system status and performances evaluation
- updating of mission scenarios, constraints, procedures and software
- development and maintenance of MPLM plans and procedures

- development of hardware and software related information products
- deviation/waiver processing
- requirements and specifications change handling
- support to system re-test and verification activities
- support of safety assessment, reviews and certifications
- support to Ground Processing Operations planning and execution
- real-time support to mission operations (at JSC), including anomaly resolution and troubleshooting phases.

The MTSC ESF will closely co-operate with the corresponding function of the ISSA program.

3.0.3 SUSTAINING ENGINEERING FUNCTION (SEF)

The Sustaining Engineering Function is driven by the requirement to maintain and improve the MPLM system performance throughout its lifetime. The SEF tasks relate to the provision of approved H/W and S/W updates whether for the problem correction or for performance improvement, as well as for data and documentation updating. The SEF process will thus be applicable to the MPLM Flight H/W, S/W and delivered GSE and will also involve all the models, simulators, trainers, etc..
The SEF is structured to provide the following support services:

- Coordination and Planning
- Flight and Ground H/W Design Maintenance
- Flight and Ground S/W Maintenance
- MPLM System Integration and Verification
- anomaly resolution/troubleshooting plannning.

The SEF process may be activated by:

1. Engineering Changes Request (ECR) due to:
    - Problems/requirements identified and assessed throughout all mission phases
    - System upgrading, due to new customer requirements (including crew assessment), performance upgrade needs, change of standards, etc.
2. Software Problem Report (SPR), issued by the SEF itself during testing of S/W or mission operations
3. Software Change Request (SCR), issued by the ESF due to new customer requirements or system upgrading. The SCR will be processed by the MTSC Software Engineering Team. Change Contract Notices will be issued when external organizations are involved e.g. Space Segment Contractor for the MDM.

The SEF activities will generally lead to:

- H/W acceptance including Testing and Qualification Control
- H/W integration and verification at system level
- delivery, installation and verification (including H/W and S/W compatibility testing) of updated or new S/W.

3.0.4 TRAINING FUNCTION (TF)

The Training Function (TF) is the function of the MTSC that will support the flight and ground crew training with respect to the MPLM design and operations features.
The TF will benefit from the availability of the MPLM tools and models based at the MTSC in order to contribute to the overall ISSA training system.
The MTSC will sustain lessons/courseware developed during the Phase C/D and provided to NASA for flight crew and operations personnel training. MTSC instructors will train NASA trainers on MPLM and will give support, as required, during the execution of training activities at JSC and KSC. The MTSC TF will train and certify the MTSC personnel which is located at JSC, as engineering support, and at KSC, for logistics and ground operations.

4.0 MTSC ARCHITECTURE OVERVIEW

The length of the MTSC operational lifetime implies that the architecture design should be such to simplify maintenance and successive upgrades of its components.
State-of-art technologies have been thus considered to enhance the overall modularity and possibly limit the effort for future upgrading (e.g Fiber Distributed Data Interface (FDDI) for the backbone LAN, powerful off-the-shelf workstations for nearly all the positions in the center, etc.).
In addition the MTSC has been broken down in facilities associated with the technical support functions and main services to be provided. Each facility will group the subsystems supporting one or more specific MTSC tasks. Each subsystem in turn is operated by a dedicated team of personnel and is only allocated function-unique hardware and software tools. The common data processing, archiving and communication resources will be provided and managed at central level and will be remotely accessed by the various subsystems through defined service levels.
The architectural design approach has also taken into account the following criteria:

- maximized H/W and S/W commonalty in order to limit procurement and running costs as well as to increase the overall flexibility, modularity and operational compatibility
- "robust" design to reduce the system down-times
- isolation and encapsulation of the major functions to fulfill the security, safety and maintainability requirements and allow maintenance to be executed on no-interference bases to routine operations
- decentralized data processing by means of work station clusters with local data storage and data base management services, which allows the off-load of the centralized mainframe services, the physical separation of functions and the unambiguous cluster-specific allocation of tasks
- use of off-the-shelf platforms, standard S/W (e.g. OS., graphic std. and Data Base mgt.) and common H/W and S/W items out of the MPLM C/D phase.

With respect to the MTSC services availability the current concept is to provide adequate redundancy to ensure reasonably responsive SSCC support and high probability that the increment preparation activities will be accomplished in due time. The following design features are being considered:

- high speed redundant backbone LAN
- standard workstation
- standard PC
- S/W back-plane
- dual power supply
- diversified external communication routings
- high availability PABX
- duplication of selected H/W components

In particular the high speed backbone LAN is based on FDDI technology and supports the center communication services and data distribution. The backbone consists of a dual ring to which standalone facilities, servers and workstations are hooked up. Moreover the standalone facilities (e.g. FCRF) have their own internal LAN connected to the backbone LAN by a switch system which enables to isolate the facility from the rest of the center (e.g. for security or set up of reproducible test conditions in the center). The common servers, workstation and gateway (e.g. Archiving Servers and security gateway) are directly connected to both rings of the backbone by Dual Attachment Stations (DAS). They will provide services to any part of center which need them. The application workstations have access to all the MTSC services and applications in accordance to the client-server architecture.
The implementation of a distributed system where the local processing capabilities are complemented with centralized common services fulfills flexibility requirements, minimizes S/W license needs and allows the standardization of H/W platform and S/W products . All the S/W applications available to a user workstation may be accessed through an integrated menu system (S/W back-plane) that matches security and licensing constraints. Consequently the H/W platforms can provide a minimum amount

of resources (e.g. memory, HD size, CPU) without being constrained by the specific application and user needs.

5.0 MTSC FACILITIES DESCRIPTION

In accordance with the architectural design approach described in Para.4.0 the MTSC functions have been grouped as follows:

- Common support services including communications, processing, archiving, infrastructure
- MPLM application specific services
- Common support resources including building, administration, transport and warehouse.

The adopted grouping approach has led to the definition of the following facilities and subsystems :

- Communication and Computing Infrastructure Facility (CCIF):
  - Central Data processing S/S
  - Central Archiving S/S
  - Communication S/S
- Application Support Facility (ASF):
  - Operation S/S
  - Logistic S/S
  - Training S/S
  - Maintenance S/S
- General Service Facility (GSF):
  - Warehouse and Transport S/S
  - Building and Infrastructure S/S
  - Workshops and laboratories S/S
- Configuration Reference Test Facility (CRTF)
  - MPLM EQM
  - other C/D equipment and S/W.
- Management Facility (MF)

The various facilities and subsystems will be briefly described in the following paragraphs.

5.0.1 Communications and Computing Infrastructure Facility (CCIF)

The CCIF will support:

- MPLM telemetry monitoring
- MTSC internal and external link data routing, multiplexing/demultiplexing, monitoring and control
- central databases configuration
- networks management and configuration
- network and data access security
- audio/video buffering, recording, playback, duplication, security, switching and distribution
- internal/external voice/video conferencing
- automatic central archiving of telemetry and processing services
- reception, switching and distribution of data from PTT public networks

The CCIF consists of the following subsystems:

- Central Data processing S/S
- Central Archiving S/S
- Communications S/S

5.0.2 Central Data Processing Subsystem (CDPS)

The CDPS will provide an array of tools and equipment that support:

- MTSC communication network coordination and configuration
- MTSC facilities monitoring and control

- MTSC operational databases management (e.g. access control, configuration, etc.)
- MPLM telemetry monitoring and processing
- file transfer processing
- preparation database management
- temporary data storage and retrieval of processed data
- file and data security management
- user nodes administration
- documentation maintenance and preparation.

The CDPS will provide the following tools and equipment:

- application computers and telemetry S/W processing
- workstations and related peripherals with general S/W applications and communication protocols
- database systems
- short term storage for processed data.

5.0.3 Central Data Archiving Subsystem (CDAS)

The CDAS will support the MTSC applications as well as the general services of the center such as:

- storage, archiving and retrieval of the MPLM telemetry
- storage, archiving and retrieval of mission, training, logistic, maintenance repository data and files
- storage, archiving and retrieval of MPLM flight configuration reference data and files
- storage, archiving and retrieval services for products such as: planning and preparation data, execution reports, etc.
- data security/protection against unauthorized access and accidental loss
- data base definition and maintenance
- telemetry acquisition and monitoring

The CDAS will consist of a set of dedicated data base systems, namely:

- Telemetry Data Base
- Operations Data Base
- Engineering Data library
- Logistic Data Base
- Training Data Base
- Management and planning Data Base
- History Data Base

The CDAS will interface both NASA centers and internal subsystems (e.g. MPLM telemetry/Mission data transfer and file exchange with the SSCC).

5.0.4 Communications Subsystem (CS)

The CS will support the MTSC applications as well as the general services of the center such as:

- data/files routing, distribution and transfer services for all MTSC user nodes connected to the internal LAN
- exchange of application messages and distribution of mission/MTSC status reports
- internal and external MTSC networks monitoring, maintenance and node coordination
- interactive access and data transfer to/from remote database
- Gateway/bridge control and monitoring
- Audio and video network management and distribution
- External and internal data security services
- E-mail and WWW interface management
- User administration and directory services
- Network user address management

The CS will consist of the following:

- security and conversion gateway
- main audio, video and LAN Control

- data transfer processor
- facility bridges and forward MUX/DEMUX
- communication Support and telemetry Acquisition S/W

The CS functionality will be set up by means of three independent networks for data, voice and video. The data network includes the following main elements:

- LAN data backbone (LDB)
- work group LAN's (WLAN's)
- Directly Attached Facilities (DAF)

The LDB is a high speed optical fiber-based LAN, using the following protocols:

- ISO levels 1/2 --> Ethernet 802.3
- ISO levels 3/4 --> TCP/IP
- ISO levels 5 to 7 --> X11/FTAM/TBD

The LDB user may be a workstation, a server or another sub-network. The backbone LAN is used to circulate data between work-groups and DAF's. The work group LAN's support clusters of work stations and local peripherals. The LAN's are in looped configuration to take advantage of the self-healing capability that this confers. The LDB physically consists of two fibers which run across the building floors.

The voice (audio) channels arriving at and leaving the MTSC will be digital. This includes normal telephone calls from PTT. The voice channels are fed into a digital PABX. The PABX distributes voice services using a fiber optic network. The fibers run to small sub-PABX's which have a capacity of six to ten bi-directional channels. These will normally serve a work group. The operational PTT audio circuits are managed separately by a small PABX. Terminations for these loops are only in secure areas. The small PABX has a capacity of twenty bi-directional channels.

A single commercial standard will be used for the Video LAN within the center. The conversion from different standards will be done using commercial equipment. All video signals are then distributed through optical fibers. As only a few signals are generated within the center itself, there is no need to have a full LAN capability. The signals generated internally are sent to the LAN controller (as baseband signals) via dedicated fibers. The LAN controller then mutiplexes these signals, together with those from external sources, onto the distribution fiber. The multiplexing method is FDM, a state-of-art technique for this type of video distribution. The standard fibers used for the subsystem would enable to handle HDTV in the future, if this became necessary. Video circuits connected via the public network are all two-way (video-conferencing circuits) and need no special security measures. Either they are terminated directly to the center internal video standard and then distributed via protocol-free, unidirectional internal circuits. The signals are then converted to the center internal video standard and distributed via protocol-free, unidirectional internal circuits.
Two-way (video-conferencing) circuits connected via the IGS would be dealt with in the same way as the public network video-conferencing circuits. In the case of dedicated terminals, these would have to be located in a secure area.

5.0.5 Application Support Facility (ASF)

The Application Support Facility will consist of the following subsystems :

- Operations S/S
- Logistic S/S
- Training S/S
- Maintenance S/S

Each subsystem is organized into work-groups of workstations sharing a common, dedicated LAN in order to minimize the traffic load requirements on the main LAN. Each work group will host a set of function-specific S/W tools, e.g. the OS work group of workstations will run the following S/W tools:

- operation development and integration S/W
- mission planning S/W

- mission trend analysis S/W
- mission performance analysis S/W
- documentation generation, updating and maintenance S/W
- Mission Data Base application S/W
- operation S/W support tools
- operating system S/W
- network S/W
- local Data Base management S/W.

5.0.6 Maintenance Subsystem (MS)

The MS subsystem will support the following functions during pre-launch, on-orbit, post-landing and turnaround phases:
- coordination, control and planning of engineering activities
- technical data and documentation generation and maintenance
- deviation/waiver processing and reporting
- MPLM H/W and S/W change/update assessment, development, verification and certification
- flight S/W integration and qualification
- engineering assessment of flight data products
- engineering Data Base generation and maintenance
- anomaly/troubleshooting plans/procedures generation, updating and maintenance
- flight configuration control, updating, changing and Data Base maintenance
- telemetry Data Base maintenance
- failure and malfunctions assessment
- troubleshooting management and coordination
- product assurance, configuration and project control

As other S/S's the MS is organized around a work group of workstations running dedicated S/W packages, e.g.:
- configuration management S/W
- engineering Data Base application S/W
- engineering S/W support tools.

5.0.7 General Service Facility (GSF)

The GSF will provide the building and infrastructure facilities and the general services to support both technical support tasks and management and administration functions, i.e.:
- warehouse and transportation
- building and infrastructure
- workshops and laboratories:
    - electrical and electronic workshop
    - mechanical workshop
    - fluidic workshop.

5.0.8 Flight Configuration Reference Facility (FCRF).

The FCRF will cater for the representation of the MPLM on-board configurations to support:
- training activities
- design upgrading, changes and new development assessment and verification
- MPLM system S/W qualification
- integrated MPLM system simulation for interfaces verification
- development and testing of simulation models, etc.

The FCRF will inherit a number of items from the MPLM C/D Phase such as the MPLM EQM, etc.

6.0 MTSC IMPLEMENTATION PLANNING OVERVIEW

The first MPLM launch will be in January 1999.
The Phase C/D activities are approaching, at the moment, the Project CDR (Critical Design Review) which will be held in January '97.
At the CDR the ASI Contractor, Alenia Spazio will issue the final analysis of the MTSC tasks and the preliminary architecture. In parallel ASI is going to issue a RFQ for the implementation of the MTSC functions through the MPLM life time (Space Station time frame). The activities for the acquisition of an already existing building capable to host the entire ALTEC , and therefore the MTSC facilities and staff, are, at this moment on-going.
The MTSC is planned to be ready mid-98.

BRAZILIAN EXPERIENCES IN UPGRADING A SATELLITE CONTROL SYSTEM

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ABSTRACT. This paper presents the experience of migration of National Space Research Institute (INPE) Satellite Control System from a centralized architecture to a distributed one. The aims of this migration are: to fulfill the requirements of the different space missions planned for the next years; to reduce the costs of hardware maintenance and software development/maintenance; to provide facilities to increase the software reutilization; and to provide necessary hardware and software configuration flexibility for specific needs of each mission. Along with the change of the architecture, the migration of INPE´s Satellite Control System (SICS) from a VAX/VMS platform to a ALPHA/OpenVMS one was also done.

1. INTRODUCTION

INPE has under its responsibility the development and the control of the six satellites of the Brazilian Complete Space Mission (MECB)[1]: three data collecting satellites (SCD1, SCD2 and SCD2-A), two remote sensing satellites (SSR1 and SSR2) and one data collecting satellite with a low orbit communication experiment (SCD3). INPE is also taking part in the development and control of the two remote sensing satellites of the CBERS (China-Brazil Earth Resources Satellite) program and of small scientific satellites.

INPE has developed a control system named SICS (Satellite Control System) in order to control the in-orbit first Brazilian satellite (SCD1) launched in February 1993. SICS has fulfilled the control requirements of the SCD1 and it will fulfill the control requirements of the SCD2 and SCD2-A as well. These are scheduled to be launched in 1997.

Until the end of 1995, the SICS was installed in an environment composed of Digital machines of the VAX family, using the VMS operational system, with a high maintenance cost for INPE. The SICS migration to ALPHA machines environment, with the Open VMS operational system, was planned and executed in order to reduce such cost. This migration assured the continuity of the SCD1 control as well as the future control of SCD2 and SCD2-A satellites. Section 2 presents this migration experience.

Because the SICS doesn't fulfill all the requirements for the control of the other satellites the updating of some of its subsystems is mandatory. This fact together with the advantages of the use of new technologies led to a new concept, based on a distributed architecture, for the satellite control system. Section 3 presents the new architecture as well as the foreseen strategy to make it possible.

Section 4 presents the development of a new Telemetry and Telecommand System based on microcomputers and Microsoft Windows environment which is the first step in order to reach the distributed architecture.

Section 5 presents the conclusion of this work.

1- This program is funded by the Brazilian Space Agency-AEB, contract 004/95

2. MIGRATION OF THE SATELLITE CONTROL SYSTEM FROM VAX/VMS TO ALPHA/OPENVMS

In december 1995, aiming at reducing maintenance costs, the Satellite Control System (SICS) of the Satellite Control Center (CCS) was transfered from Digital computers of the VAX family to ALPHA family computers. In march 1996, the same procedure was carried out in the Cuiabá Ground Station (GS). CCS and GS are part of the ground segment used by INPE to control its satellites. These sites are interconnected by a private communication network (RECDAS) which uses the X.25 protocol.

This migration was necessary because besides being used to control the SCD1 satellite SICS will also be responsible for the control of the SCD2 and SCD2-A satellites which are foreseen to be launched in 1997.

2.1. HARDWARE UPDATING

Until the end of 1995, the CCS made use of two VAX 8350 with 16 MB of RAM and 2 GB of disk, connected in a cluster, to control the SCD1 satellite and a VAX 11/780 with 8 MB of RAM and 1 GB of disk for software development. In the Cuiabá Ground Station a MICRO-VAX II with 8 MB of RAM and 180 MB of disk was used. The operational system used in all these computers was the VMS 4.7. The previous VAX architecture, which was a part of the INPE ground segment, is shown in figure 1.

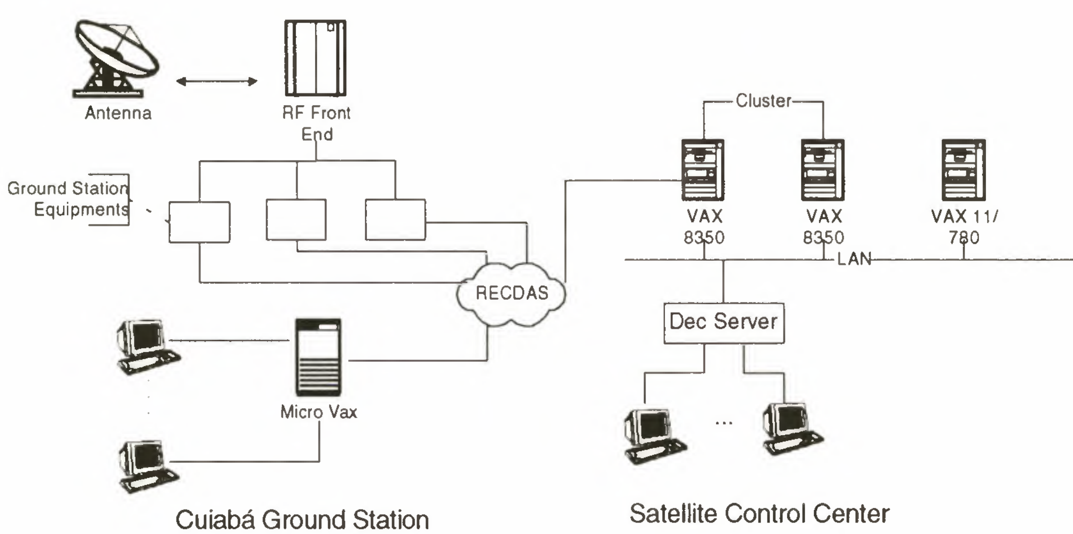

Fig. 1 Previous VAX Architecture

INPE was spending about US$ 200,000 per year on the CCS and GS computers maintenance. As this cost was very high and was tending upwards, the replacement of the old computers by ALPHA computers was decided. So INPE bought two ALPHA/300 (64 MB of RAM and 1 GB of disk) to replace the MICROVAX at GS and two ALPHA-2100 (128 MB of RAM and 12 GB of disk) to replace the CCS computers (see figure 2).

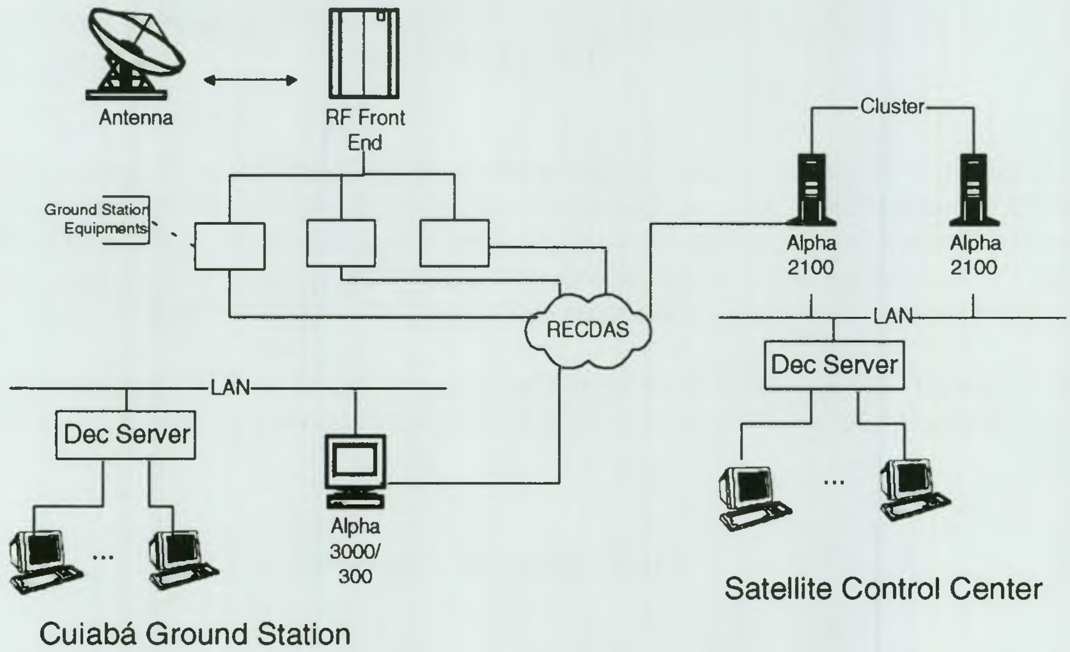

Fig. 2 - Present Alpha Architecture

These computers were bought for about US$ 120,000 carrying a 3 year warranty. With this information we can foresee that in 3 years the migration will result in savings of about US$ 480,000 besides having much higher performance machines in operation.

2.2. SOFTWARE MIGRATION

SICS, composed by about 2000 software units (programs, subroutines, functions and include files) with a total of about 185.000 FORTRAN 77 code lines, was developed between 1986 and 1992 according to an analysis and design structured methology by a team of up to 36 people during the design period. SICS is used in CCS as well as in GS where, besides acting as a CCS backup in case of a its failure, it has other functions such as to manage the antenna and to monitor and configure the GS equipment.

The migration of the SICS to the ALPHA/OpenVMS environment used 740 man-hours from INPE and about 60 man-hours from DIGITAL technical support. It is important to emphasize that a large part of the migration success must be credited to the standards and to the configuration control used during the SICS development. This fact allowed that few people, without a deep knowledge of all the SICS subsystems, performed all the migration process. After the conclusion of the migration process, it was verified that 104 out of a total of 2000 SICS software units were modified.

A great improvement in the SICS performance was noticed after the SICS migration. For instance: the system startup in the old environment took about one minute while now it is almost instantaneous; the telemetry file recovery took about one minute and now it takes about 10 seconds; the recovery of data stored on magnetic tapes took about one hour and now it takes about 15 minutes. A great increase in the reliability of the process of data transfer from disk files to magnetic tape files was also noticed. This transfer process, which used to present failures, has no longer requested maintenance team action.

2.2.1 IMPLEMENTATION ASPECTS

The more important aspects noticed during the migration process are presented as follows:

a) DATA ALIGNMENT
All software units were compiled with the option of "no alignment" in words of 64 bits instead of the default option (data alignment) of the FORTRAN compiler. This was done to avoid making changes in many SICS data structures which would have been necessary if the default option had been used. For instance if we had modified many record file structures we would have had to rebuild several SCD1 files to preserve compatibility. The SICS performance with the ALPHA processor became much better despite the use of this option.

b) GLOBAL SECTION
Most changes, 96 out of 104, were made to correct parameter input to System Services which handle creation and mapping of global sections. This difference between the ALPHA/OpenVMS and the VAX/VMS Application Programming Interfaces (API's) required very simple changes after all software units using these services were located.

c) OPENVMS 6.2 BUGS
Three software units had to be modified in order to get over 3 bugs of the OpenVMS 6.2. The found bugs are: BACKSPACE FORTRAN command doesn't work for magnetic tape files; messages sent to computer operator during the magnetic tape mount presents a delay of about 5 minutes; and one of the ASCII to decimal services (OTS$CVT_T_D) returns wrong results.

d) X.25 COMMUNICATION
The Packnet System Interface (PSI) Digital software is used in the X.25 communication between CCS and GS. In this case, it was also noticed the existence of differences between the ALPHA/OpenVMS and the VAX/VMS PSI API's. These differences demanded help from the Digital technical support so that the necessary changes could be made.

e) IEEE488
The SICS Antenna Management Subsystem (GAN) communicates with the GS Antenna Controller through a IEEE488 interface. The IEEE488 API (EQUIcon Software GmbH) purchased together with the IEEE488 interface for the ALPHA machines is completely different from the old API (Simplified User Interface/IEX-VMS-DRIVER) used with the VAX machines. Because 3 services of the old API were called by several GAN subroutines, we decided to emulate them with internal calls for the services of the new API.

f) UNFORMATTED FILES CONVERTION
Neither the compiler option nor the OPEN FORTRAN command option allowed succesful conversion of unformatted files with floating point data from VAX/VMS to ALPHA/OpenVMS. It was necessary either to rebuild some files on the ALPHA machines or to convert the unformatted files to ASCII files on the VAX machines. Then it was necessary to copy these files to the ALPHA machines where they were converted to unformatted files.

3. DISTRIBUTED SATELLITE CONTROL SYSTEM

Despite the improvements yielded by the SICS migration, this system does not fulfill all the software requirements of the planned missions for the next years. For instance the handling of new telemetry and telecommand types and the communication with the future GS equipment which will use the TCP/IP protocol instead of the present X.25.

A new satellite control system was then proposed in order to fulfill these new requirements. The new system is being developed based on new technologies and shall present the following features:

a) Software reutilization to decrease the development/maintenance software costs;
b) Flexibility to allocate hardware and software resources according to specific needs of each mission;
c) Utilization of a Graphic User Interface aiming at making user-system interaction easier;
d) Utilization of the same Telemetry and Telecommand System for the satellite tests (Overall Checkout Equipment) and for the satellite control.

The new control system is based on a distributed architecture composed by microcomputers and data servers (ALPHA machines) interconnected by a local network (LAN). This LAN will be linked to the present RECDAS by a router which will allow the applicatives to communicate with the GS equipment using the TCP/IP protocol. The applicatives will be developed so that they will run in CCS as well as in GS where they will be able to act as a backup in case of a CCS failure (see figure 3).

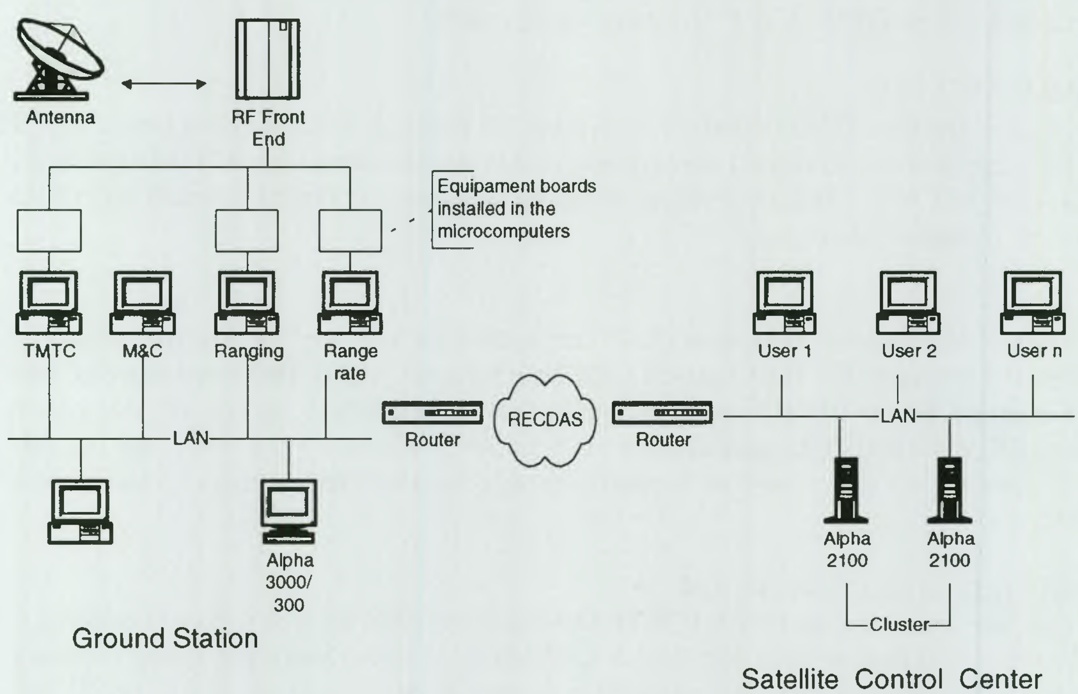

Fig. 3 -- Architecture of New Control System

SICS subsystems (Telemetry and Telecommand, Ranging Measurements, Monitor & Control of the GS equipment, Antenna Management and others) are very independent and this will allow the evolution to the new distributed architecture be made gradually, one subsystem at a time. The development of the new Telemetry and Telecommand System, to fulfill the first CBERS satellite requirements, is the first step of this evolution (see section 4). The new subsystems, running on the microcomputers, and the other SICS subsystems, running on the ALPHA machines, will be responsible together for the control of the next satellites, while all of the SICS subsystems are not replaced.

4. TELEMETRY AND TELECOMMAND SYSTEM

Because SICS Telemetry and Telecommand Subsystems do not satisfy the CBERS mission requirements, a new Telemetry and Telecommand System (TMTC) has been conceived. The object-oriented software development was adopted in order to make the TMTC reuse easier for other satellites with a minimum effort; to support the satellite control as well as the integration and test phases, and to follow world trends.

The TMTC Software System is constituted by two basic subsystems: the Telemetry and the Telecommand Subsystems.

The Telemetry Subsystem receives, processes, stores and displays all the telemetry data received at a GS and transmitted to CCS through the Data Communication Network. The telemetry messages are generated at GS in the SDID format with the satellite telemetry data organized according to ESA PCM Telemetry Standard. The telemetry data are displayed in real time or in retrieval mode from history files.

The Telecommand Subsystem provides edition, management, logging and transmission of telecommands to GS. The telecommand messages are generated by the Telecommand Subsystem in the SDID format carrying the telecommand frames coded in 96 bits ESA standard.

Microsoft Windows operational system is being used in the development with the following tools: Visual C++ 1.5 to implement the telemetry and telecommand applicatives, and Access 2.0 to implement the editor of the telemetry and telecommand parameters. The following standards are being adopted in the software development to provide portability: API Winsock to allow the TCP/IP communication with the GS equipment; ODBC (Open Database Connectivity) to access the system database; and Microsoft Foundation Classes (MFC).

The TMTC is being developed and implemented in object-oriented environment according to a spiral approach. Two versions were established to drive the development process of the TMTC. These versions were defined in order for the team to gain experience with object-oriented approach, C++ language and new tools, besides presenting partial results to the users.

4.1 THE MONO-USER VERSION OF THE TMTC SYSTEM

The first version, still under development, supports only one user with a minimum set of satellite controlling functions. It will be used as a GS back-up and could also be used as a check-out station. The telemetry and telecommand messages are transmitted from and to the Telemetry-Telecommand Processor (PTT) through the SDID protocol. Figure 4 shows a microcomputer with the TMTC software system, PTT using some slots in the same microcomputer and the SDID Interface Communication Software (SIC) which allows communication between the TMTC and the PTT.

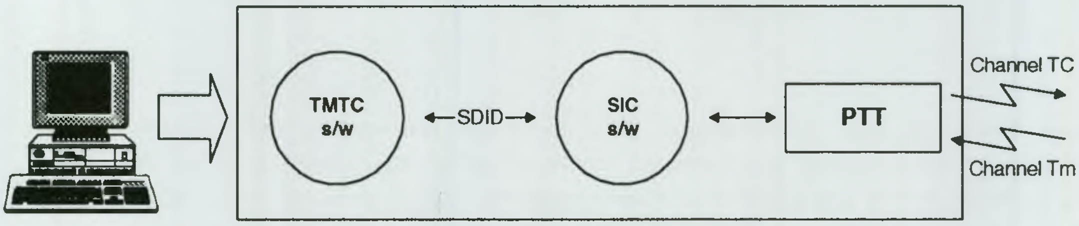

Fig.4 - The mono-user version of the TMTC System

This version is being developed for the Windows 3.1 operational system because this is the available environment so far. But this environment is not adequate to support applications with the characteristics presented by our system and a future migration to the Windows NT operational system will be necessary. In order to facilitate this migration some cares are being taken: all the user interface and database access are being designed with the use of the MFC; support classes (such as PTT communication, user event message, timers, date-hour) are being developed; and other operational system services not available in the MFC are being encapsulated.

4.2 THE MULTI-USER VERSION OF THE TMTC SYSTEM

The second version of the system supports more than one user. The telemetry is received at GS by PTT and sent to CCS through the RECDAS Network. The telecommands are prepared in the CCS and sent to PTT through the RECDAS.

This version includes a Data Base server and several PCs linked by a LAN in CCS environment. Two routers connect the two LANs, one at GS and another at CCS through the RECDAS, a private X.25 WAN. In GS the microcomputer which includes the PTT is supported by the first version of the TMTC system as back-up of the CCS in case of RECDAS network malfunction. Figure 5 illustrates this second version.

The TMTC was designed so that each site will have a microcomputer where the telemetry module responsible for the communication with the GS telemetry equipment will be installed. This module will make connection with the telemetry equipment, receive the telemetry messages and broadcast such messages to all LAN microcomputers. The telemetry processing and visualization modules will be installed on all LAN microcomputers. The telemetry processing module will receive the telemetry broadcast messages, process all the telemetries contained in these messages and put the processed telemetries available so that the telemetry visualization and telecommand transmission modules can use them. The telecommand transmission module will be installed in just one microcomputer of LAN and it will send telecommands requested either through its user interface or through a communication interface with other LAN applications.

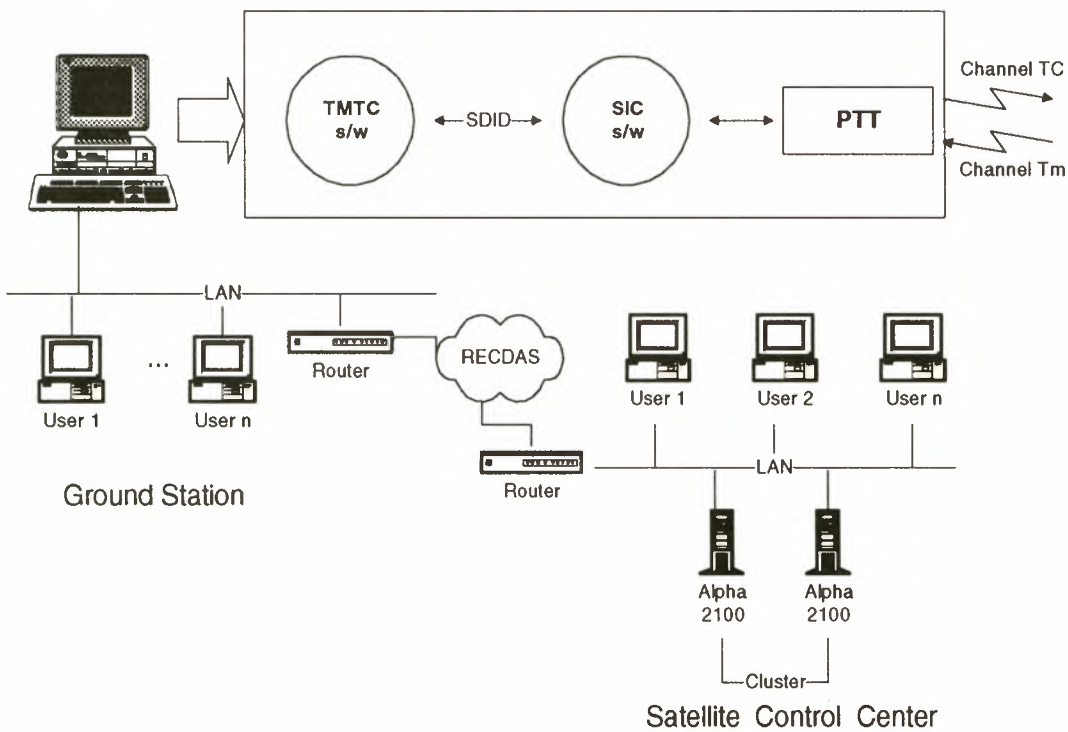

Fig. 5 - The multi-user version of the TMTC System

5. CONCLUSION

The first part of this paper showed the successful SICS migration experience from a VAX/VMS to a ALPHA/OpenVMS environment. Besides reaching its main objective of reducing the hardware maintenance costs, this migration also yielded additional gain in reliability and better performance of the system. The success of this migration must be credited to the high compatibility between the VAX/VMS and ALPHA/OpenVMS environments and to the standards and configuration control features of the SICS.

The second part showed the strategy adopted for the evolution of the INPE Satellite Control System as well as its present status of development. This evolution has two main characteristics: the new system is based on a distributed architecture composed of microcomputers and the system development follows a object-oriented software methodology. The first characteristic will provide flexibility in the allocation of the Satellite Control System resources according to each satellite. The second characteristic will lead to the reduction of the time and costs of the development due to the reutilization facilities offered by this type of methodology.

With the present experience of the TMTC development we can foresee that this system, or some of its parts, will have a large reutilization. For instance: telemetry and telecommand classes shall be easily used in the development of the new GS Equipment Monitor & Control System due to the similarity between the two systems; and the TMTC system shall be easily incorporated into a new Overall Checkout Equipment as one of its subsystems.

THE TECHNICAL ARCHITECTURE OF THE MEDOC CENTRE FOR SOHO

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ABSTRACT. This paper describes the technical architecture of MEDOC (Multi-Experiment Data and Operations Centre), as an element of the SOHO Mission ground-segment. It is a French project initiated by SOHO PIs and located at the Institut d'Astrophysique Spatiale at Orsay. This paper presents the design and the implementation of the technical part of the center and its functions :
For the Operations Center : (1) reception of the telemetry from the SOHO EOF (located at the GSFC) using a dedicated link and its distribution to local Instrumenters' workstations, (2) archiving all the telemetry and processed data needed for (3) observation planning and coordination with European ground-based observatories, especially during MEDOC campaigns. For the Analysis Facilities : (4) archiving all mission data as a copy of the SOHO US Archive. The base of the architecture has been built from the one developed at the EOF but with original concepts.

1. INTRODUCTION

The SOHO (Solar and Heliospheric Observatory) [1] mission is an international cooperation between ESA and NASA for the study of the Sun. Twelve instruments are mounted on this satellite, which is a very complex observatory, launched December, 2 1995. ESA is responsible for the spacecraft and NASA for the launch, the ground system and the operations with a mission nominal duration of 2 years and half.
Most of the observations are collaborative programs between instruments, including ground-based observatories. To coordinate the operations, an Experimenters' Operations Facility (EOF)[2] was built as one of the main components of the SOHO ground system. All Instrumenters' Workstations (IWS) are located at the EOF. Real-time telemetry distribution and commanding operations are managed from there in coordination with the other components of the ground system.
NASA provides also an archive for all the SOHO data. It is implemented at the Experimenters' Analysis Facility (EAF) located near the EOF.

In addition to all this means, MEDOC (Multi-Experiment Data and Operations Centre) was designed to function as an ancillary center to the EOF. It provides the European solar scientific community with the possibility to effectively participate in the operational phase of SOHO. This includes real-time telemetry reception, data analysis and participation to joint planning. MEDOC is also one of the European Archiving Centers for SOHO approved by ESA.
This paper presents the design and the computing architecture of MEDOC in terms of hardware, software and management. It discusses the particularity of the technical choices and the way of using such a center.

2. SOHO GROUND SYSTEM OVERVIEW

Considering MEDOC role towards the EOF, a brief description of the SOHO Ground System is necessary.
After orbital transfer, SOHO was placed into a halo orbit around Sun-Earth L_1 Lagrangian point. From that position, SOHO is continuously pointing toward the Sun, which allows uninterrupted observations. Real-time data are received at a 56 kb/s rate by the NASA Deep Space Network (DSN) during one long (8 hours) and three short (1 hour and half) passes. During these real-time reception passes, instrumenters are allowed to send real-time commands to their instruments. The rest of the time, the data are recorded on-board and played back during the short passes. For two consecutive months per year, data are transmitted 24 hours a day.

The telemetry (see Figure 1, left hand side) is received first by DSN which sends it to the EOF Core System (ECS). Then ECS distributes it only to local IWS. Playback files are received by the ECS via the Data Distribution Facility (DDF). These files are sent to local and remote IWS. At last, Near Real Time (NRT) Commands are sent by local IWS to the ECS, which forwards them to the Command Management System (CMS). The CMS interacts as well as with the satellite and the instruments.

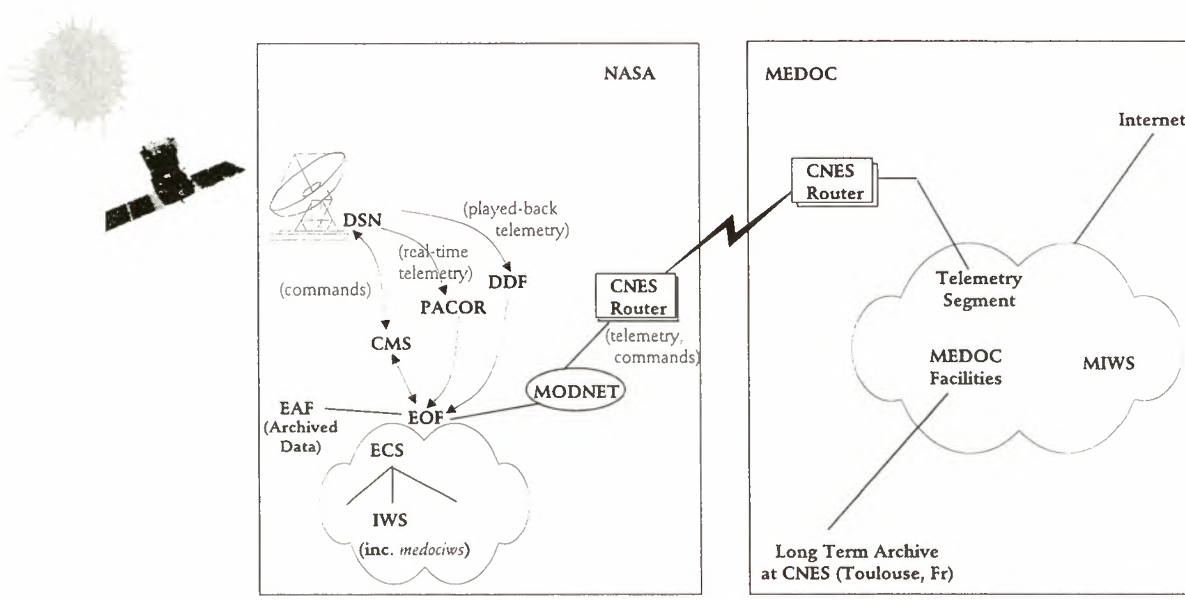

Figure 1 : SOHO Ground System with its link to MEDOC.

The meeting point between the SOHO ground system components and instrumenters is the EOF [3]. It is divided in two main parts:
(a) The ECS is providing communication facilities (hardware and software), dedicated to commanding, telemetry reception, distribution and archive, and planning. A new software [4] was developed for the SOHO project, including some parts reused from earlier missions.
(b) IWS brought by instrumenters teams and dedicated to operations and data analysis, including a "MEDOC IWS".
Moreover, planning and scheduling of coordinated observations are managed at the EOF.

The EAF is another facility offered to experimenters related with data analysis. Its main function consists in archive facilities implemented with on-line hard disks. In addition, the SOHO data catalog and the implementation of the data rights policy defined by the Principal Investigators (PI) for the SOHO archive are managed at the EAF.

From an ECS point of view, MEDOC is seen as a regular IWS with this important feature: it receives all the data and will be able to command any given instrument. Communications to MEDOC are built up using a dedicated workstation located at the EOF and a special network link up to Orsay, France.

3. MEDOC DESIGN

The MEDOC was designed to be an EOF complementary center for the SOHO mission in aid of European solar scientists. Each of its components is specially designed for MEDOC needs: new installations entirely dedicated to MEDOC which is based on specific network and computers.

The participation of more than one instrument, including ground based observatories (e.g. THEMIS at Canaries Island, Spain) or other satellites, to joint observations during some dedicated times is a scientific major objective. Everything was studied to put together the facilities for the operations as well as for the data analysis in the same location. MEDOC provides services to its users, the MEDOC IWS (MIWS), in such a way that the users can coordinate their activities.

MEDOC had to meet the following requirements [5]:
- To be an analysis center for the SOHO data;
- To be an operations center; whose duties include receiving real-time telemetry, sending near-real-time Commands, and organizing observations campaigns during a few months per year;
- To be an European SOHO archive copy with the goal of being a Long Term Archive maintaining data 10 years after the end of the SOHO mission. Moreover, MEDOC has to implement the US Archive interface for accessing the SOHO data via a data catalog.

To achieve these goals, the following constraints must be satisfied:
- The telemetry and commands cannot be sent through the public network. This is mandatory because there is no way for (a) insuring sufficient confidentiality and (b) allocating a minimal bandwidth. Considering these two points, the obvious solution is the utilization of a dedicated link.
- To distribute the telemetry, the same software than the one developed for the ECS has to be installed on one of MEDOC servers. To reduce development efforts, the same hardware and operating system must be acquired.
- The same philosophy has been adopted for the implementation of the SOHO data catalog and concerns the ORACLE database system.
- To accommodate guests users and CO-Is, servers and terminals are required.
- Due to a telemetry rate of 56 kb/s and the data compression rate on board instruments, high volume of data can be expected. In fact the amount of raw data represents 0.7 GB per day. It was estimated that the US Archive will receive and store about 2 GB per day of processed data corresponding to 1.5 TeraBytes for 2 years.
  Analysis processes and planning preparation require high speed peripherals and network. Therefore, the archive must be organized in two parts: Operations Archive and Long Term Archive. The first part must be implemented in Orsay and covers the first two years of data. Once data will be placed in the Public Domain, they will be moved to the second part.The latter task is supported by the CNES (Centre National d'Etudes Spatiales) located at Toulouse, France.
- To guarantee data confidentiality according to rules defined by PIs, dedicated hardware and software must be installed such as a Firewall and applications to check data accesses.

Figure 2 shows MEDOC definition in terms of operational procedures. All of these software will be discussed in the following paragraphs.

4. MEDOC IMPLEMENTATION

To satisfy the requirements quoted above, MEDOC had to set up a computer resources department. This architecture will be described in details in the following paragraphs.

4.1. Network

First, the network was implemented with security concerns in mind (see Figure 3). It is based on routing for increasing performances and security. We divided the network in several physical segments organized around activity domains and secured locations (needed for operation time). However, the physical architecture of the center had to cope with the diversity in IWS hardware including mobile notebooks (Unix WorkStations, VMS Servers, PC, Macintosh, ...) and operational requirements. One of the difficulty was to find a trade off between efficiency, interoperability and security.

An important component is a dedicated link for receiving real-time telemetry from the EOF. This 128 kb/s rate link is provided by the CNES and NASCOM (NASA Communications). It is composed of several parts: France Telecom (French Phone Operator) leased line, CNES routers, NASA transatlantic link, various NASA and CNES equipments (see Figure 1). This link is very secure: only designated computers are allowed to use it. It is managed by the CNES/Toulouse.

The internal part of MEDOC is based on CDDI (Copper Distributed Data Interface, 100Mb/s) and Ethernet protocols. We preferred CDDI to FDDI (Fiber Distributed Data Interface) because the

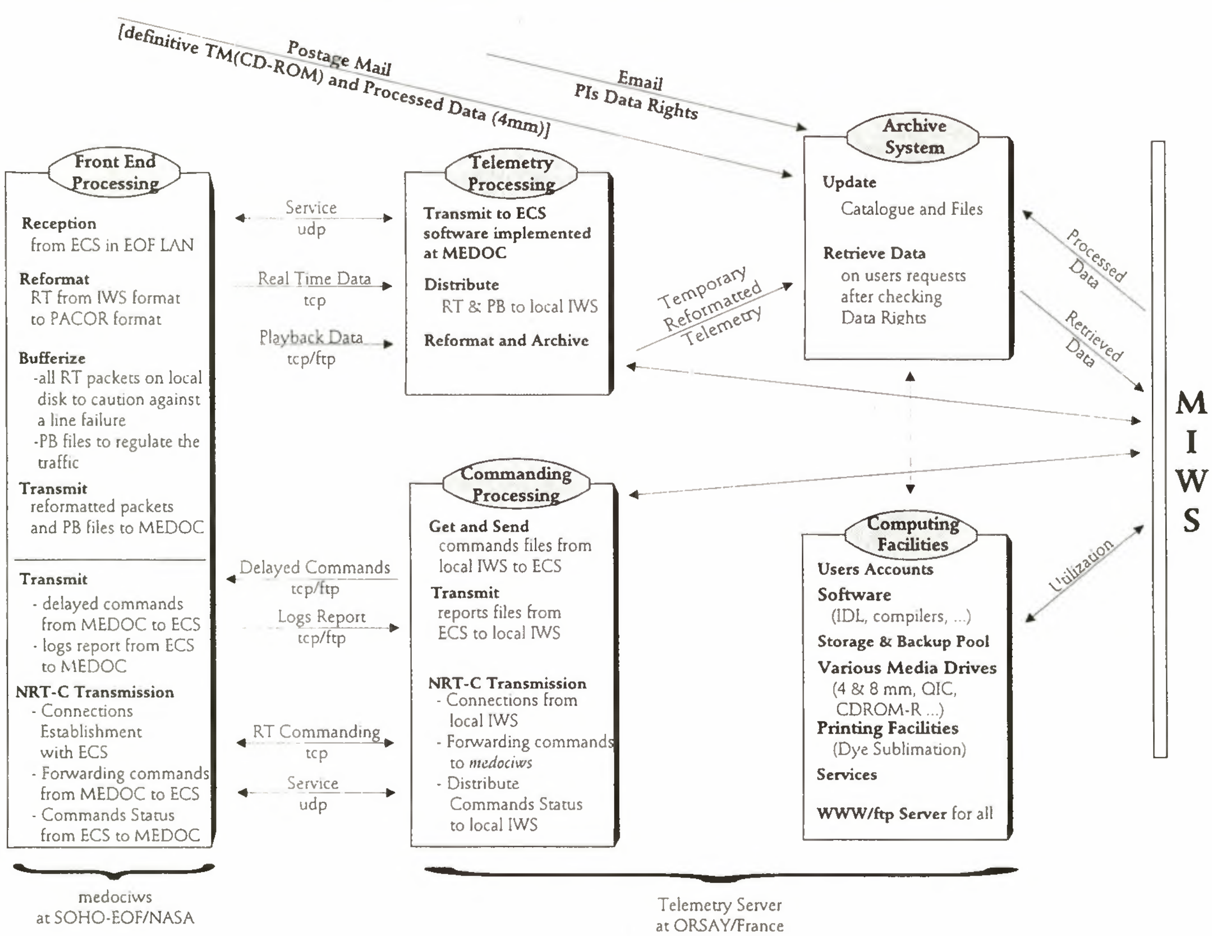

Figure 2 : MEDOC procedures data flow

regularity of the cabling system allows a greater flexibility and the confidence of an evolutionary system associated to an optimal cost. With that goal, we designed a Category 5, Class D physical network. CDDI is used for MEDOC main servers when Ethernet is used for regular MEDOC facilities (such as printers, office computers, ...) and MIWS. About 150 ordinary connection points for computers and phones are installed and managed with the same cabling system.

The Paris-Sud University Network Administration allowed MEDOC 3 IP Class C and 1 sub-domain name. MEDOC is responsible for its own domain and classes. The network is directly connected to Paris-Sud backbone to reach the Internet (via RENATER, the French Research Network) via one of their routers. Since the network is split into subnets, three classes are needed: one for the external part, one for the internal and one for computers which are using the dedicated link. For performance and security reasons, some computers and servers are equipped with more than one physical network interface which then use several IP addresses. To secure the internal network a gateway will be installed between the external and internal subnets, our WWW/FTP server being located in the external part of the network.

MEDOC also has an ISDN link with an European institute, dedicated for transferring experiment results files. Two other links are underway: a better connection to NASA sites using SPAN-IP which will replace SPAN DecNET, and an eventually experimental ATM connection to French Institutes in the Paris area.

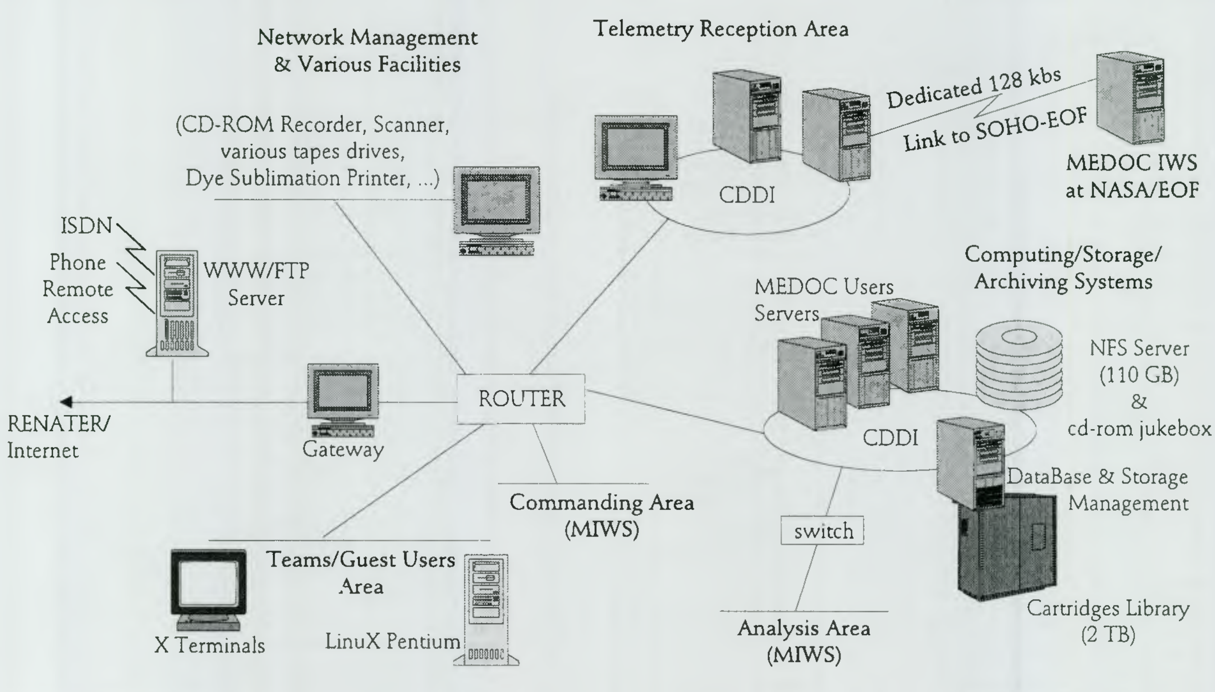

Figure 3 : MEDOC Network and Systems Architecture

4.2. Telemetry Reception

To be able to distribute telemetry from MEDOC, we first had to install the same software which is running at the ECS. We likewise had to develop an interface to reformat telemetry packets because the input packet format is not the one expected by the ECS software running in MEDOC. They come from the ECS in IWS packet format and have to be rebuilt as ECS input packet format (Packet Processor format, PACOR). We could also update ECS software but we wanted to be independent from it and minimize developments because this software is still evolving.

Unexpected problems arose when we tried to connect the ECS for receiving real-time telemetry in MEDOC via the 5000 kms link. The ECS software was designed to send telemetry (26 kb/s max. per IWS) in a local area network context. Buffers and time-out were just too small for a WAN connection. Moreover, sharing the link with playback files transfers and real-time telemetry increased the number of dropped packets.

To solve this problem, three solutions were studied : increasing the link capacity, updating the ECS software (running at the ECS) and installing a workstation at the EOF to set up an interface for managing our own parameters. This latter solution was the only realistic one because (1) it was not possible for the ECS to update their software for MEDOC and (2) increasing the link capacity would not probably fix all problems.

Now the telemetry is sent by the ECS to a medociws located at the EOF like other IWS. Then it is buffered, reformatted and sent to MEDOC under ECS input packet format using the dedicated link. Two processes developed above TCP-IP, guarantee a very reliable communication. A disconnection from one of the two parts is immediately detected and will not affect MIWS connection state. If the link breaks, the telemetry is still stored on the *medociws*. When it is working again, the buffered telemetry will be sent faster to MEDOC without losing any packets. (cf . Figure 2).

Telemetry is also distributed using playback files. This happens when the DSN reception is not available or when some reception problems appear. Usually these files are sent in parallel to IWS using FTP by the ECS. Since we get all files for each instruments, we preferred to use the FTP mirror principle to get playback or missing files for regulating a serial transfer: 30 simultaneous automatic transfers is an important load considering the line capacity. Later they are sent to requesting MIWS.

At the EOF, one computer is playing the role of *medociws*. At MEDOC, another one is dedicated to make the interface with MIWS, for telemetry reception and distribution. Another workstation is configured as a backup of the first one. If something wrong happens to *medociws*, we can continue to receive data directly from the ECS.

4.3. Commanding

Commanding is available from MEDOC but not yet used. It is asked by Instrumenters who are no longer installed at the EOF and who would like to send commands occasionally. The similar principle is used for sending commands than for receiving telemetry. Two interface modules operate for establishing 3 connections:
- one between the 2 modules, one located on *medociws* and one on the MEDOC telemetry server;
- one between MEDOC and MIWS, which ask for a NRT-Commanding session;
- one with the ECS, between *medociws* and the ECS.

In this configuration, *medociws* is the only MEDOC workstation known from the ECS and the only one which is allowed to establish a NRT-Commanding session with the ECS. Furthermore reports are forwarded in real-time to MIWS.
Commanding is hosted by the same workstations than telemetry.

4.4. Archive

MEDOC is approved by ESA as an European Center for archiving SOHO data. MEDOC archive is divided in two segments: an Operation Archive and a Long Term Archive. The first one is located in MEDOC and will store at least 2 years of processed data. The second is supported by the CNES STAF (Service de Transfert et d'archivage de Fichiers) which will be in charge of maintaining data at least 10 years after the end of the SOHO mission with similar access interfaces.
In addition, as we must provide the same access interface to the SOHO data catalog, we use the ESA software developed by NASA and ESA personnel. With a HTML pages front-end, this software is based on PRO*C queries. In MEDOC implementation of this software, tables, forms, queries, scripts and data rights are basically the same.
Now we present the different processes of data storage and retrieval:
(a) Our physical implementation is radically different from the US Archive: two levels of hierarchical storage hardware are used. The most recent data or most used files from the archive are migrated on 50 GB on-line hard disks. These disks are provided by a NFS server which is a separated computer running a NFS dedicated operating system including RAID-4 storage. Older data are stored on a cartridge library. This hardware is an IBM-3494 with two MAGSTAR drives which allows a throughput of 9 MB/s. Up to 200 cartridges can be put on the library which allows more than 2 TeraBytes without compression. The hardware compression device provides a three fold storage capacity.
The library is managed by the ADSMv2 software installed on a dedicated workstation. File migration and backups are also managed by this software as well as database management for the SOHO data Catalog. The difficulty was to establish communications between the NFS server and ADSM for which this server is not a known device. Migration can be a complicated process based on various rules such as data aging, disk usage, etc. Since the ADSM server cannot mount NFS disks, a stand alone process must check the mounted file system disk usage. Then another process must be triggered for moving files from NFS server to ADSM server on a special file system organized as a pre-migration buffer. The disk usage of this file system is automatically checked by ADSM: files are migrated as soon as required. Another difficulty is to tune all these thresholds.
(b) Data retrieval is a much more complex process than storage. No data can be accessed directly from a disk. To access files, a user must satisfy the PIs' data rights policy. To check data rights, a higher application level is needed above the catalog browser, from which every access to data must pass. Moreover, controls are based on an account and password. According to pre-defined rules (such as locations, volume of requested data , ...) the client will receive data either via the network or via postage mail on a media.
To retrieve the selected data, the system must first check data rights and then file locations. If they are already on disks, a link or a copy to the user account (MEDOC user servers or MIWS via NFS) is made. To avoid files duplication on disks a link pointer is maintained by software. If files are not

present on disks, data must be retrieved from the library. This cannot be done automatically by ADSM (because of the incompatibility of the two servers), therefore files are moved back from the pre-migration buffer to the NFS server, etc.
All the data related to the mission are archived at MEDOC. This includes raw telemetry (on-line: one week, off-line: later official NASA CD-ROM containing raw data of each instrument), ancillary data and summary data (available on the web server) as well as all kinds of reports. MEDOC receive the processed data from the US Archive twice a week on 4mm tapes. CD-ROM also come each week and other data are mirrored by FTP each night.

4.5. Services

In the context of a Computer Resources Center, many services are essential for the users (MEDOC Server Users and MIWS).
Three servers are dedicated to data analysis. They are organized in cluster and have IDL, Fortran and many other tools and software installed. One of them (a bi-processors computer) is the only entry point for users, where each MEDOC user has an account and a MEDOC e-mail address. Depending on the kind of job to execute (IDL with heavy calculation, Fortran, etc.) and the current load, jobs are distributed to one of the two other servers. The bi-processor is mainly used for mail, news, text processing and regular tasks, when the 2 others are mostly for calculation and science data analysis which need more memory and computing power.
For all computers installed at MEDOC, additional services are available in the center such as dye sublimation color printers, CD-ROM recorder, various media drives, ...
Several X-Terminals and PC-Pentium (running Linux with IDL license and Fortran) are also available.

MIWS and MEDOC server users can use some disk space of the NFS server especially for data processing. Another NFS facility for MIWS is a CD-ROM juke-box with several drives.
MEDOC also provides a WWW/FTP server. It welcomes MEDOC and Instrumenters' pages. It is likewise a mirror site for the SOHO server and for some remote instrumenters' sites.
At last, dial-up access to MEDOC computers are setup on the WWW server.

4.6. Management

We dedicated two workstations to management purposes. One is running all primary services while the second, held as a backup, runs the print server. To reduce management efforts, MEDOC computers are chosen only between two Operating Systems which are managed with distributed tools.
We need a lot of information to follow the activities of the center. Many operations are automated using PERL scripts and TK interfaces which generate mail reports. We also use SNMP for load reports, a commercial product for managing the network active equipments with RMON probes and SunNetManager for monitoring links status. From the management workstation, many parameters are monitored coming from servers and network equipments. For instance, processes status, disk space usage, NFS links and accesses, telemetry connections, mirror update results, router and network (load and throughputs), printers status, etc., are continuously checked. We use mail and graphical console displays for reporting these events.

5. CONCLUSION

This paper has presented the design and the implementation of an European ancillary center for the SOHO mission. A large part of the functions described in this paper is currently used by Instrumenters' teams. Five teams are already installed and some of them process real-time telemetry. Three new MIWS are expected in the coming months and guest users use continuously these facilities with data analysis objectives in collaboration with scientist teams located at the EOF.
Furthermore, MEDOC technical team also provides continual help to MIWS personnel for system management. However, the center is still evolving: for instance, new developments are planned to make easy archive access and to automate most of the MEDOC operator tasks. The infrastructure is now set up and the resources involved ensure the future of MEDOC for more than the 2 initial years.

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ACKNOWLEDGMENTS

The design and implementation of MEDOC has benefited from many constructive discussions and works held with IAS personnel. A special mention goes to Jean-Claude Vial, MEDOC Project Scientist, for his attention and careful readings of the earlier versions of this paper.

CNES support is also acknowledged for this project.

The EOF team deserves a special attention for their help during tests and operations.

ACRONYMS

ADSM	ADSTAR Distributed Storage Manager
CDDI	Copper Distributed Data Interface
CMS	Command Management System
CNES	Centre National d'Etudes Spatiales
CO-Is	Co-Investigators
DDF	Data Distribution Facility
DSN	Deep Space Network
EAF	Experimenters' Analysis Facility
ECS	EOF Core System
EOF	Experimenters' Operations Facility
FDDI	Fiber Distributed Data Interface
FITS	Flexible Image Transport System
FTP	File Transfer Protocol
GSFC	Goddard Space Flight Center
HTML	Hyper-Text Manipulation Language
IDL	Interactive Data Language
ISDN	Integrated Services Digital Network
IWS	Instrumenters' WorkStations
MIWS	MEDOC IWS
MODNET	Mission Operations and Data Systems Directorate Operational Development Network
NASCOM	NASA Communications
NFS	Network File System
NRT	Near-Real-Time
PACOR	Packet Processor
PI	Principal Investigator
RAID	Redundant Array of Inexpensive Disks
RENATER	Réseau National de Télécommunications pour l'Enseignement et la Recherche
SQL	Structured Query Language
SOHO	Solar and Heliospheric Observatory
STAF	Service de Transfert et d'Archivage de Fichiers
TCP-IP	Transmission Control Protocol - Internet Protocol
WAN	World Area Network

APPLICATION OF WORLD WIDE WEB (W3) TECHNOLOGIES IN PAYLOAD OPERATIONS

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ABSTRACT

World Wide Web (W3) technologies such as Hypertext Transfer Protocol (HTTP) and Java object-oriented language offer a powerful and yet relatively inexpensive framework for distributed application software development. This paper discusses the suitability of W3 technologies for payload monitoring system development. Furthermore, the lessons learned from the construction of an insect habitat monitoring system based on W3 technologies are discussed.

1. BACKGROUND

A payload monitoring system ensures the proper operation of a specific payload experiment. Such a system typically comprises:

- A data acquisition front-end, which decodes and translates incoming telemetry data.
- An on-line monitor, which displays telemetry data in real time.
- A rule-based data processor, which detects any anomalies in the telemetry data and immediately notifies the operator.
- A database, which archives the payload data, the operation log, and all additional information related to the payload experiment.
- An off-line data analysis or visualization tool, which supports the payload engineer or scientist in problem analysis.

The data flow diagram in figure 1 shows the processes involved and their relationships in a payload monitoring system. These processes can be catagorized into two groups: Real-time Operation and Off-line Operation.

Because of the system's inherent complexity, developers of payload monitoring systems will find such commercial software packages as Talarian RTworks [1], Gensym G2 [2], and Kinesix Sammi [3] useful in reducing development time and increasing system reliability. While these commercial proprietary tools are undeniably useful, they share the following liabilities:

(1) High Cost: The tools typically cost tens of thousands of dollars per license. After the initial purchase, they require recurring maintenance fees for technical support and upgrades.

(2) Software Customization Difficulties: Because the software packages are provided as binary rather than source code, extensive modification or customization is difficult. Although many packages provide Application Programming Interface (API) in C or C++, the authors often found serious limitations using the API approach for customization.

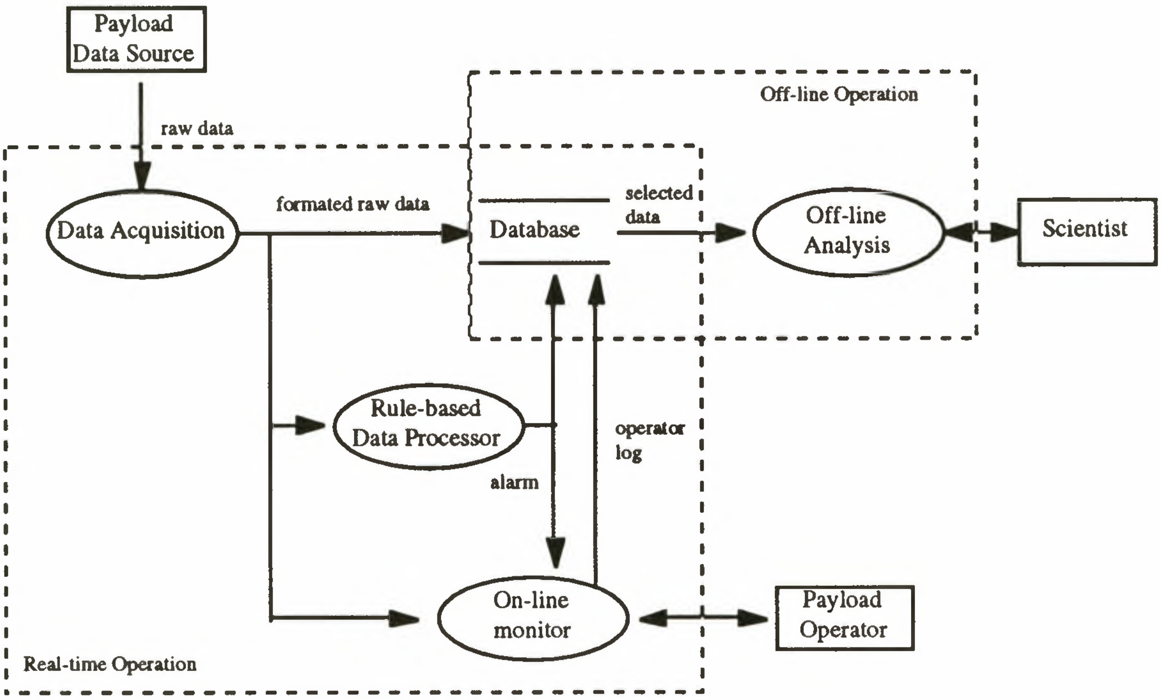

Figure 1. Processes of a payload monitoring system.

2. WORLD WIDE WEB (W3) TECHNOLOGIES

Emerging W3 software technologies offer an alternative to commercial proprietary tools. The World Wide Web (W3) client/server framework, which originated at the European Laboratory for Particle Physics (CERN), uses a simple protocol called Hypertext Transfer Protocol (HTTP) [4] for file transfer from servers to clients. The availability of free technical information and source code from CERN and other research centers has fueled the rapid growth of W3 server sites. As a result, W3 is today a standard for information publishing on the Internet.

In additional to HTTP, W3 technology is enabling more sophisticated methods of client/server interactions over the Internet by allowing "plug-in" modules written in a variety of programming languages. For example, a new generation of network-based programming languages, such as Sun Microsystem's Java [5] and Microsoft's Active X [6], use W3 as their software's launching pad.

For payload monitoring systems development, the emerging W3 technologies offer the following potential benefits:

(1) Cost Saving: Virtually all W3 software is available for free from the Internet.

(2) Ease of Customization: Because the source code of most W3 software can be easily obtained, modification or extension is often easier.

(3) High Availability of Information and Support from Multiple Sources: Because W3 technologies are based on open standards, an abundance of publications, training programs, and consulting services is available to developers. The developers are no longer dependent on a single source for technical information and support.

Because it was originally designed for distributing static information, the model of W3 HTTP client/server interaction works well for the off-line data analysis portion of payload operation. Payloads such as Extreme Ultraviolet Explorer (EUVE) [7] are using W3 technologies for payload data distributions. Remote scientists download a selected set of data from the Internet and then use analysis tools on local computers for data visualization.

The HTTP client/server interaction appears to match poorly with the software requirements of real-time operations, however. Specifically, the real-time monitor needs to be interrupted by other processes. For example, the rule-based data processor will need to notify the real-time monitor of the arrival of alarm messages. As soon as the data is received from the data acquisition process, the real-time monitor needs to refresh the screen and update its display.

To the best of the authors' knowledge, there are no publications reporting success in building a complete payload monitoring system using W3 technologies. Clearly, major customization effort is needed to make W3 technology work for the real-time operation portion of the system.

3. A WEB-BASED MONITOR FOR INSECT HABITAT PAYLOAD

In the spring of 1996, two of the authors developed a W3-based monitoring system to support the Space Station Biological Research Project (SSBRP) Insect Habitat Payload. The payload is an artificial environment used to study the reproduction of insects over several generations in microgravity.

The payload monitoring system periodically takes video snapshots of the specimens, as well as temperature and humidity readings, at intervals specified by the scientists. The collected data is archived in a database for tabulation and analysis. The real-time monitor needs to be notified when the temperature or humidity sensor readings exceed or fall below a predefined range of values.

To keep the system simple and to minimize code writing in the first attempt, our development effort focused on the traditional W3 HTTP client/server integration, which has many supporting tools on the marketplace. We selected Oracle's WebServer as the primary database interface, and used SGI's WebMagic HTML authoring tool to design the monitor screen layout. Development was complete in less than two months.

The rule-based data processing is embedded in the Common Gateway Interface (CGI) Tcl script for sensor data collection. When an anomaly is detected, the CGI generates HTML tags, which will change the background color of the data display to red on the HTTP client, the real-time monitor. Figure 2 displays the system's architecture. Sample snapshots of the system's user interface are shown in figure 3 and 4.

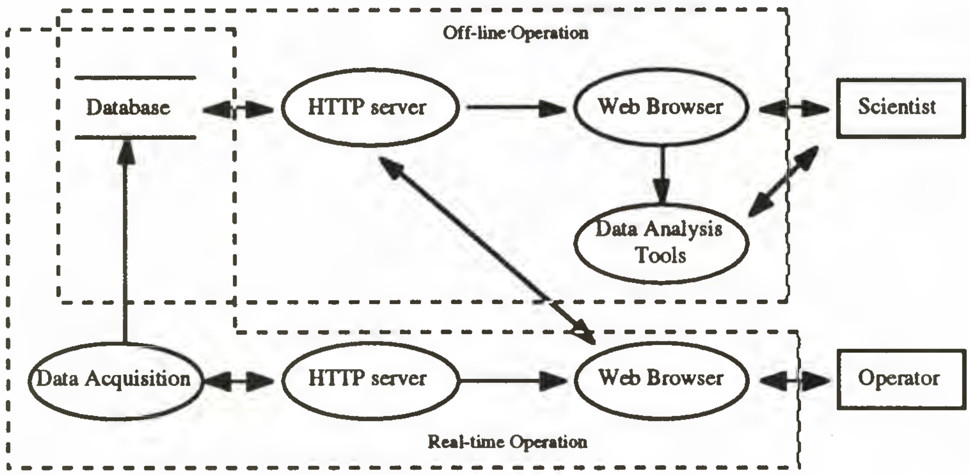

Figure 2. The Web-based monitoring system architecture.

