ABSTRACT

In this paper, we describe the failure which caused the loss of the original CryoSat mission and the measures which have been implemented to prevent a reoccurrence. We outline the improvements which will be implemented in the new satellite and present the schedule for this recovery mission.

1. INTRODUCTION

On 8 Oct 2005 the CryoSat satellite was launched by a Rockot launch vehicle from the Plesetsk Cosmodrome. As expected, telemetry was lost from the launcher about 500 seconds after launch, some 200 seconds after the nominal separation of the third stage from the second, with the ranging data showing the third stage apparently following the nominal trajectory. The launcher telemetry available at ESOC and other ESA sites was intermittent, with drop-outs, and not all events (including first stage ignition and third stage separation) were visible in the reported telemetry.

After almost a full revolution (90 minutes after launch) we expected the upper composite of CryoSat and the third stage to be acquired by the Redu ground station, with slightly later acquisition at Villafranca and then Kiruna. Separation would occur five minutes after nominal acquisition of signal, when the satellite would be in coverage of Kiruna. No signal was acquired. Following the attempts by the ground stations to acquire the signal a series of “blind” telecommands was sent to attempt to reconfigure the satellite’s telemetry system. Searching and commanding was continued from 4 ground stations (including Svalbard which was due to acquire after Kiruna) for the duration of the nominal pass: almost 20 minutes. During this time the Flight Operations Director attempted to obtain information from the launch authorities as to whether telemetry from the third stage was being received (which would indicate whether it was purely a satellite problem) but clear information was not available.

The Flight Dynamics team at ESOC computed a possible orbit which would result from a failure of the apogee boost burn of the third stage. This was based on minimal information and it was not possible to get confirmation or additional data from the launch authority. Nevertheless, in the second pass the 4 ground stations...
stations implemented a search pattern based on this orbit and blind commands to reconfigure the telemetry system were again sent.

At this time, some 3 hours after launch, the Flight Control Team was informed of reports on the internet of a launch failure, some being quite specific. Nevertheless, attempts to make contact with the satellite were maintained until the launch authorities made their first announcement of a launch failure, some 4 hours after launch. In this announcement it was reported (confirming the internet reports) that the failure was due to a failure to separate the third stage from the second, with a ballistic flight into the second stage drop zone near the North pole.

Following this, the activities at the Flight Control Centre were terminated.

2. THE LAUNCH VEHICLE

Rockot is a 3-stage launcher formed by combining the 2-stage booster unit of the SS-19 Intercontinental Ballistic Missile with a manoeuvrable upper stage called Breeze-KM. The booster stages have flown 148 flights as the SS-19 of which 145 were successful. The first test flights of the Rockot vehicle were launched from silos in Baikonur and used an earlier variant of the Breeze, called Breeze-K. This vehicle flew 3 times, all successfully. With the commercial partnership of Khrunichev and EADS to form Eurockot the Breeze was modified structurally and the launch facility moved to Plesetsk. This modified Breeze is the Breeze-KM. The one test launch, one national launch and five commercial launches prior to CryoSat were all successful. Finally, a variant of the Breeze, with different subsystems (including the flight control system) is flown on Proton, as Breeze-M. CryoSat was the sixth commercial launch of Rockot.

3. CAUSE OF THE FAILURE

3.1. The destruction of CryoSat

Before describing the cause of the launch failure, we describe the events which led to the destruction of CryoSat. In this account we give times referenced to EOGS, which is “end of gyro setting”, a time 14 seconds prior to lift-off at which the inertial reference unit in the launcher is initialised.

At EOGS + 14 s the Rockot carrying CryoSat lifted off from Plesetsk, which is about 800 km north of Moscow. The first stage was discarded at EOGS + 136 s and 48 s later the fairing, which protects the payload during its ascent through the atmosphere, was also discarded. At EOGS + 319 s the separation of the second stage was due, 21 s after the shut-down of the second stage cruise engine. The command to shut down the second stage engine was correctly triggered within the flight control system in the Breeze-KM, but it was not propagated to the second stage. The engine continued to burn until it depleted the fuel, while an oxidiser supply still existed. This resulted in an engine burn-through or other catastrophic event with the generation of large torques. The torque caused deviations in pitch, roll and yaw. Some 10 s after the failed shut-down command the pitch deviation exceeded the specified limits: the trigger to issue a mission failure command. This aborted further commands in the timeline, and in particular, no command to separate the Breeze-KM was issued. The composite of second stage, fully fuelled Breeze-KM and CryoSat continued on an unpowered ballistic trajectory, tumbling in all axes. At the time of the failure the composite was travelling at 5.7 km/s at its height of almost 200 km.

The composite effectively underwent a full re-entry into the atmosphere, combining severe deceleration (while tumbling) and heating through atmospheric drag. The combination of the strong deceleration, degraded structural integrity and the build-up of pressure from the heated fluids inevitably caused the rupture of the fuel tanks, somewhere in the upper stratosphere, with the explosive combination of the full load of hypergolic propellants (that is, propellants which do not need external ignition to react). The combination of the re-
entry heat and the explosion completely destroyed CryoSat. The remains fell within the planned second stage drop zone, at 87 deg 45 min N, 70 deg 02 min E, just over 12 minutes after lift-off.

Prior to the failed second stage shut-down, all telemetry showed a completely nominal flight. Mechanical loads (acoustic loads, loads at separation of first and second stages, loads in the area of the flight control system) thermal conditions and the trajectory were extremely similar to previous flights and within all specified limits. Everything was nominal until the failure to shut down the second stage cruise engine.

