Reprint ESA Bulletin No. 83

ERS-2: A Continuation of the ERS-1 Success

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Introduction

The successful launch of ERS-2 on 21 April 1995, nearly four years after that of ERS-1 on 17 July 1991, not only ensures the data continuity indispensable for both the scientific research and operational applications initiated with ERS-1, but also opens a new chapter in research in the field of atmospheric chemistry. For the latter, ERS-2 is carrying a completely new instrument known as GOME, the Global Ozone Monitoring Experiment. Through the enhancement of another instrument, the Along-Track Scanning Radiometer (ATSR), already flying on ERS-1, ERS-2 will also provide an additional capability for the monitoring of changes in the Earth's vegetation cover.

The ESA Council's decision to finance the simultaneous operation of ERS-1 and ERS-2 in a so-called 'tandem mode' for a period of several months will allow uniform data sets to be collected, in particular from the identical Synthetic Aperture Radars (SARs) on board the two spacecraft. That will open completely new perspectives for many areas of scientific research as well as for operational and commercial applications.

ERS data are providing:

- The ability to map the Earth's surface through clouds:
  Geological features — Topography — Sea ice — Deforestation — Bathymetry in shallow seas — Coastal zones — Agricultural assessment — Hazard and disaster detection (flooding, oil spills).
- Fundamental discoveries about the oceans and atmosphere:
  Global wind and wave fields at high spatial and temporal resolution — Global ocean dynamics and climatic instabilities — Identification of previously unidentified physical ocean features — Sea-surface manifestations of atmospheric phenomena.
- More accurate information about the polar regions:
  Topographic maps of polar ice sheets at an increased accuracy and at higher latitudes — Monitoring changes in ice sheets as indicators of climate change — Monitoring changes in sea ice patterns — Understanding the formation of the Arctic Basin.
- Development of global and regional databases for use in climate modelling:
  Sea-surface topography at increased sampling density — Sea-surface temperature at increased accuracy — Monitoring temperate glaciers and small ice sheets — Sea-ice extent and concentration — Crop growth and desertification — Monitoring atmospheric aerosols.
- The ability to detect small changes in the Earth's surface:
  Detection of landslides — Evolution of volcanic eruptions — Detection of surface movement caused by earthquakes — Horizontal displacement along active faults.

How successful is ERS-1?

In as little as four years, ERS-1 has revolutionised many areas of the Earth sciences and their practical applications. Data from ERS-1 sensors are helping scientists greatly to improve their understanding of the processes that control our environment. Such an understanding is the basis for models that can be used to forecast the effects of future natural and man-made changes.

As foreseen in the original mission objectives, ERS-1 data are being used extensively within the international scientific community for physical oceanography, polar science and climate research. Beyond these anticipated areas, the data have stimulated a much broader range of scientific utilisations than was originally thought. This is the case, for example, in the field of solid Earth and terrestrial sciences.

Thanks to the use of advanced observation techniques, primarily radar, ERS-1 provides both global and regional views of the Earth, regardless of cloud coverage and sunlight conditions. An operational near-real-time capability for data acquisition, processing and dissemination, offering global data sets within three hours of observation, has allowed the development of time-critical applications particularly in weather, marine and ice forecasting, which are of great importance for many industrial activities.

How much are ERS data being used?

Every space agency that develops and launches a completely new type of satellite faces the same question: 'Will users have as much call for the data as was predicted in preparatory studies and surveys?' Four years after its launch, the demand for ERS-1 data has not only lived up to expectations, but has indeed exceeded them and is continuing to grow at a rate of 20% to 30% a year.

A few figures will serve to illustrate this point: the Proceedings of the two ERS-1 scientific symposia (held in Cannes in 1992 and Hamburg in 1993) contain a total of 410 original scientific papers. Many have also been published in recognised learned journals, including *Nature*.

At the first ERS-1 Application Pilot-Project Workshop, held in Toledo, Spain, in June 1994, more than 100 projects covering a wide spectrum of operational applications were presented. A significant number of those projects have now reached the operational stage, in particular in such fields as meteorology, ice forecasting and bathymetry.

The customer service at ESA's data handling centre ESRIN has dealt with some 15 000 orders for ERS SAR data from all corners of the Earth. This does not include the thousands of orders that went directly to non-ESA ground stations rather than to ESRIN. The large number of users in North America and the Asia-Pacific Basin is particularly striking.

The breadth of ERS users is enormous, ranging from individual scientists to multi-institutional research groups, and from small high-tech firms to large corporations and crucial public services such as meteorological offices.

Another important element is the availability of a well-maintained and accessible data archive. This is especially true in the case of radar data, which is unaffected by cloud cover and is in principle continuously usable. ERS-1 has provided more than half a million distinct radar images, each of an area of 100 km × 100 km, covering virtually the whole of the Earth's surface. They can be used either alone or in combination with optical images from satellites such as Spot and Landsat.

The high standard of performance in terms of satellite instrument operations and the reliable provision of well-calibrated data have stimulated and encouraged the use of both the SAR and the low-bit-rate data. This has been achieved through close and fruitful cooperation between the European and Canadian industry involved in the development of the ERS-1 satellite and ground segment, the scientific community, and the ESA project team.

What are the prospects and challenges for ERS-2?

Built in the same way as ERS-1 by a consortium led by Deutsche Aerospace, ERS-2 carries the same radar instruments, together with GOME and the enhanced ATSR. It will thus have to deal with an even more demanding range of tasks and an even greater number of users.

Following a worldwide Announcement of Opportunity issued in the spring of 1994, using very strict criteria, ESA selected a further 340 research teams interested in using data from both ERS satellites. A number of them are particularly eager to acquire data obtained when the two satellites are working in tandem. Such unique data are especially useful for SAR interferometry to generate accurate Digital Elevation Models (DEMs) which are of high value for many applications, such as hydrology and cartography, or to detect small (cm-level) movements in the Earth's crust, for example following earthquakes, prior to volcanic eruptions, or as a result of glacier flows. A large number of users are interested in the scientific exploitation of data from GOME, since it offers significant advantages over conventional instruments in terms of both measurement accuracy and spectral coverage.

The number of ERS receiving ground stations is also expanding. There are now mobile stations that allow data to be provided for areas not previously covered, such as Central and Eastern Africa, or incompletely covered with the existing stations, such as Antarctica.

ERS-2 will benefit greatly from the expertise and experience gained with ERS-1 in terms of data processing and dissemination, sensor calibration and data validation.

At the time of printing, ERS-2 is still in its commissioning phase but has already provided data of high quality, demonstrating its capability to continue the ERS service until the end of the 1990s, Then, the next generation of satellite, Envisat-1, with even more advanced sensors, will be launched and will take over the service to users until 2005.

With ERS-1 and ERS-2, ESA is playing a major role in the provision of the continuous, high-quality and reliable data that is needed for a better understanding of our complex home habitat Earth and its fragile environment.

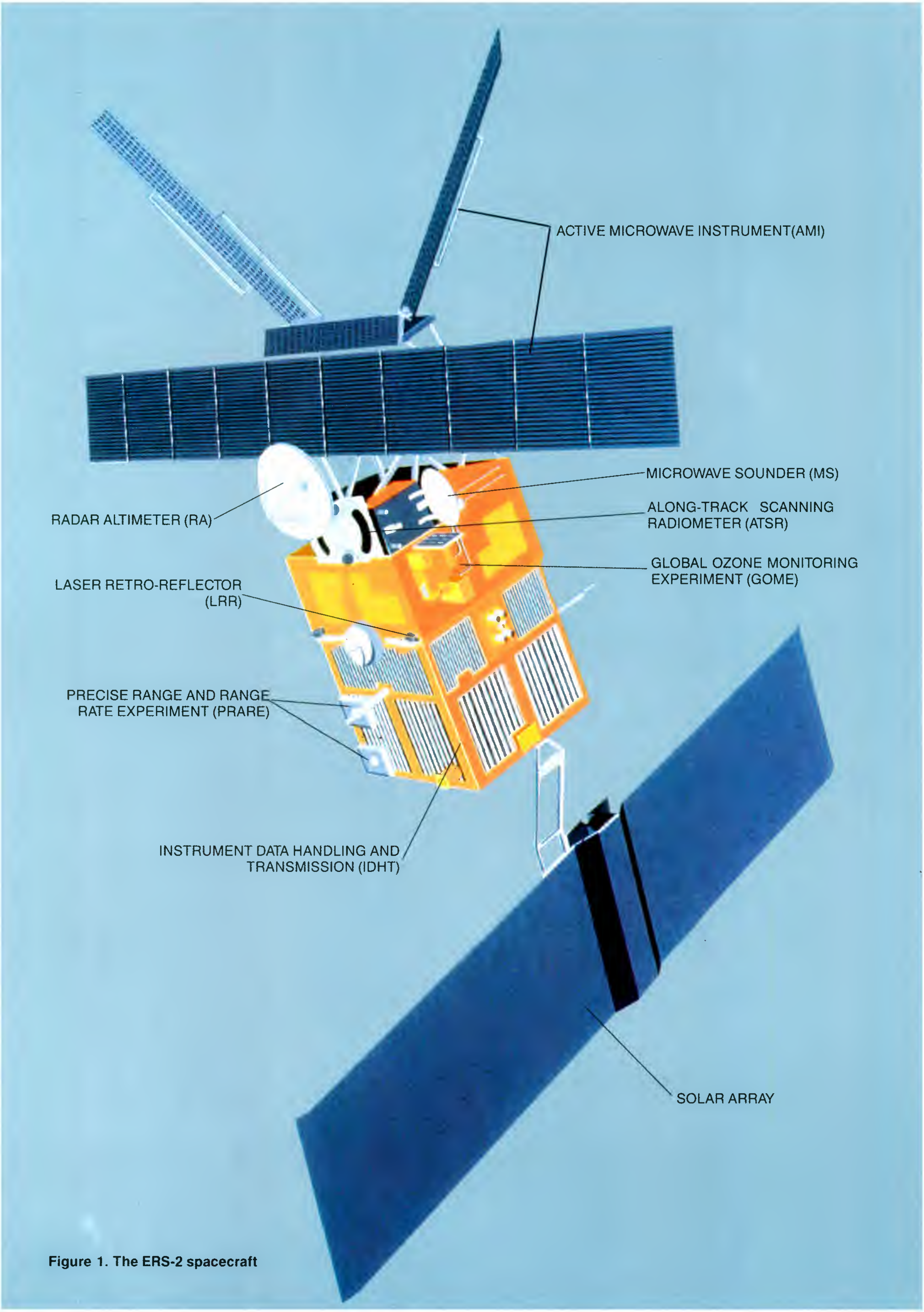

Figure 1. The ERS-2 spacecraft

The ERS-2 Spacecraft and its Payload

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The ERS-2 satellite is essentially the same as ERS-1 except that it includes a number of enhancements and it is carrying a new payload instrument to measure the chemical composition of the atmosphere, named the Global Ozone Monitoring Experiment (GOME).

Other major instruments common to ERS-1 and ERS-2 are the Active Microwave Instrument (AMI), the Radar Altimeter (RA), the Along-Track Scanning Radiometer (ATSR), the Microwave Radiometer (MWR) and the Precise Range and Range Rate Experiment (PRARE). The AMI operates in three different modes devoted to radar imagery, and oceanic wind and wave measurements. The RA measures precisely the altitude over ocean ice and land surfaces and also measures oceanic wind and waves. The ATSR measures sea-surface temperatures and has been enhanced for ERS-2 by including visible channels for vegetation monitoring. The MWR and PRARE both support the RA mission by providing information respectively on propagation delays of the radar signal and satellite positioning.

Note: This article is an updated version of an article describing ERS-1 which appeared in ESA Bulletin 65 (February 1991).

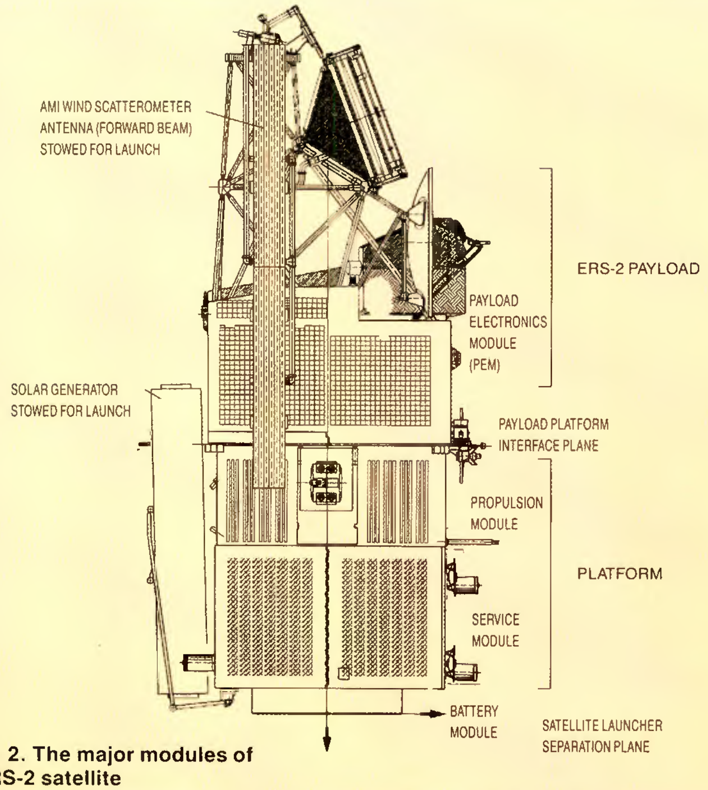


Figure 2. The major modules of the ERS-2 satellite

The first European Remote Sensing satellite, ERS-1, was launched on 17 July 1991. The satellite had been developed during the 1980s with the objective of measuring the Earth's atmosphere and surface properties, both with a high degree of accuracy and on a global scale. The primary scientific reason behind acquiring such data is to increase our understanding of the interaction between the Earth's atmosphere and the oceans, in order to deepen our knowledge of the climate and improve global climate modelling.

Other major benefits have been derived from ERS-1 data, including: improved weather and sea-state forecasting and 'nowcasting'; a greater knowledge of the structure of the sea-floor, which is useful for oil and mineral exploration; detailed measurements of the Earth's movements following seismic events; measurements of ice coverage; and the monitoring of pollution, dynamic coastal processes, and changes in land use.

In order to ensure the continuity of those measurements, ERS-2, a second flight model of the satellite, was planned. Its development was started in the late 1980s and the satellite was launched on 21 April 1995. Although it is essentially the same as ERS-1, the satellite includes a number of enhancements and, in particular, it is carrying a new payload instrument that measures the chemical composition of the atmosphere.

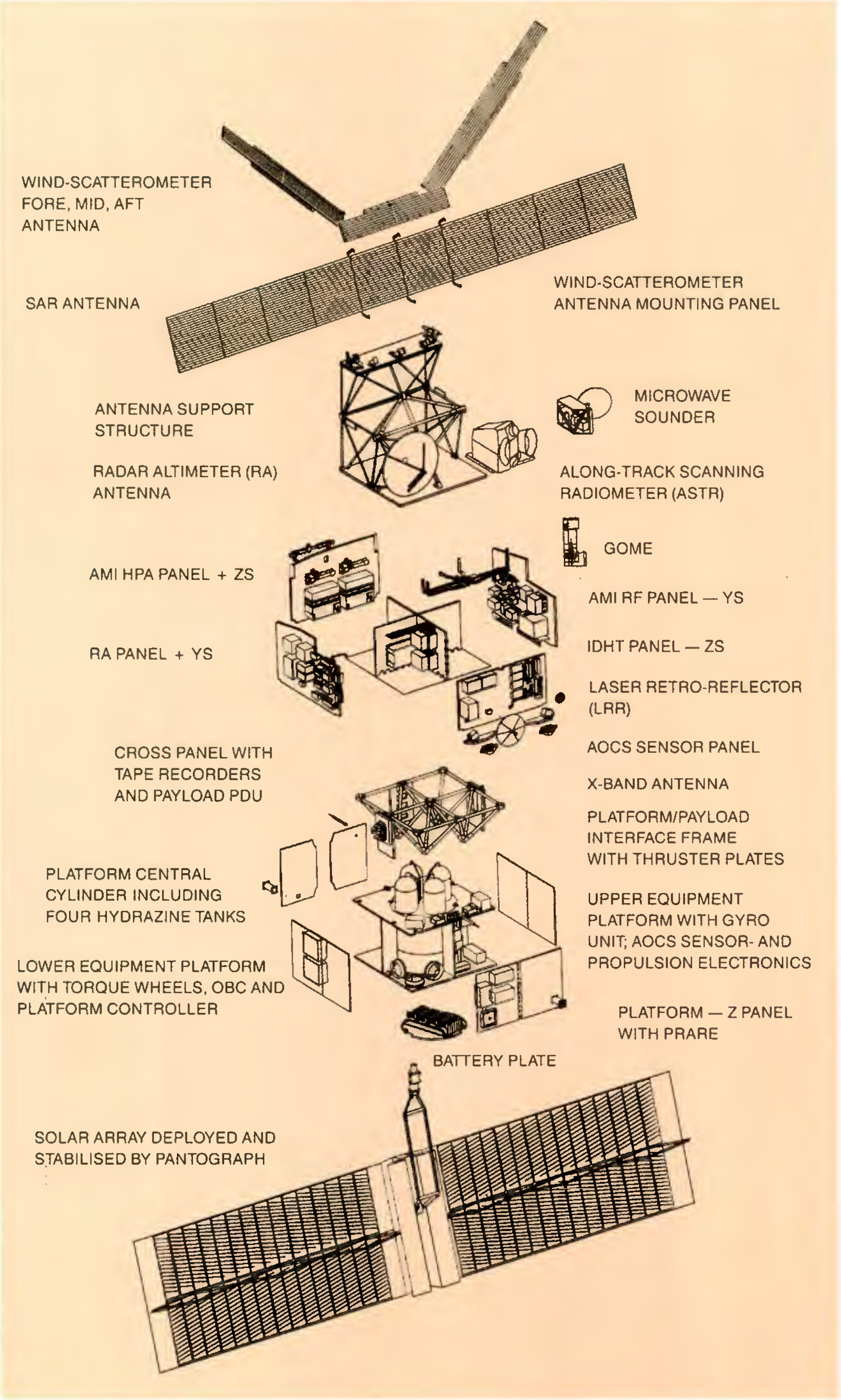
The spacecraft

In common with ERS-1, the major components of the ERS-2 payload are active microwave instruments or radars. Powerful radar pulses are needed to provide sufficient illumination of the Earth's surface to produce detectable echo signals from the satellites' polar orbits, which have a mean altitude of about 780 km. The spacecraft also need large antennas to be able to pick up the returning signals. Consequently, the satellites have to be rather large: they each weigh about 2.3 tonnes. The payload alone weighs about 1000 kg and consumes about

1 kW of electrical power when in full operation. The antennas, after deployment, are up to 10 m long; the main payload support structure has a 2 m × 2 m base and is some 3 m high. To support the payload by providing electrical power, attitude and orbit control, as well as overall satellite operational management, a platform module (derived from the French national SPOT programme) is attached to the payload (Fig. 2). That module is roughly equivalent in size to the payload itself and is equipped with a deployable 12 m × 2.4 m solar array.

When the main ERS-1 development contract started, in 1984, the satellite was far larger and more complex than any that ESA had flown previously. A comparison between the Meteosat satellite and ERS-1, for example, shows that ERS-1 is 7.5 times heavier, transmits 750 times more bits of data per second, and has nine active onboard computers, while Meteosat had none.

Figure 3. Exploded view of the ERS-2 satellite



The largest of ERS-2's sensors, the Active Microwave Instrument (AMI), is capable, in its imaging mode, of producing highly detailed radar images of a 100 km strip on the Earth's surface. This mode is also known as the Synthetic Aperture Radar or SAR mode. Because that mode consumes a large amount of energy and produces a vast amount of data which cannot be stored on board, it is only used regionally, for periods of approximately 10 min per orbit. The same instrument has alternative global measurement modes, namely the Wind (or Scatterometer) Mode in which the wind speed and direction at the sea-surface can be measured over a 500 km swath, and a Wave Mode which provides small radar images at 200 km intervals. Those images can be used to generate ocean-wave spectra, showing wave energy as a function of wavelength and direction.

A second instrument, the Radar Altimeter, provides very precise measurements of the satellite's height above the ocean, ice and land surfaces. The successful exploitation of those height data — which are to be used to study, among other topics, global ocean circulation and height profiles across the ice caps — is dependent upon precise determination of the satellite's orbit, which is derived from the onboard tracking systems. Those systems are a laser retro-reflector, which is a passive device used by ground-based satellite laser-ranging systems, and the PRARE instrument, which is a two-way microwave ranging system that uses small, dedicated ground stations. The PRARE on ERS-1 failed shortly after launch. For ERS-2, the cause of that failure has been eliminated and, furthermore, a second PRARE has been embarked.

Another payload instrument is the Along-Track Scanning Radiometer (ATSR), which consists of two parts. Detailed images of the sea surface are made by an infra-red scanning radiometer, which allows extremely precise measurements of sea-surface temperature. For ERS-2, additional channels have been incorporated to provide imagery in the visible part of the spectrum as well. The other part is a passive microwave radiometer, which is used to determine the water-vapour content of the vertical column of the Earth's atmosphere passing beneath the satellite.

ERS-2 is also carrying one completely new instrument compared to ERS-1: the Global Ozone Monitoring Experiment, GOME. That instrument provides spectra of backscattered sunlight in the ultra-violet/visible/near-infrared part of the spectrum, while scanning a swath below the satellite. Processing of those spectra, in combination with direct solar spectra which are also measured by GOME for reference, allows the determination of concentrations and profiles of many trace gases, but particularly ozone, in the atmosphere.

The large amounts of data from those instruments are transmitted to the ground via the Instrument Data Handling and Transmission (IDHT) Subsystem. That system includes two high-capacity onboard tape recorders to store the data being gathered while the satellite is outside the visibility of the various ground stations.

The orbit

Both ERS-2 and ERS-1 are in a Sun-synchronous polar orbit, highly inclined to the equator, giving the satellites visibility of all areas of the Earth as the planet rotates beneath their orbits. The inclination is such that the precession of the orbit, caused by the non-spherical components of the Earth's gravity field, exactly opposes the annual revolution of the Earth around the Sun. Consequently, the orbital plane will always maintain its position relative to the Sun, crossing the equator with the descending node at about 10:30 am local time. The constant illumination conditions throughout the year which that provides are advantageous for the ATSR and GOME. They also have benefits for the satellite design, in that, for example, the solar array only needs to rotate about one axis, normal to the plane of the orbit, in order to maintain its correct alignment with the Sun.

The orbital inclination required to achieve Sun-synchronism is a weak function of satellite altitude. For a mean altitude of approximately 780 km, it needs to be about 98.5°, making it a so-called 'retrograde' orbit. The orbital altitude, and consequently the revolution period, may be adjusted by use of the orbit control thrusters provided on both ERS-1 and ERS-2, so that a harmonic relationship exists between the revolution period of the satellite and the rotation period of the Earth. Consequently, after a certain number of orbits, the satellite re-traces its tracks over the Earth's surface. In practice, the orbital altitude of ERS-1 has been changed, by a few kilometres, several times during the four years it has been in orbit. Five orbital patterns have been flown: two had repeat periods of three days but over different ground tracks; for most of the mission, a multi-disciplinary 35-day pattern has been used; and two others had a pattern with a 168-day repeat, offset by half of the track spacing to provide a very dense spatial coverage. Each individual orbit in those patterns lasts approximately 100 min.

ERS-1 and ERS-2 are both flying in the same 35 day orbit, over the same ground tracks. It is foreseen that both ERS-1 and ERS-2 will always remain in that orbit. The phasing of the two satellites around that orbit plane has been adjusted so that they overfly the same track with a one-day separation, ERS-1 being ahead. That provides excellent opportunities to compare the results from the two satellites.

The platform

The spacecraft platform provides the major services required for satellite and payload operation. Those services include attitude and orbit control, power supply, monitoring and control of payload status, telecommunication with ground stations for telecommand reception and telemetry of payload and platform housekeeping data. The platform also houses the two independent PRAREs as passengers.

The platform has been modified with respect to the SPOT programme, in which it was developed as a multi-mission concept, to meet the special needs of the ERS missions. The major modifications have included extension of the solar-array power and battery energy-storage capability, modification of the attitude-control subsystem to provide yaw steering and geodetic pointing, and the development of new software for payload management and control.

The solar array's performance had to be appreciably increased to support ERS-1's power-hungry microwave payload. This has been achieved firstly by increasing the array's effective area (and corresponding power) by about 66%, to approximately 24 m^2, and secondly by using more efficient solar cells, which produce about 12% more power.

The solar array (Fig. 4) consists of two 5.8 m × 2.4 m wings, manufactured from flexible reinforced Kapton, on which are mounted a total of 22 260 solar cells. The two wings are deployed by means of a pantograph mechanism, and the whole array rotates through 360° with respect to the satellite during each orbit in order to maintain its Sun pointing.

During the 66-min sunlit phase of each orbit, the array provides electrical power to all of the onboard systems. It also charges the

Figure 4a. Front side of the solar array (Photo: Aerospatiale)

Figure 4b. Rear of the solar array, showing the pantograph deployment mechanism

spacecraft's batteries, located in a cylindrical compartment at the solar-array end of the platform, so that they can provide the energy necessary for a similar level of payload operations during the 34-min eclipse periods. The four nickel-cadmium (NiCd) batteries are sized to allow payload operations to be independent of the satellite's orbital position. Connected directly to the spacecraft's unregulated 30 V bus, they power it during the 14 eclipses that occur each day, using their combined capacity of 96 Ah. The precise management of the charge and discharge cycles is handled by the onboard computer, with the possibility of ground intervention if required.

Attitude and orbit control

ERS-2, like ERS-1, is a three-axis-stabilised, Earth-pointing satellite. Its yaw axis is pointed towards the local vertical with respect to a reference ellipsoid, taking the Earth's oblate shape into account. The direction of the pitch axis oscillates slightly during each orbit to keep it oriented normal to the composite ground velocity vector, taking account of the Earth's rotation, to assist the operation of the AMI. The residual attitude errors are no more than 0.06° on each axis for ERS-1, and ERS-2 is expected to have a similar performance. The attitude control system has the capability to be offset to compensate for any static error that may be observed, but that has not proved to be necessary.

ERS-2 has a range of attitude sensors. The long-term reference in pitch and roll is obtained from one of two continuously operating, redundant infrared horizon sensors. The yaw reference is obtained once each orbit from one of two redundant narrow-field Sun sensors aligned to point at the Sun as the satellite crosses the day/night terminator. The short-term and rate reference are obtained from an inertial core, with a pack of six gyroscopes, of which any three can be in use. Finally, there are two wide-field Sun-acquisition sensors for use in the initial stages of attitude acquisition, and in safe mode, when the satellite is Sun-pointing rather than Earth-pointing.

The primary means of attitude control is provided by a set of momentum wheels (large flywheels), which are nominally at rest. They can be spun in either direction, exchanging angular momentum with the satellite in the process. It is also possible, if there were permanent torques on the satellite due, for instance, to radiation pressure on the solar array, to bias one or more wheels to a nominal non-zero speed. This has not been necessary with ERS-1. Angular momentum also needs to be dumped from the wheels on a regular basis and a sophisticated system has been devised for this purpose. The onboard computer contains a simple model of the Earth's magnetic field, and is also able to control the current in a pair of orthogonal magnetic coils. These coils, called 'magneto-torquers', generate torques by interacting with the Earth's geomagnetic field. Using a servo loop and the built-in field model, the spacecraft's onboard computer continuously adjusts the magneto-torquers to keep the wheel speed close to the nominal values.

ERS-2 has a number of monopropellant-type thrusters, aligned about the spacecraft's three primary axes, in which hydrazine dissociates exothermically as it is passed over a hot-platinum catalyst. They are used in different combinations to maintain and modify the satellite's orbit and to adjust its attitude during non-nominal operations. That is normally done by using pairs of thrusters to provide in-plane thrust when slightly changing the orbital height or speed, or by turning it in yaw to obtain out-of-plane thrust when slightly modifying the orbital inclination.

The payload module

The mechanical structure of the payload has to meet a number of challenging requirements, including rather tight mechanical-stability and thermal-isolation constraints. It was also foreseen that the payload would need to be disassembled many times, and this had to be considered in its basic design. There are two main parts to the payload module (Fig. 5), the Payload Electronics Module (PEM) and the Antenna Support Structure (ASS), for which different design solutions were adopted.

The Payload Electronics Module (PEM)

The PEM is an aluminium face-sheet/honeycomb structure supported by nine internal vertical titanium beams (titanium was selected for its low thermal conductivity and expansion coefficient). The central beam lies at the intersection of two internal cross-walls, so that the PEM is effectively divided into four separate compartments. Each outer panel is dedicated to a particular instrument, to simplify integration logistics, and is fixed to the vertical beams by close-tolerance bushes and titanium screws. This construction minimises settling effects due to vibration and ensures good structural-assembly repeatability.

The payload is separated from the platform by a non-load-bearing electromagnetic (EMC) shield. An aluminium-honeycomb panel closes the opposite end of the structure, stabilising the beams and providing the interface to the ASS at the beam locations. The beams provide a load path from the ASS to the platform.

It was clear that the integration programme would involve many separations of the PEM and the platform and so a system of tapered dowels and shims was developed to ensure repeatability of assembly. To facilitate the connection and disconnection of the instrument panels to and from the main harness, there are large connector brackets attached to the lower parts of the panels, with simple covers.

The Antenna Support System (ASS)

The ASS (Fig. 6), requiring structural stiffness while minimising thermal distortion, has been manufactured primarily from high-modulus carbon-fibre-reinforced plastic (CFRP) tubes, with titanium being used for all the highly loaded structural elements such as nodes, strut end-fittings, and interface brackets.

The lower part of the assembly consists of five tripods, three of which provide support points for the SAR antenna and two intermediate support points for the upper assembly. These tripods are also connected to each adjacent node. The CFRP sandwich plate at the top, which carries the Scatterometer antennas, is supported by three further tripods attached to the intermediate points and the SAR central point. The Altimeter's antenna is attached at three node points by a triangulated strut system.

That intricate, highly stable assembly was challenging in terms of design, manufacture and integration. That is amply illustrated by the central titanium node, which interfaces to ten high-tolerance struts without inducing built-in stresses.

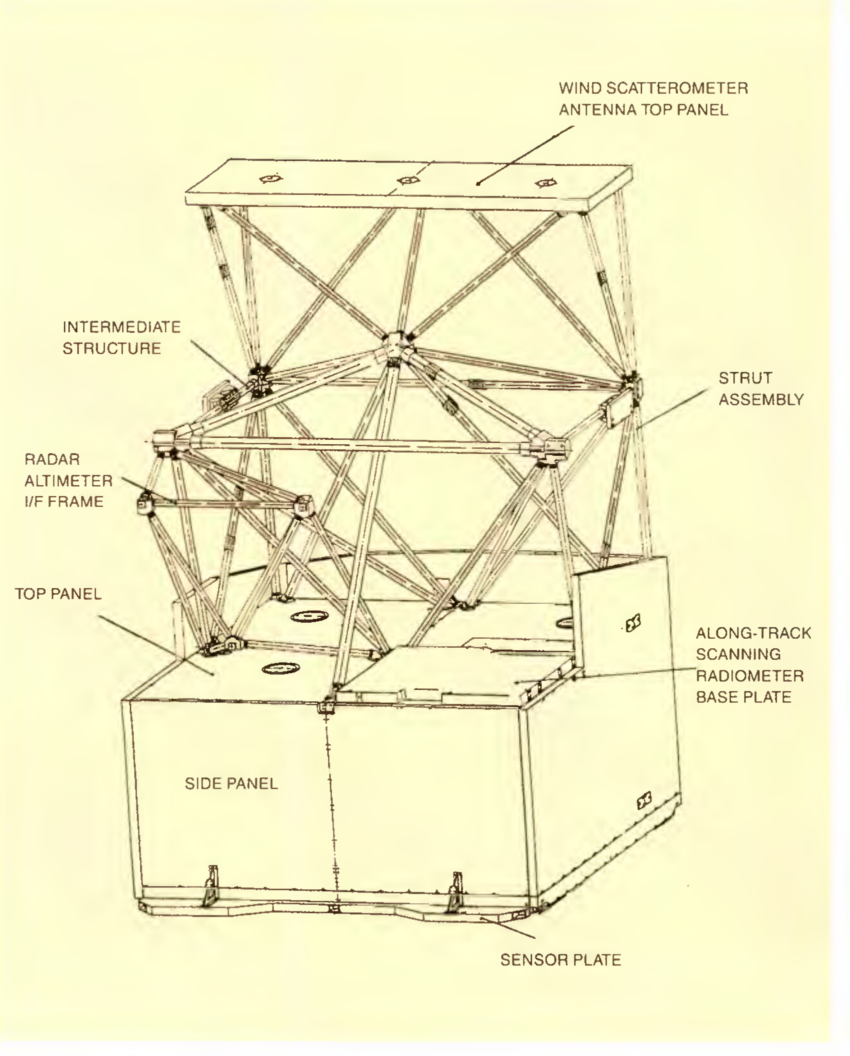


Figure 5. The payload support structure, showing the box-like Payload Electronics Module (PEM) structure and the complex strut assembly of the Antenna Support Structure (ASS)

The thermal-control system

The thermal-control system is basically a passive design, complemented by an active heater system. The thermal-control approach complements the modular overall design of the satellite, the payload, platform and battery compartment being thermally insulated from one another as far as practicable, allowing separate analysis and testing. The individual modules are also insulated from the external environment by multi-layer insulation blankets, except for the radiators. The latter are covered mainly with materials of low solar absorptance and high infrared emittance, which reject the internally dissipated energy. The radiator areas have been optimised for the extreme hot and cold operating conditions that will be encountered in nominal Earth-pointing attitude, and during the Sun-pointing safe mode in which the payload would be inert. A heat pipe is used to transfer heat from the ATSR to one of the radiators. The GOME, which was added to the payload for ERS-2, obscures one of the original ERS-1 radiators. The necessary thermal dissipation is now provided by a further heat pipe to an enlarged radiator on a nearby panel. The GOME itself has a relatively large built-in radiator panel facing cold space, to which the Peltier coolers, which are used to keep the detector temperatures at −30°C, are connected by heat pipes.

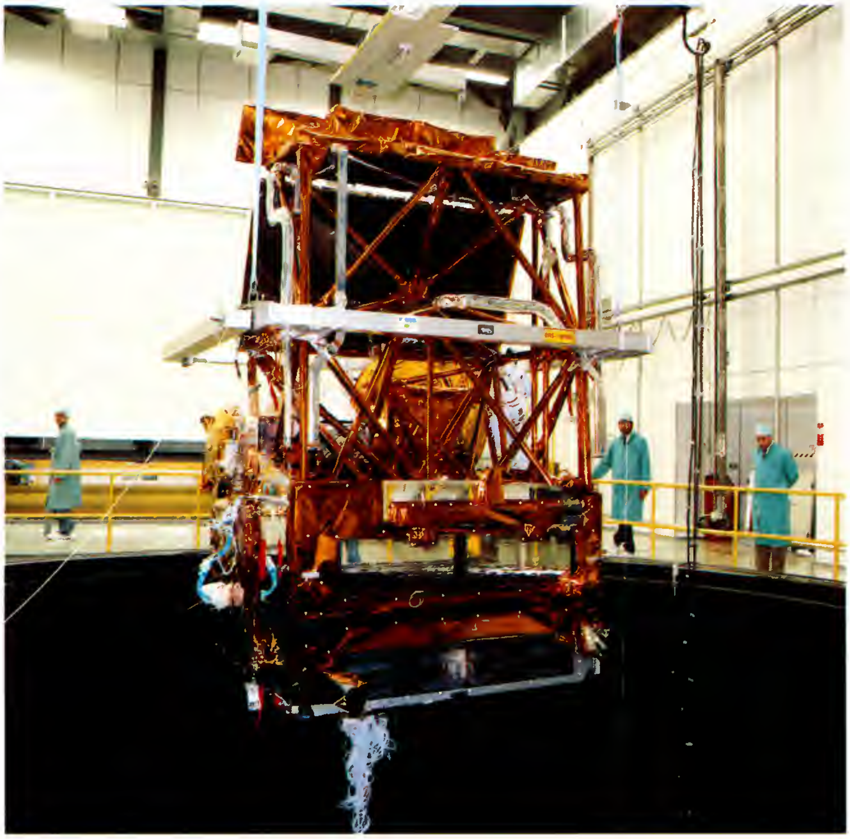


Figure 6. The ERS-2 payload being placed in the Large Space Simulator for environmental testing. The Antenna Support Structure (ASS) can be seen.

High heat fluxes in the payload electronics module are spread over larger areas by local skin-thickening of honeycomb side panels or by constant-conductance heat pipes embedded in the panels.

Active heater systems, which are fully redundant during nominal operations and partially redundant in safe mode, provide autonomous thermal control to cope with periods of limited ground contact. The heater systems themselves are controlled predominantly by onboard software in nominal modes and by thermostats in safe mode, or in failure cases where the onboard computer is not available. An anomaly-management system is triggered by failures in the heater systems and/or out-of-range equipment temperatures. It decides on the appropriate corrective action, which can be to switch to redundant heater branches and/or to switch off the payload.