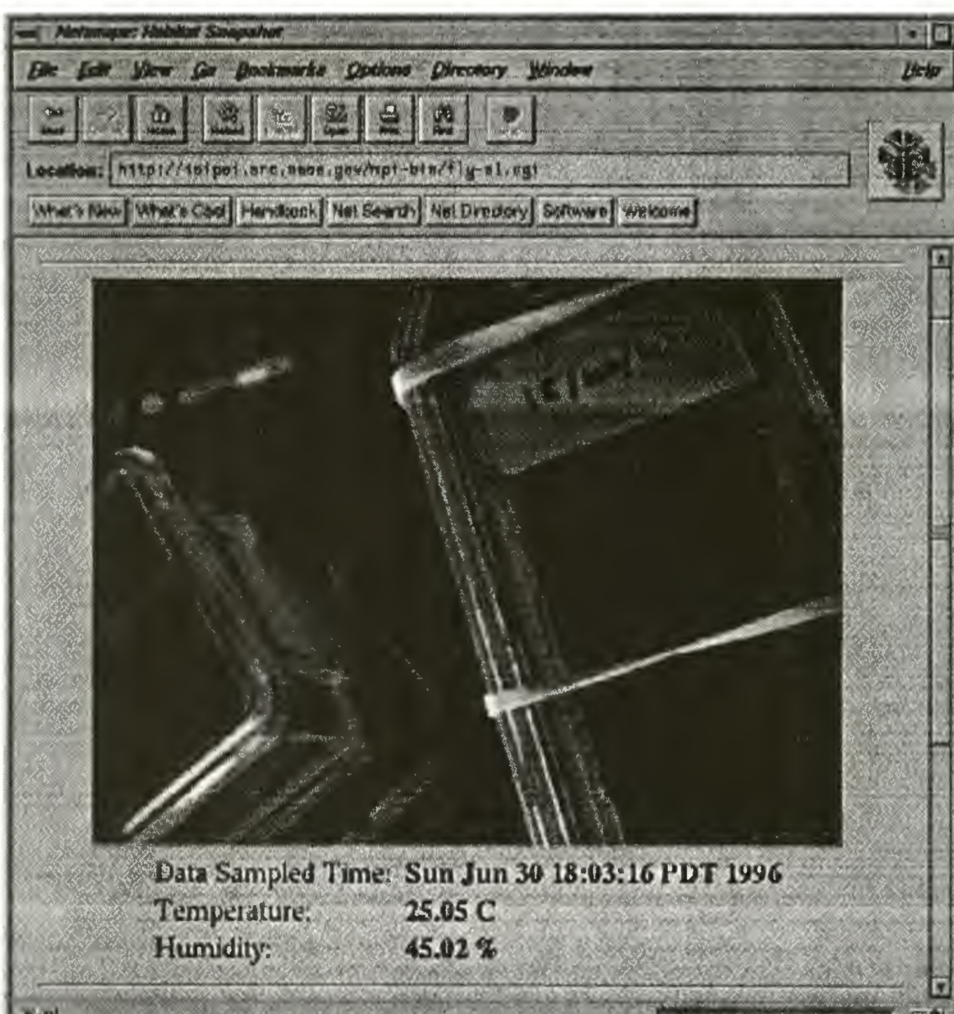

Figure 3. Sample On-line Monitor user interface.

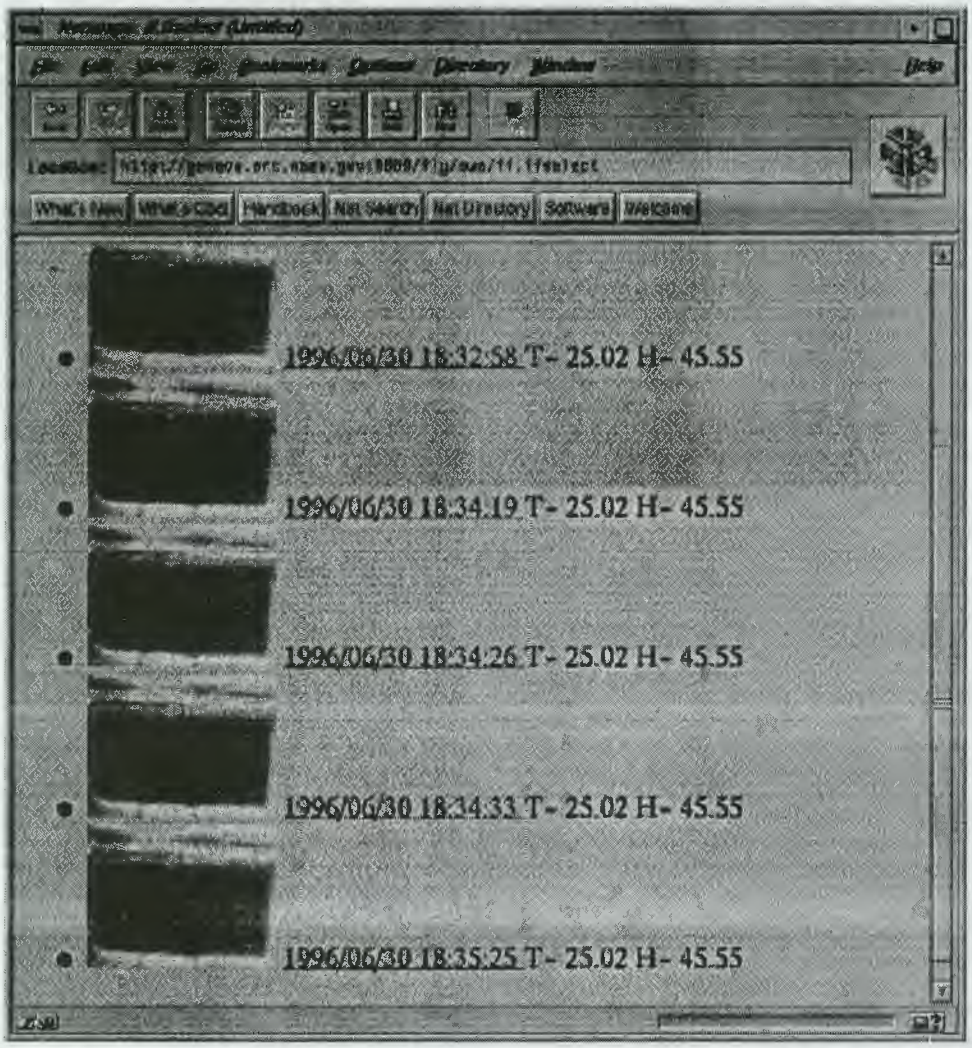

Figure 4. Sample Off-line Data Analysis user interface.

4. LESSONS LEARNED

Database Integration

To simplify interface development for the payload database (an Oracle7 relational database management system), we used Oracle's new WebServer, which allows direct access to existing database Stored Procedures and eliminates the need for CGI scripts.

Automatic Screen Update

To allow for periodic screen update, the HTML Refresh command, embedded in the document itself, can force the HTTP client to reload the document at specific internals. The Refresh command isn't a standard part of the HTML language, unfortunately, and is thus supported only by Netscape's Navigator W3 browser. The HTML syntax is:

<META HTTP-EQUIV="Refresh" CONTENT=$DELAY>

where $DELAY specifies the number of seconds to delay before sending a request to the HTTP server for reloading the current document.

Although this approach is simple to implement, it leaves unsolved a fundamental problem: server/client communication is point-to-point rather than broadcast. As the number of clients increases, the load on the HTTP server and network will increase proportionally. A possible solution is to modify the client software to listen to multicast IP addresses for periodic data update.

An Improved Design

With the experience gained from our first W3 based payload monitor, we have developed an improved design that incorporates Java programs to implement the following processes :
(1) On-line Monitor that reads continuous data streams from IP multicast channels.
(2) Data Analysis Tools that display selected data sets in various 2D and 3D graphs.

The diagram below presents the general design concept:

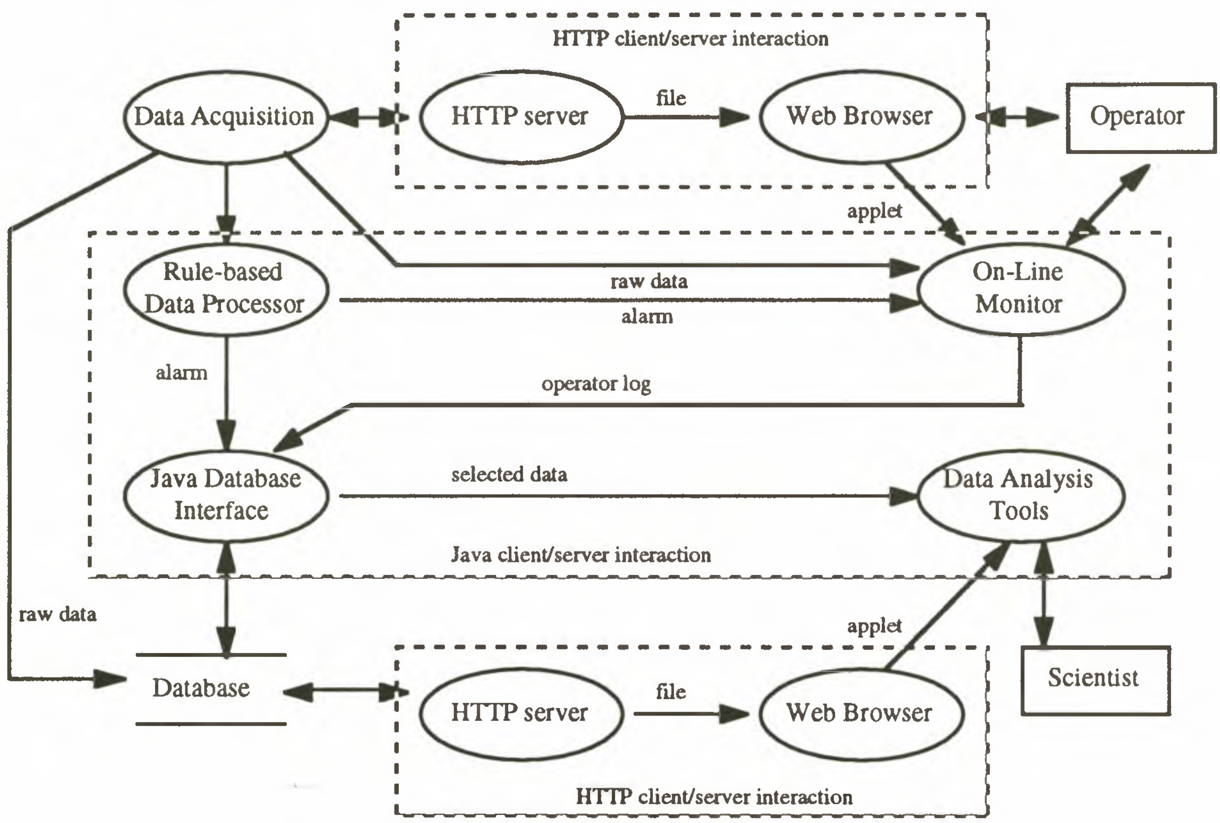

Figure 5. An improved software design for Web-based payload monitoring system.

5. CONCLUSIONS

Compared to traditional commercial proprietary tools, W3 technologies and their associated tools offer significant cost savings and improved maintainability for payload monitoring systems. The authors' experience in developing a W3 based monitoring system for the SSBRP Insect Habitat Payload proved that a simple monitoring system can be implemented with the traditional W3 HTTP interactions. For better use of network sources and more sophisticated client/server interactions, the authors recommend the integration of multicast protocol and "plug-in" programs, such as Java Applets.

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[5] Java Programming Language. http://www.javasoft.com

[6] Active X. http://www.microsoft.com

[7] EUVE, Center for EUV Astrophysics. http://www.cea.berkeley.edu

INTEGRATION OF OPERATIONAL HARDWARE AND TEST TOOLS IN ESA'S GENERIC SATELLITE SIMULATION INFRASTRUCTURE SIMSAT[1]

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ABSTRACT: Satellite simulators have become an essential element for the preparation of space missions. They have an important role with regard to the validation of spacecraft control facilities, the validation of flight control procedures, staff training and mission rehearsals. As current trends aim on the one hand at a reduction of simulator cost leading to more generic reusable simulator infrastructures, the need for higher realism of the simulations on the other hand tend to increase their complexity and cost. Furthermore simulations not only take place during early phases of the missions but also during advanced phases where parts of the hardware are already available and best suited for validation and training. In this context we have examined if it was technically feasible to increase the realism of a simulation by replacing software models of an existing satellite simulation infrastructure by hardware equipment. It has been investigated if the new telecommand (TC) and telemetry (TM) packet standard compliant generation of generic hardware equipment can be used to replace corresponding simulation models.

1 INTRODUCTION

In the last years a new generation of telemetry and telecommand infrastructure (ground station and onboard) has been developed and is still under development. The reasons for this modernisation effort are:

- Future satellite missions shall adopt the new ESA telecommand and telemetry packet standards (e.g. ARTEMIS, XMM).
- Modernisation of equipment which is no longer adequate for the present mission requirements.

Since the packet standards are more complicated than the presently used PCM standards and introducing a new technique always requires a higher testing effort, a need for realistic test of satellite operation, which use the corresponding new equipment arises. It is of special interest how errors appearing anywhere in the TC - TM chain are reflected to the mission control system (error propagation). An example for such a problem is :
How does the TC chain handle a buffer overflow on board at the output of the transfer layer? What time delays are caused by the TC frame retransmissions? What error message is sent to the mission control system by the TC encoding equipment, if the buffer overflow cannot be recovered?
To get precise answers to such type of questions, ESA has initiated the Generic End-to-End Simulator Enhancement (GESIME) study. The objective was to study the possibility to get a realistic and cost efficient simulator by using operational hardware in the simulation.

[1] This work was carried out by Siemens Austria in a contract for the European Space Operations Centre (ESOC), contract number 10902/94/D/IM. Responsibility for the contents resides with the authors and organisation that prepared it.

2 SATELLITE SIMULATION INFRASTRUCTURE

This work is based on the Simulation Infrastructure for Modelling Satellites (SIMSAT) at the European Space Operations Centre (ESOC). SIMSAT constitutes the basis for specific mission simulator development. It shall optimise the reuse of satellite simulation components for different mission simulation. The platform for SIMSAT are DEC VAX and DEC ALPHA workstations running OPENVMS. The main parts of the SIMSAT are implemented in Ada programming language.
The simulation of a mission includes the ground stations network, the ground satellite links, the position and environment of the satellite and the satellite equipment. So the simulator interfaces directly to the mission control system via an X.25 network.

An overview of the architecture of SIMSAT is given in Figure 1. The components are:

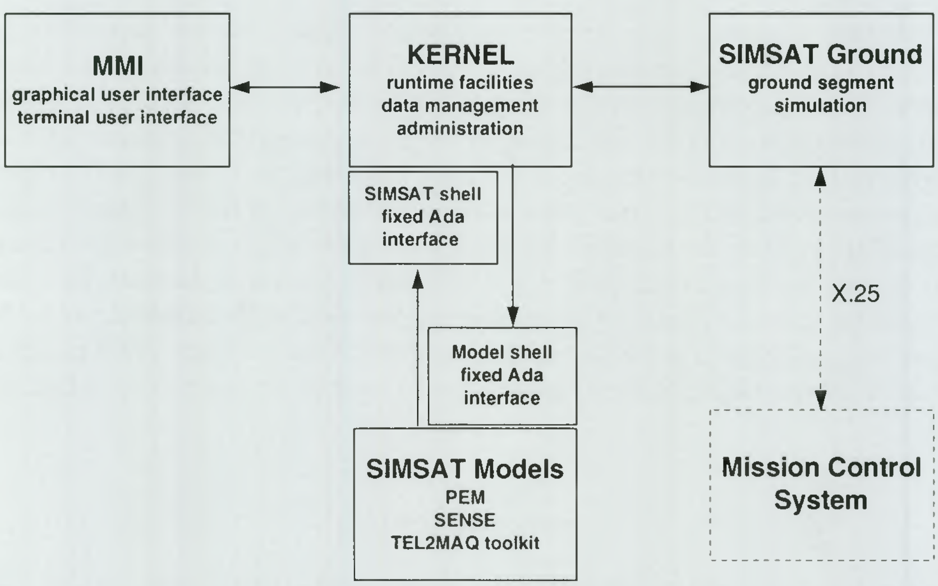

Figure 1. SIMSAT architecture.

- *SIMSAT Man Machine Interface* which is a Motif based graphical user interface providing monitoring and control facilities.
- *SIMSAT Kernel* which contains the real time part of the system and is responsible for tasks such as the co-ordination and processing of all events within the simulator, the hardware and software setup of the simulator, the different modes and states of the simulator. The SIMSAT Kernel also includes such facilities as logging, data management, command handling and the handling of the communication between the satellite models and the ground station models.
- *SIMSAT Ground* which represents the ground system simulation and consists of ground equipment models, the data packet switching system interface, the station definition management and the ground status control.
- *SIMSAT Models* which comprise *generic* models (e.g. Position and Environment Model (PEM), Satellite Electrical Network Simulation at ESOC (SENSE)). Also included is the Telecommand, Telemetry, Measurement and Acquisition (TEL^2MAQ) toolkit which provides

means for building telemetry generation, telecommand reception and measurement & acquisition sub-systems.

The SIMSAT and the Model shell components provide the interfaces for the mission specific model parts. Based on these generic components, simulator developers implement a simulator by adding mission specific models. The present work concentrates mainly on the SIMSAT Models and the SIMSAT Ground components.

3 GENERIC HARDWARE INFRASTRUCTURE

The mission control system is connected via an X.25 network to the ground stations. This is also the interface to the simulator as mentioned above. This section gives a simplified overview of the generic hardware elements in the TC/TM chain (Figure 2). In this work only generic elements are considered to avoid dependencies on a specific mission. Also we deal with the new generation of satellite and ground equipment, which are compliant to ESA TC and TM packet standard. Since we are concentrating on generic equipment the ground segment gets more attention in this work, because for satellite equipment it is more difficult to identify generic hardware components. A short description of the equipment involved is given below.

The Telecommand Encoder (TCE) Mark IV in Figure 2 encodes TC packets[2] according to the TC packet standard and sends the encoded data to the transmitter front end for uplink to the satellite. From the Return Protocol Handling System (RPHS) the TCE Mark IV receives the Command Link Control Word (CLCW), which returns the status data of the TC decoding machine onboard to the ground.

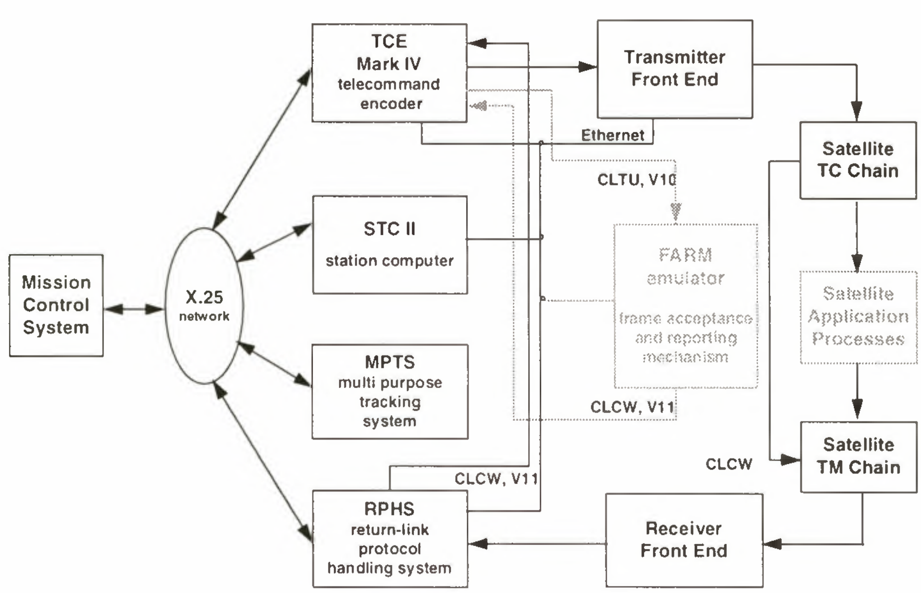

Figure 2. Generic TC - TM chain hardware overview.

The RPHS decodes the received TM data from the satellite. It can operate in two different modes. One is the *online data delivery* mode, where the received data are transmitted immediately to the mission control system. Due to higher data rates between ground station and satellite compared to RPHS and

[2] The TCE Mark IV can also operate in PCM mode, but the mode considered in this study is the packet mode

mission control system, data loss can occur in this online data delivery. The other mode is the *immediate data access* mode, where earlier stored TM data are delivered to the mission control system. The data loss in the online data delivery mode is only between RPHS and the mission control system. The lost data can be retrieved in the immediate data access mode afterwards.

The station computer II is used for status monitoring of the station subsystems and for configuration of the station equipment.

The multi purpose tracking system is used for tracking the satellite.

The Frame Acceptance and Reporting Mechanism (FARM) emulator in the picture, which is normally not used in the operational TC - TM chain is a test tool for the verification of the TCE Mark IV. That is why it is shown gray in the figure. It realises the onboard part of the coding layer and the transfer layer (FARM) as described in the TC packet standard and returns the command link control word to the TCE Mark IV. For our study the FARM emulator was of special importance, because it was used as a replacement unit[3] for the onboard TC decoding model.

The satellite TC chain consists of the onboard parts of the TC packet standard layers. It includes the physical layer, the Command Link Transmission Unit (CLTU) decoding, the FARM and the packet assembly controller. The output of this chain are the TC packets to the satellite application processes. The satellite application processes are shown in grey, because these are nongeneric parts.

The satellite TM chain receives TM source packets from the satellite application processes and encodes them into TM frames. These frames are Reed Solomon and Viterbi decoded for down link to the ground station. The CLCW from the FARM is embedded in the TM frames by the TM frame encoder.

4 LOGICAL MODEL REPLACEMENT

A main point of this study is the identification of suitable replacement units for simulation models. In this chapter the logical components of the *enhanced* SIMSAT[4] are collected and shown with their corresponding candidates for replacement. They are listed in the table below. The criteria for the replacement unit selection are:

1. The interfaces of the replacement units must be well defined and they should be generic. For the packet assembly controller model and the TM packet encoder no generic implementations are defined, so the replacement of their logical models cannot be considered in this study for example.
2. The replacement unit must be available.
3. The replacement must be technically feasible. In this context it must be examined which interfaces of the replacement unit must be driven by the simulator to make the replacement unit work properly in the simulator environment.

TC Packet Encoder model	Telecommand Encoder Mark IV
TC Packet Decoder model	FARM emulator

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[3] A operational hardware equipment or a test tool, which can be used for replacing a simulation model is called replacement unit.

[4] Enhanced SIMSAT means a new verion of SIMSAT, which contains also TC and TM packet standard compliant model, because when we start our work SIMSAT contains only PCM standard compliant models.

Packet Assembly Controller model	no generic replacement unit available
TM Packet Encoder model	no generic replacement unit available
TM Packet Decoder model	RPHS without Concatenated Decoding System 2A
Station Computer II model	not considered
Multi Purpose Tracking System model	not considered

The station computer II model and the multi purpose tracking system model are not considered because this work concentrates of the elements directly involved in the TC and TM chain.

5 SIMSAT ENHANCEMENT CONCEPT

5.1 HARDWARE OVERVIEW

Once the replacement units have been selected, the interfaces to connect to the simulator must be examined. Figure 3 shows the hardware replacement configurations for the selected replacement units.

Common to all replacement configurations is that an *interface* PC is used as a router for most of the interfaces between the VAX running the simulator and the replacement unit. This PC is a IBM compatible PC equipped with the necessary interface boards to drive the replacement unit interfaces. This interface PC has been selected to overcome some interface limitations of the SIMSAT platform (VAXstation 4000/90A). The special problem was that no synchronous communication option exists to this VAXstation, which would allow a user implemented protocol (TC packet standard physical and coding layer protocol) at low cost.

Another advantage of the interface PC solution is that there are less restrictions with respect to the spatial locations of the VAX and the replacement units. If the PC is not used the VAXstation and the replacement units must be rather close together.

The drawback of the interface PC is that an additional platform is required.

The first replacement configuration shown in the figure is the one using the TCE Mark IV. As can be seen, three interfaces from the simulator to the replacement unit exist.

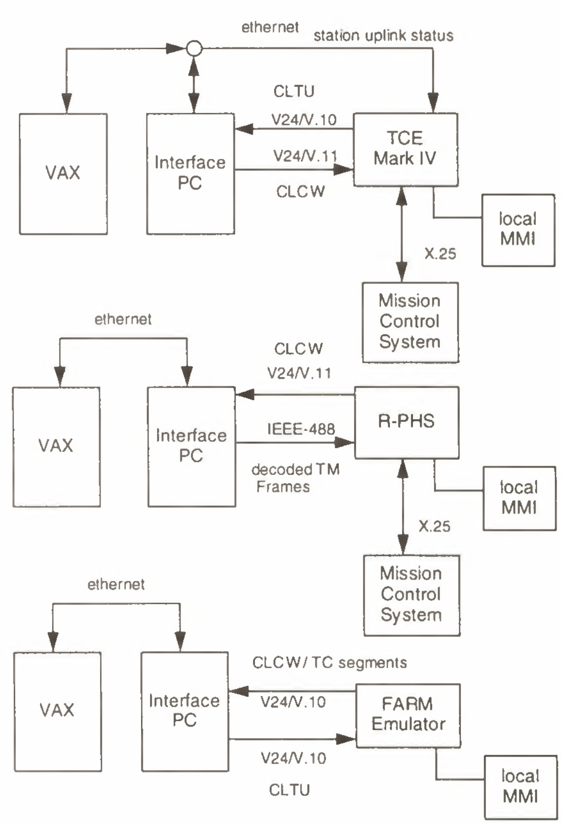

Figure 3. Replacement hardware configuration.

1. The ethernet interface is used for the delivery of the uplink status to the TCE, because the TCE receives this uplink status from the front end equipment. If the TCE does not get an uplink status

it will report an error to the mission control system under normal conditions. To avoid this, the uplink status check could be locally disregarded on the TCE Mark IV. We have taken into account this interface because it could be interesting for injecting errors.

2. The CLTUs are received from the TCE via a serial synchronous V.24/V.10 interface. The *external video modem data output* of the TCE Mark IV is used for this purpose.

3. The TCE receives the CLCW via a serial asynchronous V.24/V.11 interface. One of the three *operational CLCW inputs* of the TCE Mark IV is used for this purpose.

The second configuration uses the RPHS as replacement unit. The used replacement unit interfaces are:

1. The RPHS sends the CLCW via a serial asynchronous V.24/V.11 interface. This interface is compatible with the operational CLCW interface of the TCE.

2. The TM frames are sent to the RPHS via an IEEE-488 interface. The interface used is that between the Concatenated Decoding System 2A and the Return Link Data Processor of the RPHS. So the Concatenated Decoding System 2A is excluded from the replacement. This is reasonable, because if the Concatenated Decoding System 2A is included the TM frame must be Reed Solomon and Viterbi encoded, which will increase the effort for the simulation and which is not of interest for the simulator user in the mission control system.

The last replacement configuration shown is the replacement of the onboard TC decoding model by the FARM emulator. This configuration contains the following replacement unit interfaces.

1. The FARM emulator sends the CLCWs and the TC segments to the simulator via a serial asynchronous V.24/V.10 interface. The interface used is the *external frame generator interface* of the FARM emulator. The data sent on this interface are the CLCW, the frame acceptance report, the authentication status report and the TC segments. The frame acceptance report and the authentication status report are ignored by the simulator.

2. The FARM emulator receives the CLTU on a serial synchronous V.24/V.10 interface. The *external video modem data input* of the FARM emulator is used. This interface is compatible with the external video modem data output of the TCE.

As can be seen in the replacement configurations, only one replacement unit is considered at a time in our study. But the concept can be easily extended, if several replacement unit should be used simultaneously.

5.2 SOFTWARE CONCEPT

The main features of our software concept to realise the replacement feature is that the replacement functionality is embedded into the corresponding simulation model. An other simulation objects, which interface to the simulation model do not recognise if the simulation model works in pure simulation or if it uses a replacement unit. This was of special importance because a requirement was to have the least possible impact on the existing SIMSAT design. An architectural design of the new equipment models has been prepared which adds the replacement functionality for equipment models with available replacement units.

As an example the replacement concept is shown for the TC packet encoder model in Figure 4. This model can operate in simulation mode, where the TC packet encoding model is active (dashed lines), or in replacement mode, where the real TCE is used (solid lines). In the replacement mode the TCE is directly connected to the mission control system (via X.25) as in the normal operational case. The interface PC decodes the CLTUs arriving from the TCE and it encodes the CLCW for delivery to the TCE. The coding layer is implemented in the firmware of an intelligent synchronous communication board contained in the interface PC. This means that the simulation on the VAX is performed only down to the transfer layer and not to the coding layer. The status modelling bubble is for the delivery of the station uplink status to the TCE.

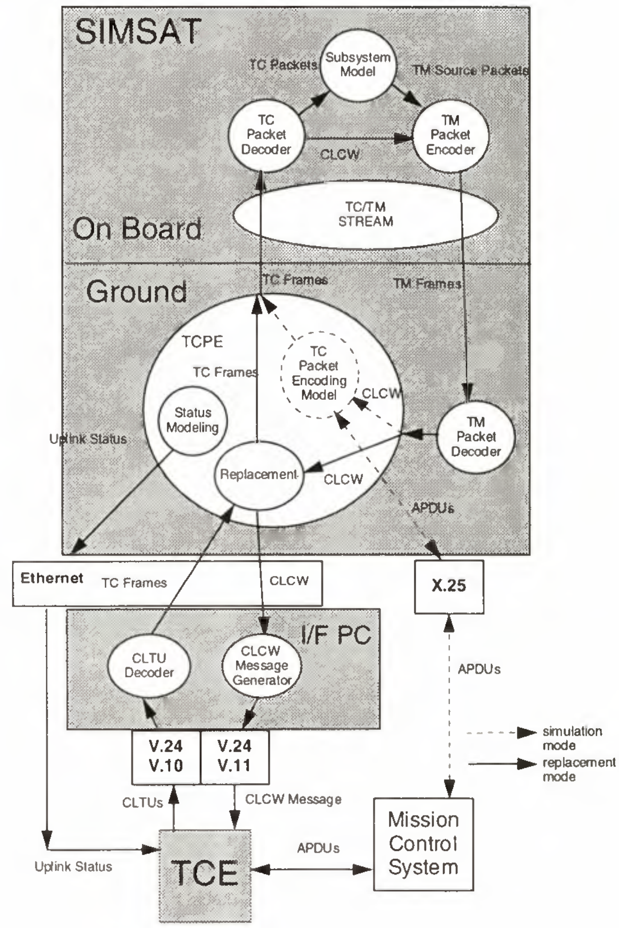

Figure 4. Replacement concept for the TC packet encoder model.

6 HYBRID SIMULATION CHARACTERISTICS

For the verification of our concept, a SIMSAT based simulator prototype has been implemented, which simulates the packet standard compliant TC chain processing using once the TCE Mark IV and once the FARM emulator as replacement units. The counterpart to the replacement unit in the chain is simulated (e.g. When the TCE Mark IV is used as replacement unit for the ground model the onboard decoding part is simulated). Also an error injection possibility was foreseen for the prototype for the testing of the various error correction and detection mechanisms contained in the TC packet standard (e.g. TC frame loss). In the following some features of these hybrid simulations are mentioned.

Increased Realism

The main advantage of the replacement concept is the increased realism of the simulation. This is of special importance for the TCE Mark IV and the RPHS, because these instruments are very complex and a simulation model of these instruments without major simplifications would be a very high effort. Furthermore the interface of this equipment to the mission control system is very complex and when replacement units are used, no restriction to this interface is applicable because they are connected directly to the mission control system (X.25 network).

Cost Reduction
As mentioned in the previous paragraph a high realism of the simulation can be achieved by replacement. So this concept can reduce the simulator cost, if a high realism of the simulation is important. The efforts to develop the model of an equipment to the level of realism required on the one hand and to implement the replacement possibility and to make the replacement unit available on the other hand must be compared to estimate the cost reduction.

Testing with Real Equipment
It is an advantage of the simulation model replacement that the simulator operators get a better understanding of the operation of the replacement unit. Also this testing can be useful to detect errors in the replacement units, because the operation of the replacement unit as part of a full mission simulation is of course a more realistic test than only an acceptance test of the replacement unit.

Availability of Replacement Units
A crucial point for the replacement of simulation models is the availability of the replacement units. It depends on the usage of the replacement feature, and how much effort must be spent to have a replacement unit available. When the replacement unit is used all the time for the simulation, additional equipment must be procured. If it is used only for some verifications, an already procured replacement unit (e.g. ESOC reference station) could be used.

Restrictions to Simulation
There are some restrictions to the simulation because the simulator operator has no access to data in the replacement units. Error injection is restricted and also no interruption of replacement unit operation using break points is possible.

Complex Simulation Infrastructure
The simulation infrastructure becomes more complex when using replacement units, because one has to set up the configuration and make some initial settings on the replacement units, too. So it is not recommended to implement no simulation model and use the replacement only, because this needs more time for simulation preparation.

7 CONCLUSIONS

The replacement of simulation models by real equipment will not fully replace simulation models, but it can be useful for special verification tests of new equipment operations. Especially the TCE Mark IV and the RPHS are very interesting for replacement, because these are rather complex equipment and a full simulation will not be feasible with justifiable effort.
Another reason is that for the first missions which use the TC/TM packet standard the replacement will allow a better mission preparation, because eventually characteristics of the TCE Mark IV or the RPHS, which cannot be predicted, appears already during mission simulation.

8 ACKNOWLEDGEMENTS

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Development and Operations in the Dutch Utilisation Centre

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ABSTRACT. At the early beginning (1989) of implementation of the European User Support Organisation (USO) concept, development and implementation of a Dutch Utilisation Centre (DUC) started at NLR premises. After development of several pilot DUC facilities, DUC participated in a Columbus simulation mission and in the 2nd International Micro-gravity Laboratory mission (IML-2). Different ground segment configurations were set up at different locations to meet the specific requirements for the missions. DUC development focuses on achieving a flexible support concept in teleoperations, telerobotics, and visual (video) information processing and presentation, using different communication concepts and video equipment. The configurations are prepared for the purpose of future missions onboard International Space Station. Support will be provided to both experiments and systems operations, such as operations with the European Robotic Arm (ERA).
The paper will describe the technical set-up of the DUC, focusing on the communication infrastructure and the ground segment systems for receiving the various data streams.

1. INTRODUCTION

In 1989, the European Space Agency (ESA) set up an international team, with NLR participating, to establish better concepts for the utilisation of the relatively expensive research facilities on board of spacecraft. This team worked on the concept of a User Support Organisation (USO) (Ref.1). A key element in this concept is the establishment of utilisation centres relatively close to the scientific user groups, offering utilisation support services. Several ESA member states have adopted and implemented the concept of Utilisation Centres.

1.1 THE USO CONCEPT

Backbone of the defined USO concept comprises an infrastructure of co-operating and interlinked (national) elements. The idea was that each nation would realise a national point of support: the National Utilisation Centre, that would serve as an entry point for scientists, and that would provide support in the process of defining, designing, developing, operating and possibly even evaluating an experiment. Five potential fields of support were foreseen: familiarisation, administrative support, scientific support, technical support and operational support.
Each Utilisation Centre has the freedom to implement support up to a level and nature that best fulfils the national needs. In the USO concept Utilisation Centres can become Facility Responsible Centre. This implies that the centre has special expertise and operations responsibility for one or more specific multi-user facilities.
On a European level the various national Utilisation Centres would be united in a so-called E-USO.
Task of this organisation was foreseen to perform overall co-ordination of activities and maintain a certain

level of mutual awareness of the individual centres. The E-USO has not yet been realized.
Since the publication of the USO concept some years have passed. In some countries national activities to implement user support have emerged. Progress is slow, caused by the fact the Space Station, with its continuous experiment capability, is not yet available and current flight opportunities are minimal. Many countries decided to adapt the level of user support to the amount requested by the scientist.

1.2 THE DUTCH UTILISATION CENTRE

In addition to participating in the ESA-team, NLR played an active role in the establishment of the Dutch Utilisation Centre (DUC) at NLR premises (Ref.2). The DUC provides microgravity users (and other scientists interested in performing experiments on board of spacecraft) with (mainly) technical support. Various tools have been developed to facilitate among others:
- communication between crew member (astronaut) and Principal Investigator (PI);
- on-line real-time processing of scientific data;
- remote experiment operation by the ground-based PI.

The development and implementation of DUC is focused on the following utilisation aspects:
- promotion of decentralised operations support, with a strong involvement of the users;
- international cooperation, as was derived in the IML-2 mission, with ESA/ESTEC, MUSC (Germany), CADMOS (France), MARS (Italy), and other UCs in Europe;
- follow standards and practices within the European Space community concerning payload development (payload end-to-end process) and communication;
- technical and operational support, including training, payload development, and communication;
- recommendations for automation and robotics servicing, and teleoperations with crew intervention rather than crew operations.

In 1994, the use of the DUC has been demonstrated twice. The DUC was involved successfully in a realistic manned mission demonstration, simulating activities of ground-based Principal Investigators (PI) and Space Station crew. During the second International Microgravity Laboratory mission (IML-2), a critical point experiment was supported. In this experiment the DUC provided on-line support to the remote science team. In addition, DUC supported preparation of experiments onboard the D-2 mission, and later on, for the Euromir mission. Other experiments and operations have been performed in the area of Automation & Robotics (A&R). For more information, see reference 7.
Many development activities have been supported by the Netherlands Agency for Aerospace Programmes NIVR, and have been performed under contract with ESA.

2. CREW SUPPORT VERSUS AUTOMATION

One of the objectives of (operational) support is to increase the chances of successful experimentation in a space laboratory, by providing the scientist with possibilities to operate or interact with his experiment. This way the user is brought into close contact with his experiment during actual execution.
The crew is in a situation where they can interact directly with the experiment, when tasks have to be performed that cannot be done by teleoperation. In the Spacelab era, training of crew for all foreseen tasks was feasible, as the mission duration was limited. In the Space Station era, however, both mission duration and the amount of experiments will dramatically increase. Hence, thorough training of the crew for all possible situations and all experiments will not be feasible anymore. To ensure that the crew members can still support ongoing experiments, even in contingency situations, the tools and procedures must be provided on board, by means of crew support systems. Recent activities of the DUC included the development and verification, under operational circumstances, of a laptop computer for crew support

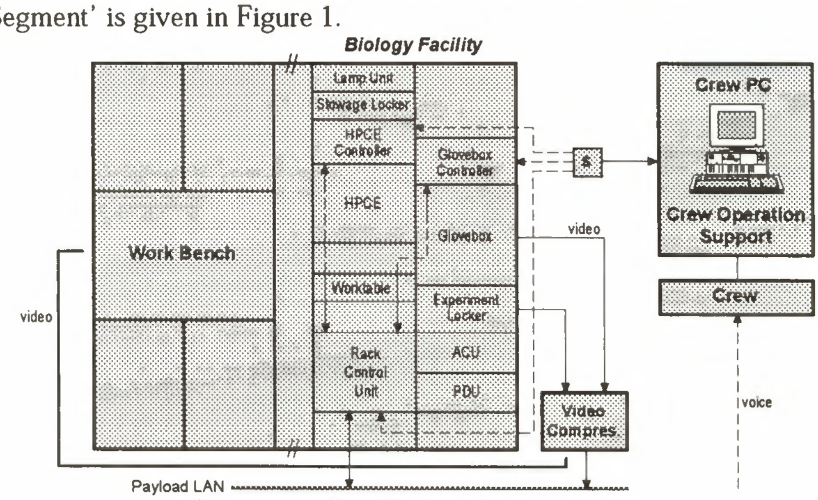
purposes: the Crew Portable Computer (CrewPC), and later the Advanced Crew Terminal-ACT. These crew support systems increase the efficiency of the communication between ground-based scientist and the crew member, and provide the crew with access to information on the experiment in the form of multimedia documentation and crew procedures (Ref.3).
By using two support systems, one on ground (the GroundPC) and one on board (the CrewPC), each containing the same applications and experiment databases, a synchronising mechanism enables easy communication between space and ground. Both systems were equipped with identical (experiment/ facility dedicated) multimedia databases, that could be controlled from ground and space. In this way it is possible for the user and the crew to communicate by means of annotations and drawings, and for the user to monitor the crew activities. During the manned mission demonstration, this synchronisation concept showed to be very efficient and indeed decreased the ambiguity in communication. Current activities, in ESA context, extend the crew support system with a speech Input/Output interface, that allows the crew to use it in an eyes- and hands-busy situation.

3. MANNED MISSION DEMONSTRATION

The Space Station crew simulation session (also known as DAMS) at NLR was an extension of ESA's earlier mission simulation activities (Ref.4). After some events, simulating one day out of the life of an astronaut, a longer period was called for, with an increased level of experiment realism and with higher payload operations complexity. In addition, a crew support concept was investigated using different control and monitoring modes for space and ground segment. The DUC, as the remote user support centre, provided ground support for payload integration, preparation, repair and maintenance of a breadboard Biology Facility which housed two multi-user payload facilities: the Glovebox and the High Performance Capillary Electrophoresis (HPCE) instrument. Identical man-machine interfaces for crew and ground terminals were implemented, according to an existing design of the Crew PC and Ground PC. The demonstration set up was developed by a Dutch consortium of industries and institutes headed by NLR (see also Ref.5).

3.1 DEMONSTRATION SET-UP

A three-day mission demonstration was set up at NLR. The set-up comprised two different sites: a 'space segment', where the experiment and facility hardware was located and where the simulation crew performed their activities, and a 'ground segment', the DUC, where Principal Investigators (PIs) and support personnel monitored and operated the experiments and communicated with the crew. An overview of the 'Space Segment' is given in Figure 1.



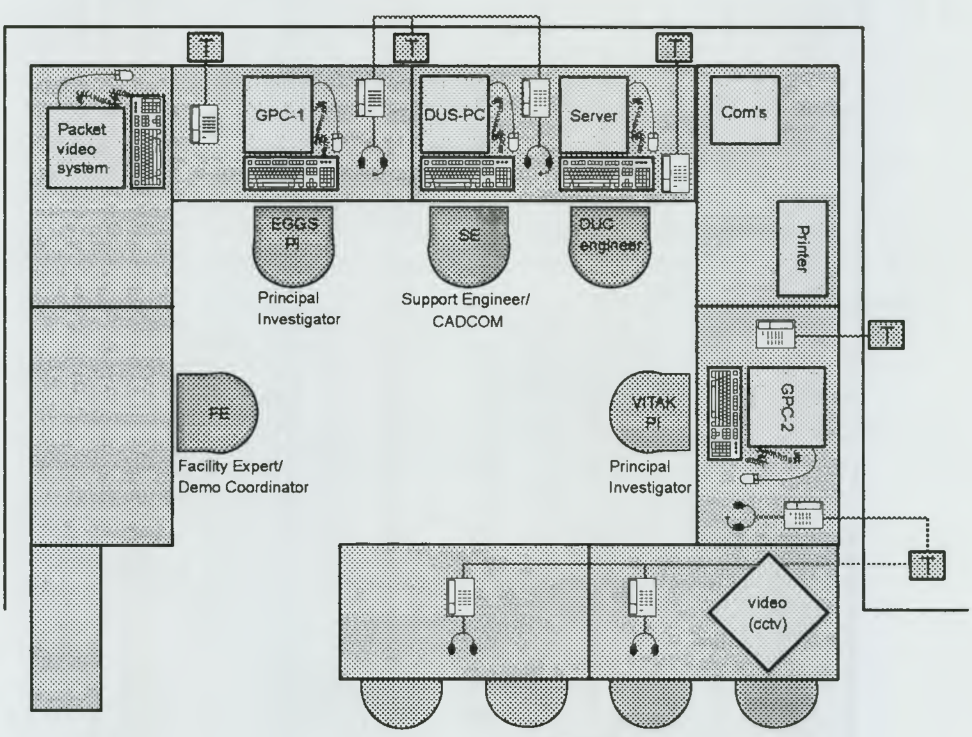
(Figure 1 - Set-up of the 'space segment')

The communication of voice, data and video images between a (simulated) space segment and ground segment were based on a realistic communication set-up.
The payload data communication was based on a standard path service protocol on Ethernet. The ESA Packet Utilisation Standard was used to identify payload and video data packages.
Voice communication was implemented on the NLR telephone network in a conference mode.
A closed circuit television system from space segment to DUC-site was installed for observers.

Two PIs were active during the demonstration, performing two different experiments.
One PI performed an experiment involving the fertilisation of toad eggs and the observation of their development 'on board'.
The other PI performed an experiment related to the study of bone demineralisation in microgravity. For this experiment, urine samples of the crew were prepared and analysed with the HPCE.

3.2 THE GROUND SEGMENT

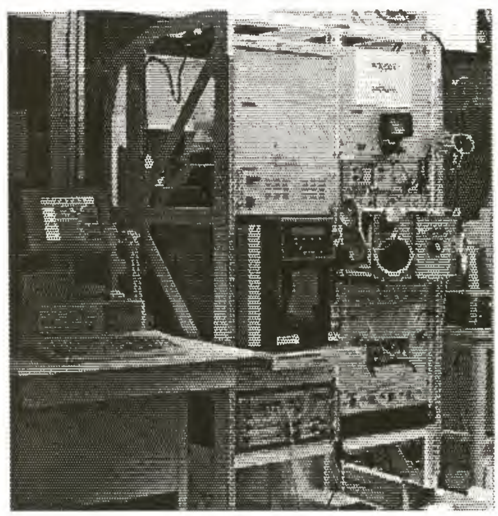
Experiment and facility operations were performed from three functional positions at the DUC-site. The PI, the originator of the experiment, performed on-line operation and monitoring of the experiment. A Support Engineer, assigned to assist the PI, was responsible for crew communication and on-line support to the PI. A Facility Expert was responsible for support to dedicated on-board facility operations and maintenance.
The DUC lay-out (see Fig. 2) included two Ground PCs, a DUC User Support system for off-line experiment analysis, a Server Station, and a Video PC. The server dealt with the DUC internal data distribution, while the DUS-PC provided special applications for experiment data processing. The Video PC was dedicated to the presentation of toad egg experiment video images. A Packet Video System allowed video images to be transmitted to the ground segment (Ref.6).



(Figure 2 - Set-up of the 'ground segment' (DUC))

3.3 THE SPACE SEGMENT

The space segment comprised the breadboard Biology Facility and some general purpose facilities, such as the Portable Workbench, and the Crew PC. The Biology Facility houses the two multi-user facilities, and one experiment-dedicated facility, the Experiment Locker. Figure 3 presents the hardware configuration the Biology Facility and the Crew PC. Major activities of the crew in the space segment are the operation of the experiments and facilities as part of the execution of the experiments. The Crew PC is the crew's major tool for performing these tasks.



(Figure 3 - Breadboard Biology Facility and Crew Portable Computer)

The CrewPC is the interface between the astronaut and the on-board systems. It includes a number of dedicated crew support tools. A Crew Procedure Execution Support system assisted the crew in the step-by-step execution of on-board procedures. At each step, the required support could be obtained from a Document Filing System that provided direct access to text information, engineering drawings, explanatory photographs or video clips.
Virtual Control Panels were used to enable payload control by crew and ground and to read-out payload status by parameter values via the PC.

3.4 EXPERIMENT FACILITIES

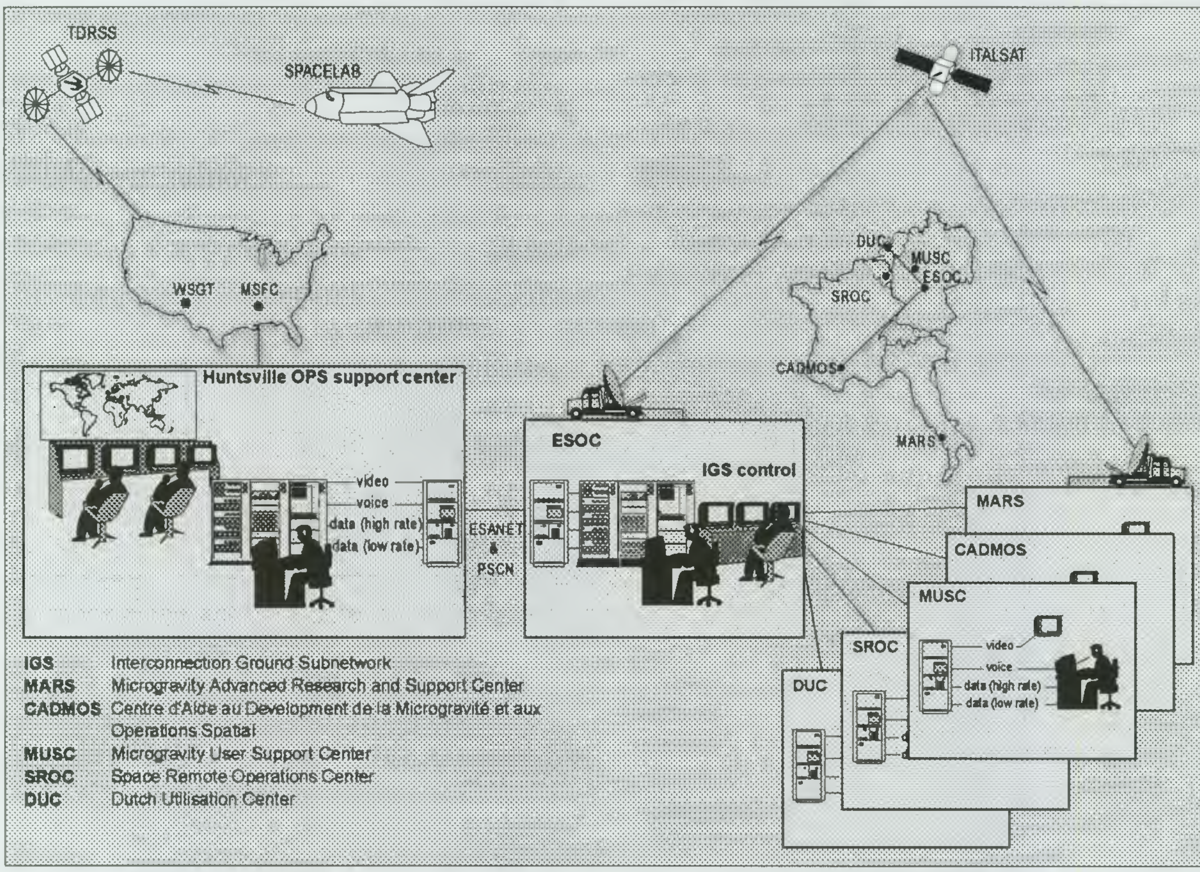
The HPCE system implemented in the Biology Facility, based on a commercially available 1-g system, was used for the analysis of crew urine samples, reflecting the process of bone demineralisation.

The Glovebox system implemented in the Biology Facility was a model based on the Shuttle Middeck Locker type. Three video cameras were available to enable monitoring of operations in the Glovebox work area. The control and monitoring of the Glovebox can be performed not only by the crew, via the Glovebox front panel and the Crew PC, but also by operators on the ground via the Ground PC. Most of the Glovebox operations during the mission demonstration were focused on maintenance and in-flight payload integration.

The Experiment Locker provided a temperature controlled environment for the Toad Eggs modules. A video system was implemented that allowed observation of the eggs in the modules. The crew could move the camera over the various modules such that different eggs could be selected for detailed observation. The video images were transmitted to the dedicated Video PC in the DUC.

4. REMOTE SUPPORT TO IML-2 MISSION

The Van der Waals-Zeeman laboratory and NLR/DUC were working together to prepare the DUC for remote support of experiment operations and to enhance the scientific return of an experiment. This experiment was conducted in the Critical Point Facility (CPF) carried by Spacelab in the second International Microgravity Laboratory (IML-2). The DUC was one of five European user centres involved in remote support of operation of European facilities and experiments.



(Figure 4 - Overview of the communications for the IML-2 mission.)

4.1 THE CRITICAL POINT FACILITY

The CPF is an multi-user facility of ESA, offering investigators opportunities to conduct research on critical point phenomena in a microgravity environment in Spacelab.
The inherent instability of the phenomena, even in microgravity, and the long time to achieve equilibrium, requires any temperature changes to be carried out in very small increments, resulting in long duration experiments. Experiment runs of 40 to 60 hours are normal, and require missions such as provided by the Space Shuttle and Spacelab.

The PI used the CPF to study the processes of heat transport in a pure fluid (SF6) near its critical point, and their fundamental relation to the density profile.
The experiment started 2 days and 4 hours after the launch of the Space Shuttle, and lasted 56 hours. During this time, full support from the DUC was available.

4.2 COMMUNICATION

The end-to-end communication layout for the concept is depicted in Figure 6. Three different data communication streams can be distinguished.
- Data from Space Shuttle to Marshall Space Flight Centre (MSFC), Huntsville

The Telemetry and Data Relay Satellite (TDRS) system of geosynchronous satellites allowed the orbiter to have line-of-sight transmission capability with at least one of the TDRS satellites at most times.
- Data from MSFC to ESOC, Darmstadt

ESA had installed a single physical link to ESOC, Darmstadt, with all the different data streams of the remote centres integrated. A transatlantic data connection was provided by ESA.
- Data from ESOC to DUC, Amsterdam

To transfer data between ESOC and DUC, seven ISDN channels were used The ISDN connection was used only when necessary, keeping the communications costs for DUC low.

4.3 DUC SET-UP

At the DUC all experiment data from the CPF were received and stored. The most important data streams were extracted from the incoming data and immediately processed for (near) real time analysis:
- the still video information, giving every six seconds an updated interferogram;
- the data from the experiment computer including temperature data and light scattering data.

The processed data were observed and verified by the remote science team at the DUC in Amsterdam (Fig.7). They discussed their findings over a voice connection with Dr. Michels, who was at the POCC in Huntsville. The DUC used the NASA Voice Distributed System for the communication with the POCC. This voice matrix system groups all voice loops used to conduct a space mission. Electronic data could be transferred by means of an Ethernet connection between the POCC and the DUC.

The advantage of the set up at the DUC over Huntsville was the possibility for the remote support team to have all the scientific data available in digital form (as opposed to the PI team in Huntsville, who had to work with analog slow-scan video). Furthermore, the DUC offered the possibility to the scientists to work in an environment provided with all they needed at hand.
Another advantage of the DUC was the capability of correlating the different measurement systems of the CPF.

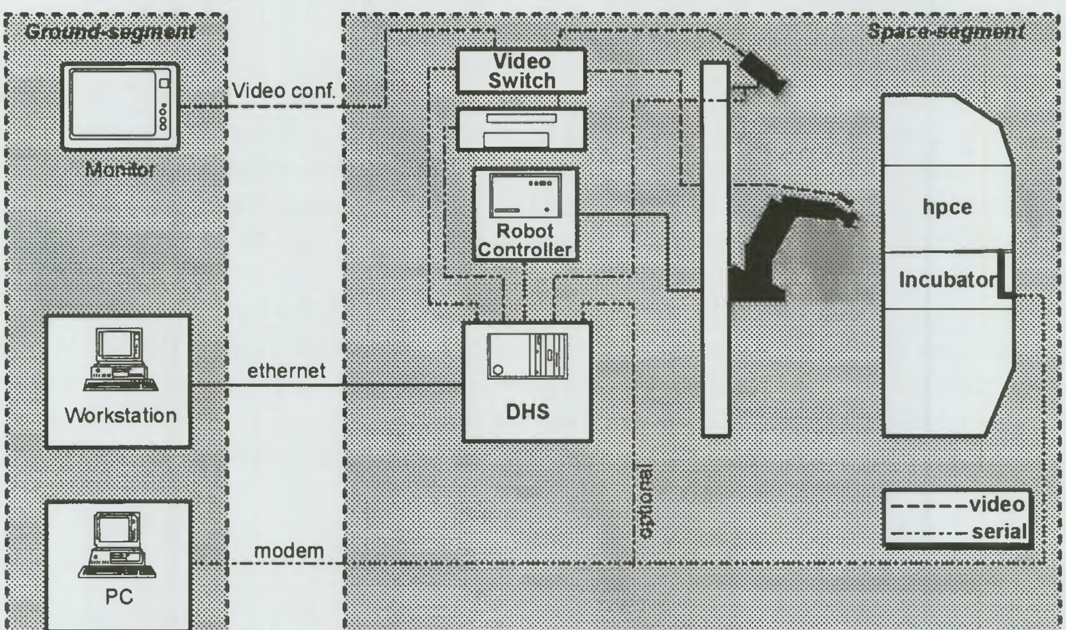
(Figure 5 - The DUC team)

5. TELEROBOTICS AND AUTOMATION CONCEPTS

In order to be able to support development and operations of experiments and payloads for future (partly) automated facilities, national projects have been set up in the area of Automation & Robotics, headed by NLR.
For payload development, standards and methods developed under contract with ESA have been re-used, such as Space A&R Controller (SPARCO), Integrated Payload Automation (IPA), Interactive Autonomy (IA), and Control Development Method (CDM).

5.1 AUTOMATION & ROBOTICS FOR MICROGRAVITY PAYLOADS

The national study ARMADE - Automation and Robotics (A&R) for Microgravity Applications Demonstrator supported the development of the Columbus A&R Testbed (CAT) at ESTEC.
The objective of this project was the development and demonstration of a microgravity model payload for automatic, robot manipulator supported, experiment execution.
The experiment facility consists of an incubator and an analysis instrument, and between these two a sample cartridge has to be transferred by a robotic arm. It has enhanced CAT with a more realistic payload - the first one with actual 'science' data output -.



(Figure 6 - Telerobotics system configuration)

5.2 TELEROBOTICS EXPERIMENTS

During the CEAS Symposium on Simulation Technologies 1995, the concept of remote payload operations supported by A&R was further demonstrated as a 'ground-based simulation with hardware-in-the-loop' (Ref.9). At the same time the demonstration was an experiment with different forms of modern communication technologies. The demonstration configuration consisted of three major elements. Firstly, the ground segment, containing equipment for preparation, operation and monitoring of the experiment. Secondly, the space robotics laboratory, containing a 7 degrees of freedom robot system, a payload rack and remotely controlled video system. And thirdly, communication equipment connecting the two sites consisting of a high speed ATM link (>30 Mbs), an ISDN connection and a standard internet connection.

The ATM connection was realized with real-time, high quality video equipment from AT&T.
The ISDN connection was used by a desktop video conferencing system as a means for crew support. The internet connection was used for a simplified TM/TC protocol (over TCP/IP) to control the different elements in the remote laboratory. The concept of multiplexing several control paths into one TM/TC link was maintained.
Experiences gained during the demonstration could be valid for both the tele-operation of a remote laboratory as for the case of a distributed ground support for which the used communication technologies are more readily available. For critical tele-robotic operations the higher image quality of the ATM system was a clear advantage (eg. inspection tasks), while for cooperative work between the two sites the lack of a delay in the ATM system was shown to be a major improvement over ISDN. Further the use of a TM/TC link over TCP/IP using the internet infrastructure, demonstrated the possibilities thereof.
Figure 8 shows the whole system set-up.

6. USER SUPPORT AND CREW SUPPORT IN THE SPACE STATION ERA

The support provided to scientists in the context of the manned mission demonstration and the IML-2 experiment demonstrated that user support as implemented in the DUC fulfils the expectations. The participating users were enthusiastic about the offered interaction with their experiment and with the added scientific value that was gained by the immediate presentation of the experiment results (instead of after the mission).
The direct involvement of the users, combined with user support during the entire development path, is also the way to go for the Space Station era. For experimental use the Space Station has two important characteristics:
- the capacity for scientific experiments is increased (comparing with Spacelab) due to its continuous operation;
- the crew members will be less trained for experiment handling due to the large amount of experiments performed during their period on board.

The problems associated with these two characteristics, where do the experiments come from and how can proper operation and interaction be guaranteed, are more or less solved by the support concept described above. Hence the Netherlands will, in context of DUC, continue their activities in development of tools for user support. The activities foreseen comprise the extension of the support offered to the other fields mentioned. Still the effort introduced in user support will be tuned to the amount of Dutch users actually flying experiments and requiring support.

7. CONCLUSIONS

Since 1989 NLR has been involved in studies concerning the preparation and organisation of a national user support organisation and the Dutch Utilisation Centre (DUC). The DUC, located at NLR premises, is preparing itself for support activities for the Space Station era, focusing on technological support. A number of experiments have been supported, in real missions and demonstration environments. Crew and user support technologies have been developed in a national consortium.

The manned mission demonstration using the DUC appeared to be very realistic. Payload utilisation, stowage locations, integrated experiment operations, time-lines, and operational procedures could be tested very well. The demonstration yielded many recommendations for improvements on payloads, crew and ground procedures, crew interfaces, and communication.

During the IML-2 flight all data from the Critical Point Facility were received by the DUC, enabling the remote science team to analyse the data in real time or near real time. The PI team in Huntsville could be provided with a sound basis for real time decisions concerning the execution of the experiment, so that the valuable experiment time was used to the largest possible extend.

In addition, NLR is preparing to support the development of payloads to be operated by crew or to be compliant with A&R concepts, re-using ESA's payload development and A&R concepts.

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Track 3 – Mission Planning

Track Manager: M. Wickler (DLR/GSOC)

Review: Mission Planning Track

small statistics:
19 presentations, 21 planned;
(min. 40-50 attendants)

Very interesting presentations about three different aspects:

- Mission Planning for satellite missions (mainly earth observation missions)
- Mission Planning for the International Space Station (ISS)
- Mathematical methods and software tools for mission planning purposes

Mission planning for satellite missions

- Concepts about on-going missions *(e.g. ERS1&2, MOMS-2P, ISO, ROSAT)*
- Concepts about future missions *(e.g. CLUSTER, XMM, ENVISAT, CASSINI)*

Trends:

⇒Flexible concepts *(different concepts have been presented (centralized vs. de-centralized); the discussion must go on)*
⇒Concepts adaptable to other missions (transfer from recent or on-going missions to future missions)
⇒Reuse and exchange of mission planning system components (at the moment each control center uses its own mission planning system)

Mission Planning for the International Space Station (ISS)

- Requirements modeling technique (by using implicit /explicit resources);
- ISS planning concept
- InterNet/WWW-based access to mission data bases

Trends:

⇒Concepts as well as s/w should be verified during ISS-precursor missions

Mathematical methods and software tools

- Mission analysis software
- Generic Mission Planning software (e.g. orbital analysis, requirements generation, procedure management)
- Scheduling methods and software (goal: optimized timelines)

Trends:

⇒Reusable tools (= for general purpose)
⇒Flexible tools (= easy to modify)
⇒Intuitive to use
⇒Modular system (library with small dedicated "functions")
⇒Standardized tools and interfaces (exchangeable between different "users")
⇒Use of COTS tools (especially for GUI or other user I/F's)

Highlights

- New Mission Planning concept for the ISS: continuous planning instead of incremental planning (see paper 3.9)
- New planning process for (scientific) missions: Market-based resource distribution to managing (science) return (see paper 3.14)

SAR MISSION PLANNING FOR ERS-1 AND ERS-2

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ABSTRACT. The Mission Planning activities performed at ESRIN to schedule data acquisitions for the Synthetic Aperture Radar (SAR) instruments on board of ERS-1 and ERS-2 (alone and in Tandem) are described as initially organised and as they evolved with experience and changed requirements, after a short description of the ERS Ground Segment and an introduction, which lists other key mission factors and summarises ESRIN responsibilities in Earth Observation (ESA and Third Party Missions).

The major topics discussed are user interface, User Requests and their conflicts, Baseline Plans, Data Policy, Mission guidelines, and platform, sensors, ground segment and exploitation constraints, as well as planning tools, manpower needs and interfaces with ground stations. The experience gained can be used for future missions in the identification of the really achievable objectives, the definition of the offer to the user and the design of the Mission Planning system, in particular for user interface, mission planning tools and preparation of agreements with ground stations.

1. ERS MISSION & GROUND SEGMENT

The ERS-1 and ERS-2 satellites, launched respectively on July 17, 1991 and April 21, 1995, represent so far the unique case of a dual Remote Sensing mission and have provided results beyond expectations, in particular for Tandem data acquisition with one day difference, serving with data many user categories like real-time operators involved in meteorological, oceanographic and environmental applications, long-term research groups working off-line, commercial users, etc. The two satellites, carrying on board the set of instruments listed in Table 1, have been exploited in the different mission phases listed in Table 2.

The ERS Payload Data Ground Segment, sketched in Figure 1 and providing SAR coverage as per Figure 2, is managed by ESRIN, via its Earth Remote Sensing Exploitation Division (RS/E), and is composed of:

- The ESRIN ERS Central Facility (EECF), located in Frascati, in charge of:
  - user interface and user support (training, promotion, documentation, tools, etc.)
  - monitoring of investigations and transfer of technology
  - mission planning in conjunction with the Mission Management and Control Centre (MMCC) at ESOC
  - ground stations' interface & coordination of National & Foreign Stations (NFSs: National = stations of countries participating in the ERS programme, Foreign = stations of non participating countries)
  - planning and monitoring of production and delivery of near real-time and off-line products
  - generation and maintenance of a world wide inventory of acquired data
  - coordination of the commercial Eurimage, Spotimage and Radarsat International Consortium (ERSC)
  - assessment of instrument behavior and of related margins
  - monitoring and control of ERS data and product quality
  - management of the Ground Segment facilities and monitoring / control of related files' routing
  - maintenance of the "Reference System" for the High- and Low-Rate Fast Delivery Processing chains
  - maintenance of data-processing software for the entire Ground Segment

- The ESA Ground Stations: Kiruna (Salmijaervi, Sweden), Fucino (Italy), Maspalomas (Canary Islands), Tromsoe (Norway), and Gatineau and Prince Albert (Canada). All stations but Kiruna, operated by ESOC and fully dedicated to ERS operations (including telemetry, tracking and control activities), are multi-mission and operate under ESRIN contracts. This network ensures acquisition of regional ERS SAR data and acquisition, processing and delivery of global ERS LBR data within three hours from sensing.

- A network of 26 NFSs which acquire ERS SAR data around the world (no on-board tape recorder for SAR) under the terms and conditions of a standard Memorandum of Understanding (MoU).

- Four Processing and Archiving Facilities (PAFs), which are joint national / ESA endeavors to support / expand the applications of ERS data (SAR and/or LBR) through data archiving and off-line generation of precision products, in Brest (France, operated by IFREMER), Farnborough (UK, operated by NRSCL), Oberpfaffenhofen (Germany, operated by DLR) and Matera (Italy, operated by the Italian Space Agency).

2. INTRODUCTION

In this paper, the term "Mission Planning" indicates (is limited to) only the activities performed at ESRIN for planning SAR acquisitions. Other linked activities, like planning of LBR instruments (mostly performed by default at ESOC) or production planning are not discussed.

SAR acquisition planning, even if a complex task, has not caused bottlenecks or problems for the ERS mission. The overall effectiveness of the ERS SAR mission was or is affected much more by:

- Experimental nature of radar data:
  - off-the-shelf tools to manipulate data are just emerging on the market
  - application potentialities are still being demonstrated (research and promotion to be funded)
  - users are not yet familiar with radar image interpretation (training required)
- Data coverage and continuity:
  - possibility to plan at short notice for special events (24 h service depends on funds)
  - high revisiting frequency is essential for operational applications
  - data should be systematically acquired and long term archived for future use
  - NFSs should be encouraged to build and maintain a long term data archive (Data Policy)
- Products:
  - reasonable quota should be defined for investigations (and budget allocated)
  - commitments for data from foreign stations should be carefully taken (contract vs. MoU?)
  - formats should be homogeneous across all generation facilities and, possibly, missions
  - products should be tailored to user needs (e.g.: fast delivery low resolution, terrain corrected, etc.)

ESRIN is in charge of the planning and handling of the Earth Observation data from ESA and Third Party Missions (TPMs). For TPMs (e.g.: Landsat and JERS-1), planning is limited to the collection of user needs, the definition of other potentially relevant acquisitions, the transmission of the resulting plan to the satellite operator, and the scheduling of ESA stations. ERS-1&2 SAR activity planning is instead by far much more complex because, besides the number of on-board instruments and the parallel activities of two satellites, it must match user requirements (USER REQUESTS), gathered through the USER INTERFACE, and the BASELINE PLAN (derived from Mission / Data Policies, anticipated user needs and contingency planning) with the system CONSTRAINTS. This activity is supported by a balanced combination of dedicated PLANNING TOOLS & MANPOWER and relies on INTERFACES with the ground stations. All these elements are discussed below, describing their initial implementation and their evolution in line with the experience made and the changing requirements.

3. USER INTERFACE

The User Interface has been organised around three Desks: the ESA Help Desk (for information, documentation, tools, etc. to all users), the ERSC Customer Service (for commercial users) and the ESA Order Desk (for non commercial users), with the possibility to exchange correspondence through fax, telephone, letter, E-mail, etc., on user choice.

Currently 3068 users are registered, of which only 760 have a kind of on-line access (mainly E-mail) and 735 have submitted at least one User Request (of these only 263 have E-mail). It is evident that normal correspondence media are still widely used. Their use will continue in the coming years also in view of the opening of Eastern and African markets (telecommunication links to be set-up).

The ERS User Interface was designed to serve a variety of user categories (see Table 3):

- Investigators participating to ESA Announcements of Opportunity (AO) or Pilot Projects (PP)
- National and Foreign Stations
- Commercial / Operational users or Institutional Organisations
- Others (calibration / validation, training, promotion, public relation, etc.).

The service was set-up to treat all users on identical footing, but some users feel "more identical" than others, following strange routes instead of the standard ones, causing overhead, confusion and possibly bad service. Any service should be set-up to deal with such exceptions and be ready to dig out detailed history even after a few months, in order to face possible complaints.

After mission start, it was evident that interaction with users was more difficult and demanding than expected, despite that some key documents describing the system had been prepared and widely distributed (some users had the impression that we could move the satellite wherever necessary). It became essential, particularly for planning, to improve the user "visual" knowledge of the mission and to have him and our Desks to speak the same language. Therefore the graphic, simple and powerful Display ERS-1 SAR Coverage (DESC) tool, running on PCs, was developed and distributed. It was enhanced over time through valuable user feedback, up to the most recent Display ERS Swath Coverage for Windows (DESCW), which is multi-mission, supports quick-look display, provides on-line help, etc.

DESCW shows graphically the coverage of the various sensors in the future and/or in the past (through inventory search and filter). It is based on visibility files for possible future acquisitions and on compressed inventory files for past and planned acquisitions. The inventory files are either historical (past years) or updated weekly and are available online for free-of-charge downloading via FTP or Internet, together with the software and all supporting data. The entire software, the basic files, the Help text, the inventory files (about 20 years of inventory data in total for ERS-1, ERS-2, JERS-1 and Landsat) take less than 2 Mbytes and therefore are also distributed on two PC diskettes on user request.

Over time DESCW has been more and more used by our Desks and also by the mission planner, particularly to identify possible acquisition conflicts with other missions (the ERS mission planning system is not multi-mission), to derive rough indications useful for detailed mission planning and to quickly check future planning over small areas.

4. USER REQUESTS

The system was designed to permit formalisation of user needs through User Requests, which, for acquisition planning, mainly define the area and time period of interest and can equally well identify single frames and very large acquisitions (e.g. the full station visibility area for some months).
Large sensing requirements must be submitted to planning about one month ahead of acquisition, limited ones up to five working days ahead and exceptional cases have been handled up to two-three working days ahead (uplinking of the spacecraft telecommands is done one day before the acquisition).
User Requests can be submitted and their status verified on-line through dedicated forms, via X.25 and VT200 terminals. Users are also actively informed via e-mail or fax at major status changes.

Figure 3 shows the total number of User Requests per User Category since mission start and Figure 4 shows their variation over time. It must be noted that:

- Commercial requests are increasing (even if absolute value is still much below other categories)
- Investigator requests are lined up with the number of accepted projects
- National stations and Foreign stations with no-exchange of funds agreements request large amounts of acquisitions (even with few User Requests, since area and time range are wide)
- Foreign stations ("pay per frame") limit data requirements to the minimum (limited area & time)
- the complexity of the Baseline Planning is increasing (more specialised User Requests)

A few months after exploitation start, its was realised that some NFSs and most of the Investigators were submitting large acquisition requests, causing overhead in mission planning and possible waste of satellite resources. Since most of the investigations had a production quota defined, the Investigators were asked to limit their acquisition requirements to those to be associated in future to a product. This simple measure permitted to drastically reduce not the number of User Requests, but their size. However, when justified, the excess acquisitions were accepted within the Baseline Plan (see below).

The need emerged to speed up provision of information to users in case of sensor unavailability (some users take in situ measurements during satellite over-passes). Therefore an automatic procedure was added to inform via fax all affected users, immediately after reception of a sensor unavailability information. Many times this information is available only after the event, as in the case of arching (it can be imagined the reaction of a group of Japanese scientists, taking in situ measurements out on the cold Antarctic pack, while the SAR overflying the site did not acquire the data: complaints were flowing in all directions, hyperspace included).

5. BASELINE PLAN

Shortly before ERS-1 launch, when starting to handle User Requests, it was realised the need for an ESA Baseline Plan (a set of mission planner User Requests), implementing Data Policy and Mission Guidelines (see Table 4 for the most relevant ones) and collecting data of potential commercial, operational or scientific interest. In particular, the Mission Guidelines, defined for each Mission Phase in the High Level Operations Plan, influence planning over selected areas depending on the phase, while the Data Policy has large impacts on data requests from NFSs.
The Baseline Plan was more and more defined and complex. Currently it is centered on acquisitions for:

- a mapping mission (build up consistent thematic data archives; anticipate future user needs; collect data for exceptional events and natural disasters; etc.)
- phase / season dependent targets (monitor seasonal changes such as ice, ice boundaries and vegetation growth; collect full data sets over selected areas for applications like interferometry, change detection; etc.)

- system related objectives (optimise instrument and ground segment utilisation; plan instrument calibrations; optimise acquisition over stations working on campaigns; etc.)
- large Investigators' requests (follow moving targets like icebergs or ships; scan large areas for oil pollutions or special phenomena; etc.)
- anticipated user requirements (that is not yet formalised)

During the Tandem Phase, data acquisition from both satellites was implemented through a special Baseline Planning considering:

- areas as large as station visibility for descending passes
- small areas around steep slopes for ascending passes
- stations' availability (linked also to signature of MoUs, which for ERS-2 were normally late)
- conflicts among stations due to SAR acquisition limits (in practice only one station can be in full tandem at any time along the same meridian)
- orbit maintenance manoeuvres (for best Tandem data, the orbits of the two satellites were made to cross around equatorial regions during Winter and over the poles during Summer)
- segments linked to user requests on one satellite and unavailable for Tandem on both satellites

6. CONSTRAINTS

Some of the system constraints (the major ones in Table 4) are imposed by the physical characteristics of the instruments, spacecraft or orbit, while other derive from ground segment and exploitation possibilities (of course more detailed constraints are taken into account at ESRIN and ESOC). Even a few of the listed constraints make the planning process complex, also because their relative emphasis changes over time in relation for example to day/night, season, mission phase, etc. (likely, some of the most complex constraints were avoided, with the excuse that we were having already enough fun).

The constraints marked with an asterisk in Table 4 were defined a few months before ERS-1 launch, after a pre-release of the ESRIN mission planning system was delivered, and therefore induced late changes. Those with a slash were defined around the same period but were not implemented. The constraints marked with a plus have been encountered during exploitation.

It is evident that, a part from a few technical issues, the major constrains influencing mission planning have been drastically changing during the real mission exploitation.

7. PLANNING TOOLS & MANPOWER

The basic implementation of the ESRIN Mission Planning System was embedded in the development of the Central User Service (CUS) by MacDonald Dettwiler. In such core sub-system the planning is based on User Requests, shared with other sub-systems (User Request Handling, Order Handling, Production Planning, etc.), while a specific set of tools (forms, graphics and reports) assists the planner in his activities.

Before mission start, an attempt was made at ESTEC to include planning rules into an expert system based on Key / Lisp and running on a SUN workstation. Its use was successful in analysing LBR dump strategies, but it was judged not efficient and flexible enough for the complex and changing SAR mission. Moreover, it required additional expertise on the application package and it was difficult to interface it with CUS. It was therefore decided not to use it for acquisition planning.

ESRIN had developed with Advanced Computer Systems a mission analysis tool used to verify possible use of SAR sensing in various mission scenarios (different launch dates and cycles). Since the major concern was related to the probability of acquisition conflicts, this tool was upgraded to test a simple algorithm for possible conflict resolution, reduction or at least identification. The problem was extremely simplified, generating for three key types of User Requests all the visible (by a ground station) orbit and frame combinations, with all their possible alternatives. The algorithm was designed to allocate acquisitions starting from the less critical orbits (those with more frames available and less requests) and propagating the effects to all involved User Requests (the algorithm was designed to minimise conflicts and not to optimise planning, allocating the minimum number of sensing segments).
The results were promising, since, feeding the tool (which could have also been easily interfaced with CUS) with the available AO User Requests, practically no conflict was detected.
It was decided to verify CUS planning in practice before connecting this algorithm to CUS.

An analysis was made on the real conflicts experienced among User Requests. From Table 5, related to Phase C, it is evident that the limited commercial (top priority) requirements could not cause conflicts, while Investigators have larger conflict probabilities, even if, with a share of only 1/5 of the total allocation, other resources could have been freed for them if necessary. But this was not the case, since only 0.25 % (5 out of 2024) of the requests were in conflict and therefore marginally descoped.
During Phase D the requests in conflict grew to 1.75 % (13 over 743), because the short repetition cycle (3 days) and Phase (3 months) forced the grouping of the large requirements from the ice scientists over much less orbits (43 against 501).

Currently the orbit configuration for both satellites is the one of phase C and large Investigator requests tend to decrease. Therefore even less conflicts are being experienced among User Requests.