3.2. What went wrong

The direct cause of the failure has been unambiguously identified: the failure to shut down the second stage engine was caused by the incorrect interaction between the pre-burn pressurisation sequence of commands required prior to the start of the Breeze-KM engine and the overall flight control timeline. The commercial Rockot flights were optimised, with a variable fuel load in the upper stage, requiring mission-specific adaptation of the command sequence to achieve the required pre-burn pressurisation. In designing the CryoSat command sequence a human error was made, with the result that the commands associated with pressurisation were not completed before the second-stage shut-down command was generated. Due to the system design the consequence of this overlap was that the shut-down command was not executed. This error was compounded by inadequate testing: specifically the validation process used was unable to detect this fatal error condition.

3.3. The remedy

Both of the underlying causes of the failure have been addressed for future missions:

Firstly, a fixed programming scheme has been reintroduced, ensuring adequate margin for all critical commands.

Secondly, an improved test rig has been implemented and all commands are now validated. We are now confident that this weakness in the system has been eliminated and that Rockot can be regarded as a reliable launcher.

4. CRYOSAT-2

Following the failure there was a consensus that the lost satellite should be replaced. But transforming that consensus into a practical implementation required a considerable effort and good will from all those involved: in industry, in the science community, in the delegations of our member states and in ESA too. Urgent actions in the weeks and months after the failure were to:

• establish that the replacement mission could be funded; by distributing the costs among the three 5-year slices of the overall Earth observation funding envelope, and exploiting synergies with other funded activities, CryoSat-2 could be accommodated without any special funding request, albeit at the cost of a rather complex budget structure;

• secure political support; in fact there was a great deal of good will towards a replacement and this was emphasised by leading members of the Earth science community who confirmed that CryoSat was even more relevant that when the mission had first been selected;

• secure the availability of staff; obviously at the time of the failure most of the development team, both in industry and in ESA, had been committed to other projects – this has caused some practical difficulties but has been largely overcome;

• order “long-lead items”, that is, items which have a long delivery time; some of the high-reliability electronic parts have delivery times of up to a year so early ordering would clearly be very important to maintain a reasonable schedule;

• start the contractual process; this required establishing all of the technical documents which define the industrial work (which is necessarily different for a re-build), the preparation of a binding offer by industry, and the evaluation and eventual negotiation of this offer.

In preparing these documents, a question which had to be faced was that of whether to build an exact copy or whether to implement improvements. However, this question was easily answered in some respects:

• the main payload, the SIRAL, had been a single instrument on the original CryoSat, and it was full of “single-point failures”, that is, single components whose failure would cause the loss of the whole instrument. It was an easy decision, for a rescued mission, to implement full redundancy in this payload;

• there were several areas of obsolescence in the original design, both at the level of components and in some complete equipments; these had to be replaced by current designs;

• we took the opportunity to rectify a number of shortcomings in the original CryoSat design, which had been found during system testing;

• finally, we also made many improvements in operability of the satellite; usually these improvements took the form of small changes to the central flight software.

5. GROUND SEGMENT

Some updates were required in the ground segment too. Although the ground segment was ready at the launch of CryoSat there were some outstanding minor issues which had been scheduled for remedial action during
the Commissioning Phase of the original mission, for example an upgrade to use the latest version of the environmental correction data. Following the launch failure we decided to implement all of these planned updates to bring the full ground segment into a stable configuration. Following this, the systems were effectively put into hibernation: the software configuration was frozen and the science data processing hardware largely removed from the Kiruna station. This hardware, which will be obsolescent by the CryoSat-2 launch, has been reused in support of other projects. Both the science data processing system (called PDGS) and the command and control system (called FOS) will be re-hosted on new hardware and operating system platforms to avoid obsolescence issues, and furthermore some development work is needed to cope with new features of the satellite. For example the redundant SIRAL on CryoSat-2 means that the ground segment has to be able to manage two distinct sets of characterisation data, while the new features of the satellite mean that the satellite simulator at ESOC needs update too. During the second half of 2007 the ground segment facilities will be brought out of hibernation and implemented on their new platforms, to be followed by rigorous testing. Like the original CryoSat, the ground segment will be fully ready to support the launch.

6. SCHEDULE
As we have mentioned, the schedule for the recovery of the CryoSat mission is very compressed. Starting with the industrial kick-off in March 2006 the procurement of equipment started almost immediately. A year later, in March 2007, the structure was delivered to the prime contractor Astrium GmbH. During the remainder of 2007 most of the satellite’s equipment will be delivered, and in the same time-frame the ground segment will be established. The first half of 2008 will be devoted to testing the satellite at system level, including the start of the series of tests to verify the compatibility between the satellite and the ground segment. Halfway through 2008 the satellite will be shipped to IABG in Munich where it will undergo a series of environmental tests which will verify that it is able to withstand the launch to verify its correct functioning in the space environment. At the end of 2008 we will scrutinise all of the results from these activities and the Flight Acceptance Review will be convened; in the same period the Operational Readiness Review of the ground segment will be held. Finally, in early 2009 the satellite will be transported to its launch site in Plesetsk, and in March 2009 it will be launched, to continue the mission so unfortunately interrupted in October 2005.

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The authors would like to recognise here the efforts of all those who contributed to the original CryoSat mission, some of whom did not join the team working on its replacement due to assignments to other tasks. Furthermore, we want to recognise the special efforts which resulted in CryoSat-2, the recovery of the CryoSat mission. This was due to good will and hard work on the parts of industry, the scientific community, the delegations of the member states and the ESA team.