All software parameters used for control or surveillance can be enabled, inhibited or updated by ground command, providing a high degree of flexibility for coping with a variety of unforeseen events or conditions.

On-board command and control

ERS-2 carries a significant number of software packages run by different processors spread throughout the platform and the payload. In the platform, the On-Board Computer (OBC) runs the so-called 'Centralised Flight Software', which is a small software package (44 kwords) incorporating all the basic functions needed to conduct the mission in an optimal fashion. In addition, each payload component (AMI, RA, ATSR and IDHT, described in more detail below) contains its own decentralised Instrument Control Unit (ICU). These five computers are linked by the On-Board Data-Handling (OBDH) bus, and communicate with each other via a high-level packetised protocol. The PRARE, as a platform passenger, is not a user of the OBDH bus, but also has built-in intelligence, as does the GOME, which is controlled by the control unit of the ATSR.

That set of interdependent computers fulfils a critical requirement. ERS-2 is an extremely complex satellite, with a great many modes, parameters and logical conditions to be set and respected throughout each orbit. It is required to have 24-hour autonomy, and that could only be achieved by providing intelligent payload elements controlled by a capable central computer. A basic concept in that philosophy is the 'macrocommand', a coded instruction expanded and acted upon by the ICU. In that way, the ICU relieves the OBC of many detailed tasks related to internal instrument configuration and operations.

It was a primary requirement that all of the onboard processors be reprogrammable in flight, and many of the operating characteristics are controlled by tables of variable parameters. Commands are provided for manipulation of those tables to enable major changes in the operating characteristics to be easily achieved.

The main functions of the OBC flight software are:

— to take the spacecraft from launch to operational configuration, by automatically sequencing such events as the firing of

pyrotechnic cable-cutters and unfolding of antennas;
- to manage the spacecraft in orbit, operating the platform subsystems and managing the overall payload. That includes overall power regulation, power distribution and thermal control of the platform subsystems, the PEM and the antennas. The Attitude and Orbit Control System (AOCS) is also piloted by the OBC flight software;
- to monitor the spacecraft, in order to detect and neutralise any critical failure and thereby preserve the mission. In the case of serious failure, the flight software will autonomously reconfigure the faulty platform subsystem to the redundant hardware, or switch-down any payload instrument that shows anomalous behaviour. If the reconfiguration fails, the spacecraft will be put into a so-called 'safe mode', in which the payload will be switched off, the solar array parked in the canonical position, and the satellite placed in a Sun-pointing attitude, awaiting further intervention from the ground;
- to allow mission pre-programming from the ground. The OBC flight software can memorise up to 16 orbits' worth of macrocommands for scheduled transmission to the various payload instruments, usually when the satellite is out of ground coverage. This mechanism can also be used to achieve temporary attitude (e.g. roll-tilt) effects;
- to report to the ground. Every second, the S-band telemetry link transmits 256 bytes of data obtained by the OBC flight software, either on the real-time status of the platform and payload, or from dedicated memory areas where the significant event history has been recorded. The flight software can also support trouble-shooting via S-band telemetry, in that it is able to access and transmit the contents of all the computer memories onboard the satellite.

The ICUs run software packages whose functionality depends on the particular instrument that they serve, but there is some commonality. The common ICU tasks are:
- interfacing between the OBDH bus and the instrument hardware, receiving macrocommands and providing packetised telemetry, so-called 'ICU Formats';
- executing macrocommands, by putting the instrument into the appropriate mode to perform commands sent from the ground;
- monitoring sensors within the instruments in order to detect any critical failure, and if necessary switching the instrument to 'standby mode';
- reporting to the ground by the telemetry of 'ICU Formats' consisting of real-time data (such as sensor measurements, science-data samples, and software variables) or data recorded to trace the history of the instrument (such as mode transitions and anomalies).

The other functions of the ICUs are related to scientific data conditioning/processing, and are therefore more specific to each instrument. Both the AMI and RA ICUs interface with scientific computers, known as the Scatterometer Electronics and Signal-Processor Sub-Assembly (SPSA), respectively. The AMI ICU manages a large memory buffer which accommodates the data originating from the sampling of the radar echo in SAR and Wave modes, while the IDHT ICU manages the tape recorders.

There are two types of time-management functions to be carried out onboard, namely the scheduling of events and the time-stamping of measurements. All timing is referenced to a clock maintained by the OBC, providing time signals with 4 ms resolution and correlated with UTC (Universal Time Coordinated) by the Kiruna (Sweden) ground station. Events are scheduled by associating a time with each macrocommand.

The time-stamping of measurements, known as 'datation', is also performed by the ICUs, which write the appropriate binary time code, transcribed from the ICU clock, into the secondary header of each source (data) packet.

Deployments

During the first few orbits after ERS-2's separation from the launch vehicle, a period known as the Launch and Early-Orbit Phase, or LEOP, several units of the spacecraft were deployed (Fig. 7). They include the solar-array arm and panel on the platform, and the SAR antenna, fore and aft Scatterometer antennas and ATSR antenna on the payload. In designing these deployments and their sequencing, a number of constraints had to be observed:

- Dynamic

  The sequence of deployments is driven primarily by the results of a shock analysis, which showed that the SAR antenna could be deployed with the solar array already out, but the array drive mechanism had to be locked. This also applies to the Scatterometer antennas, but they could also be deployed after drive-mechanism release if need be.

— Timing
The SAR and Scatterometer antennas must be deployed after the AOCS fine-pointing mode has been achieved, which is at most 2000 s after separation. The SAR deployment takes 18 min, and the Scatterometer antennas 8.5 min each.

— Visibility
The critical deployment phases must take place within the visibility of one of the seven ground stations participating in the LEOP.

— Power
During the LEOP, the battery depth-of-discharge must not exceed 60%. Before solar-array deployment, the spacecraft has to rely entirely on its batteries, which would be 60% discharged after three orbits. Once the solar array is deployed but is not yet rotating, a short battery-charging cycle is possible, thereby raising the batteries' operating limit to 20 orbits.

— Thermal
The payload elements must be maintained within their survival temperature limits despite the need to use as little power as possible. During the first orbit, therefore, low-level heaters were switched on during the day only. There would also be potential thermal difficulties at some orbital positions if the active face of the deploying SAR antenna was exposed to the Sun.

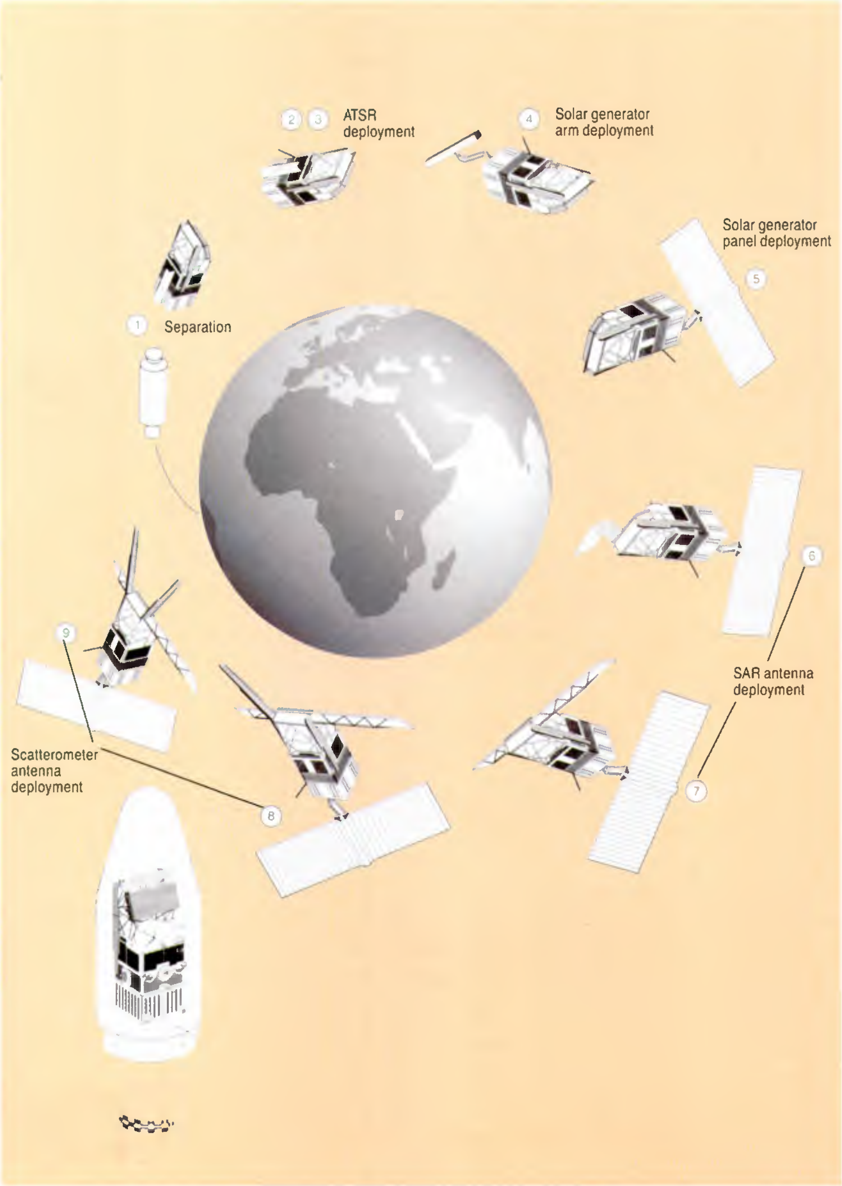


Figure 7. Nominal operations sequence for the Launch and Early-Orbit Phase (LEOP)

All of the deployments were controlled by the OBC, some via a pyrotechnic activation sequence triggered by the separation from the launcher, and some via time-tagged macrocommands. The macrocommands were loaded into the OBC before launch and were thus executed at times independent of the actual time of launch during the 5 min window. To maintain synchronism between the two types of deployment, had ERS-2 not been launched at the opening of the launch-window, the macrocommand queue could have been updated very shortly after separation from the launcher, when ERS-2 was visible from the Wallops ground station, on the east coast of the USA. There was also a possibility of updating from Fairbanks in Alaska, or Perth in Australia.

The ATSR microwave antennas were released by pyros 5 s after separation. A spring drive then rotated it into its latched position in just a few seconds. Next, the solar-array arm's deployment began with a pyro release firing, less than 1 min after separation, the further deployment requiring no additional commands and being mechanically sequenced and driven by spring forces (Fig. 8). Deployment of the solar-array panels themselves did not start until about 45 min after separation, when ERS-2 was visible from Perth. The deployment was again passive, with the two panels being pulled out of their container by spring-driven pantographs.

The SAR-antenna deployment (Fig. 9) started 75 min after separation, within the visibility of the Santiago de Chile ground station. The two antenna wings each have spring-driven and motor-driven phases, and the whole sequence was initiated by firing a pyro to release six lever clamps holding the folded antenna in launch configuration.

The Scatterometer antennas were deployed immediately after the SAR antenna. They were stowed at the sides of the PEM for launch, and were also released by pyro firing. Each antenna deployment involves a single motor-driven rotational movement.

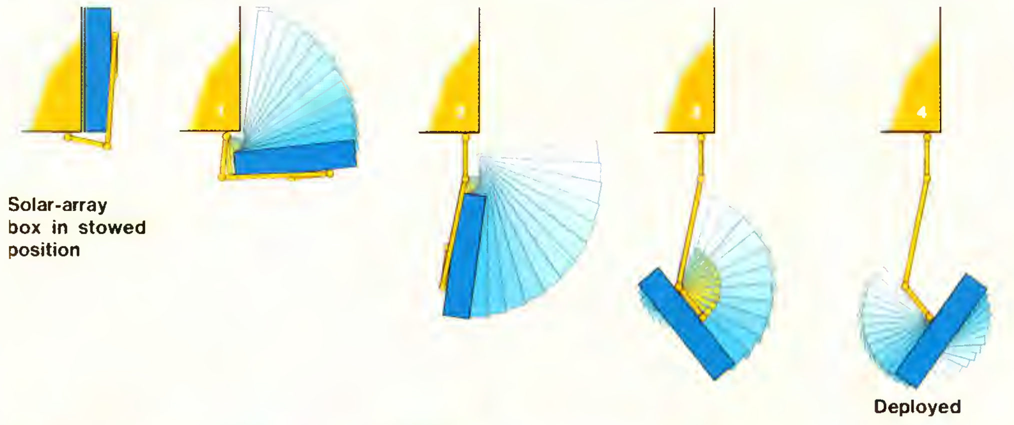


Figure 8a. Deployment of the solar-array arm

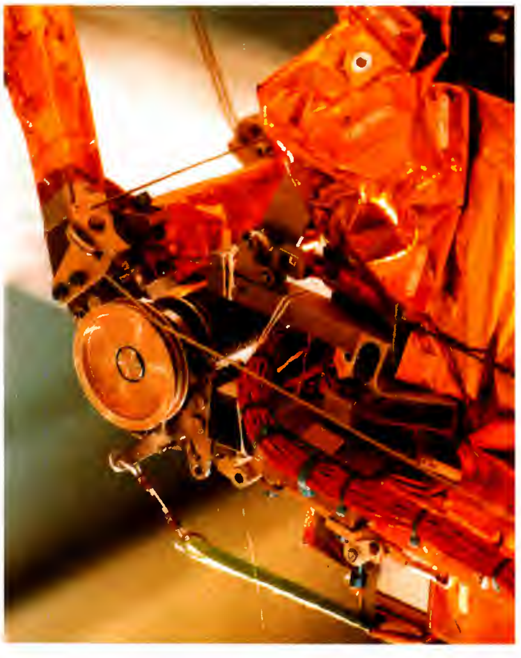


Figure 8b. One of the spring drives for solar-array deployment

Finally, after 2¼ h and 1¼ orbits, when the Sun was directly overhead, the solar array rotation was enabled. All the ERS-2 deployments occurred precisely as planned.

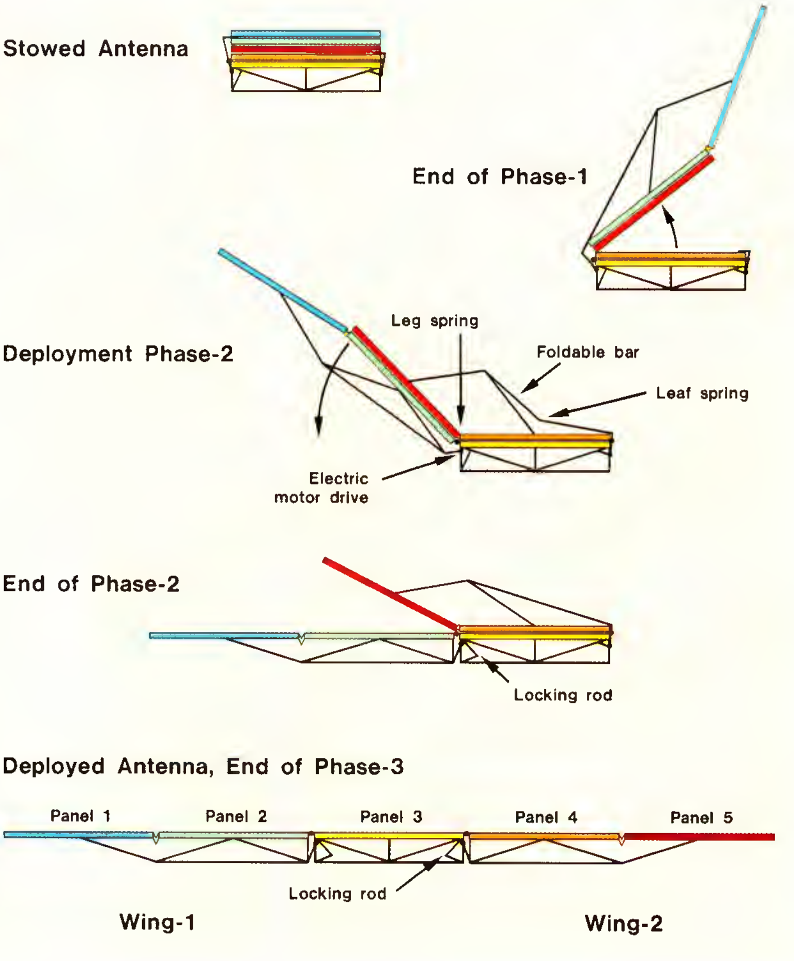
Instrument data-handling and telemetry

ERS-2 has two telemetry systems. The platform's needs are served by a classical-type Telemetry, Telecommand and Control (TTC) system operating at S-band. That low-rate (2 kbit/s) system is used to transmit the ICU formats for housekeeping purposes. Because of the high bit rates involved, the science data cannot use this link and the payload therefore includes a so-called 'Instrument Data Handling and Transmission' (IDHT) system. That system allows real-time transmission of AMI Image-Mode data, providing a regional service to local ground stations and global recording and telemetry of the other sensors.

The instruments generate data in the form of 'source packets', which constitute a logical division of telemetry data from the instrument point of view. However, they are not the fundamental unit as far as transmission to the ground is concerned, for which a further division into 'transport frames' is made. The latter are smaller than source packets and, in addition to pieces of source packets, contain synchronisation and transmission error-control information. The source-packet structure is then reassembled from transport frames at the ground stations.

Three data streams are transmitted from the IDHT (Fig. 10). The first contains the high-rate data from the AMI Image Mode, with auxiliary

Figure 9. Deployment of the SAR antenna



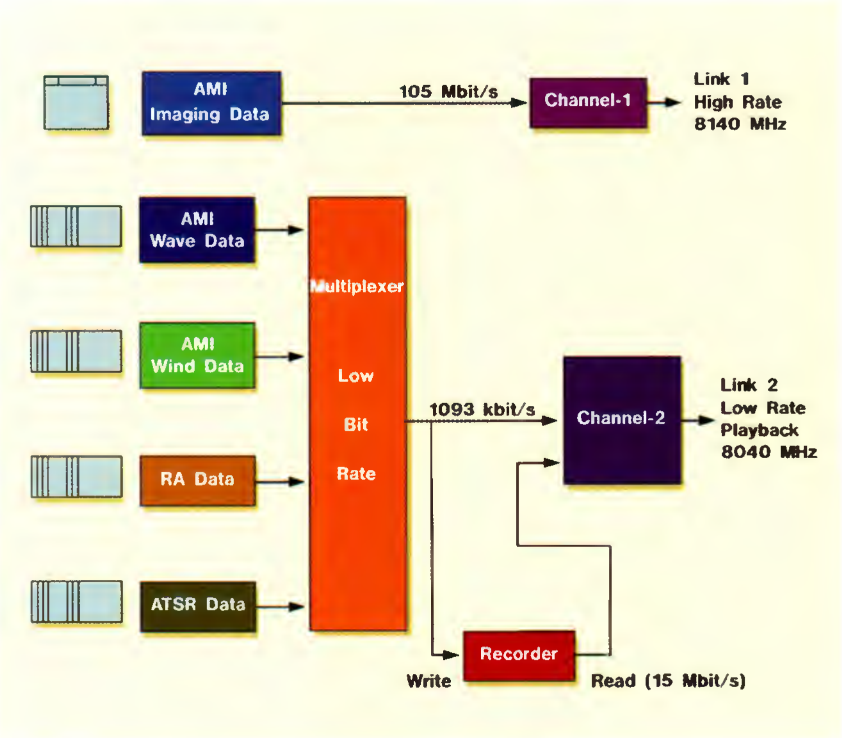


Figure 10. Block diagram of the X-band science data transmission system (IDHT)

data and a copy of the S-band telemetry data, at a total rate of 105 Mbit/s. This channel has an X-band link dedicated to it. The other sensors have their data combined, again with a copy of the S-band data and satellite ephemeris information, into a (comparatively) low-rate data channel, operating at 1.1 Mbit/s, which is continuously recorded by the onboard tape recorder (Fig. 11). This recorder is replayed at 13.6 times recording speed (in reverse order to save rewind time) when over the ground stations to form a second data channel, at 15 Mbit/s. It shares the second X-band link with the live transmission of the combined low-rate data, which constitutes the third data stream.

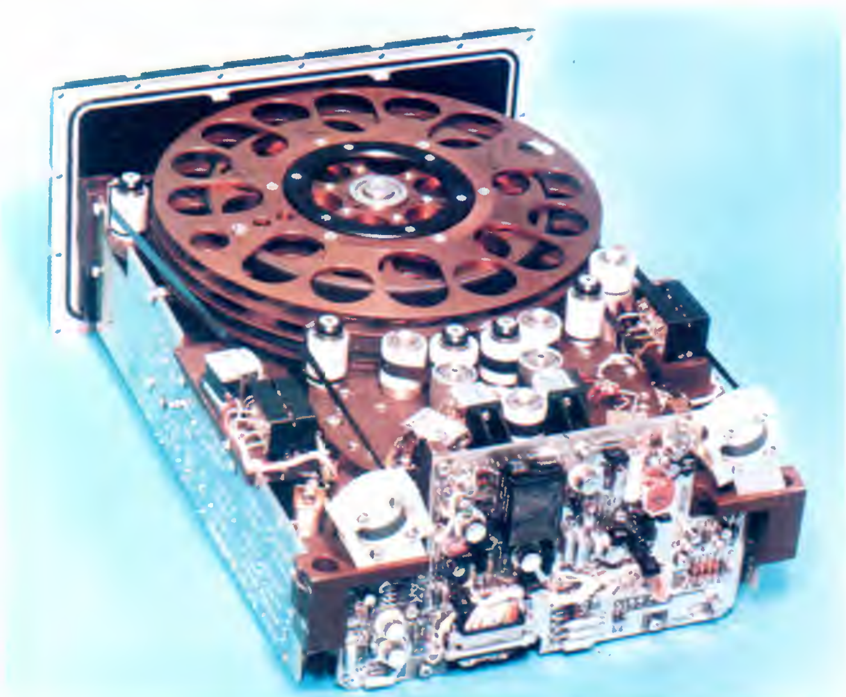


Figure 11. One of the two 6.5 Gbit tape recorders, which can hold 3000 ft of 1/4-inch tape

The tape recorder has been designed to store a full orbit of continuous 1.1 Mbit/s low-rate data on 3000 ft of ¼-inch magnetic tape, leading to a total data-recording capacity of 6.5 Gbit. When performing a data dump to high-latitude ground stations, such as the primary Kiruna station, the spacecraft's solar array might cause a brief occultation of the link, due to the system geometry. On passes when that occurs, the on-board command scheduling includes a stop in playback before the occultation, a slight rewinding of the tape, and a reactivation of playback mode after the occultation.

The modulation scheme used for the high-rate channel is quadrature phase-shift keying, called QPSK, which allows four distinct states per clock cycle and makes it possible to transport two bits of information per cycle. That reduces the radio-frequency bandwidth required for transmission by a factor of two compared with a simpler modulation scheme. The low-rate link uses unbalanced quadrature phase-shift keying, or UQPSK, to modulate the 15 Mbit/s recorder dump and the convolutionally encoded real-time data onto a single link. If there are no recorder dump data, bi-phase-shift keying (BPSK) is used for the real-time data.

Immediately before and after recorder playback, the link is automatically switched between BPSK and UQPSK operation, with minimum impact on the real-time data stream. The ERS-1/ERS-2 ground demodulators have been designed to accommodate that mode-switching automatically.

The fact that the X-band transmission was required to have a minimum power-level fluctuation during the satellite pass led to the design of a shaped-beam antenna able to compensate for losses at low satellite elevation angles, when the distance to the ground station is long, and the attenuation due to the atmosphere's water content is high. To achieve that, the antenna reflector is shaped so that its radiation pattern compensates for the inverse-square-law variation in received power with distance as the satellite passes across the sky at the ground station. The polarisation of the radiated energy is rotated to compensate for Faraday rotation due to the Earth's ionosphere.

The IDHT is physically located on the Earth-facing panel of the PEM, with the tape recorders mounted inside, on one of the cross-walls.

The scientific instruments

The Active Microwave Instrument (AMI)

Two separate radars are incorporated within the AMI, a Synthetic-Aperture Radar (SAR) for Image and Wave Mode operation, and a Scatterometer for Wind Mode operation. The operational requirements are such that each mode needs to be able to operate independently, but the Wind and Wave Modes are also capable of interleaved operation, in so-called 'Wind/Wave Mode'.

In Image Mode, the SAR obtains strips of high-resolution imagery 100 km in width to the right of the satellite track (Fig. 12). The 10 m long antenna, aligned parallel to the flight track, directs a narrow radar beam onto the Earth's surface over the swath. Imagery is built up from the time delay and strength of the return signals, which depend primarily on the roughness and dielectric properties of the surface and its range from the satellite.

The SAR's high resolution in the range direction is achieved by phase coding the transmit pulse with a linear chirp, and compressing the echo by matched filtering. Range resolution is obtained from the travel time. Azimuth resolution is achieved by recording the phase as well as the amplitude of the echoes along the flight path. The set of echoes over a flight path of about 800 m is processed (on the ground) as a single entity, giving an azimuth resolution equivalent to a real aperture 800 m in length. This is the 'synthetic aperture' of the radar.

Operation in Image Mode excludes the other AMI operating modes, and power considerations limit operating time to a maximum of 10 min per orbit. The data rate of 100 Mbit/s is far too high to allow onboard storage, and so images are only acquired within the reception zone of a suitably equipped ground station.

Wave-Mode operation of the SAR provides 5 km × 5 km images at intervals of 200 km along track (Fig. 13), which can then be

AMI Wave-Mode Characteristics

Wave direction	0—180° (180° ambiguity)
Wave length	100—1000 m
Accuracy	direction ±20° length ±25%
Spatial sampling	5 km × 5 km every 200—300 km, programmable anywhere within the SAR swath
Incidence angle	23°
Frequency	5.3 GHz (C-band)
Polarisation	Linear-Vertical (LV)

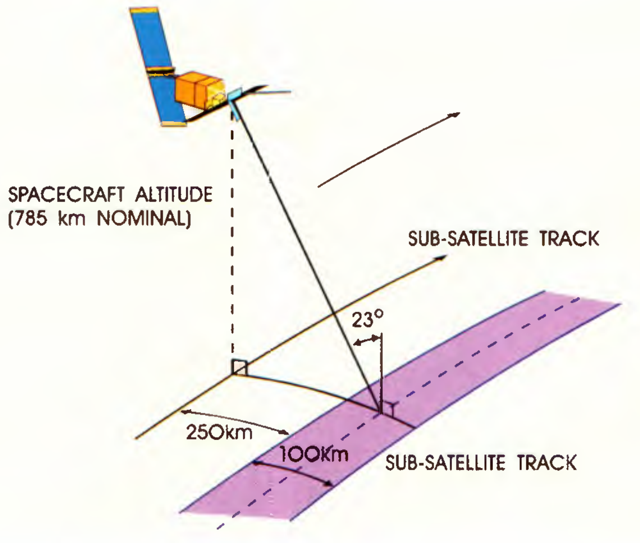


Figure 12. The SAR Image Mode

AMI Image-Mode (SAR) Characteristics

Bandwidth	15.55±0.1 MHz
PRF range	1640—1720 Hz in 2 Hz steps
Long pulse	37.12±0.06 μs
Compressed pulse length	64 ns
Peak power	4.8 kW
Antenna size	10 m × 1 m
Polarisation	Linear-Vertical (LV)
Analogue/digital complex sampling	18.96 million samples/s
Sampling window	296 μs (99 km telemetred swath)
Quantisation	5I, 5Q if range compression on ground (nominal 6I, 6Q if range compression on board)
Spatial resolution	30 m × 30 m
Radiometric resolution	2.5 dB at $\sigma_0 = -18$ dB
Swath stand-off	250 km to the side of the orbital track
Swath width	100 km
Incidence angle	23° at mid-swath
Frequency	5.3 GHz (C-band)
Data rate	<105 Mbit/s

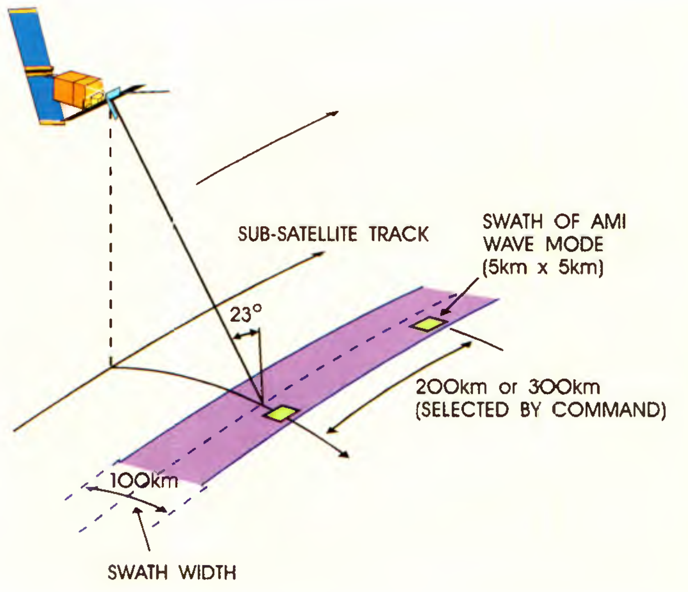


Figure 13. The SAR Wave Mode

interpreted to provide wave spectra. The relatively low data rate allows onboard data storage, and thus a global sampling of wave spectra is obtained.

The Wind Mode uses three antennas to generate radar beams looking 45° forward, sideways, and 45° backward with respect to the satellite's flight direction (Fig. 14). These beams continuously illuminate a 500 km-wide swath as the satellite moves along its orbit, and each provides measurements of radar backscatter from the sea surface on a 25 km grid. The result is three independent backscatter measurements for each grid point, obtained using the three different viewing directions and separated by a short time delay.

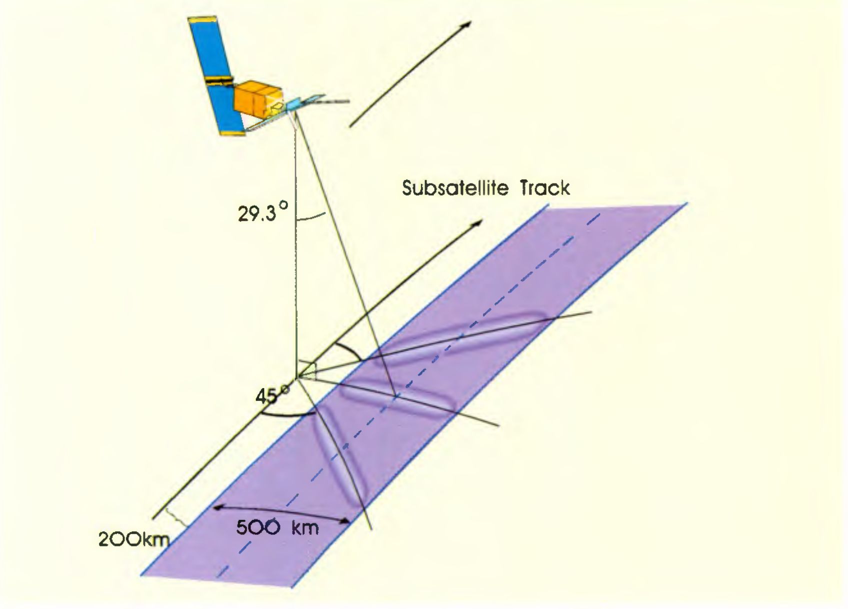


Figure 14. The SAR Wind Mode

AMI Wind-Mode Characteristics

Wind direction range	0—360°		
Accuracy	±20°		
Wind speed range	4—24 m/s		
Accuracy	2 m/s or 10%		
Spatial resolution	50 km		
Grid spacing	25 km		
Swath stand-off	200 km to side of orbital track		
Swath width	500 km		
Frequency	5.3 GHz ±200 kHz		
Polarisation	Linear-Vertical		
Peak power	4.8 kW		
	Mid	Fore	Aft
Incidence angle range (approx.)	16—42°	22—50°	22—50°
Antenna length	2.3 m	3.6 m	3.6 m
Dynamic range	—	42 dB	—
Pulse length	70 μs	130 μs	130 μs
No. of pulses per 50 km	256	256	256
Radiometric resolution	8.5%	9.7%	9.7%
Detection bandwidth	25 kHz	25 kHz	25 kHz
Sampling scheme		Complex I/Q 8 bits each	
Return-echo window duration	2.46 ms	3.93 ms	3.93 ms

As the backscatter depends on the wind speed and direction at the ocean surface, it is possible to calculate the surface wind speed and direction by using those 'triplets' within a mathematical model.

The AMI electronics (see right panel) cover two full 2 m × 1 m side panels of the PEM. In addition, the calibration unit is mounted on a cross-wall inside the PEM, the switch matrix and its controller are on the top panel, and the four antennas, one of the most characteristic elements of the ERS-1 and ERS-2 satellites, on the Antenna Support Structure (ASS).

The Radar Altimeter (RA)

The Radar Altimeter is a nadir-pointing pulse radar designed to make precise measurements of the echoes from ocean and ice surfaces. It has two measurement modes, optimised for measurements over ocean and ice, respectively. In the so-called 'Ocean Mode', the echo characteristics of interest are:

— Time delay with respect to the transmitted pulse, which provides the altitude measurement.
— Slope of the echo leading edge, which is related to the height distribution of reflecting facets and thus to the ocean wave height.
— The power level of the echoed signal, which depends on small-scale surface roughness and thus on wind speed.

The radar echoes over ice sheets, particularly the rough surfaces at the continental margins, show much greater variances in shape than oceanic echoes. In order to maximise the data return in those areas, the Ice Mode includes three features designed to improve its 'robustness'. The range window width is increased by a factor of four, which also degrades precision by a similar amount. A simplified height-tracking loop greatly improves the ability to keep the echo in the range window, although it cannot distinguish the leading edge of the signal. Finally, the tracker is more agile.

In the Ice Mode, as in the Ocean Mode, the telemetered data stream contains the effective height of the range window, and the digitised echo waveform within this window. They allow ground processing to retrieve topographic information. The returned power level is also telemetered.

The effective pulse width is 3 ns, which is equivalent to about 45 cm in two-way range. The radar is said to be 'pulse-width-limited' because not all of the target is illuminated simultaneously by the short pulse, and the received power is controlled by the illumination.

The AMI Electronics

The radio-frequency (RF) subsystem units, covering half of a panel in the spacecraft, contain all the electronics needed to generate the transmit pulses and to amplify and filter the received signals.

The intermediate frequency (IF) radar contains a transmit and a receive section. The transmit section, in Image Mode, generates a linearly chirped pulse of 15.8 MHz bandwidth and 37.2 µs length. This pulse is generated by gating the 123 GHz output of the frequency generator into a short pulse and applying it to a dispersive delay line. At the output of the delay line, the pulse is amplified and cut to the correct length of 37 2 ms. In Wind Mode, the transmit pulse is generated by the Scatterometer electronics, and the IF radar acts only as an amplifier.

The up- and down-converters are contained in a single unit. The upconverter converts the output signals of the IF radar to 5.3 GHz and amplifies them to a level of about 250 mW, required for the input of the high-power amplifier (HPA).

The two redundant units of the HPA occupy one complete panel each consists of a large power conditioning unit (EPC), a travelling-wave-tube amplifier, an output isolator, and an output filter. The latter two elements are located on the outside of the panel. The HPA amplifies the input signals to output levels of about 5000 W.

The output signal from the HPA arrives at the circulator assembly, or switch matrix, on the top panel of the PEM. This matrix of ferrite circulators switches the signal coming from the HPA to any of the four antennas, and on the return path directs the receive signal from the chosen antenna into the receive chain.

The waveguides from the switch matrix to the four antennas are lightweight CFRP units with a rectangular cross-section of 4 cm × 2 cm, internally metallised. They are rigidly connected to the SAR antenna and the mid Scatterometer antenna, while the connection to the deployable fore and aft antennas is by choke flanges, without a fixed connection.

The largest of the AMI antennas is the SAR antenna, with a radiating area of 10 m × 1 m. It is a slotted-waveguide array made of metallised CFRP. The antenna itself is subdivided into ten electrical and five mechanical panels. Its planarity across its 10 m length is better than 1.5 mm when in orbit.

The three Scatterometer antennas are made of aluminium alloy. Like the SAR antenna, they are slotted-waveguide arrays, and each is subdivided electrically into two panels. The central unit, measuring 2.3 m × 0.34 m, contains eight waveguides, while the fore and aft arrays, measuring 3.6 m × 0.25 m, each contain six waveguides.

All of the antennas are designed for vertical polarisation.

The receive echo arrives at the receive part of the IF radar, via the circulator assembly, the receiver shutter, which safeguards the sensitive low-noise receiver against transmission-pulse leakage, and the down-converter. In nominal operation, the IF radar works for both SAR and Scatterometer mode as an amplifier and filter stage. In SAR mode, however, onboard range compression can be commanded from the ground, which then switches the signal through an inverse dispersive delay line, compressing the echo pulses by a factor of about 600. Depending on the mode of operation, the output is fed to the SAR processor or the Scatterometer electronics.