Acquisition planning is currently performed at ESRIN by one contract staff supervised by 50 % of an ESA staff, who ensures back-up during working days, but also contributes to the preparation of planning documents, defines detailed acquisition strategy in line with mission guidelines, sets-up the baseline plan, follows specific cases, contacts the stations for special arrangements, ensures correct reporting, etc. This manpower level is just adequate and in periods of particular load, such as Tandem Mission, some low priority activities are descoped, deferred or canceled (e.g.: internal reporting, analysis of station reports, etc.). The use of an expert system would have not reduced the manpower requirements below this limit, since, in addition to the planner, there would have been the need for an expert of the expert system for changing the rules according to the constantly varying mission needs (and possibly additional manpower for corrections and tuning).

To play fair, no real conflict can exist with such type of (politically sensitive) missions. In fact, even before a problem can be anticipated, users let us know about it, not plainly contacting the mission planner or our Desks, but with the proper emphasis through high level links (no push from the top of the hierarchy so far, unless the recent lightning at ESRIN is a sign of it).

8. INTERFACES

Besides the internal ESA interface between EECF and MMCC for mission planning, the EECF has planning Interfaces with acquisition stations, mainly for sending Acquisition Schedules and spacecraft ephemerids, and receiving Acquisition Reports. This loop is essential for the User Request satisfaction, since, in case of lost acquisitions, the sensing must be replanned, if it is still acceptable to the user. This interface was defined in two documents, one for ESA stations and a simplified one for NFSs, both based on files exchanged through telecommunication links using two file transfer protocols (FTAM and FTSV) over X.25.

When NFSs started to join the ground segment, it became evident that only a few of them had prepared their interfaces in line with the specifications. Therefore new interfaces and procedures had to be quickly defined and implemented based on faxes. Even these simple procedures were some times not applied (only telex working; requested report provided irregularly and after solicitations; reports not containing all required information or not providing adequate visibility; etc.). Slowly over years some of the stations started to migrate towards online connections, but unfortunately using their preferred protocols (in some cases also changing over time). We had to progressively add new protocols to our system, in order to simplify our operations, but at the expense of complexity.

The stations can submit User Requests like any user, except that they should indicate whether the request is for general data acquisition with lower priority or coming from an end user with higher priority. Table 6 shows the number of SAR frames acquired over all stations for both missions.

9. CONCLUSIONS

Due to the experimental nature of the mission, the complexity of the ground segment and the political drive and sensitivity, the ERS SAR Mission Planning, like many other activities related to the ERS mission, has been dealt with in many cases more by exceptions than through stable rules, since it was not possible to anticipate many of the ground segment constraints and the requirements' evolution. Therefore the planning system of similar missions should be designed starting from simple and adding complexity over time, when the real constraints, requirements and possibilities are known. The initial system should be flexible and enough resources should be foreseen for this expansion / adaptation.

Since the user is an integral part of the system, large information exchange is necessary. This should happen through the user's preferred methods and possibly supported by a graphic, simple, powerful and friendly tool, running at least in the most popular environment. This tool should be enough precise and complete to be also used internally, in order to talk with the user on the same ground. The resources (facilities and manpower) necessary for a proper interaction should be carefully evaluated and allocated, since they are essential to reduce problems and workload and to improve overall service quality.

The initial forecast that practically no conflict would exist with 12 minutes of SAR per orbit was confirmed by the experience, reassuring that the decision not to implement neither an expert system nor a special conflict resolution tool was correct. The absence of conflicts and the variability of constraints and rules, make flexibility more important than plan optimisation, with mission planning better based on natural more than on artificial intelligence (supported by powerful tools). A smart mission planner can anticipate and resolve conflicts before they are formalised, can judge new requirements against his knowledge of the constraints and his mental representation of the already performed planning, can learn from past and dynamically adapt procedures to the changing environment (missions with inconstant pattern represent still an area of revenge for the natural intelligence, if available, over the artificial one).

In conclusion, SAR Mission Planning has never been a limiting factor for the ERS mission. Other factors had and have much larger overall impacts, like:

- data policy
- experimental nature of the radar missions
- product types and formats
- behavior of stations in developing countries (such data is essential also for the rest of the planet)
- data availability (revisiting frequency) which would require either a cluster of satellites or coordinated and homogeneous access to data from all available remote sensing satellites

Table 1 : *ERS-1 and ERS-2 On-board Instruments*

INSTRUMENT	*ERS-1*	*ERS-2*
Active Microwave Instrument		
SAR Image Mode	X	X
SAR Wave Mode	X	X
Wind Scatterometer	X	X
Radar Altimeter	X	X
Along Track Scanning Radiometer-1	X	
Along Track Scanning Radiometer-2		X
Global Ozone Monitoring Experiment		X
Precise Range and Range-rate Equipment	(not active)	X

Table 2 : *ERS-1 and ERS-2 Mission Phases*

Mission Phases	*Start*	*Cycle*	*SAR Mission Objectives*
ERS-1			
- Launch	17-Jul-91		
- Payload switch-on & verif.	17-Jul-91		
A Commissioning	25-Jul-91	3 days	all instruments; until 10-Dec-91
B Ice	28-Dec-91	3 days	ice & pollution; interferometry possibil.
R Roll-tilt (Experimental)	02-Apr-92	35 days	Different SAR incidence angle (35 deg)
C Multi-disciplinary	14-Apr-92	35 days	AO; land & ice mapping; consistent set
D 2nd Ice	23-Dec-93	3 days	see Phase B
E Geodetic	10-Apr-94	168 days	radar-altimetric mission; SAR as C
F Shifted Geodetic	28-Sep-94	168 days	8 km shift vs. phase E for denser grid
G 2nd Multi-disciplinary	21-Mar-95	35 days	see Phase C
G Tandem	17-Aug-95	35 days	Interferometry & mapping
G Back-up	2-Jun-96	35 days	
ERS-2			
- Launch	21-Apr-95		
- Payload switch-on & verif.	21-Apr-95	35 days	
A Commissioning	02-May-95	35 days	SAR commissioning
A Tandem	17-Aug-95	35 days	see ERS-1 Tandem Phase G
A Multi-disciplinary	3-Jun-96	35 days	see ERS-1 Phase C

Note: 3 days = 43 orbits; 35 days = 501 orbits; 168 days = 2411 orbits

Table 3 : *Current number of Users per User Category*

USER CATEGORY	*No. of USERS*
AO / PP	1004
NA / FO	28
Planning	7
Commercial	233
ESA	223
No Project	1973
TOTAL DISTINCT	**3068**

Table 4 : System Constraints
*(- = initial; * = close to ERS-1 Launch; / = * but not implemented; + = during exploitation)*

DATA POLICY:
- national stations (with signed a MoU) can acquire data in a non interference basis
- stations with approved MoU can request data acquisition (at no cost for national stations and for foreign stations with no-exchange of funds agreements)

MISSION GUIDELINES:
- adhere to Mission objectives (phase dependent)
- SAR has priority in descending passes, Wave and Scatterometer in ascending passes (night)
- solve conflicts applying priorities to the user categories and then to users according to past allocation
/ allocate acquisitions for AOs within the assigned quota, in a 6 months moving window, varying their priority according to remaining time, past allocation for country and application category
* LBR activity has priority over SAR in ascending passes every other cycle

PLATFORM AND SENSOR'S CONSTRAINTS:
- SAR can be activated only in visibility of a ground station (no HR tape recorder on-board)
- in each 100 min. orbit, SAR can be activated < 12 minutes in total, < 10 minutes per segment on descending passes, < 4 minutes in eclipse (in addition, merge gaps <30 seconds)
- max. number of SAR on/off switches = 6 per orbit
- SAR imaging mode of AMI mutually incompatible with SAR Wave mode and Windscatterometer
- Windscatterometer must be switched on 128.2 seconds (850 km) before and after the site of interest

GROUND SEGMENT CONSTRAINTS:
- take into account the real station visibility mask in planning SAR sensing
- instrument planning and Kiruna station scheduling must follow defined time constraints
* schedule SAR sensing from 5 to 2 degrees above horizon
* handle station unavailability at major subsystem level
\+ adhere to ground station specific operational constraints, like: working hours (depending on campaign, country or religion), conflicts, available tapes, interval between adjacent passes, etc.
\+ schedule all stations in visibility of planned segments, unless no MoU exists, unless it is national or there is a commercial request or for a natural disaster, unless there is no hope to serve the user
\+ schedule overlapping stations depending on reliability and on station or PAF processing capability
\+ some stations report on acquisitions with a variable delay (even of months, causing loss of replanning opportunities) and occasionally their reports are discovered to be incorrect
\+ some MoUs signed later than expected or signature proceeding with hiccups
\+ reduce number of HDDTs avoiding overlapping acquisitions and minimising night passes

EXPLOITATION CONSTRAINTS:
* avoid bridging of specific segments (precise start flag)
/ monitor and control energy and thermal balances over and across orbits
/ handle SAR gain setting at User Request level
/ permit planning of sensor modes (e.g.: OGRC / OBRG)
/ handle solar panel occultation of downlink antenna (changing over the year and with latitude)
\+ 12 SAR minutes not per orbit, but from eclipse start to eclipse start (changing with seasons)
\+ apply 'common sense' (strict application of HLOP rules prevents optimised use of resources)
\+ assign higher priority to 'production requests' requiring new planning over 'acquisition only' ones
\+ assign higher priority to requests over stations working in campaigns
\+ change confirmed requests only in case of natural disasters or calibration
\+ ensure proper and complete tandem planning (no multimisson planning tool, user requirements might conflict with tandem mission, ground stations operational constraints more difficult to match, etc.)
\+ keep to a minimum the number of IDHT on/off switches (from June 1996, to extend lifetime)
\+ "keep alive" scenario requires planning of at least two segments per day, about 12 hours apart

Table 5 : *frames allocated during ERS-1 Phase C vs. User Category*

USER CATEGORY	*No. of FRAMES*
AO / PP	66331
NA / FO	80028
Planning	171116
Commercial	1479
ESA	3305

Table 6 : *Total SAR frames acquired worldwide for both missions*

	ERS-1	**ERS-2**	
GROUND STATIONS	**PHASES A-G**	**PHASE A**	**TOTAL**
FUCINO	99198	24536	123734
KIRUNA	252740	38716	291456
MASPALOMAS	32559	6578	39137
TOTAL ESA STATIONS	**384497**	**69830**	**454327**
Aussaguel	4843	0	4843
Gatineau	101314	12708	114022
Libreville	5975	3711	9686
Neustrelitz	3783	3320	7103
O'Higgins	37080	11247	48327
Prince-Albert	150371	19638	170009
Tromsoe (*)	215452	27996	243448
West Freugh	54119	6128	60247
TOTAL NATIONAL STATIONS	**572937**	**84748**	**657685**
Alice Springs	22372	5889	28261
Bangkok	5858	0	5858
Beijing	7834	4814	12648
Cotopaxi	7058	407	7465
Cuiaba	19445	3204	22649
Fairbanks	212328	18933	231261
Hatoyama	20874	0	20874
Hobart	3753	2661	6414
Hyderabad	24012	3961	27973
Johannesburg	5870	2919	8789
Kumamoto	18561	0	18561
Norman	2588	2287	4875
McMurdo	12851	12858	25709
Parepare	8395	2	8397
Singapore	2924	2765	5689
Syowa	6700	1183	7883
Taiwan	3990	1256	5246
TOTAL FOREIGN STATIONS	**385413**	**63139**	**448552**
GRAND TOTAL	**1342847**	**217717**	**1560564**
Distinct frames	831824	152809	984633
Distinct/Grand Total (%)	61.94%	70.19%	63.09%

Figure 1 : ERS Payload Data Ground Segment

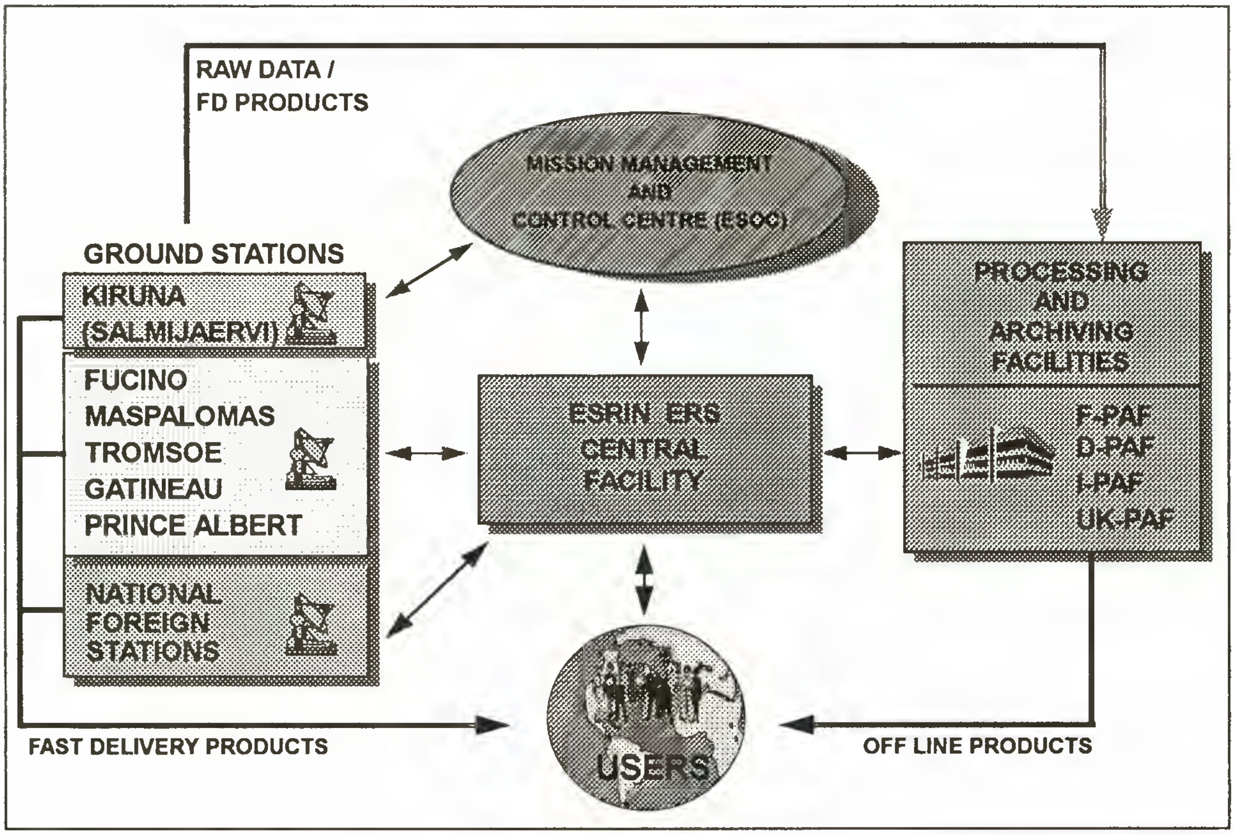
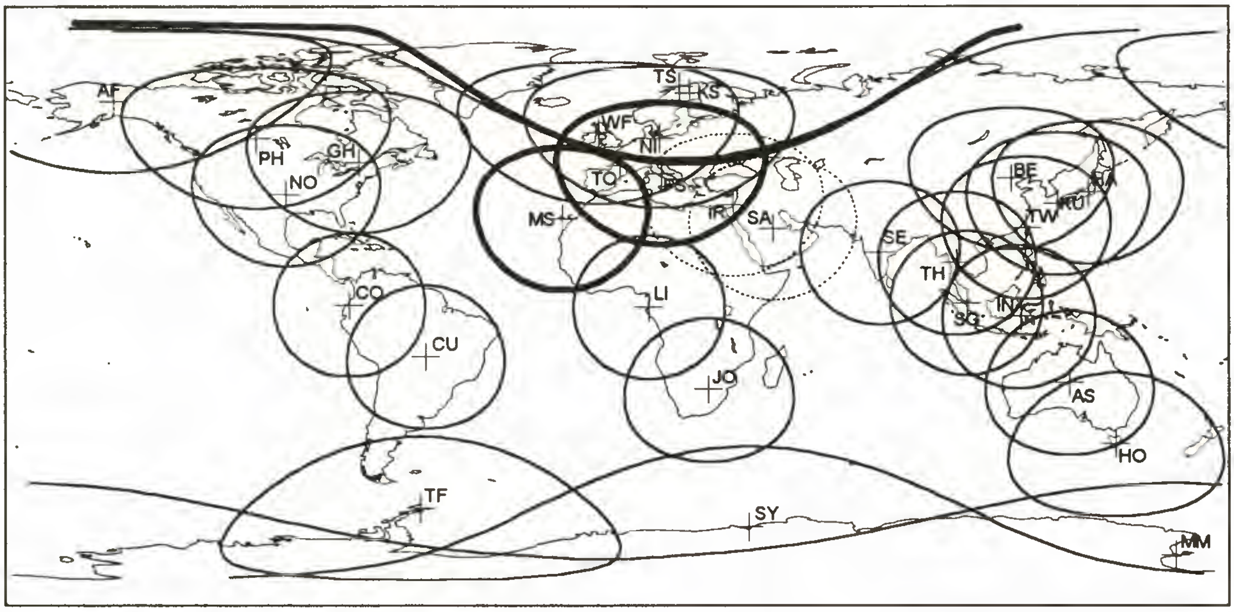


Figure 2 : Network of all Stations (ESA & NFSs)



(5° antenna elevation) ESA Stations — Stations with MoU ······Other Stations * available during campaign periods

AF	Fairbanks, Alaska, USA	IR	Tel Aviv, Israel	SA	Rhyad, Saudi Arabia
AS	Alice Spring, Australia	JO	Johannesburg, South Africa	SE	Hyderabad, India
BE	Beijing, China	KS	Kiruna, Sweden	SG	Singapore
CO	Cotopaxi, Ecuador	KU	Kumamoto, Japan	SY	* Syowa, Antarctica, (Japan)
CU	Cuiabá, Brazil	LI	* Libreville, Gabon, (Germany)	TF	* O'Higgins, Antarctica, (Germany)
FS	Fucino, Italy	MM	* McMurdo, Antarctica, (USA)	TH	Bangkok, Thailand
GH	Gatineau, Canada	MS	Maspalomas, Spain	TO	* Aussaguel, France
HA	Hatoyama, Japan	NO	Norman, USA	TS	Tromsoe, Norway
HO	Hobart, Australia	NZ	Neustrelitz, Germany	TW	Chung-Li, Taiwan
IN	Parepare, Indonesia	PH	Prince Albert, Canada	WF	West Freugh, United Kingdom

Figure 3 : Total Number of User Requests per User Category

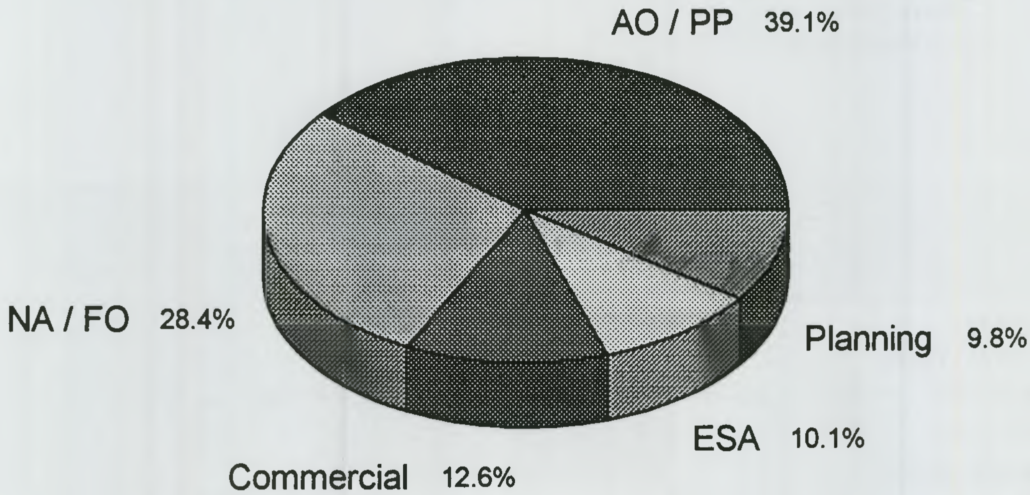
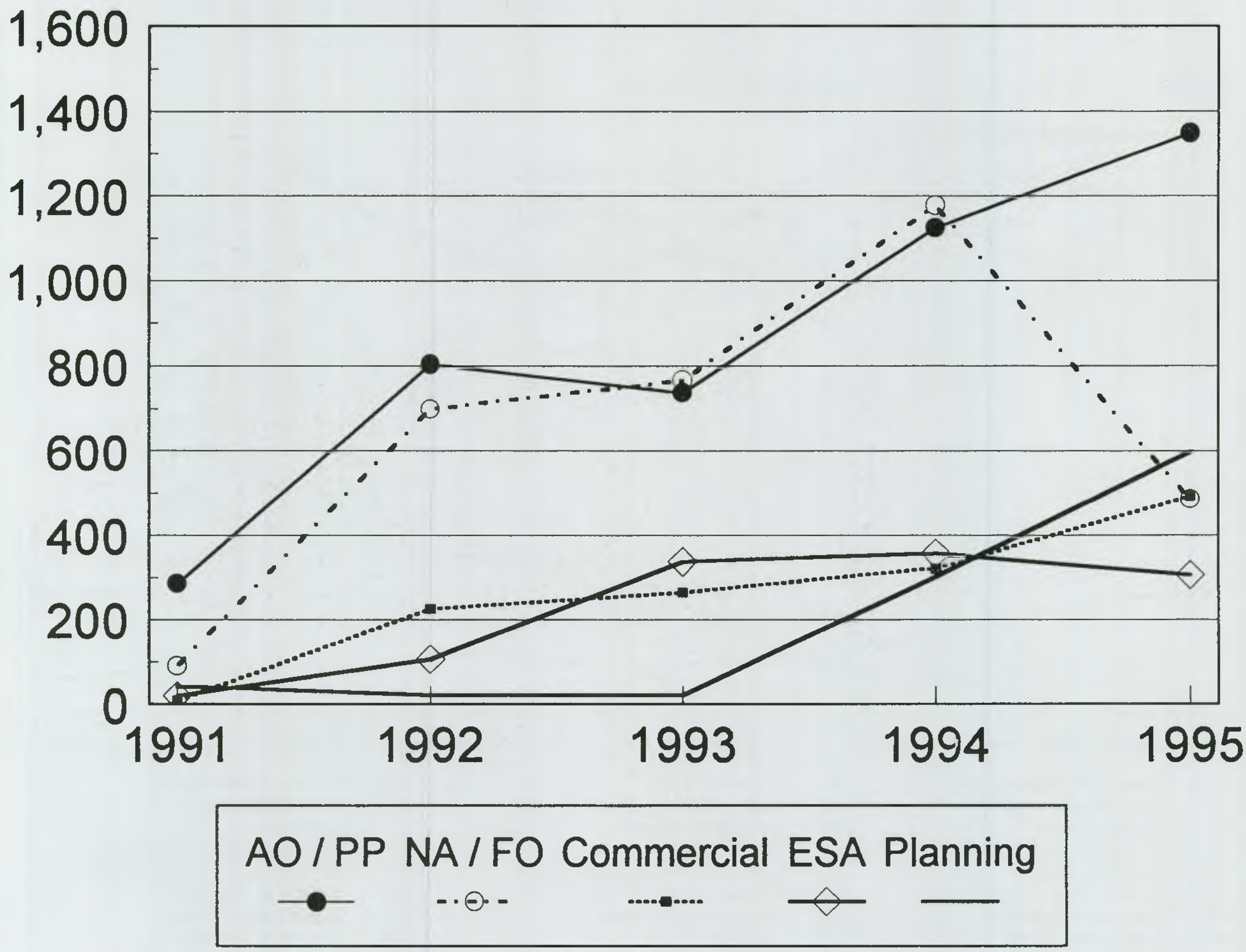


Figure 4 : Number of User Requests per User Category vs. Time



CLUSTER: A CHALLENGING MISSION TO PLAN

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ABSTRACT. The Cluster Mission Planning System (CMPS) is an off-line software system that allows the European Space Operations Centre (ESOC) mission operational staff to carry out advanced planning of the 4 spacecraft Cluster mission. Initially, the CMPS supports the ESOC operational staff in the process of schedule construction based on inputs from the Principal Investigators (PIs) via the Joint Science Operations Centre (JSOC) and also the operational staff. This allows resource conflicts to be identified and corrected. In checking for schedule conflicts, the CMPS has to take into account constraints imposed by the Cluster orbits (e.g. eclipses, distance from the Earth), the on-board systems (e.g. data storage, power availability) and the on-ground systems (e.g. ground station visibility, availability). The final output of the CMPS is the generation of machine and man readable schedules to command the four spacecraft and the two ESA ground stations.

1. MISSION DESCRIPTION

Cluster forms part of the Solar-Terrestrial Science Programme and is intended to investigate the small scale and/or transitory phenomena that govern and modulate the transfer of particles and energy between the solar and terrestrial environments. Specific regions of interest include the polar cusp region, the magnetopause, the bow shock and the geomagnetic tail. In order to measure the time-varying, small scale phenomena in these regions, which are crucial to the understanding of the global solar-terrestrial coupling process, the Cluster mission consists of four identical spacecraft which were to be launched into an eccentric polar orbit in June 1996. Cluster's unique four-satellite strategy, employing an adjustable tetrahedral configuration, allows an unambiguous separation of spatial and temporal scales through comparison of the data from instruments carried by the four spacecraft. Each spacecraft carries an identical complement of 11 scientific instruments.

Since the main objective of the mission is to simultaneously capture data from the instruments on all 4 spacecraft, while operating in the regions of scientific interest, it is obvious that planning such a mission raises special problems both from the operational viewpoint, and for the software tools required to support the planning. The planning process for Cluster has to take into account the platform operations, input into the CMPS by means of Operation Request files (OPRQs) generated at ESOC by the operations staff, the observation requests of the science community (co-ordinated by JSOC based at the Rutherford Appleton Laboratories (RAL) in the UK, and submitted in Observation Request files (OBRQs), the availability of on-board resources, the visibility and availability of ground stations and orbital constraints, such as eclipses and distance from the Earth.

Clearly in this case, the challenge to mission planning is the co-ordination of simultaneous operations on the four spacecraft and of the four ground stations used during mission routine phase. There are two ESA stations, Odenwald in Germany and Redu in Belgium and two NASA Deep Space Network (DSN) stations, Goldstone in the USA and Canberra in Australia. The DSN stations are used for the Wide Band Data (WBD) experiment. The complexity of the scheduling problem is such that it is necessary that the CMPS has full control over determining the contact periods of each of the spacecraft with the appropriate ground stations, at least during the routine operations phase of the mission. In actuality the CMPS, once all resource clashes have been resolved, automatically generates the appropriate commands to put the spacecraft and ESA ground stations into the correct modes by means of "template commands" defined by the operations staff in OPRQs, this is discussed in more detail later. The interface to the DSN stations is not so sophisticated and is handled by means of FAX requests to the DSN scheduling office.

2. THE PLANNING PROBLEM

The basic planning problem addressed by the CMPS is to take the scientific observation requests submitted by the science community, combine these with platform and housekeeping operations requests generated by the operations staff at ESOC and produce a command schedule for each of the 4 spacecraft and 2 ESA ground stations which ensures that the available resources are not exceeded. In order do to this, the CMPS has to take into account the available data storage capacity of the 2 on-board solid-state recorders (SSR) and also the on-board power consumption.

Of the on-board constraints the most significant, in terms of the CMPS, is that imposed by the capacity of the SSRs. The reason for this is that during nominal operations, 2 spacecraft are assigned to each of the ground stations, which are capable of communicating with only one spacecraft at a time. Therefore, although the Cluster orbit does give long visibility periods of up to 28 hours, the contact periods for each spacecraft must be assigned in such a manner as to stay within the on-board storage constraints, to avoid loss of data. The CMPS is responsible for calculating these contact periods, and also the times during contacts when the contents of the SSRs are dumped to the ground. In doing so, the following factors have to be taken into account:

1. Telemetry Data Acquisition (TDA) mode; this basically specifies the rate at which data is generated on the spacecraft and essentially takes one of 3 values, 3972 bps in housekeeping mode, 21845 bps in normal science mode and 131072 bps in burst science mode.
2. Visibility periods of the ground station from a particular spacecraft and, in conjunction with this, the possible unavailability of a ground station due to planned periods of maintenance for example.
3. Resource availability at the ground station; each station has 4 telemetry processors (TMP) which are used to process the telemetry dumped from the spacecraft. Since the processing can take a long time to complete, depending on the quantity of data dumped, and given that there are 2 TMPs allocated to each spacecraft, the CMPS must model the usage of the TMPs when scheduling the contact periods.
4. Antenna switches; since during antenna switches there is a temporary loss of telemetry the CMPS ensures, as far as possible, that telemetry dumps occur at times where they will not be affect by antenna switches (e.g. by performing the switch outside of a contact period if possible).
5. Spacecraft range from ground station; when the separation between the spacecraft and the ground station is greater than 35000 km the link budget is such that a lower downlink bit rate has to be used (131,072 bps as opposed to 262,144 bps) when dumping SSR playback data. In order to avoid the data loss that would occur if the rate was changed part way through a telemetry dump, the CMPS schedules the dumps such that they are carried out at the highest rate possible for the given range and dump duration.

The spacecraft power usage checks performed by the CMPS are, in comparison, much simpler. Each operational and payload command, or command sequence, has a power profile associated with it, describing the power requirements with respect to time. As a result of scheduling the operational and observational requests, the individual power profiles are summed to generate a prediction of the power requirements over the period being planned.

One factor omitted in constructing the model used in the CMPS was the line capacity between the ground stations and ESOC. This was not included because, in the original baseline scenario, where data storage on the spacecraft consisted of tape recorders of 1 Megabit capacity, only one of which was used at a time, the line capacity was not a constraint. Replacement of these by SSRs of 2.25

Megabit capacity, both of which can be used at the same time, mean that the line capacity can at times be a constraint and it may prove useful to enhance the CMPS to include this in the model.

3. SYSTEM CONTEXT AND INTERFACES.

In order to help appreciate the role of the CMPS, Figure 1 below places the system into the context of the complete Cluster ground segment.

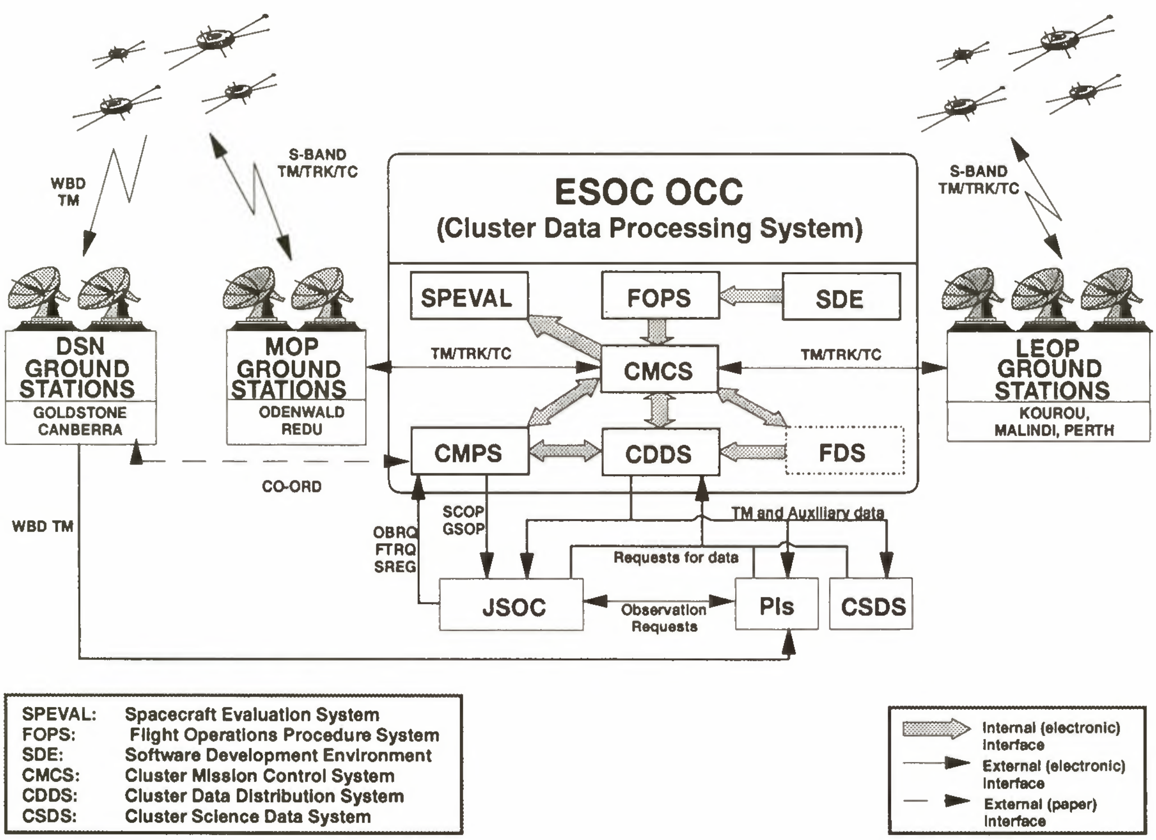

Figure 1. CMPS System Context.

It should be noted that this diagram is in itself something of a simplification. For instance the block labelled CMCS (Cluster Mission Control System) actually comprises 8 separate control systems (a dedicated prime and backup system for each spacecraft), a prime and backup network control system (NCTRS) used to control the network links between the various control systems and ground stations, and a dedicated database system (CDBS) used to maintain the telemetry and telecommand database for all 4 spacecraft. The diagram does however serve to indicate the complexity of the ground segment.

Figure 2 below gives a schematic view of the various data flows to and from the CMPS. In addition to identifying the primary inputs and outputs of the system, the diagram indicates at which stage in the planning cycle the flows occur. There are 4 main stages to the planning process, defined as long, medium, short and operational planning levels. Each data flow is annotated with an identifier signifying at which stage in the cycle the flow occurs and in which order. A more detailed discussion of the planning cycle is contained in a later section.

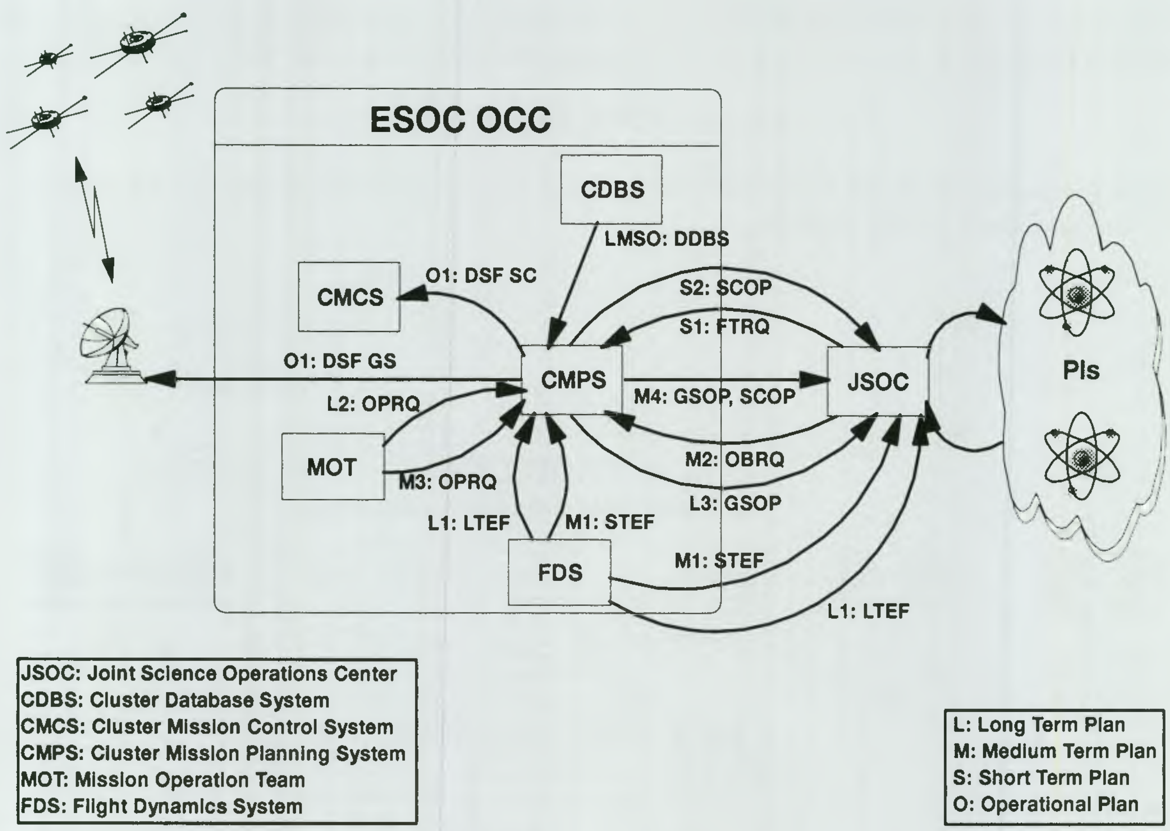

Figure 2. CMPS Data Flows.

The primary inputs to the CMPS are described below:

- STEF; Short Term Events Files are generated by the Orbit and Attitude division at ESOC and contain all orbit events that are relevant to the Cluster spacecraft such as eclipse start/end times, ground station visibility start/end times, antenna switch windows, perigee and apogee crossing, times above 35000 KM etc. These files are generated 2 to 3 times per week and contain reconstituted data (from tracking data) for the previous 10 days and predictions for the next 3.5 months.
- LTEF; Long Term Event Files are similar to the STEFs except that they are generated once for each spacecraft constellation (each spacecraft constellation lasts for approximately 6 months) and contain only a subset of the events in the STEF at a somewhat lesser degree of accuracy. These files are used in the initial phases of the planning.
- OBRQ; Observation Request Files are generated by JSOC based on input from the PIs responsible for the various instruments. These essentially contain the observation modes which the spacecraft should be in (the Cluster spacecraft have basically 3 modes for observation, the first being housekeeping where no science telemetry is acquired, the second is normal science and the third burst science where higher rate telemetry data is generated) at specified times and the commands required to put the payload instruments into the operational condition required during these times.
- FTRQ; Fine Tuning Request Files are generated by JSOC and are used to submit minor changes to a plan once it has nominally been “frozen”. In particular, they allow the insertion, modification and deletion of certain commands or sequences. Those commands/sequences which can be updated are predefined and the main criteria for allowing update of a command/sequence is that it should have no impact on resource usage.
- OPRQ; Operation Request Files are generated by the operations staff at ESOC, and contain either explicit commands to carry out required operations at specified times or “template” commands which are used to put the spacecraft and ground stations in specific modes depending on the schedule requirements. These template OPRQs are generally identified by a naming convention.

The syntax of these files is fairly flexible and allows scheduling relative to a large number of events.

- DDBS; Derived Database Files are sent to the CMPS system from the CDBS. The files contain the definition of all commands and sequences including the valid range for parameters which are associated with a particular command/sequence. These are used in the validation of OBRQs received from JSOC, and also to validate commands/sequences in OPRQs generated by MOD. Additionally those command/sequences which affect onboard power usage have a time varying power profile associated with them.

The primary outputs of the CMPS are described below:

- FVSR; File Validation Status Reports are generated by the CMPS on receipt of a file from JSOC and contain a report of the validity of the files and indicate what syntax errors, if any, were contained in the file.
- SCOP; Spacecraft Operation Files are generated by the CMPS and are sent to JSOC at various stages in the planning process following a scheduling of the observation and operation requests. The contents of the file confirm the inclusion of each observation in the planning period, unless constraint violations have been detected, in which case the reason for the violation is given.
- GSOP; Ground Segment Operations Files, like the SCOP above, are generated by the CMPS and sent to JSOC. They contain schedules regarding ground segment related events, derived as a result of the scheduling process.
- SC DSF; Spacecraft Detailed Schedule Files contain a list of time tagged commands which are sent from the CMPS to the appropriate spacecraft control system for uplink to the spacecraft.
- GS DSF; Ground Station Detailed Schedule Files contain a list of time tagged "jobs" (i.e. commands) which are sent from the CMPS, via the NCTRS, to the appropriate ground station computer in order to ensure the correct station configuration.

An additional point to note about the interfaces external to ESOC is that all data transferred across the interfaces are routed via the Cluster Data Distribution System (CDDS). The reason for this is to add security to the Cluster ground segment. Since the CMPS generates command schedules which are uplinked to the spacecraft it is obviously of paramount importance that the integrity of the system can be guaranteed, and hence there is a "firewall" implemented between the CDDS and the rest of the Cluster ground segment to stop unauthorised access. The syntax checking of files received from JSOC and the "handshaking" carried out by means of the FVSR, SCOP and GSOP files provide an additional degree of security.

Implementation of the CMPS was carried out on a DEC 4000-90A VAX workstation running VMS. The language used was 'C', and extensive use of Motif/X-windows was made in the user interface. Graphical and timeline displays were developed using Xrt-Graph, a third-party widget supplied by the KL Group. The use of the Motif and Xrt widget libraries has resulted in a flexible user interface, which provides for easy interpretation of planning information, with facilities such as event filtering and zooming.

Additional software tools used during the development included the public domain software, FLEX and BISON which were used to generate the code that performs syntax and semantic checking of the CMPS files. The powerful syntax of these tools allowed for relatively simple coding to perform these checks, and modifications to file syntax and structure generally led to only minor changes of the FLEX and BISON scripts.

4. PLANNING PROCEDURE

The planning activity for a particular interval goes through 4 separate levels before the command schedules are finally generated. In the nominal case each planning period lasts for 3 orbits, which since the Cluster orbital period is approximately 56 hours, corresponds to closely to 1 week. Under these conditions the interchange of information between ESOC and JSOC has been agreed, to simplify operational use of the planning system, to cover pre-defined intervals. The CMPS itself can plan intervals of arbitrary length (in multiples of 1 orbit), and indeed in case of anomalies may have to. The remainder of this section outlines the procedure that is carried out in the nominal planning cycle and expands further the relative timing of the data flows introduced in Figure 2.

Long term planning; this initialises the planning process. It covers a period of about 6 months, corresponding to a Cluster "Constellation". This plan includes the initial orbital event predictions generated by Flight Dynamics at ESOC and delivered in the LTEF. Also included are the generic Operation Requests generated by the Operations staff at ESOC. The output from this stage of the planning is the GSOP, which is sent electronically to JSOC, and this contains the preliminary list of ground segment operation.

Medium term planning; This is the level at which most of the planning process takes place. To start with a Long term plan is used to generate a medium term plan. The length of the plan generated is normally 6 orbits in duration (corresponding to 2 planning periods). It should be noted that, since each of the 4 spacecraft is in a slightly different orbit, the start time of the orbit is defined to be the ascending node crossing of an arbitrarily chosen "reference" spacecraft. At this stage the refined Flight Dynamics event predictions are included from the appropriate STEF files, as specialised platform and payload operation requests and the OBRQs from JSOC are included into the plan. Each OBRQ from JSOC normally contains observation requests covering 3 orbits. Thus a "nominal" medium term plan will contain 2 OBRQs, the first covering the 3 orbits of the plan, and second the last 3. The CMPS issues warnings to the operator if this is not the case. Activities between ESOC and JSOC start 6 weeks before the start of the period being planned. There then follows various iterations of OBRQs and SCOP/GSOPs up until one week before the planning period starts when a final OBRQ covering the initial 3 orbits of the planning period is sent to ESOC from JSOC and included. Once this OBRQ has been included into the plan, and successfully scheduled, the plan is then "frozen".

Short term planning; once a medium term plan has been frozen it is used to generate a short term plan. This typically covers the first 3 orbits of the medium term plan from which it was generated. At this level no further scheduling is carried out. Minor changes can be carried out to the plan, known as fine tuning, which have no effect on resource usage, by the submission of FTRQs by JSOC. Any FTRQs for a particular planning period must be received at ESOC at least 72 hours before the start of that planning period. Once the deadline for receipt of the FTRQs has passed, any previously received FTRQ is included into the plan and a SCOP and GSOP generated and sent back to JSOC. On completion of short term planning activities an operational plan is generated.

Operational planning; An operational level plan normally covers the same period as the short-term plan from which it was generated. This plan is completely frozen, no changes at all being possible. It is used for generation of the detailed schedule files for the spacecraft and ground stations. Once these files have been generated the spacecraft DSFs are automatically sent to the appropriate computers of the CMCS where they are expanded into the Cluster commands that can then be uplinked to the on-board time-tagged queue. The ground station DSFs after generation are automatically transferred to the NCTRS from where they are sent to the appropriate ground station and then executed by the station computer. Due to size limitations of the on-board time tagged queues the spacecraft DSFs are generated on a daily basis, while the ground station DSFs are generated for the complete duration of the operational plan.

A considerably more detailed of the Cluster planning procedure is given in Ref. 1.

5. SCHEDULING ALGORITHM

The CMPS scheduling algorithm, which forms the core of the CMPS, is deterministic and is driven by a number of configurable rules and constraints, the values of which can be altered to produce different planning results based on the same observation and operational request inputs. An outline of the algorithm is given below and a more expanded description can be found in Ref. 2.

The first point to note about the algorithm is that for each ground station and spacecraft combination, it loops many times over the duration of the plan in order to determine the TDA modes to be in effect for the spacecraft. The starting point for the algorithm is the plan start time, or later if a ground station contact is in effect as a result of the initialisation of this planning period from an existing plan. The algorithm then searches for possible downlink windows in which it can assign contact between a spacecraft (SC) and the ground station (GS) assigned to it. It attempts to do this in such a manner as to avoid the oversubscription of the on-board recorders which are modelled and updated continuously throughout the processing loop.

The first step in the processing is to determine which SC requires downlink the most. This is based on a number of calculations concerning the forecast usage of the recorders for each SC, from which the latest possible time that each SC can dump the recorded data to the ground station without loss of data (i.e. both recorders spilling over) is calculated. Once a SC has been identified as a candidate for having downlink with the ground station, the algorithm determines if the SC recorder usage exceeds the minimum dump threshold. If so, a recorder dump is scheduled as soon as possible, allowing for user-configurable margins. The start time and duration of the recorder dump is calculated, and the TDA mode to facilitate the recorder dump is inserted into TDA model. The provisional downlink window end-time is also evaluated, and is the latest time that another SC assigned to the GS requires a recorder dump. The next step is then to calculate an exact time for the end of the downlink window, based on a number of factors such as the usage of recorders on other spacecraft and the time of the next ground station visibility period.

When the exact downlink window end time has been calculated, the TDA modes are selected in the TDA model for the downlink SC. In addition, the Acquisition Of Signal (AOS) and Loss Of Signal (LOS) events of the chosen downlink SC are inserted into the plan. These are required to allow preparatory operations at the GS and on-board the SC to be scheduled using the generic operation request templates. After successfully selecting the real-time TDA modes for the downlink SC, the TDA modes for all other spacecraft assigned to the GS are selected, based on the fact that they must be recording for the duration of the calculated downlink window.

At this point the processing is now complete for the downlink window. The above processing is then repeated, taking the end of the previous downlink window as the window start time for the next iteration. This process continues until the entire planning period has been covered.

6. CONCLUSIONS

A planning system has been developed capable of supporting the planning activities required by the Cluster mission, arguably the most complex ESA mission to date, involving as it does the co-ordination and simultaneous control of 4 spacecraft and associated scheduling and control of ground stations.

Our experience in implementing the Cluster mission planning system reinforces what has been found before (Refs. 3 and 4), that while the basic requirements of a spacecraft control system (e.g. telecommanding, telemetry reception etc.) are readily definable in considerable detail near the beginning of a project the same is not true of mission planning. Here it is most definitely the case that a very steep learning curve must be climbed before the user requirements of the planning system can be accurately defined. Unfortunately it is usually the case that the manpower available is insufficient to allow enough time to be spent on mission planning at the user requirements phase of a mission. Problems then arise at a later stage when the software developed is found not to be completely adequate. Also adding to these difficulties are the "Gottchas", aspects of the mission whose impacts on the planning process only become obvious late in the day. Further care must be taken in applying lessons learned from previous missions. Even missions which appear to be broadly similar turn out to have planning requirement which are substantially, if not completely, different (cf. Ref. 5). For instance in the case of the CMPS some of the initial concepts were derived from ERS, and turned out later not to be completely appropriate.

In order to overcome these difficulties it is desirable that someone on the operations staff (the end users) can spend most (ideally all) of their time working on aspects of mission planning, and that they and the software developers form a close working relationship, where ideas can be freely, and informally, exchanged. It is also desirable that the software be designed from the start to be as flexible as possible (subject to budget constraints). Experience has shown that mission planning requirements are never engraved in stone and continue to evolve and change up to, and after, launch. This has certainly been the case with Cluster, Ref. 3 also supports this for EURECA.

With respect to future developments in the mission planning area, it is interesting to note how the market in scheduling tools is developing. The scheduling algorithm developed for the CMPS is completely bespoke, since when development started, in 1993, there were few if any tools available which could realistically be used to provide a scheduling engine capable of handling all the constraints which apply to the Cluster mission. In the intervening period various products have surfaced, such as ILOG Solver, a constraints based scheduling 'engine', which could possibly be integrated with bespoke software to form the core of a mission planning system. It is suggested that for future planning systems some time be spent at an early stage evaluating these products to see if it is realistic to build a planning system around them. This could potentially reduce the budget required to implement mission planning systems, and also provide a higher degree of flexibility, something to be greatly desired in view of how late mission planning requirements usually stabilise.

7. ACKNOWLEDGEMENTS

The authors would like to express their thanks to the Cluster spacecraft operations manager P. Ferri, and in particular his mission planning team of B. Charrat and M. Beckers, for a fruitful, if at times lively, partnership in the development of the CMPS.

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THE MULTI-SATELLITE SPACE MISSIONS AND CAMPAIGNS LONG-TERM PLANNING

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ABSTRACT. The problem of the orbital situation analysis are discussed in this paper as a foundation of the multi-satellite missions and campaign long-term planning. INTERBALL mission and its participation in the IACG/ISTP campaigns are presented as examples (see World Wide Web site http://www.iki.rssi.ru./vprokhor/amisan.htm.)

I. INTRODUCTION

The modern space research is based on close international cooperation. Under the International Solar-Terrestrial Physics Program (ISTP) there exist many scientific trends like the Global Geophysical Science (GGS) and the International Auroral Study (IAS) Programs which are based on the acting space missions, such as Wind, Polar (NASA), Soho (ESA), Geotail (ISAS, NASA), Interball (IKI-RKA).

The Inter-Agency Consultative Group (IACG) coordinates international campaigns aiming at understanding of solar-terrestrial correlation. For example, in October 1995-January 1996 there was successfully conducted the Campaign No.1 devoted to problems of magnetotail energy flow and non-linear dynamics. This campaign combined 4 missions: GEOTAIL, INTERBALL TAIL, IMP8 (NASA), WIND (NASA).

In scheduling global measurements in multi-satellite missions and campaigns the most important element is the selection of location strategy and based on it the situation analysis of orbits with the main task to predict, select and visualize the missions and campaigns key situations in space and time.

Major contribution into this activity was made by the Satellite Situation Center (SSC) and the National Space Science Data Center (NSSDC) of the Godard Space Flight Center (FSFC) distributing empirical models of magnetosphere, varied information of orbits of space vehicles operating under the above mentioned programs, and results of the scientific measurements through the Internet service.

Russian scientific community contributed into the above mentioned international programs by the multi-satellite international project Interball developed at the IKI RAN which comprises two couples of spacecraft - Tail Probe (TP) and Auroral Probe (AP), each supplied with its own subsatellite. The Tail pear is launched in August, 3 1995, with its subsatellite (Magion 4) separated in August, 4, 1995. The Magion 4 was provided with thrusters for maintaining proper distance from the satellite to the subsatellite (up to 10,000 km). The apogee altitude of the Tail pear initial value is 192,000 km, the perigee altitude - 790 km, the orbital inclination - 62.9°. The Auroral pear is planned to be launched in late August, 1996. The apogee-perigee altitude is due 20,000-700 km, respectively, the orbit inclination - 62,9°; the scheduled satellite-subsatellite separation - up to 500 km.

According to the main goal of the Interball mission - to study active processes in the magnetospheric tail and magnetosphere-ionosphere coupling the Interball orbits configuration is selected to conduct simultaneous measurements in the magnetic conjugate regions - Tail Plasma Sheet and Auroral Region. The scientific equipment includes instruments measuring plasma, plasma waves, magnetic and electric fields, and particles. Aboard the Auroral Probe ultraviolet auroral imagers are installed.

Scientific teams from 18 countries participate in the Interball project. Comprehensive investigations performed under this project are founded on the wide net of ground-based stations.

During preparation of the Interball mission the hardware and software were developed at IKI intended for informational support of the mission. One of the aspects of this activity is the situation analysis of orbits originating from the empirical models of the regions under study and with due consideration of the tasks of the long-term strategic and routine control of the mission.

Much efforts in the present work were made to adequately present the global situation picture in space and time at the prolonged time intervals (year, month) and to analyze distinct situations in full details. We tried to keep to the maximal visibility and unification (standardization) of the ways of showing orbital situation data for each spacecraft.

Such an approach yields much benefits for correlating orbital situation pictures of different spacecraft or missions when planning coordinated measurements in accordance with the location strategy of the corresponding mission or campaign.

Since numerous scientific teams are involved into the process of making decisions at that international missions, Russian side made much efforts to develop modern means (including software) for distributing orbital information. For this purpose the Internet service is widely used.

Some results of the situation studies under the mission Interball (Interball Tail - Auroral Probes) and IACG/ISTP Campaign 1 (Interball Tail - Geotail) are given below as examples.

2. SITUATION ANALYSIS FOR THE INTERBALL MISSION LONG-TERM PLANNING

The global situation picture for the TP orbit is shown in the Fig. 1 as a satellite passage time through regions of interest of the magnetosphere. Here, we are dealing with thin boundaries of the near-earth bowshock and magnetopause and the regions like radiation belts, tail neutral sheet, plasma sheet and cusp region. For each region a corresponding symbol is used. The date is plotted on the X axis, and the passage time from the node (in hours) for each revolution (draconian period of the orbit) is laid off on the Y axis.

For each month individually the standard set of pictures is prepared containing the information like time distribution of crossing magnetospheric regions, visibility zones for radio-control stations, geocentric distance and geomagnetic local time at the satellite site. Fig. 2a,b show this kind of information for TP and AP orbits in Oktober 1996 as an example. Fig. 2a shows time schedule of the TP passage through regions, where the date is plotted on the X axis and the universal time - on the Y axis. Fig. 2b shows the same information for AP. Correlation of the situation pictures for two orbits is helpful in choosing proper time for fulfillment of coordinated measurements in conjugate regions (plasma sheet of magnetosphere tail - auroral region). Another couple of figures (2c,d) shows in the northern polar diagram the position of footprints (projections onto the ionosphere received with the help of tracing magnetic force lines making their way through the satellite location). The polar diagram shows the footprints geomagnetic co-latitude - geomagnetic local time dependence. The passage through regions is specified by corresponding symbols. The Fig. 2c shows the corresponding picture for AP, and the Fig. 2d - for TP footprints, respectively.

In the course of the situation analysis of the orbits the modern models of magnetosphere and is different zones are used. At the state of long-term forecasts average statistical models are being employed. When getting into detailed analysis of the selected situations the parametric models are used making it possible to give due consideration to real geophysical conditions. For more information see World Wide Web Home Page (http://www.iki.rssi.ru/vprokhor/amisan.htm).

3. SITUATION ANALYSIS FOR THE INTERBALL-GEOTAIL CORRELATIVE MEASUREMENT DURING IACG/ISTP CAMPAIGN 1.

The Interball TP and Geotail orbits during IACG/ISTP Campaign 1 (November, 1995 - January, 1996) were located at the tail of the magnetosphere. These orbits well complemented each other: the Geotail orbit lies nearby the ecliptic plane, whereas the Tail Probe's orbital plane is almost perpendicular to it. One can judge of interrelation between orbital positions in November, 1995 by the figures 3a,b show projection of the orbits on the ecliptic plane in the Solar-Ecliptic System of coordinates. One-hour step of each orbit is marked by symbols of those regions, the satellites pass through. The periods of the orbits are twenty-four hours apart from each other (period of the TP orbit - 4 days, and of the Geotail orbits - about 5 days).

For the selection of preferable time intervals to perform coordinated measurements the depictions given in the Fig. 4a,b are used. The Fig. 4a shows geocentric distances of both probes in the function of time and marked by one-hour-step symbols of the corresponding regions (those a satellite makes its way through). Fig. 4b shows the geomagnetic local time along the orbit at the satellite location for both satellites.

For more information welcome to the World Wide Web Home page (http://www.iki.rssi.ru/vprokhor/camp.htm.

The above presented tools and experience can be successfully used during other missions and campaigns.

IKI - Interball Visualization Tool (IVT)

INTERBALL PROJECT TAIL PROBE

Longterm analysis (3/ 8/1995 : 4/ 5/1997) Flight data

3/ 8/1995 UTC 1: 4:15, ha = 191907 km, hp = 793 km, i = 62.9° , Ω = 261° , ω = 314° , u = 319°

The annual distribution of the orbit cross−sections with regions:

BS ✥, MP ◇, PS +, NS •, CUSP ☆, RB □, ECLIPSE ▪, 0h UTC ×

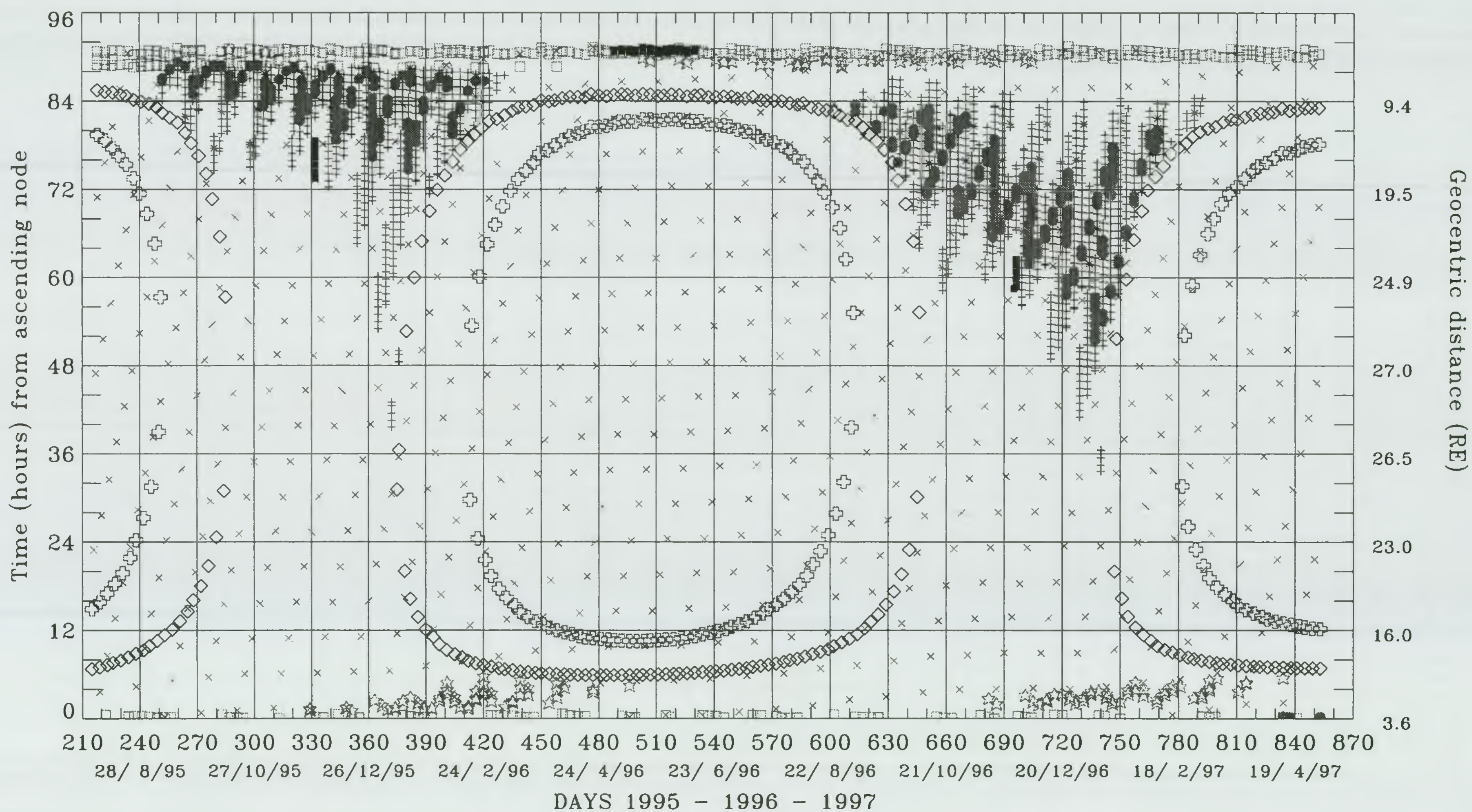
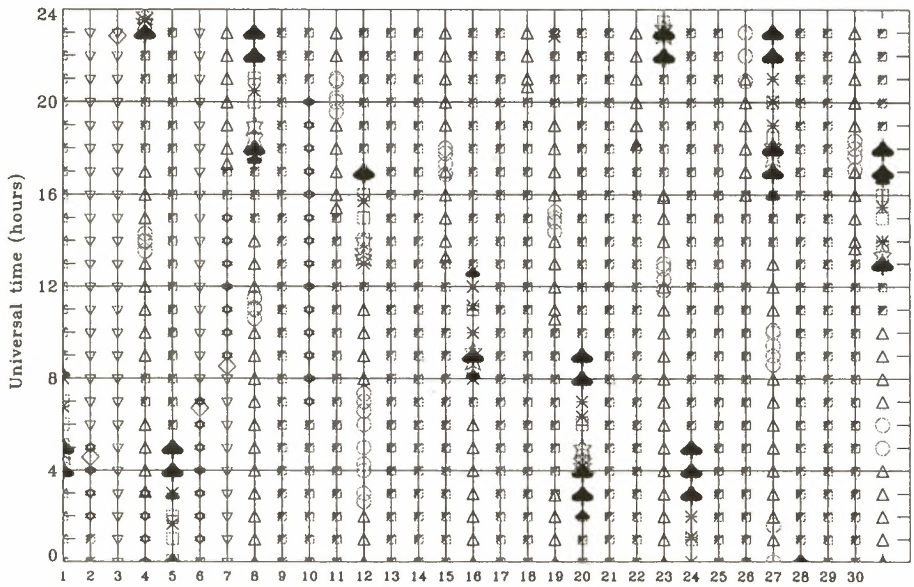


Fig. 2a,b. INTERBALL TAIL & AURORAL PROBES
The time schedule of the TP (a) and AP (b) passing trough the simulative regions,
labeled with 1 h step by the regions symbols

October 1996

(a)

TP: MS ▽ MP ◇ MBL ⭑ LOBS ▪ PS △ NS ○ CUSP ☆ AUR ✳ CAP ♠ RB □



(b)

AP: AUR ✳ CAP ♠

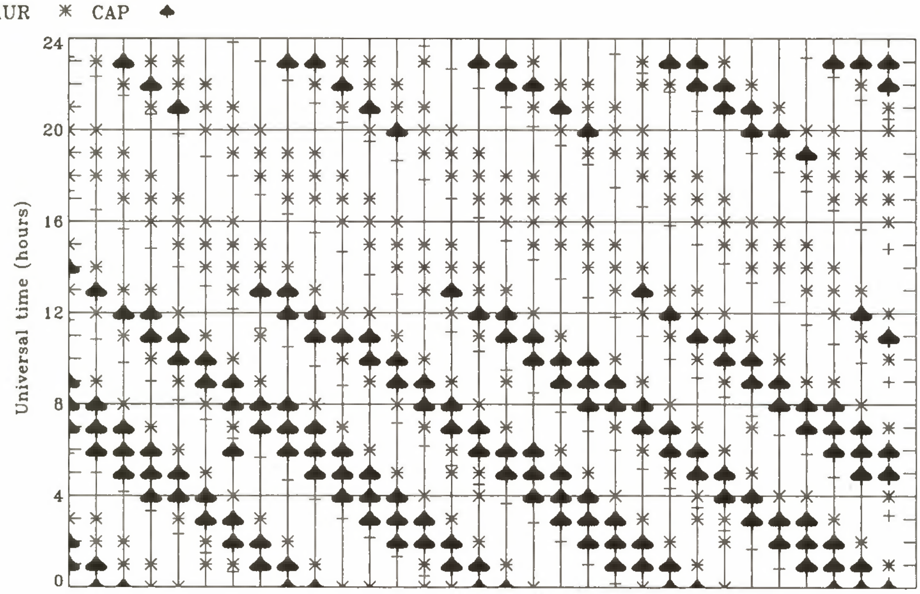


Fig. 2c,d. INTERBALL TAIL (c) & AURORAL (d)
Northen polar diagrame, footprints are labeled
by the satellite location regions symbols
October 1996

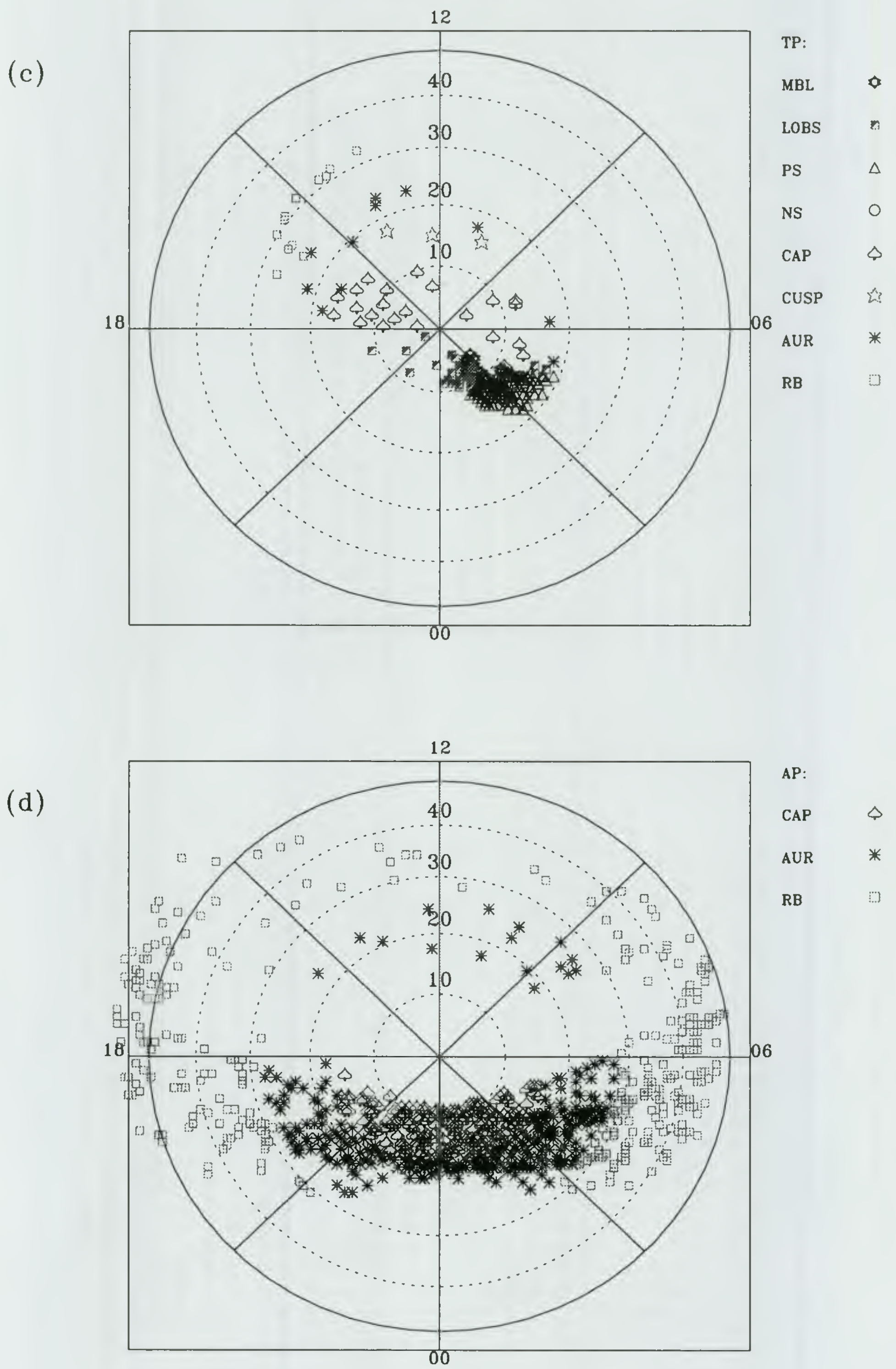


Fig. 3. INTERBALL TAIL (a) & GEOTAIL (b) orbits projection into the ecliptic plane, labeled with 1 h step by the regions symbols

November 1995

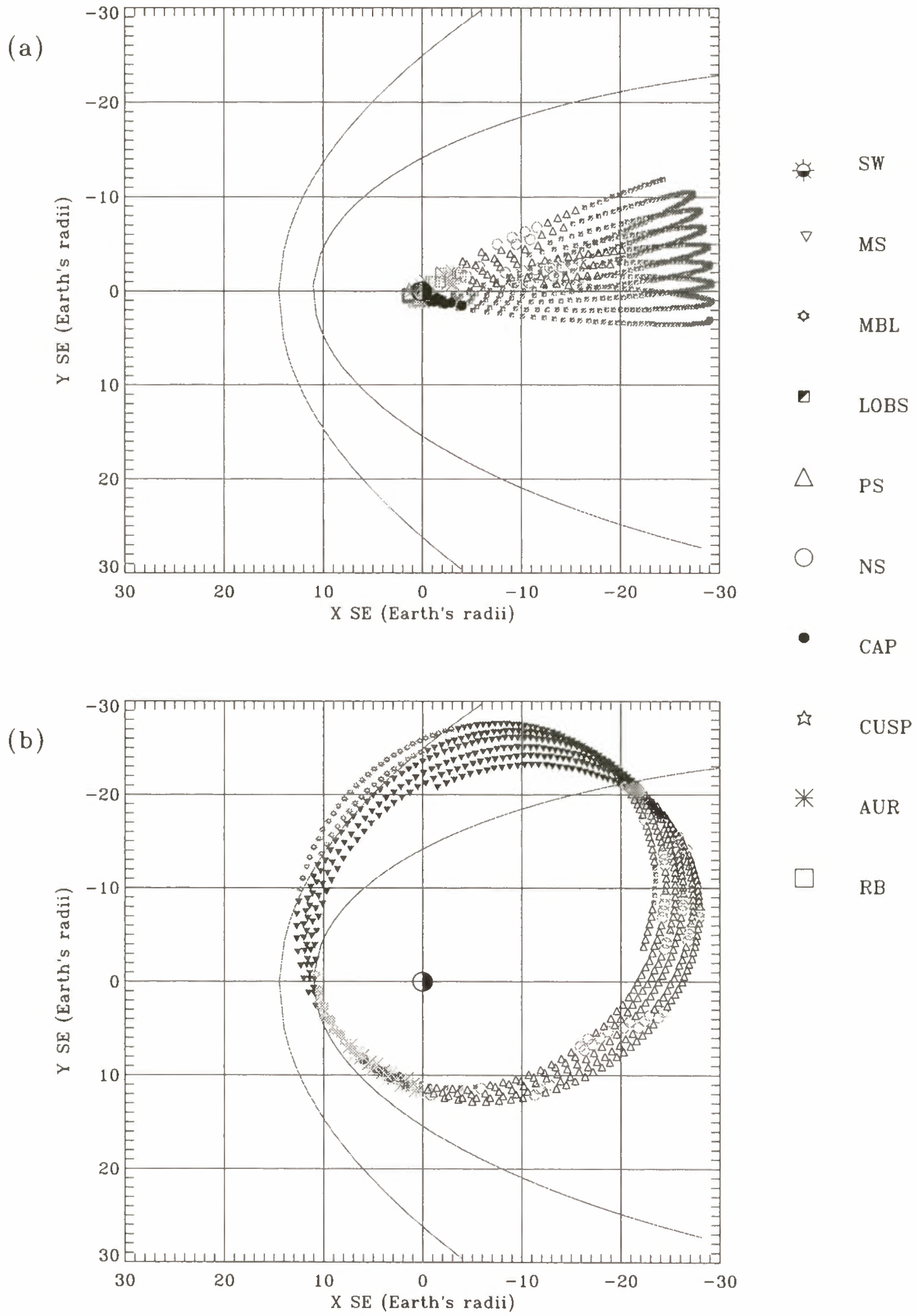
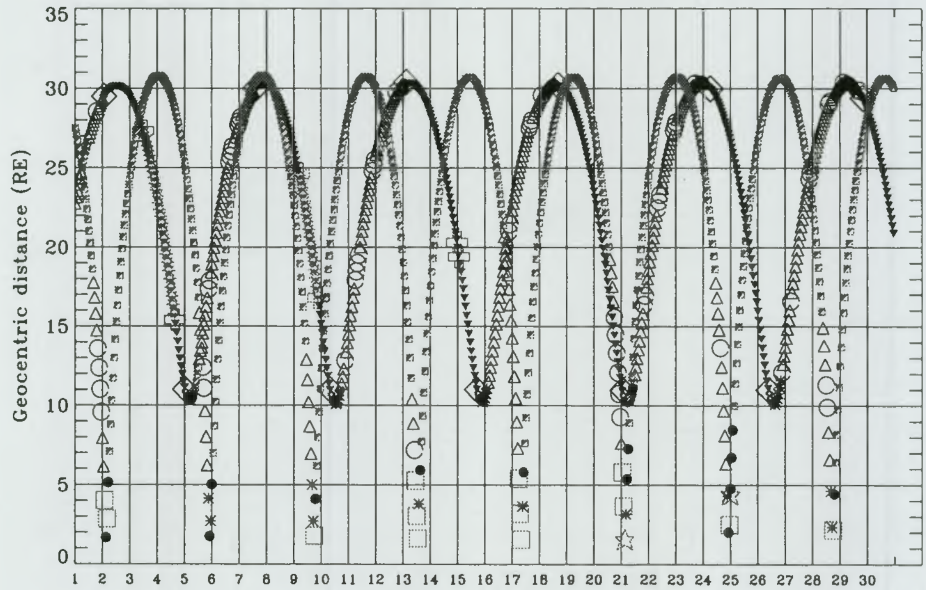


Fig. 4. INTERBALL TAIL & GEOTAIL
Geocentric Distance (a) & Geomagnetic Local Time (b),
labeled with 1 h step by the regions symbols:

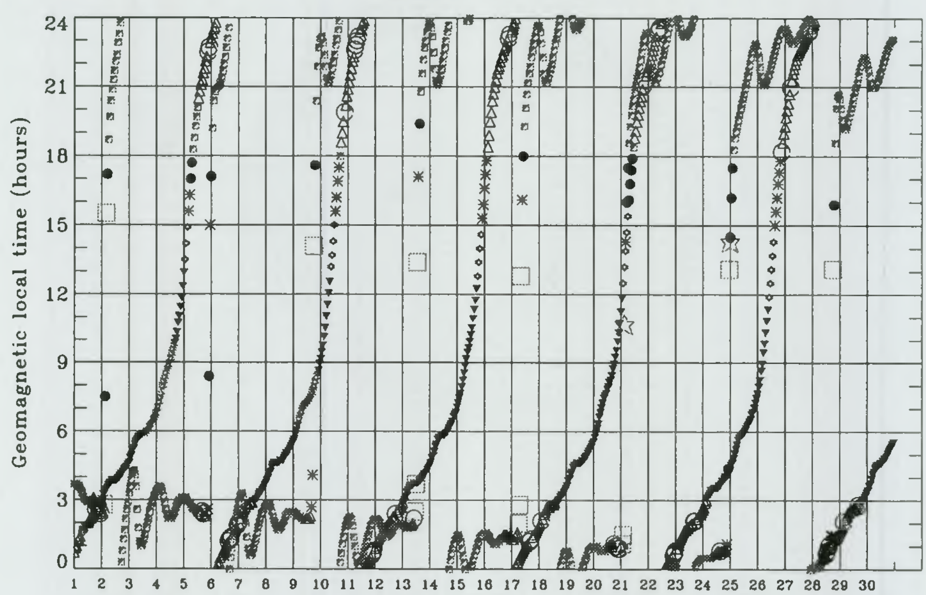
SW BS MS MP MBL LOBS PS NS CAP CUSP AUR RB

November 1995

(a)



(b)



MISSION PLANNING FOR MOMS-2P

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ABSTRACT. The spatial high-resolution Modular Optoelectronic Multispectral Scanner (MOMS-02) operating outside the PRIRODA-module of the Russian space station MIR will provide digitized high-resolution images of the earth, suitable for thematic and three-dimensional topographic mapping. MOMS-2P (MOMS-02 on PRIRODA) is a co-operative project between Russia and Germany (sponsored by DARA); the operational phase of which is expected to last 18 months starting in summer 1996. The control of and planning for the MOMS-2P camera is done by DLR/GSOC in Germany in co-operation with the PRIRODA group at the Russian control center ZUP near Moscow. The user community, consisting of Germans and Russians, has highly demanding requirements, which range from imaging whole continents to performing repetitive data imaging over small earth targets under certain seasonal and lighting conditions. On the other hand a set of operational constraints limits the possible data take opportunities (e.g. not more than 10 minutes data imaging per day are available, tape for data recordings has a capacity of 60 minutes, data dumping conflicts with recording). This calls for a sophisticated planning concept to exploit the assigned resources efficiently. This paper describes the planning concept, developed for MOMS-2P, which profits from experience gained by MOMS-planning at GSOC during the Space Shuttle mission D-2. The concept is based on a distributed planning approach. It makes use of the so-called "envelope method", which in this case regulates the exchange of requirements and resource availabilities between GSOC and ZUP, and ensures that the MOMS-planning at GSOC is harmonized with the overall PRIRODA-planning at ZUP. The planning is carried out in three stages with an ever increasing level of detail. In the top level plan, covering a period of three months, a subset of targets is selected taking into account seasonal constraints and user-defined priorities. The so-called two week plan reflects an observation timeline, which is optimized for data takes and dumps, using statistical weather information to prefer target areas with expected low cloud coverage in this time frame. Finally a one day plan allows for consideration of actual weather and any off-nominals. The concept is realized using the GSOC mission planning system with tailored add-ons developed for MOMS-2P, especially focusing on visualisation of groundtracks and scheduling of a large number of activities. In summary the MOMS-2P planning is an example for an optimizing planning concept for any kind of future earth observation missions.

