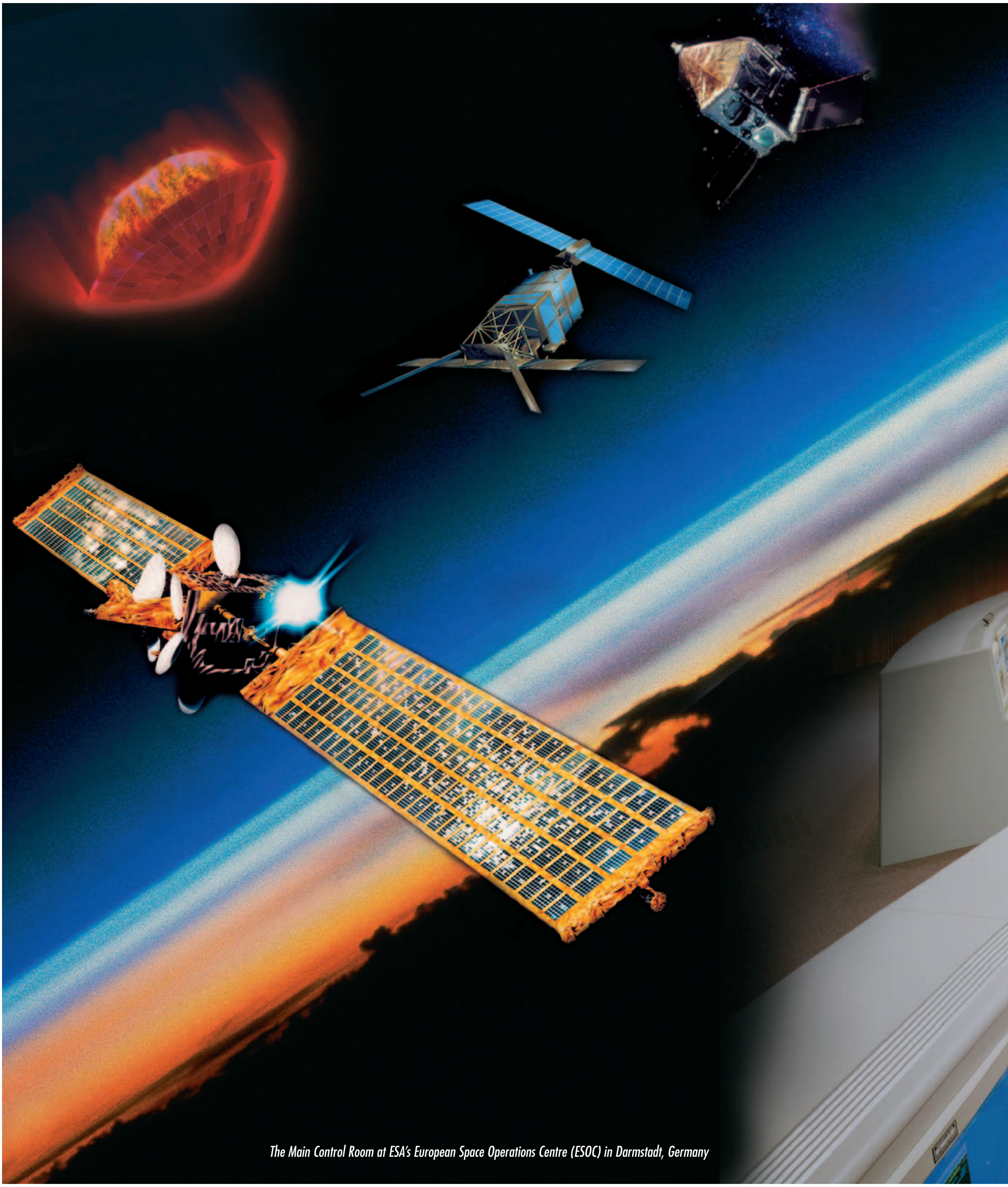

The Main Control Room at ESA's European Space Operations Centre (ESOC) in Darmstadt, Germany

Lost in Space ?

- ESOC Always Comes to the Rescue

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Since supporting its first launch in 1968, ESA's European Space Operations Centre (ESOC) in Darmstadt, Germany, has supported 51 spacecraft during the critical launch and early orbit phases of their missions, and nearly all of them throughout their subsequent operational phases. The great diversity of these missions has given ESOC a well-justified reputation as one of the world's leading control centres for unmanned spacecraft. Perhaps less well known is the contribution that ESOC has made to the rescue of many missions that have suffered major anomalies and would otherwise have had to be abandoned or would have failed to achieve their mission goals.