The SAR processor filters the signal and down-converts it to baseband. After analogue-to-digital conversion, auxiliary data are added, then the data are buffered and delivered to the IDHT for transmission to the ground. The SAR processor additionally functions as the AMI's ICU. The Scatterometer electronics also has two tasks. It filters and digitises the Wind-Mode echoes and transfers them to the IDHT for transmission to ground. It also controls the AMI during Wind-Mode operation.

The echoes from the fore and aft antennas have rather a high Doppler shift, which varies from approximately 70 to 150 kHz across the swath. This Doppler spread would prevent narrow-band filtering to reduce noise. The Scatterometer electronics therefore, while the echoes are coming in, changes the local oscillator frequency according to the expected instantaneous Doppler shifts. This acts as Doppler compensation. This is also applied to the mid echoes, but here the required compensation is small.

Apart from providing a sample of the transmitted signal into the receiver for calibration purposes, the other task of the calibration unit is to delay a SAR transmit pulse and feed it back to the IF branch of the receiver. This signal is used as a replica of the chirped transmit pulse for on-ground range compression in the ground processor, as an alternative to the onboard range compression mentioned earlier. On-ground range compression is, in fact, the nominal operating mode.

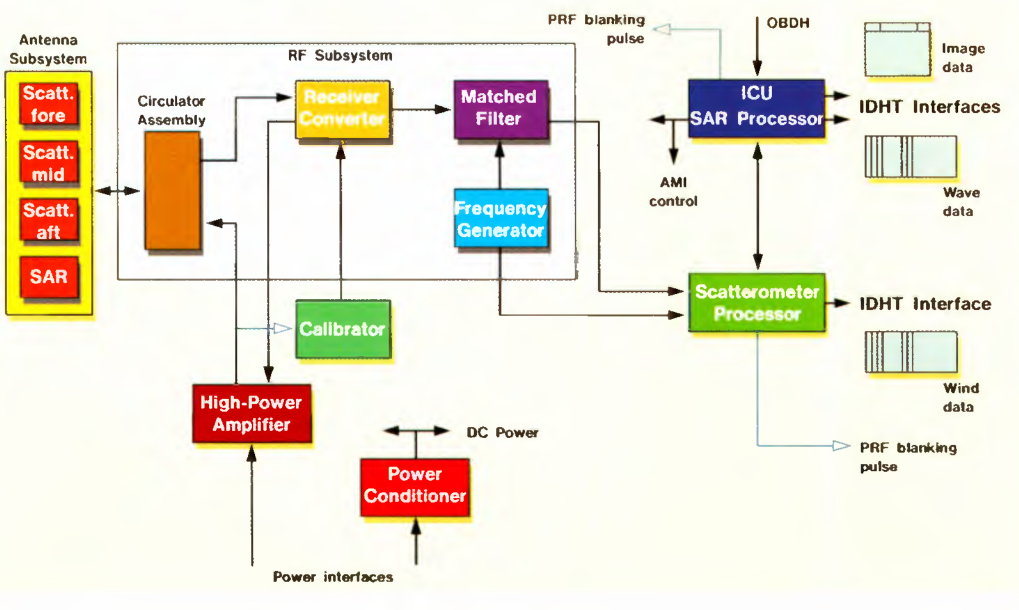


Figure 15. Functional block diagram of the Active Microwave Instrument (AMI)

Over ocean surfaces, the distribution of the heights of reflecting facets is gaussian or near-gaussian, and the echo waveform has a characteristic shape that can be described analytically. It is a function of the standard deviation of the distribution, which is closely related to the ocean wave height.

Different echo waveforms occur over ice surfaces. Over sea ice, there is generally a strong specular component, while the rough topography of continental ice sheets at the margins leads to complex return waveforms. In central ice sheet areas, the height distribution becomes more regular and echoes similar to ocean returns are observed.

Real echoes are composed of the sums of signals from many point-scatterers, each with individual phase and amplitude. To reduce uncertainties in the determination of pulse characteristics, the Radar Altimeter averages pulses together to reduce that statistical effect.

The constraints of available peak transmit power and required pulse width determined that a pulse-compression technique be used to spread the required energy over time, allowing reduced peak power (see panel below).

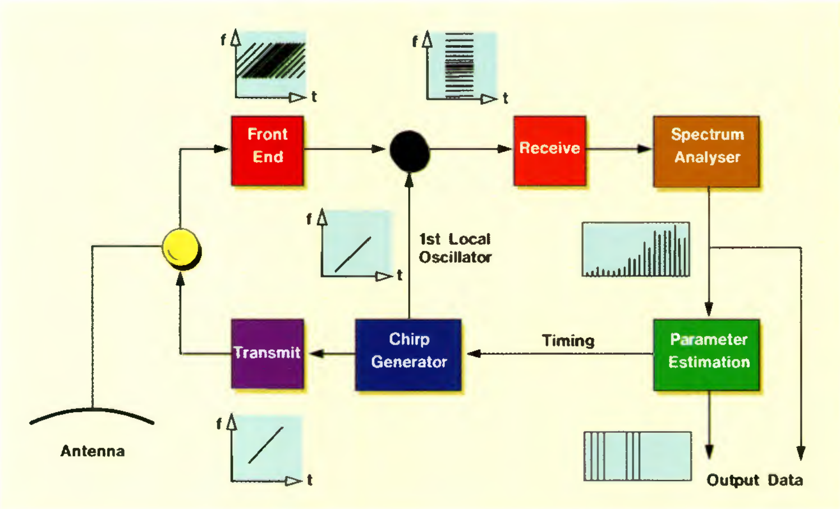


Figure 16. Schematic of the Radar Altimeter's operating principle. The signal at various points is shown as a frequency/time plot.

Table 1. Radar Altimeter (RA) characteristics

Frequency	13.8 GHz
Pulse length	20 μs
Pulse rept. frequency	1020 Hz
Chirp bandwidth	330 MHz (sea)
	82.5 MHz (ice)
Transmit power	55 W peak
Antenna diameter	1.2 m
Height noise	3 cm at 8 m wave height
Mass	96 kg
DC power	130 W

The RA Electronics

The chirp generator, which is based on surface acoustic wave (SAW) devices, is triggered at a fixed rate of almost 1020 Hz. The chirps pass through a 20 s SAW delay line used to separate transmit and receive chirps during calibration. After upconversion to the transmit frequency, they are amplified by the high-power amplifier, a 50 W travelling wave tube (TWT). The pulses pass via the front-end electronics (FEE), which is an arrangement of circulators and the calibration coupler, to the antenna, a front-fed paraboloid.

Returning echoes arrive, via the antenna, FEE, and low-noise amplifier (LNA), at the microwave receiver. When the echo is expected to return, the chirp generator is re-triggered and a second chirp generated. During the upconversion and multiplication process, a slight frequency offset is introduced, and this becomes the first intermediate frequency (IF). This local oscillator chirp is mixed with the received echo in the 'deramping mixer' in the microwave receiver. A series of tones is thus generated, centred on the first IF.

The microwave receiver is a dual-conversion system, and after conversion to baseband the in-phase (I) and quadrature (Q) signals are passed to the signal processor sub-assembly, or SPSA. The next important stage, inside the SPSA, is the spectrum analyser where the spectrum of the tones is found. This spectrum exactly represents the time structure of the echo waveform in 64 points at an equivalent spacing of 3.03 ns. The average power spectrum over 50 successive pulses is formed, and finally this information is used by the parameter estimator. This step is essential in order to provide the estimate of when the next echo is expected to return, for the chirp re-triggering. As an indication of the need for this estimate, the full bandwidth of the spectrum analyser is equivalent to a height window of about 30 m in the ocean mode. The maximum height rate is about 30 m/s; if the height estimate were not continually updated, the signal could be completely lost in about 1 s.

Sometimes, however, the echo can be lost, for example, as a result of passing over some topographic features such as mountains. In this case, the acquisition mode is automatically entered. This is a sophisticated multi-stage scheme, partially relying on dedicated hardware processing, which virtually guarantees getting any trackable surface into the tracking mode range window in just over 1 s.

The parameter estimator is a microcomputer, within the SPSA. It is used in acquisition and tracking modes. In ocean and ice tracking, it runs software tracking loops which follow the signal characteristics. In the ocean mode, there are three main loops to track echo time-delay (height), leading-edge slope, and echo power. The error signals used as input to these loops are derived from adaptive discriminators.

The time-delay and echo-power loops are also used in the ice mode, although the error signals are derived from different discriminators. Because of the reduced chirp bandwidth, the spectral points are spaced at 12.12 ns intervals, leading to a range window of about 115 m.

Internal open-loop calibration is performed every minute. This procedure is very fast (about 100 ms). The transmitted signal is coupled into the receiver through an attenuator, and analysis of the received signal is performed on the ground to determine the delay around the system. The major item omitted in this scheme is the ultra-stable oscillator (USO), which provides the echo timing. This calibration is obtained by broadcasting the USO frequency via the IDHT to enable measurements to be made on the ground.

The Along-Track Scanning Radiometer and Microwave Sounder (ATSR-M)

The ATSR-M consists of two instruments, an Infrared Radiometer (IRR) and a Microwave Radiometer (MWR). The IRR has been upgraded from the ERS-1 instrument to include three channels in the visible part of the spectrum as well as the possibility of performing some on-board averaging of data, to flexibly allow the extra channels of information to be provided within the same overall data-rate limitations.

The primary objective of the IRR is to measure the global Sea-Surface Temperature (SST) for climate-research purposes. Its absolute accuracy is better than 0.5 K when averaged over areas of 50 km x 50 km, assuming that 20% of pixels within the area are cloud-free. For the cloud-free pixels, of 1 km × 1 km, the relative accuracy is about 0.1 K.

To achieve those objectives, the IRR was designed as an imaging radiometer with four co-registered channels with wavelengths of 1.6, 3.7, 11 and 12 μm, defined by beam splitters and multi-layer interference filters. The Instantaneous Field of View (IFOV) at the nadir on the Earth's surface is a 1 km × 1 km square, which is imaged onto the detectors via a f/2.3 paraboloidal mirror. These detectors, fixed onto a Focal-Plane Assembly, are cooled to 80 K by a Stirling-cycle cooler in order to reduce their background noise to an acceptable level.

Table 2. Along-Track Scanning Radiometer (ATSR) characteristics

IR Radiometer	
Swath width	500 km
Spectral channels	1.6, 3.7, 11 and 12 μm
Spatial resolution	1 km × 1 km (at nadir)
Radiometric resolution	<0.1 K
Predicted accuracy	0.5 K over a 50×50 km^2 with 80% cloud cover
Conical scanning	
Microwave Sounder	
Channels	23.8 & 36.5 GHz
Instantaneous field of view	20 km
Near-nadir pointing	

The 1.6 and 3.7 μm channel data are transmitted alternately, switched by a day/night logic provided as a service by the platform.

The IFOV is scanned over the Earth's surface by a rotating plane mirror in such a way that it gives two Earth views, namely a 0° or nadir view and a 47° or forward view. The rotation period is 150 ms and the scan is subdivided into 2000 pixels of 75 μs each. In order to calibrate the optical and electrical signal chain, two black bodies (one hot and one cold) within the IRR are scanned during the rotation. After onboard data compression, a packet of 960 pixels (555 nadir-view and 371 forward-view pixels, and 16 hot and 16 cold black-body pixels) is transmitted to ground, together with housekeeping and datation. Extensive on-ground data processing then permits retrieval of the IRR final product, namely the Sea-Surface Temperature (SST).

The main objective of the ATSR Microwave Sounder is to measure the atmospheric integrated water content (vapour and liquid) in order to compute the most problematic part of the tropospheric path delay in the Radar Altimeter's signals.

The MWR has two channels, operating at 23.8 and 36.5 GHz, each with a band-width of 400 MHz. The instrument is nadir-viewing, using an offset antenna deployed shortly after the spacecraft's separation from the launcher. Onboard calibra-

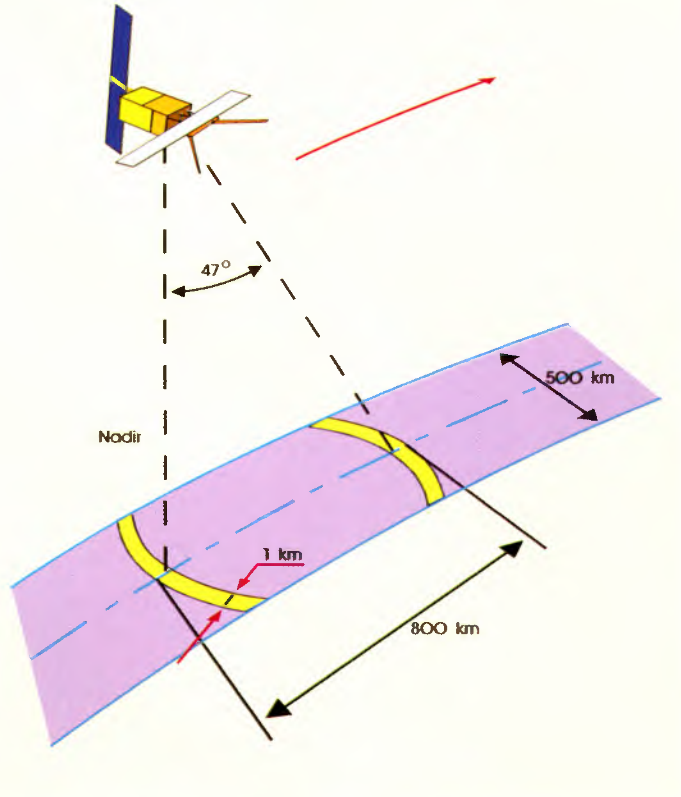


Figure 17. Measurement principle of the Along-Track Scanning Radiometer (ATSR)

Figure 18. Computer illustration of the measurement of atmospheric ozone by GOME. Each measure is represented by a rectangle of a different colour, and corresponds to 40 × 80 km of the Earth's surface. Sardinia and Corsica are in the lower left corner, and Denmark is in the upper right corner.

tion is performed by a sky horn pointing to cold space, and internal hot loads. The acquisition cycle is synchronised to the ATSR scan occurrence and the MWR data are merged into the IRR packets described above.

Global Ozone Monitoring Experiment (GOME)

GOME is an optical spectrometer spanning the ultra-violet/visible/near-infrared wavelength range from 240 to 790 nm, with a spectral resolution of 0.2 to 0.4 nm. Light upwelling from the Earth, decomposed by the instrument into its spectral components and recorded on four silicon array detectors with 1024 pixels each, carries the absorption signatures of ozone and a number of other atmospheric trace gasses. The quantitative concentration of those molecules is derived from the spectrum by fitting the highly banded absorption cross-section of the molecules to the measured spectrum.

The instantaneous field of view, corresponding to the projection of the spectrometer slit on the Earth, is a narrow rectangle 40 km long, aligned in the along-track direction. In order to observe a large fraction of the atmosphere, a scan mirror sweeps that field of view in the across-track direction. The sweep, which normally sweeps 960 km in 4.5 s with a rapid flyback, together with an integration time on the detectors of 1.5 s (30 s for the UV part), results in ground pixel sizes of 320 × 40 km. With that, global coverage can be achieved within three days. However, smaller pixel sizes can be commanded by reducing the angular extent of the scan, with spatial coverage reduced accordingly.

In order to enable high-accuracy, long-term trend measurements, a calibration unit enables regular views of the Sun. Additionally, a wavelength calibration lamp provides the possibility to regularly check the wavelength stability of the instrument and can also be used to monitor the Sun calibration path for possible degradation. During the times when it is not used, a shutter protects the Sun calibration path.

As the instrument is sensitive to the polarisation of the incoming light, a polarisation detector array monitors one polarisation direction in the broadband channels corresponding essentially to the array detector channels 2, 3, and 4.

The Laser Retro-Reflector (LRR)

The Laser Retro-Reflector is a passive device which is used as a target by ground-based laser ranging stations. The operating principle

Figure 19. The Laser Retro-Reflector (LRR). Each corner cube is individually made, to compensate for satellite motion in reflecting incident laser energy back exactly along its incoming path

Table 3. Laser Retro-Reflector (LRR) characteristics

Wavelength	350—800 nm optimised for 532 nm
Efficiency	≥ 0.15 end-of-life
Reflection coefficient	≥ 0.80 end-of-life
Field of view	elev. half-cone angle 60° azimuth 360°
Diameter	≤ 20 cm

is to measure the time of a round trip of laser pulses reflected from an array of corner cubes mounted on the Earth-facing side of the spacecraft's Payload Electronics Module (PEM) (Fig. 19).

That array consists of a polyhedral housing with a hemispherical arrangement of one nadir-looking corner cube in the centre, surrounded by an angled ring of eight corner cubes. This allows laser ranging for satellite passes in the range of 0° to 360° azimuth and 30° to 90° elevation at the ground.

The Precise Range and Range-rate Equipment (PRARE)

The PRARE is a satellite tracking system which performs two-way microwave range and range-rate measurements to ground-based transponder stations with high precision. Signal-propagation effects are compensated by two-frequency measurements, for ionospheric refraction, and ground-station collection of meteorological data for tropospheric refraction.

Two signals are transmitted to ground, one at S-band (2.2 GHz) and one at X-band (8.5 GHz) frequencies (both signals modulated with the pseudo-random noise code). The ground stations receive the two simultaneously emitted signals with a slight time difference and determine the time delay. This provides a measure of the ionospheric refraction taking place in the atmosphere.

The received signals are demodulated and a coherent regenerated copy of the X-band (7.2 GHz) sequence retransmitted to the satellite, where the two-way travel time and the two-way Doppler measurements are carried out, so that the range and range-rate can be determined. Two-way measurements are possible for up to four stations simultaneously via so-called 'code multiplexing'.

Both the space-to-ground and ground-to-space links have additional capacity for data transmission at low bit rates. Control codes and broadcast ephemerides for ground-station operation are transmitted in the downlink, and calibration data, ionospheric-measurement results and meteorological ground data are included in the uplink. All measurement data are stored inside the PRARE itself, in 512 kbytes of RAM, and dumped during the next available ground-station pass.

The PRARE on ERS-1 failed shortly after launch, a failure ascribed to destructive latch-up of a RAM chip caused by the radiation environment. For ERS-2, the parts have been replaced by radiation-resistant devices and various software modifications have been made. Furthermore, a second PRARE is installed on ERS-2 to provide a similar level of redundancy to the majority of the payload.

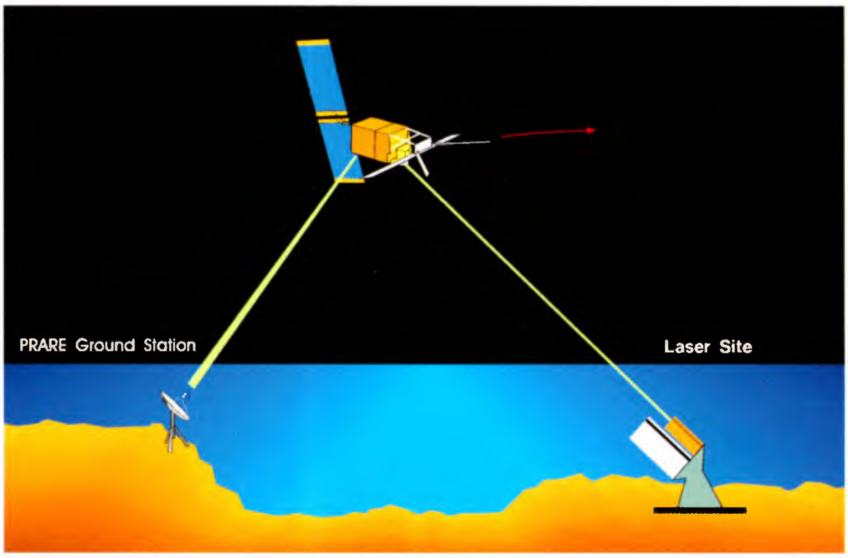


Figure 20. Precise orbit determination by PRARE and Laser Retro-Reflector range measurements

Table 4. PRARE characteristics

Up-link	7225.296 MHz 10 Mbit/s PSK (10 MHz bandwidth)
Ground transponder	60 cm parabolic dish 2 W transmit power
Down-link	8489 MHz 10 Mbit/s PSK (10MHz bandwidth), 1 W transmit power
Satellite antennas	Crossed dipoles at X- and S-bands
Ranging accuracy	5—10 cm (predicted)

Integration and testing

The main integration phase of the ERS-2 Programme started in January 1991. Since ERS-2 was, with a few exceptions, an exact rebuild of ERS-1, an assembly, integration and test programme was devised which relied on the satellite qualification having been achieved by ERS-1. Only acceptance testing was required. For ERS-1, the mechanical/thermal qualification was performed on the SM (structural model) and the EM (engineering model). The only deviations from that concept were GOME, because it was a new instrument, and PRARE, because it had undergone a major redesign after its in-orbit failure on ERS-1.

The manufacturing of the flight units for the payload core instruments and the instrument integration were completed by the end of 1992. The integration and testing of the instruments proceeded very smoothly. Since the work had been carried out by almost the same teams as for ERS-1, there was no 'learning curve' effect and the instruments were delivered well ahead of schedule.

The platform units were manufactured at the same time. Some manufacturing problems at unit level, especially in the propulsion subsystem, caused late delivery of items for the platform integration. In parallel to the manufacturing of the recurrent units, the GOME design and development was undertaken. Initially, it was foreseen to have only a GOME breadboard and flight model but during the course of the project, that was found not to be sufficient. Therefore the breadboard model was upgraded to a fully-fledged engineering model which was then exposed to environmental qualification tests. Furthermore, the initial GOME integration tests at payload and satellite level were performed with the engineering model.

After the in-orbit failure of the PRARE onboard ERS-1, the manufacturing of the PRARE for ERS-2 was halted until the results of the failure investigation were known. As a result, a major electrical redesign had to be initiated. The design changes were tested on the ERS-1 PRARE engineering model before being implemented in the flight and flight spare models. The changes affected exclusively the electronic design, and so a protoflight qualification concept was adopted for the flight unit. The flight spare was acceptance tested.

The integration of the flight model payload started at the end of 1992. After the mechanical and electrical integration of all instruments, a successful full-performance test was conducted. The payload assembly integration and test programme was completed well on schedule. It included a three-week thermal vacuum/thermal balance test in the large space simulator at ESTEC in Noordwijk (NL), and the final integration and alignment of the SAR and Scatterometer antennas.

In parallel to the payload integration, the platform was integrated. After a functional performance test and a thermal vacuum test at Intespace, Toulouse (F), the platform was delivered to ESTEC for satellite integration in December 1993, exactly on time despite the late delivery of some units.

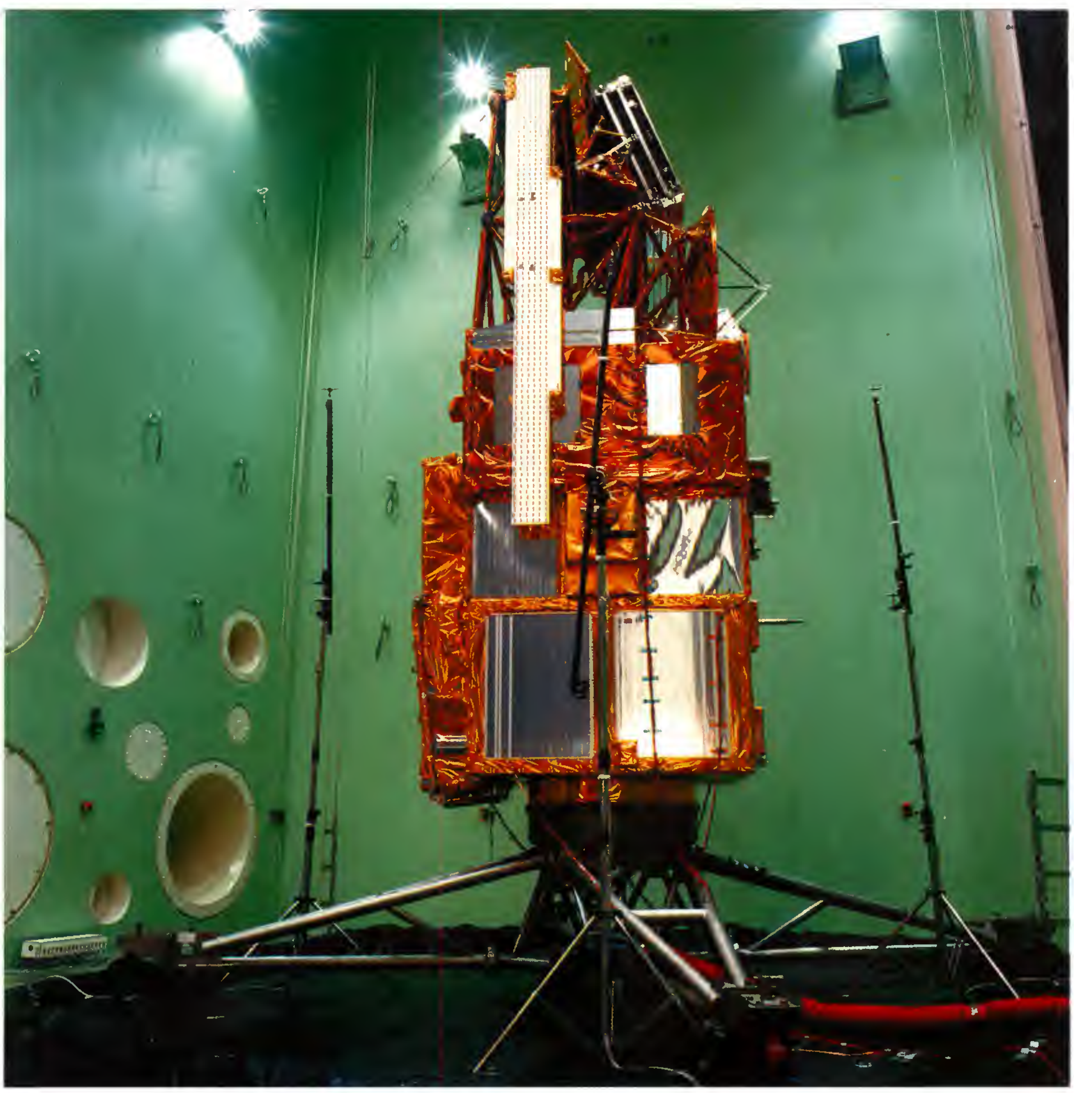


Figure 21. The ERS-2 flight model undergoing acoustic testing in the ESTEC LEAF facilities

The satellite integration started in January 1994. After payload and platform coupling, a series of electrical tests, including hardware/software compatibility and a system validation test with ESOC, were performed. Prior to the environmental test, the propulsion subsystem was checked for leak-tightness.

Vibration and acoustic testing were then carried out to demonstrate, successfully, that the ERS-2 satellite would not be adversely affected by the vibration and noise induced by the launch vehicle. That was followed by a deployment test, under onboard software and under ESOC control, of the SAR, the Scatterometer and the Microwave Radiometer antennas using special 'zero-gravity' rigs to simulate a realistic deployment.

The satellite assembly, integration and test (AIT) activities concluded with a full functional performance test and a rehearsal of the launch site procedures in August 1994. The AIT programme was completed exactly on the date that had been originally planned at the beginning of the ERS-2 programme in 1990.

Following the flight acceptance review, the flight hardware and the associated ground support equipment were prepared for shipment to the launch range in Kourou, French Guiana. Five sea containers and two dedicated 747 cargo flights were used to transport the equipment to the launch site.

ERS-2 was planned to be launched on Ariane flight V72 in January 1995. The launch campaign started on 14 November 1994. After the set-up of the check-out equipment, the satellite mechanical preparations and the alignment, a post-transport functional performance test was performed. Immediately before the end of that test, on 30 November, however, the launch of Ariane flight V70 failed. The post-transport test of ERS-2 was completed but the satellite then had to be placed in storage until the preparations for flight V72 could be resumed. The satellite was protected by a dedicated tent, which was purged and the ambient conditions inside the tent were permanently monitored.

The launch campaign was interrupted for two months, from 19 December 1994 to 17 February 1995. Only a small 'babysitter' team remained in Kourou.

In February 1995, the campaign resumed with a short functional test, the integration of the solar array and the preparation for fuelling

Figure 22. ERS-2 being prepared for encapsulation in the Ariane V72 fairing

After further delays due to hydrogen and oxygen leaks in the third stage of the Ariane V71 launch vehicle, ERS-2 was transferred to the filling and encapsulation hall. Finally, on the night of 20 April 1995, ERS-2 was successfully launched.

ATSR-2: The Evolution in Its Design from ERS-1 to ERS-2

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The Along-Track Scanning Radiometer, or ATSR, was developed for the ERS-1 mission as an Announcement of Opportunity package by the United Kingdom and France. It consists of a four-band Infrared Radiometer (IRR) to measure the Sea Surface Temperature (SST), and a Microwave Radiometer (MWR) to measure the integrated (vapour and liquid) atmospheric water content. The IRR was developed by Rutherford Appleton Laboratory (RAL, UK) and the MWR by the Centre de Recherche en Physique de l'Environment Terrestre et Planetaire (CRPE, F).

For the ATSR-2 on ERS-2 , the IRR has been upgraded by adding three more bands in the visible part of the spectrum to provide data for vegetation studies (Fig 1). The MWR is identical to that used on ERS-1, but is provided by a different industrial contractor, namely Schrack Aerospace of Austria.

The ATSR instrument on ERS-1

The IRR, an imaging radiometer equipped with four infrared channels operating at wavelengths of 1.6, 3.7, 11 and 12 microns, scans two 500 km swaths across the satellite's ground track, one being the nadir view and the other 800 km forward (47° with respect to the nadir) along the ground track (Fig. 2). Successive swaths are displaced by 1 km due to the satellite's orbital motion.

A rotating mirror scans the two tracks once every 150 ms, each scan being sub-divided into 2000 pixels (each equivalent to 75 microsec), 555 of which contain nadir-view data and 371 forward-view data. The infrared

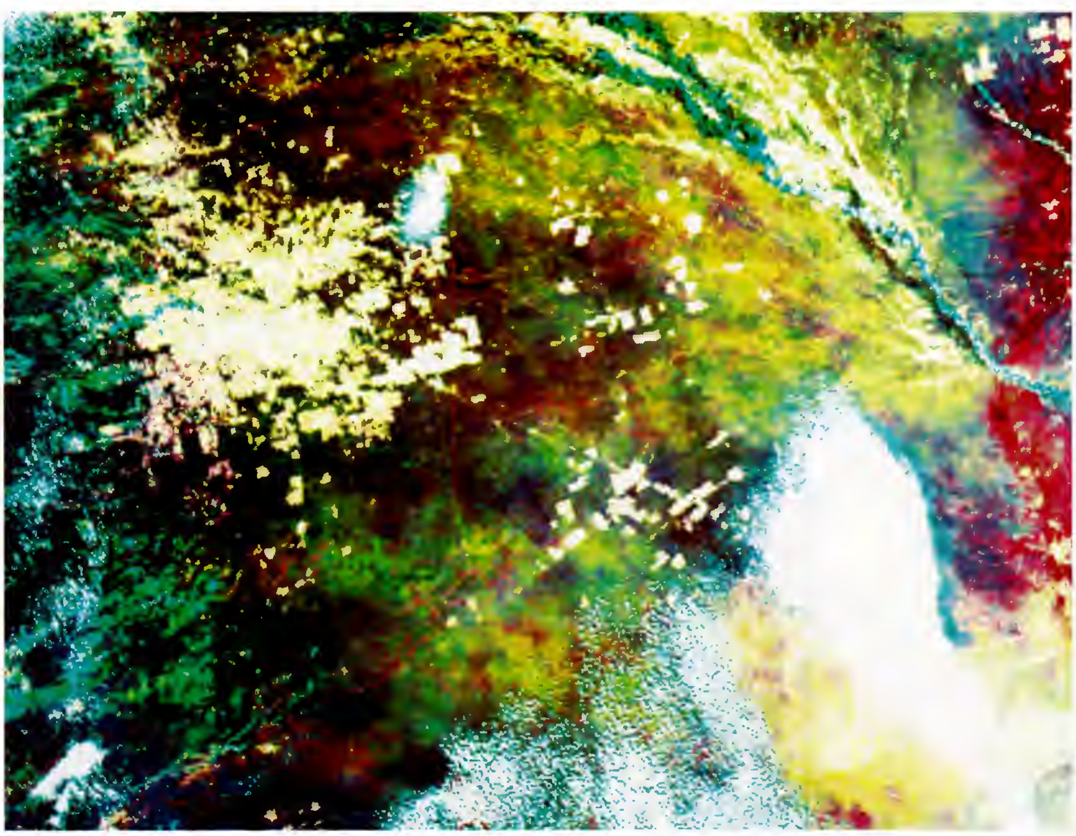


Figure 1. A 512 x 512 km section of the tropical rain forest in Rondonia (western Brazil), as seen by ATSR-2. This image combines three channels from ATSR-2, at 0.55 µm (extracted as blue), 0.67 µm (green) and 1.6 µm (red). The regularly-shaped, pale cream patches are areas where the rain forest has already been felled

channels and associated electronics are calibrated using two black bodies, one hot and one cold, located in the path of the scanning mirror.

With the 555 pixels in the nadir view, a resolution of the order of 1 km x 1 km can be achieved. Averaging over 50 km x 50 km gives an absolute accuracy of better than 0.5 K in sea-surface temperature, assuming that 20% of the pixels within the area are cloud-free. For cloud-free pixels of 1 km x 1 km, the relative accuracy is about 0.2 K.

The scanning mirror directs the incoming radiation to an off-axis paraboloidal mirror (Fig. 3). A field stop positioned at the focus of the instrument determines the field of view. Beyond this field stop, the beam diverges into the Focal-Plane Assembly (FPA), where it is spectrally divided into four infrared channels Three of the component beams, corresponding to the 3.7, 11 and 12 micron bands, are re-imaged by three off-axis ellipsoidal mirrors onto separate detectors. An aspherical zinc-sulphide lens re-images the fourth beam (1.6 micron) onto its detector (Fig. 4). Photoconductive cadmium-mercury telluride detectors are used for the 11 and 12 micron channels, and indium-antimonide photodiode detectors for the 1.6 and 3.7 micron channels.

A Stirling-cycle cooler keeps the Focal-Plane Assembly at 80 K, to provide the required low-noise performance for the detectors. Eight onboard pixel maps allow the selection and compression of IRR pixels for eight different data sets. After formatting, the data are collected by the Instrument Data-Handling and Transmission Unit (IDHT) and transmitted to ground via the X-band link.