1. INTRODUCTION

The spatial high-resolution Modular Optoelectronic Multispectral Scanner (MOMS-02), earlier versions of which flew successfully on the Space Shuttle missions STS-7, STS-11 and STS-55 (D-2), was sent up to the space station MIR in spring 1996 and installed on the new module PRIRODA. The orbit inclination of 51° provides observation opportunities over Germany. Routine operations started in July 1996 and are expected to continue for at least 18 months.

MOMS data are recorded on a tape recorder on-board, which has a capacity of one hour, and are dumped at a later time over two groundstations (Neustrelitz and Obninsk). MOMS-2P operations are conducted from GSOC, which transmits command schedules to the Russian control center ZUP for review and uplink. The command schedule is the final result of the mission planning activities described below.

This paper presents the basic ideas of how it is intended to perform mission planning for MOMS on PRIRODA. In the next future experiences from the commissioning phase will be worked in and the concept will be fine-tuned.

2. GENERAL MISSION PLANNING TASKS

Mission planning in this context means developing a plan for all the activities that are to be executed on-board a spacecraft. This plan is reflected in a command schedule for unattended operations or in a crew activity plan for activities where crew is involved.

Mission planning roughly is structured into the following tasks:

- collection and analysis of availabilities, requirements and constraints
- generation of events or opportunities (which are time windows dependent on the orbit)
- scheduling of experiments and system activities
- generation of outputs needed for subsequent execution of the plan and production of documentation.

3. AVAILABILITIES, REQUIREMENTS AND CONSTRAINTS FOR MOMS-2P

The mission planning team as part of the operations personnel (OPS) has two major interfaces. On one side there is the organization responsible for system functions of the spacecraft, which is providing the overall resource availabilities for the respective payload (such as MOMS or PRIRODA). In the following this will simply be called the "system". On the other side there are the experimenters and their representative organizations (the user community) with their intent to have experiments performed. The mission planning team as the mediator attempts to fulfill the user requirements as far as possible according to the availabilities and under the given constraints.

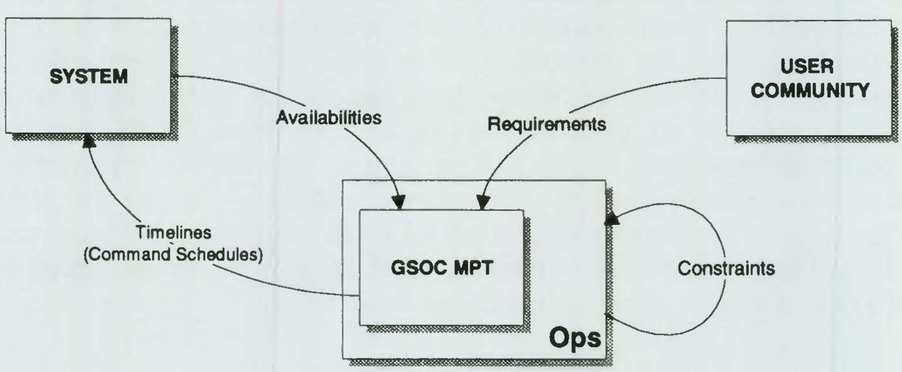

Figure 1: Availabilites, Requirements and Constraints

To give an overview of the problem domain the mission planning process for MOMS-2P has to deal with some typical examples for availabilities, requirements and constraints are listed below.

3.1 AVAILABILITIES FROM THE SYSTEM

The system provides the resources and time windows that are necessary to perform experiments. These resources and time windows are considered as availabilities for the mission planning process. In the case of MOMS-2P they are restricted for the following reasons:

- Station power is generally low.
- Earth oriented attitude is not available all time.
- The MIR station orbit is not ideal for earth observation purposes. It often leads to repetitive groundtrack patterns with big areas in between which can not be seen by the MOMS camera for a long time.
- Data takes can not be planned within 270 minutes after a dump.
- There must be a minimum delay of 5 minutes between data takes and dumps (tape repositioning).
- Data takes are to be focused in periods of 90 minutes duration.

3.2 REQUIREMENTS FROM THE USER COMMUNITY

The requirements for MOMS-2P expressed by the user community fall into three different groups:

- one data take of a well-defined earth target
- more than one data take of a earth target under different (seasonal) conditions
- imaging wide areas (parts of continents).

The information necessary to unambiguously identify an experiment must be analyzed in detail and must be transformed into computer readable form. The information comprises of:

- descriptive information about the experiment and the experimenter (name, address of the responsible PI)
- target specification (name, coordinates)
- observation conditions (sun elevation, parallel to other PRIRODA experiments, operations mode)
- time requirements (when, duration, number of performances)
- resource usages (power, tape recorder)
- priority - experiments can belong to one of five different priority groups: calibration, commercial, pilot, imaging and science
- stereo data takes require starting 20 seconds before the target area is overflown and extending operations 20 seconds after target overflight (front and back looking beams)
- prime and corresponding backup data takes are to be performed within a TBD time period

3.3 CONSTRAINTS FROM OPS

The operational handling of MOMS-2P levies a variety of constraints:

- replanning a timeline especially due to the short-term requests must be quick and easy
- logging of all mission planning relevant information of each data take must be done
- detailed weather statistics (provided by ECMWF) and weather forecasts to optimize for minimum cloud coverage are to be used by the planning process
- all commands for data takes and dumps have to be sent to ZUP many hours in advance of the execution of the activity
- the mean observation time is restricted to five minutes per day and per dump station (Neustrelitz and Obninsk)

- data takes do not need to be continuous, the five minutes limit may be filled up by many short data takes
- data take operations have priority over dumps, which might result in tape changes that have to be done by a crew member of the MIR station - 10 tapes usable for MOMS data are on-board the MIR station
- all data takes required by the German side are to be dumped via Neustrelitz, all data takes required by Russia are to be dumped via Obninsk

4. THE MISSION PLANNING CONCEPT

4.1 GENERAL

MOMS-2P is only one sensor on the PRIRODA module but there are explicit requests for combining certain MOMS-2P observations with those from other PRIRODA sensors. The user community frequently requires parallel data takes with different other PRIRODA experiments. Additionally data takes from other PRIRODA experiments covering the same area are required, but not necessarily at the same time.

For these reasons MOMS data takes cannot be planned like for a stand-alone experiment. MOMS planning must be harmonized with the planning of other PRIRODA experiments to a high extent.

Two possibilities exist how to manage this:

(A) Planning of the other PRIRODA experiments is done at ZUP. This would lead to an approach that ZUP distributes MOMS resource envelopes to GSOC reserving the time windows where MOMS operations can take place. GSOC then would take into account the overall PRIRODA timeline to identify all other experiments which require to be coordinated with MOMS observations. In an iteration cycle with ZUP the MOMS timeline is harmonized with the overall PRIRODA timeline.

(B) The second possibility would be that the whole PRIRODA planning is done at GSOC. In this case ZUP would provide resource envelopes for the complete PRIRODA payload and GSOC would do the planning for all PRIRODA sensors. Using this approach a lot of flexibility could be gained for MOMS and PRIRODA planning.

Starting with possibility (A) at the beginning of the mission a smooth transition to possibility (B) is expected as the mission progresses in time.

4.2 AVAILABILITIES, REQUIREMENTS AND CONSTRAINTS COLLECTION

All requirements from the user community are collected electronically. The used data base is set up in such way that all the detailed experiment information can be entered by the responsible experiment scientists or the experiment representatives themselves or by a member of the mission planning team.

MP relevant system availabilities and OPS constraints must also be available in computer readable form. Especially it is important to get:

- suitable orbit information of the MIR station
- an attitude timeline (as an envelope) of the MIR station
- resource availability profiles (for all relevant system resources like power)
- the overall PRIRODA timeline in case PRIRODA planning is done at ZUP.

For information exchange with ZUP an automated file transfer system is used.

4.3 ORBIT PROPAGATION AND EVENT ON/OFF TIMES GENERATION

Orbit propagation and event generation are major tasks for MOMS-2P mission planning. All possible on/off times (or opportunities) for the requested observations and all data dump possibilities are calculated depending on the predicted MIR-orbit and the pre-defined MIR-attitude. Large target areas, for which complete coverage is required, are subdivided into smaller parts so that the completeness of coverage can easily be tracked.

4.4 ACTIVITY SCHEDULING

The timeline generation or the experiment scheduling is an automated process which uses as input the calculated opportunities and the set of experiment requirements and determines for a specified time frame, which is defined by the envelopes provided by ZUP, a schedule under the given constraints that is optimized for minimum cloud coverage and experiment priority.

The result is a chronological list of all experiments that are to be performed in the specified time frame. This list is called the timeline and is the basis from which the command schedule is derived that is sent to ZUP.

4.5 LOGGING, OUTPUTS AND DOCUMENTATION

For MOMS planning it is necessary to get feedback of the success of performed data takes. This is especially important for experiments requiring a complete coverage of wide areas.

Beside the experiment timeline in computer readable form a various list of other products are generated. These include data uplink and downlink schedules and documentation for the user community about planned experiments and their resource usages.

4.6 MISSION PLANNING PHASES

The MIR station orbit changes daily due to changes in the upper atmosphere and attitude changes needed to keep the solar panels aligned. Long-term predictions cannot take into account the occasional docking operations or orbit maintenance maneuvers. This is the reason why the error of propagating a groundtrack increases with how much longer the look-ahead period lies in the future. Since all MOMS planning depends on the accuracy of the propagated orbit the planning is done in three stages with an ever increasing level of detail:

- the long-term planning covering a period of three months
- the mid-term planning covering a period of two weeks
- and the short-term planning which is done for every day.

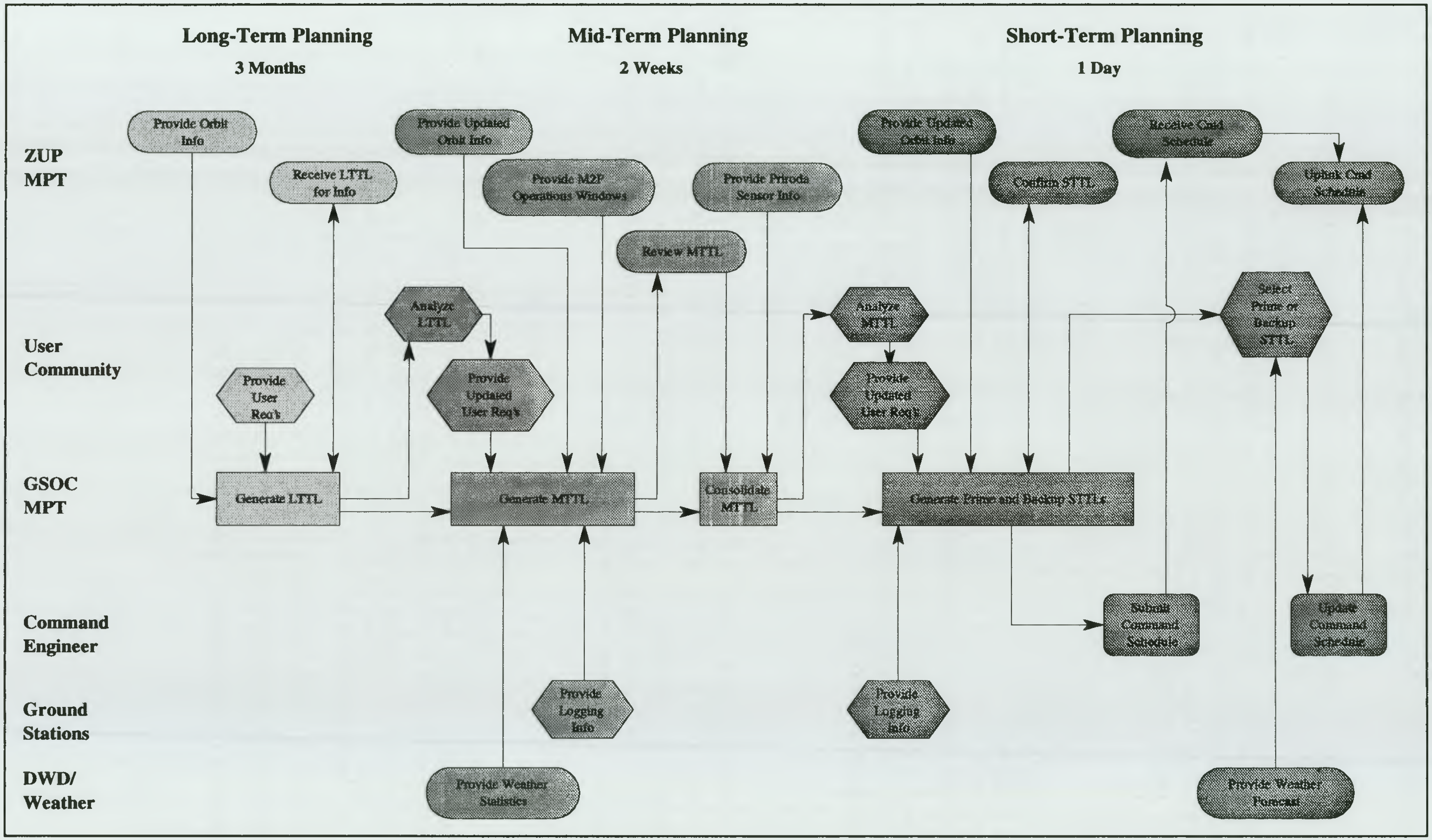

Figure 2 The Mission Planning Phases For MOMS-2P

4.6.1 LONG-TERM PLANNING

The PRIRODA mission is separated into time increments with a duration of 3 months. The long-term planning covers this time frame. Within this process a rough pre-selection of the possible experiments is done. The rules of this pre-selection take into account user requirements, general lighting conditions and overall restrictions in system availabilities. The long-term timeline (LTTL) is primarily useful to filter and extract those experiments from the whole data base, which are to be planned in the mid-term timeline. Depending on the system resource availabilities (e.g. during any docking activities no attitudes useful for PRIRODA are possible) a consolidated target observation proposal is generated. It contains a list of experiments reflecting experiment priority as well as the probability to perform it within a certain time frame. This probability depends on the target size, on the required lighting conditions and on specific time requirements.

4.6.2 MID-TERM PLANNING

Each 3-month-increment is separated into mid-term increments with a duration of 10 to 20 days. The exact duration depends on major MIR station events like orbit maneuvers, reboosts or dockings.

Mid-term planning allows considering new or updated requirements from the user community.

In a first step for the pre-selected experiments from the LTTL, which fall into the corresponding mid-term time increment, the experiment priority is adjusted according to the logging information. This is especially essential when imaging wide areas: in an extreme case for example if only a small target is missing in an otherwise completely covered area the corresponding activity would get assigned a very high priority.

From statistical climatology data so-called suitability functions are generated for each experiment which could be planned in the mid-term time frame. These functions set preferences for those observations having scheduling possibilities during low cloud coverage.

The resource availability envelopes from ZUP define the gross time windows when MOMS observations can take place. Within these time windows observations are planned under the constraint that data takes do not exceed 10 minutes per day in the average and lie within one orbit (which is 90 minutes).

Taking into account the timelining of the other PRIRODA experiments an automated scheduling process then produces a MOMS timeline which is optimized for experiment priority and low cloud coverage.

Since the on-board tape recorder capacity is limited to one hour the scheduling must ensure that data can be dumped accordingly. This might lead to the problem that possible data takes are lost because during these data take times dumps have to be planned into the timeline.

Should the actual MIR station groundtrack pattern (which varies slowly with time) not allow to cover targets having assigned a very high priority then the possibility exists to request a slight attitude change of the MIR station if this allowed observing the target.

4.6.3 SHORT-TERM PLANNING

The mid-term increment is again divided into 1-day increments (this 1-day increment covers the time from 8:00 ZUP time to 8:00 ZUP time of the following day). For each day a prime short-term timeline (STTL) and one or more backup timelines are generated.

The STTL is the basis for the command schedule. The STTL contains:

- the detailed on/off-times of the MOMS-camera (for the prime and backup data takes)
- the scheduled ground station contact times for tape dumps (as proposals for the OPS-team)
- the required attitude of the MIR station
- additional experiment information (experiment name, mode, altitude, latitude, longitude).

The STTL (with the corresponding command schedule) must be available at ZUP 6 days before experiment execution will take place. Three days before execution the possibility exists to compensate for orbit uncertainties by requesting a slight change in the MIR station attitude. Roughly 21 hours before the STTL gets valid (the exact time depends on the visibility of Russian groundstations) GSOC OPS together with the user community decide whether to go for the prime or for the backup plans. This decision mainly depends on the weather forecasts for the planned target areas. If the weather is bad for prime and backups, the prime is default - planned data takes will not be canceled.

Short-term planning takes into account:

- the latest orbit information
- the latest MIR/PRIRODA timeline
- responses to the MTTL from the user community
- ZUP response to the MTTL
- weather forecasts
- need for attitude change requests.

4.6.4 LOGGING

Information about the success of a data take is fed back to the future planning process. It influences the priorities of selected activities during the mid-term planning. Data takes over areas with less than 10% cloud coverage are considered good and the corresponding activity is considered completed.

Therefore the following mission planning relevant logging items must be stored in computer readable form:

- start and stop time of the successful parts of all data takes
- experiment specific information (e.g. the mode of the experiment)
- orbit information valid at the start time (of each successful part of a data take)
- the MIR attitude during the data take.

Start and stop times are received from the ground stations Neustrelitz and Obninsk. The orbit information is calculated from the Global Positioning System data stream which is downlinked with the science data. The attitude information and the specific experiment information is received from ZUP as part of the MIR/PRIRODA housekeeping data stream.

5. SUMMARY

Mission planning for the MOMS camera installed on the PRIRODA module of the MIR station takes into consideration the long duration character of the mission by evaluating already performed data takes and feeding this information back into the planning process. From the use of statistical cloud coverage data it is expected that the limited time available for MOMS operations is exploited more efficiently and the area covered by data takes will be increased compared to conventional planning.

ACKNOLEDGEMENT

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ABBREVIATIONS

ECMWF	European Centre for Medium-Range Weather Forecasts
GSOC	German Space Operations Center
LTTL	Long-Term Timeline
MP	Mission Planning
MPT	Mission Planning Team
MTTL	Mid-Term Timeline
OPS	Operations Personnel
STTL	Short-Term Timeline
ZUP	Zentr Uprawlenija Poljotom (MIR Mission Control Center)

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XMM MISSION PLANNING: ISO REVISITED?

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ABSTRACT. During the early months of the mission, ESA's Infra-red Space Observatory (ISO) has demonstrated the reliability and efficiency of the mission planning process: a process characterised by interacting groups of users and operators as well as tight time scales for completing all the planned observations. In developing, under tight budgetary constraints, the mission planning concept for the X-Ray Multi-Mirror Mission (XMM), it is only natural to look critically at the ISO system to identify areas of commonality, and to re-use ISO designs and software wherever applicable.

This paper reviews briefly the operations concepts of the ISO and XMM missions. There follows a short description of the ISO mission planning process. Comparisons are then drawn between the ISO system and that proposed for XMM. As will be seen, while the overall process shows considerable commonality of approach, the longer mission lifetime and longer observation intervals for XMM, move the operations concept away from a rigidly pre-planned approach with automated commanding toward one which allows greater flexibility and manual intervention.

Although the roles of the science and operations teams are discussed, detailed technical descriptions are limited to the areas affecting the Flight Dynamics development at ESOC. In particular, whereas the ISO project maintains a small dedicated team of Flight Dynamics specialists throughout the mission, the XMM team at ESOC will direct effort into producing a flight dynamics system which the spacecraft controller is capable of using for restricted mission planning activities.

1. INTRODUCTION

The European Space Agency's Infrared Space Observatory (ISO) was launched in November 1995 by an ARIANE 4 launch vehicle into a highly eccentric, low inclination orbit. After perigee raising manoeuvres, the nominal orbit had a perigee height of 1000 km and an apogee height of 71000 km giving an orbital period of 24 hours. The mission duration is determined by the cryogenic unit on-board which is continuously boiling off liquid helium to keep the payload at 3-4 degrees Kelvin. Currently, the expected mission duration is approximately 24 months. The on-board scientific experiments, conceived and built by various scientific institutes external to ESA are made available to the scientific community who apply for observing time on a competitive basis. There are four scientific instruments on-board: a short wavelength spectrometer, a long wavelength spectrometer, a photo-polarimeter and an infrared camera.

ESA's X-Ray Multi-Mirror (XMM) satellite is an observatory in the soft x-ray portion of the electromagnetic spectrum (0.1 to 12 keV). It is scheduled to be launched in 1999 by an ARIANE 5 launch vehicle. It will have a highly eccentric, high inclination orbit a perigee height of 7000 km and an apogee height of 114000 km giving an orbital period of 48 hours. The nominal mission duration is planned as 27 months with possible extension to 10.25 years (total duration) depending on consumables. There are three scientific instruments on-board: a photon imaging camera consisting of three co-aligned mirror modules, a reflection grating spectrometer and a telescope working in the visual and ultraviolet spectra.

The *mission planning* of the sequence of scientific observations and basic operations is of fundamental importance to both the ISO and XMM missions.

2. ISO MISSION PLANNING

2.1 SUMMARY OF THE ISO AOCS

The ISO Attitude and Orbit Control System (AOCS) is required to position an astronomical object within the required instrument aperture to an accuracy of 2 arcseconds. During scientific observations, ISO supports two modes: Fine Pointing Mode where a fixed attitude is maintained and Raster Pointing Mode where the spacecraft performs a series of small slews designed to build up a rectangular raster image of an extended object with raster point spacing between 2 to 180 arcseconds. Attitude control in both modes is maintained using a star tracker (aligned with the payload optical axis) and a fine sun sensor (with boresight perpendicular to the star tracker optical axis).

For each observation, an inertial unit vector to a suitable guide star and the target attitude, represented on-board by a quaternion, are uplinked. Once the requested attitude is reached, the AOCS computes the position of the guide star within the star tracker field of view. The star tracker searches for a star at that position within a given search window, the dimensions of which are prescribed from ground and restricted to avoid the possibility of detecting a neighbouring star of similar brightness. Control torques during observations and slews are provided by three reaction wheels. During slews, the active attitude sensors are three gyros and the fine sun sensor.

The AOCS must also ensure an attitude that fulfils the strict requirements stemming from the thermal sensitivity of the cryogenically shielded payload. Since the payload must not be exposed to direct sunlight at any time, the spacecraft sun shield has to be kept pointing toward the sun within close margins and the solar aspect angle of the optical axis of the telescope must be kept between 60 and 120 degrees. To avoid any direct infrared irradiation from the earth, the optical axis has to be kept outside a defined cone around the earth limb. To monitor this constraint, an infrared sensitive earth limb sensor is installed near the telescope aperture. ISO's attitude is permanently checked against these constraints. Any uplinked pointing request violating one of these constraints will be overruled by the AOCS, putting the spacecraft into an autonomous mode.

Routinely during perigee, ISO is maintained without star tracker control in Programmed Pointing Mode (PPM). This mode is also used when ISO is not in a ground controlled pointing or following an unforeseen contingency. In PPM, the spacecraft follows a sequence of typically six different attitudes which are repeated every orbit (approximately 24 hours) and valid for up to three days. The time-tagged commands prescribing the attitudes are generated daily on ground, considering all applicable attitude constraints.

2.2 MISSION PLANNING TEAMS AND PREREQUISITES

The mission planning is performed by staff at the ISO Spacecraft Control Centre (SCC) and Science Operations Centre (SOC). During the first three critical days after launch, operations were performed by the SCC at ESOC in Darmstadt. Thereafter, the SCC joined the SOC at ESOC's satellite tracking station at Villafranca del Castillo, near Madrid, from where all operations are performed (except for the routine orbit determination which is still performed at ESOC).

The SOC consists of several teams handling all scientific aspects of the mission. In the area of mission planning they are responsible for scheduling the scientific observations. As at ESOC the SCC consists of three teams:

- the flight control team, responsible for all aspects of spacecraft monitoring and control
- the flight dynamics team, providing the specialist orbit and attitude support
- the software support team, maintaining the on-ground ISO dedicated control system (IDCS).

The mission planner in the flight control team is responsible for scheduling non-scientific spacecraft platform operations, the generation of the final command schedule and tracking the progress throughout the planning cycle.

Before the formal mission planning process for ISO can begin, flight dynamics must supply the SOC with an orbit prediction file, an eclipse file and a Data Base of Observable Bins (DBOB). The DBOB provides the periods of observability for any direction of the sky over the planned mission lifetime. Within the DBOB, the celestial sphere is sub-divided into non-overlapping 'bins' of either 3x3 degrees or 10x10 degrees, with observability information provided for each bin, namely the time interval within which the entire area of the bin is free of constraints. Based on the DBOB, SOC is able to plan when a specific part of the sky, i.e. a bin, can be observed. The DBOB is valid for the complete mission, but it is re-generated periodically and after any orbit manoeuvre.

2.3 THE ISO MISSION PLANNING CYCLE

The basic planning period in the mission planning system is one orbital period, from perigee to perigee, termed a 'revolution' with a unique number. Mission planning files are identified by this revolution number and a version number, which allows re-planning starting from almost any step in the mission planning cycle. The ISO mission planning cycle (see Figure 1) for a given revolution is summarised as follows:

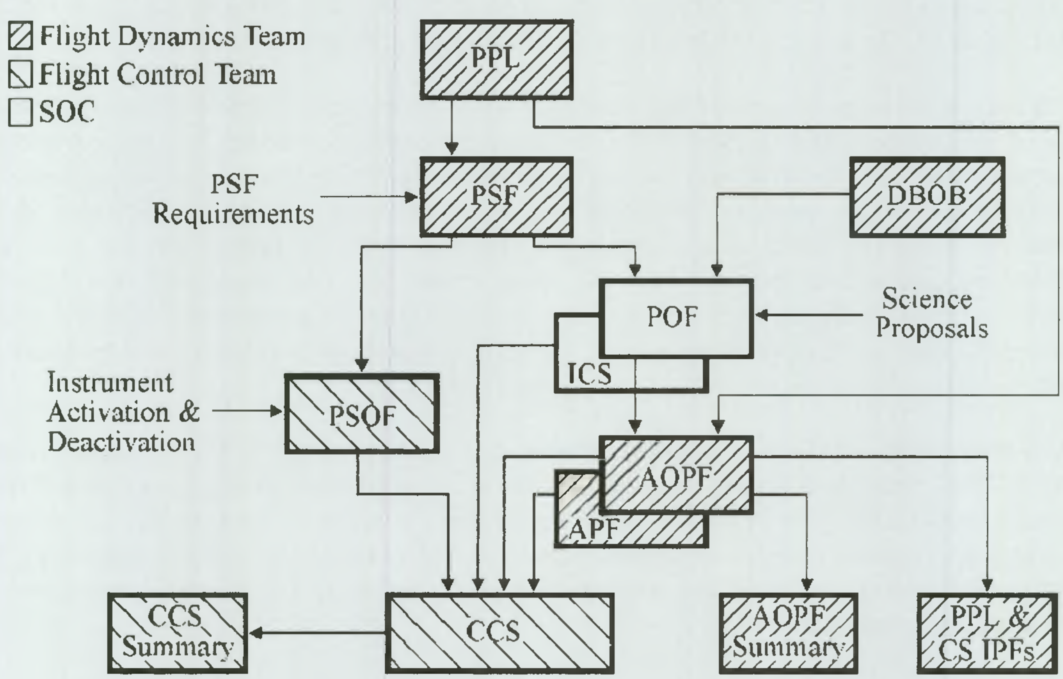

Figure 1. ISO Mission Planning Cycle and Products.

1. Flight dynamics firstly generate a Programmed Pointing List (PPL) containing the sequence of safe PPM attitudes. The generation of a PPL is usually automatic, but attitudes can be specified manually during special operations. The PPL is an internal flight dynamics product at this time.

2. Flight dynamics then produces the Planning Skeleton File (PSF) which includes events for altitude crossings, eclipses, and ground station visibility. It also splits the revolution into non-overlapping windows for scientific observations, calibrations, hand-over between ground

stations, uplink of PPL, activation and deactivation of instruments. Requirements for the positioning and length of the windows are jointly defined by the flight control team, flight dynamics and SOC. Figure 2 shows the windows for a typical revolution.

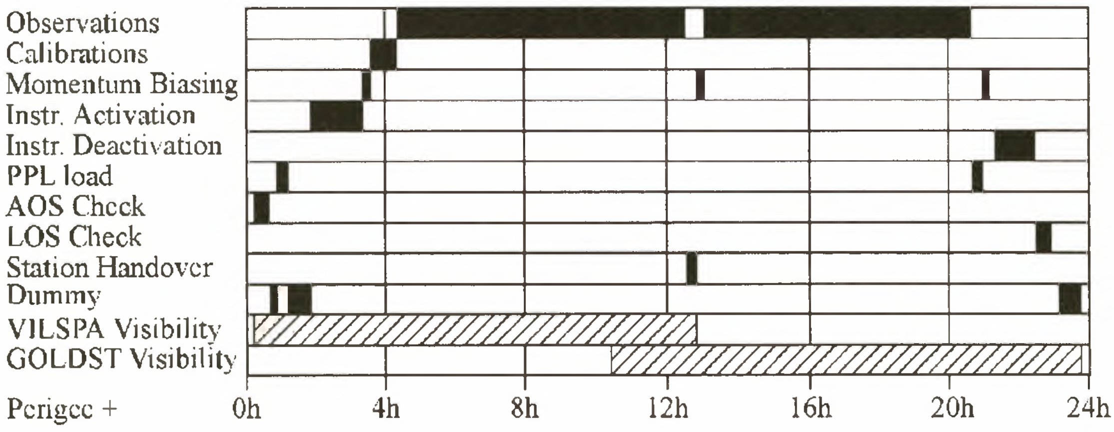

Figure 2. Planning Skeleton File showing typical windows in a revolution.

3. The mission planner transfers the PSF, via the IDCS to SOC. SOC then plan the scientific observations and, based on the DBOB and science proposals, produces a Planned Observations Files (POF) and a corresponding Instrument Command Sequence (ICS) file. The POF echoes all original PSF entries and adds pointing requests, instrument related commands (via pointers to the ICS) and messages within the windows dedicated for scientific observations. The ICS determines the precise commands to be uplinked to the instruments.

4. The mission planner then transfers the POF back to flight dynamics who add AOCS parameters and commands. Two files are produced; the Augmented Operations Planning File (AOPF), which has the same structure as the POF, and the Attitude Parameter File (APF), which contains parameters for each attitude command used in the AOPF. The principal steps involved in producing the AOPF and APF are the:

   - generation of suitable attitudes and command data to perform routine calibrations in the windows designated for calibrations.
   - generation of raster point series to track any solar system objects requested in the POF
   - final attitude constraint check of all the planned slews and pointings.
   - addition of PPL uplink in designated windows and generation of Intermediate Parameter Files (IPFs) containing the individual pointings from the PPL.
   - addition of reaction wheel biasing commands in designated windows.
   - addition of commands for on-board antenna switching.
   - derivation of attitude parameters including selection of one or more guide stars for each pointing. (Extra confirmation star IPFs are generated in case of guide star ambiguity).
   - production of a summary giving an easily readable overview of the planned revolution.

   Whereas the APF is a concatenation of all the command parameters for a complete revolution, each IPF contains command data for only one manoeuvre (in this case a PPL pointing) and may be used in contingencies. On-line commanding, when the products from the mission planning cycle are not used, is performed using a wide range of IPFs.

5. In parallel to this activity, the mission planner generates on the IDCS an extension to the PSF called the Planned Spacecraft Operations File (PSOF). This file contains spacecraft platform operations including instrument activation and deactivation sequences.

6. Finally the mission planner transfers the AOPF and APF to the IDCS and merges them with the POF, ICS and PSOF into a Central Command Schedule (CCS). The CCS then contains all planned commands for one revolution.

2.4 OPERATIONAL EXPERIENCE

The experience with the mission planning cycle in the first months of the mission is very positive. Although the nominal mission planning cycle starts some weeks before the revolution in question, a very late re-planning was performed regularly during the commissioning phase and occasionally during routine operations, challenging the flexibility of the mission planning system. All of these re-planning operations went smoothly. A late modification of the observation schedule requires a regeneration of the POF by SOC. If, for example, ground station coverage changes, a new PSF must be generated. In both cases, all subsequent mission planning products for that revolution must also be re-generated.

One problem can occur during the generation of the CCS when additional commands are inserted. The timing of these commands is not completely predictable during the generation of the AOPF. Consequently, there are occasional timing conflicts, so called command clashes, making additional iterations on the AOPF necessary. Since the pointing sequence will not be changed at this point and potential problems in the AOPF generation have usually already occurred and been logged during an earlier iteration, this regeneration has a limited impact. The situation could be improved by providing and implementing complete look-up tables with the time budgets for the uplink of each command. This information is only provided in cases in which the AOPF is not compatible with the planned command sequences defined by the flight control team.

3. XMM MISSION PLANNING

3.1 AOCS DESIGN

Both the ISO and XMM satellites are three-axis stabilised observatories, which are required to slew to pre-defined target attitudes and then dwell there for a period time while the scientific observation is carried out. Both rely on a star tracker and fine sun sensor controlling the attitude during stable observation periods using a system of reaction wheels for slewing. Indeed the star trackers are identical on both spacecraft although the limiting magnitude for the XMM star tracker may be slightly higher. However the attitude control method differs significantly between the two spacecraft in many aspects, particularly during slews.

- ISO maintains an inertial attitude representation on-board as a quaternion. XMM is controlled on the error signals between predicted and measured sensor output alone, without determination of an inertially fixed attitude. XMM uses differing combinations of sensors for attitude control (star tracker, fine sun sensor, sun acquisition sensors, gyros and an attitude anomaly detector) depending on the AOCS mode employed.

- ISO slews under closed loop control using three gyros and a fine sun sensor as attitude sensors. Due to the risk of gyro failure over the potentially 10 year mission, XMM will operate routinely without gyros, performing slews using only a fine sun sensor. This allows closed loop control around two axes, but relies on open loop control around the third axis where the reaction wheel speed profile is commanded from ground. XMM will use dynamically tuned gyros for autonomous safety modes and during eclipses where no fine sun sensor information is available.

- There is no equivalent of ISO's Programmed Pointing Mode (PPM) for XMM, avoiding the use of a PPL. Because of XMM's higher perigee height, the earth avoidance region through perigee is considerably smaller. XMM can therefore adopt a more 'relaxed' approach to the perigee region and select only one safe attitude. At the end of an observation, XMM will remain at the current attitude until otherwise commanded or the emergency sun acquisition mode triggers due to sun-pointing constraints.

3.2 OPERATIONS CONCEPT

XMM will use the same team structures as ISO, although the names and locations may differ.

- The Mission Operations Centre (MOC) will perform all aspects connected with the operations and safety of the spacecraft. It will be situated at ESOC in Germany throughout the mission. The MOC contains three dedicated teams (as for the ISO SCC): the flight control team, the flight dynamics team and the software support team for the real-time XMM Mission Control System (XMCS).
- The Science Operations Centre (SOC) will be developed at ESOC and ESTEC in the Netherlands. It will however be situated during operations at Villafranca in Spain, taking over the ISO facilities when that mission is complete.

A very significant difference between the two missions lies in the durations of the individual observations, due to the different wavelengths involved. ISO's infrared observations are typically only a few minutes long, whereas XMM's x-ray observations will last several hours. The consequence for ISO is that the observation sequence for a revolution is carefully planned in advance with no opportunity to manually intervene in an automatic schedule of commanding. If for any reason, an object fails to be at the prescribed attitude, there is no time to perform a trim manoeuvre or to initiate manual search procedures. A new observation would have to be scheduled at a later date. This allowed the flight dynamics team to prepare the mission planning products during normal working hours. Consequently, there was a clear separation of activities between the flight control team, using the ISO dedicated control system (IDCS) and the flight dynamics team, using the flight dynamics system (FDS).

For XMM, however, the SOC will have the opportunity to monitor the scientific output during their scheduled observation and propose small attitude trim manoeuvres optimising the instrumental pointing. With such long exposure times, if one observation has to be aborted, the SOC may need to re-plan new observations within the same revolution; requiring a faster mission planning turnaround, possibly outside normal working hours. This leads to a more flexible approach being adopted for XMM whereby the mission planner or spacecraft controller from the flight control team will have sufficient access to the FDS, in addition to the flight dynamics team, to perform mission planning.

The longer orbital period of XMM has little impact on the operational principles of mission planning. The number of ground stations supporting routine operations will differ however. ISO maintains two: at Villafranca (Spain) and Goldstone (USA), whereas XMM will maintain only one at Redu (Belgium).

3.3 THE XMM MISSION PLANNING CYCLE

Similarly to ISO, all scientific observations must satisfy the spacecraft pointing constraints to protect the payload instruments from exposure to direct sunlight at all times. The solar aspect angle of the optical axis must be kept in the range 70 to 110 degrees. Additional constraints also exist to avoid earth pointing and to orient the fixed solar panels at the sun. A more relaxed set of constraints is allowed through perigee.

The nominal XMM mission planning cycle will take a similar approach to that described in the previous section for ISO. Except for the DBOB, all mission planning products are generated for one and only one revolution as for ISO.

1. The Data Base of Observable Bins (DBOB), orbit and eclipse files will be generated by flight dynamics and delivered to SOC as for ISO.

2. The mission planner will prepare a Planning Skeleton File (PSF) on the FDS containing a time line of orbit dependent events and other general house-keeping activities, in a similar manner to ISO. Flight dynamics will perform off-line checking. Since XMM contains no Programmed Pointing List (PPL), the single safe attitude for the perigee region will be computed while generating the PSF.

   In both missions, it is necessary to deactivate the scientific instruments during perigee. However XMM differs from ISO in the need to deactivate the scientific instruments during eclipse. The operational sequence for activation and deactivation of the instruments is a clearly definable set of commands which can be uplinked as a sequence without manual intervention. Consequently, the XMM PSF generation software will insert the relevant command sequence pointers with a default time separation within special activation and deactivation windows. By doing this, the need to generate a Planned Spacecraft Operations File (PSOF) as for ISO is removed, along with the need to merge such a file with the other mission planning products. The risk of getting a command scheduling clash with the subsequent re-planning activities is therefore reduced.

3. The mission planner transfers the PSF, via the XMCS to SOC. SOC then plan the scientific observations and produce the Preferred Observation Schedule (POS) and corresponding Instrument Command Sequence (ICS) in a similar manner to the Planned Observation File (POF) for ISO. As for ISO, it is the SOC's responsibility to ensure that the pointing requests do not violate any attitude constraints during the slews as well as the stable pointing mode.

4. The mission planner then transfers the POS back to the FDS. The flight dynamics team will process the POS to produce an Enhanced Preferred Observation Schedule (EPOS) and associated Attitude Parameter File (APF) similarly to ISO. (The equivalent file to the EPOS for ISO is the Augmented Operations Plan File (AOPF)). The EPOS echoes all the original entries in the POS, after checking for constraint violations, and inserts additional events with pointers to relevant command data in the APF.

5. The mission planner transfers the EPOS and APF back to the XMCS and merges them with the POS and ICS into the Central Command Schedule (CCS), but without the additional overhead of merging them with an ISO-like PSOF.

3.4 ON-LINE RE-PLANNING AND COMMAND ACTIVITIES

In the case of operational difficulties, it will be necessary after the difficulty is resolved, to re-join the schedule as soon as possible. This will imply using the flight dynamics system to compute a safe path to slew to the next appointed observation.

A re-planning request by the SOC may include aborting the current observation and choosing an alternative before re-joining the original schedule, or slewing to a 'Target of Opportunity' such as a supernova within a few hours. The SOC will deliver a new re-planned POS to the MOC. This will have to be processed by the spacecraft controller (using the flight dynamics system) to produce an EPOS in the same manner as for routine mission planning. Although the change to the schedule may only affect one observation, it is nevertheless necessary to examine all subsequent observations until perigee to ensure that the reaction wheel speeds are never close to zero during a scientific observation. If a new observation results in an attitude where this will occur later in the revolution, further re-planning will be necessary to allow for a reaction wheel biasing command to be sent. This command would use the thrusters to impart momentum to the individual wheels while maintaining a constant attitude.

As described in Section 3.1, large angle slews by XMM are performed with closed loop control around only two axes. Open loop control is performed around the third axis using a ground-calculated reaction wheel speed profile. At the start of the mission, before in-flight calibration of the reaction wheels and moments of inertia, large slews could result in significant attitude errors around the axis under open loop control. The AOCS will therefore autonomously command the star tracker to map its field of view on completion of the slew. The flight dynamics system can then be used to determine the current attitude and compute a small adjustment manoeuvre to attain the final target.

During the early stages of the mission, it will be necessary to re-compute attitude parameters if significant differences between the measured wheel speeds prior to a slew and wheel speeds expected in the EPOS/APF mission plan are seen. The flight dynamics system must then be used to re-compute and re-transfer these parameters to the XMCS. These new parameters must replace those originally given in the APF and be incorporated in the command schedule.

4. CONCLUSIONS AND ACKNOWLEDGEMENTS

This paper has summarised the mission planning processes for both the ISO and XMM missions with emphasis on those aspects affecting the flight dynamics system and team.

The careful work done for ISO by all parties has resulted in a very successful and efficient process, despite the operational complexities. It is therefore only natural to adapt the ISO experience to the XMM mission, without following slavishly everything which was done.

The different geographic locations of MOC and SOC for XMM as well as the additional need for a fast re-plan option, gives rise to new requirements and a greater reliance on electronic interfaces. ISO maintains a dedicated flight dynamics team of three people in Spain to operate the flight dynamics system during normal hours. The need for XMM re-planning and attitude trim manoeuvres at any time of day has prompted the desire to develop a restricted flight dynamics system which requires less specialist support and can be operated by the spacecraft controller in an efficient and safe manner, throughout a hopefully long and successful mission.

As stated in this paper, mission planning involves many different teams other than those involved in flight dynamics. The authors are therefore pleased to acknowledge the contributions of many colleagues within the mission operations and science operations centres of both ISO and XMM to the definition and implementation of these processes.

THE ENVISAT1 MISSION PLANNING SYSTEM

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ABSTRACT: The paper presents the strategy which has been selected for the Envisat1 Mission Planning System (MPS) definition. The Envisat1 MPS aims at coherently operating the 9 payload instruments and the platform functions of the satellite which are associated to the command and control functions and to the retrieval (in real or differed time) of scientific data via X band stations, or via the European data relay satellite Artemis.
The functionalities provided by the Envisat1 ground segment elements, and provided by the satellite itself in order to plan and schedule the mission operations are presented. This description allows to identify the two basic sets of user data which are to be provided by the Envisat1 system: the Global Monitoring Mission, and the Background Regional or Regional Mission.

1- Overall Envisat1 mission objectives.

The main objectives of the Envisat1 programme is to endow Europe with an enhanced capability for the remote sensing observation of the Earth from space. This objective is achieved by developing:

• a package of instruments aimed at meeting the need to observe the earth and its atmosphere from space in a synergetic fashion, addressing global warming, climate change, ozone depletion and ocean and ice monitoring.

• a ground segment including: the Flight Operation Segment (FOS) dedicated to spacecraft and mission control and operations, and to the operation planning of the Envisat1 Global Mission. The Payload Data Segment ensuring payload operations planning for the Envisat1 Regional Mission, scientific data acquisition and processing, data distribution, archiving, and user services.

2- The concept of Envisat1 Regional and Global Mission.

There is a need to provide both GLOBAL and REGIONAL data to scientific and application users on various time scales.

• Continuous and coherent GLOBAL DATA sets are needed in order to understand better climatic processes and to improve for example climate models via the quantitative observation of radiative processes, ocean-atmosphere heat and momentum exchange, interaction between atmosphere and land, ocean dynamics and variability, etc...Those objectives which require only scientific products available off-line, that is to say days to week from sensing, need however permanent and continuous data sensing.

Some global applications require near real time data delivery, from a few hours to one day from data sensing. Specific examples include forecast of sea state conditions, sea surface temperature, atmospheric species, atmospheric variables (temperature, pressure, water vapour).

• Continuous and coherent REGIONAL DATA sets are needed in order to achieve a variety of objectives such as sea-ice strategic off-shore applications, snow and ice detection and mapping, coastal processes and pollution monitoring, etc...Some of the regional objectives require near real time data products (within a few hours from sensing) generated according to user requests.

The Envisat1 mission planning system is therefore tailored to the fulfilment of those two specific Global and Regional Mission objectives.

3- The Envisat1 payload complement.

In order to fulfil the Envisat1 Global and Regional Mission objectives, a set of payload instruments is at present being developed. Multi mode instruments like ASAR can contribute to both the Regional and Global Mission depending on the operational modes selected. The table 1 below characterises the contribution of each payload instrument to the Regional and Global Mission.

Instruments	Global mission	Regional mission
Advanced Synthetic Aperture Radar (ASAR)	For "Global monitoring mode" and "wave mode" Low Rate Modes	For "Image mode", "Alternating polarisation mode", and "Wide swath mode": High Rate Modes
Medium Resolution Imaging Spectrometer (MERIS)	For the Reduced Resolution data: Low Rate Mode	For the High resolution data: High Rate Mode
Radar Altimeter, Microwave Radiometer, Laser Retro-Reflector (RA,MWR, LRR)	Y	N
Michelson Interferometer for Passive Atmospheric Sounding (MIPAS)	Y	For Special Event Monitoring mode
Global Ozone Monitoring by Occultation of Stars (GOMOS)	Y	N
Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY)	Y	N
Advanced Along Track Scanning Radiometer (AATSR)	Y	N

Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS)	Y	N

table 1: Payload instrument contribution to the Envisat1 mission

4- Components of the Envisat1 mission.

The Envisat1 payload complement is fulfilling Global and Regional mission objectives according to the 3 mission elements defined below:
- The Global Monitoring Mission
- The Background Regional Mission, defined by default by the Mission Management in absence of specific user requests
- The Regional Mission driven by user request

The Global Monitoring Mission is defined in form of orbit scenarios enabling detailed and conflict free planning of instruments operations by the Reference Operation Plan generation tool (ground infrastructure supporting the Envisat1 Mission Management). The Global Monitoring Mission is based on routine and continuous sensing of data.

The Background Regional Mission is defined as a set of orbital segments with resource conflicts solved by the Reference Operation Plan generation tool.

PDS user requests for Regional Mission operations are expressed in term of zones or time segments, and transformed into orbital segments using a software function (a zone is defined as a set of points at the surface of an ellipsoid modelling the earth, a time segment is the time interval along the orbit along which the instrument mode is kept unchanged during the whole time interval.

The user request are only applicable to the Regional Mission and will be merged with the Background Regional Mission. Usually, user requests cannot specify the data downlink on their request, except station operators who may request explicitly downlink of HR data to their station (X or Ka band) as part of their operation request.

5- Envisat1 satellite recording and data transmission capabilities.

The Envisat1 Polar Platform will offer:

- A global recording capability via a set of 4 onboard recorders of 30 Gbits capacity per recorder operable independently.
  (recording will be performed at 4.5 Mb/s and playback at 50 Mb/s)
- X band direct to ground transmission at 100 Mb/s per channel with:
  - One specific RF channel dedicated to ASAR (in its regional mission modes),
  - One specific RF channel dedicated to:
    . MERIS Full Resolution multiplexed with the global mission data, and transmitted in real time. This data set is called the Medium Rate Composite (MRC)
    . Playback data of one tape recorder.
- Ka band transmission via Artemis, providing the same data transport as the X band communication channels at 100 Mb/s per channel (2 channels of 100 Mb/s available).

This system does offer possible simultaneous operation of all X and Ka band channels.

6- General ground station definitions.

The following types of X band stations will be used for data downlink:

- ESA ground stations which are the PDHS-K (Kiruna), the PDHS-E (Ka band User Earth Terminal at ESRIN) and the PDAS (Fucino).
- National X band stations of ESA member states providing ESA services (NS-E)
- Other X band foreign stations not from ESA member states (FS)
- National Ka band UET.

All the X band station visibility segments, and the orbital segments during which Artemis is geometrically visible from the Envisat1 Ka band terminal will be calculated using a specific software package developed by the Agency and delivered as a CFI to the Ground Segment.

7- Data retrieval scenarios.

The Envisat1 mission will make optimum use of the capabilities offered by the ESA Data Relay Satellite Artemis which will be available in the time frame of Envisat1.

The Global Mission data recovery (one tape recorder playback per orbit) will be performed partially via Artemis with the data acquired at the User Earth Terminal (UET) located in ESRIN-Frascati-Italy (PDHS-E), and partially via the ESA X band Kiruna station (PDHS-K).

For the Regional mission, it is planned to use Artemis in order to acquire via the UET data scenes from any part of the world (provided Artemis is visible from the Envisat1 Ka band transmission system, that is to say circa 40% of the orbital time).

Over Europe, X band direct acquisitions will still be possible via the two ESA stations of Kiruna and Fucino (circa 10 minutes of acquisition time per station and per 100.5 min orbit).

The Envisat1 satellite will continue to serve regional users in any part of the world via direct X band reception, using in particular the network of stations already acquiring the ERS data.

The Envisat1 mission planning system will therefore be based on the dual capability for X band direct transmission, and Ka band transmission via Artemis.

The Global Mission which is based on a permanent and continuous earth sensing process is nominally recorded on board and downlinked once per orbit either via Artemis or X band, as well as downlinked in real time when possible as a subset of the Medium Rate Composite.

The nominal Global Mission is characterized by the following 3 tape recorders scenarios:

- Utilisation of 2 Tape recorders alternating on an orbit basis (1 orbit = 100.5 min)
  Utilisation of PDHS-K for X band, PDHS-E for Ka band
  Downlink of 1 TR per orbit
  This scenario assumes that Artemis is available, with 7 consecutive orbits dumped via Kiruna and 7 consecutive orbits dumped via Artemis in order to share on a daily basis the Global mission processing load on the ground (14.3 orbits per day for Envisat1).

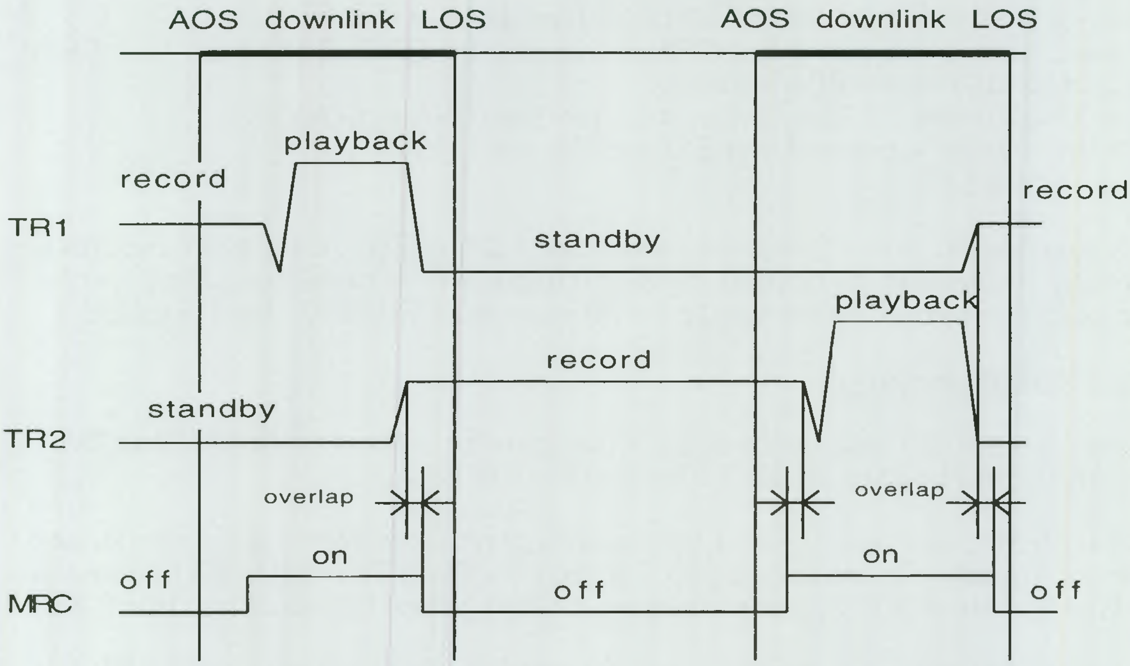

fig.1 : nominal tape dump scenario

- Utilisation of up to 4 TRs to cope with up to 5 orbits without downlink possibility
  utilisation of PDHS-K and PDAS for X band downlink
  deferred downlink to PDAS
  This scenario assumes that Artemis is temporarily not available.

- Utilisation of 2 TRs alternating on an orbital basis
  Utilisation of PDHS-K and of a 2nd high latitude station for X band downlink
  downlink of 1 TR per orbit
  This scenario assumes a permanent unavailability of Artemis and therefore the utilisation of an additional X band station.

The BRM or RM requires a data downlink in real time either via Artemis or via X band channels (specific 100 Mb/s link for ASAR HR data, and part of the 50 Mb/s MRC for MERIS Full Resolution data). The ASAR LR and MERIS LR data are recorded on board together with the Global Mission Data, and are also embedded within the MRC.

8- The Envisat1 Ground Segment mission planning concept.

The ground segment architecture of the Envisat1 mission planning system is built up around the following elements:
- The PDCC (Payload Data Command and Control) mission planning system used to plan the acquisition of Regional Mission data and to plan the processing, archiving and dissemination of all acquired data to users.
- The FOCC (Flight Operation Command and Control) mission planning system used to plan the satellite operations and utilisation of satellite resources, and to plan the acquisition of Global Monitoring data.
- The DRS mission planning system, external to Envisat1 and used to plan the Ka band downlink.

- The Envisat1 mission management providing the Reference Operation Plan (using a set of software tools known as ROP generation tools for files generation), interfacing with scientists, with Anouncement of Opportunity Instrument providers, and with the Artemis mission authority.
- The users providing requests for regional mission instrument modes

The mission management of Envisat1 will issue a Reference Operation Plan (ROP) for each mission phase (commissioning, routine, change of reference orbit if applicable) which is a detailed specification of the mission planning operation.

The Reference Operation Plan will be supported by software tools developed within the Envisat1 project in order to allow:

- The definition and the validation of mission scenarios
- The provision of parameter tables used for onboard and/or on ground processing activities
- The definition and the validation of calibration scenarios and implementation of changes to them based on long loop of calibration and monitoring data.
- Scheduling of specific calibration activities.

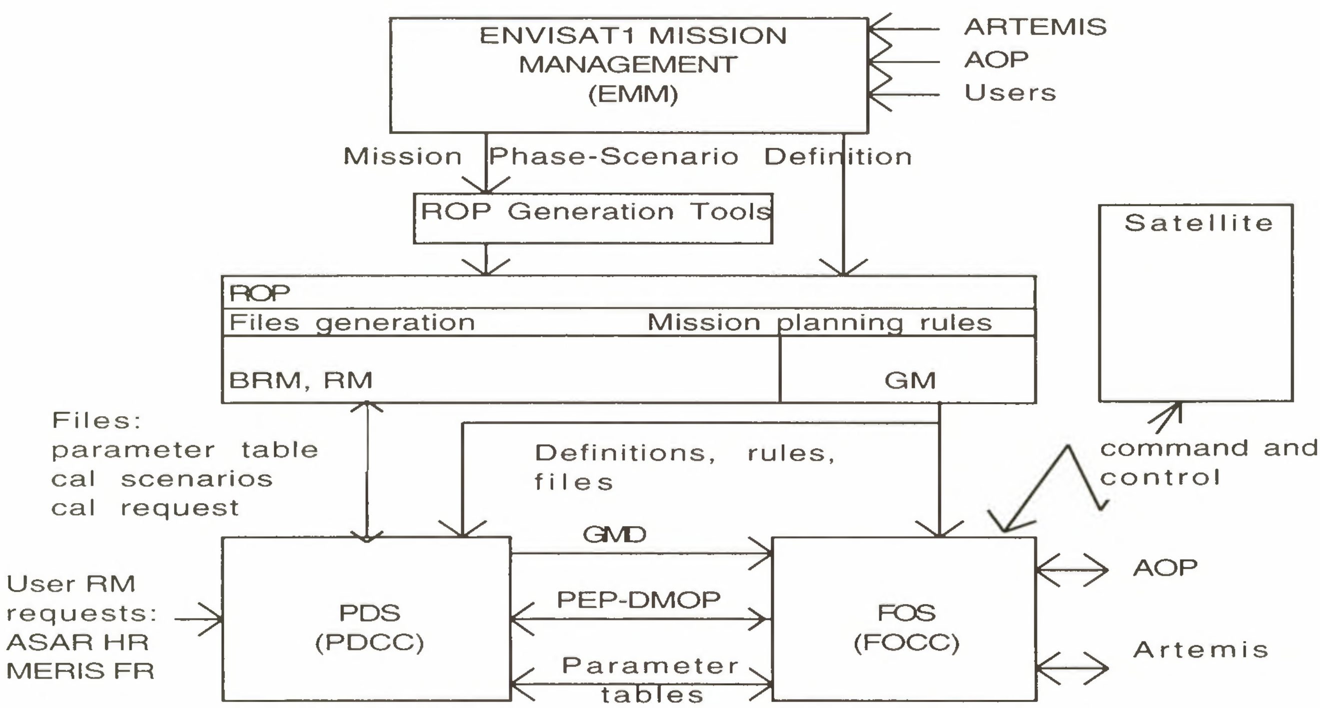

Fig. 2: Envisat1 mission planing synoptic

9- Mission planning strategy.

The Payload Data Segment (PDS) schedules the Regional Mission, Background Regional Mission, and the MERIS and ASAR calibration activities via the generation of the Preferred Exploitation Plan (PEP) issued to the FOS:

- It converts RM user request, provided in form of zones, into orbital segments.
- It merges the RM request and the BRM segments according to a strategy solving conflicts

- It generates the merged BRM and RM mission planning in terms of orbital segments per instrument mode
- It selects the X band and Ka band Ground Stations for High rate data downlink

The Flight Operation Segment (FOS) schedules the Global Mission based on the definitions of the ROP generation tool generating: orbit scenario files, Tape Recorders operational scenarios, and all necessary payload instrument files like instrument mode dependant configuration tables:

- It merges the RM-BRM-GM mission and generate a detailed sequence of operations for all the Envisat1 instruments. It particularly resolves conflicts between the Preferred Exploitation Plan issued by the PDS (merge of BRM and RM) and the satellite resources available (e.g. power)
- It schedules calibration measurement for the Global Mission instruments.
- It merges Ka and X band link operations according to the requests.
- It schedules the calibration measurement for the BRM and RM instruments (ASAR, MERIS)
- It ensures the I/F with the Artemis Mission Control Centre for the booking of Artemis communication time slots.
- It provides detailed scheduling reporting back to the PDS and to the mission management in the form of a Detailed Mission Operation Plan (DMOP).

10- Mission planning priority level definitions.

In order to resolve conflicts of operations, rules of priority have to be applied by the ground Segment, as indicated in the table below.
The safety of the satellite has the highest priority. The FOS therefore takes the necessary measures to ensure the satellite safety through the entire mission.

Priority	Sub-priority	Definition	GM	BRM	RM
0		Satellite safety	Y	Y	Y
1		natural disaster, major pollution	Y	Y	Y
2		Instrument calibration, maintenance	Y	Y	N
3		Request issued by classes of RM users assigned by the PDS in liaison with mission management	N	N	Y
3	1	Commercial users	N	N	Y
3	2	Governmental users	N	N	Y
3	3	Scientific institutions	N	N	Y
4		Global-BRM nominal activities	Y	Y	N

table 2: Definition of mission related priorities

Y: means impact to the mission planning

11- Planning cycle.

All planned activities within an orbit are defined with respect to the ascending node. The update of the time of events in UTC is performed by replacing the reference ascending node crossing (ANX) time by the predicted ANX time provided by the FOS (Flight Dynamics system). This activity, reflected by the DMOP generated by the FOS will take place 6 days prior to the event.

The following types of mission planning will be implemented:

- A long term planning cycle covering between 1 repeat cycle and 1 year, allowing to reserve resources like Artemis, and to plan the BRM and the GM.
- A nominal planning cycle covering 1 week.
- An emergency planning covering 1 to several orbits per day for user requests issued up to 2 days prior to the measurement.

The configurable scenario applicable to the planning cycles is illustrated below:

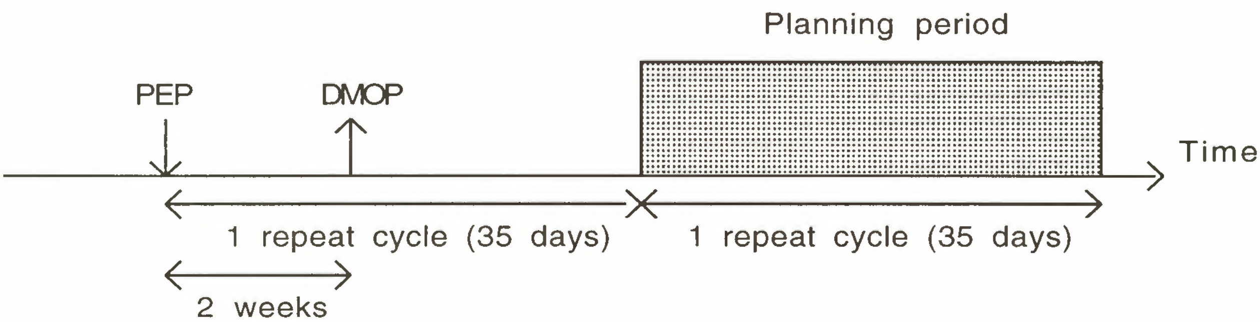

fig. 2:long term planning cycle

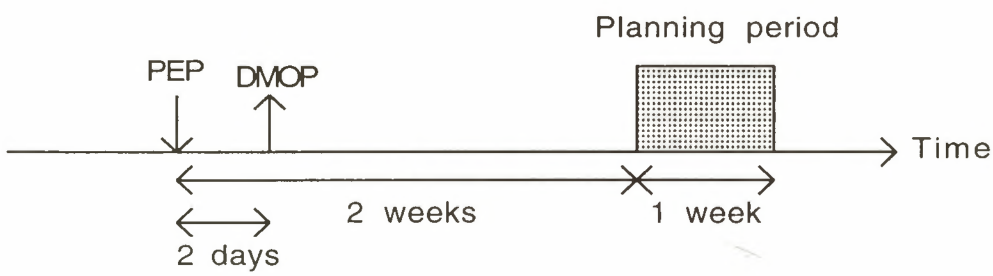

fig. 3: nominal planning cycle

12- Conclusions.

The Envisat1 Mission Planning System is at present undergoing a requirement definition phase. Because of the split of functions imposed by the share of responsibilities between the PDS and the FOS within the ground segment for the scheduling of the BRM-RM and of the GMM, the Envisat1 project team has issued two formal documents applicable to the overall MPS to ensure the completeness and the coherence of the MPS development.

• The "Reference Operation Plan" which defines the generic rules applicable to the various elements of the ground segment, and specifies the format of the various files to be either uplinked to the payload complement, or to be implemented within the scientific data algorithm processors.

• The "Operational Constraints Document" which describes all satellite design driven detailed constraints and operational rules relevant for the routine operations of Envisat1. The document provides also the list, content and formats of the instrument onboard mode dependant reference configuration tables to be regularly uplinked to the payload complement.

In order to perform coherently all calculations related to the planning of the Envisat1 mission, the Project has initiated the development and the documentation of mission software functions which are to be delivered and integrated as part of the mission planning system within the Envisat1 ground segment, or as part of the ROP generation tool. This approach ensures that all mission planning datas provided to the PDS or to the FOS are properly verified, and also coherent and consistent with physical elements like satellite orbit and performances, time reference transformation, instrument design characteristics, ground stations characteristics, utilisation of star catalogues, definition of operational zones, definition of Artemis visibility segments, etc...

FLIGHT EXPERIENCE WITH THE ROSAT MISSION PLANNING SYSTEM

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ABSTRACT. ROSAT is a scientific spacecraft designed to perform the first all-sky survey with a high resolution X-ray telescope and to investigate the X-ray emission of specific celestial objects. The mission can be broadly divided into three main phases: the test and calibration phase, the survey phase and the pointing phase. These three mission phases present very different requirements on a mission planning system. The generation of the mission timelines is performed by a system written at the German Space Operations Center called the ROSAT Mission Timeline Generator (RMTG). It is the main purpose of this article to present an evaluation of the performance of the RMTG and the experience gained from mission planning in general with the ROSAT satellite over the past 6 years. The advantages and disadvantages of the chosen approach will be presented and the article concludes with a discussion of the impacts of the lessons learned on mission planning of other satellites.

1. MISSION OVERVIEW

ROSAT (see figure 1) is a co-operation between Germany (Bundesministerium für Forschung und Technologie), the USA (NASA) and the UK (Science and Engineering Research Council). Scientific management of the project is at the Max Planck Institut für Extraterrestrische Physik (MPE) at Garching near Munich. The responsibility for satellite operations is at the German Space Operations Center (GSOC) which is a department of DLR in Oberpfaffenhofen near Munich.

There are two main objectives of the mission:

- Performance of the first all-sky survey with an imaging X-ray telescope in the energy ranges 0.1 - 2 KeV and 0.04 - 2 KeV.
- Detailed observation of selected sources with respect to spatial structure, spectrum and time variability.

During the survey phase in 1990/1991 around 60,000 new X-ray sources were discovered.

The scientific payload of ROSAT consists of a large X-ray telescope (XRT) sensitive in the energy range of 0.1 KeV to 2.0 KeV and a wide field camera (WFC) sensitive in the energy range of 0.041 KeV to 0.21 KeV. Two different detectors can be put in the focal plane of the XRT. The Position Sensitive Proportional Counter (PSPC) with a resolution of 30 arc seconds and the High Resolution Imager (HRI) with a resolution of 10 arc seconds. The PSPC is equipped with one filter. The WFC is mounted alongside the XRT and points in the same direction. It has a resolution of 1 arc minute. It has several filters which can be inserted into the optical path. Both the XRT and the WFC are equipped with calibration facilities.

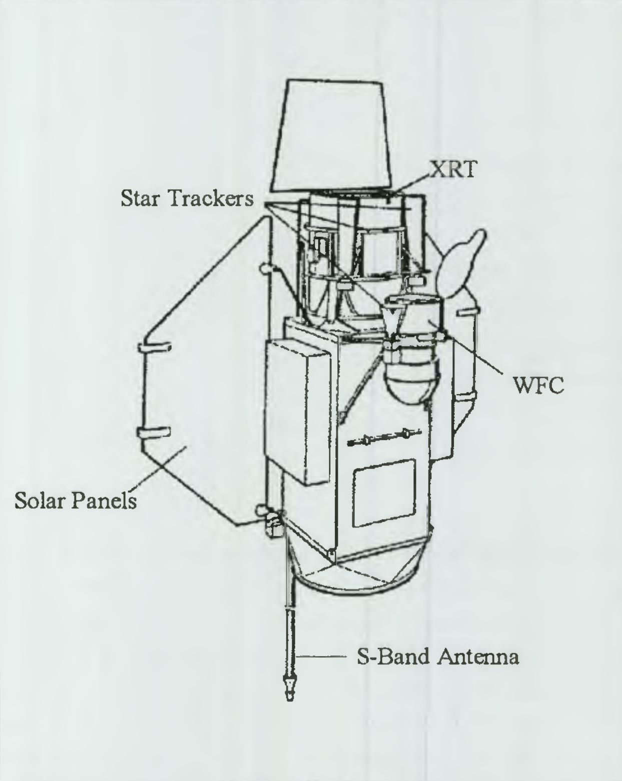

Figure 1. The ROSAT Spacecraft.

ROSAT was launched from Cape Canaveral by a Delta II rocket on June 1st 1990 at 21:48 GMT. The orbit is nearly circular with an altitude of 580 km and an inclination of 53°.

The prime ground station is at DLR's Weilheim complex south of Munich. Due to the characteristics of the orbit, only 6 to 7 passes of about 8 minutes duration are available each day for receiving telemetry and transmitting commands. Because of the expected high volume of data transfer, both telemetry and commands, these contacts must be carefully planned. Ground stations in NASA's Deep Space Network at Madrid, Goldstone and Canberra are also available as backup in emergency and have been used during various phases of the mission.

The main unit of time for mission planning is the 'ROSAT Day' which is based on the pass cycle for the Weilheim station. A ROSAT day starts at the first ascending node which follows the final Weilheim pass in the cycle of 6 to 7 passes.

The mission has been beset with hardware problems, some of which have had major impacts on mission planning. The two most important were the loss of the Y-gyro in May 1991 and the Z-gyro in November 1993. The effects of these losses on mission planning are discussed below. The failure of one of the main star trackers in 1990 did not affect planning. However, if the second star tracker were to fail, the WFC star trackers would have be used and this would involve changes to the mission planning system.

Use of the PSPC detector had to be discontinued in July 1994 as the gas supply for flushing the instrument was exhausted. Operations continued with the HRI and the WFC.

2. MISSION TIMETABLE

The mission is divided up as shown in Figure 2. In the first phase, the spacecraft systems and payload were checked out and the instruments calibrated.

The survey phase, which began in July 1990, required the implementation of a law governing the operation of the scan known as the Terminator Referenced Scan Control Law. The timeline generation procedure was automatic and needed no user intervention and no optimisation.

The rest of the mission (apart from a few mini-surveys which were necessary to fill gaps in the all-sky survey) is given over to observations of individual X-ray sources. Each pointing phase lasts 6 months and is preceded by an Announcement of Opportunity in which observation requests from the scientific community are gathered and vetted. The pointing phases, the first of which started in February 1991, present the most demanding requirements on mission planning. Many thousands of requests for observations must be satisfied. These need to be scheduled as efficiently as possible to avoid wasting valuable observing time and produce an optimised timeline. This optimisation must take into account all the constraints placed on the spacecraft and observations and consider other necessary activities such as calibrations and data transmission.

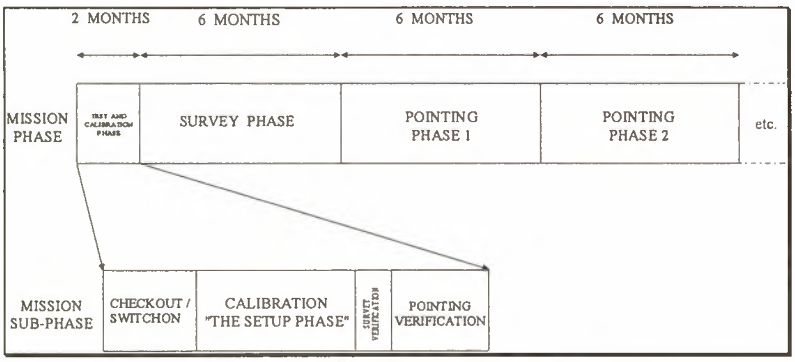

Figure 2. The Mission Timetable.

Due to the various problems encountered with ROSAT, it was found necessary to introduce some smaller pointing phases so that instead of phase 17 the current phase is 20.

Of particular importance in the pointing phases is the manoeuvre to change the spacecraft attitude from pointing at one source to pointing at another. This is known as a 'slew'. Attention must be paid to the length of time required to slew and when it is best performed.

3. MISSION PLANNING

The ROSAT Mission Timeline Generator (RMTG) provides the master plan of spacecraft operations. It takes as input observation requests and an orbit prediction and ultimately produces a short term timeline (STL). This timeline is supplied to further systems at GSOC for telecommand generation. The attitude control management software produces commands for the Attitude Control System on ROSAT using the timeline and star catalogues. The spacecraft and experiment command generation system produces the experiment commands from the timeline. These two streams are then merged and the commands allocated to passes in the pass cycle and transmitted to ROSAT by the command system (see Figure 3).

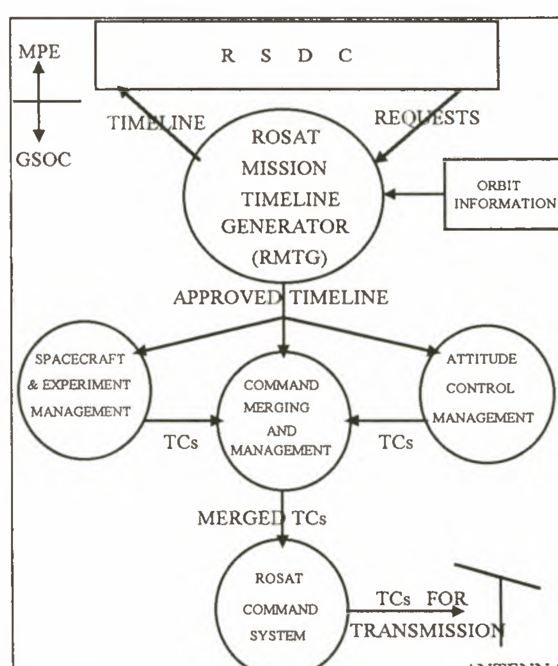

Figure 3. The Context of RMTG.

The three main operating modes of RMTG reflect the differing requirements of the mission:

- Setup. In the test and calibration phase the timeline was 'set up' by hand to perform the required calibrations of the instruments.
- Survey. Automatic timeline generation based on the scan control law.
- Pointing. Automatic production of an optimised timeline.

Mission planning is a common effort between MPE and GSOC. The primary input to planning is the request which represents a desired spacecraft activity. All requests originate from MPE and are presented in a standardised format.

There are two main types:

- Observation requests. These represent pointing or survey operations and are used to schedule the requested activity within the constraints.
- Calibrations and test requests. Each request must be scheduled taking the constraints into account.