Background

In-orbit equipment malfunctions or failures are a fact of life for all space missions, which is reflected in the on-board redundancy and fault detection and isolation techniques used in spacecraft design. The Control Centre must therefore be able to deal with such situations and normally has contingency procedures in place to respond to them. Sometimes, however, the problems are of such a magnitude that they are beyond what would normally be expected, and require an extensive team effort to retrieve the situation. ESA missions afflicted by such major problems over the years have been:

- Geos-1 and Artemis: Launch-vehicle malfunctions
- TD-1A, Hipparcos, ERS, Huygens: Major spacecraft equipment failures
- Olympus, SOHO: Loss of attitude control.

ESOC’s role in the recovery of these missions has ranged from providing emergency ground-station support, through to establishing an alternative mission concept, defining the strategy to achieve it, and ultimately conducting the rescue operations. ESOC has also been requested on several occasions to support other space agencies in rescuing their missions crippled by in-orbit failures.

When called upon, ESOC has been able to respond immediately, exploiting the facilities, experience and expertise that it has at its disposal to effect a rescue.

TD-1A

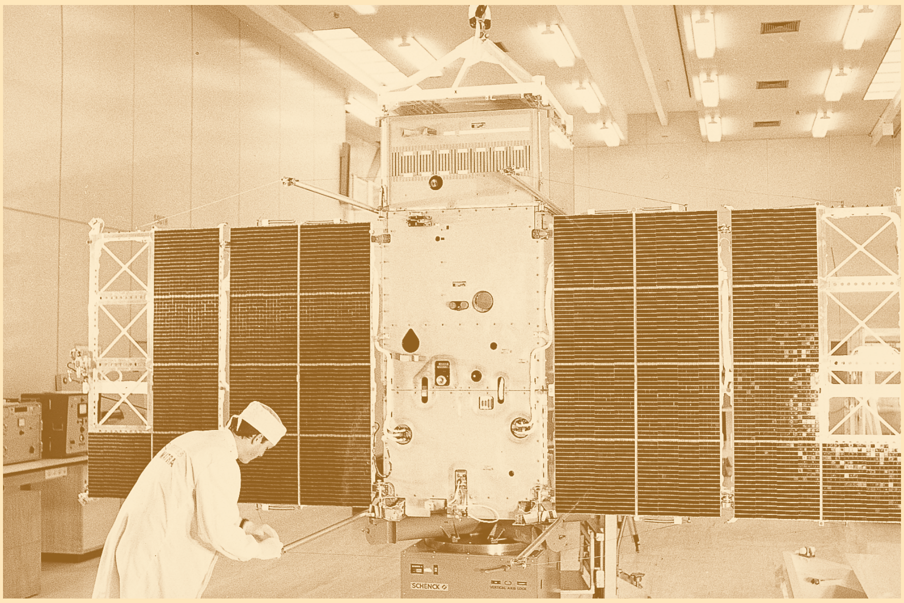
On 12 March 1972, TD-1A, Europe's hitherto largest and most complex scientific satellite, was successfully launched from Western Test Range in California. It was ESRO's first astronomical satellite and it was to look at the stars with two telescopes. However, just a couple of months later, towards the end of May, both on-board tape recorders failed. As it was impossible to repair them, an appeal for help was put out.

It was responded to immediately by NASA, CNES and CNR, who 'loaned' ESOC seventeen more ground stations to record the satellite's direct signals. In a 'fire brigade action', a further seven mobile stations were established, in Tahiti, Singapore, Easter Island, Fiji, Hawaii, Argentina, and finally on a former Dutch 'banana boat', the MS Candide, which was to position itself at 44 degS and 110 degE.

For almost two years, these mobile stations were manned around the clock by ESOC personnel, who had to battle not only against the technical problems but also the environment in many cases.

Despite hurricanes, storms, high waves and snow, the recovery operation was very successful. By the end of the mission, the scientific characteristics more than 30 000 stars had been investigated.