The MWR instrument uses a 60 cm Cassegrain offset-fed antenna to view the Earth in the nadir direction at frequencies of 23.8 and 36.5 GHz. The signals received are compared with that from the reference source at a known temperature in order to minimise the effects of

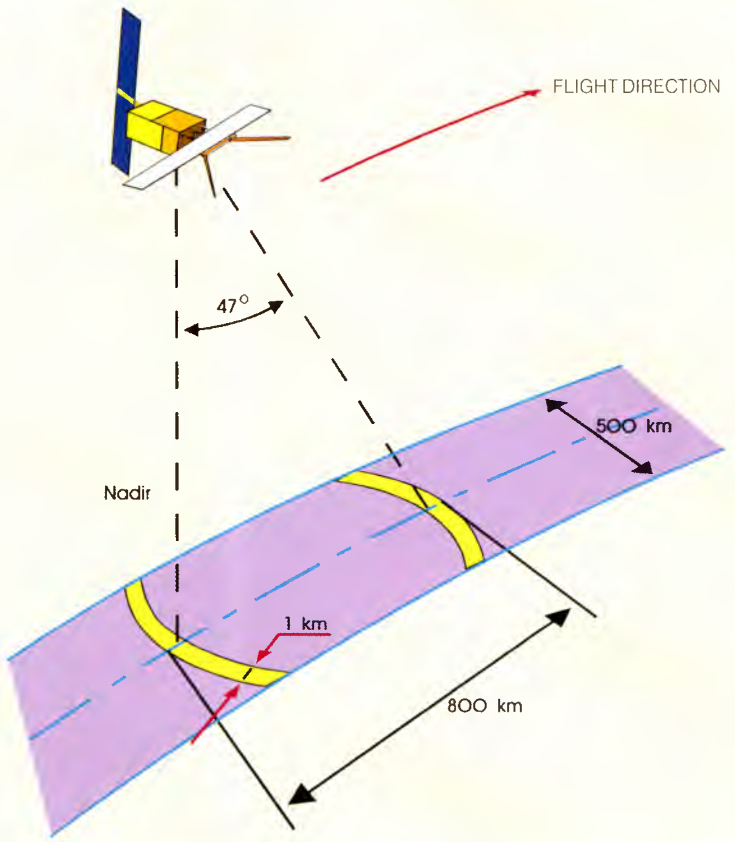


Figure 2. Measurement principle of the Along-Track Scanning Radiometer (ATSR)

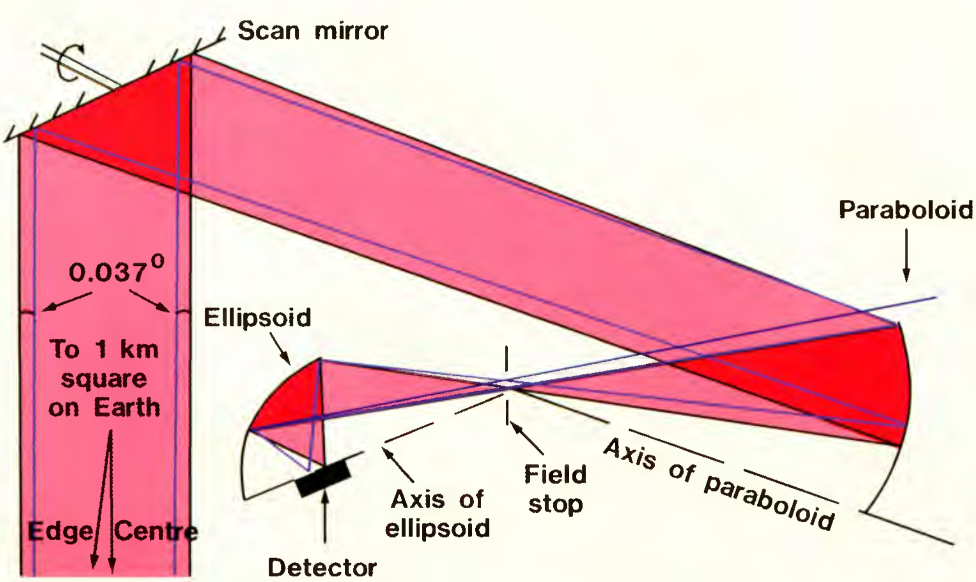


Figure 3. The arrangement of the ATSR's optical components

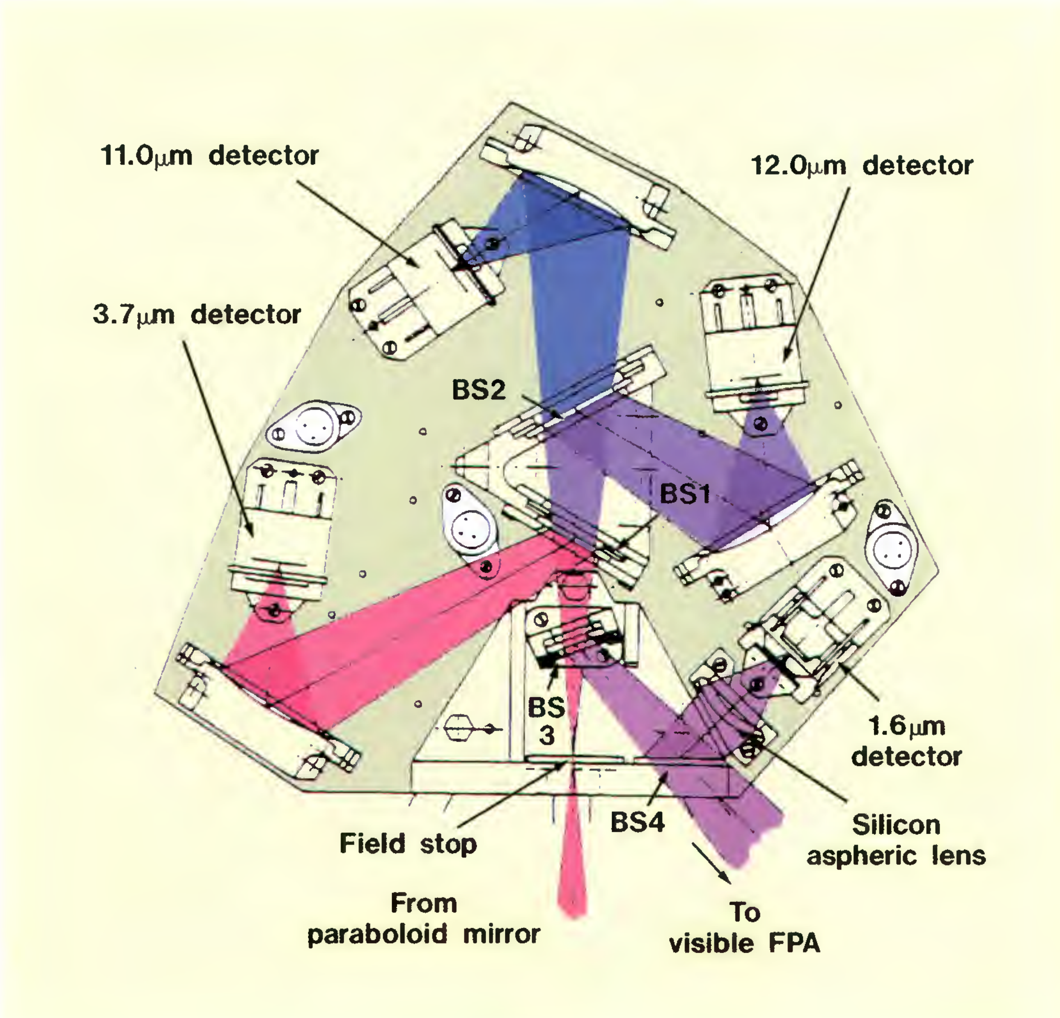


Figure 4. The optical layout of the Infrared Focal-Plane Assembly (IRFPA) for ATSR-2

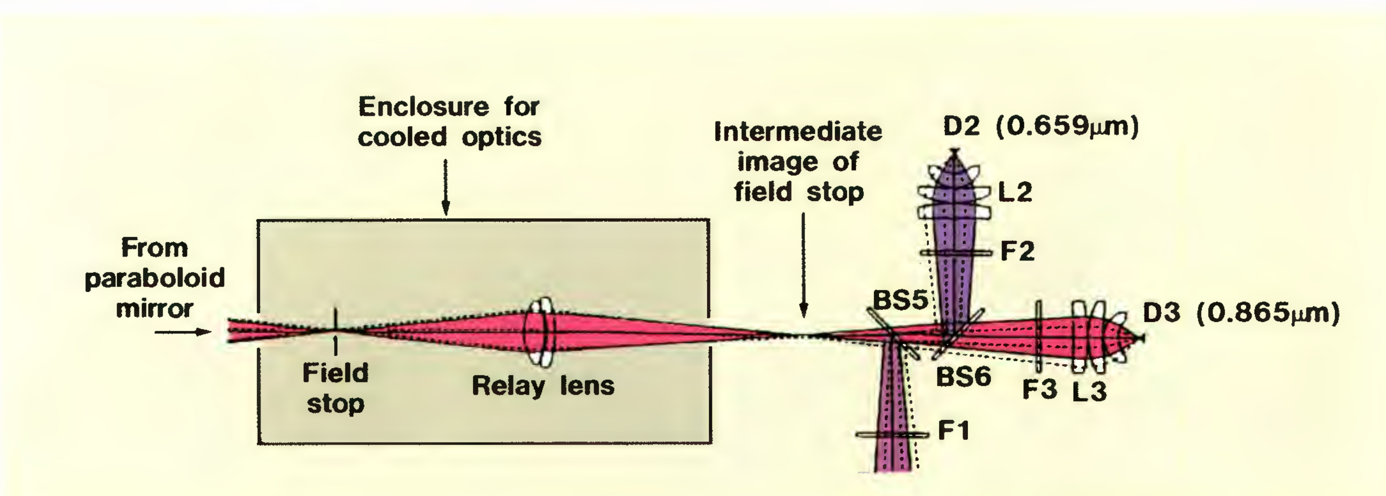
short-term variations in the receiver-chain gain. To calibrate the MWR, additional features are used: the sky-horn antenna is pointed towards the very low cosmic background radiation of deep space at about 4 K for 'cold reference' measurements, while the 'hot reference' is obtained from measurements within the instrument itself.

The ATSR-2 instrument on ERS-2

In the ATSR aboard the ERS-2 mission, three additional visible channels are accommodated by adding of a second Focal-Plane Assembly, with the constraint that it was not to impact adversely on the existing channels.

The Infrared Focal-Plane Assembly (IRFPA) on ERS-2 differs somewhat from that on its predecessor ERS-1. The mirror used to reflect radiation into the 1.6 micron detector has been replaced by a dichroic beam-splitter. This allows the visible beam to pass out of the IRFPA (Fig. 4), via a sapphire window and radiation-resistant doublet relay lens, and enter the

Figure 5. The optical layout of the Visible Focal-Plane Assembly (VFPA) for ATSR-2



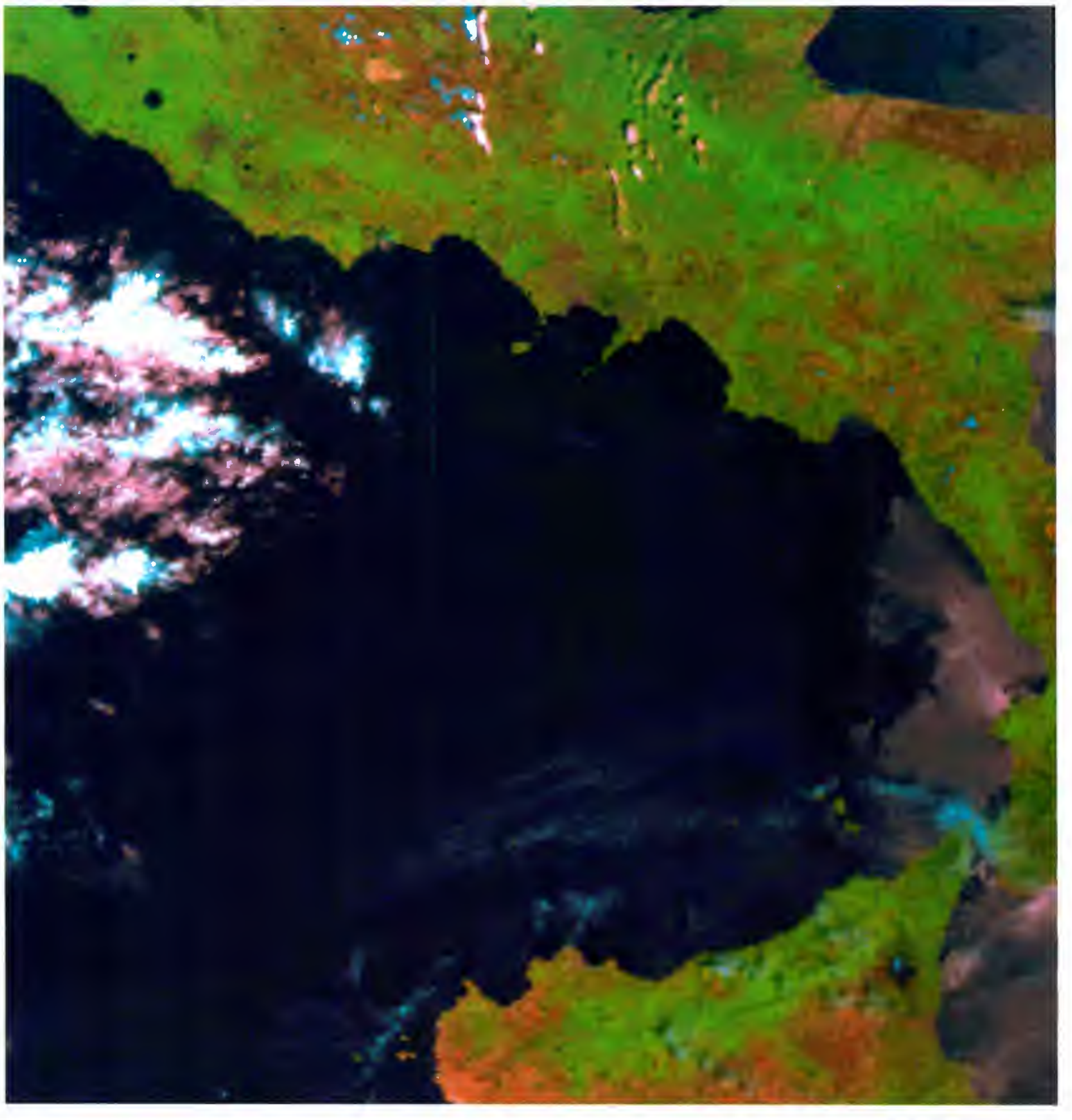
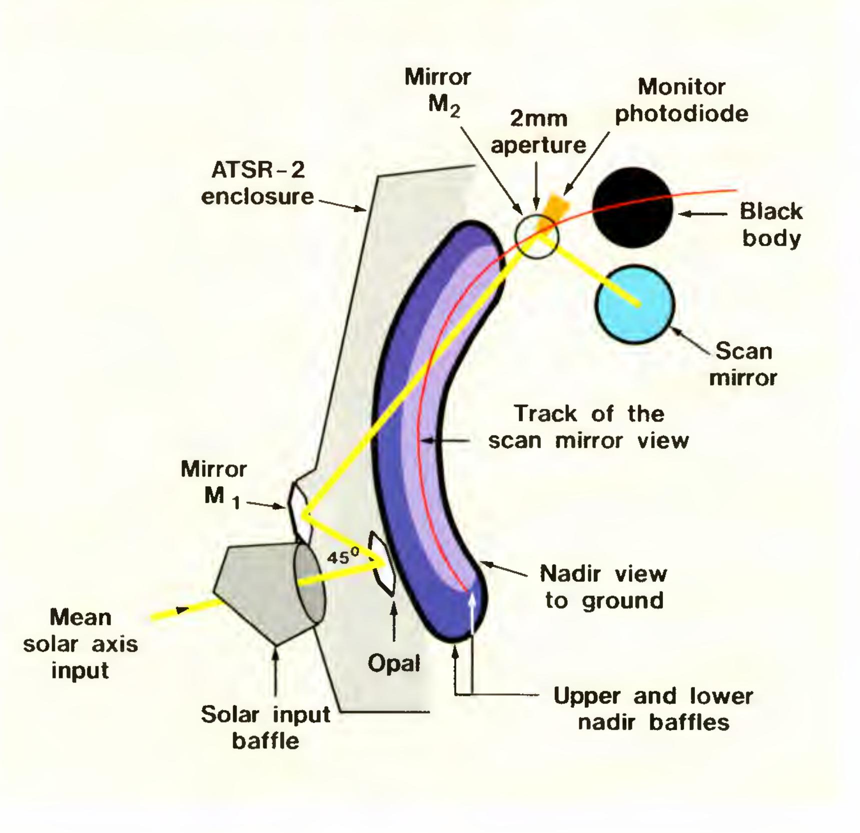


Figure 6. This ATSR-2 image, recorded on 8 May 1995 over Central Italy and Sicily, is a false-colour composite, compiled from the uncalibrated data in the 0.67 µm (as a blue extract), 0.87 µm (green) and 1.6 µm (red) spectral channels

Visible Focal-Plane Assembly (VFPA, Fig. 5). There the beam is split into three, using dichroic beam splitters, before being focussed by zinc-sulphide triplet lenses onto the visible-channel detectors. The centre wavelengths of these three channels are 0.555, 0.659 and 0.865 microns, respectively.

The visible channels are calibrated with a Visible Calibration Unit, as shown in Figure 7. The opal MS20 diffuser, located behind the solar input baffle and radiation-resistant glass window, is illuminated by the Sun during some parts of ERS-2's orbit. Mirror M1 reflects the diffuse beam onto the plane mirror M2, located between the nadir view and one of the black-body units in the path of the scanning mirror. The size of the M2 mirror determines the aperture stop in this calibration system, adding 16 visible-calibration pixels to the ATSR-2 data stream. Calibration takes place close to the time of local satellite sunset, when the Sun is 13° below the tangent to the Earth's surface at the satellite's nadir point. The nadir- and forward-viewing baffles are designed to exclude stray radiation from entering the

Figure 7. Optical components of the visible calibration system



calibration system, which would degrade its accuracy.

Three new amplifiers have been added to the pre-amplifier unit to cope with the three visible channels on ATSR-2, and three corresponding Single Channel Processors have been incorporated into the electronic system.

The increased data flow on ATSR-2 called for a new set of data-compression algorithms. In addition, uncompressed infrared and visible data can be transmitted in a high-data-rate mode, which provides double the normal throughput. This mode is limited, however, to the periods when other payload instruments are not making full use of the X-band data capacity.

The possibility with the original ATSR of choosing between eight fixed pixel-selection maps is replaced for ATSR-2 by a facility for uploading different pixel formatting maps from the ground, thereby providing greater operational flexibility. Two pixel maps can be loaded at any given time, which allows two different maps to be used during an orbit, for example one over the sea and a different one over land. It also allows swath-width modulation and a reduction in the number of detector

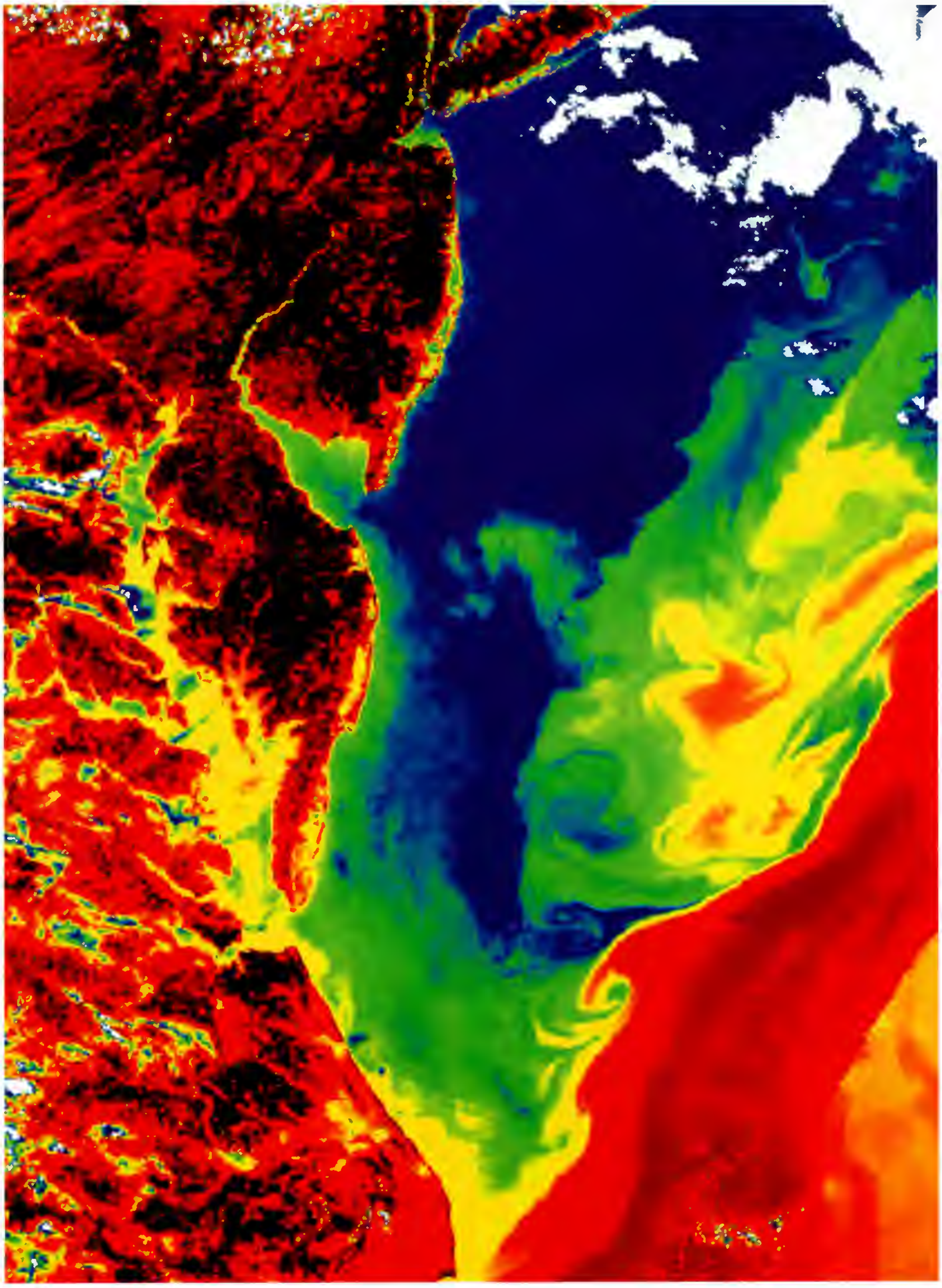


Figure 8. ATSR-2 view of the Gulf Stream, which gives Europe its temperate climate, acquired on 16 May 1995. It shows the eastern seaboard of North America, stretching from New York (at the top) to Charleston, South Carolina (at the bottom). Off the coast is the warm Gulf Stream (in red), which comes up from the south and meets the cold Labrador current off Cape Hatteras. The sometimes quite wide transition zones stand out very clearly, as do the swirling eddies and broken-up currents that occur further on. The varying colours of the clouds near the top and bottom edges of the picture are also due to temperature differences

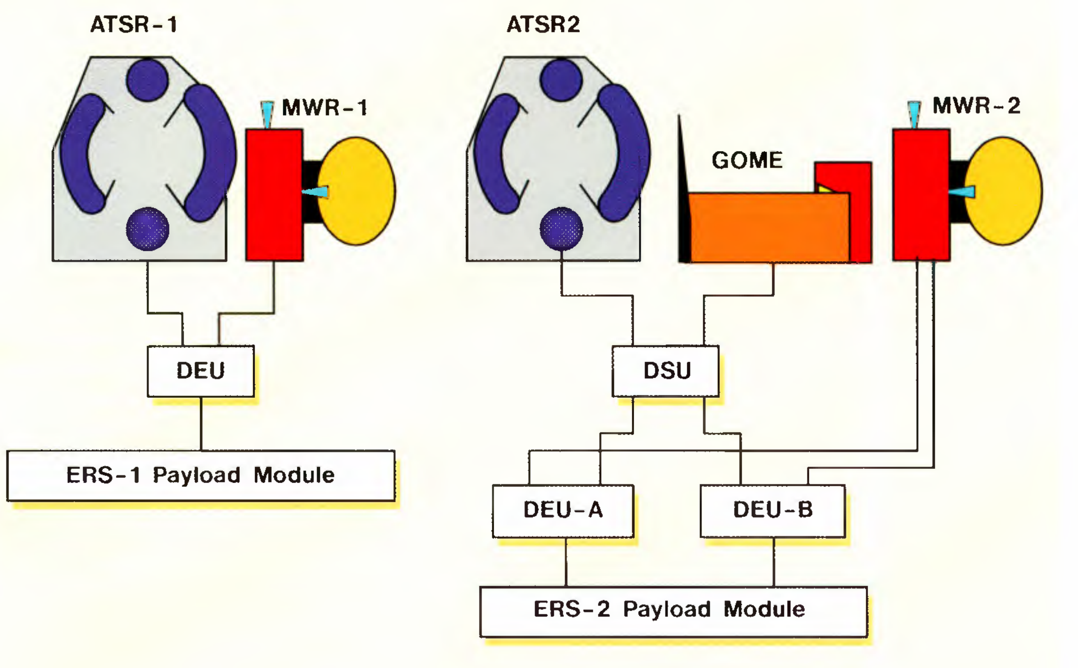


Figure 9. Schematic of the configurations of the IRR, MWR and DEU aboard ERS-1 and ERS-2

channels to be traded-off against better resolution in the remaining channels in low-data-rate mode.

Major mechanical modifications were made to the ATSR-2 Infrared Radiometer. The carbon-fibre structure has been substantially re-designed, the vestigial ATSR-1 optical bench has been removed, and all optical elements are now mounted directly onto the structure.

With the addition of the Global Ozone Monitoring Experiment (GOME) for the ERS-2 mission, and the need to interface this experiment to the satellite via the ATSR-2's Digital Electronics Unit (DEU), it became important to add more redundancy to the latter as it now interfaces with the IRR, the MWR and GOME. A second identical DEU was therefore added to the payload module, together with a DEU Switching Unit (DSU in Fig. 9).

The ATSR products

The main application objectives for the original ATSR instrument aboard ERS-1 are:
- sea-surface temperature measurements
- cloud and atmospheric measurements
- lake measurements
- sea-ice measurements
- land-ice measurements
- deforestation measurements
- forest-fire detection.

With the new features that have been incorporated into the ATSR-2 instrument carried by ERS-2, the following additional objectives are being addressed:
- combined visible/infrared remote-sensing of vegetation in both the nadir- and along-track viewing directions
- improved spatial resolution and coverage in high-data-rate modes, when the Active Microwave Instrument (AMI) is in low-data-rate mode
- quantitative vegetation measurements, using the 0.65 and 0.85 micron channels
- leaf-moisture measurements, using the 0.85 and 1.6 micron channels
- vegetation state (growth stage and health) measurements, using all three visible channels.

PRARE-2 – Building on the Lessons Learnt from ERS-1

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The Precise Range and Range-Rate Experiment (PRARE) instrument is designed both to give the ERS-2 mission a geodetic and geodynamics capability and to support the satellite's Radar Altimeter instrument. It is a two-way microwave ranging system operating at S- and X-band, providing state-of-the-art microwave positioning (Fig. 1).

Introduction

The PRARE instrument's operation is based on onboard measurement of the propagation delay between signal transmission and reception at X-band to provide range information. The round-trip X-band carrier phase is also measured to derive range-rate data. The purpose of the instrument is to provide high-precision measurements of the satellite's position using a network of dedicated ground stations.

The PRARE on ERS-1 was an 'Announcement of Opportunity' instrument funded and procured by the German Bundesministerium für Forschung und Technologie (BMFT) and the Deutsche Agentur für Raumfahrt-angelegenheiten (DARA). It was developed by the Technische Universität Berlin and the Institut für Navigation in Stuttgart. ESA's involvement was limited to management of the satellite interfaces and to the instrument accommodation aspects. The PRARE-2 instrument for ERS-2 was procured directly by ESA.

The PRARE instrument on ERS-1

PRARE-1 was launched aboard ERS-1 on 17 July 1991 and was switched on for the first time seven days later. After almost five days of

Figure 1. The PRARE-2 instrument during integration

operating nominally, the instrument automatically switched itself off and could not subsequently be recovered. Prior to the failure, all instrument telemetry was nominal, except for a high number of errors appearing in the main processor memory.

Failure occurred whilst the spacecraft was in the so-called 'South Atlantic Anomaly', which is a region of the Earth's magnetosphere notorious for its high levels of proton radiation. Unfortunately, the spacecraft was not in contact with a PRARE ground station at the time the anomaly occurred, which meant there was very little telemetry data available for the subsequent analysis conducted by the ESA Failure Review Board (FRB).

This Board's final report, issued in December 1991, indicated that the failure could have been caused by a proton-radiation-induced destructive latch-up of a Random Access Memory (RAM) device in PRARE's main processor. This conclusion was supported by a radiation test with a particle accelerator exposing the RAM device to proton radiation, which resulted in its failure. Further tests showed that only this component was radiation-sensitive. It transpired that this first PRARE contained no radiation-hardened components, mainly to keep the instrument's cost to a minimum. The Failure Review Board also identified a number of other more minor design and manufacturing deficiencies that could have given rise to problems later in the mission. All of these areas were addressed in the subsequent design and development of the PRARE-2 instrument for ERS-2.

The fact that PRARE-1 had consciously been designed to have an absolute minimum number of telecommand and telemetry interfaces between it and the spacecraft, with a view to providing instrument compatibility with several different spacecraft, turned out to be a major drawback after the failure. It imposed severe limitations on those investigating the in-orbit failure.

The PRARE-2 instrument aboard ERS-2

As already mentioned, it had been agreed prior to ERS-1's launch that the PRARE flight segment for ERS-2 would be directly procured by ESA. The PRARE-2 contract had therefore been signed in 1990 assuming that just a simple rebuild of PRARE-1 would be needed.

Following the PRARE-1 in-orbit failure in July 1991, and the first findings of the Failure Review Board, all PRARE-2 manufacturing activities were put on hold. Once the FRB's final report was published, the ERS-2 Project Team decided that the PRARE-1 design would have to be substantially modified prior to the re-flight on ERS-2.

The design changes were related primarily to the suspected cause of the in-orbit failure and the other potentially problematic areas, i.e.

- the latch-sensitive memory devices were replaced by latch-up-free chips
- whenever possible, commercial parts were replaced with Hi-Rel or MIL standard components
- the critical software was no longer stored in an EEPROM (Electrical Erasable Programmable Read-Only Memory), but in a PROM
- the EEPROM carrying the non-critical software was protected against under-voltage damage
- the design of the power-supply current limiter was modified and a redundant unit was added.

These changes were first implemented and tested using the PRARE-1 engineering model, which ultimately successfully survived a rigorous proton-radiation test.

Changes were also made in the PRARE operating concept, largely as a result on the findings of the Failure Review Board, although not directly related to the in-orbit failure of PRARE-1:

- The telemetry / telecommand interface between the instrument and the spacecraft has been extended, within the constraints of the satellite capabilities. The number of PRARE telemetry channels has been increased from two on ERS-1 to eight on ERS-2.
- The PRARE-1 standby mode has been deleted, putting the instrument immediately after switch-on into a mode with all transmitters and receivers active and the main processor running only vital software.
- PRARE-2 has been given redundancy by also accommodating onboard ERS-2 the PRARE-1 flight-spare model, which has been upgraded to the same specification as the main unit.

The PRARE-1 in-orbit failure and the short time then remaining for the above re-design effort meant that extensive support from the ERS-2 Project Team was needed to fulfil the Agency's responsibilities in the procurement of the PRARE-2 instrument. This support covered all aspects of product assurance, electrical and software engineering, electrical ground-support equipment, assembly integration and testing, as well as management support.

Only through the combined efforts of the Contractor and the ESA Team was it possible to implement all of the above-mentioned modifications successfully and still deliver both PRARE units in time for the overall satellite integration and test activities.

The PRARE products

As part of the German/Russian space cooperation, it was agreed to fly a PRARE precursor mission on a Russian Meteor satellite. Apart from the satellite interface, this instrument, launched in January 1994, is identical to PRARE-2. Since it was switched on in February 1994, the PRARE on Meteor has performed flawlessly, delivering excellent results. This Meteor experience served to demonstrate the validity of the modifications implemented following the problem on ERS-1.

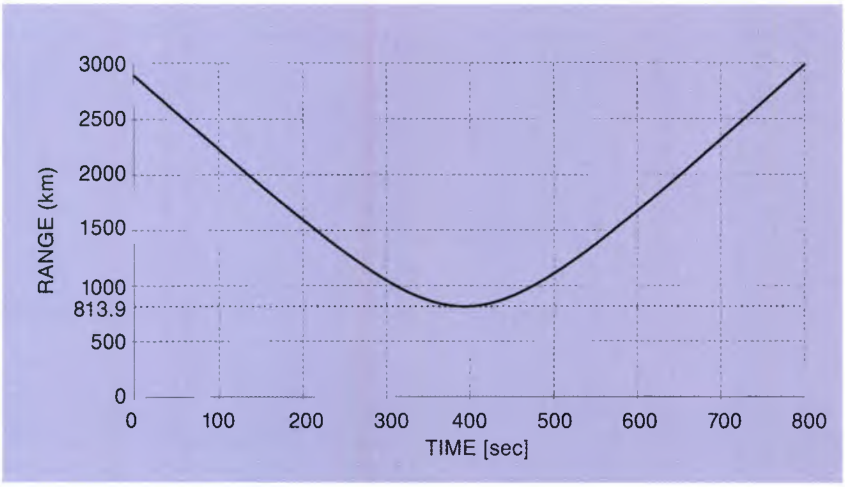

Figure 2. Typical range variation during ground-station contact

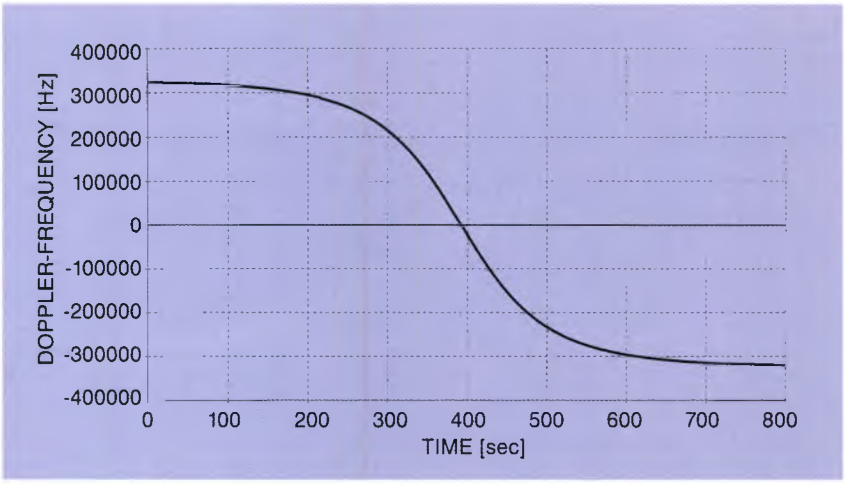

Figure 3. Typical Doppler variation during ground-station contact

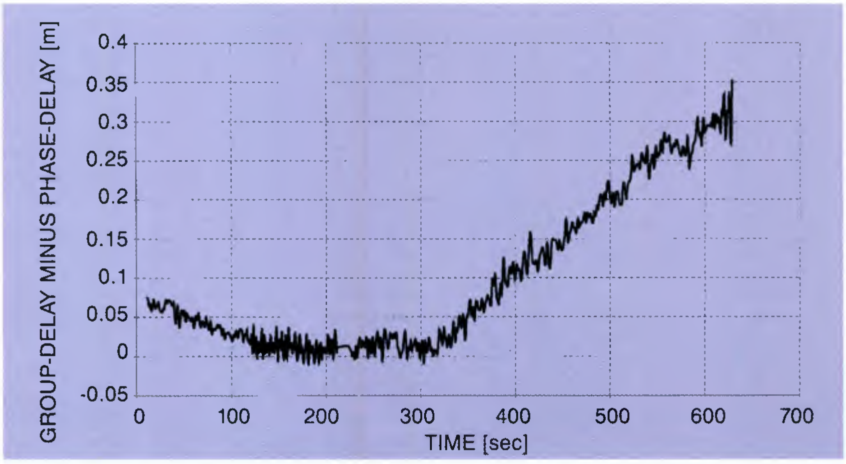

Figure 4. Difference between group delay and phase delay as a measure of total electron content

PRARE-2 on ERS-2 was switched on immediately after the satellite launch and early orbit phase, on 26 April 1995. It has now been operational for several weeks and all of its functions have been verified. The range (Fig. 2) and range-rate (Fig. 3) data are already providing good results. The instrument has successfully demonstrated its ability to detect the total electron content in the signal-propagation path by comparing the group delay and phase delay in the round-trip signal (Fig. 4).

The uncalibrated instrument stability over the first five weeks of operation was of the order of 1.9 cm. Each ranging session is further enhanced by closing the instrument's internal calibration loop after the ground-station contact, leading to a final measurement uncertainty of less than 1 cm. Consequently, confidence is high that all PRARE-2 scientific and mission objectives will be met.

The PRARE-2 instrument will enter its routine operational phase in August, once the current in-orbit commissioning activities have been completed.

Conclusion

The history of the PRARE instrument has allowed two important lessons to be learnt:

- The development of a demanding experiment like PRARE with the overriding constraint of keeping cost to an absolute minimum has to be recognised as being extremely risky.
- The combined efforts of a scientific institute and its subcontractors working in harmony, with substantial technical support from the Agency, have resulted in a flightworthy instrument being delivered in a short time scale, despite the system's high complexity and novel design.

The early results from PRARE-2 are demonstrating the high precision of the instrument. This, together with PRARE's unique capabilities, will hopefully stimulate further research into microwave tracking systems and their applications.

GOME – The Development of a New Instrument

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GOME is an across-track scanning optical spectrometer, covering the wavelength range 250 – 790 nm. This spectral range is split into four channels, each equipped with a 1024-pixel linear array detector. The resulting spectral resolution is 0.2 nm in the ultraviolet and 0.4 nm in the visible/near-infrared parts of the spectrum.

GOME's task is to sense the sunlight being reflected or scattered in the Earth's atmosphere and at its surface. The measured spectrum contains absorption features, which can be used to derive quantitative information on the amount of ozone present, and a number of other atmospheric species.

GOME is the only new instrument on ERS-2 compared with ERS-1. A full technical description of it was published in ESA Bulletin No. 73 (February 1993).

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Further reading about GOME:

A. Hahne et al. 1994, Calibration of the GOME Instrument for ERS-2, *ESA Journal*, Vol. 18, p. 119.

Ch. Readings & T.D. Guyenne (Eds.) 1993, GOME Interim Science Report, ESA Special Publication SP-1151.