The constraints affecting the ROSAT mission are as follows:

- Sun constraint. The plane of the solar panels must be perpendicular to the Sun direction with a maximum deviation of 15 degrees. This is to protect the telescopes and ensure proper operation of the solar panels. This constraint places a window on the observability of a given source called the Sun Constraint Window.
- High energy particle belts. These include the north and south auroral zones and the South Atlantic Anomaly. The telescopes cannot be operated while passing through these regions. RMTG works by considering the observation periods between belt passages when the telescopes can be used. These periods are known as 'slots'.
- Weilheim constraints. To ensure good communication during the contact periods, the spacecraft antenna aspect angle must not exceed 150 degrees. Slew manoeuvres from one source to another must also be avoided.
- Strong sources. The PSPC detector could be damaged by high X-ray fluxes. The telescope must not be directed towards a strong X-ray source if the PSPC is in the focal plane or it must be switched off. In practice, this constraint only affected the survey phase.
- Earth blockage. In the survey phase the scan control law ensures that the Earth does not appear in the field-of-view. In the pointing phases, the Earth appearing in the pointing direction can result in a degraded attitude solution and the scientific value of the data would be diminished.
- Moon blockage. In the survey phase, there is no requirement to avoid the Moon although timeline entries will be generated if the pointing direction is within 20 degrees of the centre of the Moon's disc. In the pointing phase a degraded attitude solution may result if the XRT direction is within 14.5 degrees of the Moon (20 degrees for WFC).
- Atomic oxygen. The telescope must not be pointed in the direction of the velocity vector because atomic oxygen, swept up by the telescopes, can oxidise carbon in the detectors or filters and thus damage them. PSPC and WFC are affected but both have safe filters. HRI is not affected. The requirement to consider this constraint was introduced relatively late in the development phase of RMTG. The resulting requirements on the timeline have been changed drastically during the life of the mission leading to extensive changes in the software.
- Detector changes. Prior to the loss of the PSPC, only one of the XRT detectors could be in the focal plane at any one time. Thus a request which specified a particular detector could not be scheduled unless that detector was in the focal plane. Detector changes had to be made regularly (about every 20 days) for mechanical reasons. The WFC is mounted separately and thus can always observe.
- On-board attitude system memory capacity. The attitude control system has a limited memory capacity to store 'time tagged' commands. This restricts the number of slews and thus pointings that can be scheduled in one day to around 35.
- Request priority. There are three levels of request priority: mandatory (P1), important (P2) and optional (P3). The percentage of observation time allocated to P1 requests must not exceed 15% and that for P1 and P2 together must not exceed 80% of the total available observation time.
- Country time allocation. Each observation request comes from one of the 3 participating countries. The allowed percentage observing times are fixed at USA:50%, WG:38% and UK:12%. The scheduling process must ensure that these figures are adhered to.

The steps needed to generate a timeline are as follows. The requests are received from MPE and validated. New requests may be submitted to correct any errors and the process continues until no more are found. A long term timeline can now be generated and submitted for validation. MPE may wish to change or issue new requests or detector changes in which case the timeline must be regenerated. This process continues until the timeline meets the approval of MPE. At this point the short term timeline can be generated for commanding the spacecraft (see figure 4). This process is discussed in the next section.

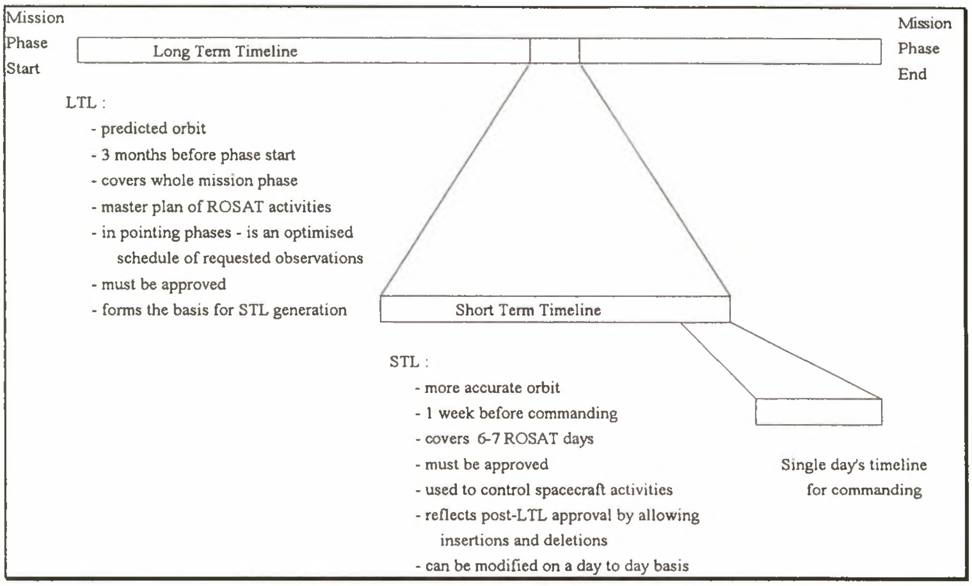

Figure 4. Timeline Generation.

4. TIMELINE GENERATION

The long term timeline (LTL) provides a master, long term plan of spacecraft activities over a period of 6 months. For the pointing phases it is an optimised schedule of the requested observations taking all the constraints into account. The LTL forms the basis for the short term timeline. It can be updated or modified following new or changed requests.

The short term timeline uses a more accurate orbit prediction and covers a period of about 1 week. It is developed in the week prior to commanding and the telecommands are produced directly from it. In the survey phase it is recomputed without reference to the LTL. In the pointing phases, however, the STL is extracted directly from the corresponding LTL by adjusting the observations. No new optimisation is made. The STL also reflects changes to requests made after LTL approval.

It is at STL generation time that the calibration and test requests are inserted into the timeline.

4.1 SETUP PHASE

In order to perform the calibrations in the initial mission phases it was necessary to insert specific requests directly into the timeline in a particular order. As there is nothing in the normal requests to indicate when to place them in the timeline and there is no prior knowledge of the blockages preventing the observation, this had to be done in an interactive fashion. An editor was thus developed for this purpose although many thought the effort not worth while as the original phase was very short. Since that time, however, the timeline editor has proved to be a valuable tool in emergency situations where timelines need to be set up by hand. It is particularly useful where special constraints appear that cannot be covered by the main program. The editor has been used on both occasions when the Y- and Z-gyros were lost to generate special timelines. Modifications and the provision of graphical displays have considerably improved the functionality of the program.

4.2 SURVEY PHASE

In this phase, ROSAT operates in a scanning mode in order to survey the whole sky in 6 months. The solar panels (-x axis) are directed towards the Sun with an offset which must be within the Sun constraint. The satellite rotates about the -x axis once in each orbit. The phasing of the rotation with the orbital motion is fixed in such a way that the telescope axis (z axis) is directed radially away from the Earth at the terminator crossings. Thus, on each orbit, a stripe of the celestial sky is scanned. This stripe is 2 degrees wide for the XRT and 5 degrees for the WFC. Due to the apparent motion of the Sun of about 1 degree per day, the whole celestial sphere will be surveyed in a 6 month period.

RMTG is programmed to generate a survey timeline automatically based on a request from MPE. All the necessary activities are computed and written as entries in the timeline. The program can also process the other types of survey request associated with the survey verification phase and repeating parts of the survey (mini-surveys) which were not performed successfully for one reason or another.

4.3 POINTING PHASES

As mentioned previously, RMTG has a slot based approach to scheduling. The typical observation time requested in an observation request is longer than a slot. This means that observations will generally need to be spread over several slots. Because of Earth blockage, it would waste too much observation time to stay on the same target until it was fully observed. The period in a slot is used to observe and the following belt passage can be used to good advantage to slew to another target. As there are generally two belt passages per orbit, this method is a reliable way to schedule the observations. The optimisation method used to schedule the timelines is described in Ref. 1. In practice, it was found that some slots could cover a complete orbit. For this reason long slots are divided up artificially into more manageable sections. A more serious problem with this philosophy arose, however, when the Z-gyro was lost in 1993. As the gyro could no longer be used for attitude control, the on-board attitude control software was modified to use the magnetometer and Sun sensor. This had the implication that all slews had to be performed during orbital day thus making slews no longer dependent on the slot/belt pattern but on the orbital day/night pattern. Extensive changes had to be made to the software to accommodate these new requirements.

The operational philosophy behind LTL production is stepwise generation. Firstly, a basic timeline with no observations is prepared. Secondly the high priority, time critical P1 observations are inserted (see below) and lastly the P2 and P3 observations are scheduled to produce an optimised timeline. If any changes are required it is a simple matter to revert back to a previous timeline and redo the step. In some extreme cases whole new sets of observations have been delivered, resulting in a return to the basic timeline. Experience has shown that up to five iterations are necessary before the timeline is finally approved by MPE. The original requirement that the final timeline should be ready 3 months before the relevant phase starts has been shown to be unrealistic and unnecessary.

The scheduling of P1 requests is of great importance to MPE and much time and effort is applied to ensuring that as many as possible are accommodated in the timeline. The P1 requests are time critical requests of four types:

- Co-ordinated. The observation must be made within a given time window.
- Phase-Locked. The sequence of observations must be made at the requested intervals starting at the given time.
- Monitoring. The sequence of observations must be made at the requested intervals but the start time is not important.
- Contiguous. The observation must not be distributed over more than the specified number of slots.

The original philosophy behind the placing of P1 requests was changed drastically during the course of the mission. The order of processing into the basic timeline corresponds to the list above but can mean that P1s placed first can block later ones thus causing them to fail. As the phase-locked and monitoring requests are intrinsically harder to schedule, and can easily be blocked by co-ordinated requests, the order was changed to fit them in first.

The original order of placing the P1s was based on the order of the requests and not on the time sequence in which they would appear. This meant that the orbit file, which is stored sequentially, had to be continually positioned and rewound. Changing the order of placing to a time sequence method considerably improved the processing time.

P1 requests are placed in any slot where they will fit, without making any attempt to optimise the observing time. It would be possible to change this situation, however, by modifying the way they are placed to increase the efficiency.

If a source is not fully observed when its Sun Constraint Window (SCW) closes then this is known as a scheduling failure. In this case there is a backtracking option available which allows the system to attempt to rectify the situation. In the case of the low priority P3 requests a return is made to the place in the timeline where the request was first scheduled, the request removed from consideration and the process repeated. In the case of the higher priority P2 requests, which cannot so lightly be removed from consideration, extra action is necessary. The method is to go back to the start of the SCW of the source, change some of the scheduling parameters and repeat the process. This process is continued until either the request is scheduled or the scheduling parameters can no longer be changed and the request must be removed from consideration.

This method works in theory and in the current implementation but is in practice unusable due to two considerations. Firstly, there is a heavy oversubscription of observing time in the set of submitted requests by a factor of about 2. Any attempt at scheduling with backtracking would have led to many scheduling failures and thus many backtracks. LTL production would take much too long. Secondly, there is very little freedom to change the scheduling parameters so that after a backtrack the situation would not be very different. Other methods are thus used to avoid scheduling failures or keep them to a minimum and produce an LTL satisfactory to MPE. The main method is to adjust the weightings in the cost function to favour observations which have already begun thus ensuring that they will probably be completed before their SCW closes.

The philosophy adopted for ROSAT is to generate a detailed LTL in which all the requests are put into the timeline at the place where the sources will ultimately be observed. As mentioned previously, the STL is generated by extracting the observations directly from the LTL. This method has the disadvantage that the orbit prediction used for the LTL generation may be very different from that used for the STL generation. The basic premise of the solution to this problem is that, however much the orbit may change, the slot/belt pattern will remain the same, shifting only backwards or forwards in time. In practice, this premise has been shown to be a valid one. The initial worries over serious mismatch problems have proven unfounded. Thus, in generating an STL from an LTL, the absolute time of an observation is not used but instead the slot in which the observation occurs. Even though the difference between the orbit predictions can be up to 2 hours, the method has been shown to work. One of the main drawbacks with this method is that the P1 requests, which tend to be bound to absolute times and not to slots, cannot be guaranteed to fit into the STL. This however, has not been a serious problem.

The replan facilities which were foreseen as requirements on the original RMTG, particularly the provision of timeline edit requests (TER), have turned out to be very useful in practice. TERs are heavily used by MPE to replan STLs.

A very important addition to the system was the timeline verification tool. This is a standalone utility which checks a timeline for a whole range of possible problems. The tool has proved itself to be invaluable in uncovering faults in the original program as well as checking for problems following changes to the software.

5. HARDWARE, SOFTWARE AND OPERATIONS

The system is implemented on VAX 3200 workstations with 10Mb memory and 19" colour monitors. Prime and backup machines are in use. The long computation times for LTLs and the heavy use of the disks, particularly for storing orbit files, demonstrates that the hardware must be carefully sized before selection. In the case of RMTG the sizing of the hardware was generally satisfactory.

RMTG is written in VAX FORTRAN and runs under VMS 5.x using the Transportable Applications Environment (TAE - originally from NASA) to provide menu and graphic capabilities. The operating system includes a development environment with a code management system. This, together with a good GUI builder has been essential for supporting the mission by not only allowing RMTG to be modified and improved but also allowing further support utilities to be developed. These utilities include the timeline verifier mentioned above, the timeline edit program, several utilities to display the timelines graphically in various forms, slot comparison utilities and several types of print utility.

ROSAT mission planning is performed by the MIPS team consisting of one full-time programmer and one full-time operator. The team maintains close contact with MPE by E-mail and phone at all times. The availability of a full-time programmer with a mathematical/scientific background and fully trained in the system has been essential to the success of the mission. Only with this level of involvement has it been possible to cope with the many problems which have troubled the spacecraft and entailed changes in the mission planning area.

6. CONCLUSIONS

The following conclusions can be drawn from the experience gained in mission planning in the ROSAT mission:

- New requirements and new operating conditions are bound to arise during a mission. The software system and operations organisation must be flexible enough to cope with these and react accordingly. A proper development environment must exist for the software maintainers to be able to modify and enhance the original software.
- An interactive timeline editor for emergencies and last minute changes is essential.
- The approach to scheduling failures and backtracking must be carefully considered.
- Software designers and maintainers must have a mathematical/scientific background.
- Care must be taken with the design decisions made in relation to mission characteristics which may change during the mission.

In the authors' opinion it would be possible to adapt RMTG for missions of a similar nature and complexity to ROSAT. This would be simpler and more cost-effective than developing a completely new product.

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EXPLICIT AND IMPLICIT RESOURCES: A SIMPLIFIED APPROACH TO USER REQUIREMENTS MODELING

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ABSTRACT. The International Space Station (ISS) program is heavily dependent on the concept of distributed planning. Within the payload planning community, the concept of distributed planning places a great deal of responsibility in the hands of the science users. This approach to planning is very different from that used within the current U.S. Space Shuttle and Spacelab programs, where much of the responsibility for planning resides with the control center personnel. In the Shuttle and Spacelab programs the control center personnel interface with the science users to obtain the requirements for the operations to be scheduled. These requirements are then translated by the scheduling experts into the format required for use by the scheduling software. Within the ISS program, the interface to the control center personnel has been radically altered. The users will assume the responsibility for submitting requirements in the format required for use by the scheduling software. Therefore, it is extremely important that requirements modeling software be provided which enables non-scheduling experts to easily and accurately define their requirements. The requirements modeling process is further complicated by the very complex nature of the ISS systems against which requirements must be defined. The concept of explicit and implicit resources has been developed to support these two key requirements. This paper defines and describes the concept of explicit and implicit resources, provides examples of scheduling requirements implemented using explicit and implicit resources, and discusses the software currently being developed to support this concept.

1.0 INTRODUCTION

The distributed planning environment within the International Space Station (ISS) program presents unique opportunities for user community participation in the development of operations plans and products. (See reference 1). These opportunities, while eagerly embraced by the user community, bring with them additional responsibility and complexity. In past programs, such as the Space Shuttle and Spacelab, much of this responsibility and complexity was shielded from the user community by the control center personnel dedicated to the development of operations plans and products. A drawback of this approach to the development of plans and products was that it required a high level of interaction between the user community and the control center personnel which in turn resulted in higher operations costs to the program. The environment of the ISS program drives the need for user community involvement in the development of operations plans and products. This involvement satisfies user community requirements for participation in the planning process, and achieves efficiencies in the operations costs of the ISS program.

User involvement in the planning process does not mitigate the control center responsibility for insuring the feasibility and safety of the resulting operations plans and products. The major obstacle which must be overcome is how to convey detailed knowledge between the control center personnel and the user community. The control center personnel have the detailed knowledge of the station systems, and must be capable of defining the characteristics of these systems such that they can be understood and used by the general user community. The user community has the detailed knowledge of the operations that must be scheduled and performed, and must be capable of defining the requirements for these operations in a manner that satisfies the feasibility and safety concerns of the control center personnel. A way of accommodating this exchange of data, while providing confidence in the data provided, is to limit the opportunities for introducing incorrect or incomplete data. The use of implicit and explicit resources fills this need by hiding the complexities of station systems from the user, while insuring that requirements are levied against the appropriate station systems. Data consistency and completeness is enhanced through the modeling software used for defining scheduling constraints and scheduling requirements.

2.0 TERMINOLOGY

In order to fully grasp the concepts described within this paper, it is necessary for the reader to have a clear understanding of the terminology used to explain the proposed concepts. The following are key terms and their definitions.

Explicit Resource - A resource defined as a constraint or limitation on scheduling which is directly requested by a user in the definition of scheduling requirements.

Implicit Resource - A resource defined as a constraint or limitation on scheduling which is not directly requested by a user in the definition of scheduling requirements, but which is derived from the requirements as defined by the user.

Functional Relationship - A mathematical expression which defines the requirements for one resource based on the specified requirements for some other resource.

Modes - The representation of the possible operating states for a given piece of equipment. Associated with each defined operating state is the definition of the resources that are utilized by the particular piece of equipment.

3.0 CONCEPT DESCRIPTION

The basic premise of the explicit and implicit resource concept is to hide the complexities of the station systems from the user in the definition of scheduling requirements. Explicit resources are defined within the modeling software to correspond to the physical and logical resources that a science user can relate to when defining requirements for scheduling. The requests for these explicit resources are interpreted by the modeling software. Through this interpretation, the modeling software associates the appropriate implicit resources with the user's scheduling requirements. In this manner, the user's scheduling requirements account for all of the necessary requirements without the user ever having to have a detailed understanding of the station systems required to support the defined operations. Without this capability, the user would be required to include all of the necessary resources on a given model. There are three primary functions associated with the use of implicit and explicit resources: 1) resource definition, and 2) requirements modeling, and 3) scheduler formatting.

3.1 RESOURCE DEFINITION

The resource definition function is performed first to establish and define the context within which the scheduling requirements can be defined. As such, this function must be access controlled to insure that the user community has a consistent and accurate set of constraints to use when defining requirements. The resource definition function is generally performed by the control center personnel.

The first step within this function is the identification of the station systems and their components that must be considered during scheduling. These systems and their components are modeled within the planning system as nondepletable, depletable, or condition resources.

A *nondepletable resource* is a resource whose availability is temporarily changed for the duration of its use. Power is a good example of a nondepletable resource. When an operation is scheduled which uses power, the availability of power is temporarily decremented to account for the power consumed by the operation. Once the operation is completed, the availability of power is returned to its original state.

A *depletable resource* is a resource whose availability is permanently changed as a result of its use. Nitrogen is a good example of a depletable resource. When an operation is scheduled which uses Nitrogen, the availability of the Nitrogen resource is permanently changed as a result of the operation.

A *condition resource* is a resource whose availability is specified in binary terms, which can be used to support an infinite number of concurrent activities. Sun periods are good examples of a condition resource. Any number of operations can be scheduled which have a requirement to operate during Sun periods. The execution of these operations in no way affects the availability of Sun periods.

Once the constraining resources have been identified, a decision must be made as to how the resources are to be defined within the planning system. Each resource must be defined as either an *implicit resource* or an *explicit resource*. A resource cannot be defined as both, as this could result in double booking the resource during the requirements modeling phase. An exception to this rule is the designation of condition type resources. This rule does not apply to these types of resources due to the fact that they are not magnitude constrained.

In addition to defining a resource as either explicit or implicit, the definition must also take into account the complexities of the resource and the relationships or interdependencies with other resources. *Functional relationships* and *modes* are the two primary means of satisfying these requirements.

Functional relationships are used to account for the use of one or more resources through the use of other resources. The following examples illustrate possible types of functional relationships and how these relationships could be applied to actual resources.

Example 1 - Use of a resource is defined as a function of the use of another resource over time. In this example, the resource Energy is defined in terms of the duration and magnitude of the resource Power.

usage (x) = f(usage(y), time)
Energy = Power x Time

Example 2 - Use of a resource is defined as a percent of the use of another resource. In this example, the resource Avionics Air Cooling is defined in terms of a percent of the resource Power.

usage (x) = f(usage(y), factor)
Avionics Air Cooling = Power x 40%

Example 3 - Use of a resource is defined as the sum of the use of some number of other resources. In this example, the use of power on an electrical bus is defined as the sum of the power used by each of the racks connected to the bus.

usage (x) = f(usage(y_1), usage(y_2), usage(y_3),...,usage(y_n))
Bus power = Rack A Power + Rack B Power + Rack C Power

Modes are somewhat more complicated than functional relationships in that they not only account for the other resources that are used, but also take into account the magnitudes of the resources that are required. Different modes must be defined to account for the different combinations of resources that can be used, as well as to account for differences in the magnitudes of any given resource. The following example illustrates the definition of modes.

Example 4 - A piece of equipment has three operational modes. Each mode requires a particular set of resources, where the magnitudes of the resources may vary from one mode to the next. Table 3.1-I illustrates the definition of modes for this example piece of equipment.

Mode	Power	Data	Samples
Stand-by	100w	0kb	0
Calibrate	500w	100kb	0
Operate	500w	750kb	1

Table 3.1-I: Example of equipment with modes

3.2 REQUIREMENTS MODELING

The requirements modeling function is performed to represent the constraints and support necessary to execute a particular operation. These requirements can typically be categorized into the following areas:

Performance Requirements - Requirements that define the performance window, number of performances, and frequency of performances of an operation to be scheduled.

Resource Requirements - Requirements that specify the magnitude and duration of the resources needed to perform an operation.

Temporal Relationship Requirements - Requirements that specify a timing or sequencing relationship between one or more operations. These include requirements for predecessor, successor, concurrency, and avoidance relationships.

This paper deals only with the specification of Resource Requirements. Collection of requirements for the other categories is out of the scope of this paper.

The concept of explicit and implicit resources provides a very powerful way of simplifying the user's definition of scheduling requirements that fall into the category of resource requirements. Two key components required to support or implement this concept are: 1) Functional Relationships, and 2) Modes. The Functional Relationships and Modes provide a convenient way of defining requirements for one or more resources through the user's requirement for some other resource. In this manner, when a user explicitly defines a requirement for a specific resource, requirements for other resources are implicitly appended via the Functional Relationships and Modes associated with the specified resource. An example might be the user's requirement for a piece of equipment that when operated requires power, heat dissipation, and data resources. Refer to figure 3.2-1 for a pictorial representation of requirements specified in this manner.

The example in figure 3.2-1 illustrates the user's definition of requirements for explicit resources; e.g., the user's requirement for equipment A and equipment B. Modes, which identify the possible operating states, are pre-defined for these two pieces of equipment. The Modes and Functional Relationships provide the links to the complete set of resources required to support the operation of the equipment in the state as specified by the user. It is important to note that the user does not define the modes for a particular piece of equipment, but merely selects from the possible set of modes that were created via the resource definition function. It is also important to note that the user can only define requirements in terms of the resources which have been defined as Explicit Resources; i.e., the user cannot directly specify requirements for resources defined as Implicit Resources.

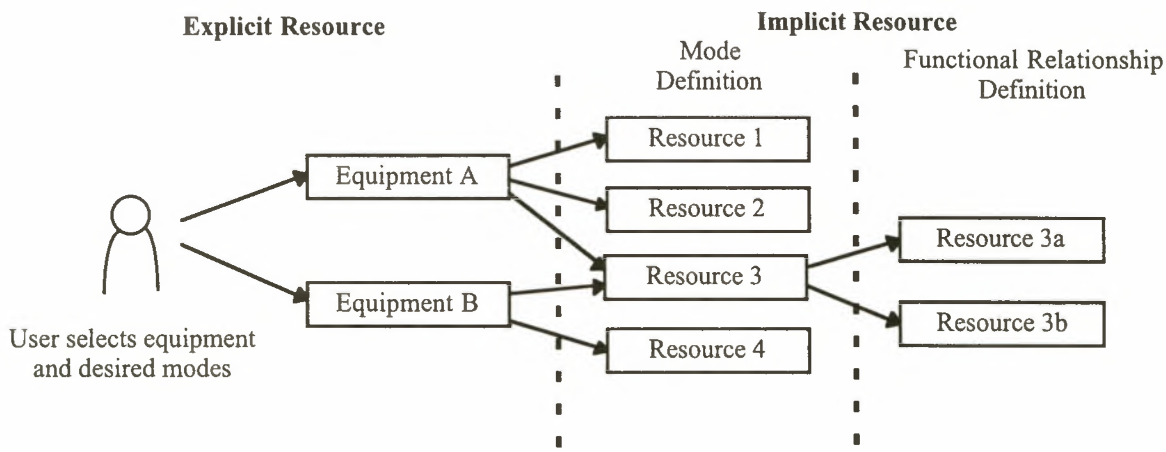

Figure 3.2-1: Requirements specification using explicit and implicit resources

3.3 SCHEDULER FORMATTING

While the resource definition and requirements modeling functions make extensive use of implicit and explicit resources, the scheduling function deals with individual resources and has no knowledge of whether a resource was explicit or implicit in terms of the definition of resources and/or requirements. Therefore, it becomes necessary to take the abstract representations of implicit and explicit resources and convert them into individual and unique resources that can be used by the scheduling engine. Explicit resources that have no associated implicit resources are extracted on a one-to-one basis. Explicit resources that have relationships to one or more implicit resources are extracted on a one-to-many basis.

4.0 EXAMPLE

The following example provides further clarification of the explicit and implicit resource concepts as presented in this paper. References to specific resources and their capabilities are for example purposes only, and should not be considered as official statements of ISS vehicle capabilities, limitations, or implementations.

4.1 EXAMPLE RESOURCE DEFINITION

The Resource Definitions that apply to this example are identified in Table 4.1-I.

Resource Name	Type	Description
Nondepletable Resources		
Total Power	Implicit	Primary power distribution capability
Bus-1, Bus-2	Implicit	Secondary power distribution capability
Rack-1, Rack-2,...,Rack-N	Implicit	Power capability of structures housing payloads
Data	Implicit	Data downlink capability
Crew	Explicit	Number of crewmembers available for operations
Bio Facility	Explicit	Hardware used to support biological operations
Consumable Resources		
Energy	Implicit	Amount of energy available

Table 4.1-I: Example resource definitions

In order to support scheduling, all of the above resources must be defined and utilized in requirements modeling. In the case where explicit and implicit resource capabilities exist, additional resource definition information must be supplied to account for the Modes and Functional Relationships. This information is shown in Table 4.1-II.

Functional Relationship Definition

Total Power = Bus-1 + Bus-2
Bus-1 = Rack-1 + Rack-2 + ... + Rack-N
Energy = (Rack-1 x Duration) + ... + (Rack-N x Duration)

Bio Facility Mode Definition

Mode	Rack Power	Data
1 - Install Sample	100w	10kb
2 - Grow Sample	500w	10kb
3 - Collect Data	525w	1510kb
4 - Remove Sample	100w	10kb

Table 4.1-II: Explicit/Implicit Resource Definition Information

4.2 EXAMPLE REQUIREMENTS MODELING

In this example, a user needs to define requirements to install, grow, and remove a sample in the biology facility. The user determines that the installation procedure takes 30 minutes, the growth procedure takes 20 hours, and the remove procedure takes 1 hour. Figure 4.2-1 illustrates how the user would define these requirements using the explicit and implicit resource concept. It also provides for comparison the larger set of information the user would have to provide if all resources had to be explicitly requested.

With Explicit/Implicit Resources

Install Sample
Duration: 30min
Resources: 1 Crew
Mode 1 Bio Facility

Grow Sample
Duration: 20hrs
Resources: Mode 2 Bio Facility

Remove Sample
Duration: 1hr
Resources: 1 Crew
Mode 4 Bio Facility

Without Explicit/Implicit Resources

Install Sample
Duration: 30min
Resources: 1 Crew
Bio Facility
100w Total Power, Bus-1, & Rack-1
0.05 kwh Energy
10kb Data

Grow Sample
Duration: 20hrs
Resources: Bio Facility
500w Total Power, Bus-1, & Rack-1
10 kwh Energy
10kb Data

Remove Sample
Duration: 1hr
Resources: 1 Crew
Bio Facility
100w Total Power, Bus-1, & Rack-1
0.10 kwh Energy
10kb Data

Figure 4.2-1: Resource requirements modeling with and without explicit/implicit resources

4.3 EXAMPLE SUMMARY

From the simple example illustrated in figure 4.2-1, it is obvious that the use of explicit and implicit resources simplifies the requirements modeling process for the user. The possibility for errors or inconsistent data significantly increases when all resources must be explicitly requested by the user. These errors and/or inconsistencies result from the fact that the user must ensure that all appropriate resources have been requested, and that the values of all related resources are consistent. These problems are alleviated when explicit and implicit resources are utilized, since all of the relationships and interdependencies are accounted for in the definition of the resources.

While the use of explicit and implicit resources simplifies the specification of user requirements, it results in added complexity in the definition of resources. This additional complexity is acceptable since the resource definition function is performed in a controlled fashion by the personnel with the knowledge and expertise of the systems and hardware being defined as resources. The additional complexity is also justified by the fact that these resources are defined early in the planning process, and are only modified when configurations or capabilities change. The burden of this additional work is levied on the experts and, therefore, shielded from the general user community.

5.0 SOFTWARE IMPLEMENTATION

The concept of implicit and explicit resources relies heavily on the development and implementation of capabilities within the ISS planning systems. This work is currently funded by the ISS program and included in the development of the Payload Planning System (PPS). (See reference 2.) The PPS is actually a suite of applications which are being developed to support the distributed planning needs of the general user community, as well as the control center personnel responsible for payload planning product development and integration. The PPS is comprised of six major components, all of which exchange data with one another through a single database. This single database also provides the mechanism for exchanging planning data with the planning systems utilized by the international partners and the systems planning community. The PPS architecture is shown in figure 5-1.

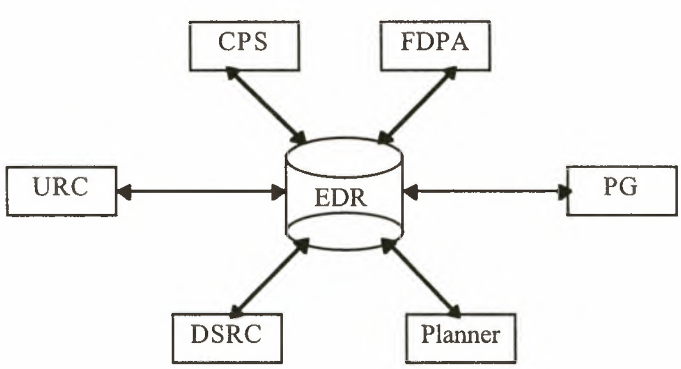

Figure 5-1: PPS architecture

The following are brief descriptions of each of the six components, as well as a description of the database used for the exchange of planning data.

User Requirements Collection (URC) - The URC provides the capabilities required to define resources, collect user requirements, and transform user requirements into the format required for use by other PPS components.

Consolidated Planning System (CPS) - The CPS provides the capabilities required to develop detailed schedules based on the user requirements and resource availabilities. CPS also provides the resource distribution and schedule integration capabilities necessary to support distributed planning.

Planner - The Planner provides the capability to develop high-level plans based on user requirements and projections of resource availabilities. These plans satisfy long-term planning needs and provide guidance and direction to the CPS for use in generating detailed schedules.

Data System Routing and Configuration (DSRC) - The DSRC provides the capabilities required to schedule the routing of data through the onboard systems, and to determine and plan the configurations of the onboard data systems required to support the routing of the data.

Flight Dynamics Planning and Analysis (FDPA) - The FDPA provides the capabilities required to generate and propagate space station and earth-to-orbit vehicle ephemeris data.

Product Generation (PG) - The PG provides the capabilities for the user community and control center personnel to view and print planning data.

External Data Repository (EDR) - The EDR provides the database of approved planning data. This database supports the exchange of data between planning systems, as well as the exchange of data between the components of PPS.

While each component of PPS performs key functions, it is the URC component that performs the functions necessary to implement the concept of implicit and explicit resources as defined in this paper. URC supports the definition of resources, the collection of user requirements, and the transformation of those requirements into the format required for use by the other components of PPS.

6.0 SUMMARY

The implementation of the explicit and implicit resource concept should simplify the requirements modeling process for the user community, while at the same time increasing the confidence and reliability of the data provided. The examples provided within this paper illustrate the manner in which the complexities of the systems can be hidden from the user community. The implementation of these concepts relies heavily on the development of new and better software tools.

7.0 REFERENCES

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PLANNING IN THE CONTINUOUS OPERATIONS ENVIRONMENT OF THE INTERNATIONAL SPACE STATION

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ABSTRACT. The planning processes developed for the International Space Station (ISS) must recognize the fact that the ISS is an on-orbit facility which will operate continuously over its ten to fifteen year lifetime. In effect, the ISS is one "mission" with an extremely long duration. To date, much emphasis has been placed on subdividing the ISS mission into sequential time periods called "increments" in an attempt to apply the planning concepts used for discrete short duration missions to the ISS planning problem. An alternative approach, called *"Continuous Operations Planning"*, has been developed which may provide a more robust and cost-effective method for planning in the continuous operations environment of the ISS. It separates ISS planning into two basic planning functions: 1) long-range planning for a fixed length planning horizon, which continually moves forward as ISS operations progress and emphasizes the preparation for operations; and 2) short-range planning, which takes a small segment of the long-range plan and develops the detailed operations schedules. This paper compares the continuous operations approach with that of the increment-based approach, describes the long and short-range planning functions, and summarizes the benefits and challenges of implementing a continuous operations planning approach for the ISS.

1. INTRODUCTION

The International Space Station (ISS), once its assembly begins, is a continuously operating on-orbit facility which provides the systems, resources, and environment necessary to support scientific and commercial research goals. The ISS is visited periodically by various U.S., Russian, and European Earth-To-Orbit-Vehicles (ETOVs). These ETOV flights support the assembly of the station and provide for the transportation of crew, supplies, and payloads to and from the ISS. Onboard systems and payloads, once put in place, will operate for months or years. Over the lifetime of the station, new components will be added, onboard systems will be upgraded, payloads and crew will be changed out, ground facilities will be reconfigured, ETOVs will come and go, and onboard hardware will occasionally fail. The ongoing ISS operations will adapt to these changes and continue on.

The ISS planning processes should recognize the fact that the ISS is a continuously operating facility with a ten to fifteen year lifetime. In effect, the ISS is one "mission" with an extremely long duration. Therefore, planning techniques which are used in other continuous operations environments should be investigated for potential applicability to the ISS planning problem. Examples of other continuously operating space vehicles include the manned Russian MIR space station, and various unmanned space vehicles. However, unlike the ISS, the unmanned vehicles do not have to deal with periodic ETOV resupply/assembly flights or with the unique considerations of the onboard crew. Examples of non-space environments in which a facility operates continuously with periodic resupply and/or reconfiguration include: factories, retail establishments, naval operations (submarines, aircraft carriers, etc.), and hospitals. Some might argue that the planning processes for these non-space environments cannot be directly applied to space operations planning because the complex nature of space operations dictates some unique planning constraints and considerations. This is of course true to some extent. However, some of the basic concepts can and do apply; for example, the need to perform long-range, high level planning in support of operations preparation, as well as short-range, detailed planning in support of operations execution.

Because manned space operations have typically revolved around discrete, limited duration "missions", the space community has attempted from the beginning to force fit this "mission" paradigm into the ISS program rather than develop a new paradigm more appropriate for a continuously operating space station. There are several reasons for this. First, the processes for performing mission integration and preparation, crew training, and planning are well established and understood by the space community. Second, in the early years of the ISS program, most of the on-orbit activity is focused on the assembly of the station, which occurs primarily during ETOV flights to the ISS vehicle. Because of this early emphasis on the assembly flights, the current ISS processes for operations planning and preparation tend to be designed around individual "missions".

In order to create discrete ISS missions, current concepts call for ISS operations to be divided into sequential time periods called "increments". An increment is defined as the period of time between designated ETOV flights to the ISS, as illustrated in Figure 1. Typically, the particular ETOV flights which define a new increment are those which result in a changeout of the onboard crew. Therefore, it is possible that a single increment may include multiple ETOV flights, each of which can result in changes to the ISS configuration, system capabilities, and onboard payload complement. This division of station system and payload operations into segmented time periods based on the arrival of designated ETOV flights is called "*Increment Operations*". In effect, each increment is treated as a discrete mission for planning purposes.

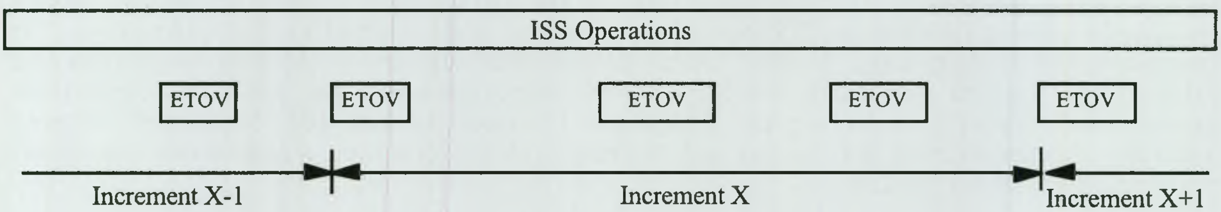

Figure 1. Typical ISS "Increment" based on designated ETOV flights

This paper offers for consideration an alternative planning approach, designed around the fact that the ISS is one continuous, ongoing mission, not a series of consecutive, independent missions (increments). This non-segmented approach to the planning and operation of systems and payloads onboard the ISS is known as "*Continuous Operations*", and has the potential of greatly simplifying the planning process and reducing operations costs during the mature phase of the ISS program. The remainder of this paper compares the concepts of increment-based planning and continuous operations planning, and discusses the benefits and challenges associated with implementing a continuous operations planning approach for the International Space Station.

2. INCREMENT-BASED PLANNING APPROACH

In the ISS program, on-orbit operations planning must be performed both for the ISS vehicle and for the various earth-to-orbit vehicles which visit the ISS. This results in several independent, yet interrelated planning functions:

<u>ETOV planning</u> addresses the operations on the earth-to-orbit vehicle during the periods en route to/from the ISS as well as the ISS-attached period. Each nation's ETOV program already has its own unique, well-established planning processes and templates.

<u>ISS planning</u> addresses the ongoing operations onboard the ISS. It is performed by the ISS planning organizations and will follow the independent ISS planning templates and processes.

Joint operations planning addresses the time periods when an ETOV is docked at the space station. This requires significant coordination between the ISS and ETOV planning organizations.

2.1 ISS INCREMENT-BASED PLANNING TEMPLATE

With the increment-based planning approach, ISS on-orbit operations plans are produced long in advance for each and every defined increment. The increment operations planning template for an individual increment, as depicted in Figure 2, begins 18 months prior to the start of the increment (I-18). The Preliminary, Basic, and Final versions of the Increment Operations Plan (IOP) are developed and released at I-12, I-6, and I-2 months, respectively. The IOP contains high level plans for the entire increment, along with detailed operations schedules for the ETOV-attached periods, showing planned activities onboard both the ISS and the ETOV. Detailed schedule development for ISS operational periods between the ETOV flights is performed on a weekly basis during the increment; that is, the schedule for a given week of ISS operations is generated only one week prior to its execution. In addition to developing the next week's detailed schedule, the weekly planning process also maintains and updates the high level plan describing the operations to occur during the remainder of the increment.

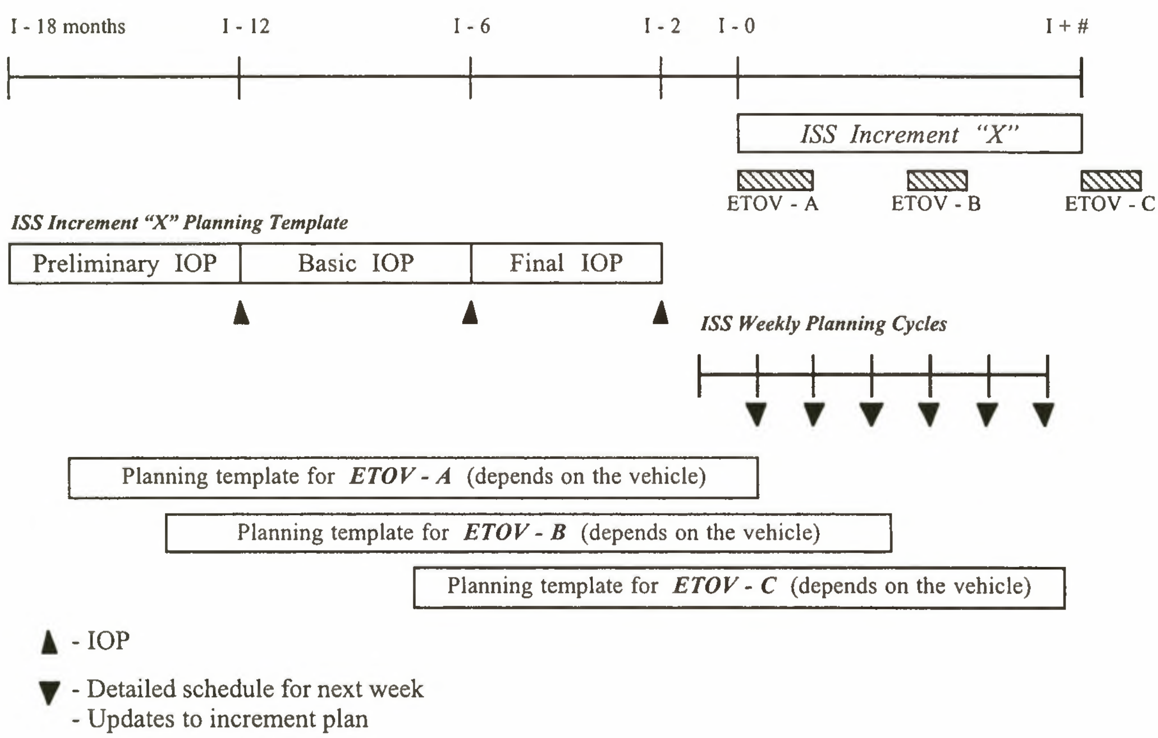

Figure 2. ISS increment-based planning template

2.2 PROBLEMS INHERENT IN THE INCREMENT-BASED APPROACH

With a typical increment duration of from one to three months, it is obvious that there will be significant overlap of the increment planning templates, with planning for multiple increments being performed simultaneously. This overlap of templates introduces several complications. First and foremost, planning personnel must be assigned to support each increment's planning template. This may not be desirable or even possible in today's tight budget environment.

Second, there is the possibility of discrepancies between the Increment Operations Plans for the various increments. Because the specific operations planned for one increment may significantly affect the planning for all subsequent increments, and because each increment is planned independently (and concurrently, given the overlapping templates), the probability of inconsistencies being introduced between the multiple increment plans is quite high. The process is further complicated by the fact that ISS operations continue during the two month gap between the release of the Final IOP and the start of the increment.

Also, in order to reflect in the IOP the planned joint operations during the ETOV-attached phase, the planning for the joint ISS/ETOV operations must occur at appropriate points within the ISS planning template. This joint operations planning requires the support of both the ISS and ETOV planning organizations. However, there is no guarantee that the ETOV planning templates will line up sufficiently with the ISS templates to allow this to happen, as is effectively illustrated in Figure 2. Because each ETOV flight may have a different planning template, tied to its specific launch date, and because there may be multiple ETOV flights within a particular increment, there will likely be major disconnects between the ETOV planning templates and the ISS increment planning template. In fact, many of these disconnects are becoming readily apparent as we get closer to the actual start of ISS operations, not only in the operations planning templates, but also in the templates for crew training, simulations, increment and ETOV flight reviews, etc.

3. CONTINUOUS OPERATIONS PLANNING APPROACH

The continuous operations planning approach, on the other hand, is designed around the fact that the International Space Station is one continuous ongoing mission, not a series of consecutive, independent missions (increments). Because no planning is performed for individual "increments", many of the problems inherent in the increment-based, segmented planning approach are avoided.

The continuous operations approach recognizes the need to perform: (1) *long-range, high level planning* in support of execution preparation, as well as (2) *short-range, detailed planning* (schedule development) in support of realtime operations execution. Long-range planning is required to provide some reasonable assurance that the long term goals of the ISS payloads and systems can be satisfied over time within the known constraints. It also provides a feasible prediction of expected onboard activities so that payload users, ground controllers, program management, and others can make the necessary preparations to support them. This approach also recognizes the fact that in a continuous operations environment, detailed operations schedules should not be developed far in advance because unexpected events, updated orbital predictions and resource availabilities, and changes in scheduling requirements resulting from the ongoing systems and science operations need to be factored into the scheduling process. (See Reference #1 for a more in-depth discussion of long-range vs. short-range planning.)

3.1 ISS CONTINUOUS OPERATIONS PLANNING TEMPLATE

With the increment-based planning approach, long-range, high level planning is performed primarily during the 18 month IOP development process, and detailed schedule development for the ongoing ISS operations is performed primarily during the weekly planning process. In contrast, with the continuous operations planning approach, both functions are performed exclusively as part of the weekly planning process.

With this approach, long-range planning is performed for a fixed length planning horizon, which continually moves forward as ISS operations progress. This planning horizon can be of any duration, from a few weeks to several months, as deemed appropriate to meet the needs of the ISS program. The long-range plan basically defines those payload and system activities which will likely be scheduled during the upcoming weeks of ISS operations in order to satisfy the long term station goals. A big advantage of the continuous operations approach is that instead of having multiple long-range plans (one for each increment) in development at any point in time, there is a single, consistent plan for use by all participants in the ISS program.

The short-range planning function develops the detailed schedule for a specific one-week segment of the long-range plan. As in the increment-based approach, this detailed schedule is generated only one week prior to its execution. As each given week is scheduled and executed, it will be dropped from the long-range plan, and a new week will be added to the end of the plan. Refer to Figure 3 for a graphical depiction of this continuous operations planning template.

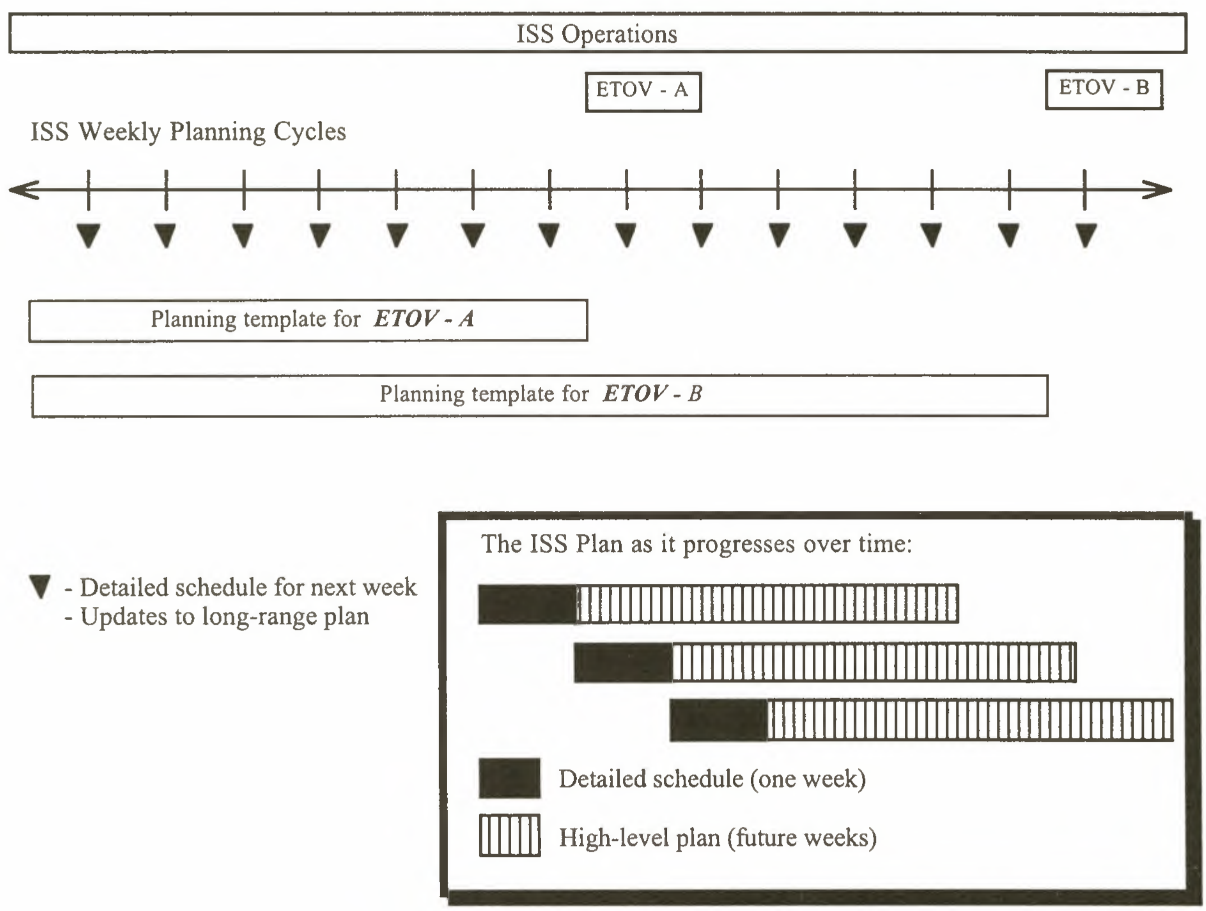

Figure 3. ISS Continuous Operations Planning Template

3.2 ETOV AND JOINT OPERATIONS PLANNING

To eliminate the problems caused by disconnects between the ISS and ETOV planning templates, the ISS planning must be decoupled from the ETOV planning processes to the maximum extent possible. This does not mean that there will be no coordination between the ETOV and ISS planning organizations for development of the attached-phase joint operations plans. Rather, it means that primary responsibility for the planning of the joint ISS/ETOV operations must be assigned to either the ISS planning function or the ETOV planning function. For several reasons, it is more appropriate to plan the joint operations according to the ETOV planning processes and templates. First, most joint activities are either assembly or resupply operations which are heavily focused around the ETOV vehicle. Second, the ETOV planning will occur much earlier than the

ISS planning if following the ISS continuous operations planning template. The operational goals outlined in the ISS long-range plan can be considered in the development of the detailed ISS/ETOV joint operations plans. These ISS/ETOV joint operations plans, once established, can then be folded into the ongoing ISS planning through the long-range and short-range planning functions described above.

4. BENEFITS OF CONTINUOUS OPERATIONS PLANNING

A continuous operations planning approach would provide a number of valuable benefits if adopted for the International Space Station program. It would do the following:

- Streamline the ISS planning process, eliminating overlapping planning cycles.
- Prevent discrepancies between multiple, independently-developed increment planning products by providing a single, consistent long-range plan for use across the ISS program.
- Reduce the manpower/resources required to plan ISS operations. Note that this is a significant savings for the National Aeronautics and Space Administration, the other ISS International Partners, and the individual payload users since all are actively involved in the distributed planning process for the ISS (see Reference #2).
- Focus the attention of ISS operations personnel on the ongoing on-orbit operations, where it ought to be, instead of on concurrent planning for a multitude of future increments.
- Allow the payload users to concentrate on the realtime execution and near term planning of their experiments rather than on the planning for increments which are months or years away. In the long run, this may result in better science return.
- Decouple ISS planning from ETOV planning to the extent possible. This would alleviate the planning template disconnects between ISS and ETOV flights caused by the inclusion of multiple ETOV flights within a single increment.

In addition, if the continuous operations planning approach is implemented for ISS, the concept of "increments" could potentially go away altogether since they would no longer be needed for planning purposes. The elimination of increments could reduce the complexity and costs of the ISS program by eliminating the need for increment-specific planning, requirements, documentation, and reviews. Other processes which are currently being driven to support increment preparation schedules and reviews could instead be linked to more natural and appropriate events. For example, since new payloads, onboard systems, and ground facilities may be introduced by an ETOV mission in the middle of an increment, templates for crew training, ISS hardware delivery/integration/return, simulations, and ground control facility additions/upgrades should, in reality, be tied to specific ETOV launches rather than to the start of an ISS increment.

5. IMPLEMENTATION CHALLENGES

This paper proposes an alternative planning approach which makes sense in the continuous operations environment of the International Space Station and has tangible benefits to the ISS program and its customers. There are, however, several obstacles which must be overcome to successfully implement the continuous operations planning approach.

5.1 SELLING THE IDEA

The most difficult challenge will be in overcoming the "mission" mindset which is inherent within the space operations community. "Increments", which represent discrete ISS missions to many people, have been around for years, and are firmly ingrained in the ISS program, even though the definition of "increment" has changed significantly as the ISS program has matured. To overcome this mindset, the advantages of switching to a continuous operations paradigm will have to be clear cut, technically and financially quantifiable, and overwhelming. A full commitment by all affected parties is required to effectively implement the concept.

5.2 RE-ENGINEERING THE ISS PROGRAM

To some extent, the ISS program must be re-engineered to implement continuous operations. Current ISS processes, templates, program requirements documents, and even organizational structures, are designed to support increment operations. New processes must be developed, negotiated, and documented for the continuous operations planning approach. Resistance to change, inertia, and political forces could make this re-engineering effort quite difficult.

The program must decide early on if the concept of "increments" must be retained for purposes other than operations planning, or if the complete benefits of the continuous operations approach can be realized by doing away with increments altogether. For example, increments are currently being used as a time period over which resources are allocated and requirements are applied. If increments were to go away, other schemes would have to be developed for allocating resources over time and for reporting the satisfaction of ISS requirements and goals. One possibility might be to borrow a technique from industry and track ISS resources and goals on a yearly/quarterly basis; for example, allocate resources on a yearly basis, and report resource usage and goals attainment on a quarterly basis (i.e., quarterly reports).

A partial implementation of the continuous operations approach might also be considered in which increments are retained for program management purposes (allocations, goals), but not for operations planning purposes. Operations planning would follow the templates outlined in Section 3 of this paper. This hybrid approach would yield many of the benefits of continuous operations planning, but might also be a constant source of confusion.

5.3 PROVIDING FOR A SMOOTH TRANSITION

Today, the "*Increment Operations*" paradigm is firmly established in the ISS program, and processes and personnel are already being set in place to support increment-specific planning for the early increments. Even if the "*Continuous Operations*" paradigm were to be adopted for ISS, it would be some time before the specific planning processes could be developed, negotiated, and implemented across the ISS program. Therefore, it is likely that planning would have to begin using an increment-based approach and transition at some point to the continuous operations approach.

A transition plan would have to be established early, and formalized in the official ISS program requirements documents, to facilitate a smooth transition from one planning mode to the other. Of course, there is a real danger that once the ISS program begins operations in the increment mode, some participants will be resistant to making the final transition to continuous operations. Because of this, the transition should occur as early as possible. In addition, to help mitigate this risk, selected portions of the concept might be gradually incorporated into the increment-based planning approach. This would provide for a smoother transition, and would help to practically demonstrate the benefits of adopting the continuous operations planning approach for the International Space Station.

6. REFERENCES

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INTERNATIONAL SPACE STATION(ISS)/COLUMBUS STRATEGIC AND TACTICAL PLANNING SUPPORT TOOLS PROTOTYPE

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ABSTRACT. The paper describes the results of the project "Strategic and Tactical Planning Support Tools Prototypes", conducted by SSI for ESA. It first presents an overview of the planning process as it is being developed for the ISS. Then, the prototypes of two Strategic and Tactical Planning support tools are described. The first prototype allows a what-if assignment of resources per year to the individual European level 1 payloads, starting from initial allocations. It allows different planning scenarios to be maintained in parallel, of which one can be selected as baseline for a particular year. The resources associated with a baselined scenario can be exported as files in different formats. The second prototype investigates the implementation of a World Wide Web (WWW) front-end to the planning databases, to minimize the efforts needed to compile user inputs to the planning process, and to provide a simple way of distributing the results of the planning process to the user community at large.

1. INTERNATIONAL SPACE STATION PLANNING PROCESS

The planning process adopted for the International Space Station is a multi-layered approach with progressive detail and complexity in the individual layers. The planning process has both a multi-lateral contents, and a partner-specific one. The results of the most recent developments in the definition of the Space Station planning process are listed below.

The multi-increment planning is the beginning of the planning process. It deals with transportation system planning and the maintenance of the overall Space Station capabilities. The main outputs of this process are the Multi-Increment Manifest (MIM), and the Operations Summary (OS). The MIM identifies the up- and down-load transportation support to the Space Station for crew support, maintenance and logistics, utilization, and consumable resupply. The OS summarizes the capabilities of the Space Station over the years to come, based on the MIM and other supporting services, and the accommodation capabilities of the Space Station.

The OS and MIM are used by strategic planners to provide long-range, high level direction and guidance for Space Station operations and utilization. They formally establish and control ISS resource capabilities and allocations, approved payload lists, increment start and end dates, servicing and resupply schedule, and Earth To Orbit (ETO) vehicle cargo manifests. The strategic planning process results are documented in the annually published Consolidated Operations and Utilization Plan (COUP), which normally covers the upcoming 5 strategic planning periods.

The COUP drives the tactical planning process which deals with the management of critical activities and resources necessary to plan and implement the operations, utilization and maintenance of the Space Station. It refines and integrates the definition and requirements for a specific increment. (An increment is defined as the period between two designated ETO vehicle visits.) The main results of this process are the Increment Definition and Requirements Documents (IDRDs), which contain the objectives, requirements, and allocations for each of the increments, and the On-obit Operations Summary (OOS) which assigns system and payload operations activities to individual periods of nominally a week.

The final step in the planning process is to prepare the planning products needed to conduct Space Station real time operations. The principal output of this step is the short term plan, from which are derived the ISS On-board Short Term Plan (O-STP), the COF Master TimeLine (MTL), the crew activity plan, the various ground activity plans, and the resource allocation plan. The O-STP and MTL are time ordered sequences of commands/automated-procedures which are uplinked to the Space Station and executed automatically by the appropriate on-board systems.

ESA's involvement in the Space Station has changed significantly over the last several years and now also includes the provision of space transportation services (through the ATV). Within the context of the ISS programme, ESA will be responsible for performing element-related planning activities in Europe as part of the overall ISS planning process, as well as participate in the relevant multi-lateral planning teams residing at JSC and MSFC. To ensure effective long and medium range management of ESA's involvement in the Space Station programme, tools will have to be developed to support the strategic and tactical activities.

2. STRATEGIC AND TACTICAL PLANNING SUPPORT TOOL PROTOTYPE

A candidate tool identified to support ESA's planning activities is the Strategic and Tactical Planning support Tool (STPT). The purpose of the STPT is to help ESA's strategic and tactical planners during the planning process by providing the following functionality: access to databases relevant to the planning process; import of strategic and tactical parameters; "what-if" assignment of resources; electronic exchange of data with related applications. The subset of the STPT functionality implemented in the current STPT prototype is described in the following.

The STPT prototype runs on an IBM-compatible PC running Microsoft Windows version 3.1 or later. The STPT prototype has been developed using the Visual Basic tool version 3.0. The STPT prototype uses a database to store data, based on Microsoft Access Database Management System version 1.10, which is the native format for data storing in Visual Basic. The prototype can be used in a multi-user environment if a shareable network drive is available, on which the prototype executable file, the report files, and the database file have to reside.

Four types of users of the current STPT prototype have been defined: strategic utilization user, strategic system user, strategic generic user, and tactical user.

The strategic utilization user is the only one authorised to insert payload strategic parameters, while the strategic system user is the only one authorised to insert system strategic parameters. The strategic generic user cannot insert neither of the strategic parameters. These are the only differences existing in the way the prototype can be used by the different strategic users. All the other strategic functions provided by the STPT prototype are accessible by all the categories of strategic users.

Since the current STPT prototype does not implement any of the tactical planning functions, the only task the tactical user can perform up to now is the inspection of the CPDB data and viewing the ISSA capabilities and strategic assignments.

Once the user has started the prototype, the window shown in figure 1 is displayed, which is the prototype main window. This window shows three distinct frames, one for each of the main tasks the users can perform: Inspect Data Bases; Insert/Review Strategic Data; Assign Operation Activities.

The upper left frame of the main window, entitled "Inspect Data Bases", contains 6 icons representing the following databases: User Mission Data Base (UMDB), Strategic Planning Tool Data Base (SPT DB), Columbus Payload Data Base (CPDB), Tactical Planning System Data Base (TPS DB), On-orbit Operations Summary Data Base (OOS DB), .. (place holder).

The only database accessible for inspection through the prototype is the CPDB. It has been implemented as a full read-only access to data exported from the CPDB. The logic implemented to access the CPDB data follows as far as possible the logic implemented in the original CPDB application. The access to the other databases mentioned, all of which are NASA databases, has not been implemented in the prototype since their structure was being defined or modified at the time of the prototype implementation.

The upper right frame of the main window, entitled "Insert/Review Strategic Data", allows the user to perform yearly assignment of resources to overall system and utilization. It contains the following two command buttons: ISSA Capabilities and Strategic Parameters. The "ISSA Capabilities" button allows the user to edit/view the total capabilities provided by the ISSA and the supporting services for each year for all the partners and at partner level. The "Strategic Parameters" button allows the user to edit/view the system and payload strategic parameters.

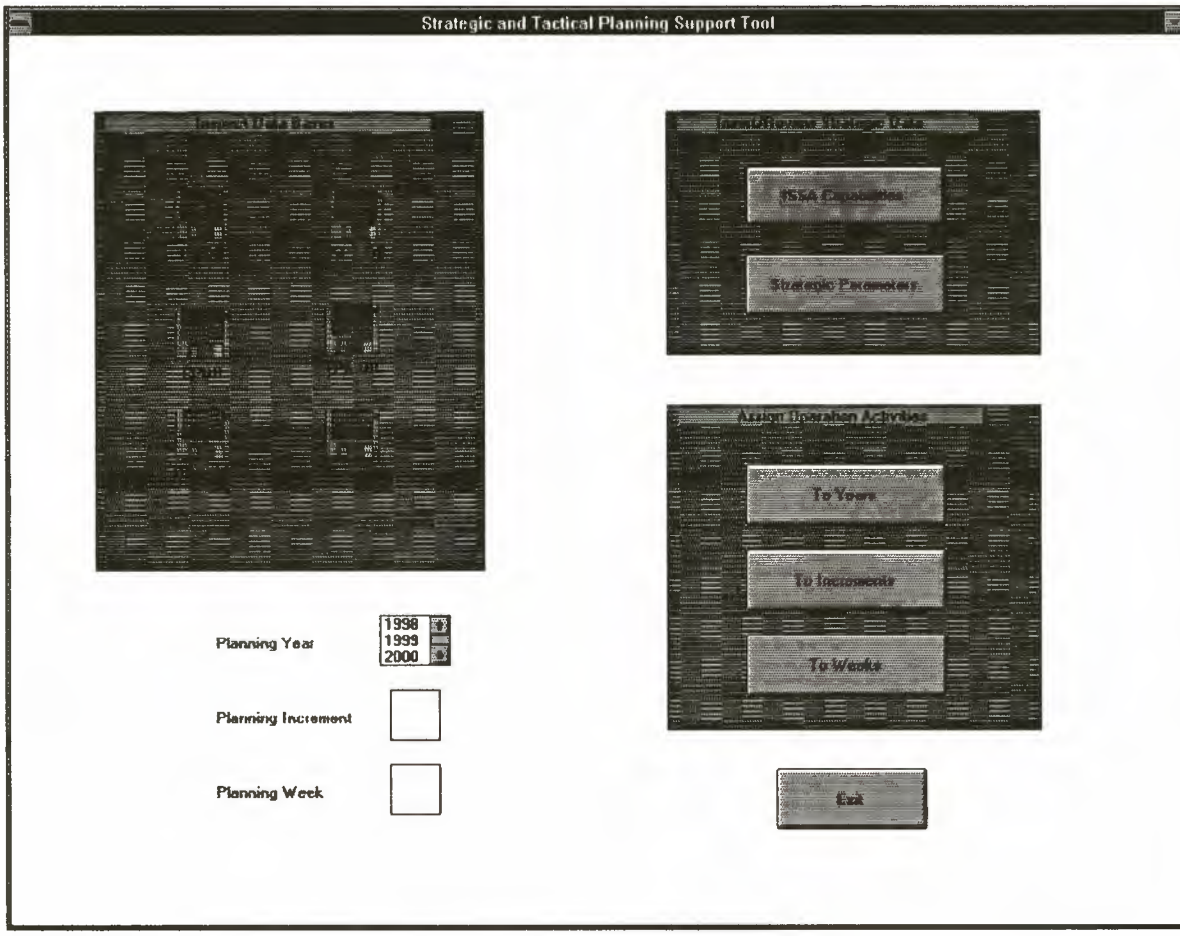

Figure 1. STPT Prototype Main Window

The lower right frame of the main window, entitled "Assign Operation Activities", allows the user to perform "what-if" assignment of resources to individual European facilities, starting from an initial allocation. Different scenarios can be created and maintained in parallel for the same period. The assignment of resources to increments and weeks has not been implemented in the current prototype.

To assign operations activities to years, the user must select a planning year and click the "To Year" command button in order to bring up the window shown in figure 2.

The frame in the right part of the window shows for each of the listed resources a bar with the related amount available for utilization, and a bar with the related amount required by all the payloads. The colour of the bars representing the resources required by the payloads changes from green (the percentage of the resource used by the payloads is less than 80% of the available resource) to pink (the percentage of the resource used by the payloads is between 80% and 100% of the available resource) up to red (the percentage of the resource used by the payloads is more than 100% of the available resource). The seven command buttons displayed on the window allow the user to perform the following functions:

New Scenario, to create a new scenario. The resources associated to the payloads when a new scenario is created are based on the initial allocation of resources to payloads defined by the payload strategic parameters. The resources required by a European payload can be viewed/edited by clicking the related picture. Figure 3 shows the Biolab Resource Requirements window. The user can change all the editable parameters. The parameters which are not editable are derived parameters. If the changes made to the parameters are saved, the contents of the frame in the right part of the window will be updated to reflect the new values of the resources allocated to the payloads.
The resource requirements windows for the other European payloads contain similar parameters which can be changed in the same way as for the Biolab payload.

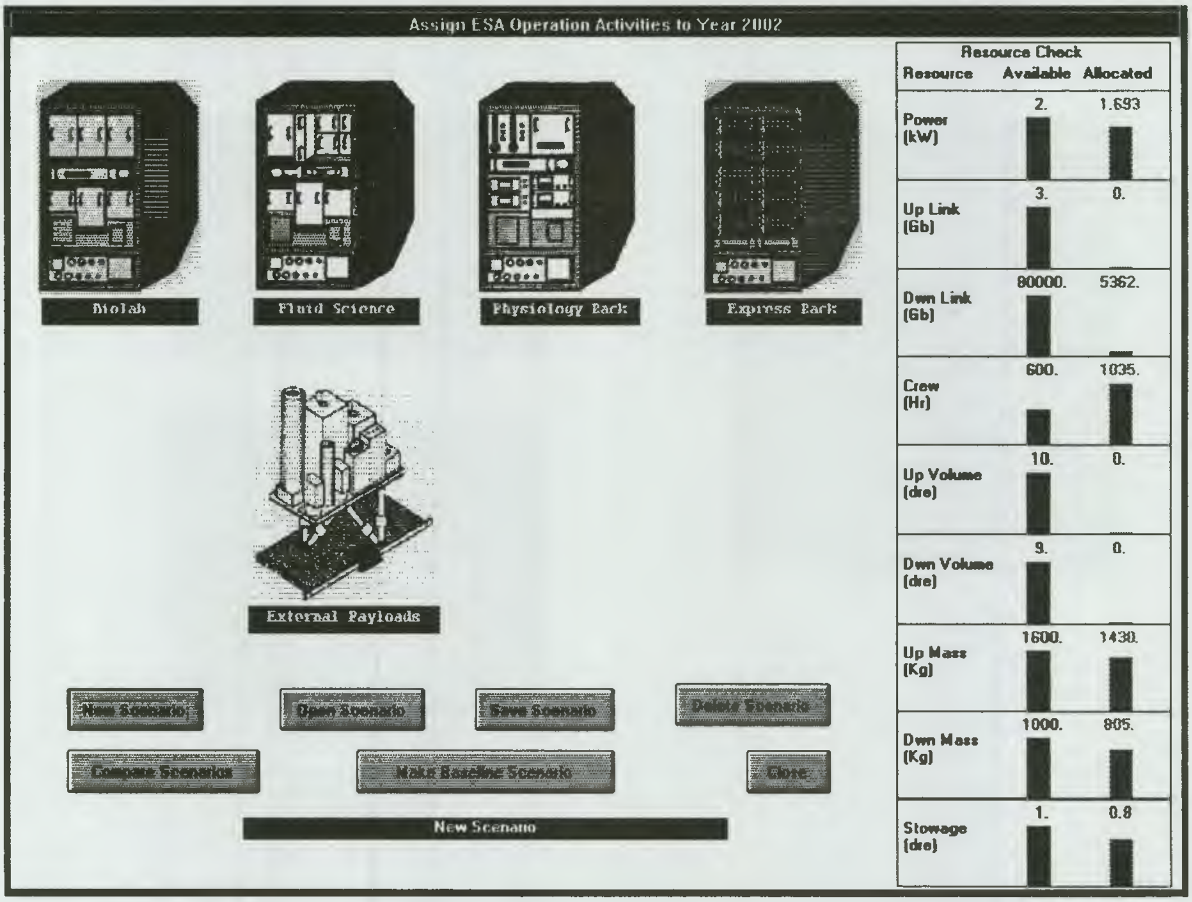

Figure 2. Assign ESA Operation Activities to Year

Open Scenario, to open an existing scenario.

Save Scenario, to save the current scenario.

Delete Scenario, to delete the current scenario.

Compare Scenarios, to compare the resources required by the defined scenarios.

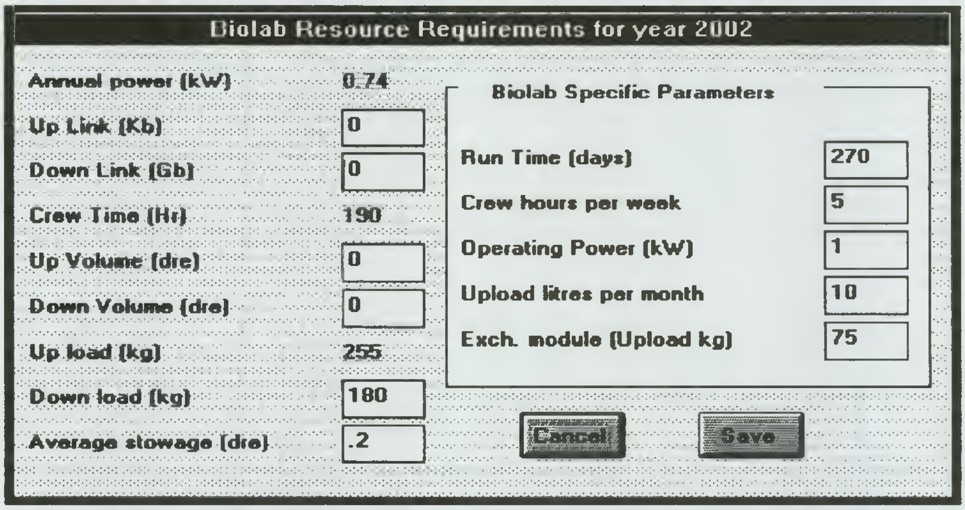

Figure 3. Biolab Resource Requirements for year 2002

At any time, the user can compare the resources allocated to the scenarios against the available resources for the planning year, to determine which scenario is most effective within the constraints of the available resources. One resource at a time can be compared, or all the resources at once.

Figure 4 shows the resource checks window for the absolute value of all the resources. It contains for each resource a bar with a label indicating the available value, and a bar with a label for each selected scenario indicating the value of the resources allocated to the payloads in the scenario.

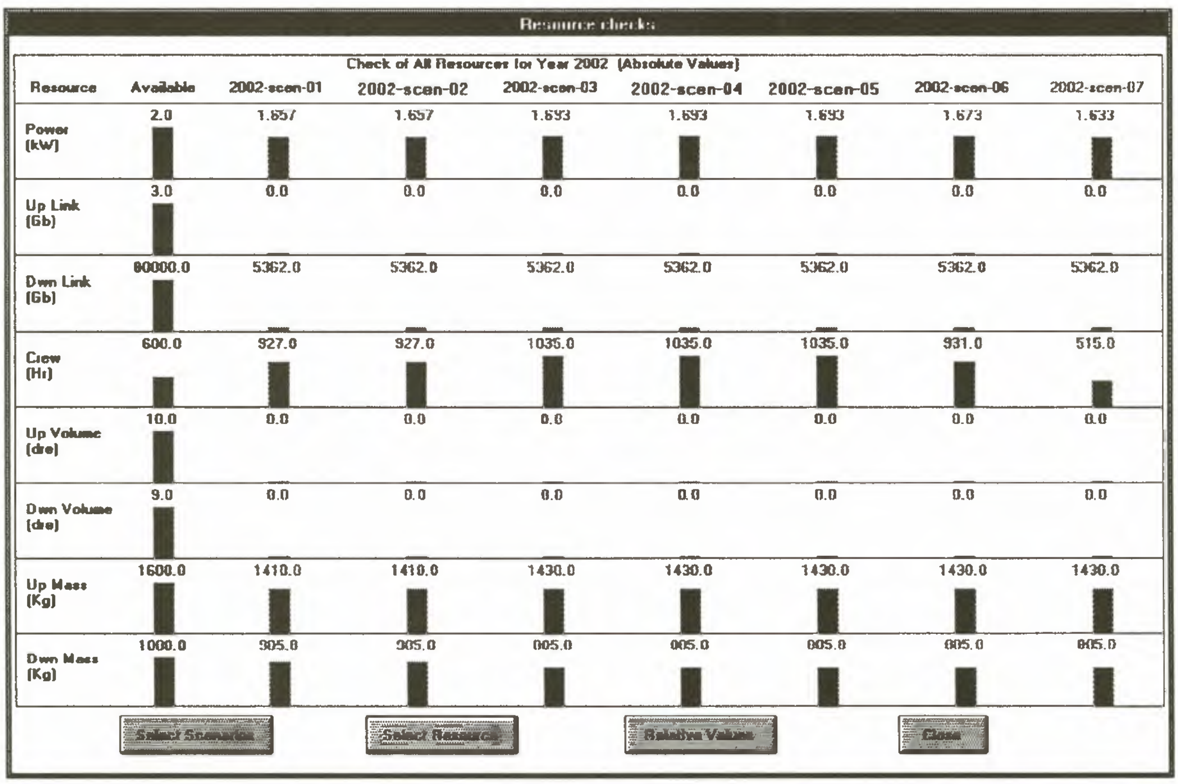

Figure 4. Resource Checks - All Resources, Absolute Values

Make Baseline Scenario, to make a scenario the baseline scenario. Once various scenarios for a planning year have been defined and analyzed, a scenario can be set as the baseline scenario. When baselining a scenario, two sets of data can be exported: information to be included into the ESA Partner Utilization Plan (PUP), and payload strategic parameters. Data for the ESA PUP can be exported in various file formats. Payload strategic parameters, related to the scenario being baselined, are exported in a format which can be imported into the User Mission Data Base (UMDB).

Close, to close the window

3. MISSION MANAGEMENT SUPPORT TOOL WWW FRONT-END

The MMST WWW front-end is aimed at providing both the user community and the ESA planning staff with a user friendly mechanism to view, enter, and maintain the information in the planning databases.

The MMST WWW front-end will collect input data for the STPT tool, and will obtain from the STPT tool the payload resource assignments to be displayed to the user community. The STPT tool and the MMST WWW front-end will eventually access the same set of databases, eliminating the need of data import and export mechanisms between the tools. The WWW service is established on an Apple server running WebSTAR server software. The WWW front-end has been developed by using the tools Tango and Butler. Tango is a full-featured visual development tool that integrates the WWW server with a SQL database system. Butler is a client-server relational SQL database which contains the data used by the application.

Figure 5 shows the main menu of the WWW front-end as implemented in the second prototype.