The launch of TD-1A from Western Test Range on 12 March 1972



The TD-1A satellite in the Integration Hall at ESTEC in Noordwijk in July 1971


The ESOC Control Room in the 1970s


The GEOS spacecraft being prepared for boom-deployment tests in the Dynamic Test Chamber at ESTEC in Noordwijk (NL)

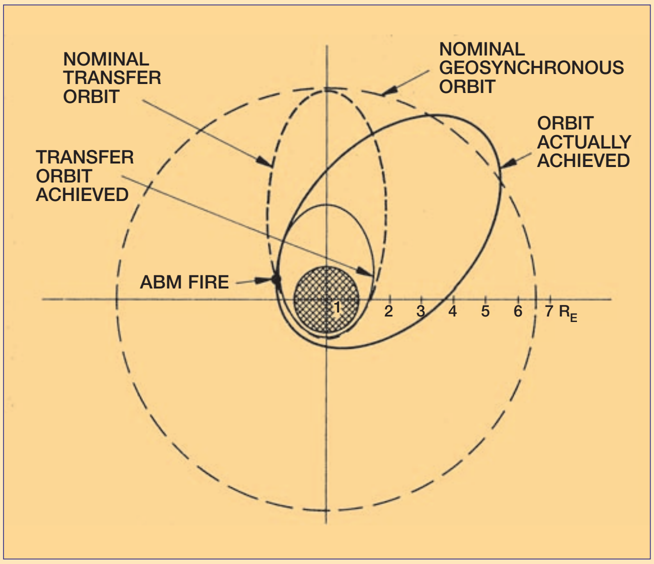
GEOS-1

GEOS was an ESA scientific satellite designed to investigate the Earth's magnetic environment. In April 1977, the Thor Delta launch vehicle should have placed the spacecraft, spinning at 90 rpm, into a 10.5 hour period transfer orbit. About 37 hours after launch, a single firing of the integral, solid-fuel apogee boost motor would then have achieved an orbit very close to geostationary. Due to a partial failure of the launcher, however, the orbit that was actually achieved had a period of just 3.8 hours, the satellite was spinning at only 1.5 rpm, and it was wobbling with a cone angle of 35 degrees.

Because the predicted pointing angles for the ground-station antennas were no longer valid, just a few attitude measurements and tracking data were received after the satellite's separation from the launcher. Only after an unplanned spin-up manoeuvre had been performed, and after extremely careful processing of the data, could the first rough orbit and attitude estimates be made. Attitude manoeuvres had to be executed as quickly as possible to improve the thermal and power situation. Steady degradation of the solar cells, and thus the available power, due to long periods in the radiation belts, was soon detected. The spacecraft had certainly to be manoeuvred into a different orbit, but a geostationary orbit was no longer reachable.

Over the next few days, a team of ESOC experts worked around the clock writing new software and amending existing programs in their search for the optimum orbit that could be achieved, depending upon when the apogee boost motor was fired and with what satellite orientation. The final orbit had to be the best compromise for meeting the needs of the scientific payload, but also had to take into account a whole range of constraints such as ground-station visibility and antenna tracking, the viewing angle of the spacecraft's antenna, orbit stability, eclipses, etc.

Five days after launch, the firing of the apogee boost motor put the spacecraft into an inclined elliptic orbit with a period of 12 hours. Mission planning is normally a matter of months if not years, so it is remarkable that later analysis clearly showed that the solution that had been found was indeed optimal. As a result, GEOS went on to provide very useful scientific data.



The originally planned and launch-failure-degraded GEOS orbits. The spacecraft's apogee boost motor was fired at the point indicated to achieve a 12 hour eccentric orbit as the best recovery compromise

Hipparcos

ESA's Hipparcos satellite, launched on 8 August 1989, was dedicated to making highly accurate measurements of star positions, distances and proper (apparent) motions. Due to the satellite apogee boost motor's failure to fire on 10 August, the planned geostationary operating orbit could not be reached and a complete mission redesign was neeeded to meet as many of the original Hipparcos objectives as possible. Thanks to a magnificent effort by ESOC, ESTEC, European Industry and the Hipparcos Science Team, this mission redesign was completed in just a matter of weeks.

The ground-station network had to be enhanced, adding three ground stations (including a NASA station) where originally only one was originally foreseen. By using the remaining hydrazine fuel onboard the satellite, its orbit was adjusted to maximise ground-station coverage whilst also optimising the attitude scanning law derived from the observation strategy. The onboard software needed to be modified to increase the buffer space for time-tagged commands and star parameters, and a new torque model was needed to control the spacecraft around the orbit's perigee.