The instrument's beginnings

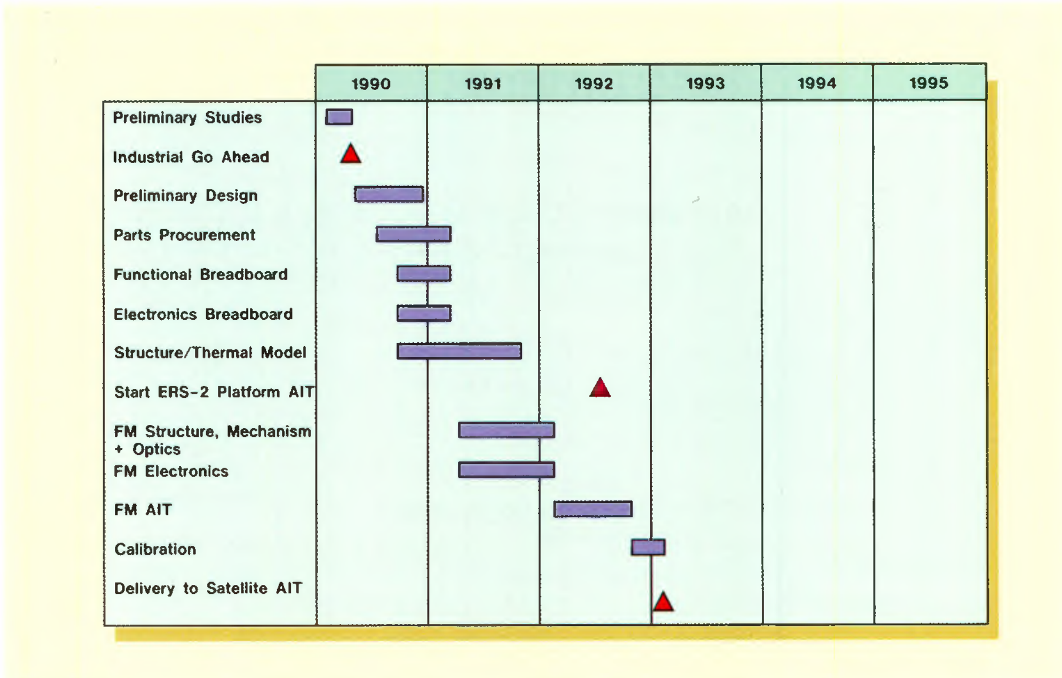
As early as 1988, the Agency's Executive started with the preparatory work for ERS-2 as the follow-on to ERS-1 which, at that time, was just starting its assembly phase. It was felt necessary to complement the capabilities of ERS-1 with instrumentation that could contribute to the growing discussions taking place in the public arena about such contentious issues as global warming and ozone depletion. In November 1988, selected European scientists involved in atmospheric chemistry instrumentation were therefore approached with a request to submit proposals for such an instrument to be included in ERS-2's payload, possibly replacing the Infrared Radiometer part of the ATSR instrument.

Among the proposals received was one prepared jointly by J. Burrows and P. Crutzen, called 'Sciamini', being derived from the 'Sciamachy' instrument concept proposed for flight on the Polar Platform (which later became part of the Envisat project). An in-house assessment of the technology involved confirmed the feasibility of such a concept in principle, and the authority was given to proceed with a more detailed instrument concept study. Some simplifications were, however, already introduced at this point: no limb viewing and only one unit, rather than two side by side. The modified instrument was also renamed the 'Global Ozone Monitoring Experiment', or GOME.

By the end of 1989, a contract had been placed with the Dutch firm TPD to develop the optical concept in more detail. In parallel, ESA performed in-house studies on the possible accommodation of the instrument inside the ERS-2 Service Module, and on the details of the detector's analogue electronics. In February 1990, the first contacts were made with the Italian firms Officine Galileo and Laben, to complement TPD in conducting a Phase-B study beginning in July that year. In parallel, ESA's Earth Observation Programme Board endorsed the ERS-2 Programme, including the GOME instrument.

The industrial Phase-B activities cumulated in a Design Baseline Review in March 1991 in Noordwijk (NL). The outcome was quite significant in a number of areas:
- The electrical configuration presented, with a dedicated Instrument Control Unit (ICU) and a pre-multiplexer to multiplex GOME and ATSR data prior to presenting the combined stream to the Instrument Data-Handling and Transmission Subsystem (IDHT), was considered far too power-consuming (at that time ERS-1 had yet to be launched and the actual system margins established). It was therefore proposed instead to provide the necessary services for command and control and data formatting and transmission directly via the ATSR's Digital Electronics Unit (DEU).
- It was decided to change to active thermal control for the detectors, with Peltier coolers rather than a passive radiator.
- A change was made in the calibration optics: the light path was routed via the scanning mirror, the Sun diffuser was

Figure 1. The initial GOME programme planning



protected by a shutter and a mesh, and the possibility of monitoring potential diffuser degradation by means of the calibration lamp was introduced.

Another major outcome, initiated at the DBR but confirmed only later in terms of its feasibility, was the change in the accommodation of the instrument from inside the Service Module to the outside of the Payload Module.

The main development phase for GOME was prepared and negotiated on this basis, and began in April 1992. A separate contract was placed with RAL and BAe for the necessary modifications to the ATSR's DEU hardware and software.

The political and technical boundary conditions as set forth by the Programme Board for the inclusion of GOME into the ERS-2 Programme can be summarised as follows:

- GOME was not to jeopardise any other aspect of the ERS-2 mission, either technically or programmatically.
- GOME had to 'live with the system margins' as known at the time of its approval, namely 30 kg, 60 x 30 x 20 cm^3, 40 kbit/s, and approx. 30 W, non-redundant.
- There were to be no financial provisions made in the ERS-2 Programme for GOME data routing and processing.
- Project management and system engineering were to be provided directly by ESTEC staff, this being considered the only possibility for complying with the schedule constraints.

The instrument development programme

The development programme for the GOME instrument, as initially envisaged, implied some breadboarding activities for critical subunits and a bench model for scientific testing, but was essentially a protoflight programme aiming for instrument delivery in early 1993 (Fig. 1).

Soon after starting the detailed definition of the breadboard model, it became obvious that some critical performance parameters could only be evaluated in vacuum. Hence, the first upgrade to the breadboard was to make it suitable for thermal-vacuum testing. In a next step, it was realised that the critical spectral-stability aspect could only be thoroughly evaluated if the structure were in close to final form. As a result of these concerns, the final step to producing a full engineering model was taken and this was subjected to a full environmental test programme at qualification vibration, EMC, and thermal-vacuum levels. In addition, this model was used for interface testing with the entire payload and was also subjected to a full calibration programme to exercise all necessary setups and procedures.

Whilst these activities were still in process, the flight-model programme was started. For schedule reasons, after the instrunent-level vibration and EMC tests, the flight model was used for the satellite-level alignment, vibration, acoustic and EMC tests and was then returned to the contractor for thermal-vacuum testing. The GOME flight model was declared flight-ready just in time for transport to the launch site together with the ERS-2 spacecraft. The major steps in this development programme are summarised in Figure 2.

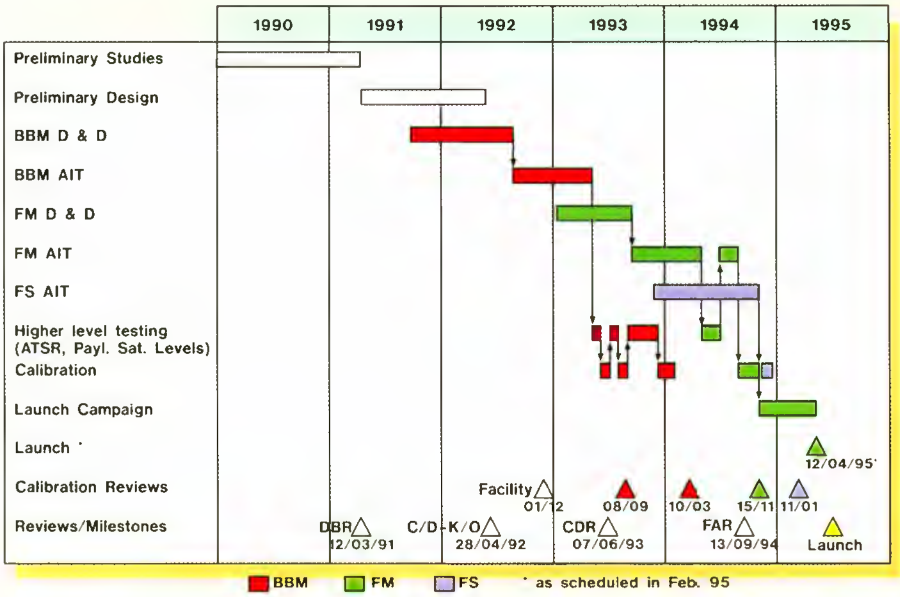


Figure 2. The actual GOME development schedule

The ground segment

No financial provisions were made in the ERS-2 Programme for the processing of the GOME data. Still, it was recognised that, in order to optimally exploit the sensor's capabilities, a ground processing system was necessary and that it must be comparable in capability to those for the other instruments on ERS-2.

Early in the GOME programme, scientists had started to work on some specific ground-processing issues, such as radiative-transfer modelling and an instrument simulator. In 1991, the German Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR) (Fig. 3) volunteered to implement, within the framework of the German Processing and Archiving Facility (D-PAF) and with national funds, the core of an operational GOME Data Processor. This comprised the conversion of the raw data to geo-located, wavelength and radio-metrically calibrated radiances (level 0 to 1) and the retrieval of ozone total column amounts (level 1 to 2). This proposal was endorsed by the ESA Programme Board in November 1992. Additional level-2 products, related to the retrieval of ozone profiles and cloud/aerosol parameters, were earmarked for being generated at the UK and Italian PAFs, respectively.

Figure 3. The German Aerospace Research Establishment (DLR) in Oberpfaffenhofen, which hosts the D-PAF facility, including GOME data processing

How was GOME possible?

Compared to many space- and ground-segment development programmes, the time needed for the GOME instrument's development was extremely short. The obvious question is why is this not generally possible? The answer is that there were numerous favourable boundary conditions in GOME's case that are not generally valid:

- ERS-2 was a repeat of the ERS-1 programme, so that the overall system architecture, satellite configuration, mission profile, environmental loads and conditions, etc. were all well-known, and the many iterative loops involved in establishing them were not needed. Consequently, the interfacing of the instrument including its ground segment was rather straightforward.
- Being a repeat programme also meant that the engineering and management teams, both within ESA and at the satellite Prime

Contractor, were confident about the system capabilities and able to decide quickly what was possible and what not. Most saw the inclusion of a new instrument as an interesting challenge in an otherwise repetitive programme. Consequently, GOME issues received high priority within the specialist teams.

- Despite the extensive goodwill within the industrial team, if the system engineering and management responsibility had not been directly with ESA/ESTEC, the unavoidable delays in communication and decision-taking would have made the already tight schedule impossible. Rapid progress kept the motivation high among the small GOME team, and this rubbed-off on the industrial and scientific partners and the other ESA establishments.
- The schedule pressure actually helped in that it forced quick decisions, without lengthy trade-offs of conflicting approaches, and imposed the discipline needed not to develop 'nice to haves', but to focus on the main issues. Seen in retrospect, most of the decisions proved to be right, the only notable exception being the means selected for measuring polarisation, which is admittedly less than optimum.
- Last but not least, a rigid payload and satellite assembly, integration and test (AIT) programme would have caused severe problems. Only by providing flexibility in scheduling AIT tasks to cope with GOME's specific needs and problems was a complete and coherent instrument programme possible. This is reflected in the many jumps between instrument-level AIT, higher-level AIT, and calibration of both the breadboard and flight models (cf. Fig. 2).

Lessons learnt

Although every project differs in terms of its particular boundary conditions and constraints, some worthwhile lessons can be learnt from the GOME Project experience:

Model philosophy

Although at first glance costly and leading to many activities having to be conducted in a short time, the breadboard model, which ultimately became a fully-fledged engineering model, proved to be an invaluable tool in the overall GOME programme. Not only did it enable the discovery of difficult-to-predict effects, such as straylight and electronic crosstalk, in time to implement remedies on the flight model, but it also served as a 'place holder' in many system-level tests where the presence of 'a GOME', but not necessarily the flight model, was required.

Calibration programme

Another benefit of the breadboard model was that it passed through the entire calibration programme. The main benefit was that the acquisition of these breadboard calibration data allowed the necessary software tools for data analysis and processing to be written and debugged. The experience gained allowed the time needed for the entire calibration campaign to be reduced, from more than six months in the case of the breadboard model to less than two months for the flight and flight-spare models.

The first GOME results

Few results are yet available from GOME, due mainly to the outgassing time of about one month needed after launch. During this initial period, certain instrument functions could be tested, but no performance evaluations or onboard calibrations could be performed.

When the closed-loop coolers were activated for the first time, and the first solar spectrum was acquired a few days later, it was proved that all of the hardware is functioning correctly.

The temperatures of the four detectors and of the optical bench are very stable and within the uncertainty range of the predictions. From the wavelength calibration, one can conclude that spectral stability is excellent: the measured wavelength drift as a function of the orbital temperature is of the order of just 1/50th of a detector pixel (Fig. 4).

As expected, GOME shows some sensitivity to the space radiation environment. To quantify this effect, the instrument was left for three days in 'dark-current mode' and the results mapped; Figure 5 clearly shows the location and extent of the South Atlantic Anomaly (SAA). The radiation has two effects: a general increase in noise level, which is evident when comparing Figures 6a and b, and the high sharp spikes evident in Figure 6c. The ground-processing software has been configured to cope with the latter.

On 15 May, GOME recorded its first solar spectrum, which is being used both for instrument calibration and in the retrieval of ozone data in the ground processing chain. The spectrum was largely as expected, except that for the wavelength range 289 – 307 nm the detector was in saturation. This was corrected by adjusting the integration time for the affected band, and the next Sun acquisition was then within the nominal range. Detailed investigations and fine tuning of the processing are still going on, but first impressions are that the GOME measurements compare very well with the external references.

The acquisition and initial processing of earth-shine spectra is currently in progress,

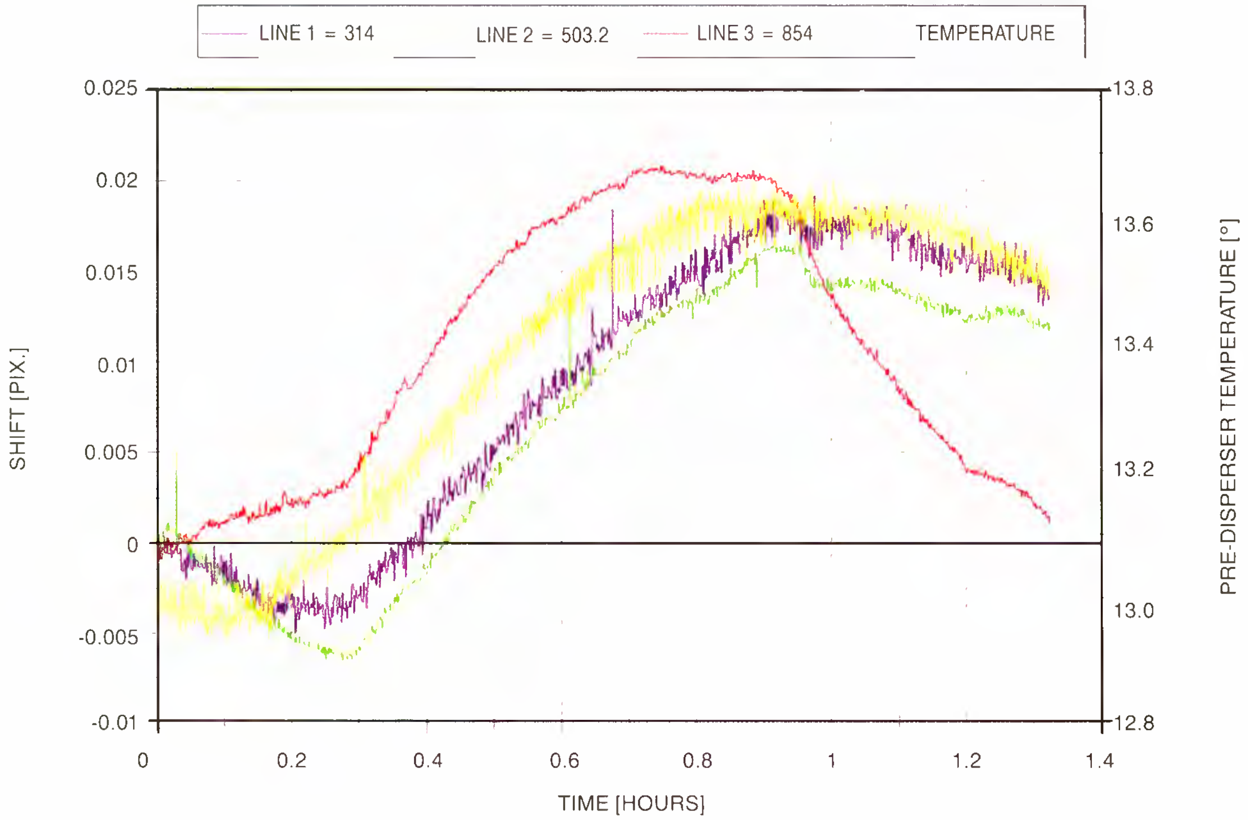


Figure 4. Wavelength shift as a function of orbital temperature variations. The plot shows the relative shifts of three selected lines of the wavelength calibration lamp, in fractions of a detector pixel. One pixel in channel 1 corresponds to 0.1 nm. Also shown is the temperature at the disperser prism, as the most temperature-sensitive optical element (yellow curve)

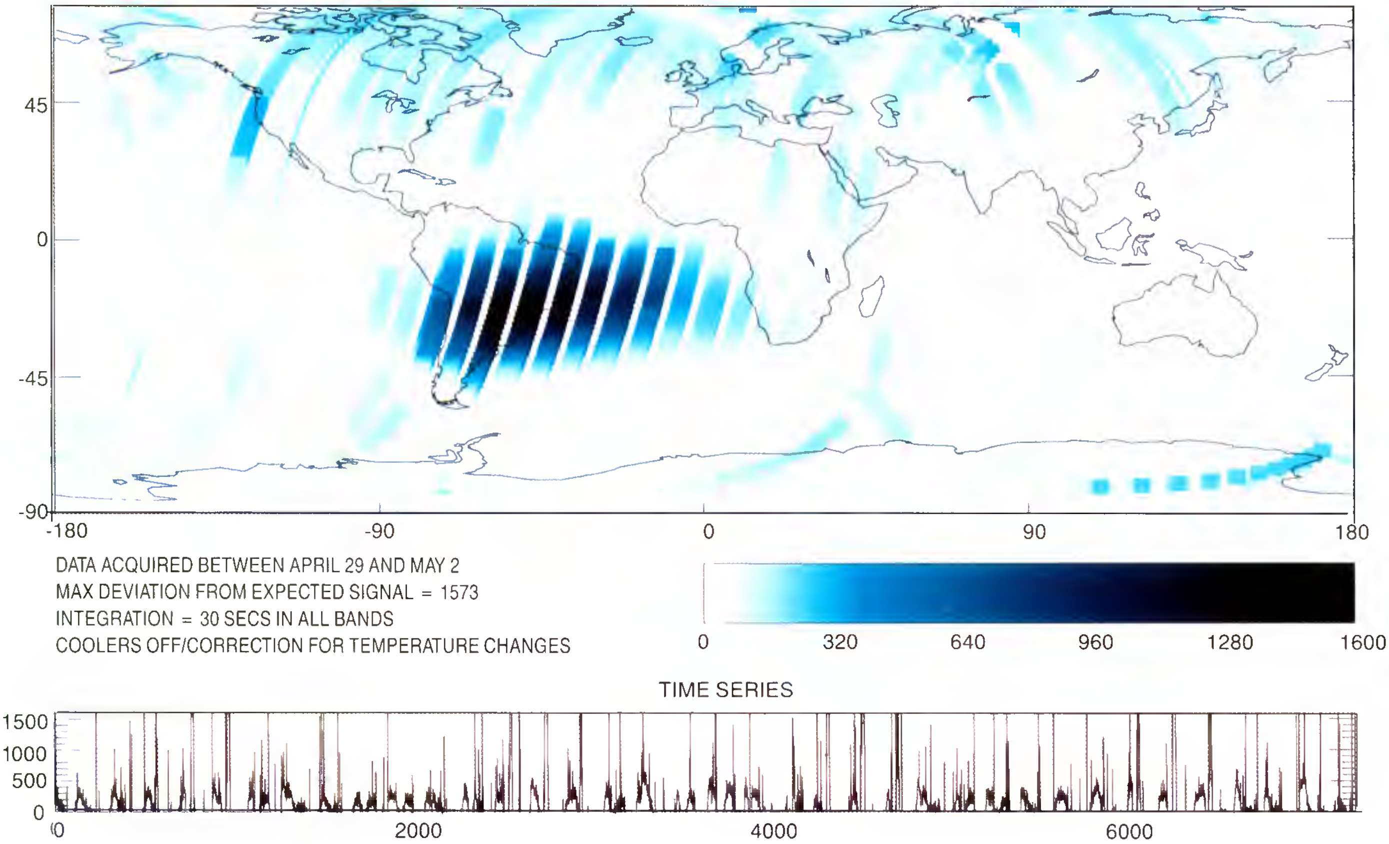


Figure 5. GOME radiation impact mapping as a function of geographical location. The plot shows the highest occurring peak (see Fig. 6c also) in any of the four channels

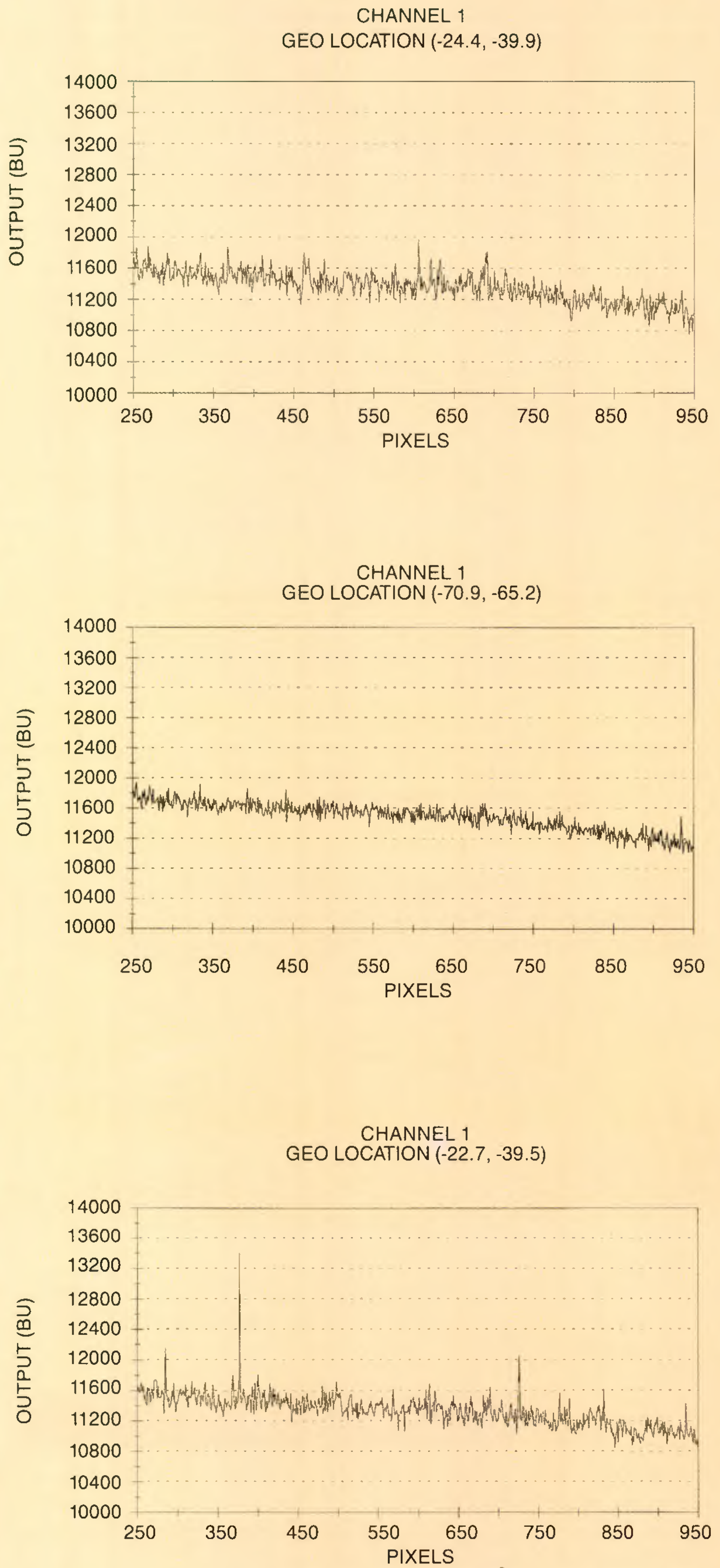


Figure 6. Dark-current readouts of one channel: (a) at a location inside the South Atlantic Anomaly; (b) outside the SAA, showing a less noisy behaviour; (c) the spikes on individual (or very few) detector pixels, as plotted in Figure 5

together with the optimisation of integration-time settings, stepping through different scan patterns, and fine-tuning of operational procedures.

Acknowledgement

It has to be pointed out that the whole GOME programme has truly been a team effort, involving many engineers, scientists, managers and support staff.

The instrument Prime Contractor was Officine Galileo (Florence, I), with major contributions from Laben (Milan, I) for the DDHU and EGSE, TPD-TNO (Delft, NL) for the Calibration Unit, and Dornier (Friedrichshafen, D) for the Thermal-Control Subsystem.

Under separate contracts, TPD-TNO performed the instrument calibration, and Rutherford Appleton Laboratory (Chilton,UK), with the support of BAe (Bristol, UK), made the necessary modifications to the ATSR-DEU.

Credit has also to be given to the ERS-2 Prime Contractor Dornier, and the team of the AIT subcontractor Fokker (Leiden, NL) for their continuous support and their flexibility in coping with the special needs of GOME.

The Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR), in Oberpfaffenhofen (D), developed the GOME Data Processor with only a limited financial contribution from ESA, the majority of the funding being provided by the German Space Agency (DARA).

In addition, the GOME project has enjoyed the continuous support of a large number of scientists from all over Europe and the USA, with J. Burrows from the Institut für Fernerkundung, Bremen (D) acting as the lead scientist. He has been supported by the members of the GOME Science Advisory Group, the subgroups for calibration, data processing and algorithm development, and validation: K. Chance (USA), A. Goede, S. Slijkhuis, P. Stammes (NL), R Guzzi (I), B. Kerridge, R. Munroe (UK), D. Perner, U. Platt, H. Frank, D. Diebel (D), J-P. Pommereau (F) and P. Simon (B).

Last but not least, the specific contributions of the various ESA establishments – ESA Head Office, ESOC, ESRIN and ESTEC – to the overall success of the GOME project are gratefully acknowledged.

ERS-1: Four Years of Operational Experience

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The first European Remote-Sensing Satellite (ERS-1) was launched from Kourou on 17 July 1991 (Fig. 1). Today, with the celebration of its fourth anniversary in orbit, ERS-1 has exceeded twice its planned operational lifetime, having completed more than 20 000 revolutions of the Earth.

The platform providing the major services for satellite and payload operation continues to perform exceptionally well. In particular, the power and thermal-control subsystems are very stable, and there is still a large reserve of hydrazine onboard for a further extension of operations. The comfortable power-budget margin allows continuous and extensive operation of all payload elements.

The healthy condition of ERS-1 is currently allowing the unprecedented tandem mission with ERS-2, as well as providing additional confidence that its data-gathering role could be maintained for several more years.

Figure 1. The ERS-1 spacecraft

Orbit maintenance

ERS-1, being the first mission of its kind, has been operated in various orbital scenarios, ranging from the 3-day reference orbit used during the commissioning phase, to the 168-day repeat cycle allowing a very high density of Radar Altimeter (RA) tracks.

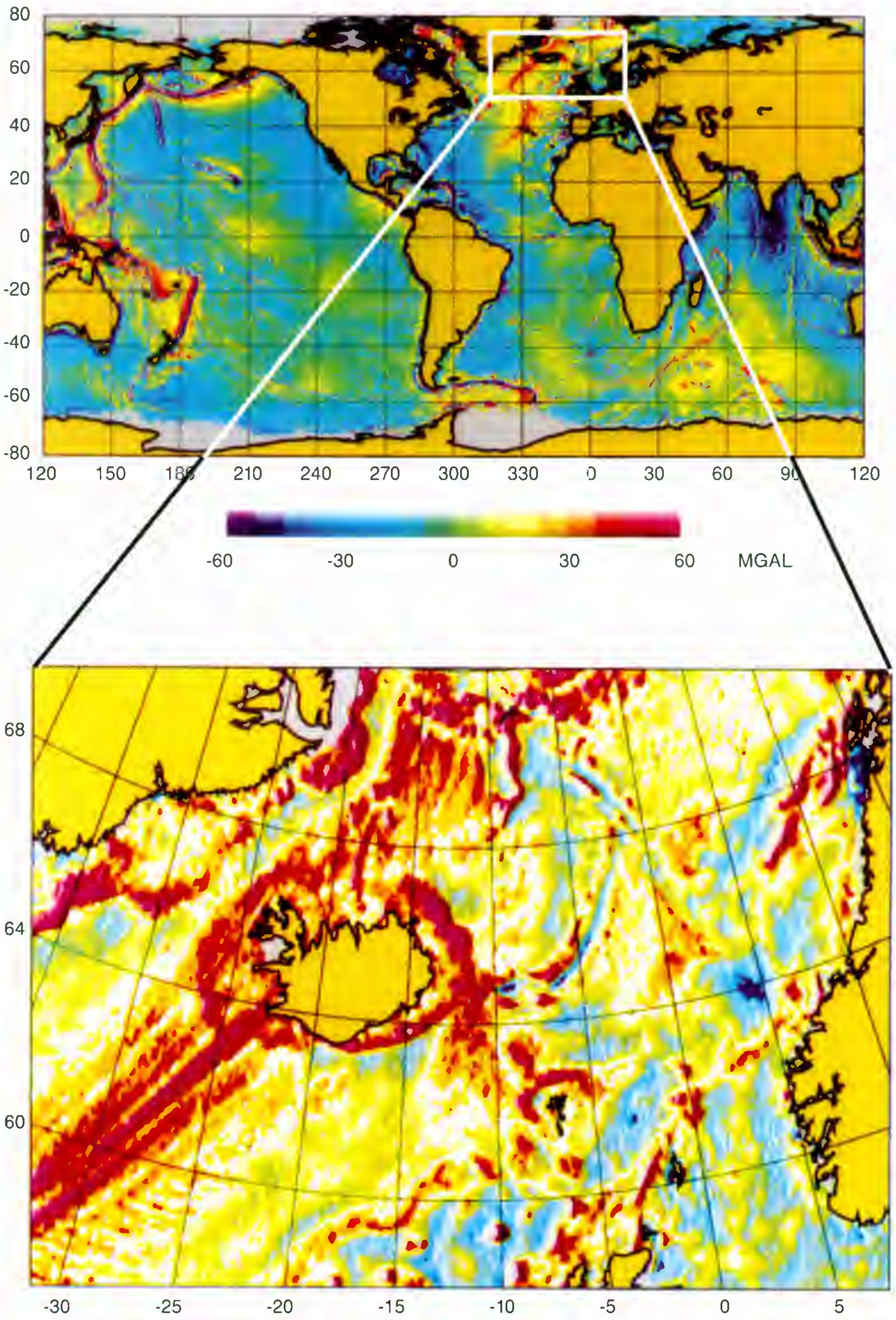
The latter orbit covering the so-called 'geodetic phase' has been visited twice by ERS-1 (with an offset introduced to improve the track density) and has provided scientists with a detailed mapping of the topography of the sea-surface for the first time. This topography is dominated by the structure of the gravitational equipotential surface called the 'geoid', the shape of which is largely determined by the sea floor's topography. ERS-1 is therefore providing us with a glimpse of the vast hidden parts of our planet that lie beneath the sea (Fig. 2).

At present, ERS-1 is operating in the nominal 'multi-disciplinary phase' with a 35-day repeat cycle, and is leading the ERS-2 satellite which is in the same orbit with a one-day offset.

Aside from these planned changes in repeat cycle, orbit maintenance is required to compensate for the air drag on the spacecraft, which varies with the degree of solar activity. The compensatory in-plane control interventions generally consist of two-burn thruster manoeuvres.

During 1991 and early 1992 solar activity was high and control cycles were typically in the order of 1 to 3 weeks. In the subsequent period of low solar activity, the time between in-orbit corrections has grown to one month or more. Out-of-plane manoeuvres to correct for the reduction in the inclination of ERS-1's orbit have also been required every 9 to 10 months. The ERS-1 ground track has been kept within a deadband of better than ± 1 km since launch. For the current tandem operation, the maximum distance between the ERS-1 and

Figure 2. Map of marine gravity anomaly derived from ERS-1's Radar Altimeter instrument



ERS-2 ground tracks is fine-tuned to just a few hundred metres.

Shortage of fuel, often the commodity that determines the end-of-life for a satellite, will not be a key factor in the continued operation of ERS-1. The average rate of consumption is just 0.9 kg of hydrazine per month and 255 kg of the original 300 kg of fuel still remain. This abundance of fuel is a direct result of the perfect performance of the Ariane-4 launcher back in 1991. Additional hydrazine, carried as a contingency for fuel-hungry orbital corrections in the event of a dispersion in launcher injection parameters, was therefore not needed and part of it can be used for other purposes, including rapid de-orbiting of ERS-1 at its eventual end-of-life.

Spacecraft performance

The platform's thermal-control system has worked perfectly throughout the four years in orbit. The observed onboard temperatures lie well within the acceptable operational limits, the maximum average being lower than 16°C. The maximum temperature observed so far has been 30°C for the solar-array drive mechanism and the gyroscopes. The observed degradation in spacecraft-radiator temperature amounts to less than 1°C for each year in orbit (Fig. 3).

The power subsystem provides an equally positive picture. The battery compartment contains four NiCd batteries, each with a specified capacity of 24 Ah. Their actual in-orbit capacity at beginning-of-life (BOL) was 32 Ah, since when the battery compartment has been maintained at about −4°C, providing optimum and stable conditions for a long lifetime. Nominal ERS-1 operations have resulted in a mean depth of discharge (DOD) of around 20%, which is notably lower than the 24% anticipated before launch.

The end-of-discharge voltage at the end of eclipse is a good indicator of battery degradation. The battery supplier guarantees a minimum end-of-discharge voltage of 26 V after a four-year mission, to be compared with the 28 V presently being measured. This value has not changed for a long time, leading to the conclusion that battery health is good.

ERS-1's solar-array power is regularly monitored. A survey starting from launch in 1991 is presented in Figure 4. It shows that BOL performance exceeded expectations and that the degradation in available power is presently 1% per year. The available power level will therefore approach 2300 watts after five years in orbit, thereby considerably exceeding the two-year specified design goal of 2100 watts.

The lifetime predictions for both the thermal-control subsystem and the solar array are based on typical degradation factors taking into account mainly solar ultraviolet radiation and in-orbit particle radiation effects. The ERS-1 platform, derived from the French national Spot platform, has confirmed the experience from earlier Spot flight models that factors used to model degradation in polar Sun-synchronous orbits are too conservative. Studies are therefore underway to use this knowledge to optimise the design of the future generation of polar-orbiting spacecraft.

ERS-1's attitude and orbit control subsystem consists of Earth and Sun sensors, gyroscope package, reaction wheels and magneto-torquers. This subsystem is also closely monitored and regular gyroscope maintenance campaigns are performed to determine long-term drifts. During one such campaign, the onset of noise was noted in one operational gyroscope. Although the noise level was within acceptable limits, the active-gyro configuration has been modified to keep the gyroscope in question as a redundant unit.

The payload itself provides a further means for direct verification of AOCS performance. The Radar Altimeter (RA) accurately detects the off-nadir pointing, while the Active Microwave Instrument (AMI) determines the Doppler shift with respect to the Synthetic Aperture Radar (SAR) antenna, allowing a precise estimate to be made of the satellite's combined yaw/pitch mis-pointing. Actual mis-pointing has proved in practice to be less than 50 mdeg, and thus a factor of five better than the specified AOCS performance.