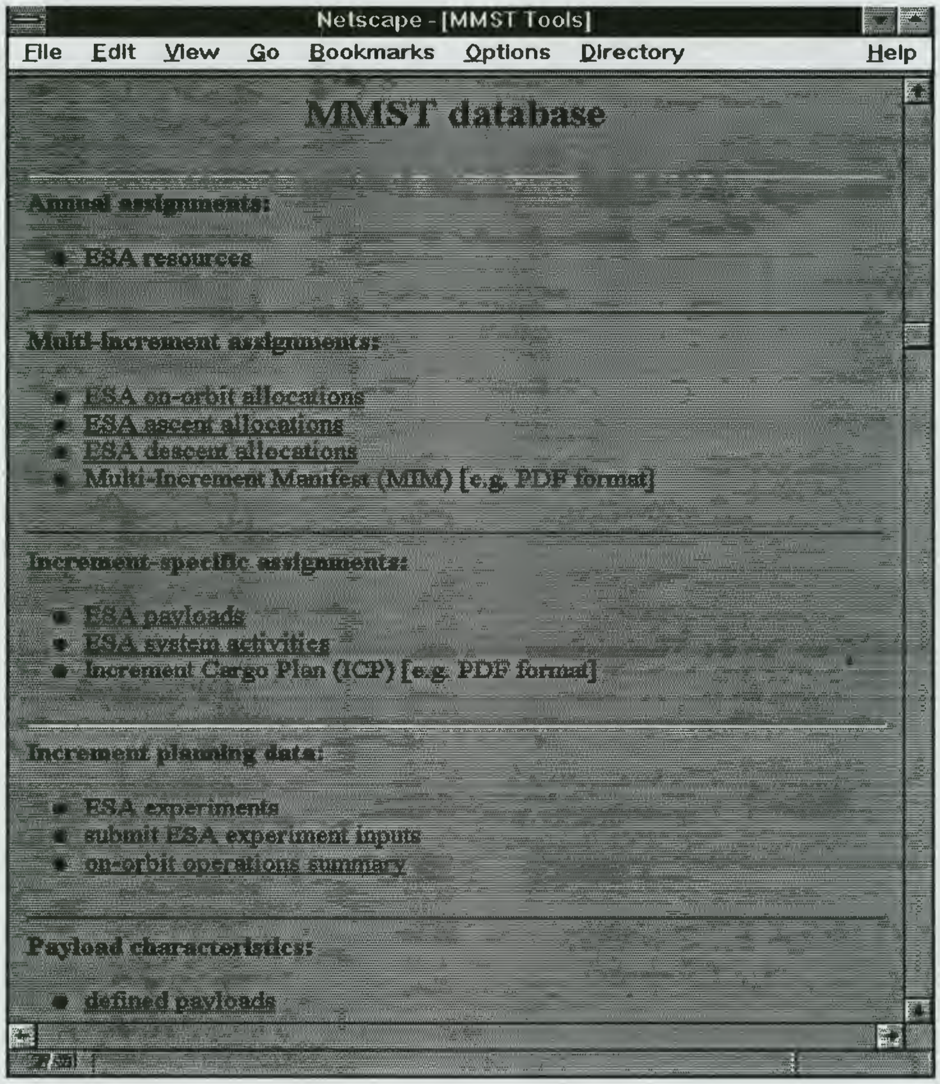

Figure 5. MMST WWW front-end main menu

The following four categories of users have been defined: user community, which has a read-only access to all the payload and system data; payload administrator, appointed by the agency, which is the only user allowed to enter and maintain the payload data; system administrator, appointed by the agency, which is the only user allowed to enter and maintain the system data; database administrator, appointed by the agency, which performs maintenance of the database.

The various users perform different tasks through the WWW front-end, and, as such, need to have different views of and access rights to the same information. For this reason, the WWW front-end main menu contains items which are visible to all the users and items which are visible only to a particular category of users. The menu shown in figure 5 is the WWW front-end main menu available to the user community. The main menu reserved to the payload administrator contains the same items shown in figure 5 plus some items which allow the creation and maintenance of payload data. The main menu reserved to the system administrator contains the same items shown in figure 5 plus some items which allow the creation and maintenance of system data. The main menu reserved to the database administrator contains links to the main database tables to allow the maintenance of the database itself.

The main menu lists some items which are plain text and, thus, are not linked to any information. These items have been included in the main menu only to present the complete layout of the final MMST WWW front-end. In fact, currently, only the tactical part of the MMST WWW front-end has been implemented.

The multi-increment assignments contain the ESA allocations for ascent, descent and on-orbit phases. The increment-specific assignments are related to payloads and system activities requirements at increment level. Figure 6 shows the increment specific requirements for the payload EA999.99P related to the increment number 0002. To view the specific requirements the user must click the related "X". The "0" means that the related requirements have not been entered yet.

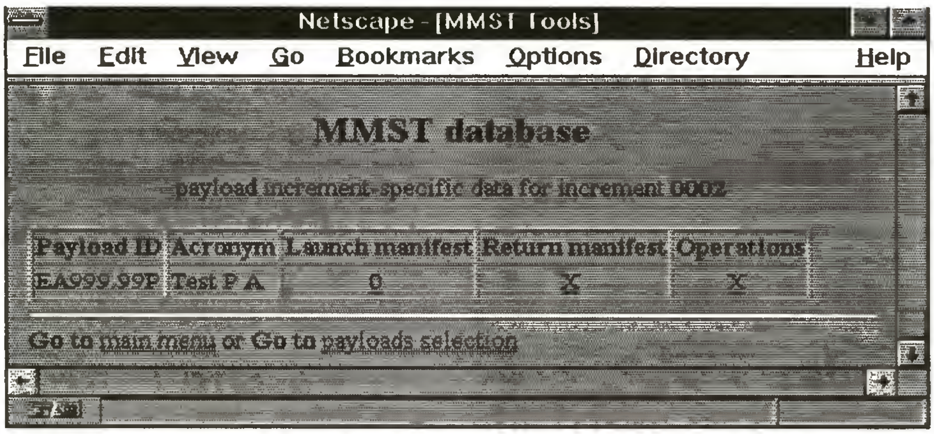

Figure 6. Payload increment-specific requirement window

The system activities require system items in order to accomplish their objective (e.g., the activity "replace a battery" needs the item "battery"). Both the system activities and the associated items have increment-specific requirements. Figure 7 shows the selected system activities and the number of items associated to them. To view the system activity requirements the user must click the related "Activity ID". To view the item requirements the user must click the related "Associated items".

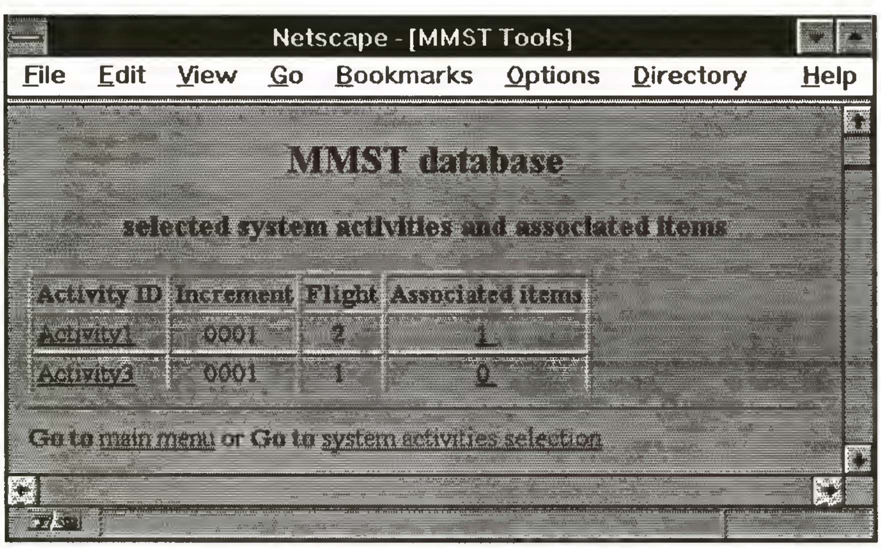

Figure 7. System activities and associated items window

The payload characteristics contain information which is not specific to the increment, such as payload cover information; information related to the payload point of contact; payload overview information; and on-orbit placement information. Figure 8 shows the characteristics for the selected payloads. To view the specific requirements the user must click the related "X" or the related "number". A number appears instead of the "X" for the contact and the on-orbit placement information. For the contact information, the number indicates how many point of contacts have been defined for the payload. For the on-orbit placement information, the number indicates how many racks are required to accommodate the payload on board. A "0" means that the related information has not been entered yet.

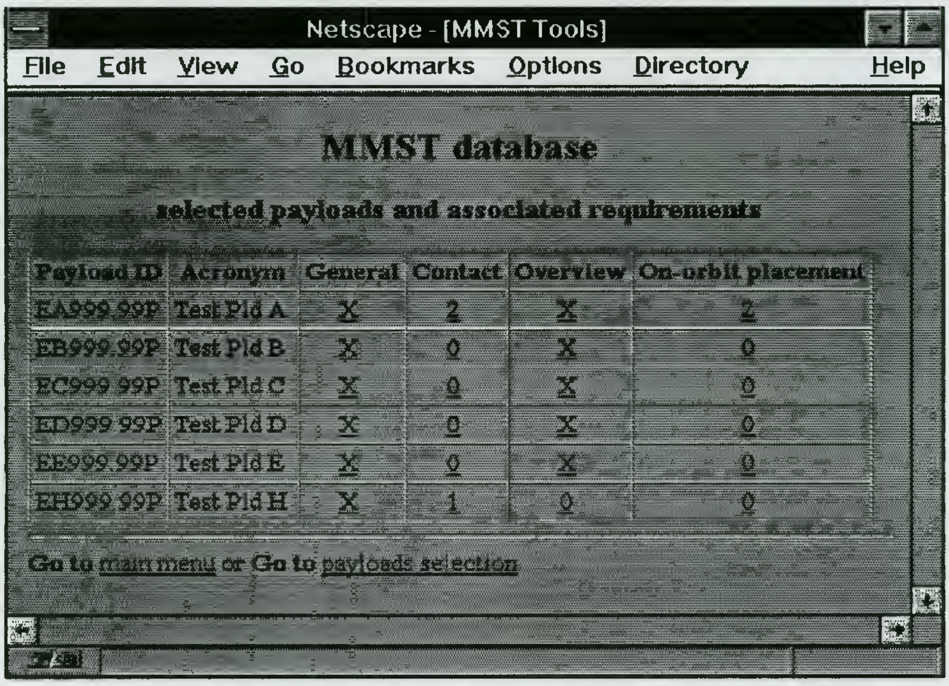

Figure 8. Payload characteristics window

EXACT AND INEXACT METHODS FOR THE DAILY MANAGEMENT OF AN EARTH OBSERVATION SATELLITE

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ABSTRACT. The daily management of an observation satellite like *Spot*, which consists in deciding every day what photographs will be attempted the next day, is of a great economical importance. But it is a large and difficult combinatorial optimization problem, for which efficient search methods have to be built and assessed. In this paper we describe the problem in the framework of the future *Spot5* satellite. This problem can be formulated as a *Variable Valued Constraint Satisfaction Problem* or as an *Integer Linear Programming Problem*. Within the VVCSP framework, exact methods to find an *optimal* solution, like *Depth First Branch and Bound* or *Russian Dolls search* and approximate methods to find a *good* solution, like *Greedy Search* or *Tabu search* have been developed and experimented on a set of representative problems. Comparison is also made with results obtained by running the *Linear Programming* environment *CPLEX* on the corresponding linear models. The conclusion addresses some lessons which can be drawn from this overview.

1 PROBLEM MODELING

The *Spot5* daily scheduling problem [1] can be informally described as follows :

- given a set S of *photographs*, *mono* or *stereo*, which can be achieved the next day *w.r.t* the trajectory of the satellite;
- a *weight* w_p associated to each photograph p, which is the result of the aggregation of several criteria like the client importance, the demand urgency, the meteorological forecasts ...
- a set of *trials* associated to each photograph corresponding to the different way to achieve it : up to three for a *mono* photograph (because of the three instruments on the satellite) and only one for *stereo* (because such photographs require two trials : one with the front instrument and one with the rear one);
- given a set of *hard* constraints (which must be satisfied) :
  - non overlapping and respect of the minimal transition time between two successive trials on the same instrument;
  - limitation of the instantaneous flow of data through satellite telemetry;
  - limitation of the recording capacity on board;
- the problem is to find a subset S' of S which is admissible (hard constraints met) and which maximizes the sum of the weights of the photographs in S'.

This problem belongs to the class of Discrete Constrained Optimization Problems (it can be seen as a kind of *multi-dimensional knapsack problem*). It is an NP-hard problem, according to the complexity theory.

1.1 VALUED VARIABLE CONSTRAINT SATISFACTION PROBLEM MODEL

The Variable Valuated Constraint Satisfaction Problem framework (VVCSP) is a specialization of the VCSP framework [2] (which is itself an extension of the CSP framework), where each problem can be characterized by a set of *variables* and a set of *constraints*. Each variable is characterized by its weight and a finite domain of values (defining its possible instantiation) and containing a special value * (expressing the fact that the variable do not participate to the solution. Each constraint links a subset of variables and defines forbidden combination of values for these variables.

Given an assignment A of all the problem variables, the valuation of A is the sum of the weight of variables instantiated to a value different from the special value *. The standard objective is to produce an assignment with a maximal valuation.

The modeling of the *Spot5* scheduling problems, within the VVCSP framework [3] consists in :

- associating a *variable* v to each photograph p;
- associating to this variable a *domain* d of values corresponding to the different possibilities to achieve p :
  - a subset of $\{1, 2, 3\}$ for a *mono* photograph (values 1, 2 et 3 corresponding to the possibility of using the *front*, *middle* or *rear* instrument to take the photograph);
  - the only value 13 for a *stereo* photograph (corresponding to the only possibility with both *front* and *rear* instruments);
- adding to d, the special value 0 corresponding to the possibility of not selecting p in the schedule;
- translating as *binary* constraints, the constraints of non overlapping and respect of the minimal transition time between two trials on the same instrument;
- translating as *binary* or *ternary* constraints , the constraints of limitation of the instantaneous flow of data;
- translating as a *n-ary* constraint, the constraint of limitation of the recording capacity.

The biggest problem, from our data set corresponds to a problem with 1057 variables and 21786 constraints.

1.2 INTEGER LINEAR PROGRAMMING MODEL

The modeling of the *Spot5* scheduling problems, within the *Integer Linear Programming* framework consists in :

- associating a *binary variable* $x_{p,i}$ to each trial (p being the photograph and i the instrument) : $0 \leq x_{p,i} \leq 1$ (1 meaning selection, 0 meaning rejection);
- expressing the fact that for each mono photograph p, at most one trial among the possible trials, is selected by : $\sum_i x_{p,i} <= 1$
- expressing the fact that for stereo photograph s, trials must be both attempted or rejected : $x_{s,1} = x_{s,3}$
- translating as *binary* constraints of the form $x_{p1,i} + x_{p2,i} <= 1$, the constraints of non overlapping and respect of the minimal transition time between two trials on the same instrument;

- translating as *binary* or *ternary* constraints of the form $\sum_{(p,i)} x_{p,i} \leq 1$, the constraints of limitation of the instantaneous flow of data;
- translating as $\sum_{(p,i)\in M} c_{p,i}x_{p,i} <= Size_m$, the constraint of limitation of the recording capacity ($c_{p,i}$ being the amount of data to record when photograph p is done on instrument i);
- the objectif is to maximize $\sum_p w'_p(\sum_j x^j_p)$, with $w'_p = w_p$ if p is a mono photograph and $w'_p = w_p/2$ for stereo (because both trials will be necessarily selected).

The biggest problem induces a formulation with 2356 binary variables and 36586 constraints.

2 EXACT METHODS

Two strategies have been experimented within the VVCSP framework : the standard *Depth First Branch and Bound* and a new algorithm called *Russian Dolls Search* (for a detailed presentation see [4]. For the *ILP* framework, we use an algorithm based on *Best First Branch and Bound.*

2.1 DEPTH FIRST BRANCH AND BOUND

The *Depth First Branch and Bound* algorithm, which is the equivalent to the *Backtrack* algorithm widely used within the standard CSP framework [5], presents the following advantages :

- it requires only a limited space (linear w.r.t the number of variables);
- as soon as a first assignment is found, the algorithm behaves like an *anytime* algorithm : the quality of solutions cannot but improve over time and if interrupted, the best solution found can be returned.

The main problem is that a *Depth First* search can easily be stuck into a portion of the search space where no optimal assignment exists, because of the first choices made during the search.

2.2 RUSSIAN DOLLS SEARCH

Russian Dolls Search [6] is a generalization to the VVCSP framework, of a *Spot5* specific algorithm developed by D. Blumstein and J.C. Agnèse for finding optimal solutions. It is in fact build on top of the standard *Depth First Branch and Bound.*

Given a problem p with n variables; the method, which assumes a static variable ordering, consists in performing n searches, each one solving (with the standard *Depth First Branch and Bound* strategy) a subproblem of p limited to a subset of the variables. The i^{th} problem is limited to the i last variables. Each problem is solved by using the same variable ordering, *i.e.* from variable $(n - i + 1)$ to n. The optimal valuation is recorded as well as the corresponding assignment. They will be used when solving the next problems, to improve the valuation of the partial assignment and thus to provide better cuts.

This method, which can be surprising since it multiplies by n the number of searches, has proved to be very efficient, mainly because of the quality of the valuation of the partial assignments provided by previous searches.

2.3 BEST FIRST BRANCH AND BOUND

Best First Branch and Bound is the base for solving *Integer Linear Programming* problems. The evaluation, at each node, is made by solving the corresponding relaxed problem (integrity constraints removed) with a classic algorithm for Linear Programming like simplex algorithm for instance. In our experiments, we have used the *CPLEX* environment, which embeds powerful algorithms for this class of problems.

3 APPROXIMATE METHODS

This section presents algorithms which are aimed at providing "good" solutions to the problem, but cannot prove optimality. Although not specific of the VVCSP framework, they will be described in this framework to keep an unified presentation (details of algorithms can be found in [4]).

3.1 GREEDY ALGORITHMS

This algorithm works in two phases :

1. computation of a feasible solution : trials are first heuristically sorted, then a solution is built by trying to insert each trial in the current solution and rejecting it if impossible;

2. improvement of the solution, result of the first phase, by a perturbation method based on an inhibition of the retained trials : an iterative process successively computes the effect of the suppression of each trial on the quality of the solution. For each trial belonging to the current solution, its rejection is attempted and a new schedule is recomputed from this point (the portion of schedule from the beginning up to the trial is kept). If a better solution is found, the trial is definitively rejected and the current solution is updated.

The efficiency of the algorithm depends greatly on the quality of the sort performed in the first step. Trials can be sorted according to (the aim is to maximize the quality of solution and limit the conflicts):

- decreasing weights (trials with important weights are privileged),
- at equal weight, mono trials are placed before stereo trials (because a stereo trial requires twice more resources),
- trials with low data flow have priority (to limit conflicts due to data flow and memory requirements),
- trials in conflict with a little number of other trials are privileged,
- chronological order is adopted.
- mono trials are preferably affected to the middle instrument (stereo trials are realized with the front and rear instruments),

Another variant of the basic algorithm, called *Multi Greedy Algorithm*, consists in computing several initial schedules, by using different variable orderings (up to five) and performing the improvement phase on the *best* one.

3.2 TABU SEARCH

Tabu Search (see [7] for a detailed presentation) like any other local search method can certainly be best introduced by taking a geometric analogy of the search process. Each assignment of all the n variables of the problem can be considered as a point in the n-dimensional search space. Each point receives then a valuation $val(P)$ characterizing the goodness of the solution ($val(P) = -\infty$ means that the point P does not represent a feasible solution).

The search process can then be seen as "moving from point to point" trying to find points with a better valuation than the best point encountered since then. A first initial and "feasible" point can always be found : either the void solution (all variables instantiated to the value 0) or some good initial solution as one provided by the greedy algorithm for example. Each time the search process moves from current to next solution an iteration counter is incremented.

In the search we do not consider completely arbitrary moves (changing lot of values at the same time) but only the simplest ones : only one instantiation is changed at the same time. More precisely, we considered only two types of moves :

- add a photograph to the current solution : instantiation changed from 0 to i;

- suppress a photograph from the current solution : instantiation changed from i to 0.

This limitation makes that many points in the search space cannot be reached from a given point P. The set of points that can be reached from the point P via feasible moves is known as the neighborhood of P or $N(P)$. A move between current solution P and next solution P' can be given a value $\Delta_{val}(move(P/P')) = val(P') - val(P)$. Basically the move selected at one iteration is the one in $N(P)$ which has the best value. A useful remark at this point is that moves leading to a worse solution than the preceding one, are still possible, to allow the search to escape from local optimum. However, due to this possibility, endless cycling is avoided by forbidding the reverse move for a certain time after the current iteration. The move is declared *tabu* for this period (where the name of the method comes from).

Forbidding certain moves, which are in $N(P)$, can be seen formally as a modification of $N(P)$ under the constraints induced by the history of the search. So the next move is not selected in $N(P)$ but in a subset $N(P, H)$ of $N(P)$. In the *Tabu Search* we have implemented, the history of the search consists in recording, for each photograph : the last iteration at which the photograph has been inserted or removed from a solution and the number of insertions tried for it. This second kind of memory which tracks mid-term behavior of the search is used to penalize insertion of very frequently inserted moves. Such penalization induces a way to force some kind of diversification of the search, guiding the exploration in yet unexplored area of the search space.

4 EXPERIMENTS AND COMPARISON

4.1 DATA

The set of available data involves 498 scheduling problems provided by CNES [1] :

- 384 problems, named *one orbit*, corresponding to scheduling problems limited to one orbit, where the recording capacity constraint is ignored. These problems correspond to 362 basic problems generated with the simulator *LOSICORDOF* (number 1 to 362); 13 problems, built from the biggest of the 362 previous ones (number 11), by reducing the number of photographs (number 401 to 413) and 9 problems, built from the same problem, by reducing the number of conflicts between photographs (number 501 to 509).

- 114 problems, named *several orbits*, corresponding to problems over several consecutive orbits, between two dumping of data, where the recording capacity constraint cannot be ignored. They correspond to 101 basic problems generated with the simulator (number 1000 to 1101); 6 problems, built from the biggest of the 101 previous ones (number 1021), by reducing the number of photographs (number 1401 to 1406) and 7 problems, built from the same problem, by reducing the number of conflicts between photographs (number 1501 to 1507).

To experiment and compare the different methods, 20 representative problems (available on Internet at `ftp://ftp.cert.fr/pub/lemaitre/LVCSP/Pbs/SPOT5`) have been selected in the different classes : 13 problems *"one orbit"* (54, 29, 42, 28, 5, 404, 408, 412, 11, 503, 505, 507 and 509) and 7 problems *"several orbits"* (1401, 1403, 1405, 1021, 1502, 1504 and 1506). . Tables 1 and 2 present the results obtained on these problems by the five following methods :

- *BFBB* : the *Best First Branch and Bound* embedded in *CPLEX 4.0* (time limit 1800s);
- *DFBB* : the standard *Depth First Branch and Bound* (time limit of 600s per sub-problem);
- *RDS* : the *Russian Dolls Search* (time limit 1800s);
- *GR* : the *Multi Greedy Algorithm*;
- *TS* : the *Tabu Search*.

4.2 RESULTS ON "ONE ORBIT" PROBLEMS

Table 1 presents the results on the subset of "one orbit" problems (*Pb* is the problem number and Nv is the number of variables of the problem) For each couple problem-method the first number is the best valuation (sum of the weights of selected photographs), * indicates that optimality has been proved and the second number is the cpu time in seconds.

Pb	Nv	*BFBB*		*DFBB*		*RDS*		*GR*		*TS*	
54	67	70*	2	70*	32	70*	3	69	4	70	253
29	82	12032*	2	12032*	12	12032*	1	12032	1	12032	1
42	190	108067*	74	104067	1201	108067*	14	108067	13	108067	634
28	230	56053*	916	53053	612	56053*	415	50053	4	56053	1416
5	309	114	1800	112	1213	114*	1702	114	43	114	293
404	100	49*	7	48	600	49*	2	47	3	49	237
408	200	3082*	292	3076	603	3082*	184	3078	19	3082	279
412	300	16102*	1667	15078	611	16102*	255	16097	43	16101	1166
11	364	22118	1800	21096	646	22120*	419	22112	68	22116	1433
503	143	9096*	3	8094	611	9096*	38	9093	22	9096	272
505	240	13100*	76	12088	603	13100*	108	12102	39	13100	1269
507	311	15137*	1270	13101	620	15137*	303	15129	54	15136	1385
509	348	19123	1800	19104	638	19125*	382	19116	63	19123	1384

Table 1: *"one orbit" problems*

Concerning these problems :

- *BFBB* find the optimal solution on 11 problems (proof for 10 only);
- *DFBB* find the optimal solution and the proof of optimality on only two of them and not very good solutions for the others;
- *RDS* find the optimal solution and the proof of optimality on all the problems;
- *GR* is the fastest algorithm, do not find optimal solutions but provides solutions better than the ones produced by *DFBB*, but worse than those produced by *BFBB*;
- *TS* find optimal or near optimal solutions, without any proof of optimality and is slower than *RDS*.

4.3 RESULTS ON "SEVERAL ORBITS" PROBLEMS

Table 2 presents the results on the subset of "several orbits" problems (same presentation than for table 1).

Concerning these problems :

- *RDS* fails on all problems except 1502, because of the high arity constraint (an anytime version would be able in fact to deliver solutions);
- *BFBB* performs a little better than *RDS*, but becomes limited by the size of the problems (extra computing time may improve results);
- *DFBB* because of its anytime capabilities, is able to produce solutions for all problems, but with a low quality compared to *TS* or even *GR*.
- *TS* provides the best solutions, but time increase significantly.

Pb	Nv	*BFBB*		*DFBB*		*RDS*		*GR*		*TS*	
1401	488	162060	1800	165058	648	-	-	167060	93	174058	846
1403	665	-	-	165133	1867	-	-	167143	279	174137	1324
1405	855	-	-	165154	1342	-	-	167182	692	174174	1574
1021	1057	-	-	165221	1988	-	-	167249	1241	174238	2197
1502	209	61158*	1	60155	601	61158*	13	61158	60	61158	454
1504	605	124235	1800	115228	1808	-	-	120239	405	124238	1011
1506	940	-	-	153226	1906	-	-	163244	897	165244	1945

Table 2: *"Several orbits" problems*

4.4 GLOBAL RESULTS

Results obtained on the whole data set show the efficiency of both *Russian Dolls Search* for "one orbit" problems and *Tabu Search* in general.

4.4.1 Efficiency of *Russian Dolls Search*

For optimality proof, the *Russian Dolls Search*, outranks other methods. Its performances are summarized in table 3 *w.r.t* the size of the problem : the class i-j is the set of problems with a number of variables Nv such that $i \leq Nv \leq j$, N_{pb} is the number of problems in the class and N_{opt} the number of problems solved optimally with *RDS*. Globally, the procedure solved optimally 85.7 % of the initial data set (90.8 % for the subset *one orbit*, 68.4 % on the subset *several orbits*).

$Class$	N_{pb}	N_{opt}	%
1-100	315	313	99.4
101-200	74	67	90.5
201-300	47	29	61.7
301-400	24	18	75.0
401-1100	38	0	0.0
Total	498	427	85.7

Table 3: *Efficiency of Russian Dolls Search*

This table shows also the limitations of the procedure : when problems become large ($Nv > 400$), efficiency falls. It should be quoted, that the main reason is not the number of variables itself, but the presence of the high arity recording capacity constraint (large problems correspond to "several orbits" problems where the recording capacity limitation is enabled).

4.4.2 Efficiency of *Tabu search*

Starting from the solution provided by the *Greedy* algorithm, the *Tabu Search* generally succeeds to substantially improve it. On the subset *one orbit*, it provides solutions worse than the best known ones on only 10.5% of the problems (the best known solutions are the optimal ones provided by exact methods when they succeed or the best ones whatever method is used).

On the subset *several orbits Tabu search* improves solutions provided by *Greedy search* in 56.1 % of the problems.

5 CONCLUSION

5.1 LESSONS

Exact methods, aimed at finding optimal solutions and proving optimality, fail when problems become too large or in presence of high arity constraints.

Approximate methods can find solutions, whatever the problem size or characteristics. They provide often good solutions but sometimes loose time in trying to improve optimal solutions on small or medium size problems.

5.2 TRENDS

Besides experimenting other exact approach (based on Dynamic Programming principles for example), one of the most interesting prospect is to investigate a closer cooperation between exact and approximate methods. We can easily imagine combinations of exact and approximate methods by using them in sequence or in parallel. But it can be interesting also to try to make them cooperate at a lower level, like for example making *Linear Programming* and *Constraint Satisfaction* work together.

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MAEOBS: A MISSION ANALYSIS ENVIRONMENT FOR EARTH OBSERVATION MISSIONS

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ABSTRACT. MAEOBS, as an analysis environment for Earth Observation Missions, helps the mission analyst to investigate the different aspects related to the payload data attainment problem i.e, all the processes associated to the generation of data by the instruments, its management by the Payload Data Handling S/S and their downlink to ground. In particular, the scheduling of payload and platform activities to optimize mission outcome accounting for the different user needs as well as for all system/payload constraints and requirements is a major issue to be investigated. This analysis requires procedures similar to the ones used for advanced mission planning but even more complex as they have to be flexible to cope with different missions and different system configurations. The production of timelines for ENVISAT mission is an example of utilization of the tool.

1. INTRODUCTION

The main objective of the MAEOBS Tool is to integrate in an unique environment the mission analysis tools required to analyze and optimize Earth Observation Missions in aspects related to **payload data attainment** (i.e. data production, handling and downlink). In particular the customization of the tool for the ENVISAT mission was one of the principal goals.[1]

The overall operational sequence of mission analysis activities can be summarized in the following steps (which not have to be performed necessary in the same working session since some intermediate data can be already available or the analyst can be interested only in some particular results):

- Definition of the "*problem*" to be analyzed.
- Production and preprocessing of auxiliary data to be used.
- Processing of information in order to obtain the schedule of operations and mission timelines.
- Presentation of data in a user friendly way.
- Analysis of data.

While first and last points are mainly human tasks, the rest of points can be implemented in a computer by means of the appropriate application SW. These activities can be performed using the MAEOBS SW. According to that, four main modules of the tool can be identified:

- ***Environment Task Manager*** (ETM) that provides the means for allowing the analyst to define a particular "*problem*" by managing the different data files and SW modules in a coordinated and simple manner. It centralizes most of the interfaces with the analyst, allowing to model the constraints applicable to the different components of an Earth observation mission including payload (instruments) and platform (power, data handling and communication

[1] MAEOBS has been developed following ESTEC/NW specifications, under ESTEC/CONTRACT No. 10800/94/NL/SF (*Development of Mission Analysis Environment for Earth Observation Missions*).

subsystems) aspects.

- ***Elementary Mission Analysis Tools*** (ELMAT). It integrates a set of basic tools, including ESTEC SW modules such as orbit propagator, zone visibilities computation (for different instrument/modes), ground station visibilities computation, DRS visibilities computation, etc. These tools generate the data to be later used by the rest of MAEOBS modules.

- ***Mission Timeline Optimization*** (MTO), whose main functionality is to compute optimal timelines for instruments usage and for the data recording & playback strategy (and as a consequence, the data communications timeline), considering both instrument operation requests as well as constraints, operations strategies and optimization criteria. This module optimizes instruments and on-board tapes recorders usage by using artificial intelligence techniques. It constitutes the core of the tool since one of the major operational problems of an Earth observation mission is to obtain optimal **instrument** and **recording & playback** timelines which define the data produced by the payload, the instrument modes scheduling, the on-board data storage usage and the communication periods for ground station/DRS data transmission.

- ***Data Exploitation and Presentation*** (DEXPRE) that provides the means for allowing the user to analyse the results generated from the different modules. It makes use of graphical visualization techniques and permits the user to select different output representations such as chronograms, XY graphs, bar-charts or graphics on Earth maps.

Concerning the scope of the MAEOBS tool, it is important to highlight that MAEOBS covers mission analysis aspects directly related to **payload data production**, **handling** and **downlink**, as for example, ground station and DRS visibility periods, zone visibilities, instrument and power aspects, etc. Other mission analysis issues such as orbit selection, launch window or orbit manoeuvres are out of the scope of the tool.

This paper describes the functional and architectural characteristics of the MAEOBS tool as well as the lessons learned from the optimization of payload and on-board tape recorders operations.

2. MISSION AND PROBLEM MODELLING

The main problem to be solved by the Mission Timelines Optimization (MTO) module can be enunciated as:

Compute optimal instruments, recorders and communication timelines, in order to maximize the mission outcome mainly defined by the instrument operation requests and the background mission, accounting for different system and payload constraints as well as specific optimization criteria derived from the system (e.g. minimize number of start/stops of the recorders). This being able to be performed not only for a specific but for any generic Earth Observation mission in LEO, i.e. considering different mission/system characteristics as far as instruments, platform, communications scenarios and ground segment are concerned.

The problem is similar to the one to be solved during mission execution (mission planning involving both instrument and system operations) but with additional complexity since used methodology has to be **flexible** to cope with different missions and system configurations (as required for mission analysis). It is to be emphasized that the problem under analysis involve both, payload and platform aspects, whose couplings have to be properly managed.

Each of the different issues describing the above identified problem (see figure 1) will be properly modelled in terms of constraints, optimization criteria and operational strategies to be used. Additionally, the required input data (to be generated by ELMAT module) will be identified.

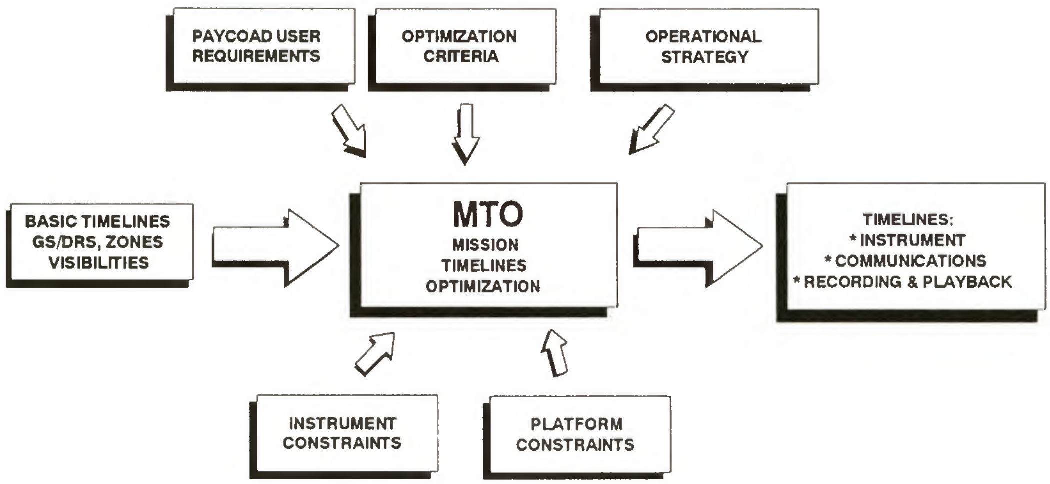

Figure 1: *Main aspects considered in the optimization processes.*

2.1 PLATFORM DESCRIPTION

The most relevant aspects of the platform that have been modelled in the tool affecting the described problem are the following:

- On-Board Payload Data Handling (PDH) subsystem allowing an appropriate management of the instrument data which involve multiplexing, recording & playback or direct sent to the communications subsystem for downlink. Recording and Playback is based on tape recorders devices (up to four in the case of ENVISAT). The use of those recorders has to be defined according to different predefined strategies describing their basic operational rules (e.g. sequential use of different tapes). Different constraints and optimization criteria are also applicable to the PDH as it is the minimization of start/stops of the tapes (to maximize their life time), minimization of the number of tapes involved, etc.
- Communications subsystem considering different frequencies and channels and different management strategies. Communications may involve both direct communications with ground stations as well as communications via a Data Relay Satellite.
- Power subsystem with its two main elements, batteries and solar array. A model of the on-board battery charging cycle must be considered and a model of solar array degradation may be defined and integrated. An energy balance is necessary to be computed as input for the optimization process in order to ensure the different constraints accomplishment.

2.2 PAYLOAD DESCRIPTION

Very different instruments have been considered having as reference the instruments planned to fly in ENVISAT missions. For each instrument the following aspects have to be considered:

- Different modes and allowed transitions among them defined in terms of the so called transition constraints matrix.
- Zones being observed as a function of time computed based on platform orbit and instrument swaths and made available as input to the optimization process.
- Amount of data being generated distinguishing between low rate instruments/modes (whose data can be stored on-board) and high rate instruments (whose data need to be necessarily

downlinked in real time).
- Instrument power consumption.

Constraints associated to the use of instruments are derived from the instruments themselves (e.g. incompatibility between instruments modes) as well as from limitation imposed by the platform such as limited power supply and recording capabilities.

2.3 COMMUNICATION SCENARIO

As previously highlighted, various communications scenarios are foreseeable involving both direct communications with ground stations as well as use of data relay satellites providing much broader coverage. Thus, for any communications scenario (defined by the available ground stations and/or DRS), a visibility timeline (periods where communications are possible) are generated as input for the optimization process. Examples of typical ENVISAT communication scenarios are Kiruna+Artemis, Kiruna+Pokerflats and Kiruna+Fucino (not nominal scenario).

Optimization criteria related to the communications are associated to the existence of preferred ground stations for data downlink, minimization of communications periods when using DRS, etc.

2.4 INSTRUMENT OPERATION REQUESTS

The optimization of the mission timelines are mainly driven by the instrument operation requests (defining the particular user's needs during a certain period of time) and the overall mission objectives when no requests exists. The formalization of those user's requests constitutes a major step in order to allow those requests to be properly managed by the optimization tool while being easily enunciated in a language close to the one user knows (i.e. the user should be able to ask for some particular data without requiring any knowledge of the mission/system which provide that data).

Major objectives to be achieved with these requests are the global coverage for low rate data (default mission), the observation of zones for all the period to be studied (background mission), the observation of local zones with possible sensing time selection (regional mission) and the usage of an specific instrument mode for a zone/time or for a local period within a zone (specific mission).

Requests may involve information on zone to be observed, required period of time, instrument mode, minimum observation time, particular observation preferences, etc. In addition to the satisfaction of those user's requests, mission timeline has to consider further optimization criteria (from the user point of view) as it is the minimization of time from acquisition to distribution to the users.

3. TOOL ARCHITECTURE

As it was presented in the introduction, MAEOBS consists of four main components (figure 2). Each of these modules is briefly described below.

3.1 ENVIRONMENT TASK MANAGER (ETM)

The Environment Task Manager provides the means for allowing the analyst to investigate a particular "*problem*"[2] by managing the different data files and SW modules in a coordinated and

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[2] The concept of "*problem*" was introduced to simplify input of data allowing to create a new problem by simply modifying the inputs w.r.t. previous one. A *problem* is defined as a set of parameters (with a given value) and configurations associated to a particular situation to be analyzed. An example of problem is: { orbit propagator = PPFORB, ground stations to be used = Kiruna+Fucino, number of tapes = 4, tapes capacity = 30 Gbits, ... }

simple manner. It is in fact the upper layer of the MAEOBS which centralizes most of the interfaces with the analyst. The Environment Task Manager provides the following services to the analyst:

- Support the definition/modification of input files by offering the different existing versions and providing the possibility to select/change parameters from a menu, further implementing consistency checking for introduced data.
- Appropriate input/intermediate/output files management based on a files hierarchy which simplifies the data modification and minimize the effort when performing different analyses. It facilitates reuse and recovery of data and procedures by means of managing "*comments*" files associated to *problems*, *scripts* and *stopped sessions* (the user is requested to provide descriptive information every time one of the previous items is saved).
- Execute different SW modules either interactively or in batch mode based on a predefined set of commands (script file).
- Automatic generation of script files based on a set of actions previously introduced interactively.
- Control most of the GUI. The ETM presents the available options by means of menus, buttons and list boxes in a windowing environment.
- Guide the analyst on the steps to be executed in order to reach a particular result based on the modified input files and the availability of different intermediate/output files. It simplifies the user's MAEOBS knowledge to get the required results and also reduces the execution time.
- Use of help facilities for the different defined windows.
- Stop/resume the computation process in certain break points.

The Environment Task Manager is flexible to allow the introduction of new SW modules in the MAEOBS.

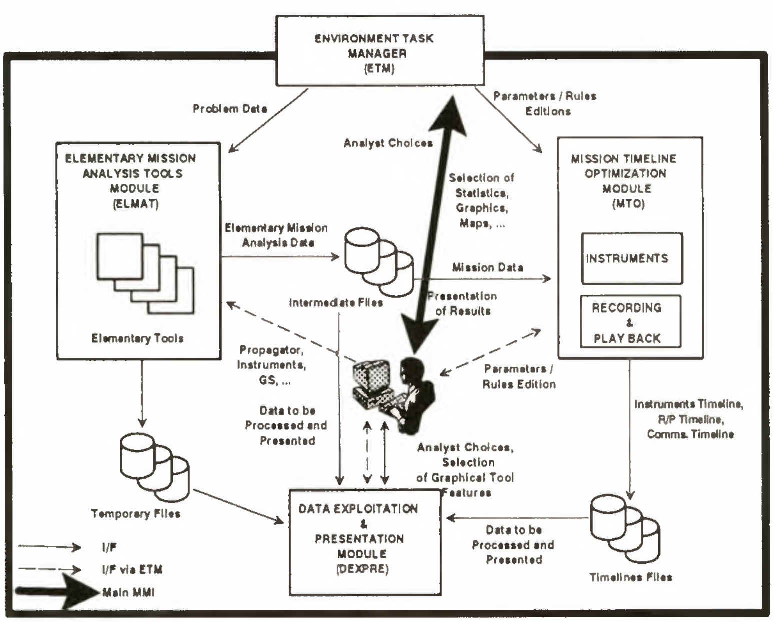

Figure 2: *MAEOBS main components*

3.2 ELEMENTARY MISSION ANALYSIS TOOLS (ELMAT)

The **Elementary Mission Analysis Tools (ELMAT) Subsystem** integrates existing SW developed by ESTEC (both ERS and ENVISAT projects) with the objective of providing services to the ETM, MTO and DEXPRE subsystems. It includes modules such as:

- MPS SW:
    - MODA (Generation of the Orbit Event File)
    - MODB (Generation of the Station Visibility Segments)
    - MODC (Generation of the Zone Visibility Segments)
    - MODD (Generation of the DRS Visibility Segments)
- Parameters Computation SW (as required by DEXPRE for particular time interval):
    - GENSTATE (State Generation)
    - ERSORB/PPFORB (Orbit Propagator)
    - STAVIS (parameters related to ground station visibilities)
    - TARGET (parameters related to payload to target pointing)
    - DRSVIS (parameters related to DRS visibilities)

There are clearly defined interfaces between submodules allowing their replacement by equivalent ones. The outputs of the different submodules are stored in files in such a way they can be used as inputs for other submodules.

3.3 MISSION TIMELINE OPTIMIZATION (MTO)

The Mission Timelines Optimization overall process has been split in two independent modules, the **Instrument Timelines Optimization (ITO)** and the **Recording & Playback Timelines Optimization (RTO)** that are sequentially applied. The possibility of combining both modules in a simple one was investigated. Main conclusion was that it would require a much more complex and less efficient architecture without improving the optimization results. The instrument timeline is calculated before the recording and playback one, and used as input for the last one. Only in case of descoping derived from the recording & playback limitations, the instrument timeline can be locally modified in descoped zones or globally on the whole period under study (feed-back mechanism). The communications timeline is directly derived from instruments and recording & playback ones.

3.3.1 Instruments Timeline Optimization (ITO)

Instrument Timeline mainly defines the on board instruments data production including both high and low rate. The generation of this timeline takes into account all major aspects involved in this problem, such as:

- Payload user's requests, setting the basic data production.
- Payload resources and constraints (i.e. instrument aspects).
- Platform resources and constraints interfacing with the payload (i.e power and on board data handling aspects).
- Ground segment resources and constraints (i.e. ground station/DRS visibilities aspects).
- Instruments operational strategy.
- Optimization criteria.

Thus the resolution of this problem involves both constraints satisfaction and resources optimization. In order to increase the flexibility of the ITO module, it was split in two major parts:

- the one implementing the basic *methodology*. It is implemented mainly by methods.
- the other one implementing resources definition, constraints, operational strategy and optimization criteria. It is implemented by using *rulesets*.

The ITO methodology is hereafter explained based on figure 3. As depicted, interactions among *methodology* and *rulesets* are presented.

First of all, user's requests are translated to instrument mode operations (events). Some of them are descoped based on "a priori" constraints (e.g. ground segment resources and constraints for high rate data). Events are sorted on a stack using priorities imposed by the user.

Thus events are included in a timeline such that all instruments constraints are fulfilled. Notice that it may imply the descoping of the whole or part of the event (instrument mode conflict solver used at this stage). After this processing, transitions among scheduled instrument modes are computed, considering concerned constraints. Therefore a timeline fulfilling instruments constraints is obtained.

Platform constraints are considered (i.e. payload power consumption) and all conflicts solved, following the strategy set into the dedicated rulesets. Again transitions are recomputed and a new instrument timeline fulfilling all constraints is generated.

This instrument timeline may be optimized, feeding-back with the original list of events, excluding those descoped in this last step. This process is stable, being its convergence ensured. Thus several instrument timelines fulfilling all constraints are obtained. At this stage optimization criteria are fully applicable to select the one that better satisfies the imposed criteria.

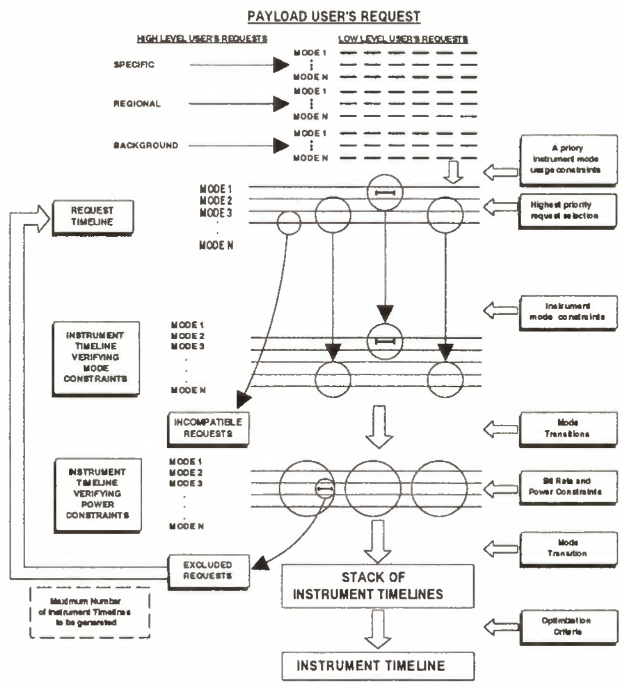

Figure 3: *Instrument Timeline Optimization Logic*

3.3.2 Recording & Playback Optimization (RTO)

Main RTO objectives are to obtain the optimal Recording and Playback timelines defining the on-board tape recorders usage scheduling together with the low rate communication timeline (including real time transmissions) and the descoping information timeline when limitations make it necessary, accounting for input timelines, parameters and rules. Input timelines are the high rate communications timeline, the low rate data production and priority (from ITO) and the visibility periods available to downlink low rate data.

Two important optimization parameters are associated to the methodology in order to modify the optimization degree of the obtained solution. These are **depth level** (defining the local period to be studied at each stage) and **breadth level** (defining the maximum number of potential plans to be propagated in next stage, and therefore the maximum number of global potential plans to be obtained).

RTO methodology hereafter described and summarized in figure 4 has intended to be as generic as possible and to provide the flexibility to modify most relevant functionalities implemented as rulesets. The global period under analysis is to be studied in terms of local optimization, being the global solution made from the concatenation of local optimization processes.

First step will be the computation of a basic period for local optimization, based on the data to be covered and the communications scenario. The depth level will indicate how many of those basic periods are considered within a period for local optimization. Following step will be the generation and sorting of possible combinations included in that period, rejecting those combinations that will drive to bad solutions.

The recording and playback procedure will be applied for every selected combination and for each initial state vector (with the information coming from previous period which have not been solved) imposed by recording and playback plans selected in previous periods locally optimized, by using those rulesets defining the playback and recording strategies and the one implementing the real time transmission policy. All potential local solutions for each period are checked against analyst constraints and sorted following the optimization criteria.

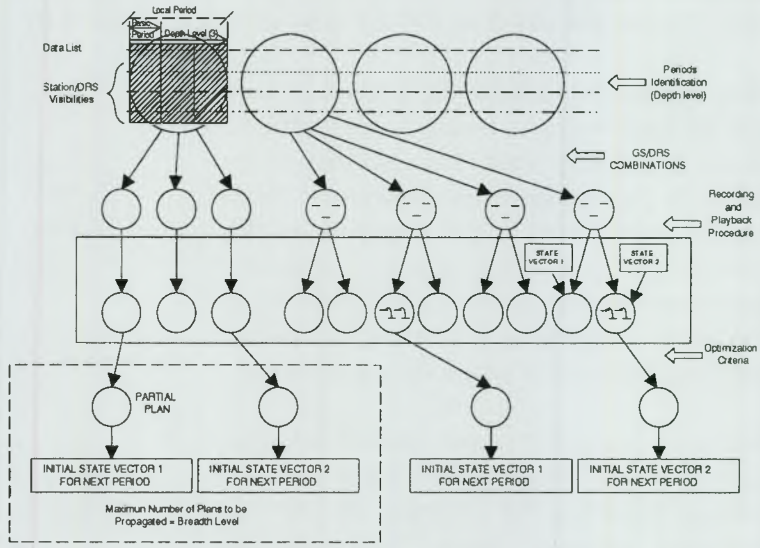

Figure 4: *Recording & Playback Timelines·Optimization Logic*

This process continues until last period is studied. At that point several recording and playback timelines (potential solutions) are obtained concatenating those partial plans previously computed. The timeline that better satisfies the optimization criteria ruleset will be selected as the final solution.

3.4 DATA EXPLOITATION AND PRESENTATION (DEXPRE)

The **Data Exploitation and Presentation Subsystem** provides the means for allowing the analyst to observe the results generated from the different modules. It makes extensive use of graphical visualization techniques and shows outputs in different possible representations selected by the analyst such as chronograms, XY graphics, graphics on the Earth map, bar and pie charts.

Not all data that the analyst wants to plot can be directly available in the output files generated by the other modules but, in many cases, particular calls to specific ELMAT subroutines or certain post-processing (data exploitation) could be necessary. For instance, the following processing could be requested:

- call to ELMAT subroutines;
- statistic associated to certain variables;
- logical/mathematical combination of two different variables (e.g. visibility from ground station "A" **during** daylight periods) by means of a particular query language;
- value of one variable as a function of other based on the availability of files containing the evolution of those variables along time.
- transformation of time events into longitude/latitude representation.
- identification of information to be presented by the *Point & Click* functionality.

Generated results based on either outputs from other modules or as produced by the Data Exploitation function can be able to be shown on the screen, sent to a printer or stored in a file. In any case, outputs make reference to the inputs on which results are based.

4. HW AND SW ENVIRONMENT

Figure 5 contains an overview of the MAEOBS HW and SW environment required to run the tool. It has to be noted that two different processes must be run in parallel: *MAEOBS* to start the GUI and *MAEWAVE* to start the Data Presentation application.

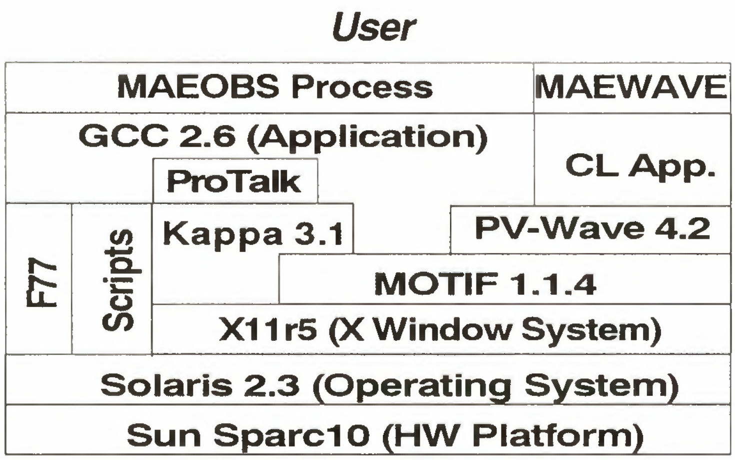

Figure 5: *HW and SW Environment*

5. CONCLUSIONS

This paper presents the MAEOBS Tool developed for mission analysis and in particular its module in charge of Mission Timelines Optimization (MTO). Instruments and recording & playback timelines optimization problems are intrinsically very complex and its resolution requires a good knowledge of the elements affecting the expected solution. MAEOBS takes into account all on-board resources, constraints, operational strategy and optimization criteria associated to the optimization problems identified for planning Earth observation missions. Thus, MAEOBS is a very advanced tool that involves a great amount of different sources of information to be processed and includes all aspects needed to perform an overall optimization process including platform and payload ones. Since flexibility to cope with different missions, systems, scenarios and strategies, was one of the major requirements, the MAEOBS tool provides the user with a high degree of flexibility at different levels.

6. ACKNOWLEDGEMENTS

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MARKET-BASED APPROACHES TO MANAGING SCIENCE RETURN FROM PLANETARY MISSIONS

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ABSTRACT: The return of science is the fundamental objective of any planetary mission. However, which constellation of science observations constitute the best return of "science" is hard to evaluate. Past approaches toward planning science observations have been based on co-location of the payload scientists who debate the merits of which investigation had the "stronger" science. This advocacy approach is time-consuming and does not provide appropriate incentives for science teams to reveal the tradeoffs concerning how their observations were implemented.

An alternate approach, currently under evaluation by the Cassini Mission to Saturn, is one based on providing better incentives for the science teams to reveal their tradeoff information. Incentives can produce better tradeoffs because the individuals who can make the best decisions about which science observations to propose, what resources are required to implement the observations, and which observations are most important are the science team's Principle Investigators (PI) themselves.

1.0 THE VOYAGER PLANNING PROCESS

To illustrate the difference between the new planning process and previous approaches, we will compare a market-based science planning process to the one used during the Voyager Mission. The Voyager Mission represents a good baseline from which to compare since both Cassini and Voyager are extremely long missions. The Voyager Planetary Missions had a total of six planetary encounters and lasted twelve years. Figure 1 shows the geometry of one of the encounters, namely the Voyager 2 encounter with Saturn. Cassini, on the other hand, will have only one encounter and that is with the planet Saturn. After seven years of cruise, it will arrive at Saturn and then spend the next four years exploring it. Figures 2 and 3 show Cassini's initial orbit about Saturn and the next 63 orbits about the planet, respectively.

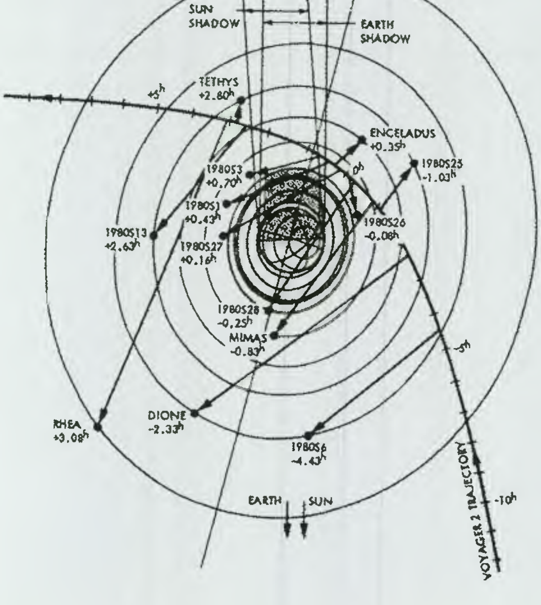

Figure 1. Voyager 2 encounter trajectory with Saturn. The encounter lasted four months with closest approach to the planet occurring on 1981 August 25.[1]

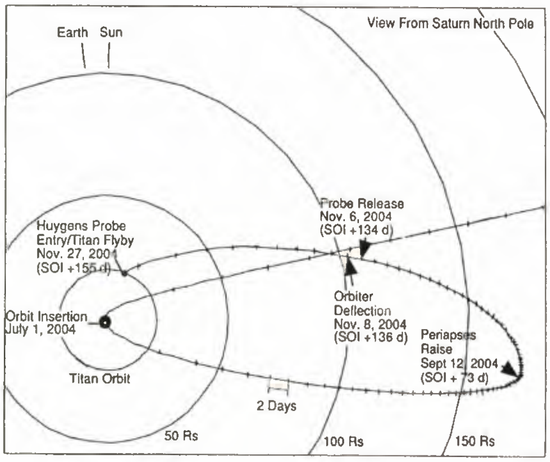

Figure 2. Cassini initial orbit about Saturn. Orbital period is anticipated to be approximately five months.[2]

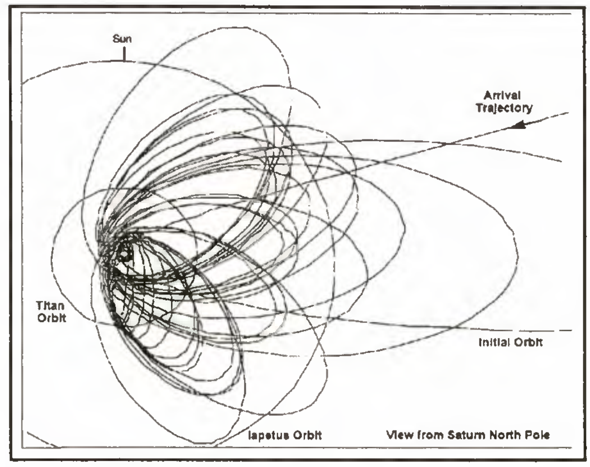

Figure 3. A typical Cassini four-year tour about Saturn. In this example, orbital periods are approximately two months long and circle the planet 63-times.[2]

The Voyager Planning Process[3] evolved over the 12 years of its use. The final process, used for both the Voyager 2 Uranus and Neptune encounters, began with Science Workshops. The workshop's task was to define the current state of knowledge of the planet to be encountered and develop the associated science objectives. From these objectives, the Discipline Working Groups developed observation strategies.

The Voyager Flight Science Office (FSO) had the difficult task of developing the timelines from the observations recommended by the working groups. The results, known as Scoping timelines, were presented to the PIs, who then evaluated and proposed changes (see Fig. 4).

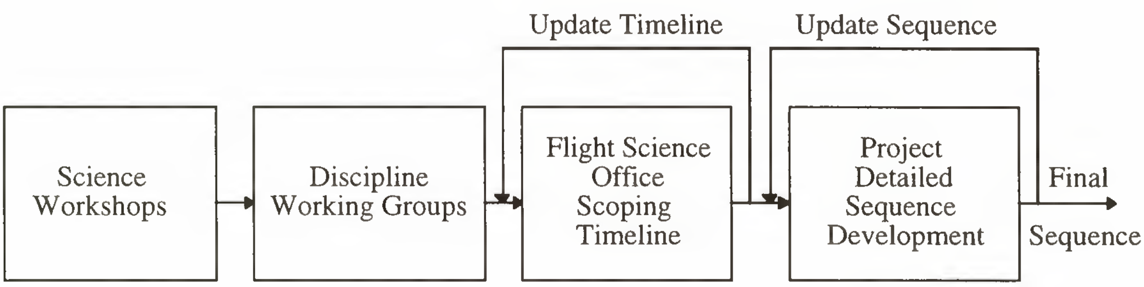

Figure 4. The Voyager Planning Process. Updates were required to both the Scoping timelines and the detailed sequences to incorporate PI and engineering changes.

1.1 VOYAGER WORKSHOPS AND WORKING GROUPS

The Voyager approach began with Science Workshops. These workshops brought together scientists who had expertise in the study of the particular planet. Their goal was to define the current state of knowledge of the target, and produce a list of major planetary objectives.

The objectives were divided into three disciplines, the totality of which defined the planetary system. The three Voyager disciplines were Atmospheres, Rings and Satellites/Magnetosphere. The science experts were then grouped according to their particular specialty. The resulting groups made up the Discipline Working Groups. In each group one individual was assigned as chairperson. Representation of the Voyager science investigations in the Discipline Working Groups were designated by the respective PIs.

The chairperson of each working group presented the respective group's major science objectives to the Voyager PIs. This was then followed by a list of suggested observations, their durations and approximate times of execution in order to acquire the previously mentioned science objectives. The observations themselves were prioritized from 1 = highest value science, 2 = high value science and 3 = moderate value science.

1.2 VOYAGER SCIENCE SCOPING

Once each Discipline Working Group submitted their prioritized list of observations, the FSO integrated them into a single, conflict-free timeline. This "balanced" timeline contained the most important science observations identified by the working groups. However, since the FSO preferred to leave tradeoffs between the major observations to the assembled PIs, it unilaterally resolved only the more obvious issues.

The approach taken was to place all suggested observations into a data base. From the data base a timeline was produced. All observations that conflicted with others were identified and shifts in start-time were proposed to resolve each issue. If an acceptable shift could not be found, the observations were combined into a single observation meeting both objects, albeit at somewhat degraded levels. In the case where no such single observation existed, the observation with the lower priority was deleted from the timeline

When high or equal priority objectives from different working groups had irresolvable conflicts, the FSO resorted to trying to provide equal total observation time for each working group. In addition, the FSO suggested possible conflict resolutions and the PIs chose between them or came up with an alternative of their own.

The Scoping timeline was complete when as many of the observations, recommended by the working groups, were incorporated into the timeline. If Scoping showed an overusage of spacecraft resources (e.g., computer memory, integration time, propellant, etc.), the science teams were asked to try simplifying observations to make them less resource-intensive. This was often an iterative process.

1.3 VOYAGER DETAILED SEQUENCE DEVELOPMENT

Once the Scoping timeline was produced, it went through a relatively large number of review cycles. During each cycle, the FSO presented the "new" timeline or sequence to the PIs, along with a detailed summary of the spacecraft resources required to implement the sequence.

The presentation to the PIs gave the investigators a chance to evaluate which observations were incorporated into the sequence and how they were implemented. Though the Discipline Working Groups were experts in their field, they did not know all of the observations that were important to the PIs themselves. This lack of information forced many time-consuming review cycles. It also illustrated that the PIs do bring information into the sequence development process and that they should be brought in as early as possible to reduce the number of review cycles.

With each review cycle, recommendations were made to remove certain observations and replace them with others. Some observations may have required longer integration times which would force the FSO to try to "find" time in the sequence to accommodate them. Other recommendations might require the science office to find unallocated spacecraft resources from which observation implementation problems could be solved.

1.4 PROS AND CONS OF THE VOYAGER PLANNING PROCESS

The multiple planetary rendezvous allowed the science community, and the associated science planning process, a chance to mature with each successive encounter. PIs learned what observations were of high value to the other investigators and which were not. This, in turn, taught the PIs which observations were available for trades. These trades between investigations could be outright exchanges of time on the timeline, spare spacecraft command words, or a change in the rate at which the spacecraft collected data from each instrument.

The process was well defined, robust and produced timelines that were able to provide the science community a wealth of information that is today still revealing secrets about Saturn. Unfortunately, the process was time-consuming, labor-intensive, and did not provide the FSO with the detailed information needed to make the best observation tradeoffs.

2.0 MARKET-BASED APPROACHES TO SCIENCE MANAGEMENT

The Voyager Planning Process described above has as its roots the idea that each science discipline should get its "fair share" of observation resources. Since the individuals who are scheduling observations resolved only the most obvious issues, the schedulers are left with the imprecise task of trying to schedule observations based on prioritized lists and a notion of "balanced" science. The questions they are confronted with are:

1. How many resources does the observation really require (e.g., Can I reduce the observation's duration or does it need all of the stated time)?
2. Is it safe to assume that similar priority items have similar science values and tradeoffs?
3. What level of resource reserves should be held to assist in the rescheduling of resources among users?

The individuals in the best position to answer these questions are the PIs. The FSO, in order to obtain a balanced timeline, must make these decisions and as a result, significant time and energy are used to debate for and make changes to the timeline. The question is whether the planning process can be revised so that it provides incentives to the science teams to supply the appropriate information so that the final timeline reflects their relative science tradeoffs.

This type of allocation problem is not unique and is faced by almost all organizations that must allocate shared resources among users. Examples include use of supercomputer time, railroad tracks, computer networks, telescopes and laboratories, club facilities, etc. There are many different ways in which organizations deal with the allocation of shared resources. Our focus will be on decentralized or market-based approaches. The main feature of market-based approaches is that the decision-making is left to those individuals that are in the best position to make the tradeoff (see Ledyard (1993)[4] for a description of decentralized mechanism design). In the commercial sector, this allocation problem is solved by charging for the use of congested services. For examples of pricing schemes used to reduce congestion in shared resource facilities see Westland (1992)[5], Senkow (1992)[6], and Sankaran (1989)[7].

When direct pricing is not a viable option, some organizations turn to fixed budgets. That is, individuals are provided with a budget that can be used for a variety of services. For example, professors at the University of Chicago are given annual budgets that they can use for secretarial support, travel, computer hardware and software, etc. The use of fixed budgets relieves the manager from making tradeoff decisions that are best understood by the individual.[8]

2.1 A MARKET-BASED MECHANISM

The design question we seek to address is whether we can construct a decentralized science planning system for Cassini that can outperform the Voyager method. This is an ambiguous question since we must define what we mean by outperforming and then we must be able to demonstrate that the mechanism results in better performance. Since we have no way of making inter-investigation science comparisons, it seems senseless to talk about maximum science value. If there is such a metric available, then it should be used directly as part of the planning process.

For our purposes, we are interested in two measures of relative performance. First, if one uses a market-based mechanism, is every investigation no worse off in the science it recovers, and at least one investigation does better than if a Voyager Planning Process is used. Second, within an investigation, we want to know what the relative science loss and gains are from each investigation. The method by which we will make these measurements is the use of experimental methods in economics. We will now describe the market-based mechanism we plan to test.

The mechanism (See Fig. 5) begins with fixed scheduling point budgets being allocated to each

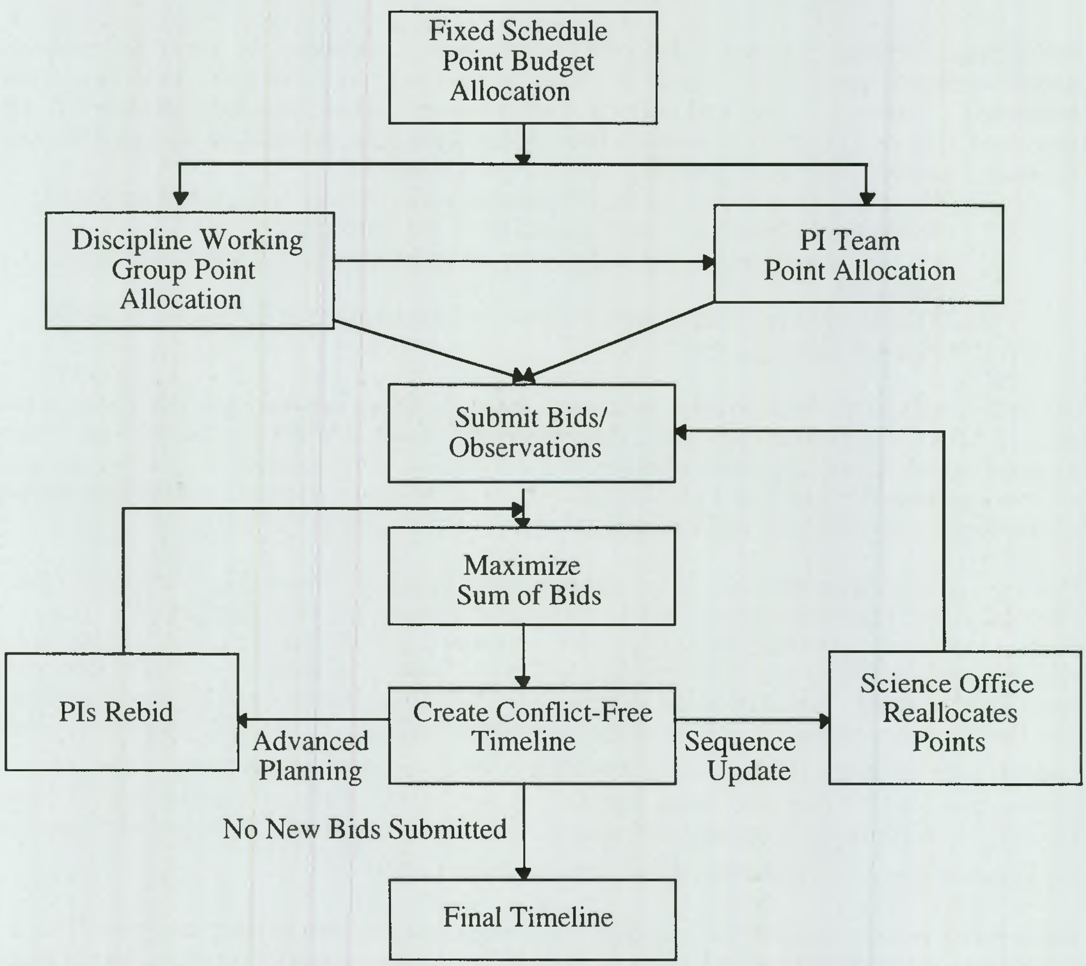

Figure 5. A market-based approach for generating a conflict-free timeline based on PI inputs. Notice that either the Discipline Working Groups or the PIs may allocate the points.

science discipline or PI. The Discipline Working Groups then use scheduling points to rank observations instead of coarse priority classes. For lack of a better term, the allocation of scheduling points to observations will be called a "bid". The Cassini Science Office (CSO) then creates a conflict-free timeline from the bids by maximizing the number of scheduling points. Thus, conflicts for the use of resources by competing observations is resolved by the number of points submitted with the observation. Discipline Working Groups are also allowed to give their allocations of scheduling points to specific investigations or to the CSO. The recipient of these scheduling points then can use them to influence the timeline after the observations are incorporated into it. In addition, after seeing the current timeline, bids can be revised. Specifically, bids on unincorporated observation can be INCREASED and new observations can be tendered.

Once the preferences of the Discipline Working Groups have been registered and a preliminary timeline has been formed, the PIs and the CSO can fine-tune the timeline by using their scheduling points to ensure observations stay in the timeline, or make new bids for alternative observations. The process is open and all bids are available for all to see. Every so often the timeline is updated with an algorithm that maximizes the number of scheduling points in obtaining a conflict-free timeline. Thus, the process provides feedback to the teams to redesign their observations to fit into the timeline. The scheduling points are used to signal the relative worth of the observations. Hence, incentives are provided to not over-demand resources since this will require a large portion of scheduling points from a fixed budget. The process stops when changes to the schedule stop or are small.

Notice that this mechanism replaces the subjective scheduling decisions of the CSO and the rescheduling/adjudication process to the timeline with a single decision of allocating scheduling points to relevant participants. While this is not an easy decision process, it seems much less demanding, time consuming and less costly than the Voyager model. Given the limitations of space in this paper, we will not provide a discussion of methods to make the initial allocation of scheduling points.

2.2 TESTING THE EFFICACY OF THE MECHANISM

While the intuition behind the design of the mechanism presented above might be apparent, how the cognitive processes of individuals interact in such an intricate mechanism is not as clear. What rules make the process more transparent and what type of information feedback works best are open issues. To test the ability of this mechanism to get real people to make tradeoff decisions, we will use experiments.

An experiment is basically a small scale prototype of the process described above in which real individuals make decisions within the mechanism. These experimental subjects are motivated by cash payments. Specifically, subjects are recruited with the understanding that they will make money based on the decisions made in the experiment (mechanism). Subjects are provided with a description of how their specific allocations are transformed into individual monetary payments. Since the experimenter controls the underlying values, we can both replicate the experiments and can also make measurements and comparisons across mechanisms by knowing the underlying preferences. For those interested in the details of experimental economics methods see Smith (1982)[9], Plott (1994)[10] and Kagel & Roth (1995)[11].

2.3 AN EXPERIMENTAL DESIGN

In order to test the difference in the performance and behavior of individuals in a Voyager Planning Process and the market-driven process described above, we plan to conduct the following experimental design. An environment which involves scheduling science observations is constructed. The experiment has seven subjects representing seven PI teams. Each subject is then given a table showing the "science payoff" if their observations are included in the final timeline. See Table 1 for an example payoff sheet for a subject.

The table represents tradeoffs for the Imaging Science System (ISS) for high resolution surface mosaics. It describes the science value tradeoffs for this investigation, and this observation in particular, over three revolutions (e.g., rev. 1, rev. 2 and rev.3) past Titan. The first two columns show the start and end time of the observation relative to Titan closest approach. The next three columns show the science return to the investigation by obtaining the corresponding start and end time for each revolution. So, if this investigation obtained time in the timeline from -02:20 to -01:00 on rev 2, they would get a science value of 70. This will be translated into dollars by a fixed proportional amount that will be kept by the subject. The table shows the tradeoffs for each combination of revolutions and various start and end times.

Start hh:mm	End hh:mm	rev. 1	rev. 2	rev. 3	rev. 1&2	rev. 1&3	rev. 2&3	rev. 1,2&3
-02:35	-01:00	80	75	70	95	90	85	100
-02:20	-01:00	75	70	65	90	85	80	95
-02:35	-01:15	70	65	60	85	80	75	90
-02:05	-01:00	65	60	55	80	75	70	85
-02:20	-01:15	60	55	50	75	70	65	80
-02:35	-01:30	55	50	45	70	65	60	75

Table 1. Science values for ISS high resolution surface mosaics.

Given the specified payoff tables provided to subjects, we can compare the performance of a Voyager-like approach and a market-based approach. We will also examine the robustness of the market-based system under different initial scheduling point allocations.

3.0 CONCLUSION

This paper has described a research plan to design and test a new method for planning and negotiating science observations. The current method of a hierarchical process of science working groups followed by challenges to the timeline, if applied to Cassini, would suffer from several ills. First, the process is time-consuming and much time and energy would be used to make and remake the timeline. Second, the use of simple priority designations and a notion of “balanced” science is not enough information for schedulers to make important science tradeoffs. The information needed to make these tradeoffs reside with the PIs. Third, the Cassini Science Office, using the current method, does not have the resources to support a mission of such complexity and duration.

A more direct way to obtain science tradeoff information in which participants are given an incentive to provide accurate information is through a market-based approach. The market-based approach that we consider is one in which participants are given fixed budgets of scheduling points that are allocated by the project. The points are used to provide an intensity of preference for the observations being scheduled. In this way, schedulers no longer have to limit themselves to only solving major conflicts. The schedulers just try to maximize the number of scheduling points that result in a conflict-free timeline. Incentives are placed on the participants because they have a fixed budget from which to make their tradeoff decisions. Another important feature of the proposed market-based process is that there will be feedback so that individuals can rebid based on the current timeline.

Since the proposed process is new and has not been tried in the context of planning science timelines, the processes will be tested and designed using experimental methods in economics. This method allows for the direct testing of the performance of resource allocation schemes. This methodology will be used to provide scientific evidence on the performance of mechanisms that are used to allocate and develop science timelines.

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Re-Engineering JPL's Mission Planning Ground System Architecture for Cost Efficient Operations in the 21st Century

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ABSTRACT

Over the last several decades, engineers at the Jet Propulsion Laboratory have developed a vast array of analytical tools to design missions to Earth orbit, the moon, sun, planets and various other bodies in our solar system, and beyond. Due in part to the unique objectives and requirements of each new mission, many early tools were developed in an ad-hoc environment to support the immediate needs of specific projects, with little thought given to developing an overall system architecture, maintenance, or reuse by subsequent projects. Nonetheless, the tools that emerged began to represent a rich heritage of mission design experience and capability.

In recent years, advances in computer hardware, modern programming languages, and the need for faster and more cost efficient operations for small missions have highlighted the need to streamline, consolidate, and generalize JPL's mission planning software. Realizing this, JPL's Multi-mission Ground Systems Office and Project Design Center have jointly undertaken the task of transforming existing "legacy" software into an integrated, general purpose, multi-mission tool set.

This paper summarizes ongoing efforts at JPL to re-engineer the mission analysis segment of the mission planning ground system architecture. Issues addressed include: developing a partnership between software developers and users, developing a consensus based architecture, evolutionary change versus revolutionary replacement, reusability, and minimizing future maintenance costs. The status and goals of new developments are discussed, and specific examples of cost savings and improved productivity are provided.

1. HISTORICAL OVERVIEW

In keeping with JPL's charter to explore the solar system, a variety of missions have been launched to various locations including Earth orbit, the moon, the planets, heliocentric obit, and to small bodies such as comets and asteroids. Mission objectives have included initial flyby reconnaissance, detailed orbital mapping, satellite tours, and surface landings to name a few. Until recently, activities have centered on a relatively small number of unique, first-of-a-kind projects, and most of the mission analysis software was created on an as needed basis by mission design engineers to solve their immediate problems. Because of the unique nature of each mission, little thought was given to reuse by subsequent projects. After all, how often was NASA likely to send a Viking style lander to a planet's surface, conduct a "grand tour" of the solar system like Voyagers 1 and 2, or explore an outer planet gas giant and it's moons like Galileo?

Computer systems have also changed greatly over the years. Before switching to mostly UNIX based systems, engineers developed and used software on early platforms such as the IBM 7044, 7094 and finally Univac mainframes. By comparison to modern engineering workstations, these earlier systems were much more difficult and costly to use. Frequently, the charges for computer time could greatly exceed the engineering labor rates. As a result, the mission analysis software that emerged favored minimizing computer run time for both development and operations, at the expense of ease of use, reusability, and therefore engineering labor charges.

2. CURRENT ENVIRONMENT

In the early 1990's JPL's Multi-mission Ground Systems Office (MGSO) began the Multi-mission Software Transition Project (MSTP) to port Univac based software to Sun and Hewlett Packard engineering workstations. The intent of the effort was to preserve much of the legacy software developed by prior projects for use by future missions as the laboratory made the transition from mainframes to micro computers. As work progressed in the mission planning area, it became clear that much of the mission analysis software being ported would not be directly usable by other missions. For example, some software developed for use by the Galileo project to Jupiter and its moons presupposed that the mission was in orbit around Jupiter, and that the spacecraft would fly by the four Galilean satellites. It also modeled the orbits of the Galilean moons as perfectly circular, with no inclination with respect to Jupiter's equator. Clearly, this software was developed under the assumption that saving computing cycles was more important than obtaining a high fidelity result, or to be useful to any subsequent project. Realizing these shortcomings, the task objectives expanded to make the software as applicable to other missions as reasonably possible. This included general features such as making the central body for spacecraft orbits a user input, and causing programs to access standard planetary and satellite ephemerides for the bodies of interest instead of using a hard wired approach.

Other forces were at work during the early 1990's as well. NASA's out year budgets began to show increasing reductions, and it became clear that the days of costly "flagship" missions were over. JPL management repeatedly communicated the top level direction from NASA Headquarters to the work force: conduct missions that are faster, better, and cheaper. Therefore, the emphasis switched to performing a larger number of smaller, less expensive missions. This further highlighted the need to create an institutionally supported, multi-mission software base, since it was clear that the many small missions would not have sufficient time or money to develop their own tools. Perhaps more importantly, the tools would need to be easier to use, thereby allowing project analysts to spend their resources designing a mission rather than struggling with difficult, uncoordinated, and error prone software. By addressing the problem in this light, it became evident that improving ease of use satisfied "faster", integrating applications and streamlining information flow to reduce errors meant "better", and the combination of saving time and reducing errors inherently satisfied "cheaper".

3. FORMING PARTNERSHIPS - USERS, DEVELOPERS, MANAGERS, SPONSORS

As the MST effort to port software from the Univac to UNIX systems neared completion, the budgetary and technical considerations outlined in the preceding sections became increasingly clear. Users and developers of mission analysis software had long known that the system needed to be re-engineered, but the MST effort funded by the Multi-mission Ground Systems Office helped to bring the issues to the forefront. As a "grass roots" initiative, a special meeting of the Mission Design section was called in the fall of 1993 to provide users and developers a forum to discuss their views on the current status of mission analysis software, and to suggest possible courses of action.

The special section meeting was well attended, and it soon became clear that there was a ground swell of support to resolve a number of problems. Meeting members identified six main topics to address including: software standards, organizing known software tools, introducing modern computer graphics techniques, improving use and maintenance of modern computers and networks, coordinating related software efforts to maximize shared benefits, and finally, how to obtain institutional support to build a greatly improved multi-mission software system. Leaders were selected to represent each of the six areas, and a series of panel discussion meetings were held over the next several weeks to discuss issues and form recommendations for a plenary session. Line managers made a strategic decision not to take part in the panel group activities, in order to avoid dominating discussion or discouraging a frank exchange of views.

A follow up section meeting was scheduled by the section manager for the panel groups to report their findings, and make recommendations. Ultimately, all recommendations were accepted in principal, including the recommendation to reorganize the section to create a group to consolidate related software activities. Although the final recommendations were very close to those of the few people who instigated this distributed effort, significant value was added by involving a large number of concerned people. In the end, users, developers, and managers had a shared vision of what should be done, and how to proceed.

After forming the new group, early benefits were realized as members gained greater awareness of related activities, and how tasks could be coordinated to reduce unnecessary duplication. However, there was still no defined architecture for the desired mission analysis system, nor were there dedicated resources to create one. In order to devise a workable plan, developers realized the need to evaluate the section's current software inventory, and to identify the missing components. This information could then be used as a starting point to define the requirements, which would then be modified based on the inputs of experienced mission analysts. The Mission Design section's burden account and JPL's Project Design Center (PDC, funded by the laboratory's internal burden structure) provided a small amount of funds in fiscal 1995 to carry out this survey effort.

Mission design personnel conducted the survey, and the results were discussed in joint steering group meetings involving users, project representatives, developers, and managers. Participants discussed the status of current tools, and how the system could be improved. Eventually, the teams reached consensus on classifying existing applications in one of three categories: "core" capabilities, utilities and mostly redundant programs that could be made into library functions or included as options in a core program, and a list of programs to ignore, and no longer track. Twenty programs qualified in the "core" category. This did not necessarily mean that these were the programs to keep, or that they even existed in the desired state; rather that the programs represented the kind of capabilities desired. Another sixteen programs fell into the utility or mostly redundant category, and the steering group classified roughly another 200 programs to no longer consider, since they were either too mission specific, or obsolete. At the time of the survey, only a handful of the programs in any of the categories were funded for development or maintenance at any level.

During the summer of 1995, MGSO issued it's annual call for continuous improvement proposals. Using the results of the survey as a starting point, the steering group reconvened to develop proposals to begin implementing a new mission analysis architecture, and to satisfy the specific objectives of the proposal guidelines. Three proposals emerged, reflecting the steering group priorities. The proposal objectives were to: develop new software to automate the production of standard trajectory products; create a three dimensional mission plan visualization capability; and to integrate mission analysis software into a synergistic system. Performance objectives were scoped to fit within budgetary guidelines, and specific references were made to coordinating proposal efforts with other JPL sections, divisions, and external organizations such as Purdue University, the University of Minnesota, and Lewis Research Center. Developers, project managers, users and line managers discussed and iterated the proposal objectives, and letters of endorsement from the involved parties were attached to the final proposals.

Ultimately, all three proposals were selected and funded for fiscal year 1996, which was especially remarkable since no mission analysis proposals had ever been selected in prior years. The Project Design Center also agreed to provide considerable funds to help fill in the gaps of the more specific MGSO proposals. Finally, the mission analysis software effort was funded to implement the plans developed in conjunction with their customers. The remainder of this paper describes the architecture that has emerged, reports the status of ongoing efforts, benefits realized, and plans for future efforts.

DEFINING KEY MISSION ANALYSIS FUNCTIONS

The first major step in defining an architecture was to clearly establish the major functions of mainstream mission analysis software, as graphically illustrated in Figure 1. The first column represents trajectory generation functions, where mission designers develop a flight path to satisfy mission objectives. The second column represents analysis to determine the timing of various events such as maneuvers, science sequences, solar occultations, and down link view periods, and the third column is used to perform general geometric calculations.

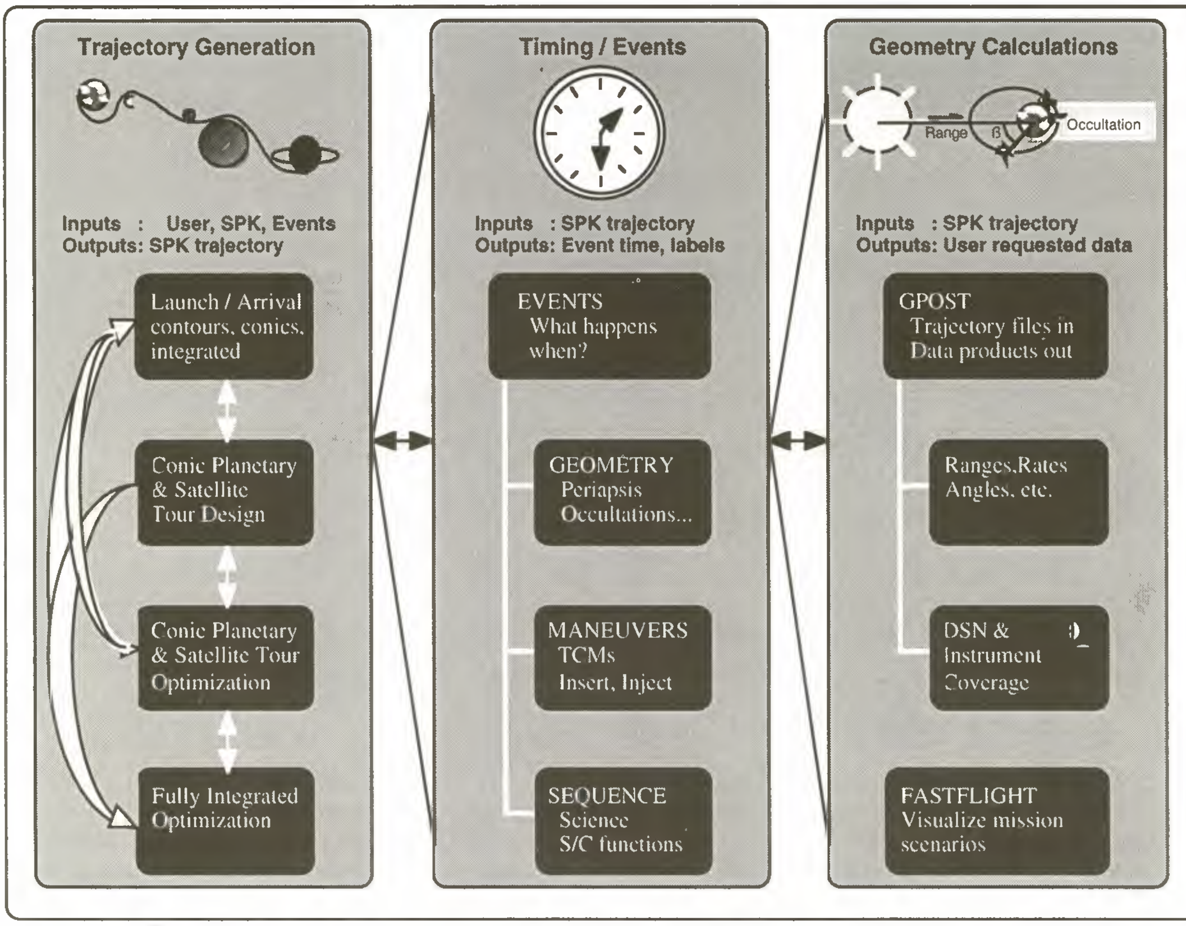

Figure 1: The mission analysis process can be diagrammed as a series of iterative refinements, suggesting a hierarchical, modular structure of trajectory generation, events, and geometric calculation.

The Cassini mission to Saturn exercises much of this capability, so it will be used as an example of how the functions are related. A designer may begin by examining launch / arrival contours commonly referred to as "pork chop" plots to find minimum energy transfers from Earth to Saturn. After determining that a direct trajectory to Saturn requires an unacceptably high launch energy, the analyst may consider using one or more gravity assists to reduce the propulsive requirements. Launch energy contours to other planets or multi-year Earth phasing orbits can be examined to search for alternate opportunities. After determining that a multiple gravity assist trajectory to Saturn might exist, the analyst might use a conic trajectory optimization program to test the hypothesis. In this case, the trajectory involves launch from Earth, two Venus flybys, another Earth flyby, a Jupiter flyby, and then entry into orbit around Saturn. The simple conic program requires only a rudimentary initial estimate of the times of the planetary flybys in order to optimize a trajectory to minimize the total Δv.

Once a candidate orbit is found, the analyst can further optimize the trajectory subject to a variety of mission constraints such as launch period requirements, minimum flyby altitudes, and many others. Finally, the trajectory can be refined using more sophisticated, fully integrated acceleration models (n-body gravitational attraction, higher order gravity harmonics, solar radiation pressure, atmospheric drag models). Ultimately, a viable flight path to Saturn can be found.

After the spacecraft arrives at Saturn, it enters an orbit that will allow many flybys of Titan and the other Saturnian moons. A conic program is used to search for natural targets of opportunity, and adjust satellite flyby parameters to allow multiple gravity assists to steer the spacecraft towards its next target while minimizing the total Δv necessary to accomplish the mission. Many possible satellite tour scenarios exist, and options are chosen to satisfy science goals, as well as spacecraft and mission operations constraints. These constraints are analyzed using software represented by the Timing / Events column, and the Geometry Calculations column After the tour is selected, it, too, can be optimized using the fully integrated trajectory optimizer. At any point in the analysis, pre-determined constraints or unforeseen circumstances may require the analyst to recycle the entire effort, and iterate the whole process many times until a satisfactory solution is found.

The scenario outlined above seems like a conceptually interesting task, with enough technical complexity to keep analysts challenged and involved. Ideally, the software tools needed to execute each stage of analysis would be easy and intuitive to use, and seamlessly integrated. Relevant data would pass automatically between related applications, and the mission designer would spend the majority of time conceptualizing solutions, and discussing them with other scientists and engineers as part of an integrated design team. This desired state is the goal of the mission analysis re-engineering effort. Historically the existing tools have been very difficult to use, and have required the user to spend more time struggling with difficult applications and interfaces than performing creative analysis.

RE-ENGINEERING PHILOSOPHY AND CONSTRAINTS

Once the re-engineering effort was funded, developers and managers got together to define the new architectural framework for mission analysis software to create the desired system. In order to encourage "stretch goal" thinking, team members were initially instructed to envision the desired system without regard to existing software. This was done to prevent hasty implementations of specific interfaces and stop-gap modifications to existing tools to meet short term objectives at the expense of long term use. Certainly, the "sunk cost" of existing tools and libraries would strongly influence final implementation plans, but developers didn't want to be overly constrained in their approach.

The most significant trades to consider in developing the new architecture were: evolution versus revolution (modification versus replacement); quick fixes to satisfy immediate user desires versus long term use and maintenance; control versus trust (how much users influence the developer's implementation); and how often to convene steering group meetings to report status and adjust priorities. Ultimately, the team decided that shortcomings in existing mission analysis software were due largely to hasty user implementations of immediate, mission specific needs, without regard to future applications. Therefore, these issues were decided in favor of long term benefits, with a few exceptions in compelling cases to meet project needs. Many users stated that they had spent enough time discussing their goals and requirements as members of the proposal team, and that they wanted to return to their work and trust developers to do their jobs.

STANDARDIZING INTERFACES

One of the desired features of the new mission analysis system is seamless exchange of relevant information between related programs. One approach would be to simply write "glue functions", or specific utility programs to take the output of program "A", massage it into the desired format, and then write it out as an input file to be read by program "B". Due to the iterative nature of the mission analysis process, it might also be necessary to create yet another utility to transfer information from B back to A. Given a sufficiently small number of programs, this scenario might be workable. However, as Figure 2 demonstrates, the number of two way interfaces increases rapidly as additional programs are included in the system. In fact, the number of connections scales by (n(n-1)/2) where "n" is the number of programs in the system. Because of this, a standardized data interface was developed based on the JPL's Navigation Ancillary Information Facility "SPICE" kernel capabilities. SPICE is an acronym where each letter represents a significant, unique capability. In the scope of this discussion, the mission analysis system chose to use the "S" kernel (reads and writes SPK files) to represent the trajectories of spacecraft, planets, and satellites, and the "E" kernel to organize relevant events. One of the benefits of the SPK system is that the orbit information can represent a simple conic, or an integrated trajectory with many flybys. Programs that use this capability can then create or read trajectory information, and issues such as changing central bodies for spacecraft orbits are handled automatically. Using this scheme, the number of two way interfaces is simply "n", so it is far easier to maintain an integrated software set.

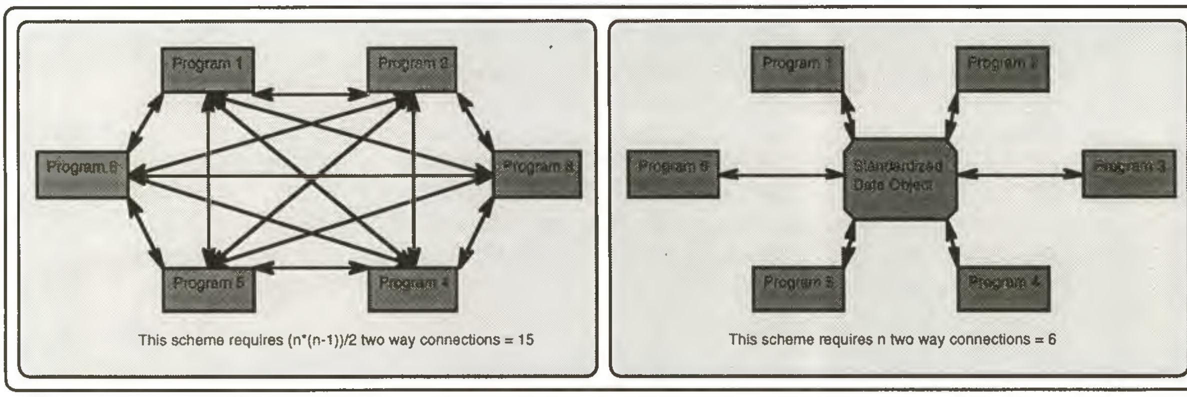

Figure 2: Standardizing trajectory and timing data in a standard format simplifies interfaces.

MODULARIZING MISSION ANALYSIS FUNCTIONS

Examination of the software that remained on the supported list after selection revealed significant overlap of key functions. Figure 3 shows six unique programs that were developed to numerically integrate trajectories, given a specific mission scenario. In some cases, a program has a unique physical model lacking in other programs. For example, CAESAR had a comet outgassing pressure model to use while orbiting a comet, the Planetary Observer Program (POP) set was customized to model terrestrial planets using higher order gravity harmonics, while LUNTRJ and the Goddard program SWINGBY included gravitational attraction of the Earth, moon, and sun. The only program funded for development or maintenance at any level was FAST which has been a core program for nearly 25 years. Between the time the group formed to consolidate efforts and the proposals were funded, the CATO program (Computer Algorithm for Trajectory Optimization) was being developed to optimize fully integrated trajectories involving multiple flybys. CATO was developed for Cassini to replace the MOSES multi-conic trajectory optimization program set used by Galileo for the satellite tour at Jupiter.

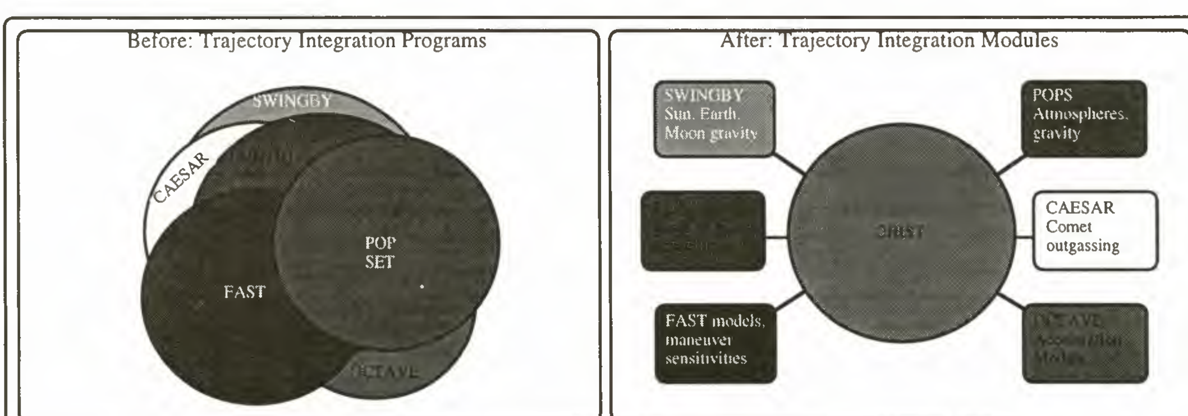

Figure 3: A single general purpose module replaces overlapping functionality, resulting in lower maintenance costs.

Initially, developers tried to adapt FAST to be the trajectory integration module used in CATO, but this plan was abandoned after considerable effort, since the desired features in FAST were distributed all through the complex program. Therefore, a new trajectory integration module called GRIST was written in object oriented FORTRAN 90 to be both a stand alone trajectory integration program, and a module to be called by other programs. Since GRIST was written to be useful to any class of mission, it was designed to integrate trajectories modeling an arbitrary number of gravitating bodies (any combination of sun, Earth, moon, planets and their satellites, comets and asteroids), gravity harmonics, solar radiation pressure, nine different atmospheric models, and other acceleration models as desired. Once GRIST was designed to solve the general problem, it represented a superset of the capabilities of the programs it replaced. If a desired acceleration model is missing in Grist, such as a specific comet outgassing model from CAESAR, it can be included as another term on the right hand side of the differential equation of motion.

The remaining mission analysis programs have other similarities, in addition to trajectory integration. Most programs calculate geometric quantities to help design trajectories, determine instrument coverage or telecommunication links to a ground station, or some other purpose. In existing stand alone programs, a large percentage of the code is typically devoted to keeping track of complicated data , vectors, and coordinate systems to make these calculations. Another function common to many programs is the need to search for and keep track of events that occur, such as propulsive maneuvers, science viewing opportunities, and entry and exit of solar occultation. In some cases, these events are unique to the mission or are specified by the user, but many events are calculated based on a geometric quantity (such as occultations and ground station view periods). Realizing this, two more modules were identified as core features, an events finding module (EVENTS), and a geometry calculation module (GPOST - General purpose post processor). In both cases, the modules were designed to be used either as stand alone programs or as part of another program.

Figure 4 shows a top level view of how the pieces fit together. The left-most block represents a generic mission analysis program, which performs a trajectory design function. Using satellite tour design as an example, the application will model a conic obit around a planet, and perform calculations to target multiple flybys of the planet's satellites. As the program is used to build up a tour, events such as maneuvers and satellite encounter times begin to accumulate. Geometric quantities are also calculated, and may be related to viewing geometry of the science instruments, for example. This information helps the mission analyst design the tour to meet the mission objectives. Ultimately, the program will produce some sort of graphical or tabular output.

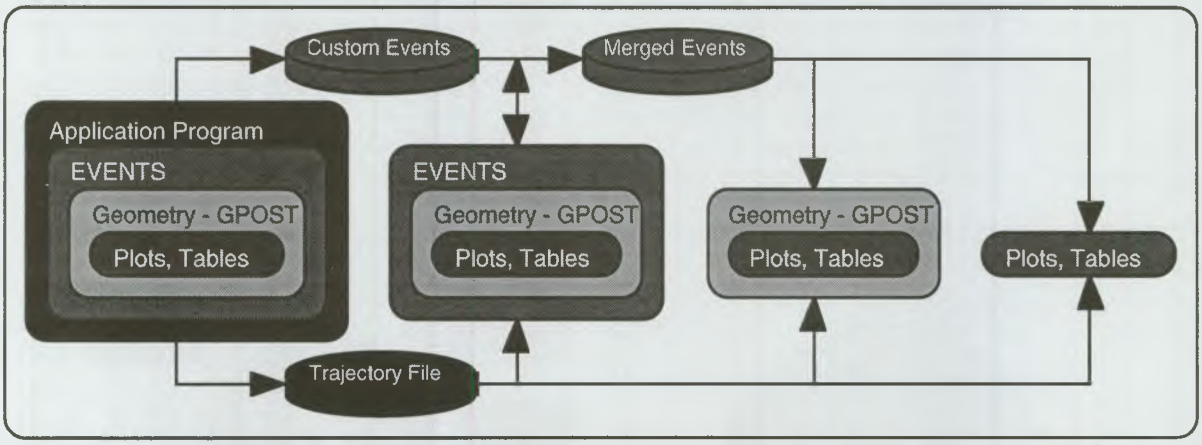

Figure 4: The new mission analysis software architecture shows the inter-relationship and reuse of common modules.

After running the satellite tour program, the custom events related to the tour are written out in a standardized format to be read by other applications downstream. In the diagram, the custom events and the standardized trajectory file are used as inputs to the EVENTS module, which can be used to calculate any number of user specified occurrences such as flux tube crossings. The EVENTS program would then produce a merged events file containing the information from the tour design program, and the unique occurrences requested. This information could then be passed to GPOST to calculate standard trajectory products such as ranges and range rates to Earth ground stations for telecommunications analysis, and the range to the sun for power and thermal considerations. Finally, the information can be plotted or tabulated in a specified format. The main message contained in Figure 4 is that most mission analysis applications have much in common, and that by identifying the major modules and designing them in a general, multi-mission fashion, they can be readily used to construct new applications while minimizing duplication of effort, and preserving standardized interfaces for a more synergistic system.

COST SAVINGS

The most important consideration in re-engineering JPL's mission analysis software has been to increase the productivity of the mission analyst, thereby saving projects considerable time and money. Equally important, however, is the cost of new developments, and the projected cost of maintaining the new system. By eliminating unnecessary redundancy and mission specific implementations, there are far fewer programs to maintain, and also fewer programs for the users to learn.

The CATO program is a good example of cost savings realized from the new architecture, Originally, CATO was only intended to replace the MOSES software set for optimizing satellite tours around outer planets. The PLATO software set was another large package, but it was intended to optimize trajectories in heliocentric space with planetary flybys. Conceptually, the two systems were very similar, so a decision was made to make CATO as general in nature as reasonably possible, and thereby replace both sets. In essence, the algorithms were formulated without making any assumptions about what bodies would be involved, whether they were planets, satellites, asteroids, comets, or any combination. Ultimately, the CATO program was delivered to the Cassini project with only an insignificant addition of cost and schedule.

After delivery, several projects realized significant cost savings due to the general purpose nature of CATO. Initially, the Cassini project only intended to use CATO for satellite tour design, but their first use was to optimize the complex interplanetary Earth-Venus-Venus-Earth-Jupiter-Saturn trajectory and produce the target specification in far less time than planned. Although developed as a Cassini product, the Galileo mission used CATO to perform an end to end optimization of the tour at Jupiter, which was not possible with earlier software. Several small mission studies requiring complex trajectories in the Earth-moon-sun system were able to reduce their propulsive requirements by using CATO to optimize their trajectories. And finally, the New Millennium Deep Space 1 mission using solar electric propulsion (SEP) to reach an asteroid successfully used CATO to model the low thrust burns and optimize the trajectory to the target. The New Millennium program will devote some funds to augment the CATO effort to make it easier to use for SEP analysis, but there are large savings realized by starting with a general purpose, multi-mission tool.

CONCLUSIONS

After decades of relative isolation, JPL flight projects and studies alike are beginning to reap benefits from the new partnership formed between mission analysis software users, developers, managers, and institutional sponsors. By coordinating a large number of tasks, it has become clear that many mission specific applications have much more in common than initially thought. Modern computer platforms, networks and language features have enabled a significant re-engineering of the mission analysis infrastructure, while eliminating unnecessary redundancy and cumbersome interfaces. Benefits include increased productivity, multi-mission applicability, error reduction, and reduced maintenance costs.

More work needs to be done, however, as the new system is integrated both internally, and with the software tools of related disciplines. Although most of the major analytical components are nearing completion, details of the user interface and interprocess communications are still under development. Also, plans are currently being made to integrate the best features of mission analysis software with those of the navigation system.

ACKNOWLEDGMENT

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GLOBAL OPERATIONS FOR THE NEXT CENTURY

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ABSTRACT

The future brings a continuing need for state-of-the-art cost effective operational systems. These systems must support and keep pace with escalating Satellite and Telecommunications (SAT) services. Space programs continuing to develop futuristic computer and telecommunications system will also demand advanced operational systems. To be effective operational system designers must centre on using rapid prototyping, collaborative computing technologies, and Commercial Off-The-Shelf (COTS) products that operate on open platforms. This paper describes a New Century Architecture (NCA) representing a typical future operational system using where possible vendor independent, shareware and COTS systems. The time frame between 1996 - 2010 fits an NCA development cycle for two reasons: (1) it permits existing systems to upgrade and not be encumbered by transition problems during current day-to-day operations, and (2), a minimum of 3 to 4 years is needed to bring NCA innovation cycles from initial concepts to general availability within operational applications.

1. TRENDS

The Internet causing dramatic changes in the business world is fundamentally altering the organisational structures of our institutions and the living conditions of our society. Looking toward the next century, it will be imperative for private enterprises, telecommunications organisations, the space industry and countries to exchange technology on world wide basis. Business will lead demand for (SAT) services and international data communications will remain the fastest growing parts of business traffic.

SAT Demand will force a significant shift towards end-to-end cost effectiveness following similar digital transmission and storage of information trends witnessed in telecommunications. Continued deployment of digital technology permitting different modes of information (voice, numbers, text, image, graphics, video) to be transmitted and manipulated via hardware and software components will result in lower development and operating costs using less physical space and fewer people.

Developers will rethink and re-engineer basic SAT processes with the goal of reducing overall programme expenditures. In all respects this may become a necessity because of declining government budgets, which as everybody knows has already resulted in business mergers, reconsideration, reduction or complete cancellation of various projects.

2. SAT BUSINESS FACTORS

Five business "Factors" will shape SAT development

Corporate Networking - Common user networks coupled to the Internet will support new business applications; a growing emphasis will be placed on using SAT networks to implement intranets for increasing access to corporate databases, building links to customers, suppliers and so on.

Satellite Backbones - Fixed ground and mobile user stations provide economic justification for combining dispersed networks to support corporate resources. INTELSAT, for example has already demonstrated that its fleet of 24 satellites are able to provide global access to the Internet.[1]

Privatisation - More and more corporate and government organisations will take responsibility for their own SAT networks; installing satellite links, high speed multiplexors, private transmission and specialised switches saves time, money and increases control of information.

The PC revolution - Computing and SAT becomes down sized and distributed. The Internet interconnected to the PC, whether at home or in the office opens a inventive communications era requiring new SAT structures to overcome limitations on existing networks. WEB subscribers has gone from 2 million in 1994 to more then 30 million by June 1996. Introduction of a WEB PC may further advance the revolution by offering a cheap computer that discards heavy memory use, OSes, specific applications, and bloated platforms.

Data communications growth - In 1985 corporations were spending 30% of their telcoms budgets on voice and 20% on data. Voice has been growing at six percent per year and data at 40% percent. It should also be noted that GSM is growing in a similar manner and it is estimated that by the year 2000 half the information over the GSM network could be data.

The simplest way to describe the growth in SAT systems is by one word ***"access". Access*** to SAT networks has created three businesses: (1) the transmission business, (2) the storage business and (3) the understanding business.

By the year 2005, almost all segments of society will include individuals who will be in the **understanding business**. These individuals will be the users of SAT systems - and be affected by or be dependent upon SAT systems in their daily work or leisure time. Requirements will vary greatly, depending on their jobs, and how interactive they become. SAT users and their modi operandi can be described by large number of characteristics, which this paper will not go into. These characteristics are not by any means, independent of one another, but many of them are nearly so. Even with tremendous change in technology the following facts will remain:

- ☹ users' needs are not adequately fulfilled today; and
- ⌛ users' needs and expectations will increase and expand with time.

Tomorrow's SAT systems must adequately serve its users. It must provide functions in a manner users expect, when needed, and at a cost users consider reasonable.

3. OPERATING ENVIRONMENT

SAT based information systems including sensor monitoring, data collection, and analysis already has produced major impacts upon operating environments. SAT driven computer models of the weather system are greatly improving long-range and large scale weather prediction. Imaging of air, ground and water pollution provides a better understanding towards forecasting. These missions include defining and measuring air quality and the effects of pollutants, thereby, introducing methods to control, for example, motor vehicle traffic patterns, stationary pollutant sources, and so on. Operational aspects of these systems requires sorting large data files in a highly structured fashion while providing their manipulation in a user-oriented language, plus accurate handling of

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[1]Satellite Journal International - Vol. 4, Issue 10, 15 May, 1996.

computational problems, rapid turn around time, and time sharing of hardware and softwsre resources.

Developing global interfaces to accommodate this constantly growing demand of unpredictable traffic volume is a primary NCA design goal. Designs must cope with increased intermingling of different traffic types, some of which are not even available for study, coupled with Internet traffic, valued added services, data bases, applications software, etc. How will NCA systems be designed, measured, dimensioned, controlled? Present lack of traffic level and characteristic data makes design, forecasting and control problems very difficult indeed. NCA operational structures must be insensitive to traffic characteristics and provide rapid and convenient rearrangement and reprocessing facilities to maintain performance standards during periods of growth or change.

4. NCA DESIGN TECHNIQUES

NCA development must have a coherence between Design, Development and Operational Phases.[2] Employing NCA technology, tools and methods provides an opportunity to bring about a condensed life cycle resulting in reduced cost and time without sacrificing quality.

Achieving this objective requires NCA building blocks to be small dedicated modules, each designed with processing and performance levels to accomplish a single task.[3] Each module contains a high degree of regularity among functions implying an ability to share logic among other modules, thereby, reducing both maintenance and operational manpower costs whole instilling a strong effect on ease of programming.

Developing small dedicated modules can decrease elapsed project time by between 30% to 50%. Total effort (i.e. number of man hours) for the same development process can be expected to decrease by between 25 % to 40%. Quality is greatly enhanced not only because of size but also due to simulations performed within all development stages of an NCA life cycle.

Significant reuse of hardware and software components are incorporated in NCA modules so that functions can be shared. Cost effectiveness is achieved by using low-cost COTS components coupled with an ability to install additional capacity, when required, in small increments.

5. NCA SOFTWARE DESIGN APPROACH

Simulations becoming standard NCA design features provide methods towards switching from traditional programming life cycles to systems employing System Description Languages (SDLs). SDL changes programming concepts and provides for increased valuation during early design stages, a must for NCA systems.

A simple overview of SDL compared to a traditional system design is shown in Figure 1

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[2]Annamaria Piras, Cesare Capararo "A Structured Methodology for System and Operations Design" Systems Engineering Workshop ESA/ESTEC, Noordwijk, November 1995.

[3] LT Col Nancy L. Crowley, Ms Christine M. Anderson, Capt Douglas E. Dyer " Multimission Advanced Ground Intelligent Control (MAGIC) Architecture Development" DASIA 96 Hotel Parco dei Principi, Rome, Italy, 20-23 May 1996.

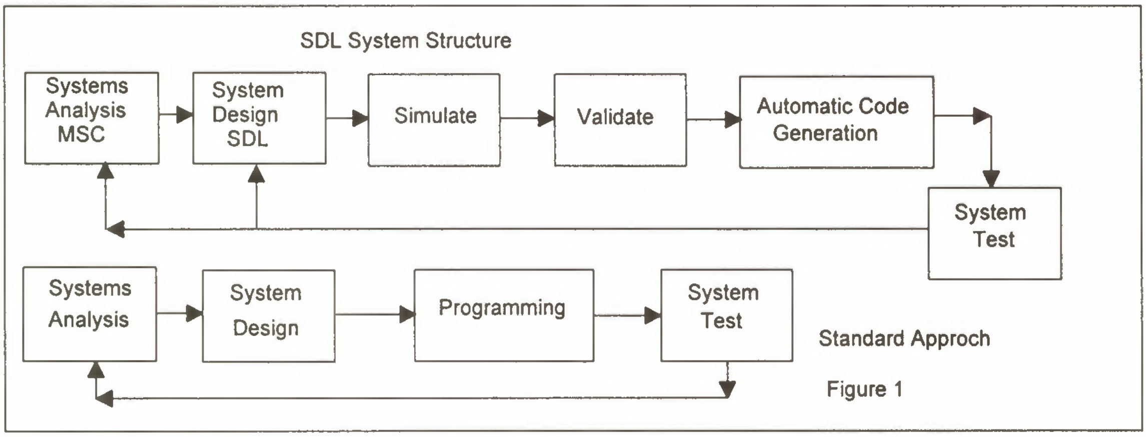

Figure 1. SDL System Structure

As shown in Figure 1, SDL development proceeds along through 5 phases.

① In the systems analysis stage, designers analyse requirements and the interactive behaviour of a NCA system and build user interactions in chart form.

② System Design stages build Specifications which involve building an SDL diagram of the blocks and processes that describe the system.

③ The simulation stage builds interactive models of the systems operation so to test design assumptions.

④ The verification stage consists of internal SDL logic checking the SDL diagram for syntactic and semantic errors, which can be corrected interactively.

⑤ Once the system has passed validation, it can be instructed to generate "C" code or a specialised simulation language which can be used as input to a simulations model, which will test and reveal run time logic errors that escaped the validation phase.

Results are C-coded test suites that are independent of both the target system and the application. This means that the generated code suites any test structure supporting "C". It is estimated that SDL Real time development tools can improve productivity in the order of 50% to 60 %.[4]

6. A COTS APPROACH TO SAT DEVELOPMENT

Building a SAT mission can be accomplished using a set of integrated COTS tools. To illustrate the concept, we will use three separate COTS tools supplied by Analytical Graphics, Inc, Satellite Tool Kit (STK), Satellite Tool Kit Programmers Library (STK/PL), and Satellite Tool Kit Visualisation Option (STK/VO). Figure 2 shows the relationship between these three modules.

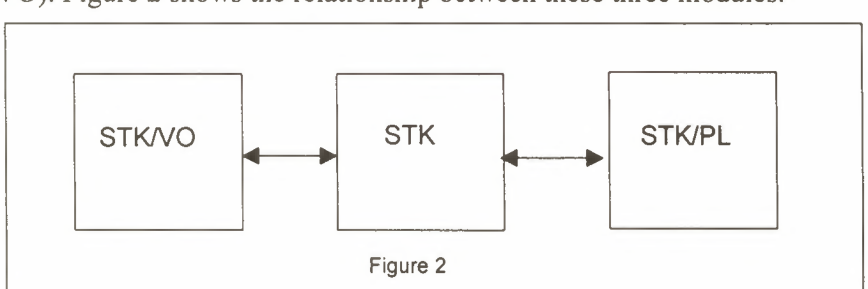

Figure 2. COTS Tools

[4] The following vendors supply SDL type systems: Telelogic Ab of Malmo, Sweden and ObjectGeode produced by Verilog of Bagneux, France. An early reference to the subject where the concepts were first used was the respecification of the Apollo Guidance Computer - Software Design Techniques 4th Edition, IEEE Computer Society, " The relationshipBetwen Design and Verification , M. Hamilton and S. Zeldin, Higher Order Software, Inc Cambridge, Mass. 1979.

The base STK system lets the user:

- Propagate vehicles (satellites, aircraft, missiles) to determine position and attitude data
- Display coverage areas
- Calculate and display access times between defined systems components

In general, the user can generate paths for vehicles (both orbiting and non orbiting) to determine access conditions between vehicles, targets, and facilities. Figure 3 shows the possible options that a user can select, for example, using a vehicle, i.e., movable land, sea, air or space objects

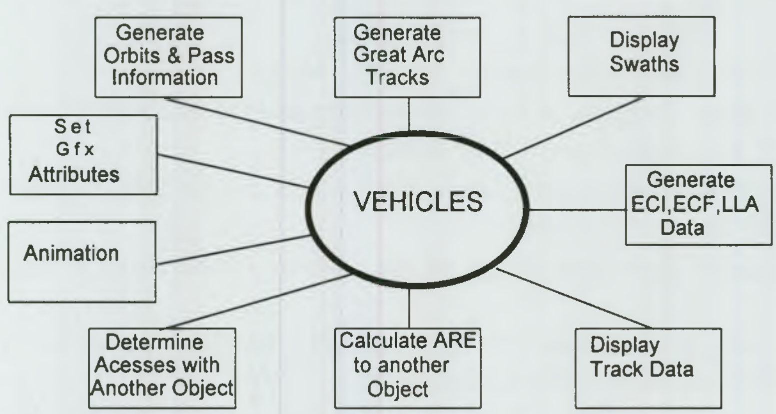

Figure 3 Vehicle Objects

Figure 3. Vehicle Objects

The interconnection of STK to STK/VO provides the user with a three dimensional viewing capability that provides mission and orbit analysts an intuitive view of complex SAT mission and orbit geometry by displaying realistic 3D views of space craft, sensor projections and orbit trajectories. Interconnection of STK/PL provides the user a set of tools that contain high level Astrodynamics, Graphics and User Interface routines and low level functions such as list and stack management, database and parsing routines.

It is the purpose of the software structure to provide a uniform framework for developing a SAT mission scenario within a heterogeneous computing, communications and applications environment. The communications environment includes several different individual network designs.

Interconnection to user applications can be accomplished by adding an Inter process Communications Module (IPC). IPC enables a user to work with STK in a client-server environment. Through IPC, a user application can load a vehicle into a STK scenario, determine access intervals between objects, and return those intervals to the user application for specialised analysis and processing. Real-time information, such as telemetry data from an actual vehicle can be passed to STK to build a scenario, in real time, complete with attitude and position information.

At the workstation level, IPC can be connected to either a Unix or TCP/IP Socket, while at the PC level, the interconnection can be Ethernet or Token Ring. The approach taken is to integrate STK tools into a resource sharing computer network under a single monitor and file system and make all

STK tools uniformly accessible to designers, programmers, project managers, and operational personnel. The communications structure sets the states for the interconnection and transmission of data and a status indicates (1) what data has been successfully sent, (2) indication when data can be sent, and (3) indicate what data has been correctly received, and which sends or receives may be in trouble and the nature of the problem.

This configuration is shown in Figure 4.

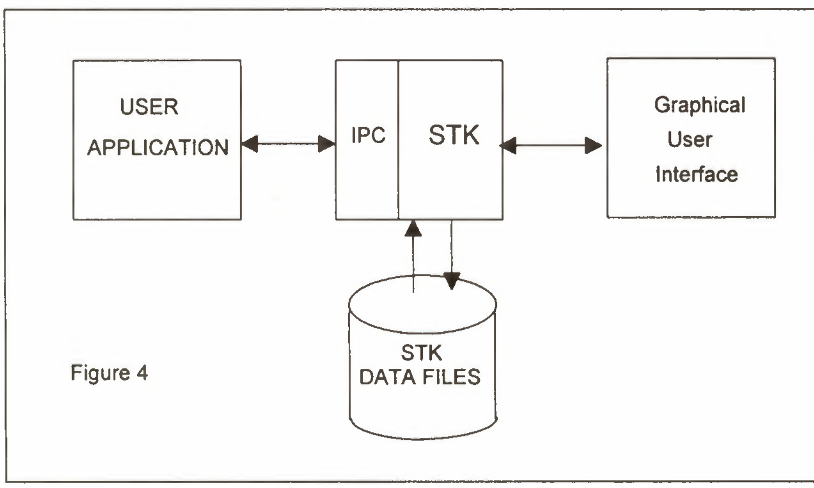

Figure 4. Communications Interface

To summarise, COTS systems coupled with technological advances in storage/processing logic and interconnecting structures used in an NCA system will reduce systems costs dramatically. NCA using COTS will attract a large community of users. Also users of existing systems will see the benefits of adding functions by installing COTS systems. The next section demonstrates how the COTS system explained above fits into an NCA system

9. NCA HARDWARE ARCHITECTURE

Major design goals for the NCA are high processing power, large memory capacity, high reliability, low cost, modular structure and flexibility. These goals can be realised through a structure where each module has its own operational structure and can perform tasks independently using existing COTS software wherever possible. Developed code would be in the form of object-oriented structures to provide flexibility and reuse among, for example Telemetry, Tracking Control and Technical Operations Control.

Each Module by means of a Network Interface has full access to other modules providing exchange of control and data information. The structure envisioned would be Windows NT operating with a PC base connected to a network. The PC interconnected through the network to an SQL Server provides a database structure providing information links between, for example, operational analysts and mission management. TCP/IP, Ethernet Routing and MAC OS support are all part of the standard NT package. Dual network interconnections can be provided to achieve desired access redundancy goals, with internal logging and backup functions for all information that is critical.

Figure 5 shows a block diagram of a typical architecture.

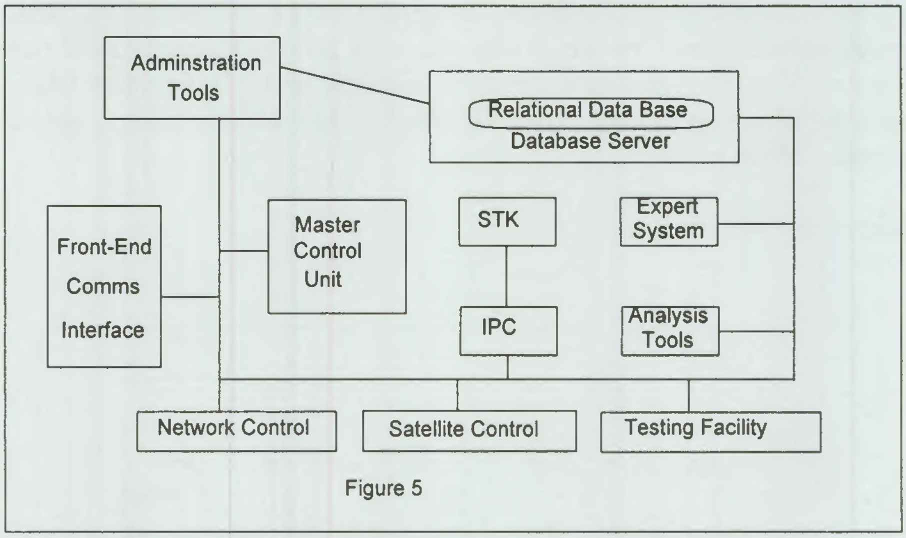

Figure 5. NCA Architecture

Internally, NCA is a multiprocessing system, but it is a unique application of multiprocessing in two respects. First, operational personal are totally unaware of its operating nature. Second, each Processor Module (PM) is dedicated to a specific computing function. For example, within the Master Control Unit, one process is dedicated to telemetry processes, another to command encode, another to command decode, whereas PMs connected to the network operate as single units with one processor dedicated to satellite control, another contains required analysis tools, another providing administrative functions, and so on. STK, for example, could be used to analyse changes in orbit positions received from telemetry data against original models calculated for a mission.

All PMs have a queuing mechanism for receipt and transmission of messages, and all PMs can be active simultaneously. Data passes from PM to PM as different activies occur. The Front End Comms Interface (FECI) acting as a fixed station is the intermediary between gateways and SAT communication, e.g., sensor data, data communications, control information utilising down link, up link or terrestrial transmission. Currently, many of these front end systems are proprietary stand alone structures but they will be replaced by sets of logic cards being inserted into PC expansion slots running under Windows NT. NT Systems equipped with Alpha or MIPs CPUs or even multiple Pentiums can overcome throughput requirements offering a price/performance advantage.

10. CONCLUSIONS

This paper has portrayed changes in operational structures as a result of a shift to COTS software. Systems generated by individuals and organisations creating and taking advantage of the opportunities provided by COTS software structures will become sufficiently large and far-reaching to collectively comprise a technical advance to operations planning.

User needs for operational flexibility, allowing continuing adjustment to exiting systems will continue to grow. An important contribution to this process is the technical and cost benefits of using COTS. The next century will see more and more operational services provided by new generations of COTS . These will emerge from new service provider organisations, who are willing and able to put technology to work to satisfy a growing number of users. The fundamental point about using COTS

PREDICTING SCHEDULING SUCCESS

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ABSTRACT. An analytical formulation is derived to predict the success of scheduling activities on discrete multiple resource time lines using sequential approaches. Success is defined in terms of the probability of scheduling a single activity and the number and cumulative duration of scheduled activities. The results are extended to include scheduling activities with flexible start times. The principal assumption is that the activity start times are randomly distributed over the available time in the time line.

1. INTRODUCTION

This analysis addresses a type of scheduling problem frequently referred to as activity scheduling. Each activity is assumed to use one of a set of equivalent resources. Each resource can be used to perform only one activity at any time. The activities are independent and have no predecessor relationships. Each activity has a specified duration and start time, although the possibility that the start time is flexible is also considered.

Scheduling becomes challenging when not all of the activities can be scheduled because of conflicting demand for the resources. The question then becomes: which activities get scheduled and at what times, and which do not get scheduled?

Ideally, an objective should be defined that can be used to identify the optimal schedule and select a scheduling approach that achieves or nearly achieves an optimal schedule as defined by that objective. A typical objective might consist of maximizing the sum of values assigned to each scheduled activity. If the value were the same for each activity, then maximizing the value is equivalent to maximizing the number of scheduled activities. If the value were proportional to the duration of the activity, then maximizing the value is equivalent to maximizing the total time scheduled.

Because optimally solving such problems is complex, most approaches do not attempt to achieve optimality directly and have resorted to a sequential scheduling approach (see Figure 1). A sequential scheduling approach typically begins by using heuristically determined metrics to order the activities by priority. It then considers each activity in priority order and attempts to find an available time for using one of the resources. Assuming such a time exists, a second heuristic approach determines the start time. If previously scheduled activities conflict with all possible start times, the activity is not scheduled. In either case, the next activity on the list is then considered for scheduling.

The principal method for evaluating scheduling approaches is to determine the extent to which the objective is met. Evaluation is typically accomplished by establishing benchmark problems and generating test schedules. The evaluation criteria generally include the fraction of activities and the fraction of activity time that gets scheduled. This paper provides an analytical technique for predicting scheduling success in these terms.

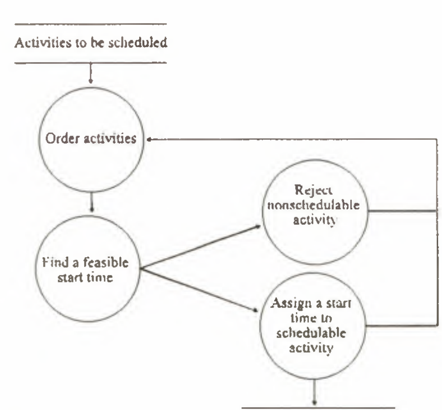

Figure 1. Sequential Scheduling Approaches

A closely related issue is the fraction of available resource time that gets scheduled. Providing resources is generally costly, and, before spending money to provide additional resource, managers want to be sure that the existing resources are being used efficiently to perform the specified activities.

The first part of this paper presents the derivation of the probability of a single additional activity being successfully scheduled on either a single or multiple resources. An iterative process is then defined to determine the overall probability of successfully scheduling any number of activities.

Next the benefits to improved scheduling success from start-time flexibility are included. Finally, the distribution of gaps remaining in the time line is discussed.

2. SINGLE-ACTIVITY SCHEDULING SUCCESS

Scheduling success probability is derived by considering an attempt to schedule a single additional activity on a resource time line that contains a number of activities already scheduled. Given a single, discrete, resource time line (see Figure 2) with n randomly scheduled activities at start times and with durations

$$\left\{s_i, d_i\right\}_{i=1,n} \tag{1}$$

such that

$$s_i + d_i \leq s_{i+1} \tag{2}$$

consider a new activity with duration δ and random start time σ . The new activity will not be scheduled successfully if its start time conflicts with any previously scheduled activity ($s_i \leq \sigma \leq s_i + d_i$) or if a previously scheduled activity has a start time that conflicts with the new activity ($\sigma \leq s_i \leq \sigma + \delta$).

Since σ is uncorrelated with any previously scheduled activity, the probability that it will not conflict with a previously scheduled activity is given by the fraction of the time line remaining unscheduled

$$\left(\frac{t_r}{t_a}\right) \tag{3}$$

where

t_a = the length of the time line

and the remaining time is given by

$$t_r = t_a - \sum_{i=1,n} d_i \tag{4}$$

The probability that no previously scheduled activity has a start time that conflicts with the new activity is determined by considering a compressed time line of length t_r (see Figure 3), generated by removing the scheduled activity durations from the available time line. The previously scheduled activities appear with zero duration randomly distributed throughout the time line. For each of the n previously scheduled activities, the probability that start time s_i will not

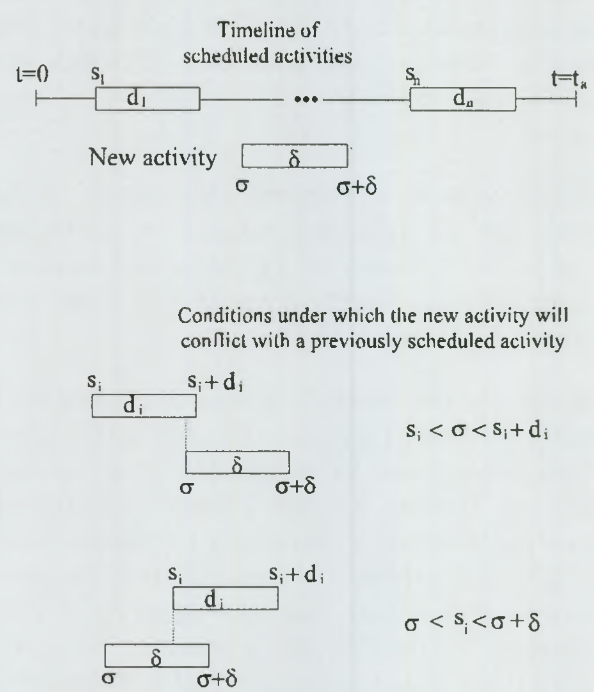

Figure 2. Scheduling a New Activity in a Resource Time Line That Contains Previously Scheduled Activities

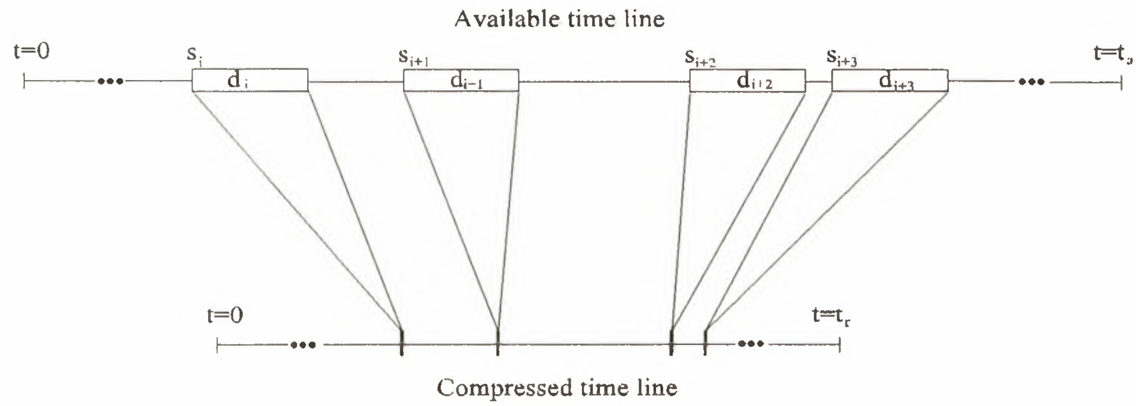

Figure 3. Compressed Time Line With Scheduled Activity Durations Removed

conflict with the new activity ($s_i < \sigma$ or $s_i > \sigma + \delta$) is given by

$$\left(1 - \frac{\delta}{t_r}\right) \tag{5}$$

under the assumption that

$$\delta << t_r \text{ and } d_i << t_a \tag{6}$$

to avoid any effects from the ends of the time line. Combining the probability that σ is not in conflict with any previously scheduled activity, with the probability that none of the s_i are in conflict with the new activity, results in the probability P_1 that the new activity can be scheduled

$$P_1 = \left(\frac{t_r}{t_a}\right)\left(1 - \frac{\delta}{t_r}\right)^n \tag{7}$$

In the limit that n becomes large while (t_r/t_a) remains fixed

$$P_1 \rightarrow \lim_{n\rightarrow\infty} P_1 = (1-L)e^{-\left[\frac{L}{(1-L)}\frac{\delta}{\langle d\rangle}\right]} \tag{8}$$

where

$$L = \frac{\sum_{i=1,n} d_i}{t_a} = 1 - \frac{t_r}{t_a} = \text{scheduled load} \tag{9}$$

$$\langle d\rangle = \left(\frac{1}{n}\right)\sum_{i=1,n} d_i = \frac{Lt_a}{n} \tag{10}$$

= average duration of scheduled activities

If each activity can be scheduled on any of m equivalent unconstrained resources, then P_1 becomes the probability that the new activity can be scheduled on each of the m resources. The probability of successfully scheduling an additional activity on any of the m resources is then

$$P_m = 1 - (1 - P_1)^m \tag{11}$$

Figure 4 shows the probability of successfully scheduling a new activity of average duration as a function of the already scheduled load. For small values of L, the probability decreases as $1-L^m$. For larger values of L, the exponential causes the probability to fall more rapidly. For a single resource, by the time L has reached 30 percent, the scheduling success for a new activity has fallen to 46 percent. Four equivalent resources are required to keep the single-activity scheduling success above 50 percent for 50 percent loading.

3. INTEGRATED SCHEDULING SUCCESS

Scheduling success integrated over all activities is determined by applying P_m iteratively. Consider N activities with random start times to be scheduled on m equivalent resources. The first m activities can each be scheduled successfully without conflict, one activity on

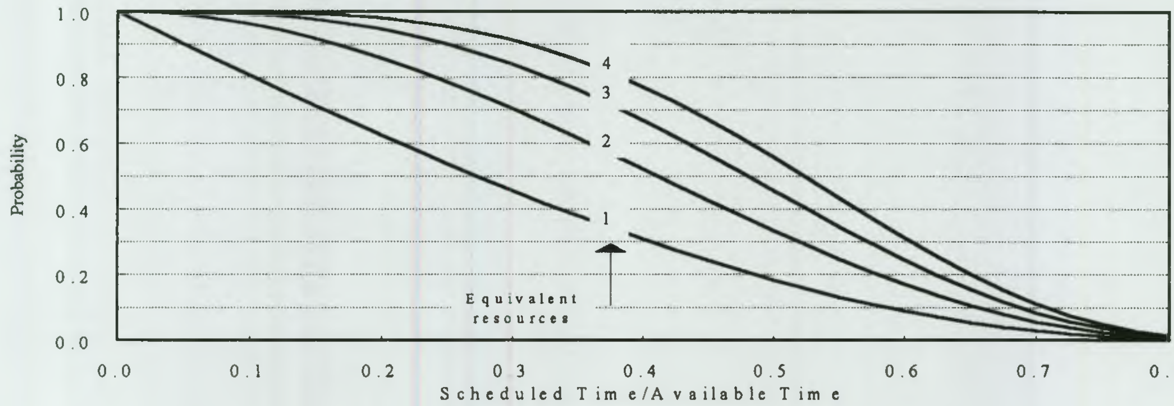

Figure 4. Single-Activity Scheduling Success

each resource. Therefore, the number of activities and the scheduled load are

$$n(m) = m \tag{12}$$

$$L(m) = \frac{\sum_{j=1,m} d_j}{mt_a} \tag{13}$$

For activities $j=m+1,N$, the steps are

1. Compute the probability $P_m(j)$ to schedule activity j, given $n(j\text{-}1)$ previously scheduled activities out of $j\text{-}1$ attempts
2. Update the number of activities scheduled out of j attempts $n(j)=n(j\text{-}1)+P_m(j)$
3. Compute the scheduled load

$$L(j) = L(j-1) + \frac{P_m(j)d_j}{mt_a} \tag{14}$$

The average scheduling success can then be computed as the ratio of the number of scheduled activities to the number of attempted activities

$$\frac{n(N)}{N} \tag{15}$$

or as the ratio of the scheduled time to the attempted time

$$\frac{mt_a L(N)}{\sum_{j=1,N} d_j} \tag{16}$$

If all of the activities are of the same duration, then the two measures are identical. Figure 5 illustrates the integrated scheduling success when all activities are of the same duration. If the demand is for 50 percent of the available time on 4 resources, 90 percent of the activities will be scheduled successfully. With 2 resources, 79 percent will be scheduled successfully. If the demand is for 70 percent of the resources, the success for 4 resources drops to 79 percent and it drops to 69 percent for 2 resources.

4. START-TIME FLEXIBILITY

The activity start times for some scheduling problems are not fixed. Rather, they have flexibility τ such that they can be scheduled to start at any time between σ and $\sigma + \tau$. The benefit of the start-time flexibility can be determined by considering an activity (see Figure 6) with start time σ that conflicts with a previously scheduled activity of duration d_i, scheduled to start at time s_i, $s_i \leq \sigma \leq s_i + d_i$. If $\tau \geq s_i + d_i - \sigma$, then the conflict with activity i can be resolved by adjusting the new activity start time to

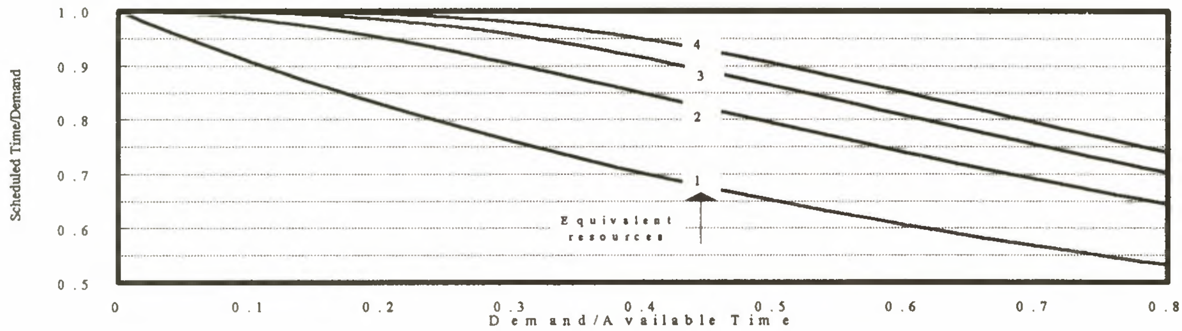

Figure 5. Integrated Scheduling Success

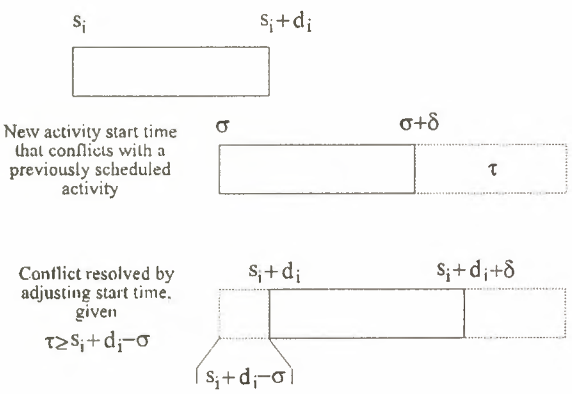

Figure 6. Start-Time Flexibility

s_i+d_i. The probability that this resolution is possible is given by

$$\left(\frac{\tau}{d_i}\right) \tag{17}$$

for

$$\tau < d_i \tag{18}$$

For larger values of τ, the probability of resolving the conflict is 100 percent. The average probability for resolving a conflict with the new event start time is given by the product of the probability that the new activity conflicts with the previously scheduled activity i, multiplied by the probability that a conflict with activity i can be resolved, summed over all previously scheduled activities

$$\sum_{i=1,n}\left(\frac{d_i}{t_a}\right)\left(\frac{\tau}{d_i}\right) = \frac{n\tau}{t_a} = L\frac{\tau}{\langle d\rangle} = Lf \tag{19}$$

where f is the normalized flexibility

$$f = \frac{\tau}{\langle d\rangle} \tag{20}$$

The probability of successfully scheduling the new activity is determined by multiplying Lf by the probability that another activity will have been scheduled in conflict with the adjusted activity and by adding the result to the previously determined value of P_1

$$P_1 = (1 - L + Lf)e^{-\left[\frac{L}{(1-L)}\frac{\delta}{\langle d\rangle}\right]} \tag{21}$$

Figure 7 shows the probability for successfully scheduling a new activity of flexibility $f = 1$ of average duration as a function of the already scheduled load. Because of the flexibility, this data shows significant improvement in scheduling success when compared with Figure 4. For a single resource scheduled at 30 percent of available time, the scheduling success for a new activity increases from 46 percent to 65 percent. With 4 equivalent resources, 50 percent scheduling success can be maintained up to a demand of 65 percent of available resources.

The improvement in integrated scheduling success is illustrated in Figure 8. Increasing flexibility from $f = 0$ to $f = 0.5$ increases the scheduling success by approximately 5 percent for high levels of demand. Increasing flexibility to $f = 1$ increases scheduling success by an additional 5 percent.

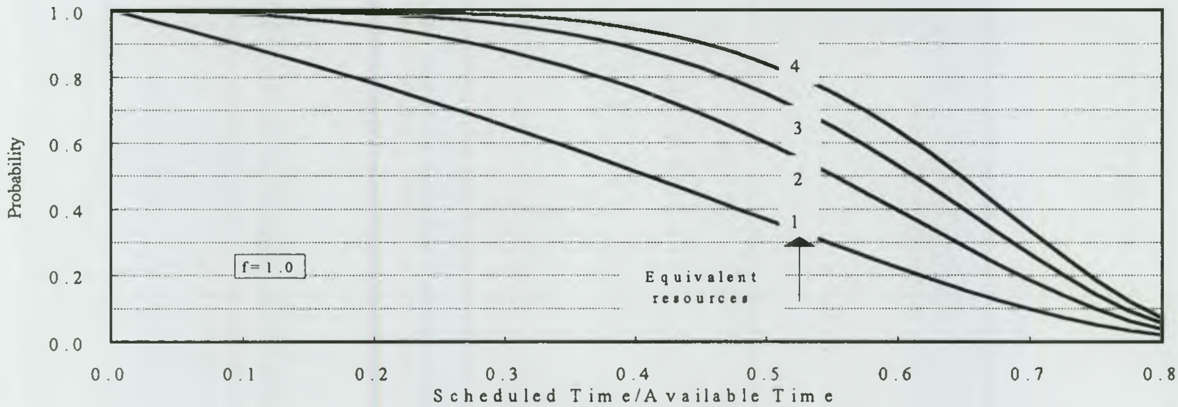

Figure 7. Single-Activity Scheduling Success With Flexible Start Times

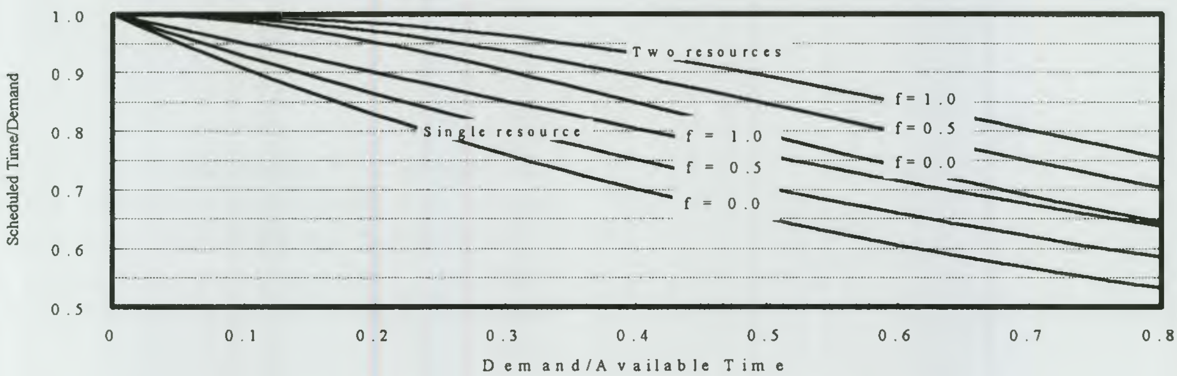

Figure 8. Integrated Scheduling Success With Varying Flexibility

5. DURATION FLEXIBILITY

As previously indicated, the exponential term in P_1 dominates the linear term for larger values of scheduled load L. The impact of the exponential term can be partially reduced by first scheduling the larger duration activities and then scheduling the shorter duration activities.

Figure 9 illustrates scheduling success when the demand above 40 percent is divided into twice the number of activities, each activity of half the duration of the activities below 40 percent. This success is compared to scheduling success when all activities have the same duration. With the reduced-duration activities, scheduling success is increased by approximately 5 percent. In practical applications, durations of unschedulable activities can be reduced to improve scheduling success.

6. HIGHLY FLEXIBLE START TIMES

As the flexibility of start times increases, the probability of successfully scheduling an activity increases. For values of $\tau > d_i$, conflicts of the new activity start time σ with a previously scheduled activity can always be resolved (see Figure 6) by delaying the new activity to start at the end of the conflicting activity. The linear term in the scheduling

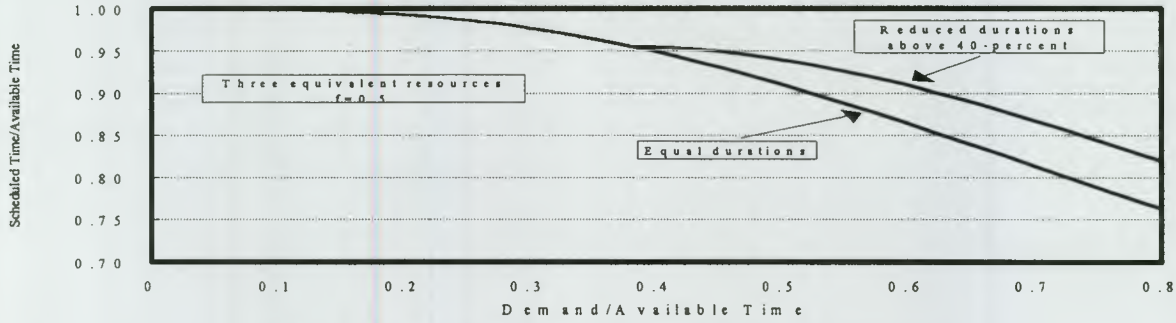

Figure 9. Scheduling Success With Reduced Durations

probability is eliminated, and the single resource success probability becomes

$$P_1 = e^{-\left[\frac{L}{(1-L)}\frac{\delta}{\langle d\rangle}\right]} \tag{22}$$

This probability is actually a lower bound. The new activity is also schedulable if the start time s_i of a previously scheduled activity conflicts with the new activity and if $\sigma + \tau > s_i + d_i$.

For values of $\tau > d_i + d_{i+1} + \delta$ (for an average-duration activity $\delta = \langle d \rangle$, this value corresponds approximately to $f > 3$), the success probability increases further, as illustrated in Figure 10. If the length g_i of the first gap following the start time σ of the new activity is less than the duration of the new activity, $g_i < \delta$, then the new activity will not be schedulable in that gap. This probability is given by

$$1 - e^{-\left[\frac{L}{(1-L)}\frac{\delta}{\langle d\rangle}\right]} \tag{23}$$

If the new activity is not schedulable in the first gap, then its start time can be delayed to the end of the next previously scheduled activity. The probability is identical that the gap following this activity is also too small in which to schedule the new activity. Consequently, the probability that the new activity will be schedulable in one of these two gaps is given by

$$P_1 = 1 - \left(1 - e^{-\left[\frac{L}{(1-L)}\frac{\delta}{\langle d\rangle}\right]}\right)^2 \tag{24}$$

As τ increases further, scheduling success continues to increase. Figure 11 illustrates the significant gain in scheduling success that accrues from this added flexibility for an average-duration activity. It also illustrates that, even with this amount of flexibility, it is difficult to successfully schedule beyond a demand of 60 percent of the resources.

This conclusion depends on the assumption that scheduled activities are placed randomly within their schedulable start-time flexibility. Techniques exist for selecting start times to optimize resource use. These techniques effectively reduce the size of small gaps and increase the size of large gaps, thereby improving scheduling success.

7. GAP SIZE DISTRIBUTION

The difficulty in scheduling more than 60 percent of the resources results from both the time line being heavily scheduled and the remaining gaps being too small for additional activities to be scheduled. This problem can be understood by determining the distribution of gap sizes.

The probability for an individual gap to have a length greater than value g can be determined by selecting the end, $s_i + d_i$, of any scheduled activity and by considering the probability that no other activity is scheduled within gap g from this point. This probability is precisely the same probability derived earlier for scheduling an activity with a non-conflicting start time

$$\nu(g) = e^{-\left[\frac{L}{(1-L)}\frac{g}{\langle d\rangle}\right]} \tag{25}$$

The distribution of gap sizes (see Figure 12) is given by the probability of finding a gap between g and $g+dg$

$$-\langle d\rangle \frac{d\nu(g)}{dg} = \frac{L}{(1-L)} e^{-\left[\frac{L}{(1-L)}\frac{g}{\langle d\rangle}\right]} \tag{26}$$

As the resource becomes more heavily scheduled, the remaining gaps become significantly smaller than the average activity duration, making them unusable for scheduling average-duration activities. The amount of time $T(g)$ remaining in gaps larger than g is given by

$$T(g) = \int_g^\infty ng \frac{d\nu(g)}{dg} dg \tag{27}$$

$$= n\left(g + \frac{(1-L)\langle d\rangle}{L}\right) e^{-\left[\frac{L}{(1-L)}\frac{g}{\langle d\rangle}\right]} \tag{28}$$

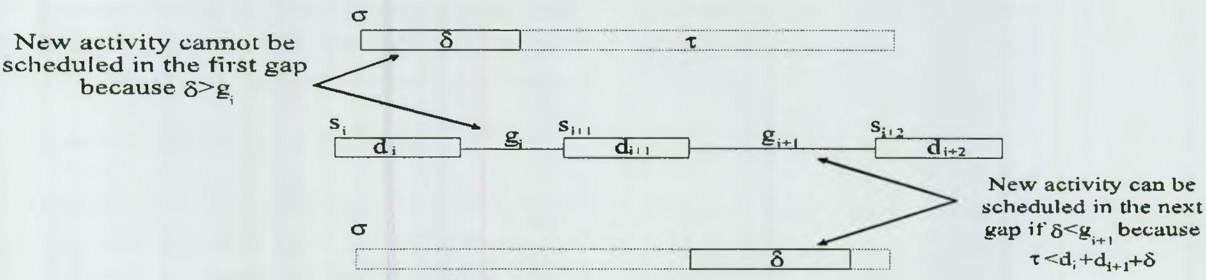

Figure 10. Highly Flexible Start Times

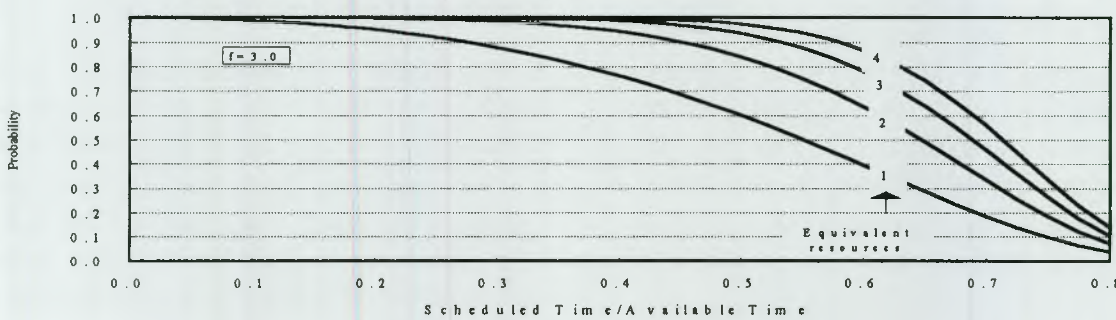

Figure 11. Single-Activity Scheduling Success For Highly Flexible Start Times

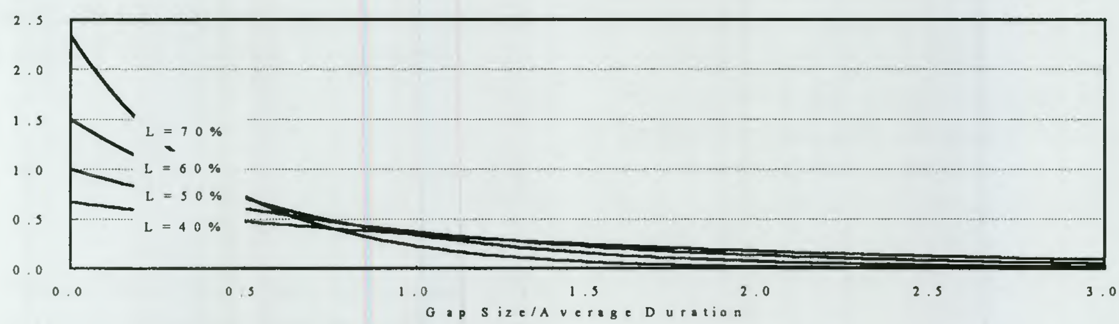

Figure 12. Gap Size Distribution

The ratios of $T(g)$ to t_a and t_r are given by

$$\frac{T(g)}{t_a}=\left(\frac{Lg}{\langle d\rangle}+(1-L)\right)e^{-\left[\frac{L}{(1-L)}\frac{g}{\langle d\rangle}\right]} \tag{29}$$

and

$$\frac{T(g)}{t_r}=\left(1+\frac{Lg}{(1-L)\langle d\rangle}\right)e^{-\left[\frac{L}{(1-L)}\frac{g}{\langle d\rangle}\right]} \tag{30}$$

which, in the case $g=\langle d\rangle$, go to

$$\frac{T(g)}{t_a}=e^{-\frac{L}{(1-L)}} \tag{31}$$

$$\frac{T(g)}{t_r}=\frac{e^{-\frac{L}{(1-L)}}}{(1-L)} \tag{32}$$

Figure 13 illustrates the fraction of the time line remaining in gaps larger than the average activity duration as a function of scheduled load L. For

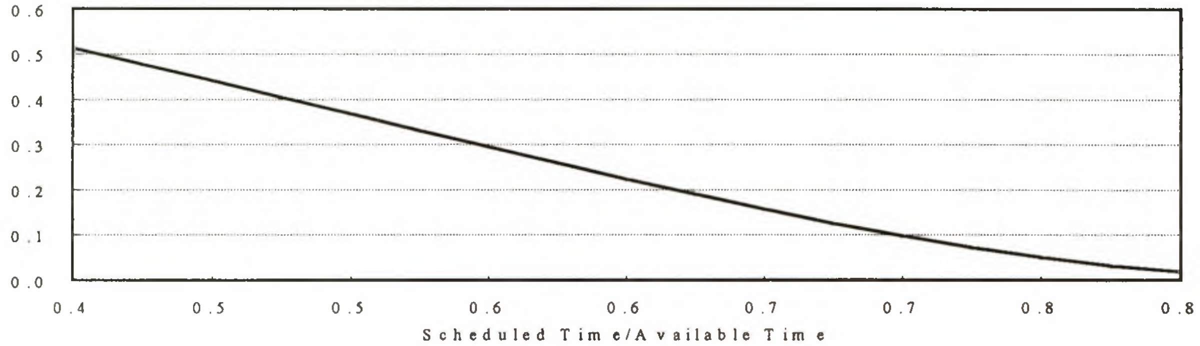

Figure 13. Fraction of Time in Gaps Larger Than Average-Duration Activities

example, when 50 percent of the time line has been scheduled, only 37 percent of it consists of gaps larger than an average-duration activity. When L reaches 70 percent, only 10 percent of the time line consists of gaps larger than an average-duration activity. The remaining 20 percent is in gaps that cannot be used to schedule activities of average or larger duration. The time in these gaps can be recovered by adjusting activity start times to reduce the size of small gaps and increase the size of large gaps.