The On-Board Computer (OBC) on the ERS spacecraft runs the 'centralised flight software', which is a small package (44 kwords) incorporating all mission-essential functions. A series of spurious parity errors detected in the autumn of 1992 led to a software re-initialisation and a redundancy re-configuration for the

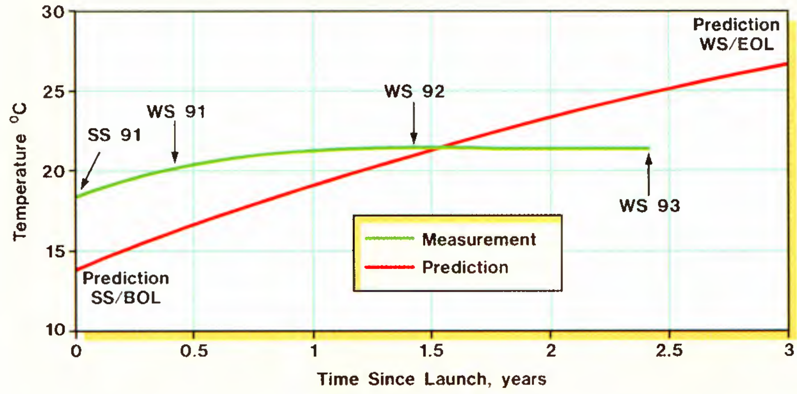


Figure 3. Evolution in the spacecraft platform's average temperature as a function of lifetime

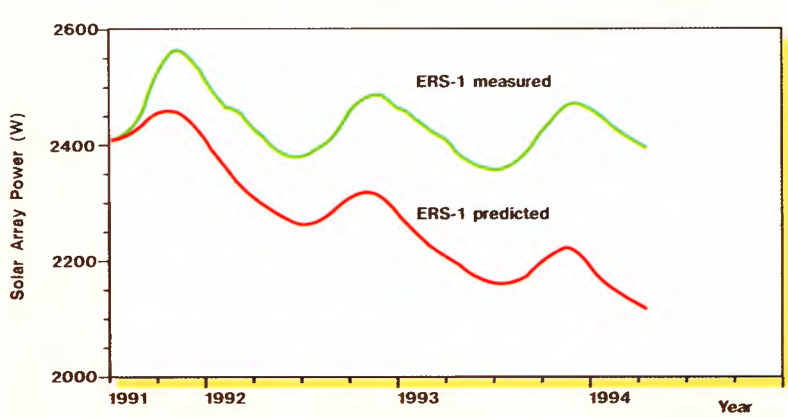


Figure 4. Evolution in solar-array performance since launch

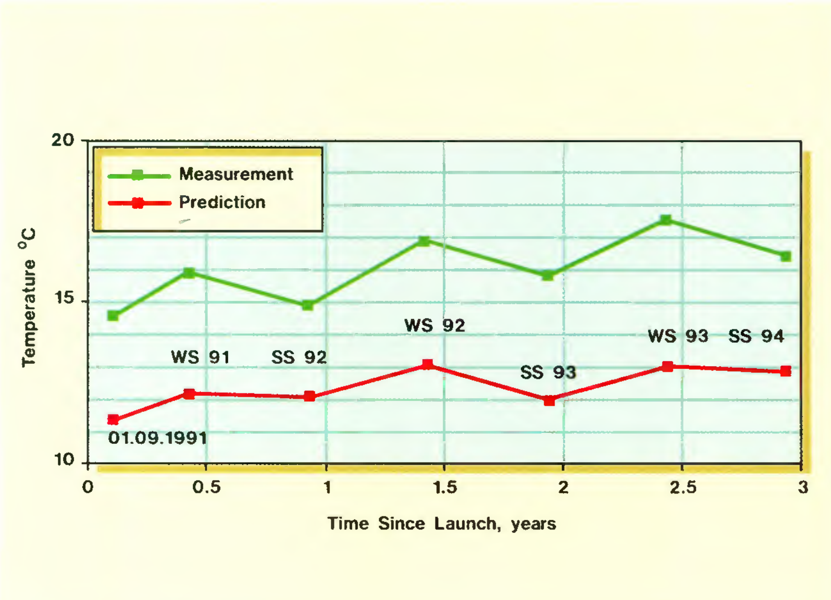


Figure 5. Average payload temperature as a function of lifetime

OBC. The failure was traced to a specific memory area dedicated to storage of the payload command queue. The inherent versatility of the memory design allowed the size of the command queue to be reduced and the failed memory block to be eliminated, whilst still maintaining sufficient capacity to store the payload commands. Full redundancy for the OBC has thereby been restored and operations have subsequently continued without further incident.

Payload performance

Thermal subsystem

The correlation between in-flight data and thermal-model predictions for the ERS-1 payload has been excellent, the overall temperature difference amounting to just 3°C. The average payload temperature of approximately 13°C is far below the maximum permissible operating conditions of 40 – 50°C for the onboard equipment, thus providing ideal conditions for the electronic units.

The payload-radiator temperature has proved just as stable as the platform's thermal control, with less than a 1°C change per year (Fig. 5).

Instrument data-handling and telemetry (IDHT) subsystem

The handling of the payload's science data, as well as its transmission to ground by X-band link, is provided by the IDHT subsystem. The lifetime-critical elements in this subsystem are the 6.5 Gbit tape recorders and the travelling-wave-tube assemblies (TWTAs).

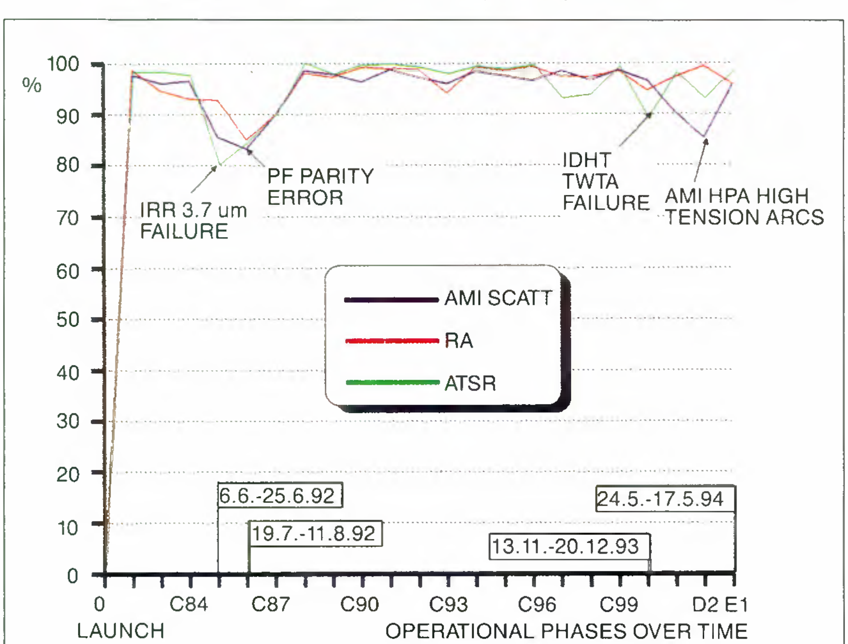
The tape recorders have been operated in sequence for three-month periods. A nominal orbit requires one complete recording and playback cycle, which means that each unit has been subjected to approximately 10 000 cycles over the four-year period. Life tests on the ground have validated such tape recorders for almost 38 000 tape passes and 120 000 start/stop cycles. The IDHT high-rate link TWTA failed in December 1993 after 2.5 years of operation. A Failure Review Board concluded that it probably failed due to fatigue resulting from thermo-mechanical stresses induced by repeated high-voltage on/off cycles. The design had been life-tested for 18 000 switching cyles, based on predicted usage over a three-year period. The favourable power conditions aboard ERS-1, however, have allowed for extensive SAR operation. The TWTA's failure after 27 000 switching cycles therefore meant that it had already greatly exceeded its expected lifetime.

Measures have since been introduced into the mission-planning system at ESOC, in Darmstadt (D), to limit the number of such switching cycles by optimising the image-acquisition sequences. The redundant high-rate TWTA has experienced just over 11 500 cycles in 1.5 years, while the low-rate TWTA in operation since 1991 has been subjected to 20 000 cycles. Assuming a lifetime capability of 30 000 switchings, the remaining lifetimes for both TWTAs are estimated to be slightly more than two years. Given that the defective TWTA is still capable of handling low-rate transmission as a backup unit, the IDHT should still be capable of providing excellent data continuity for future operations.

The instruments

The instrument availability figures have been extraordinarily high, typically ranging between and 95% and 100% (Fig. 6).

Figure 6. Availabilities of the ERS-1 instruments since launch



The Active Microwave Instrument (AMI)

High-voltage arcing is a common problem with High-Power Amplifiers (HPA) of the type needed on ERS. There have been an average of five such events per month since ERS-1's launch, which is well within the specified allowable four arcs per 100 hours. A period of excessive arcing in 1994, however, rendered the AMI inoperable, but after a few days of 'rest' the system behaved correctly once more and the good performance has continued ever since.

The long life of the prime HPA is unprecedented, exceeding the total duration of the various HPA on-ground life tests. Procedures for a reconfiguration to the redundant HPA and instrument recalibration are in place to provide a smooth transition should any such problem arise.

Monthly reports are produced concerning the radiometric stability of the AMI wind scatterometer (SCATT) over the Amazon rain forest, and the same parameter measured for the SAR over a calibration site in the Netherlands (Figs. 7 a,b). Both parameters have shown excellent stability for the AMI in both the SCATT and SAR modes over the four years since launch.

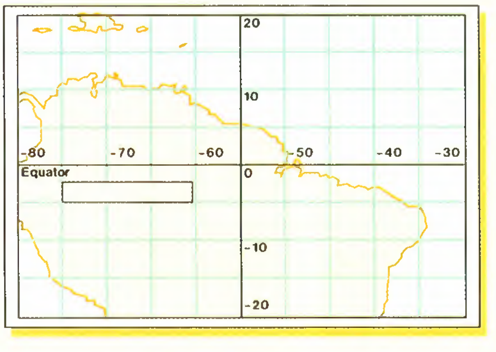
The AMI has acquired more than half a million radar images in those four years, which constitutes a true demonstration of the wealth of data being provided to users by the ERS-1 payload.

The Radar Altimeter (RA)

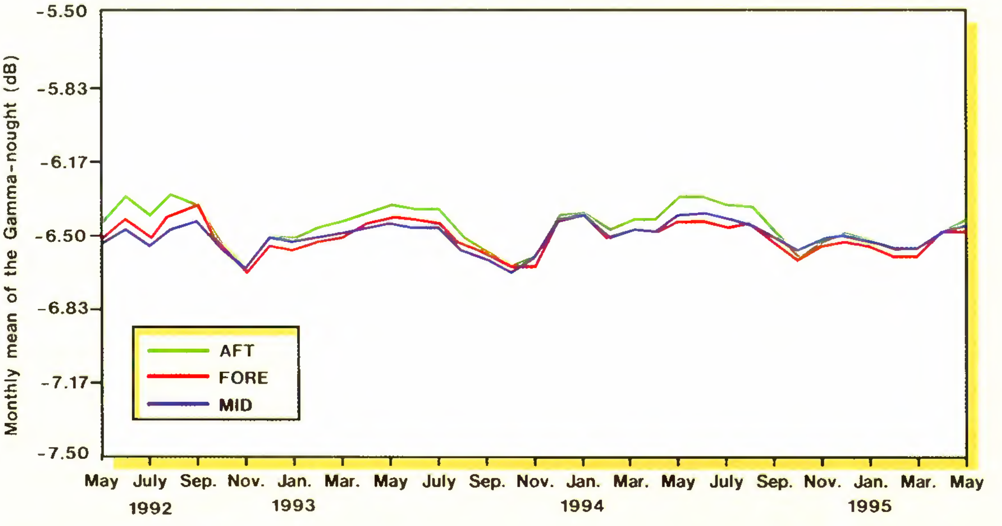
The Radar Altimeter boasts a near-perfect in-orbit availability figure close to 99%. Over the past four years, software updates have allowed the Altimeter's tracking capability over non-ocean surfaces like coastal zones, land and ice, to be further improved. The ERS-1 RA is now also capable of keeping track over medium-rough terrain, as well as terrain with rapidly changing backscatter or major changes in echo shapes. Consequently, the instrument has been available for longer periods of unperturbed operations (Fig. 8).

The Along-Track Scanning Radiometer (ATSR)

The ATSR and Microwave Sounder has experienced only one setback during the four years of operation, namely loss of the Infrared Radiometer's 3.7 micron channel in mid-1992. High-quality images have continued to be acquired, however, by the 11, 12 and 1.6 micron channels. The specified accuracy of 0.5 °C for the global day/night sea-surface temperature product has been maintained, and so the impact of one channel's loss on the ATSR's scientific return is regarded as minimal by the Principal Investigators concerned.



(a)



(b)

Figures 7 a,b. Radiometric stability of the AMI wind scatterometer, calibrated weekly over a specially selected area of the Amazonian Rain Forest (extending from 2.5 to 5°S in latitude, and from 60.5 to 75°W in longitude)

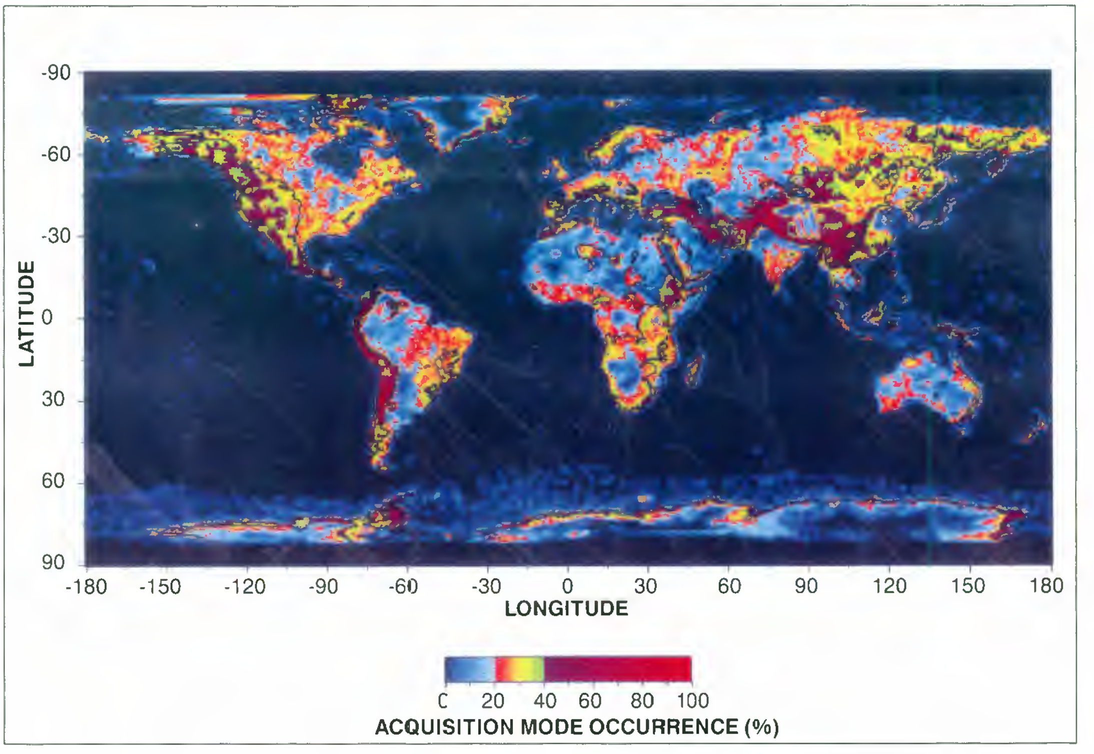


Figure 8. The tracking performance of the ERS-1 Radar Altimeter, for the period 30 July to 3 September 1993 (cycle 97)

The Microwave Sounder has an excellent track record and its product, the atmospheric integrated water content, is used to enhance the quality of the Radar Altimeter's output.

Conclusion

Despite being a completely new type of satellite, ERS-1 has provided excellent performance, exceeding all expectations and more than proving, throughout its four years of operation, the novel and sophisticated nature of its payload and data products.

A key aspect for users is data continuity and there again ERS-1 has paved the way for future missions, by demonstrating the extremely high operational availability of such a polar-orbiting platform and payload.

ERS-1's resources are still far from being depleted and, given the so far largely unexploited redundancy, the satellite has the potential to back-up ERS-2 operations until the end of 1996 and beyond.

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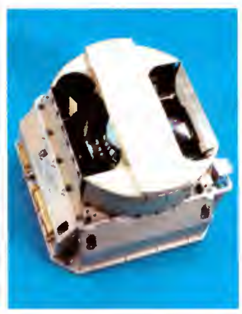

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ERS-1 and ERS-2 Tandem Operations

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Directorate for Observation of the Earth and Its Environment, ESA, Paris

When it was decided in 1990 to build ERS-2, the prime motivation was to provide a follow-on to ERS-1 and thereby ensure the necessary continuity of data and services to both the scientific research and operational application user communities. When it became clear towards the end of 1993 that ERS-1 would remain technically operational well beyond its 30-month design lifetime, strong interest was expressed, at several ERS-1 User Meetings and Symposia, in the simultaneous operation of ERS-1 and ERS-2 over a period of several months, and possibly up to one year.

To explore the potential benefit that would result from such ERS-1/2 tandem operations in more detail, several consultation meetings with both scientific and application-oriented users were organised by the Agency. They showed that a great many advantages and benefits for both research and applications would accrue from flying two identical sets of instruments in an appropriate orbital configuration; in particular, a 'unique SAR data set' could be collected for interferometry applications.

On 23 March 1995, the ESA Council adopted a Resolution on ERS-1/ERS-2 tandem operations which will 'keep ERS-1 alive' until April 1997 and allow such operations for a nominal duration of nine months, beginning at the end of the ERS-2 Commissioning Phase in autumn 1995.

What is tandem operation?

ERS-1 and ERS-2 are flying in the same orbital plane with an inclination of about 98.5° to the Earth's equatorial plane, giving the satellites visibility of all areas of the Earth as it rotates beneath them (Fig. 1). Each satellite's pattern of orbital tracks over the Earth's surface repeats itself exactly after a certain number of days. This 'repeat cycle' depends upon the altitude of the orbit; ERS-1 and ERS-2 are both flying at the same mean altitude of 785 km, providing a repeat cycle of 35 days.

The passes of the two satellites over the ground receiving stations last about 10 min. The reconfiguration of the stations between the end of one satellite's pass and the beginning of the pass of the next takes about 15 min; since the orbital period is approximately 100 min, the time interval between the two satellites has to be between 25 and 75 min. With the current orbital configuration, ERS-2 follows ERS-1 with an approximate delay (called the 'orbit phasing' of the two satellites) of 35 min.

Because of this delay and the Earth's rotation, the ground-track patterns of ERS-2 are shifted westwards with respect to those of ERS-1 (Fig. 2). The orbit phasing has been adjusted to ensure that ERS-2's track over the Earth's surface coincides exactly with that of ERS-1 24 h earlier. Within the repeat cycle of 35 days, the opportunity to observe any point on the ground under identical conditions (altitude, incidence angle, etc.) is therefore doubled during the tandem operations. Different ground-site revisiting intervals can be achieved by changing the orbital phasing of the two satellites.

The ERS-1/ERS-2 tandem mission is being operated with a very limited additional budget and with a ground-segment infrastructure that was designed for just a single satellite. It is therefore only feasible at all subject to the following assumptions:

- at the end of the ERS-2 Commissioning Phase, ERS-2 will become the nominal satellite, taking over from ERS-1 in providing routine services to the user communities
- ERS-1 will be dedicated to support the tandem mission for a nominal duration of nine months, and will be operated on a campaign basis by performing the acquisition of the Synthetic Aperture Radar (SAR) data, which will be processed off-line
- a primary objective is to acquire, as quickly as possible, complete Earth coverage with ERS-1 and ERS-2 SAR data within the visibility of the existing ERS-1 ground receiving stations, which have responded positively to this request.

The current orbit phasing of 1 day, needed to calibrate the ERS-2 Radar Altimeter during the Commissioning Phase, will be retained until the

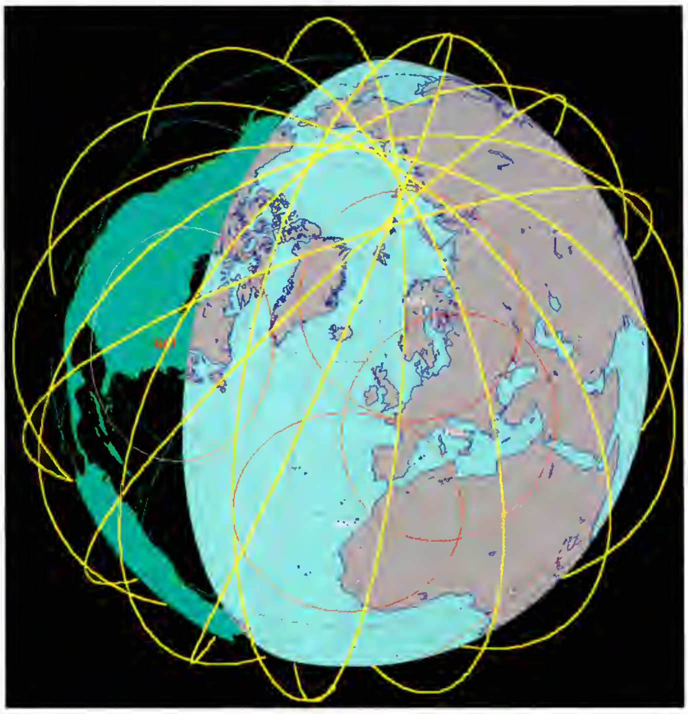

Figure 1

Figure 2

end of 1995, when orbit manoeuvres will take place to introduce an 8-day ground-site revisiting cycle, which is an attractive alternative for many scientific and application-oriented users.

What are the potential benefits of tandem operation?

The benefits of tandem operations are best characterised by the following attributes:

- When the same area of the Earth is observed by the same instrument on ERS-1 and ERS-2 with a ground-site revisiting interval of 1 or 8 days, the improvements compared to a single satellite are:
  - (i) the number of acquisitions in a repeat cycle (35 days) is doubled
  - (ii) the time interval between two successive acquisitions is shorter, being 1 or 8 days rather than 35 days.
- For global applications, for instance those involving the use of wind-scatterometer data in weather-prediction models, the ground surface covered within a given time period is doubled when acquisitions by the same instrument on both ERS-1 and ERS-2 are combined.
- When the ground-track pattern of nadir-looking instruments on one satellite overlaps that of side-looking instruments on the other, their information can be combined (Fig. 3), thereby providing synergistic benefits.

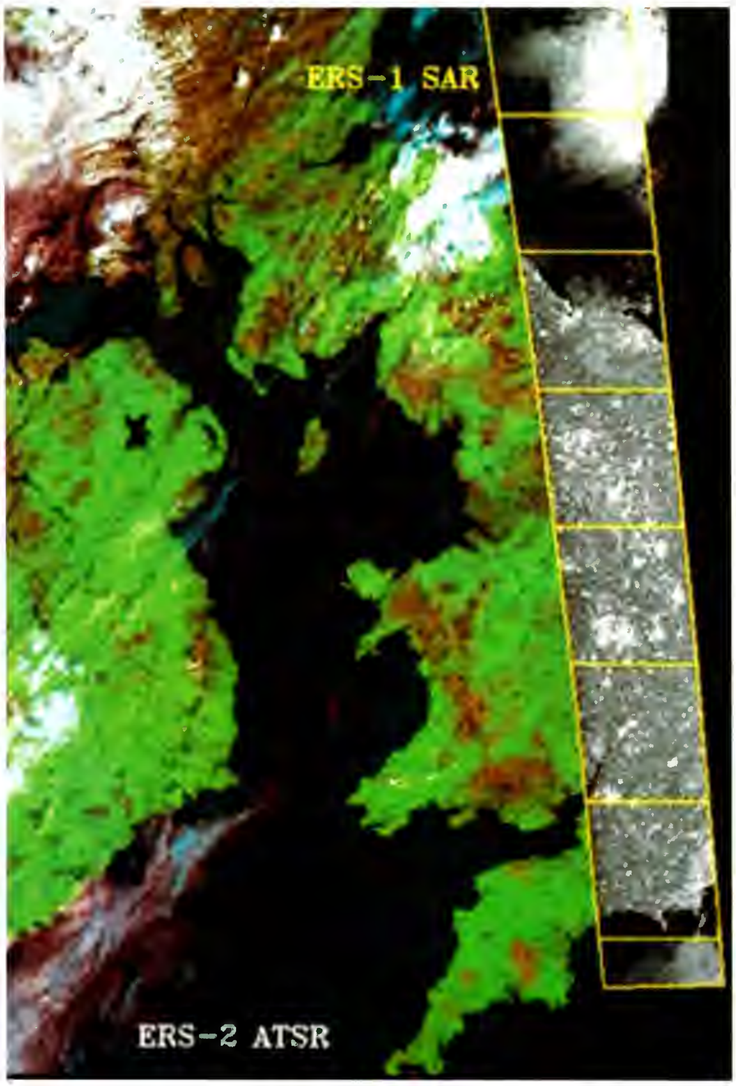

Figure 3

Consequently, data acquired jointly by ERS-1 and ERS-2 will undoubtedly give rise to numerous demonstration projects and new scientific research in many fields of earth sciences (e.g. agriculture, hydrology, and emerging applications such as SAR interferometry), and will be exploited in particular in a large proportion of the proposals selected from the recent ERS Announcement of Opportunity.

SAR interferometry

The SAR interferometry technique, which in the past was an airborne technique, has shown its true potential with ERS-1. This technique requires several satellite passes over the same area in order to obtain a suitable pair of images, with the orbital cross-track separation constituting the interferometer baseline (Fig. 4). For each pixel corresponding to the same area of ground in both images, the phase values (depending on the satellite to ground pixel path length) are subtracted to produce a phase-difference image known as an 'interferogram'. Knowing the orbit parameters, the phase interferogram can be used to generate a Digital Elevation Model (DEM) of the surface, with an accuracy in the order of 10 m. An additional product is the so-called 'coherence image', which shows bright areas where the coherence between the two SAR images is high, indicating no variation in backscatter between the acquisition times of the two images. Dark regions indicate areas where changes have occurred.

Satellite SAR interferometry is a very powerful tool for generating DEMs with medium accuracy, very efficiently and for a large fraction of the land surface. For cloudy areas or for regions with extremely low textural surface features, it is the only method that is feasible.

The large-scale generation of DEMs depends on the tandem mission for its success, as several constraints have to be met which cannot always be satisfied with just one SAR in operation; namely

- Temporal coherence between the SAR image pair must be high. For many parts of the Earth's land surface affected by fast surface-cover changes due to, for instance, vegetation growth, the 35-day repeat cycle is too long (there are various other effects that cause a deterioration in coherence for interferometric processing, such as ionospheric, tropospheric, rain, and soil-moisture changes).

  Investigations have shown that for some regions correlation degrades by as much as 10% in 5 days.

- Spatial coherence must also be high for interferometric DEM production. In addition, the ambiguity problem must be resolved. The interferometric baseline should preferably be between 50 and 150 m. This baseline is much better controlled during the tandem mission, as the orbits of the two satellites are affected by similar forces, whilst the baseline between consecutive passes of a single satellite cannot be accurately predicted.

DEMs are one of the most useful auxiliary remote-sensing data sets. They provide the ability to correct images of the Earth – from both microwave and optical sensors – for offsets caused by elevation differences, as well as facilitating adequate geo-referencing of these data.

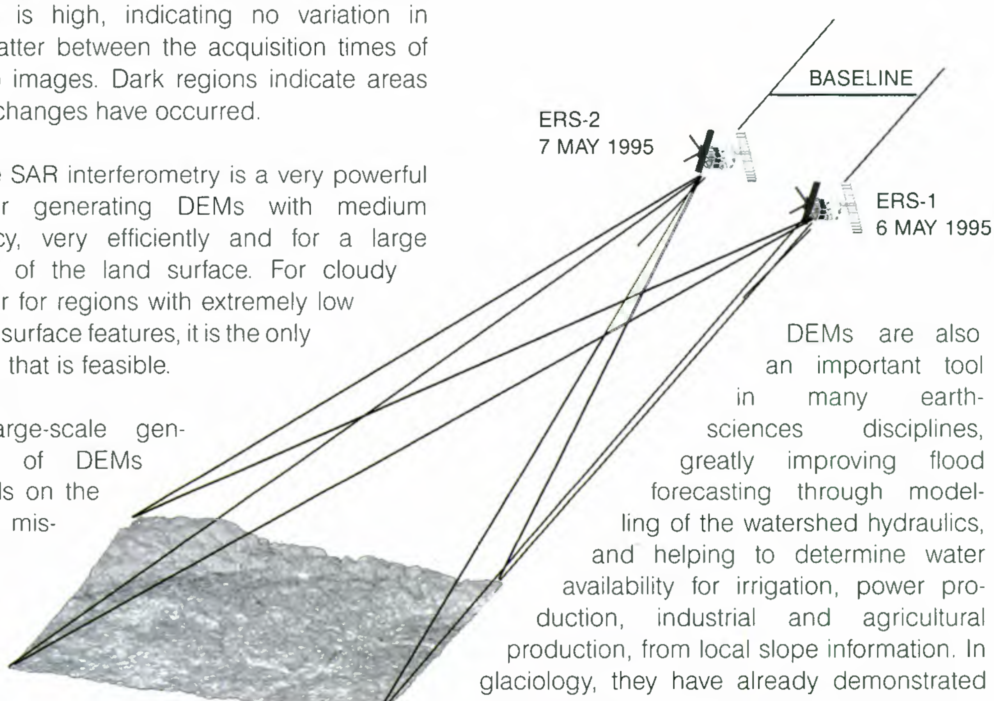

Figure 4

DEMs are also an important tool in many earth-sciences disciplines, greatly improving flood forecasting through modelling of the watershed hydraulics, and helping to determine water availability for irrigation, power production, industrial and agricultural production, from local slope information. In glaciology, they have already demonstrated their potential for determining topography over ice sheets and glaciers and deriving ice motions. Combined with spatial-analysis models, they can be used to identify and simulate viewing perspectives for land-use planning. DEMs are also useful for military applications, and there is already a significant market for commercial applications, such as mobile communications where they are an essential tool in the implementation of ground relays.

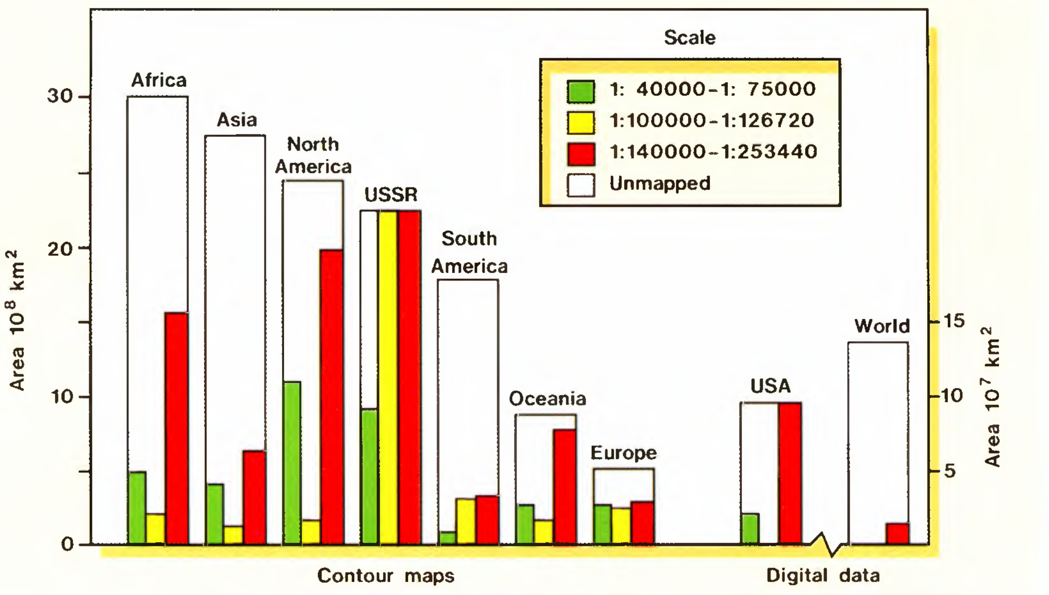

Figure 5
Source: NASA Topographic Science Working Group Report

Figure 5 shows the current availability of topographic data. Extensions of the present DEM coverage will be extremely difficult with conventional methods, because most of the globe's still unsurveyed land areas are in the predominantly cloud-covered and humid tropical regions and in the polar areas.

Results of the early tandem operations

Just a few days after the launch of ERS-2, a number of SAR images were made using ERS-1 and ERS-2 in tandem mode, observing the same region with a one-day interval. These data were quickly processed and analysed by European experts to demonstrate some of the possibilities offered by SAR interferometry for the generation of DEMs.

First example over Central Italy: generation of a radar interferogram as a basis for a three-dimensional map of the Earth's surface

An interferogram uses not the brightness (intensity) of the reflected radar beam, but the phase information it contains. The phase differences that occur for two slightly shifted viewing angles are calculated individually for each pixel, by analysing images recorded from slightly offset positions during overpasses of ERS-1 and ERS-2 on consecutive days. As these phase differences are directly related to the heights of the terrain being surveyed, when colour-coded they resemble the contour lines of a topographical map.

The tandem-interferogram in Figure 6 shows a 15 km x 20 km section from the first ERS-2 SAR image of 2 May 1995, combined with an ERS-1 image from the previous day. In this case, the orbits of the two satellites were about 400 m apart (the optimum figure is rather less). The individual interference zones (colour cycles) correspond in each case to a difference in height of around 22 m. The image processing was performed by Prof. Rocca's team at the Politecnico di Milano (Italy).

The interference patterns are seen most clearly in the mountainous regions; here 'blurred' areas point to the existence of forested areas which, because of the height of the trees, are 'seen' differently from the different viewing angles of the two satellites (this is known as the 'volumetric effect'). On the other hand, there is pronounced 'blurring' in the sea area and in parts of the enclosed lowlands, because the coherence requirement is barely met over the water. Comparison with a multi-temporal image (Fig. 7) combining the ERS-1 and ERS-2 data used in generating the interferogram provides an idea of the effect that the varying wind fields (and consequent wave patterns) and changes in soil moisture or surface coarseness can have on coherence.

Second example over the Maastricht area of the Netherlands: generation of a radar interferogram and DEM

On 7 May 1995, ERS-2's SAR imaged the area known as 'three-countries corner', where the borders of Belgium, Germany and the Netherlands meet. As Figure 8 shows, one can easily make out the valley of the River Meuse running vertically up the picture, with Liege (B) at the bottom edge and Maastricht (NL) closer to the centre. To the right of Maastricht is Aachen (D), appearing as a light-toned patch with the fringes of the Ardennes below it in a lighter grey. Eindhoven (NL) is visible at the left-hand edge of the picture.