8. CONCLUSION

This paper provides formulae to compute success for scheduling individual activities with start-time and duration flexibility on single or multiple resources. An iterative technique is presented for determining scheduling success integrated over all schedulable activities. It demonstrates the significant increase in scheduling success that can be achieved when scheduling flexible activities. It also provides a distribution of sizes of gaps remaining in the time line and demonstrates the dramatic decrease in time remaining in large gaps as scheduled time increases.

This analytical formulation can be used to calculate realistic estimates of scheduling success without actually developing schedules. Such estimates can be used for capacity planning or predicting scheduling success for varying combinations of activities and resources.

TIMELINE, A GENERIC TOOL FOR MISSION PLANNING

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ABSTRACT.

Reduction of operations costs is a key driver in the development of new Mission Control Centers. MATRA MARCONI SPACE has developed the OPSWARE software package to fulfill this demand and to propose an operational solution for automating operations. This paper focuses on the TIMELINE planning and scheduling component of OPSWARE. It begins with an overview of the OPSWARE command and control components. TIMELINE functions and main features relative to mission planning are described. Future development on distributed planning are then discussed. Finally, application of the tool on current space programs are presented.

1. INTRODUCTION

Space mission operations domain is evolving rapidly. In order to reduce development and operations costs, space operators are now looking for generic tools and are moving to automating operations. Generic tools enable quicker and cheaper development of Mission-specific Control Center (MCC) sub-systems. Operations automation reduces operations costs by relieving MCC controllers from low-level routine tasks during the whole life of the satellite.

The step from manual to automated execution calls for new tools which enable to capture much more information about the mission such as the detailed operations instructions, the constraints for performing these operations and the strategy to react to actual performance of operations. A large part of the workload is transferred from the execution phase to the preparation phase. One has to specify, check and validate activities and schedules before submitting them to automated executers.

To fulfill this demand for an increase in system autonomy, MATRA MARCONI SPACE has developed the OPSWARE package. It is a set of complementary, inter-operable and generic tools which cover all operations phases, respectively preparation, planning, command and control, and performance analysis.

2. OPSWARE

One of the main objectives of OPSWARE is to provide a high level of automation of operations.

The basic principle is to define the procedures using a formal language that supports a syntax close to the natural language used in operations and to execute automatically the procedures using an executer of this language.

OPSWARE provides two levels of automation, respectively the procedure and the plan levels. The OPSWARE architecture which implements these two levels of automation is shown on the figure 1 with the four OPSWARE components: OPSAT, OPSEXECUTER, TIMELINE and TIMELINE-EXECUTER.

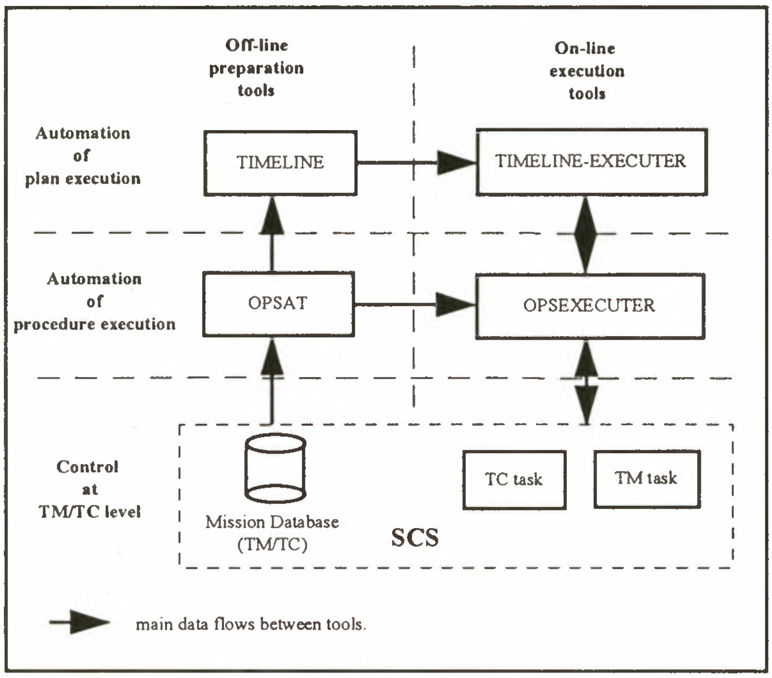

Figure1: OPSWARE components for command and control of operations.

The procedure level is the first level of automation provided by OPSWARE. Flight and ground control procedures are prepared with OPSAT. They are stored in the Procedures database from which they can be accessed by the three other tools.

A procedure is executed automatically or manually with OPSEXECUTER It executes successively each instruction of the procedure and sends the instruction command to the core SCS. OPSEXECUTER enables to manage a stack of time-tagged procedures which can be run concurrently.

The plan level is the second level of automation provided by OPSWARE. Plans of operations are built with TIMELINE. One defines all the mission constraints and TIMELINE computes the feasible execution time windows for performing activities.

The schedule is sent to TIMELINE-EXECUTER for execution. It activates the execution of activities at their scheduled times. A start command is sent to OPSEXECUTER which in return informs the executer on the progress of the activity. The schedule is continuously updated to take into account actual execution times of activities. Re-scheduling may be performed when unforeseen events make the current schedule not anymore feasible.

3. TIMELINE

TIMELINE is a planning tool which enables to define a plan of activities, to schedule them in time, to check if planning constraints are satisfied and to support user in solving conflicts. TIMELINE can be used at all stages of the operations, respectively the preparation, LEOP, routine and final de-orbiting phases.

TIMELINE 2.0 is written in C++ and is available on Unix and Windows platforms.

Objects of the plan

It is possible to create the following objects in a plan:

. Activity. The central objects in a plan are the activities. They are identified by a code which is unique in the plan. They have an expected duration. Their scheduled start and end dates is computed by TIMELINE. Most activities are associated to procedures defined in the procedures database.

. Event. Events can be considered as null duration activities. Typical events are the injections, the apogees and perigees of the satellite.

. State resource. It is a resource which can be in one or several states at the same time. Availability of a state over time is defined by a list of time intervals called segments.

State resources are primarily used to model orbitography information generated by the Flight Dynamics (FD) system. For instance, a state resource is defined for each ground station. The state resource has several states, respectively TM, TC and ranging states which correspond to all types of visibility. Periods of visibility are defined as segments.

Planning constraints

TIMELINE supports several types of constraints on activities and events:

. temporal constraints defined either as time bounds or as precedence links between objects of the plan. Time bound constraints enable to specify an earliest date for the start of an activity and a latest date for the end of an activity. A precedence link enable to define a relative temporal constraint between the start and/or the end of two objects of the plan (activity, event and/or resource segments).

. logical link. A logical link is particular type of precedence link between two activities. The successor activity cannot be executed if the execution of the predecessor activity has failed. This information is used during execution to control the activation of procedure execution.

. resource constraint. An activity may require one or several resource states to be executed. Several types of resource requirements are possible. The activity may require:

- the state of a specific resource, e.g. TM visibility for the Kiruna station.
- a state without any requirement on the resource which provides the state, e.g. TM visibility.
- a backup state, which means that at least two different resources must provide the same state during the duration of the activity execution.

The user interacts directly through a graphical timeline view of the schedule, structured into several domains which reflect distinct areas of activities (e.g. platform operations, payload operations, ground segment activities, etc). The user builds the plan by creating successively new activities and by defining the scheduling constraints. The interaction is entirely based on mouse operations.

Scheduling

The schedule is automatically re-computed in real-time after each user action. Scheduling consists in propagating the temporal constraints and in checking the resource constraints.

The temporal constraints are propagated through the graph of activities defined by the precedence links. The Time Feasibility Windows (TFW) which define the maximum time intervals in which it is possible to schedule each activity are computed and displayed. Activities are all placed at the beginning of their TFW according to an a-soon-as-possible scheduling strategy.

The system controls the edition of the plan so that temporal constraints are always satisfied. It prevents the user from adding or modifying temporal constraints (time bounds and precedence links) which would generate a temporal conflict. For instance it is not possible to move an activity outside its TFW and object attributes which have been specified a conflicting value are set to their previous values.

The resource constraints are checked. Activities requiring a resource state must be scheduled during one of the segments of the state. Activities which are not completely included in a segment are highlighted on the timeline to show the conflict. It is the responsibility of the user to modify the constraints of the plan to remove the conflicts. One may for instance force an activity to be scheduled within a given state segment by defining precedence links from the start of the segment to the start of the activity and from the end of the activity to the end of the segment.

4. Distinctive features relative to mission planning

In this section we stress the functional points that makes TIMELINE specially well suited to fulfill mission planning requirements.

- Interface with a procedures database.

TIMELINE provides on-line access to any operations procedures database supporting SQL protocol. One can insert procedures into the plan and get their main attributes (e.g. duration, definition of parameters). Parameters of the procedures can be instantiated in TIMELINE and stored into the plan with the planned procedures in order to provide a fully instantiated schedule which is ready for execution. It is possible to automatically update procedure attributes when the procedure database has been modified and to clearly identify the procedures which have been modified.

- Modeling mission analysis data.

Data derived from mission analysis can be represented using generic TIMELINE objects. All mission events can be represented as TIMELINE events: geometrical events such as perigee, apogee, ascending and descending nodes, events related to satellite manoeuvres such as injection and start of station-keeping manoeuvre. Orbital states of the satellite can be generically defined using the state resources. For instance, a TM visibility with a ground station is modelised by defining a ground station resource with possibly several states such as TM, TC and Ranging states. A state segment defines a particular ground station visibility of the satellite.

- Interface with Flight Dynamics.

Generic interface is provided to import data generated by mission analysis. It can be used in two ways.

When building a new mission plan, one first imports mission events to fix the time framework of operations. Operations are scheduled and synchronized with respect to these events. For instance, in the LEOP preparation phase, automatic import enables to quickly build several scenarios corresponding to different launch times.

In the execution phase, import from Flight Dynamics can also be used to update the predicted times of the schedule events with the most recent mission analysis data which take into account actual position of the satellite. The schedule is automatically re-computed to assess the impact of these new times.

Mission analysis also computes some of the parameter values of planned procedures, e.g. thrust duration for station keeping manoeuver. These values can also be directly imported in a schedule and stored in the plan with the activity.

- Constraints on the execution of operations.

Precedence links enable to define a sequential order between operations activities. One can associate a delay on the precedence link to synchronize the start time of a procedure with respect to a mission events. State resource constraints enable to specify that a specific state on the configuration of the mission is required to execute an activity, e.g. an operation requires visibility with a ground station or must be performed outside an eclipse period.

- Reporting

It is possible to generate a detail listing of the procedures including the procedure steps and their scheduled time, in a clear table format.

- Inter-operabiliy with other OPSWARE components.

A key feature of TIMELINE is its capability to work in cooperation with a set of complementary tools to provide a global solution to automate operations.

Functional roles and interfaces of OPSWARE components are well defined. Data are transferred by import methods and there is no duplication of information. Same object models, same functions and same MMI are used whenever it is possible, to improve consistency and homogeneity between components and continuity between preparation and execution phases.

TIMELINE generates a schedule which can be directly executed by TIMELINE-EXECUTER. Not only the computed schedule times but all the planning information is transferred to the executer. The executer gets the time margin which is available to perform an activity without violating mission constraints. Mission constraints are also provided. This information allow the executer to adapt the schedule to take into account actual execution events and to perform re-scheduling, that is to search for a new schedule solution when the current one is not anymore feasible.

5. DISTRIBUTED PLANNING

The control of operations in a Mission Control Center is a team work which involves several persons who have different roles. They frequently communicate to exchange data, to share technical expertise or to validate operations.

One may give several examples of interaction:

. When the planning is distributed over different domains which are under different responsibility, planners have to consult each other to build a conflict-free schedule because they share common facilities. Domains can be the payload and the service modules or different satellites.

. The planners build the sequence of operations and in return the controllers inform the planners on the way the operations have actually been performed.

. During the LEOP phase, several technical experts attend operations and have to be clearly informed on the progress of operations.

New groupware technology now enables to propose a new generation of tools to improve significantly the efficiency in group work. Several users can have simultaneously on-line access to the same information, can exchange messages and work concurrently on this shared information.

The next release of TIMELINE will provide an object-oriented client/server architecture based on CORBA to support distributed planning and scheduling.

Several users working on different terminals can be connected at the same time to the TIMELINE server and work on the same plans which are managed by the server. Users can have different views of the same plan at the same time.

Concurrent plan edition will be supported. It will be based on a token mechanism. Only one user is able to edit a plan at a time. This user « takes » the token and the edition of the plan is locked for other users. The server modifies the plan and computes the impact on the schedule. The views over the schedule for the other users are automatically updated to take into account these modifications. When the edition is completed, the token is given back to other users.

6. APPLICATIONS

TIMELINE is commercialised with the OPSWARE package.

It is used on the NILESAT and SINGASAT telecommunication programs which development is under MMS responsibility.

OPSWARE has been selected by ALCATEL for the command-control of the WORLDSTAR satellites and has been selected by SES for its new ASTRA Mission Control Center.

TIMELINE will also be used in the future generic Mission and Control Facility developed by MMS for LEO satellites used on earth observation programs.

The Capabilities of the Graphical Observation Scheduling System (GROSS) as Used by the ASTRO-2 Spacelab Mission

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Abstract: This paper discusses the Graphical Observation Scheduling System's (GROSS's) functionality and editing capabilities. GROSS was developed to replace a suite of existing programs and the process built around them. Limited data visibility and an awkward, outmoded user interface design were characteristic of this process. Numerous hours were spent using the process developing and modifying observation schedules for the first Astronomy (ASTRO-1) Spacelab mission. The mission planners for second Astronomy (ASTRO-2) Spacelab mission envisioned a new software tool that would combine the functionality from several of these programs and provide a graphical user interface (GUI) that would give more data visibility and new editing functionality. GROSS was created using a programmer to develop the GUI and a mission planner for expertise on the current process and programs. It binds an X-Windows/Motif GUI with existing mission analysis functionality. The ease in editing provided by this approach greatly enhanced the efficiency of the ASTRO-2 mission planners throughout mission preparation and real-time execution.

1.0 INTRODUCTION

The need for a new method of scheduling observations was driven by the intense and time consuming process employed for ASTRO-1[1]. This process was built around multiple programs with limited visibility of the schedule data and an awkward, outmoded user interface design. With the availability of graphics workstations, the mission planners for ASTRO-2 saw the possibility for the development of a new software tool that would consolidate functionality from the original planning tools into a single program providing a method for graphically building and maintaining the observation schedule. This new tool would provide additional data visibility through the GUI and incorporate both existing and new techniques for manipulating the schedule. This new tool, known as GROSS, was developed in under a year using a programmer to build the GUI and an experienced mission planner for expertise on the existing mission planning process and tools. It was developed in both the C and Fortran programming languages using MIT's X Windows System ® XR11R5.

This paper discusses the capabilities of GROSS , in particular, the data visibility and editing. The data visibility is discussed in the GROSS Display Overview section. This section describes the display and the functions available through the display. The Edit Function Overview section discusses the edit functionality found within GROSS. In addition, brief discussions of other embedded functions will also be provided.

2.0 GROSS DISPLAY OVERVIEW

Data visibility in GROSS is provided through a graphical display. The display provides a representation of the data required to build a new observation schedule or to rapidly modify an existing observation schedule. The interface follows the guidelines proposed in the *OSF/Motif ® Style Guide Release 1.1*[2] and recently developed in-house standards for X-Windows programs. These guidelines were used to drive the basic look and feel of the display, including screen layout and mouse button usage.

The GROSS display is initially blank after initialization. Several existing data files need to be loaded to make GROSS an effective tool. These files include a node file, which contains the orbital ephemeris data, a target file, which contains selected schedule items other than the observations, a South Atlantic Anomaly (SAA) file, which contains the times the orbiter is in the SAA, an attitude timeline file, which contains orbiter attitude timeline information, and the Science Plan, which is an

[1] O.T. Guffin, C.D. Olsen, J.F. Onken, and R.L. Stewart, "A Practical Approach to Astronomy Mission Replanning", AIAA Space Programs and Technologies Conference, March 24-27, 1992

[2] OSF/Motif ® Style Guide Release 1.1, PTR Prentice-Hall, Inc., Simon & Schuster Company, Englewood Cliffs, New Jersey, 1991

ASCII file, containing the observation schedule. If the schedule is still in the development process, the Mission Target List (MTL) file is loaded. This file contains a list of all possible observation targets for the ASTRO-2 mission.

Several features, such as feedback, mnemonics, accelerator keys, and cross-hairs, are built into the GROSS display. Feedback on warnings and errors is provided through a message area located at the bottom of the display and through informational boxes. The mnemonics and accelerator keys are available to speed the access to commonly used functions. A cross-hair function providing the time to the nearest second is available within the graphical area of the display. Color is used throughout GROSS to emphasize special data states. The use of color is discussed with the appropriate function.

2.1 THE GROSS DISPLAY

The GROSS display consists of several distinct areas. These areas are identified on Figure 1. They are the menubar, the tickmarks, the Schedule Display Area, the Limb/Ram Plot Area, and the manual text editor area. Each of these parts has a unique purpose to play in the use of GROSS.

As is standard in Motif programs, the menubar resides at the top of the display allowing access to a majority of the functionality of GROSS. The menubar's pulldowns group the functions as outlined in the *OSF/Motif Style Guide*. From left to right on the menubar, the pulldowns are: File, Edit, View, Options, and Help.

Actions performed on files and actions that affect the entire program are available under the File pulldown. Access to the open file and write file functions are provided from this menu. In addition, the capability to gracefully exit the program is provided here. The Edit pulldown contains the capabilities to act on the data. From here, the user can initiate various editing techniques, including creating new scheduled items, deleting scheduled items, and undoing edits. These capabilities will be discussed in more detail in the Edit Features section of this paper. Under the View pulldown, the opportunity to review the schedule itself and view more detailed information about the schedule is provided. The schedule can not be modified from the View pulldown options. However, from this pulldown, orbiter shadow times may be viewed and printed, statistics built, viewed, and printed, and the schedule verified. Also, information about specific observations may be viewed and the selected data set loaded into the text editor for further review. Customizations are accessed from the Option pulldown menu. In GROSS, these include options to select a default time span and format, and to print plots reflecting the scheduled items. The on-context Help available on GROSS is available from the Help pulldown, which is located to the extreme right on the menubar.

Two tickmark areas on the GROSS display provide the time references for the graphical display. The sets of tickmarks surrounding the graphical region reference the current time span. The tickmarks beneath the scroll bar reference the mission duration. These tickmarks reference the current time span to the time span of the entire mission. The scroll bar used in the GROSS display is a pan-zoom scroll bar, developed in-house. This scroll bar controls the duration of the current time span (zoom) and location of the time span (pan).

The Schedule Display Area is the graphical region beneath the current time span tickmarks. The labels to the left denote the data provided within the display. As seen in Figure 2, these labels are Miscellaneous, IDOP, Science Observations, Maneuvers, SAA, and light, dark, and 0 degree limb A/L (acquisition/loss). To the right of the labels, within the graphical area, the data is represented as bars, with the start and stop time of the data being the edges of the bars. The following modes are available for each bar:

- Black outlined box as shown in Figure 2 with a label, if applicable, to denote a scheduled item. Labels are provided for science observations and miscellaneous data, if a minimum set of the characters in the label fit within the box.
- Magenta box with appendages as shown in Figure 2, to denote a selected item.
- Blue box to denote a item has been loaded into the text editor.
- Red box to denote the item contains an error, either in the text editor or after a graphical move/resize.
- Green box, when a newly added scheduled observation and its associated items are waiting for user acceptance.

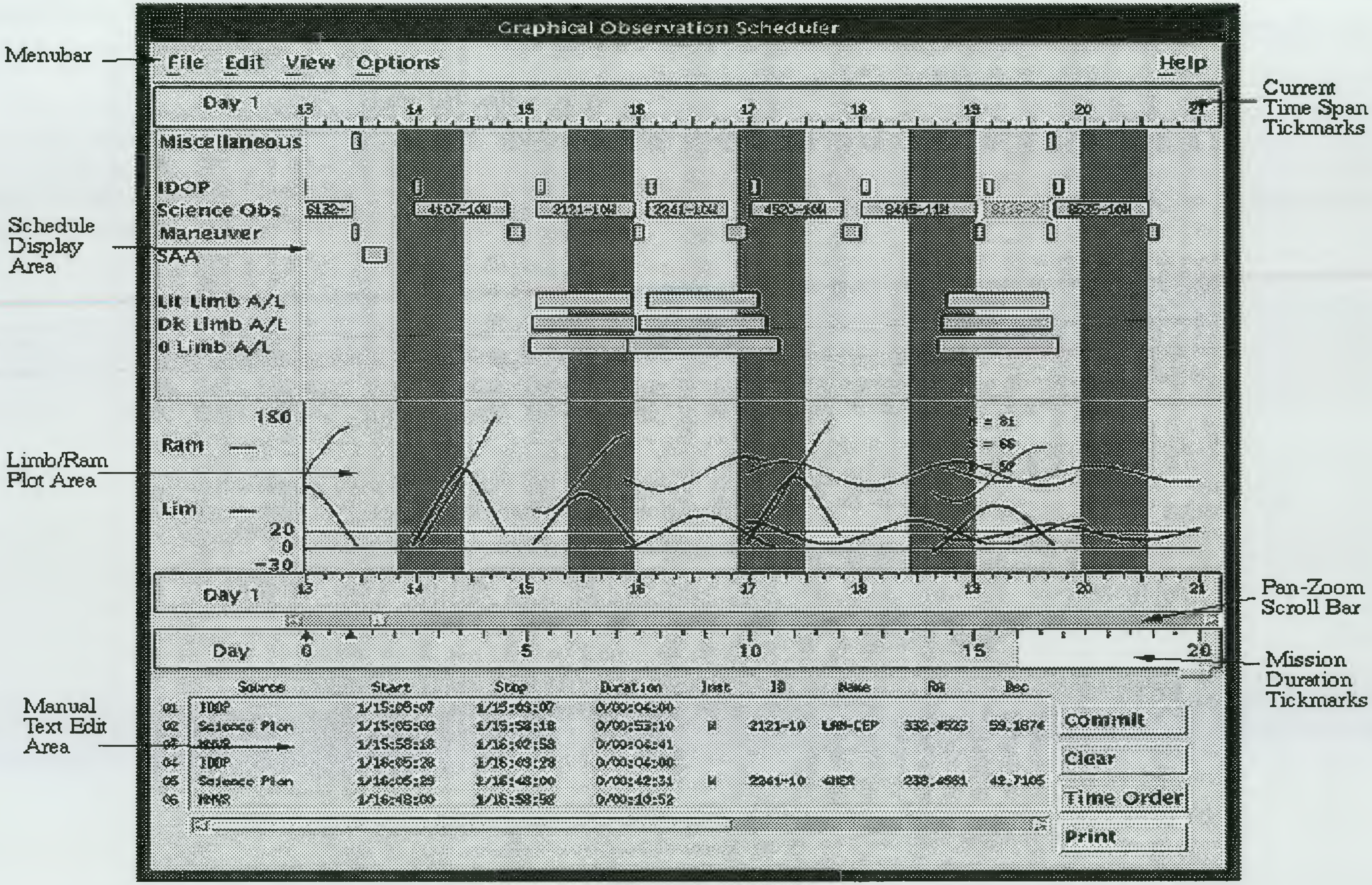

Figure 1: A View of the GROSS Display

To limit crowding within the Schedule Display Area, the light limb, dark limb, and 0 degree limb bars for scheduled observations are only provided when the observations are selected or have been loaded into the text editor. The limb data is represented as black outlined boxes and is located directly beneath its associated observation.

The shadow times are visible on the display as vertical, gray bars behind the other data. An option to view the actual start and stop times of the shadows is available from the View pulldown menu.

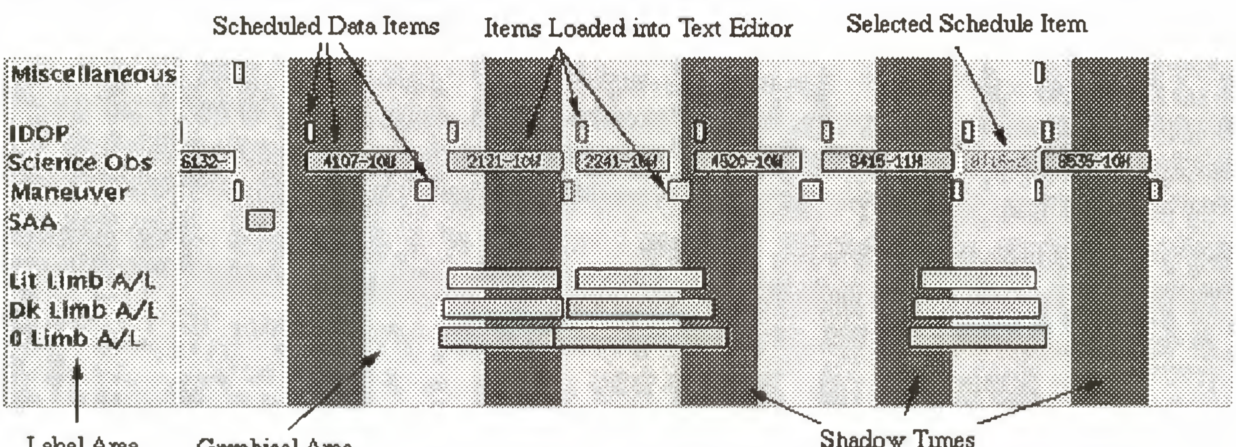

Figure 2: Schedule Display Area

The Limb/Ram Plot Display Area is immediately below the Schedule Display Area. Figure 3 shows a detailed view of this area. If the schedule and ephemeris data are available, the limb and ram plots for the science observations are shown in this area. The Sun, Moon, and Beta Angles for selected observations are also displayed. The legend and scale are to the left of the plots. Due to visibility concerns, these plots are only displayed if the selected viewing area is 24 hours or less.

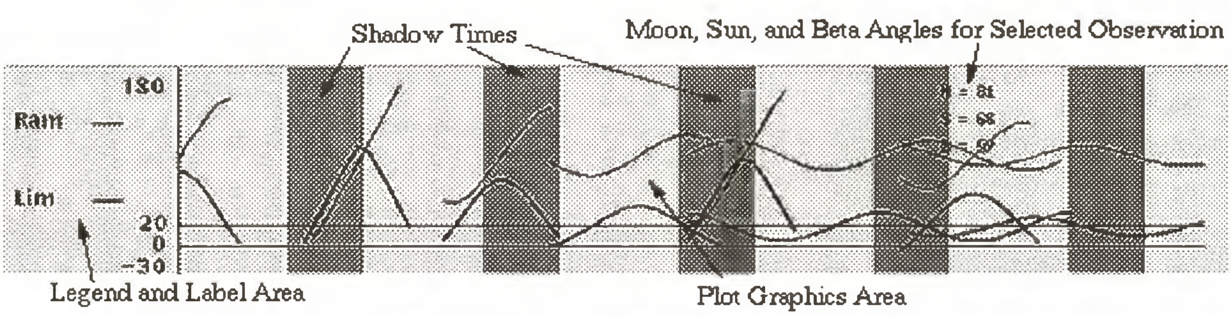

Figure 3: The Limb/Ram Plot Area

The manual text edit area is at the bottom of the display. This area provides the opportunity to manually edit loaded schedule items. It also provides a view of more detailed schedule information than can be provided in the graphical portions of the display. The text editor is discussed in detail in the Manual Editing section of the paper.

3.0 EDIT FUNCTION OVERVIEW

Inherent in GROSS are the functions required to both build and modify an observation schedule. These functions are available from the Edit pulldown menu on the menubar and through the graphical and manual editing capabilities of the display.

3.1 EDITING FEATURES

Interaction with a majority of the editing features within GROSS is available through the Edit pulldown menu. With the exception of two unique functions, the available functions fall into four major categories: modify the duration, move in time, add to the schedule, and delete from the schedule.The two unique functions are renumbering observation identification numbers and undoing graphical edits. The renumber feature is useful when the identification numbers have become out of sequence during the iterative add, move, and delete process of building a schedule. The undo feature allows the last graphical edit performed to be undone. This feature allows some trial and error in the schedule modification process.

The capability to modify the duration of scheduled observations is available through the *chop targets* and *extend targets* functions. Both of these functions require the selection of which observation time point to modify (the start time, stop time, or both), which limb to use as a constraint (light, dark, or 0 degree), and the time span over which to perform the action. With this information, the chop targets function shortens the observations within the time span; the extend targets function lengthens the observations. The results of these actions are immediately applied to the schedule and are visible in the Schedule Display Area.

The *move maneuvers* and *time bias* functions provide the capability to move items in time within the schedule. In both functions, positive time durations move items forward in time; negative durations move items back in time. The move maneuvers function slides attitude maneuvers in time within the selected time span. Time bias acts on the entire schedule, moving all scheduled items in time. The results of these actions are immediately applied to the schedule and are visible in the Schedule Display Area.

Adding items to the schedule is provided through two functions, *add target* and *add activity*. The add activity function is straight forward, allowing manual entry of the start and stop time for the new activity, the activity name, and the right ascension and declination, if required. Activities named IDOP or MANEUVER are grouped with their associated data, otherwise, the new activity is grouped with the miscellaneous data. The new activity is immediately added to the schedule and is visible in the Schedule Display Area.

The add target function is more complex and consists of two steps. Figure 4 shows the implementation of the add target function interface.

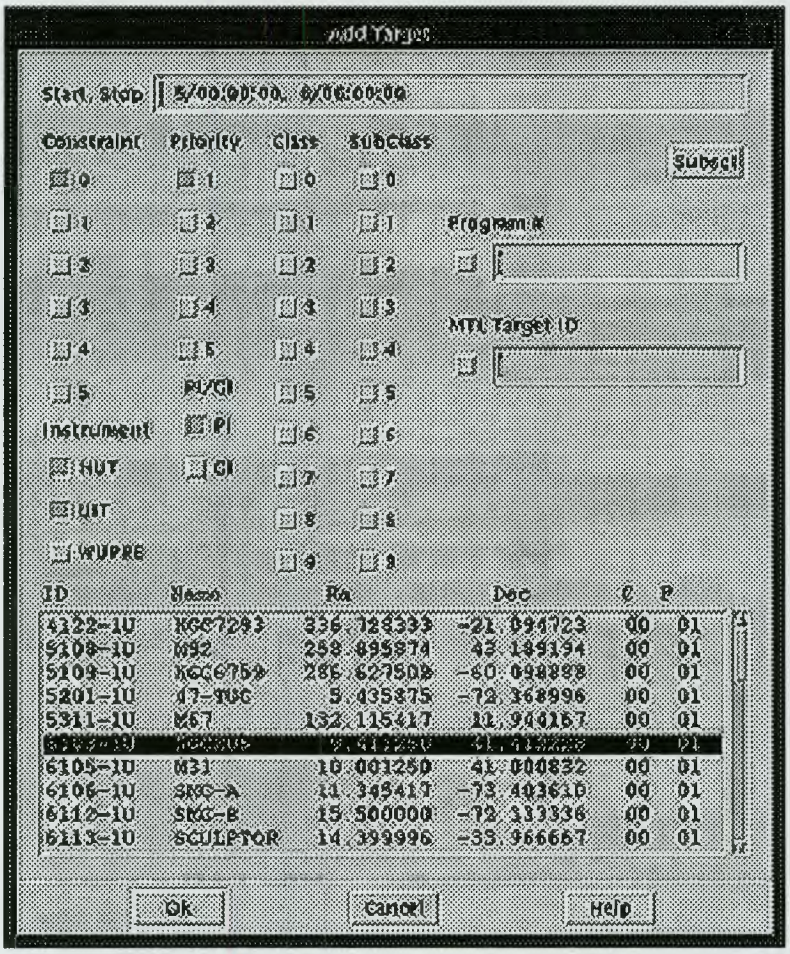

Figure 4: Add Target Function

The first step builds a subset of the mission targets list (MTL) that meets the criteria for the new observation and the second step is the actual addition of the target to the schedule. For the ASTRO-2 mission, criteria for selection into the subset included the instrument, target priority, constraint code, class, and subclass. As shown in Figure 4, the information from the created subset is at the bottom of the add target interface. To add an observation, the window is entered and an observation is selected from the subset. If a time point to schedule the selected observation within the window is found, the observation and it's associated activities are displayed in green in the Schedule Display Area at the correct time until the new observation is either accepted or denied. If the observation is not accepted, there is no impact to the schedule. The accepted observation and its associated activities are immediately applied to the schedule and are visible in the Schedule Display Area as scheduled items. If a time point to schedule the selected observation is not found, the user is notified of the failure and is returned to the add target interface.

Three methods for deleting items from the schedule are provided: *delete by time span*, *delete by activity*, and *delete selected*. Delete by time span deletes all items in the schedule within the selected window, including any items that overlap the window endpoints. Delete by activity deletes all instances of an activity within the schedule. Activities are scheduled items that are needed in support of observations that involve crew, orbiter or the Instrument Pointing System. Observations can not be deleted with this function. Delete selected deletes all currently selected items. The deletes are all performed immediately on the schedule and the deleted items are no longer visible in the Schedule Display Area. Selection of items in the schedule is discussed in the Graphical Editing section of this paper.

3.2 GRAPHICAL EDITING

The graphical editing functionality within GROSS is available in the Schedule Display Area. As discussed in the GROSS Display section, the status of each item in the display can be visibly tracked through the use of color and display modes. Prior to initiating the graphical edit an item , the item must be selected. Items may be selected singly or in groups of up to 20. Three selection methods are available, as described below.

- Single Select: The user clicks on the item to select using the Select button on the mouse. Any other selected items are deselected.
- Group Select: Using Shift-Select, the user drags the selection box over the items to select. The selected items, up to a total of 20, are added to any already selected.
- Toggle Select: The user clicks on the item with Control-Select. The item is toggle selected; i.e. it becomes selected if it was not selected, it is deselected if it was selected.

Once the items to be edited have been selected, three methods for editing are easily accessible. These methods are drag and drop, resize, and load into the text editor.

3.2.1 DRAG AND DROP

Drag and drop editing allows selected items to be easily moved in time within the schedule. This function does not affect the duration of selected items. The Drag button on the mouse is pressed and held on the selected item or group of selected items. A dashed line box is drawn around the selected items. The box is then dragged with the mouse while the Drag button is still held down. The items are dropped at their new location when the Drag button is released. More precise moving may be done while still dragging using the right or left arrow keys to fine-tune the placement of the selection box. This allows the user to select the placement to the second, required for the precision scheduling needed for ASTRO-2. This capability is enhanced through feedback provided in the upper left corner of the display showing the current location of the selected group during the drag. With the exception of SAA and shadow data, the scheduled items in the Schedule Display Area can be modified with this method. This change is made in the schedule as soon as it is performed; however the edit can be undone with the undo function until another edit of any kind is performed.

3.2.2 RESIZE

The resize capability provides a method to change the duration of a selected scheduled item. Resize is performed by pressing and holding with Shift-Drag button on a selected item and dragging the mouse. Whether the start time or the stop time is modified is dependent on where the resize is initiated; if the initial click was nearest the start edge, the start time is modified, if the initial click was nearest the stop edge, the stop time is modified. Precision resizing, to the second, can be achieved through use of the arrow keys as discussed in drag and drop. Feedback is provided in the upper left corner of the display showing the initial time and the changes in duration of the selected item during the resize. Only one item can resized at a time. This change is applied to the schedule as soon as it is performed; however the edit can be undone with the Undo function until another edit of any kind is performed.

3.2.3 MANUAL EDITING

Manual editing is supported within GROSS in the manual text edit area. This region consists of the text editor and edit action buttons as identified in Figure 5. The text editor allows manual editing of scheduled items and is an alternative method for viewing the detailed information about these items. The items are initially loaded into the editor through the use of the load selected function from the View pulldown menu. The editor places each item in its own row. Labeled columns identify the available data. If necessary, vertical and horizontal scroll bars are provided to allow viewing all the data within the editor. Individual fields to edit may be selected using the mouse. Additionally after initially selecting the text editor, the keyboard may be used to maneuver through the data fields.

Editing support is provided within the editor. GROSS protects the fields that are not suitable for editing by not allowing editing within those data fields. Invalid characters for a data field can not be entered. Data fields requiring data to be in specific ranges support data validation. Color is used within the text editor to reflect the status of each item: black is unchanged data; red indicates an error; and purple indicates an edit has been made. The edits made within the text editor are reflected in the Schedule Display Area, but are not applied to the schedule until the changes are committed.

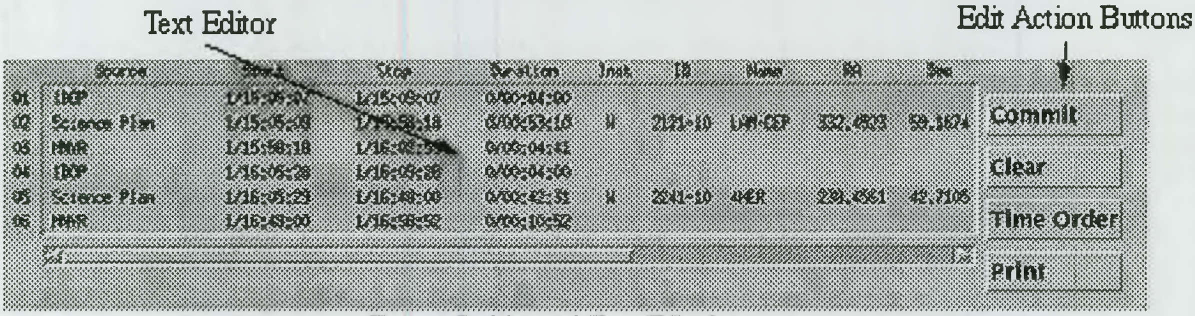

Figure 5: Manual Text Edit Area

The edit action buttons,perform actions on the contents of the text editor. The available actions are commit, clear, time order, and print. Clear empties the text editor; this action does not save the changes to the schedule, however the user is informed and given the option to cancel the action. Commit saves the current data in the text editor into the schedule; the user is informed if errors still exist and is given the option to cancel the action. Time order reorders the data within the text editor into ascending time order. A printout with the current text editor data is available through Print.

4.0 CONCLUSION

The capabilities of GROSS as discussed in this paper gave the ASTRO-2 mission planners a more efficient method of developing and modifying the observation schedule than had previously existed for ASTRO-1. GROSS provided both the data visibility and updated user interface design through the X-Windows/Motif display that were lacking in the ASTRO-1 process. Also provided were the functions required to support editing, both over large time frames within the schedule, such as *chop targets* and *time bias*, and on an individual item basis, such as *resize* and *text editor*. Both the mission planning team and the Principal Investigators (PIs) benefited from this new software tool. By using GROSS, the Principal Investigator's were able to build a preliminary schedule to review and to support the schedule development of the mission planning team. GROSS enabled the ASTRO-2 mission planners to rapidly build and update observation schedules in support of both pre-mission planning and real-time operations.

INTERACTIVE REQUIREMENTS CONTROL SYSTEM FOR SPACECRAFT MISSION OPERATIONS

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ABSTRACT. The Mission Operations and Data Systems Directorate (MO&DSD) at the NASA Goddard Space Flight Center is responsible for developing and operating the ground data systems to support many of NASA's scientific missions. During requirements analysis for these systems, major problems have been the coordination between various autonomous groups, delays in the final approval of requirements, verification that all upper level requirements are satisfied by lower level developments, and the modularization of requirements groups to encourage reuse. To address these problems, the MO&DSD proposed an interactive requirements collection system to foster communication between people and between levels in the data systems. This project, named the Requirements Generation System (RGS), was installed for operational use in the Fall of 1993. This paper describes the capabilities of the RGS and the ways in which it intends to resolve data systems analysis problems for the missions it serves.

HISTORICAL PERSPECTIVE

Several years ago, a study to suggest ways to speed up the mission development process without sacrificing quality was done by the Mission Operations and Systems Development Division (MOSDD) at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center. The study found that the requirements generation and approval process was a key factor in assuring that missions adhered to their schedules. Specific problems noted were delays in the final approval of control center requirements, the lack of coordination between various autonomous groups, verification that requirements were actually implemented, and a lack of requirements reuse. The study suggested that a better way of requirements development could be designed.

To address these problems, MOSDD management proposed to automate requirements collection and tracking. As this project progressed and showed some promise, the parent organization of the MOSDD, the Mission Operations and Data Systems Directorate (MO&DSD), decided to expand the scope beyond the control centers, to include such other mission functions as flight dynamics and data capture.

At about this time, officials at NASA Headquarters were trying to improve the process of spacecraft mission development by reorganizing the required documentation. The result was the replacement of three fundamental early documents (the Support Instrumentation Requirements Document [SIRD], the Systems and Operations Requirements Document [SORD], and the NASA Support Plan [NSP]) with a preliminary requirements checklist (the Mission Requirements Request [MRR]) and a single requirements document (the Detailed Mission Requirements [DMR]).

The change from SIRD/SORD/NSP to MRR/DMR brought all of a mission's detailed requirements into a single document, rather than three documents produced at different times, and changed the requirements generation process familiar to the mission planners, scientists, and developers. To emphasize the importance of this new process, NASA mandated the use of the MRR/DMR format for all new missions. Consequently, the MO&DSD reanalyzed the requirements automation project to correspond to the MRR/DMR format, further expanded the scope to include the entire requirements generation process, and named it the Requirements Generation System (RGS).

Of the several proposals submitted to design and implement the RGS, the one proposed by the Software and Automation Systems Branch (Code 522) in the MO&DSD was accepted. The overall structure was (and is) a central requirements database accessed by distributed software at the user's locations, all within a client/server architecture.

NASA expected that no mission was to be delayed by this new requirements process. As the only requirements development tool that followed the MRR/DMR, the RGS immediately gained wide visibility as a way to help complete the requirements document in a timely manner. The first mission scheduled to use the MRR/DMR was the Submillimeter Wave Astronomy Satellite (SWAS), and RGS development meetings focused on the needs of that mission. To date the RGS has been used on the ACER3, CAPL2, EOS AM1, EXPRESS3, GOES, GPP, IEH 1, IFMP, LANDSAT 7, MOPSS, NEWTRACE, NOAA, SAC B, SLA 1, SSBUV, SWAS, TEAMS, and WIRE missions.

THE REQUIREMENTS PROCESS

Requirements development at NASA has always ben a give-and-take process among the requirements requesters and with the requirements approvers (Figure 1). Requirements requesters include the scientists, satellite developers, ground system developers, and mission planners. These people have been involved with the mission since the earliest concept planning stages and have decided the overall requirements listed in the MRR checklist. Using the MRR as a basis, more detailed requirements are suggested by each group and reviewed by all groups. Any concerns, suggestions, or impacts are considered before a requirement is sent to the approvers for their review.

The requirements approvers are the Mission Operations Manager (MOM) and the Data Systems Manager (DSM). The MOM establishes the overall structure of the requirements groups, and verifies the rationale and traceability of each requirement. The DSM responds to requirements that have been accepted by the MOM and assigns them to NASA institutional elements (such as the Flight Dynamics Facility). In addition, both the MOM and the DSM can act as requirements generators.

In the past, requirements development has been mostly a manual process, prone to:

- inflexibility to change caused by the fixed page format of the DMR;
- delays caused by groups not responding in a timely manner;
- redundancy caused by groups generating similar requirements;
- misunderstandings caused by groups communicating poorly; and
- gaps caused by higher-level requirements not satisfied by more detailed requirements down the line.

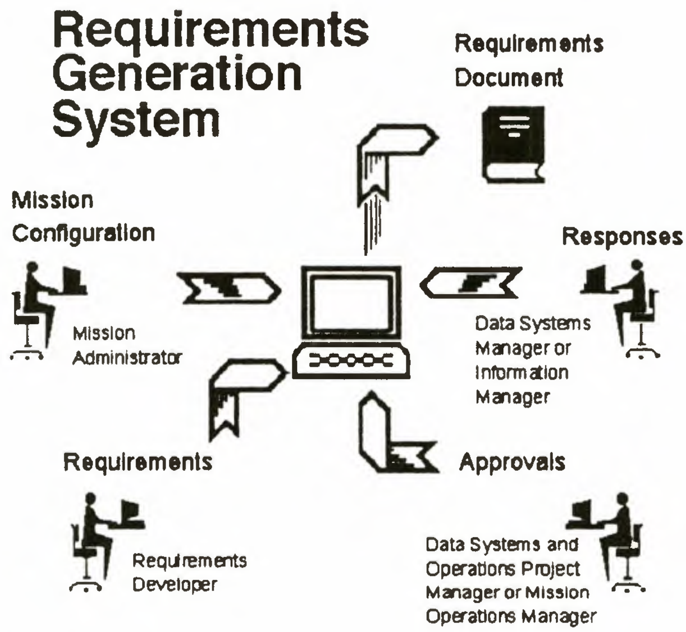

Figure 1. Requirements Entry and Approval Process

ADDRESSING THE PROBLEMS

Inflexibility to change. Hard-copy documents result in some awkward methods of referencing information. For example, some requirements demand a great deal of explanation, requiring many printed pages and possibly including diagrams. Since it does little good to question an item in "requirement 4208" when requirement 4208 extends for 14 pages, requirements developers instead have used the actual DMR page number (such as 4200.19) as an index to the item. This kind of reference becomes untenable because changed requirements, including any requirement physically located earlier in the document, may change the page number link to the original question. To compound the problem, updated DMRs are not distributed immediately to everyone. The workarounds for this situation have been more detailed page numbers when needed (such as 4200.19.1) and resorting to the "this page intentionally left blank" page.

Analysis of the requirements process, its problems, and its workarounds, quickly led the RGS developers to recommend a relational database design. With a relational database, not only is the manual fixed page approach unnecessary, it is difficult to force the system to accept fixed pages. Each requirement is referenced by its number alone, with individual item queries done using a "text search" feature. Sections (such as 4200) remain, but the page number becomes inconsequential and is only seen when the DMR is printed.

Delays. There are three situations that often cause delays in the requirements generation process. The first is in responding to another group's suggested requirements. While not all requirements for one group will impact others, requirements affecting an interface must be considered by all parties involved. With thousands of requirements and dozens of groups, it is very difficult to manually keep track of the status of all of them.

The second situation is in getting the final wording of a requirement for which alterations are suggested. Wording changes are generally requested when the original requirement would cause an unexpected impact on an organization. Until the final requirement has been approved, organizations do not know the resources they will need to dedicate to it. In addition, as all software life-cycle models indicate, the earlier in the process requirements are known the more efficiently they can be implemented.

The third situation is in getting final approval for all requirements. This has been a laborious process, often lasting well into implementation stages of the system. In fact, the author recalls one instance in which the requirements document was brought before an emergency session of mission personnel the day before launch, because it had not been signed (approved) by everyone. This situation is not only dangerous to the project developers, but it also causes concern at the highest levels of NASA and makes the mission managers appear to be incompetent.

The RGS method of handling delays is to make them visible to everyone as early as possible. This was done by putting the entire system, including comments and approvals, online. Groups that are expected to respond to an inquiry are noted, and remain noted until the response has been received. In addition, special reports are available to select requirements that are awaiting a response, including the name, organization, and phone number of the individual to contact.

Redundancy. Some of the delays in requirements generation are caused by separate groups inventing the same requirement over and over. While improved communication may seem to be the most direct solution, many missions generate thousands of requirements and developers could easily spend all their time communicating rather than developing.

The RGS solution to this problem is in visibility and reusability. All proposed requirements for a mission are visible to everyone involved in the mission. When a new requirement is considered, a text scan can be done to see if the function (based on various types of keywords) is already under development. If a near match is found, an individual can send a comment to the originator, explaining the similarities, to see if a single requirement can be constructed.

The RGS also has links to libraries containing requirements from previous NASA missions. A copy-and-paste feature has been included to allow developers to reuse blocks of requirements rather than re-specifying them for a new mission. An edit feature has also been included to make the inevitable changes from one mission to the next. The expanded use of this RGS capability is dependent on the construction of more comprehensive electronic requirements libraries from the existing paper documents.

Misunderstandings. One of the most important functions of requirements analysts is their ability to communicate, as precisely as possible, what a requirement is supposed to do. If this communication was done in mathematics there would be no confusion. Unfortunately, English remains the language of the requirements developers, and we must find methods to make the intent of the language clear.

While there have been some successful projects done by limiting and strictly defining the vocabulary permitted in requirements descriptions, this method cannot be used with a large, diverse community such as NASA's. Mission requirements are often decided by negotiation, with arduous compromises over the phrases used. Some of the most uncomfortable moments in a mission occur when one group suddenly realizes that their perception of a requirement is not how it actually works.

The RGS provides two methods to aid communication among requirements developers. The first is the comment area, in which anyone can make remarks about a proposed requirement. Comments follow a requirement throughout its consideration and approval stages, but there is no guarantee that any action will be taken or even that the comment will be read. The comment field is usually used by individuals not directly responsible for the requirement, but who think they have useful information to share.

The second method is the version feature, used by individuals with update privileges to the particular DMR section. If an individual thinks that a proposed requirement is improperly worded, he/she can "update" that requirement in more satisfactory language. The update does not destroy the original wording, but creates a new version of the requirement, tagged with a date/time stamp and the individual's ID. This new version becomes an alternative for the requirements approvers to consider. This feature forces communication, or at least conversation, among the various requirements camps. The MOM and DSM approve one version, perhaps a compromise, and the requirement is automatically locked from further version update.

Gaps. Irrespective of its name, the Detailed Mission Requirements document is not the most detailed set of requirements used for a mission. The DMR is actually considered the highest parent set of requirements for the systems and subsystems that comprise the mission. For example, the satellite control centers use a section of the DMR to define the next set of requirements for a specific mission control center. This next level still may not be detailed enough for the developers to write software, and another level containing even more detail may be defined. This process can continue for an unlimited number of levels.

One of the driving forces for the MOSDD and the MO&DSD in originating this project was the difficulty in determining that all DMR requirements were fulfilled by lower level developments, and that no spurious lower level requirements (ones that matched no DMR requirement) were included. This task is made more difficult by the non-electronic nature of the DMR, which forces lower level developers to rewrite the requirements. These developers often use slightly different wording, presumably in an attempt to make the requirements more understandable. Occasionally something is lost in the translation, especially if this rewriting process goes to additional levels, and the implemented requirement winds up being not what the original DMR requirement requested.

Developers may have to rewrite requirements for other reasons. A DMR requirement may be somewhat comprehensive (such as "Accept telemetry data from the satellite"), but the implementation may require activity from different components of the system (such as a data capture component, components for each experiment on the satellite, and an error checking component).

The RGS uses two kinds of automatic tracing to resolve the unimplemented requirements problems. The first kind uses the requirement number. Requirements that are direct descendants in a DMR section will be related by requirement number (such as parent requirement 2.1 and children requirements 2.1.1 and 2.1.2). A DMR requirement that doesn't have at least one child is flagged as "childless". The RGS eliminates the problem of "orphan" requirements by dictating that no parent may be deleted without first deleting all of the children.

The second kind of automatic requirements trace involves links to associated requirements. An associated requirement is usually a capability derived from a parent, but is not directly related. Deletions of these parents are noted as warnings for associated requirements within the RGS. Brother/Sister requirements (those on the same level but involving some common areas) are also linked to each other. A change proposed to one requirement may require a change to other associated requirements, and those requirements are flagged as possibly impacted.

THE REQUIREMENTS GENERATION SYSTEM (RGS)

The RGS appears to the user as a graphical interface with various pull-down menus, hot buttons, and display options characteristic of the needs of requirements analysts. To maintain the integrity of the requirements, there are four levels of security in the RGS - one visible and three invisible. Visible security consists of a userid and password to permit an individual to log onto the system. After successful logon, a project selection window displays only those missions the user is permitted to access. Each user has an individual set of privileges (such as update) for each mission. Finally, certain privileged users can lock all or part of the database from update.

Missions are displayed as a set of hierarchical functional categories. Figure 2 shows a typical category page of a DMR. While all categories can be viewed by any authorized user, only users with appropriate privileges can update requirements.

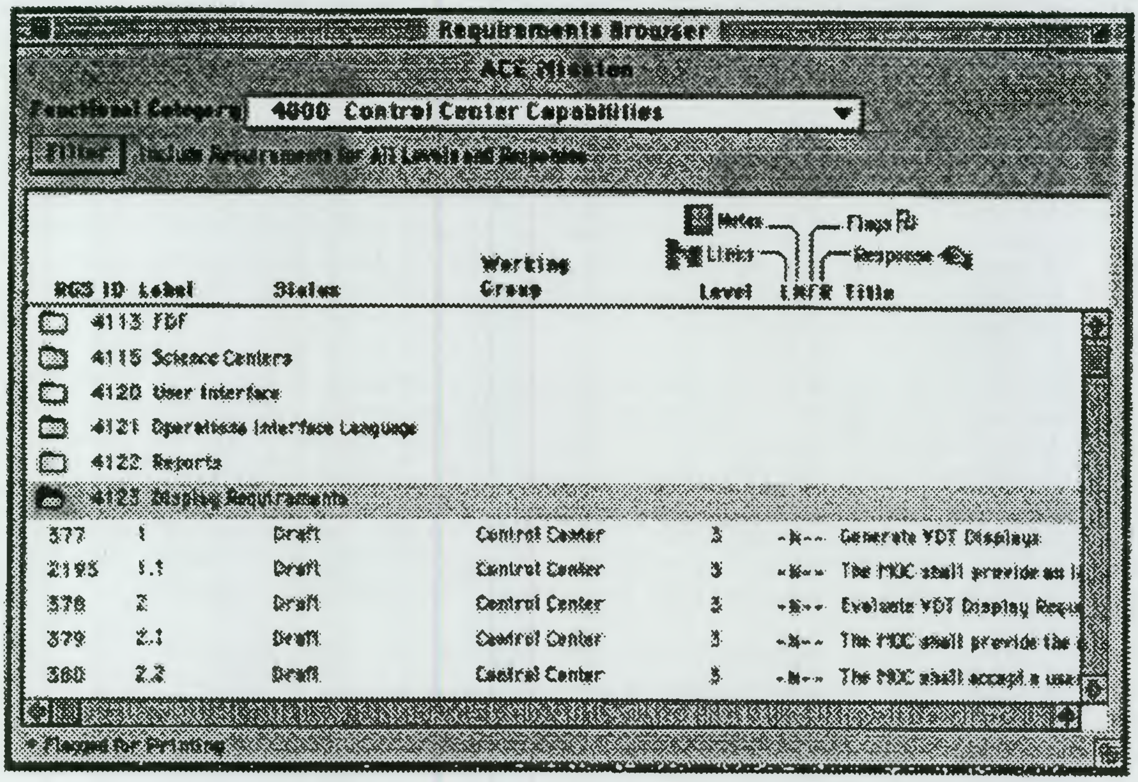

Figure 2. Control Center Capabilities DMR Page

The RGS is a client-server system in which all user activities, such as requirements entry and report generation, take place on the client machines. Both PC and Macintosh computers are supported as clients, with no change in appearance. A 486 PC with 16 megabytes of RAM, or a Macintosh with a 68040 processor and 16 megabytes of RAM, is the recommended configuration. In addition, all clients require the following commercial-off-the-shelf products: OMNIS 7 by Blyth Software; Windows 3.1 by Microsoft (PCs); Microsoft Word for Windows, V2.0 (PCs) or Microsoft Word, V4.0 or higher (Macintosh); Microsoft LAN Manager 2.1 (network drivers) (PCs); and Sybase Open Client and Mac TCP (Macintosh). The server, located in Code 522 at the Goddard Space Flight Center, houses all the RGS databases, support documentation, and database software.

SUMMARY

What started out as a group of checklists to improve satellite control center development for one Division at the Goddard Space Flight Center is quickly becoming a NASA-wide automated requirements collection, traceability, and approval system. In the process, the whole concept of requirements has changed from one based on a document type (such as the DMR) to one based on requirements linked in a relational database. Since its first release in 1993, the RGS has been continuously expanded to include new features, capabilities, and flexibility. It has evolved from a single document orientation to a general requirements development tool.

Requirements requesters have an online method of suggesting and reviewing requirements for an entire mission, and to copy large blocks of requirements from similar missions for reuse. Requirements approvers have an immediate view of comments on a requirement, forward and backward traceability on all requirements, a variety of status reports, and the ability to lock requirements groups after approval. The entire process has been streamlined and greatly accelerated, and reports in any format can be generated as needed. The use of the RGS has been recommended to assure DMR content consistency, to reduce the effort required to generate the document, and to maintain document configuration control.

Recently, NASA has initiated the Reusable Network Architecture for Interoperable Space Science, Analysis, Navigation, and Control Environments (Renaissance), a new approach to providing ground data processing systems to support Code 500 customers in a cost-effective, timely manner. The RGS is useful for Renaissance product requirements generation under existing MO&DSD methodology. Its utility will need to be accessed for requirements generation for alternate life cycles.

A future feature could be automatic configuration management, in which a change proposed to a requirement would automatically generate a change request form for electronic distribution to the individuals interested in that area, and automatically collect their responses.

Future goals are to link the RGS with historical requirements libraries to allow cut-and-paste of requirements from earlier missions, and to allow access to the system for remote scientists, possibly through the Internet.

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OBJECT-ORIENTED DESIGN FOR AUTHORING AND EXECUTING SPACECRAFT OPERATING PROCEDURES

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ABSTRACT

The purpose of the paper is to present a generic, pattern-based, object-oriented design supporting the complete procedure life-cycle. The development of a generic design is significant in that it enables re-use across a wide range of systems and applications (with attendant cost and time savings) and the development of COTS products. The generic design distills a decade of experience in designing and integrating software for the end-to-end support of the authoring and execution of spacecraft operating procedures. Applications cover crew and automated procedures for payloads and subsystems, and for in-orbit and ground operations. Manned and remote-sensing missions are emphasised. Experience also includes unmanned, ground-based, and non-space missions.

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INTRODUCTION

This paper presents a generic object-oriented design supporting the complete procedure life-cycle, including authoring/generation, storage, verification and validation, selection and retrieval, instantiation, resource allocation, execution, and post-use evaluation. The design is based on patterns. User-interface and functionality issues are separated. The development of a generic design is significant in that it enables re-use across a wide range of systems and applications (with attendant cost and time savings), and the development of COTS products.

The knowledge embodied in the generic design is distilled from a decade of experience in designing and integrating software for the end-to-end support of the authoring and execution of spacecraft operating procedures. Applications cover crew and automated procedures for payloads and subsystems, and for in-orbit and ground operations. Manned and remote-sensing missions are emphasised. Experience also includes unmanned, ground-based, and non-space missions. Systems have been implemented using Oracle, Lisp, Smalltalk, C++, Ada, MS-Word, and HTML with Booch, OOSE, OMT, Coad and Yourdon OOA, and HOOD methods.

There are three main approaches to operating a complex system. In the *command-based approach*, there is a set of commands that can be issued to the complex system, and the operator is responsible for selecting, instantiating and despatching the correct command. In the *procedure-based approach*, there is a set of prepared command-sequences that can be issued, and the operator is responsible for selecting, instantiating and despatching the correct command-sequence. In the *goal-oriented approach*, there is a set of goal-states that the system can be instructed to achieve, and the operator is responsible for selecting, instantiating and despatching the correct goal-state. This paper is concerned with the procedure-based approach. The authoring and execution of procedures will be collectively known as *procedure management*. The individual commands embedded in the procedure will be known as *steps*. Procedures may also be known as action-sequences, scripts, or recipes. Commands may also be known as actions, activities, telecommands, or (as in the International Space Station) SWOPs, (FL)APs, and entries.

The procedure-based approach has the advantage that the procedures can be tested before execution, giving a measure of certainty about the safety of the complex system. This is particularly important for rare but life- or mission-critical situations. In addition, the workload on the operator is reduced, because (the majority of) the procedures can be prepared in advance and re-used for similar situations. Procedures can also be used to improve coordination between multiple operators or actors with the minimum of communication.

There are six chapters. Chapter 2 summarises related project experience. Chapter 3 lists trade-offs in procedure management. Chapter 4 presents the generic design, identifying the key patterns to be found in it. Chapter 5 outlines experience in adapting it for specific projects. Chapter 6 identifies possible future enhancements.

RELATED PROJECT EXPERIENCE

Origin (known as Buro voor Systeemontwikkeling (BSO) until 2 May 1996) has been working on European space projects since 1980. In 1986, Origin began work under national funding on an expert system to support operators of the METEOSAT weather satellite in diagnosing faults in the on-board radiometer. Known as MERADEXP, the expert system was operationalised for ESOC in 1987 (Jongert, 1988). Having diagnosed a fault, MERADEXP prescribed the fault recovery procedure.

Recognising the limitations of the "canned text" form in which the recovery procedures were presented, in 1987 Origin began a nationally-funded study known as "PROcedures Knowledge

BASE" (PROKBASE) to identify suitable representations for procedures. Three prototypes (in Oracle, Lisp and Smalltalk) were developed successfully (Grant, 1988). A fourth prototype was developed later to support mixed-initiative procedure authoring by graphical means.

Development of the first of four versions of the Cabin Atmospheric Pressurisation Subsystem Expert System (CAPS ES) began in the same year. Originally known as the "N2O2 Expert System", CAPS ES was designed to support the on-board operation by astronauts of life-critical systems (Ockels, 1992). Fault Detection, Isolation and Recovery (FDIR) and procedure execution functionalities were integrated, with Space Shuttle ECLSS malfunction procedures being the illustrative application. User-interface issues were found to be as important as the internal representations (Kooter, van Dreumel and Grant, 1993). CAPS ES is installed in ESTEC's Crew Work Station Test-Bed (CWS-TB).

In parallel, Origin developed the Crew Portable Computer (Crew PC) Mark II, also for ESTEC's CWS-TB, but applied to payloads. Crew PC Mark II incorporated the Crew Procedure Execution System (CPES), developed for ESTEC by Computer Resources International A/S (CRI). CPES was integrated with the Origin-developed multimedia documentation and telesupport facilities to enable group-working between astronauts on-board and the PI on the ground. The on-board and ground-based Crew PCs communicated using the CCSDS packetised telemetry and telecommanding (TM/TC) protocols. Based on the Crew PC Mark II, Origin developed the Crew Support Computer (CSC) for flight on EuroMIR'94 and EuroMIR'95. In the CSC, the CPES was replaced by the DLR-developed OPIS.

Based on the subsystem application embodied in CAPS ES and the payload application in Crew PC Mark II and CSC, Origin was given a contract by ESTEC to develop the Advanced Crew Terminal (ACT). ACT is a generic framework and family of products covering the in-orbit and ground-based applications of terminals, during both the mission preparation and the mission operations phases. Of the many generic ACT services, two are of particular relevance to this paper. The Procedure Authoring Service (PAS) provides the off-line, preparation-phase facilities for authoring procedures. The Procedure Execution Service (PES) provides the on-line, operations-phase facilities for executing procedures, both in-orbit and on-ground. Under subcontract to Origin, CRI has developed implementations of the PAS (in MS-Word) and of the PES (in C++), with the procedures being represented in HTML for transmission over the World Wide Web (WWW). ACT is not required to be space-qualified and makes the maximum use of Commercial Off-The-Shelf (COTS) products. Accordingly, the ACT demonstrators are based on PCs running Windows 3.x. ACT is described in more detail in (Gale, 1966).

Origin is contracted to MMS to develop the HCI software for the International Space Station (ISS) Russian segment's Data Management System (DMS-R). This includes the Crew Procedure Language Interpreter (CPLI), which must execute procedures written in the ISS-standard Automated Crew Procedure (ACP) language. The CPLI is being developed in HOOD and Ada83 for running under Unix, because the entire DMS-R system must be space-qualified. There is no procedure authoring part in Origin's contract.

Another relevant is Origin's development under national funding of the Earth Monitoring Work Station (EMWS), based on a PC running Windows NT and interfaced to the WWW. The EMWS subsystems include a Recipe Editor and a Recipe Despatcher. The Recipe Editor is intended to be used by a meteorologist to develop recipes for processing remote sensing data.

The Recipe Despatcher executes these recipes. As in ACT, procedures are represented using HTML.

TRADE-OFFS IN PROCEDURE MANAGEMENT

There are several ways in which procedures can be classified. They can be classified according to the situation in which they are used, giving *routine* (nominal) and *contingency* (non-nominal, anomaly) procedures. Analysis shows that routine procedures are almost invariably time-triggered, and contingency procedures are event- or state-triggered. They can classified according to the type of complex (sub)system to be commanded. For example, in spacecraft operations this gives a classification into *crew* and *automated* procedures. However, closer analysis shows that each procedure-step can be issued to a different subsystem, enabling *hybrid* procedures to be constructed which support the cooperative working of man and machine.

A procedure management system divides into two parts: a *procedure authoring subsystem* and a *procedure execution subsystem*. The authoring subsystem is an off-line system that supports the manual or automatic generation of procedures, followed by their testing, approval, and archiving. The execution subsystem is an on-line system that supports the selection, retrieval, instantiation, execution, execution monitoring, and execution recording of procedures. In manned spacecraft applications, the execution subsystem would also be installed on-board. It is foreseeable that, in the longer term, an authoring subsystem installation could also be provided on-board.

There are various issues and trade-offs in designing and implementing procedure management systems:

- The number of conceptual levels of decomposition of procedures, and whether or not this number is fixed. Most procedure management systems allow just two levels (procedure and command/step). Like many project-planning systems, ACP/CPL allows exactly three levels (compare ACP's procedure, block, and step with Microsoft Project's project, phase, and activity). By contrast, ProkBase allowed procedures to be represented by an unlimited number of levels from two upwards.
- Whether or not the commands can contain *variables*.
- Whether command-sequences are linearly or partially ordered (*branching*). CPES assumed linear ordering, and OPIS extended this to branching.
- Whether command-sequences can contain iteration (FOR, WHILE and/or UNTIL).
- Whether or not a step can contain a call to another procedure (*nesting*). ACP/CPL/UCL is non-nested, but the procedure language assumed in ACT is nested.
- Whether steps can refer to manual/crew/operator actions, system actions, or both interleaved.
- Whether or not steps (or complete procedures) are time-tagged. Spacecraft operating procedures are almost always time-tagged, but remote sensing recipes are often not.

- Whether or not steps (or complete procedures) have associated resource requirements and/or constraints. If so, whether the resources are renewable, consumable or both.
- Whether or not procedures are interruptible/pre-emptible. ACP/CPL/UCL in COF is interruptible.
- Whether or not commands (and/or complete procedures) have pre-conditions, post-conditions, and/or invariants. ProkBase depended on the existence of pre-conditions at the command level.
- Whether or not commands (and/or complete procedures) have user-readable multimedia information associated with them (*warnings/annotations*). If so, whether the warnings/annotations are read-only or also writeable.

There are also various options in dividing the responsibility between the operator and the procedure execution part of the procedure management system, as follows:

- Procedures can be managed as automated checklists, as in CPES, OPIS and PES.
- Procedures can be "canned text", as in MERADEXP.
- Procedure execution can be automatic, with operator authorisation, as in ProkBase.
- Execution can be "man-in-the-loop", as in CAPS ES.
- Procedure execution can be automated under operator-predefined limits, as in DMS-R's CPLI.
- Procedure execution can be mixed-initiative. No implemented example of this option is known.

There are also software engineering issues:

- Form of user-interface presentation of procedures: canned text (as in MERADEXP), structured text (as in DMS-R's CPLI), or graphics (as in the Space Shuttle malfunction procedures and in COF's LFDs).
- Form of user-interface presentation of steps: abbreviated commands, text string/sentence, time-tags, variables, input values, whether or not pre-conditions satisfied, resources available, and step completed (eg by check-marks as in ACT's PES).
- Form of user-interface presentation of command-sequence: blocks of steps (as in ACP/CPL/UCL), branching, nesting, dependencies.
- Existence of interfaces to other systems, eg to Mission Data Base, possible-action extraction, automated procedure generation, and multimedia documentation tools in the procedure authoring part, and to synoptics, Fault Detection Isolation and Recovery (FDIR), timeline, commanding, multimedia documentation, and annotation tools in the procedure execution part. Both parts would almost certainly require interfacing to simulation systems.

GENERIC DESIGN AND KEY PATTERNS

The philosophy underlying the development of a generic design was as follows:

- The design was intended to be generic, in that it should (in principle) support whatever choice a particular implementer decided to make in respect of the above-mentioned trade-offs and issues. The generic design would be tailored by the implementer, prior to programming.
- In particular, suitable choices should enable either ISS-standard (non-nested) Automated Crew Procedure (ACP) scripts or ACT's nested procedures to be implemented.
- The generic design addressed only the *problem-domain component* of procedure management systems, leaving user-interface, database, and control component choices open to the implementer.
- The object-oriented design was intended to be the "glue" unifying the procedure authoring and procedure execution parts. In other words, it was intended to be a unifying *ontology*.

The generic design was documented using the Coad and Yourdon OOA notation (Coad and Yourdon, 1991) in the OOTher shareware tool. The static object model, comprising object-classes and attributes, is complete. Key groups of object-classes include:

- **Step** and **Block** are subclasses of **Statement**. The **Statement** object-class maintains dependencies, breakpoints and whether or not it is checked/completed.
- **Procedure** and **Statement** are subclasses of **ProcedureElement**. The **ProcedureElement** object-class maintains system and display identifiers, and is itself a subclass of **LinkedObject**.
- An instance of **Procedure** consists of **Statement** instances.
- A set of instances of **Procedure** are managed by an instance of the **ProcedureManager** object-class, which has two subclasses: **AuthoringProcedureManager** and **ExecutionProcedureManager**. The **AuthoringProcedureManager** provides the procedure developer with an off-line authoring environment, and the **ExecutionProcedureManager** provides the spacecraft operator or astronaut with an on-line execution environment.
- **Action** is the immediate superclass of **ExecutableAction** and **ControlAction**.
- **ExecutableAction** is itself the immediate superclass of **UserSupportAction**, **SystemCommandAction**, and **CrewInteraction**. **UserSupportAction** decomposes into **OpenScriptAction** and **DisplaySynopticAction**. **SystemCommandAction** decomposes into **SendSWCommandAction**, **StartAPAction**, and **ExecuteAPAction**. **CrewInteraction** decomposes into **CrewAdvice**, **CrewAction**, and **CrewInput**.
- **ControlAction** is the immediate superclass of **WhenAction**, **WaitAction**, **StopAction**, and **CaseAction**.
- **Step** instances are linked to **Action** instances, so that the same **Action** instance may be used in multiple procedures.
- **Link** is the superclass of a hierarchy of classes providing hyperlinks. Its immediate subclasses are **AnnotationLink**, **SynopticLink**, **DocumentationLink** (with its own sub-hierarchy), **VersionLink**, and **ProcedureElementLink** (providing nesting capabilities).
- **LinkedObject** instances are associated with **Link** instances.

The main methods have been identified, but (at the time of writing) the dynamic model is incomplete. Our experience with OO methods shows that it would be particularly beneficial to supplement the object model represented using the Coad and Yourdon OOA notation with use-cases and object-interaction diagrams, i.e. notations borrowed from Jacobson's Objectory method. The OOTher tool supports the two methods in such a combination.

Design patterns were identified from the generic design *post-hoc*. The following main patterns have been identified:

- The Collection-Worker pattern (pattern number 1 in (Coad, North and Mayfield, 1995)). Two instances occur (**Procedure-ProcedureManager** and **Link-LinkedObject**).
- The Plan-Step pattern (pattern number 20 in (Coad, North and Mayfield, 1995)). This pattern occurs also twice, but nested (**Procedure-Statement** and **Block-Step**).

ADAPTATION FOR SPECIFIC PROJECTS

The generic design has been central to CRI's implementation of the ACT's PAS and PES. Adaptations have included fusing the Step and Action object-classes, reducing the subclass hierarchy under Action, and addition of a structured-text user interface for PES based on the lessons learned from CPES and OPIS. Implementation of PAS and PES was found to be facilitated by the existence of the generic design.

By contrast, the generic design has not been so central to Origin's development of the CPLI for DMS-R. Reasons included:

- The DMS-R implementation language (Ada83) did not support inheritance. Extensive adaptation of the generic design would have been necessary.
- The DMS-R project team preferred for safety reasons to employ YACC and LEX technology, with which they were familiar, rather than the untried concepts embodied in the generic design.
- Work started on DMS-R before the generic design had been completed, i.e. programmatics.

Nevertheless, the generic design was used in CPLI development as a cross-check on the outputs from YACC and LEX.

POSSIBLE FUTURE ENHANCEMENTS

The static object model embodied in the generic design has been proven by its use in implementing ACT's PAS and PES. It needs to be supplemented by completing the dynamic object model, preferably using use-cases and object-interaction diagrams. If desired, the generic design could be readily transferred to a closely-related OOA/D method, such as OMT, or to another tool, such as Teamwork or Paradigm Plus.

At a software engineering level, the generic design could be enhanced to model the user-interface, database, and control components of procedure management systems. At the application level, it would be particularly interesting to extend the generic design to incorporate the capability for generating procedures automatically from system design information (e.g. output from CADCAM), as envisaged in (Grant, 1992). The Planning Operator Induction algorithm (Grant, 1996), coupled with an AI-based plan generation algorithm, would be a candidate for this purpose.

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