Whilst a single image like this will yield detailed information about, for example, forested areas

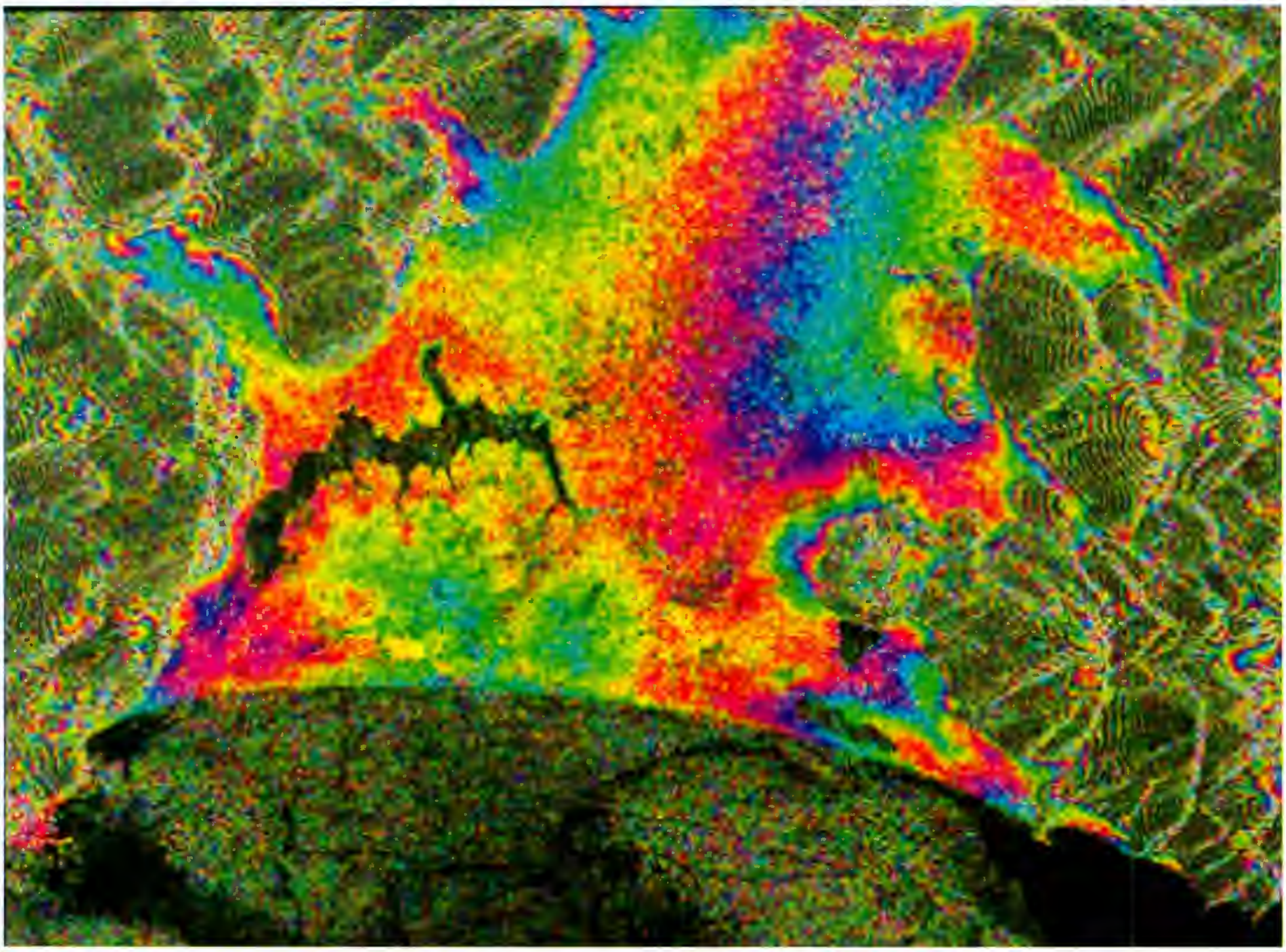

Figure 6

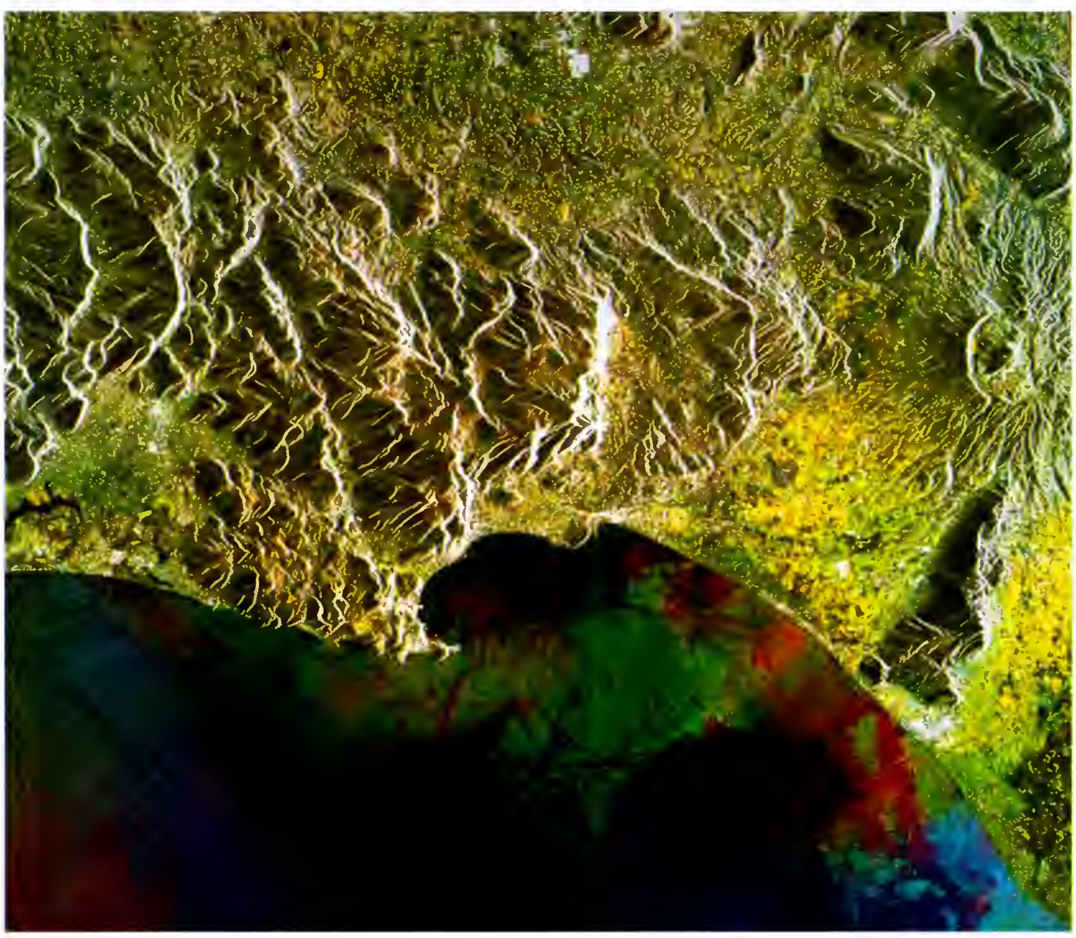

Figure 7

or other types of ground use, a great deal of examination and comparison with observations made on the ground is needed. By superimposing several images, however, particular features become apparent much more quickly and this opens up other potential applications also.

To demonstrate this, the ERS-2 SAR image of 7 May 1995 has been combined with an ERS-1 image that was recorded the previous day (Fig. 9). The resulting interferogram (Fig. 10) shows the typical striped patterns created by such superpositioning. These patterns contain information about the differences in distance of the individual pixels at the various positions from which the two satellites recorded the images (the distance between the two recording positions – the baseline for the digital triangulation – for this image-pair was approximately 220 m) and are like the contour lines on a topographical map. The difference between the chain of hills in the Ardennes to the bottom right and the very much flatter terrain elsewhere in the picture is immediately apparent.

Figure 11 shows – just like a multi-temporal image – where the phases differ and where they match (providing a measure of the differences in distance at the recording positions at a given moment) for the two satellite overpasses. Light-grey tones show a high degree of coincidence (i.e. little change), while dark areas point to 'changes' of all kinds. So, for example, the wooded areas now appear more distinctly than they did in the single images – as dark areas in which volumetric effects (brought about by differing views of the trees due to the slightly offset viewing points of the two satellites) make the phases of the reflected signals differ from one another. More detailed analysis is needed for the three light zones to the left of centre, which show up very differently in the individual images.

Figure 12 offers a quasi-three-dimensional view (looking from the northwest) of the lower right-hand part of Figures 8 and 9. The data on which this is based are firstly the raw version of a digital height model produced from the tandem interferogram (Fig. 10), and secondly the intensity values from the ERS-2 overpass, which give this height model the appearance of a landscape. The greatly exaggerated relief shows the fringes of the Ardennes together with the chain of hills in front of them leading to the Meuse valley visible on the right of the picture This demonstrates how, during the ERS-1/ERS-2 tandem mission, the sets of data from the two satellites can be combined to provide digital height models.

Figure 8
ERS-2/ERS-1 SAR images processed by CNES © Copyright ESA/CNES 1995

Figure 9
ERS-2/ERS-1 SAR images processed by CNES © Copyright ESA/CNES 1995

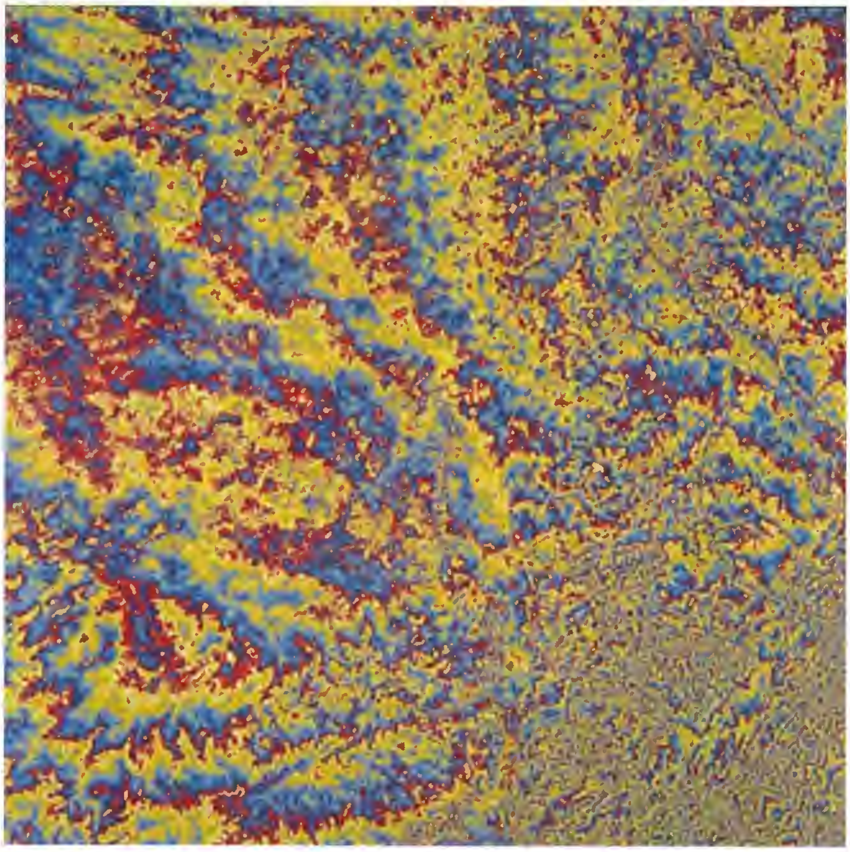

Figure 10 ERS-2/ERS-1 INSAR images processed by CNES ©Copyright ESA/CNES 1995

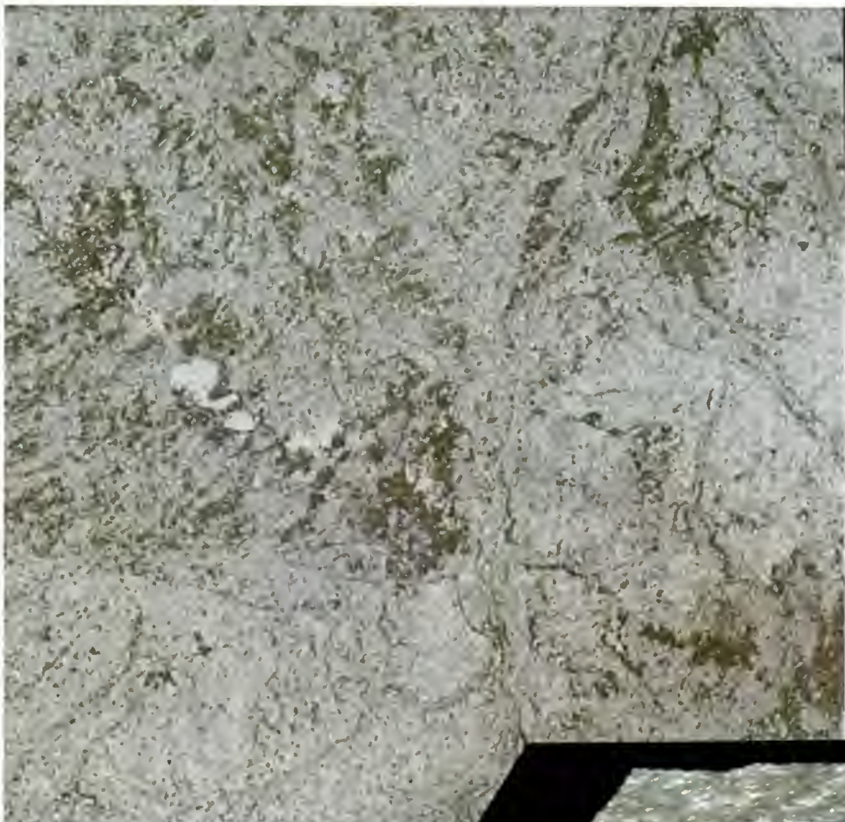

Figure 11
ERS-2/ERS-1 INSAR images processed by CNES
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Conclusion

The tandem operation of ERS-1 and ERS-2 is providing a unique opportunity to achieve significant advances in both the earth-sciences and applications domains for the next decade. In particular, the use of SAR interferometry techniques should allow the generation of consistent and homogeneous medium-resolution Digital Elevation Models over large portions of the Earth's land and ice masses. Used in a differential interferometry mode, the SAR tandem data sets will also offer a unique opportunity to detect and measure very small – of the order of a few centimetres – topographic changes such as those caused by earthquakes, landslides, volcanic activities and glacier motions.

It is ESA's intention to encourage both the scientific and application user communities to take maximum advantage of this unique tandem data set, thereby opening new perspectives for both scientific research and operational applications in the earth-observation sphere.

Acknowledgements

The authors wish to thank those experts who have generated these early tandem results and contributed to their analysis and interpretation, namely: G. Solaas, G. Pacheco (ESRIN) and F. Rocca (Politecnico di Milano) for Figure 6, R. Biasutti (Eurimage) for Figure 7, H.Laur (ESRIN), and D. Massonnet (CNES) and F. Perlant (ISTAR) for Figures 10 to 12.

Figure 12
Map-corrected digital height model from ISTAR based on an INSAR image produced by CNES
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Evolution of the ERS-2 Data Processing Ground Segment

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In its four years of operation, the ERS-1 ground segment has delivered almost 26 000 SAR scenes and a few million low-bit-rate fast-delivery products that have allowed hundreds of scientific investigations, and pilot and demonstration projects as well as many commercial and operational applications to be carried out.

Given that the ERS-1 and ERS-2 satellites will now be operated in tandem until at least mid-1996, the same ground segment must be able to manage a much greater workload. It must perform the exploitation of the ERS-2 payload data, including the data from new instruments such as GOME, PRARE and the ATSR visible channels, in parallel to the handling of newly acquired ERS-1 data and the retrieval of ERS-1 archived data. Most of the facilities have been modified to cope with the higher requirement for data and services and, where applicable, for the handling of data from the new sensors.

ESRIN, via its ERS Exploitation Division, is responsible for the exploitation of the ERS Payload Data Ground Segment and for user services.

The Payload Data Ground Segment

The ERS Payload Data Ground Segment is composed of the following facilities:

- the ESRIN ERS Central Facility (EECF)
- the ESA Ground Stations network
- the ESA Processing and Archiving Facilities (PAFs)
- the National and Foreign Stations (NFS).

Figure 1 shows the interfaces between the facilities and their relationship to the user community.

The ESRIN ERS Central Facility (EECF)

The EECF, located in Frascati, Italy, includes User Services, the Product Control Service (PCS), and the Payload Reference System. It provides:

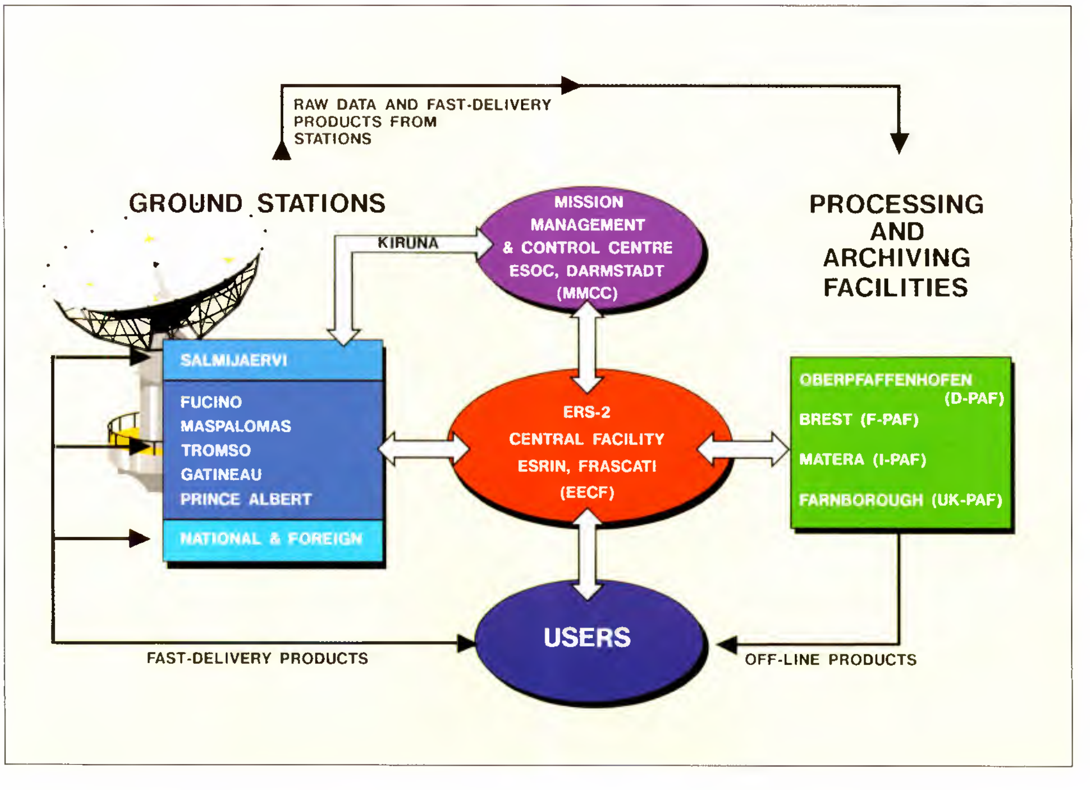


Figure 1. The ERS ground segment

— the user interface (the help and order desks)
— definition of tasks for the whole ERS ground segment
— mission planning in conjunction with the Mission Management and Control Centre (MMCC) at ESOC
— management of a facilities network for the acquisition, archiving, processing and distribution of fast-delivery and off-line products
— quality checks of fast-delivery and off-line products
— routine monitoring of sensors
— coordination of the network of national and foreign stations
— the interface to the industrial consortium charged with the promotion and distribution of data to commercial users
— maintenance of data-processing software for the entire ESA network.

The User Services unit is responsible for planning the ERS-1 and ERS-2 missions in line with the user requests and for scheduling the worldwide data acquisition accordingly. In addition, it supports the end users, maintains the centralised catalogue of acquisitions and products, and handles user requests and product orders.

The Product Control Service's operational tasks include the monitoring and control of ERS data-product quality and assessment of the compliance of system performance with the system specifications. Another of its main roles is to assess instrument behaviour and the related margins. This information provides vital feedback that will be used in the development of future programmes, including the analysis and development of algorithms for calibration and validation activities. The Product Control Service uses a range of systems, including the so-called 'Reference System' for the High- and Low-Rate Fast-Delivery Processing chains, which also supports the maintenance of the operational software installed at the ESA ground stations. For ERS-2, the Reference System has been upgraded with a dedicated GOME QA and performance monitoring system and with a tool for the continuous long-term monitoring of the newly added low-bit-rate (LBR) transcription system at the stations.

The Salmijaervi Station, in northern Sweden

The EECF also provides support for the monitoring of the progress of the pilot and demonstration projects, for the training programmes given in developing countries on the application and exploitation of ERS data, and for promotional activities in conjunction with the industrial consortium for the ERS commercial applications development, including the preparation of materials for symposia and conferences and for public-relations purposes.

The ESA ground station network

The ESA ground station network has been set up to allow the maximum coverage over the European area for the Synthetic Aperture Radar (SAR) and the global LBR payload data acquisitions.

The ERS-2 payload data network is the same as the one used for ERS-1. It is managed by ESRIN and includes six ground stations, located at Salmijaervi (Kiruna, Sweden), Fucino (Italy), Maspalomas (Canary Islands, Spain), Tromso (Norway), and Gatineau and Prince Albert (Canada).

The ground stations' systems have been upgraded to allow them to handle ERS-2. In particular, the LBR processing chain installed at the stations has been re-hosted on a Silicon Graphics platform, replacing the old chain which was based on a minicomputer plus array processor. The new chain has a much higher CPU power and growth capability and generates the specified products for all sensors, including the new ERS-2 sensors GOME and ATSR-2, within the same time constraints as the old chain (100 minutes per orbit). The new chain also has the advantage that the LBR data are transcribed in near-real time at the stations on Exabyte cassettes for shipment to the relevant archiving facilities, while for ERS-1, the transcription was performed on a dedicated off-line facility installed at Fucino station. This will drastically improve the reliability and delivery time for raw data to PAFs, thus hastening the release of LBR off-line products to end users. Also the SAR processor, the Station Control and Monitoring System, and the Broadband Data Dissemination Network (BDDN) have been upgraded to ERS-2 mission functional requirements.

Except for Salmijaervi, which is operated by ESOC and is fully dedicated to ERS operations including telemetry, tracking and control (TT&C) activities, all of the other stations are multi-mission in nature. Under contract to ESRIN, they perform the ERS-1 and ERS-2 payload data acquisition, processing and dissemination, as well as hosting the ESA equipment for the requisite data exploitation. They also provide similar services for other international Earth-observation satellites, such as Landsat (USA), Spot (France), JERS-1 (Japan), and Tiros (USA).

The division of tasks and responsibilities between these stations takes into account the constraints related to the high- and low-rate payload data characteristics (Table 1). This network ensures global LBR data acquisition (mainly from the on-board recorder dumping) on a daily basis. A station's typical daily activities can be summarised as follows:

— satellite tracking and scheduled data acquisition
— recording of the data on high-density magnetic tapes
— processing of the fast-delivery (FD) products to be made available within three hours of data sensing, to nationally nominated centres
— processing of scheduled products for distribution to users
— reporting on the activities to the EECF
— transmission to the Product Control Service at ESRIN of relevant parameters and products for routine sensor performance monitoring.

The Processing and Archiving Facilities (PAFs)
The PAFs will continue to be the core of the product distribution system for ERS-2. Their role can be summarised as:

— long-term ERS-1 and ERS-2 payload data archiving and retrieval
— generation and distribution, on request, of the off-line geophysical standard products to users as instructed by the EECF via product orders
— support to ESA for sensor data calibration, data validation and long-term sensor performance evaluation.

Each PAF receives the relevant ERS-2 payload telemetry data on a regular basis from the ground stations and ensures the long-term archiving, the routine production and the distribution of the data. Their activities are managed and monitored from ESRIN.

The Gatineau Station, in Canada

There are four PAFs, managed under contract to ESA.

F-PAF in Brest, France
It is operated by IFREMER, the French institute for research into the exploitation of the sea, and its tasks are:

— archiving all the LBR data (Wave, Scatterometer, Radar Altimeter and Wind) acquired over oceans, and generating the associated products
— backup archiving of the ATSR-1 and ATSR-2 (Along-Track Scanning Radiometer) global data set, and generation and

Table 1. Responsibilities of the ESA ground stations with respect to data acquisition and processing

Ground station	Type of data for which responsible
Salmijaervi	Global low-bit-rate (real-time and on-board tape-recorder data dumping) Regional SAR over Northern Europe and the North Pole
Fucino	Regional SAR and LBR over the Mediterranean area, North Africa and Central/Southern Europe
Maspalomas	Global LBR Regional SAR over Northwest Africa and the Eastern Atlantic
Tromso	ATSR data real-time processing and operational backup for Kiruna acquisitions
Gatineau	Global LBR
Prince Albert	Global LBR

distribution of ATSR Microwave Sounder data
— storage of relevant ESA-provided campaign data.

The F-PAF has carried out a major modernisation of its facilities for ERS-2 by re-hosting the Altimeter Ocean Product (OPR) processing chain and associated management subsystem on a new hardware configuration.

The UK PAF Computer Room in Farnborough

Table 2. Status of national and foreign ground stations acquiring or planned to acquire the ERS SAR data

Ground station		Status
Tromso	Norway	Ready
Westfreugh	UK	Ready
Gatineau	Canada	Ready
Prince Albert	Canada	Ready
O'Higgins	Antarctica, Germany	Campaign only
Libreville	Gabon, Germany	Campaign only
Neustrelitz	Germany	1995
Aussaguel	France	Campaign only
Cotopaxi	Ecuador	Ready
Hiderabad	India	Ready
Alice Springs	Australia	Ready
Hobart	Australia	Ready, only acquisitions
Hatoyama	Japan	Ready
Kumamoto	Japan	Ready
Syowa	Antarctica, Japan	Ready
Fairbanks	USA	Ready
Cuiaba	Brazil	Ready
Pretoria	South Africa	Ready
Taipeh	Taiwan	Ready
Pare Pare	Indonesia	Ready
Norman	USA	1995
Beijing	China	Ready
Tel Aviv	Israel	Ready, no MOU
Riyadh	Saudi Arabia	Ready, no MOU
Nairobi	Kenya, Teleos	1995, no MOU
Singapore	Singapore	1995, no MOU
McMurdo	Antarctica, USA	Ready, no MOU
Bangkok	Thailand	Ready, no MOU

UK-PAF in Farnborough, UK
It is operated by the National Remote Sensing Centre (NRSC) and its tasks are:

— primary archiving of SAR and global ATSR data and Altimeter data over ice and land
— secondary archiving of LBR data
— processing and distribution of SAR, ATSR and Altimeter data over ice and land.

The UK-PAF has also made a great effort to update its facilities to accommodate ERS-2 by adopting new configurations to increase the throughput of their LBR chains and by procuring new archiving and processing chains for SAR data.

D-PAF in Oberpfaffenhofen, Germany
It is operated by DLR, and its tasks are:

— archiving and processing of the SAR data acquired at the O'Higgins Antarctica station as well as of selected data sets acquired at other ESA and foreign stations
— primary processing centre for SAR precision and geocoded images
— generation of high-level Altimeter products and precision orbit calculations
— primary archiving and processing centre for ERS-2 GOME products
— primary archiving and processing centre for ERS-2 PRARE products.

In preparation for ERS-2, the D-PAF has developed the chains for GOME and PRARE products, procured new chains for the generation of SAR products and modernised its data management subsystem.

I-PAF in Matera, Italy
It is operated by the Italian Space Agency and is charged with:

— archiving, processing and distribution of regional SAR data acquired by the Fucino and Maspalomas stations
— archiving, processing and distribution of LBR products covering the Mediterranean area.

The I-PAF has upgraded its system for ERS-2 and is developing GOME-derived products.

The national and foreign stations
In addition to the ESA ground station network, a number of national ground stations, i.e. belonging to countries participating in the ERS Programme, and foreign ground stations, i.e. belonging to non-participating countries, have

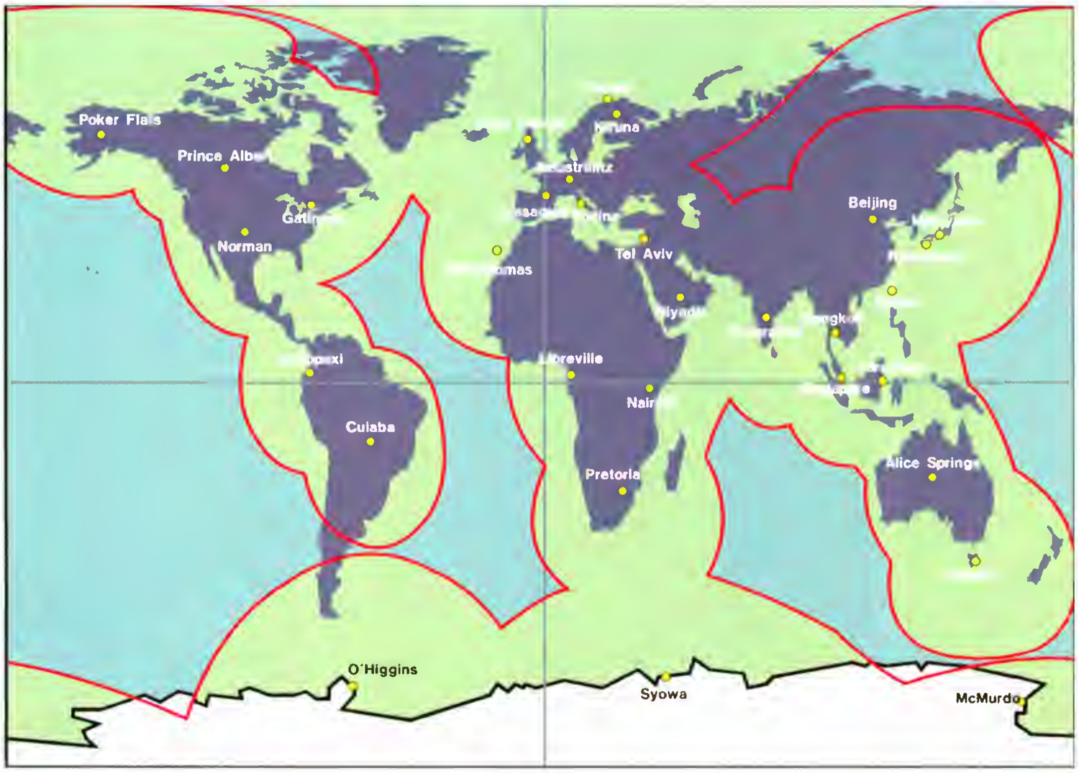


Figure 2. Total planned coverage by the ERS ground stations

been set up around the world, or are planned, in order to acquire ERS-1 and ERS-2 SAR payload data.

The current situation is summarised in Table 2. Most of the stations have been used for ERS-1 and will be used again for ERS-2 under the terms and conditions of a standard Memorandum of Understanding (MOU) with ESA.

The ground stations receive, from the EECF in Frascati, the input data needed to acquire, process and distribute the SAR data and they report back to the EECF on their station activities and status. The stations generate and distribute products developed nationally to ESA principal investigators, pilot projects and commercial users. In particular, low-resolution, near-real-time products are distributed as a service from the Tromso and Gatineau stations. Together with the ESA stations, the stations listed in Table 2 will provide the worldwide data coverage shown in Figure 2. Agreements are in place with the stations for the provision to ESA of copies of some of the raw data acquired so that ESA can, when required, serve its users directly. ESA PAFs have in this way acquired and archived valuable worldwide SAR data sets.

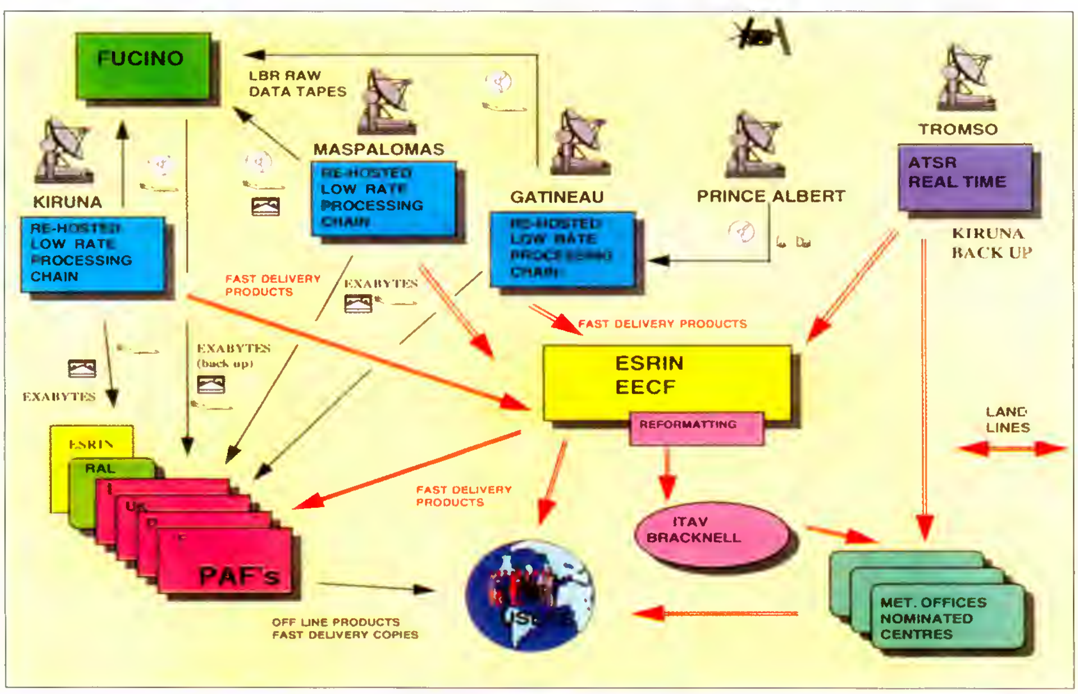


Figure 3. The flow of global low-rate data. For fast-delivery products, the ESA ground stations acquire and process the ERS data and send it to the EECF. After conversion, the data is then sent to the UK or Italian meteorological office, which in turn distributes it to met. offices around the world. For off-line products, the ground stations send the data on cassettes to the PAFs for archiving and generation of the off-line products.

Data flow and product generation

ERS-2 LBR and SAR products are distributed to users either on a routine basis or upon specific request. The full list of currently available products is shown in Table 3.

The flow of the ERS-2 LBR data is summarised in Figure 3. The LBR data obtained from the Wind Scatterometer, the Radar Altimeter, and the Active Microwave Instrument (in Wave mode) are processed immediately after reception to so-called Fast Delivery level (UWI, URA, UWA) at the ESA stations. They are then collected at the ERS Central Facility and, after being converted in an upgraded BUFR formatter delivered by the UK Meteorological

Table 3. ERS-1 and ERS-2 products currently available

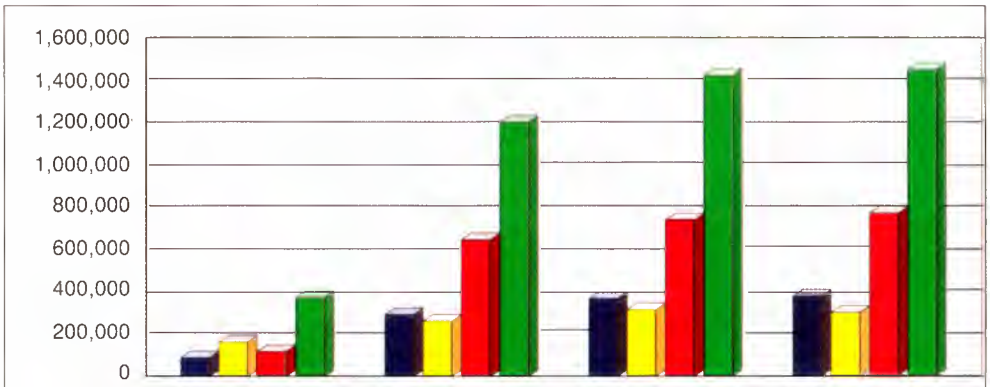
Data Type	Code	Production Facility
SAR		
Annotated Raw Data	SAR.RAW	D-PAF, UK-PAF, I-PAF
Fast-Delivery Image	SAR.UI16	Fucino, Kiruna, ESRIN
Fast Delivery Copy	SAR.FDC	D-PAF (ERS-1 only)
Single-Look Complex	SAR.SLC	D-PAF, UK-PAF, I-PAF
Single-Look Complex Full Scene	SAR.SLCF	UK-PAF
Precision Image	SAR.PRI	D-PAF, UK-PAF, I-PAF
Ellipsoid Geocoded Image	SAR.GEC	D-PAF, I-PAF, UK-PAF
Terrain Geocoded Image	SAR.GTC	D-PAF, I-PAF[1]
SAR Wave Mode		
Fast Delivery Product	SWM.UWA	Gatineau, Maspalomas, Kiruna
Fast Delivery Copy	SWM.FDC	F-PAF
Wind Scatterometer		
Fast Delivery Product	WSC.UWI	Gatineau, Maspalomas, Kiruna
Fast Delivery Copy	WSC.FDC	F-PAF
Altimeter		
Fast Delivery Product	ALT.URA	Gatineau, Maspalomas, Kiruna
Fast Delivery Copy	ALT.FDC	F-PAF
Ocean Product	ALT.OPR02	F-PAF
Quick-Look Ocean Product	ALT.QLOPR	D-PAF
Waveform Product	ALT.WAP	UK-PAF
Sea Surface Height Model	ALT.SSH	D-PAF
Oceanic Geoid	ALT.OGE	D-PAF
Sea Surface Topography	ALT.TOP	D-PAF
Microwave Sounder		
Water Vapour/Liquid Water content	MWS.VLC	F-PAF
ATSR		
Infrared Brightness Temperatures	ATS.IBT	UK-PAF
Sea Surface Temperatures	ATS.SST	UK-PAF
Precision Sea Surface Temperatures	ATS.PST	UK.PAF
Orbit		
Preliminary Orbit	ORB.PRL	D-PAF[2]
Precise Orbit	ORB.PRC	D-PAF[2]
ERS Gravity Model	ORB.EGM	D-PAF
GOME (ERS-2 only)		
3-Day engineering data	LVL13	D-PAF
Total Ozone Content	TCD03	D-PAF

The I-PAF also generates special Wind and Altimeter products over the Mediterranean Sea.

[1] GTC products need Digital Terrain Models (DTM) in input. The D- and I-PAF hold DTMs for limited areas. However D-PAF also accepts user-supplied DTMs.

[2] The Preliminary and Precise Orbits of ERS-2 are derived from PRARE and Laser tracking data, while for ERS-1, only the Laser Data are available.

Office, are injected into the Global Telecommunication System (GTS) of the World Meteorological Organisation (WMO). They are also disseminated to selected facilities and users (including the PAFs, from which they can be obtained as off-line copies). Figure 4 shows the LBR fast-delivery products distributed during the first four years of ERS-1's lifetime.



	1991	1992	1993	1994
UWI	90,356	293,241	367,139	377,832
URA	163,808	259,974	314,058	300,306
UWA	118,369	644,730	736,592	768,428
TOTAL	372,533	1,197,945	1,417,789	1,446,566

Figure 4. Distribution of ERS-1 low-bit-rate (LBR) fast-delivery products over ERS-1's four years of operation: UWI or Wind, URA or Radar Altimeter, and UWA or Wave user products.

For the ATSR data, real-time processing is performed at Tromso (10 orbits per day) for the generation of the Sea Surface Temperature Measurement, and the data is sent thereafter to ESRIN for conversion and distribution to the meteorological offices, or for temporary storage on-line for user access.

The LBR data sets (Radar Altimeter, ATSR and GOME) copied on Exabyte cassettes at the acquisition stations are sent to the PAFs for archiving and for the off-line generation of precision products. ATSR data are also sent to instrument providers, Rutherford Appleton Laboratory (UK) and Centre d'études des Environements Terrestres et Planetaires (F), for their internal investigations and support to ESA production activities.

The flow of ERS-2 SAR data is summarised in Figure 5. It is similar to the flow of ERS-1 SAR data. The SAR data are received at the ESA ground stations, processed to Fast-Delivery level, and disseminated via the Broadband Data Dissemination Network (BDDN, under ESRIN control), which allows the transmission of SAR Fast-Delivery images from Kiruna or Fucino nominally within 24 h of data sensing to nominated centres (one per country in Europe), using a Eutelsat satellite link for image transmission. The nominated centres then distribute the data to the end users. The raw data are sent to the PAFs for the off-line generation of ESA standard products (Raw, PRI, SLC, Geocoded).

Figure 6 shows the number of each ESA product type delivered to the users by the ESA processing facilities.

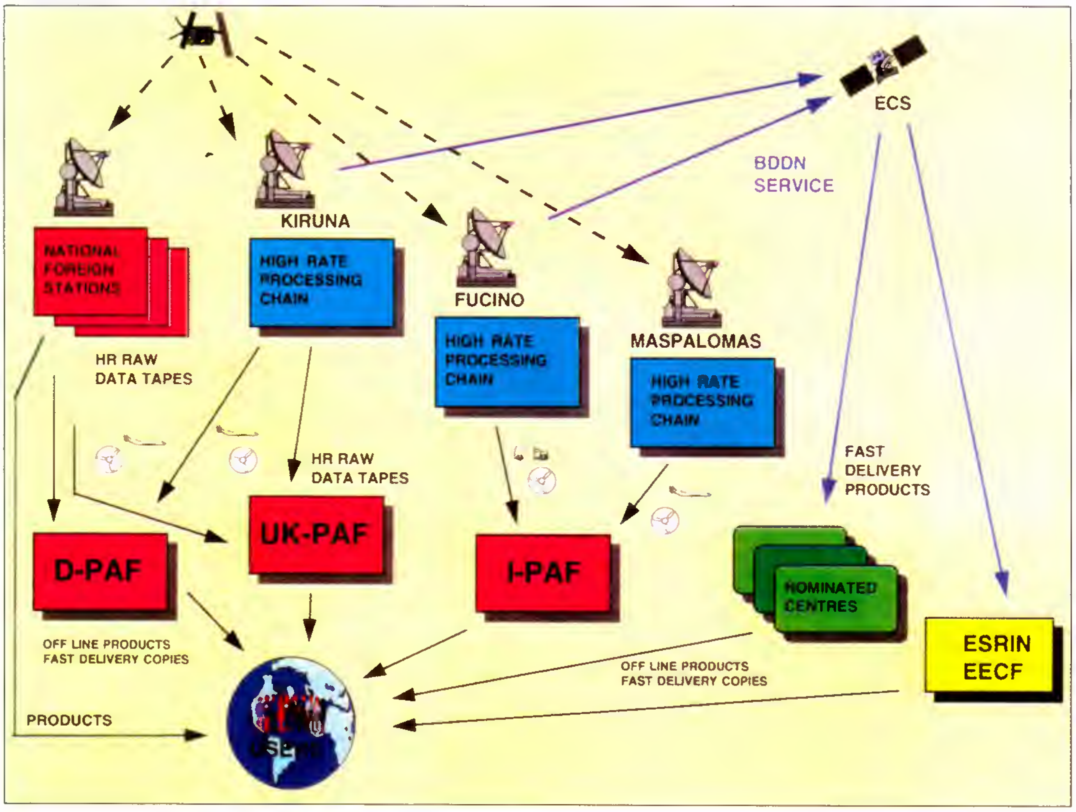


Figure 5. The flow of global high-rate data. To allow the data to reach the users quickly, the SAR images acquired at Kiruna and Fucino are transmitted directly to nominated centres via a Eutelsat satellite link. The centres then distribute the data to the users. In addition, the ground stations send the raw data to the PAFs for the off-line generation of standard products.

	RAW	SLC	FDC	PRI	RTM	GEC	GTC	TOTAL
REQUIRED	958	4312	1339	17878	82	1152	761	26482
DELIVERED	943	4256	1315	17458	82	1128	759	25941
%	98	99	98	98	100	98	100	98

(AS OF END OF MAY '95)

Figure 6. Distribution of Synthetic Aperture Radar (SAR) products by type

ERS User Services

The ERS User Services section provides support to the ERS-1 and ERS-2 user community through:

— *User interface functions,* performed via the ERS Help Desk (for queries, documentation, tools, CD-ROMs, etc.) and the ERS Order Desk (for data requests from principal investigators, pilot project leaders, ground station operators, etc.). The requests from commercial and research users are dealt with by the Customer Service section of ERSC, a consortium formed by Eurimage, Radarsat International and Spot Image.

— *On-line services,* like provision of up-to-date information and data samples via Internet; distribution of user tools, updated instrument plans, data and images through the on-line server; and on-line access to a centralised catalogue with the ability to order on-line the necessary products.

— *Internal functions,* including preparation of user documentation, information, data, tools and CD-ROMs; mission planning, ground station scheduling, production planning; centralised catalogue management, data dissemination control (via satellite or land links); telecommunication network monitoring; and systems and database management.

Figure 7 shows the ERS User Services organisation.

Upgraded User Services applications

The applications were upgraded in 1994 to support the parallel ERS-1 and ERS-2 missions. The software was revised thoroughly in order to make it fully 'multi-mission' and to improve performance and availability. The changes made are:

— The Central User Service application was re-hosted in a redundant configuration

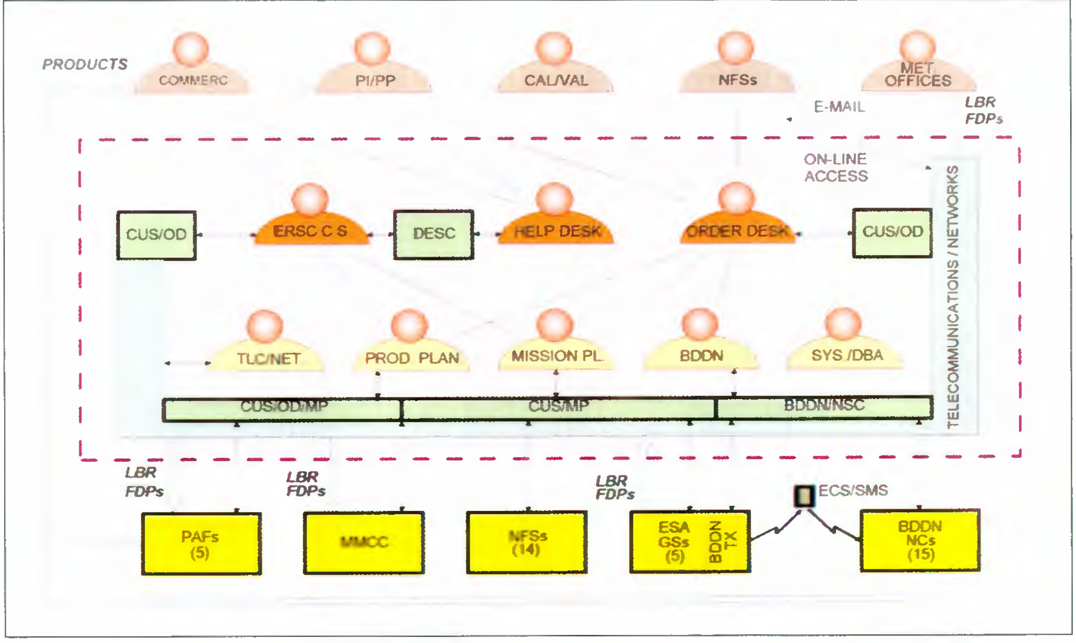


Figure 7. ERS-1 User Services. The various user categories are at the top, the ESRIN ERS Central Facility (EECF) is in the middle area, and the external facilities are at the bottom. The external facilities are controlled and operated via the telecommunications infrastructure.

made up of faster Alpha machines, with one separate machine dedicated to maintenance activities.

— The Interface Subset (which manages the telecommunications) was split: user access was separated from the operational traffic. It was implemented with a multi-machine approach, i.e. a copy of the software can run on more than one machine to share the traffic load, and was loaded into a powerful cluster with a redundant configuration. A separate machine was dedicated to maintenance activities.

— The Network Supervision Centre (which monitors and controls the BDDN) was upgraded by improving automatic mechanisms and the operator's interface.

All upgrades entered into full operation well before the ERS-2 launch. All the concerned systems are now multi-mission systems and, thanks to the hardware and software enhancements, are able to cope with the activities and load caused by the contemporaneous management of the two satellites and of related ground segment activities without an increase in personnel.

Handling of user requests

The user requirements, particularly for SAR, are expressed as user requests, which define the required product and medium types together with the geographical area and window of time of interest. Most of the LBR products, on the other hand, are distributed on an orbit basis in monthly or yearly sets of data.

Figure 8 shows the processing flow for user requests for SAR products. The requests may involve data that has already been acquired and archived; those requests are converted

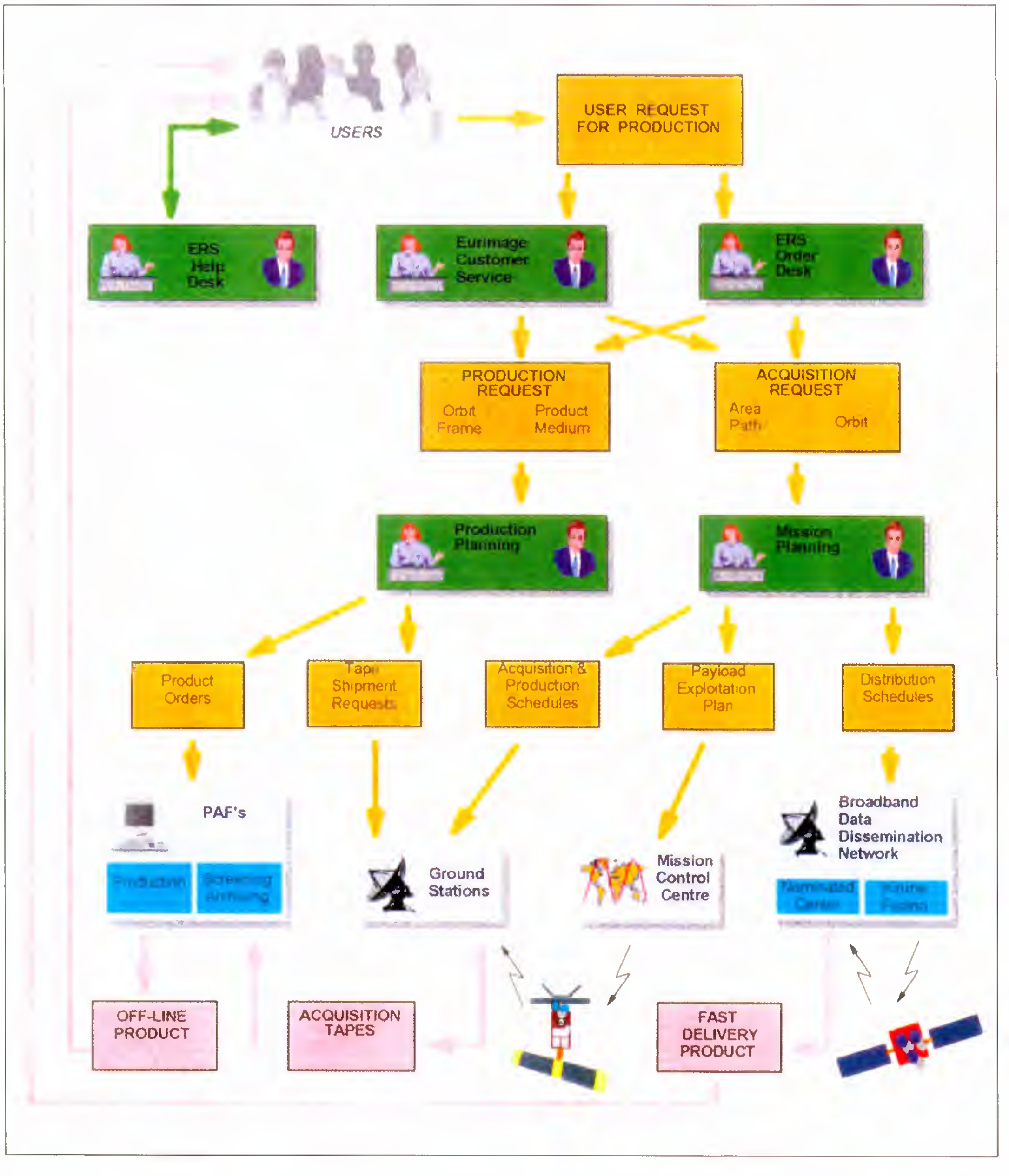


Figure 8. The processing flow for user requests for SAR products

into production orders for the PAFs, where the required products are generated and dispatched to the end user. If the request concerns data yet to be acquired, the relevant acquisition is planned taking into account possible conflicts, alternatives, or anticipated needs and then confirmed in cooperation with the Mission Management and Control Centre (MMCC) at ESOC. Upon confirmation of data reception from the relevant ground station, the product order is placed and the products are delivered to the end user either via the BDDN (for fast-delivery products) or by the relevant processing facility.

As part of the mission planning, performed at ESRIN, the specific user requests are integrated with a 'baseline' mission plan, which covers the repeated coverage for multi-temporal analysis. It permits also the optimal use of satellite resources, by limiting the number of SAR on/off switchings per orbit and exploiting the SAR on average for 9 min per orbit, with a maximum of 12 min per orbit. All areas covered by ground stations have already been acquired. The addition of new stations now permits coverage of most of the Earth's land surface.

The contemporaneous availability of ERS-1 and ERS-2 provides a unique opportunity for 'tandem' operations. Planning SAR acquisitions for the two satellites over the same area, which the two satellites visit within a short time interval, permits new applications like interferometry.

Worldwide catalogue of data and products

The EECF also maintains a catalogue of the SAR data acquired worldwide and of the products archived at the PAFs. The catalogue is updated regularly, whenever the new acquisition reports are generated at the acquisition stations and the data is entered in the database. Users can query on-line the SAR catalogue or the Global Activity Plan (GAP), which contains up-to-date information on the planned operations of the different payload instruments.

Users can also browse through a simplified version of the SAR catalogue on their PC using

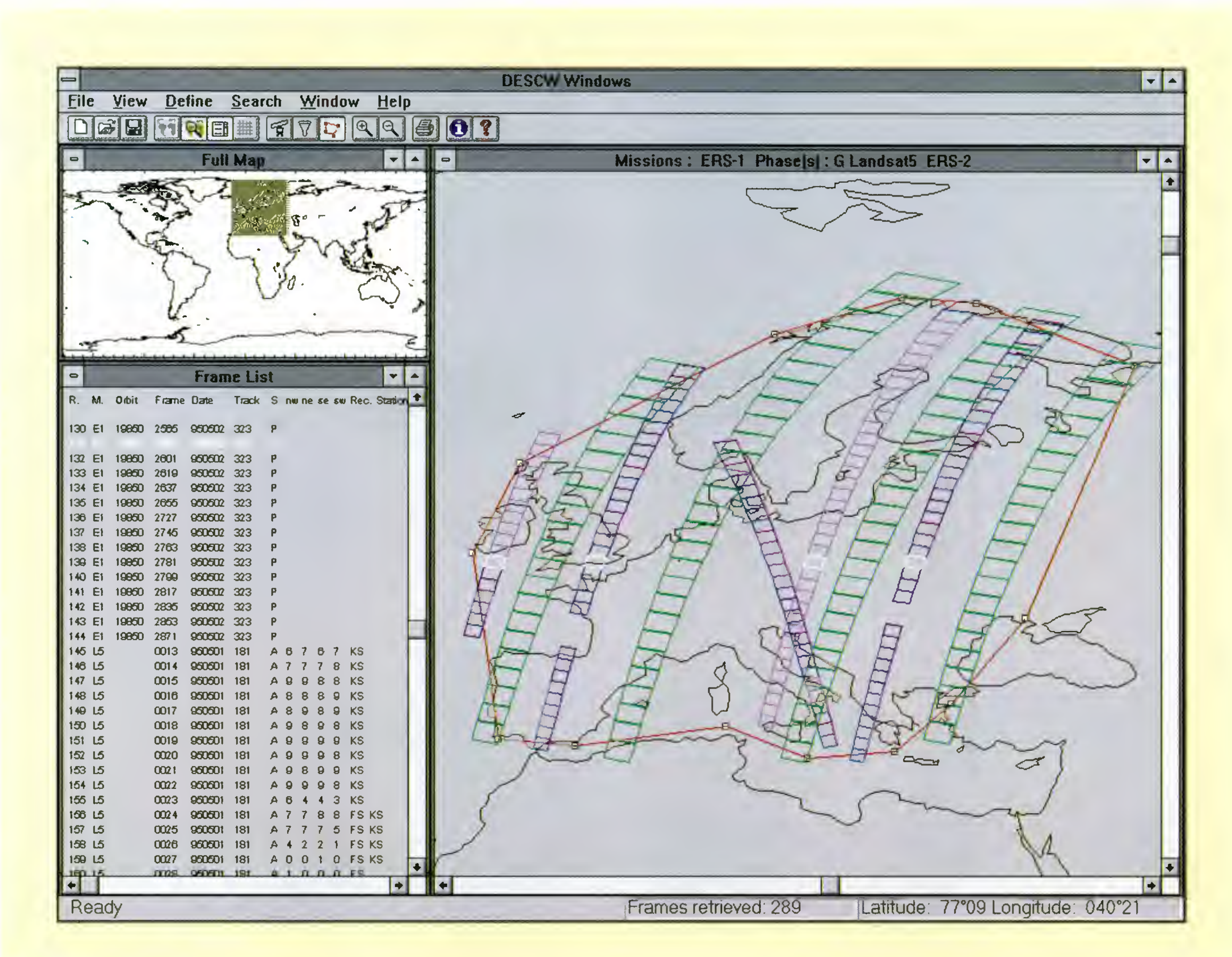


Figure 9. A sample of the new DESCW screen, with the three main windows active: the Full Map, which shows the location of the area being 'zoomed'; the zoom window, which shows in greater detail the user's selected area and the swaths of the selected missions; and the Frame List, which lists all selected frames and related parameters

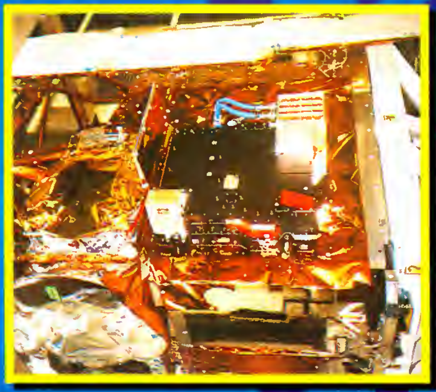
the 'Display ERS-1 SAR Coverage' (DESC) software package. That tool supports the users in defining their requirements for products and services.

With the start of ERS-2 operations, DESC was upgraded to DESCW, Display ERS Swath Coverage for Windows (Fig. 9). It is a multi-mission PC tool, covering at present the ERS-1, ERS-2 and Landsat missions, and running under MS-Windows. It provides a number of enhancements with respect to DESC, such as graphic definition of an area, search by such an area, additional mission specific filters, and on-line help. Its catalogue/inventory files are updated weekly and put at the disposal of users on the ERS on-line server. Copies of the tool were distributed after the ERS-2 launch to a large number of users and are available upon request from the ERS Help Desk.

Other services
The ERS on-line server, accessible via Internet, Span or X.25, permits the down-loading of the GAP, the weekly updates of the DESC and DESCW catalogue files, the ERS-1 SAR Low Resolution Images generated daily at Kiruna, and the Quick Look OPR products generated daily by the German PAF.

Printed material to support user activities and training, such as the ERS User Handbook, the ERS System Description, the ERS Products Specification document, and the CD Guide to ERS-1, is also available (see the order form where?? for the full list of documentation and tools available).

A new service, based on GDS/WWW (see 'ERS-2 Information Now Available on Internet' in this issue), began operation last year. It has improved over time and has been extensively used during the launch and early com-missioning of ERS-2: it permits Mosaic or Netscape clients to access via Internet a set of daily-updated information, data and sample products. This includes information on ERS-2 deployment, initial operations and commis-sioning activities, as well as first images and results. This service also includes up-to-date data and information related to ERS-1.



ERS-2 Information Now Available on Internet

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Real-time provision of news and documentation relating to ERS-2 via Internet — that is a new service that ESRIN, ESA's centre in Italy, is now offering. The special ERS-2 service gives new momentum to the utilisation of the World Wide Web and file-transfer utilities that have been maintained by ESRIN for over a year now to provide attractive, online information retrieval and publishing services to the Earth-observation community around the world.

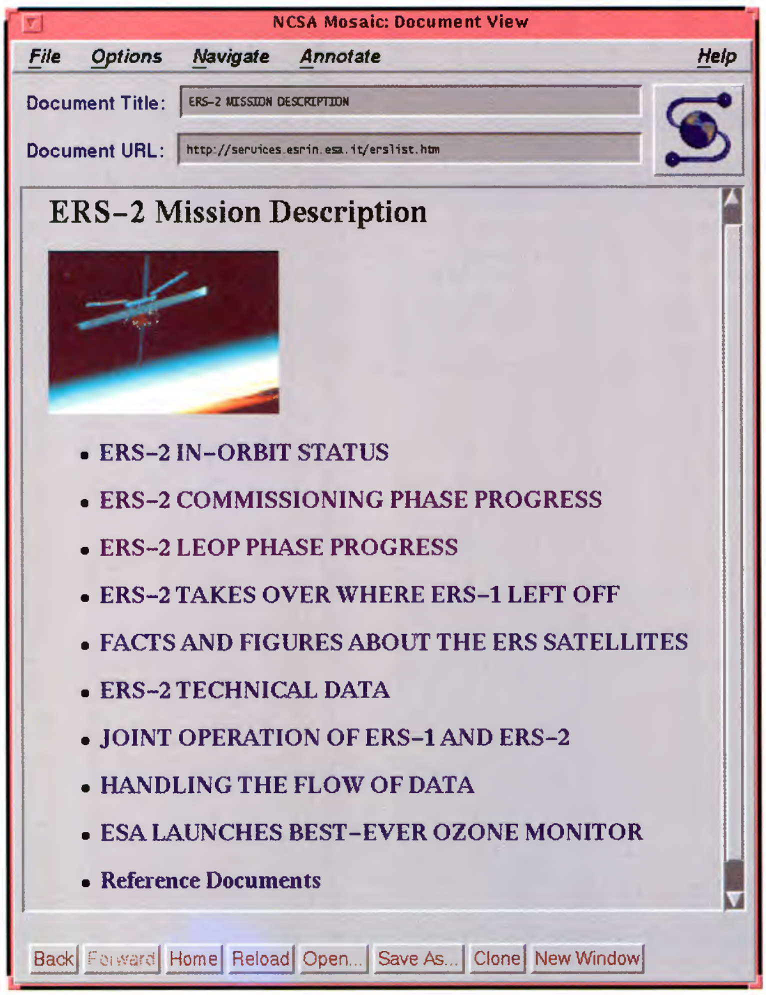

Figure 1. Example of topics relating to ERS-2 that are provided online, on Internet (under the address 'http://services.esrin.esa.it')

ERS-2: a satellite's online biography

Keeping the world informed about a satellite's life from the time of its birth may seem like an odd endeavour. As soon as people realise, however, that the satellite ERS-2 can provide unique and vital data in many areas like ocean navigation, ice or crop monitoring, and oil or gold exploration, interest grows: it becomes of utmost importance to know whether the satellite system is completely functional and whether the mission is proceeding as planned. That information is now offered on the Internet as a 'Special ERS-2 Service' and can be accessed under the World Wide Web (Fig. 1).

The special ERS-2 service has allowed those interested to first learn about many aspects of the satellite and its launch, and then to keep up-to-date as it progresses through its commissioning phase. Even before the ERS-2 launch, the special ERS-2 service provided online the full text and graphics of the most recent publications, with special emphasis on the commissioning phase and the tandem operation of the satellite with ERS-1. Immediately after launch, news on the first orbital manoeuvres was added. The very first sensor switch-on reports, describing which sets of sensors were already functioning, also appeared online.

The instrument's coverage of the Earth was shown in graphical illustration as it occurred — in the morning, only a thread ran over the map of the Earth and by the evening, long strokes of paint covered it. Day after day, as the number of completed orbits grew, the map of the Earth disappeared gradually behind lines indicating the completed orbits. In addition, vital parameters for the calibration and validation of the on-board instruments were registered and published (Fig. 2); they remain searchable for the duration of the satellite's life.

After the first exciting months of ERS-2, all will become 'routine', as it has for ERS-1. The online service will allow people to stay current on the satellite, the payload, the ground segment, the research and data applications, and thus will be essential for those using ERS-2 data and ordering ERS-2 products (see boxes).

Many interested users to date

In parallel to the updating of the online information, which takes place sometimes several times a day, ESRIN has been monitoring the usage of the new service. At first, many people connected to glance at what ERS-2 was, stopping at the high-level screens; since then, they have started to open the more detailed screens, with articles for instance on the new ozone sensor, GOME. The rapid provision of information online has also played a promotional role for ERS-2: the first images were readily available online to the press around the world.

More surprising though is the interest in the online service shown by the professionals involved in ERS-2, be they the satellite builders, the sensor builders or those responsible for the

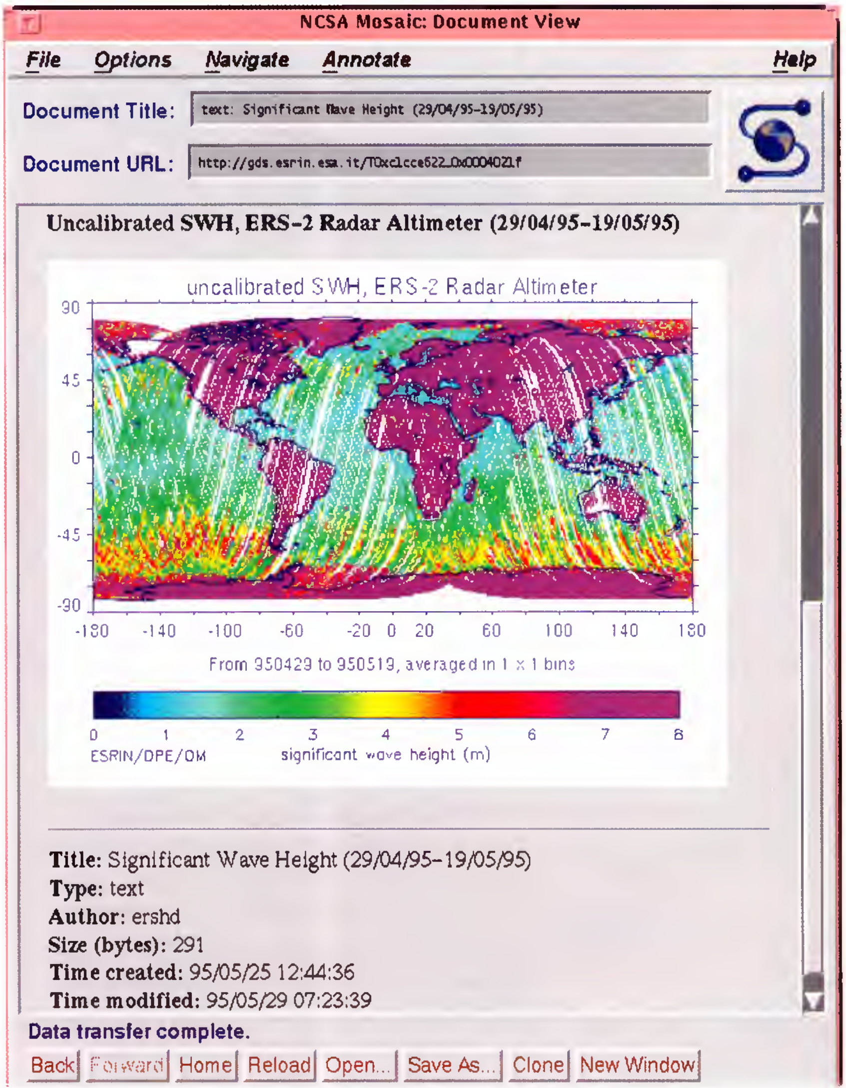

Figure 2. Example of an ERS-2 data display as shown online

To access the special ERS-2 service on the Internet

- via World Wide Web (full range of services):
  - Navigate to Document URL *'http://services.esrin.esa.it'*
- via FTP (ERS File Server):
  - Type '*ftp services.esrin.esa.it*'
  - User name: '*anonymous*'
  - Password: your e-mail address

User support and help:

ERS Helpdesk
ESA/ESRIN
Via Galileo Galilei
I-00044 Frascati
Italy

Phone: (+39) 6 94180 600
Fax: (+39) 6 94180 510
E-mail: helpdesk@ersus.esrinvas.esrin.esa.it

To order ERS-2 products

- Consult the 'Special ERS-2 Service' available on Internet and described in this article, and make your product choice
- Download the 'DESCW' software to display the product coverage and to find detailed order parameters (The software available under *ftp://services.esrin.esa.it/pub/descw* requires a PC Windows environment.)
- Order the required products:
  - Commercial users: The products are ordered via the ERS Consortium (formed by Eurimage, Radarsat International and Spot Image). Contact the ERS Helpdesk for the nearest address.
  - ESA Principal Investigators and Pilot Project leaders: Contact the ERS Helpdesk.
  - A number of Low-Bit-Rate (LBR) products are also directly available online

instrument calibration. The Earth Observation community and in particular scientists who conceived the technology behind the sensors have connected to the service from all over the world. French, British, German and Dutch research centres ranked first among the most frequent users.

Finally, ESA managers have proven to be the greatest aficionados of the online service with special ERS-2 news. They have found a tool that is at their fingertips and allows them to both control the information released and show or discuss the new satellite's performance with others around the world.

Rationale behind the design of the new service

An awareness tool, a communication tool and a reference information base — those are the functions that the new service is offering to the user community.

Finding the right mix between technology, data quality and timeliness, man-machine interface and user friendliness has been necessary to attract the user community's interest in the service.

Data quality has been secured through tight coordination among the ESA scientists themselves, wherever they are located, with the ESA mission operators and with ESA management. The information released has been designed to satisfy both the specialist and the layman.

Great effort has also been expended to ensure user friendliness. On one hand, the cosmetics relative to screen layout and the use of images have been given special care. On the other hand, preceding the technology performance and the aesthetical work, all the information to be included — several hundreds of items — has been given a solid architecture. Each data object has been given its place, and each future piece has already been assigned a location within the huge information tree.

That hidden work has allowed for the creation of an effective network of cross-references. Any information can thus be reached via several paths, all echoing each other without the user feeling lost. The manager can go to the news, the specialist can point to 'his' sensor, the teacher can go to 'his' volcano, the frequent searcher can search by date: in the end, they will all find the same piece of information, the same picture or the same graphic.

Moreover, user reaction to the service will be evaluated at regular intervals and adaptations made accordingly. By carefully monitoring the 'most successful' online items, further possible cross-references among the screens offered can be made thus tightening the hypertext links in a user-driven evolutionary process.

To complete the picture, official reference documents have been placed online in abstracted form or in full text. Those who want to obtain a printed copy of one of the documents can also order it from ESRIN without bothering about downloading times. Lastly, users can leave a message or call the ERS Helpdesk for advice on how to take advantage of all the service features (see the earlier box for information on how to contact the Helpdesk).

Evolving Internet services on Earth observation from ESRIN

The special ERS-2 information is carried by and fully integrated with a number of information services that ESRIN introduced in 1994.

Under the overall heading of 'User Earth Remote Sensing Services', or 'usERServices' for short, ESRIN provides a number of inter-linked multi-mission services to users. Besides the special ERS-2 feature, current headlines include:
— Hot News and Hot Line
— Remote Sensing Images
— Satellite Products and User Services
— Guide and Directory Service.

Figure 3. ESA also hosts information services for a number of institutions involved in Earth observation. They can be accessed directly from the WWW under the addresses shown or via the GDS Home Page.

They are all targeted at satisfying different needs for instantaneous online access to information on the ESA remote-sensing programmes and satellite missions.

The ESA Earth Observation 'Guide and Directory Service' (GDS) represented the start of ESRIN's presence on Internet. For more than a year now, it has been providing the user community with Earth-observation background information (some 40 000 documents) relevant to ESA missions (ERS and Meteosat) and those missions whose data ESA acquires and disseminates (see ESA Bulletin, No. 78, May 1994).

The GDS carries the following information:
- Descriptions of satellites, sensors and ground facilities (for ESA and non-ESA missions)
- Data application information, tutorials, and scientific papers
- Dataset and data-product descriptions at various levels of detail, and data user manuals (for ESA and non-ESA data directories)
- Pointers to internationally-shared information sources on the WWW
- Inventory service log-in information and user manuals.

Under the impetus of events within both ESA and the user community, GDS has taken on additional tasks but a number of information items have also been transferred to specially focused service headlines, an example being 'Hot News and Hot Online' which is now provided separately.

GDS's ability to publish online, in a very short time, has made it a forum for user groups with special interests. Two institutions, CEOS (the Committee on Earth Observation Satellites) and EARSeL (the European Association of Remote Sensing Laboratories), maintain information collections in GDS, and thus are accessible either under their own addresses, or from within the services offered by ESRIN (Fig. 3).

Growth of user accesses

Since the first ESRIN Earth-observation service was officially opened to the World Wide Web in May 1994, user interest has increased rapidly, as the usage statistics in Figure 4 illustrate. At the time of the initial service announcement, some 12 000 requests for information were received per month

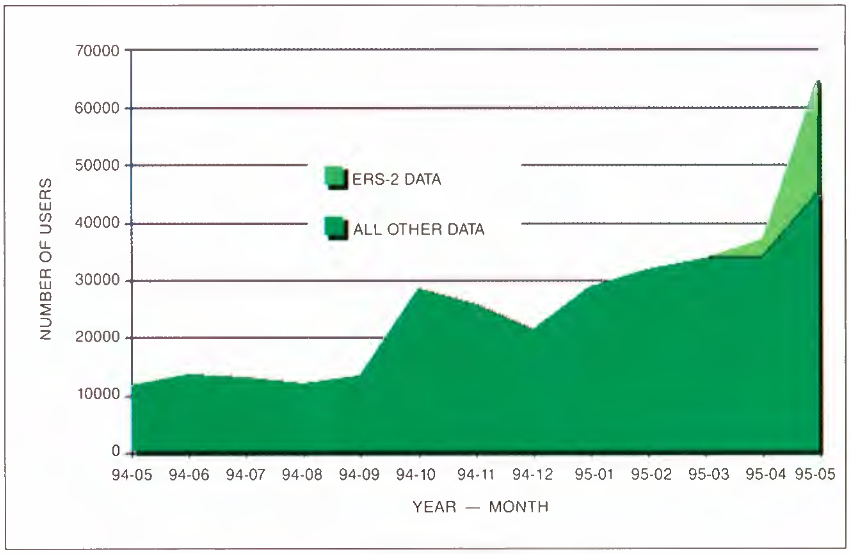

Figure 4. Usage of ESA's online Earth-observation services on World Wide Web (accesses between 1 May 1994 and 31 May 1995)

factor of almost 6. Figure 4 also shows a marked peak which corresponds to the introduction of the ERS-2 service.

The geographic location of users is quite diverse. As shown in Figure 5, Western Europeans and North Americans are the primary users of the services, but small but consistent groups of users also exist in Australia, Japan, Eastern Europe, and Southeast Asia.

Outlook for the future

ESRIN's present information services, however, are not expected to remain static. Since the information base is growing and a presence on the networks must reflect evolving user needs, the evolution of the services and the creation of optimised multi-mission information access paths will remain an ongoing activity. The immediate significant user response to the introduction of new and efficient features proves that 'information highways' like Internet allow for instantaneous user community response, in the Earth-observation domain as well.

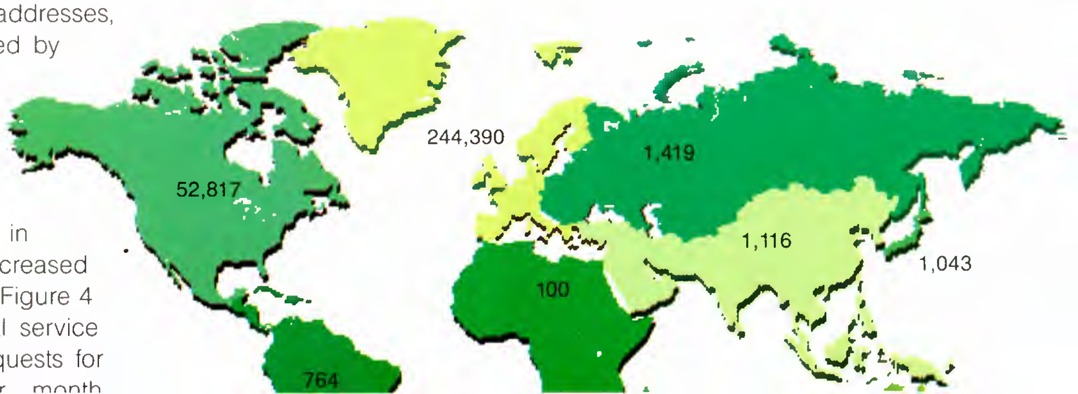

Figure 5. User access by region of the world (between 1 May 1994 and 31 May 1994). The total number of accesses was 338 799.