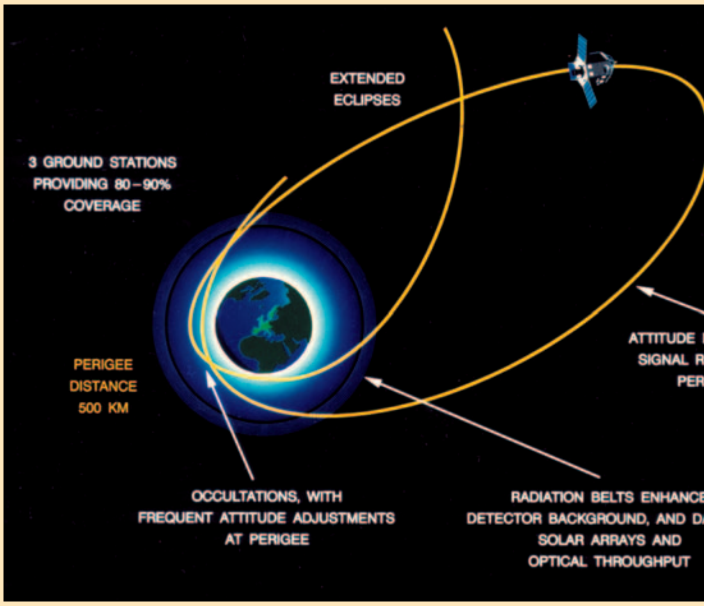
The ground software needed to be changed for the mission-planning products, a new attitude-control strategy was needed to cope with the non-geostationary orbit, the instrument had to be safeguarded during periods of non-visibility from Earth, command parameters had to be generated for the onboard torque controller, and a special control strategy was needed to cope with the extended eclipse durations. New predictions for payload occultation intervals and new real-time attitude-determination software also became necessary.

During its subsequent routine operations, Hipparcos relied on three out of its five gyroscopes for attitude control. Unfortunately, the stronger radiation environment in the revised orbit caused the degradation and eventual failure of all but one of the gyros, the first problems being seen just one month after launch.

ESOC, ESTEC, Industry and the Hipparcos Team therefore began immediately to develop an operational concept based on only two gyros, which required modified onboard software. In particular, the Real-Time Attitude Determination (RTAD) algorithm had to be re-designed to replace the missing gyro data by a dynamical model coupled with star-mapper measurements. Throughout the mission, due to the high radiation, RTAD performance around the orbit's perigee was degraded to the extent that useful science data could not be collected without ground intervention. In these cases, a significantly modified version of ESOC's Ground Real-Time Attitude Determination (GRTAD) system was

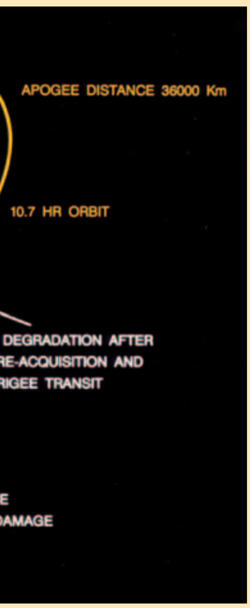
The ESOC Control Room in the 1980s

Final qualification testing of Hipparcos in the Large Space Simulator at ESTEC in Noordwijk (NL)



needed to determine the spacecraft's attitude after perigee and reset the onboard RTAD system. It was also necessary to compute and control the spin-rate after perigee passage, where the lack of control meant it could vary dramatically.

In August 1992 a further gyro failure caused Hipparcos to go into an emergency safe mode and increase its spin rate. Further recovery operations were postponed until October to allow the ESOC team time to make further improvements to the two-gyro ground system, resulting in a much higher data return once operations resumed. Hipparcos went on to collect a further seven months of science data, significantly increasing the final results, especially for the proper motions of the stars.



The revised Hipparcos orbit and the problems associated with it

The implementation of all of these changes to the mission's space and ground elements, together with a dedicated ESOC support team who 'lived with' the satellite for more than four years, made the revised Hipparcos mission a spectacular success. The unique Star Catalogues produced using its data have not only provided the World's astronomical community with a rich source for research for many years to come, but are also being used by many space missions requiring precise star information.

Olympus

Probably the most dramatic of all rescues of ESA spacecraft was the 1991 recovery of Olympus. Launched in 1989, Olympus was a large new-generation telecommunications spacecraft that carried several novel technology payloads for in-orbit testing. For example, it was ESA's first data-relay spacecraft and was used very successfully to provide two-way communications with ESA's Eureca free-flying experiment platform.

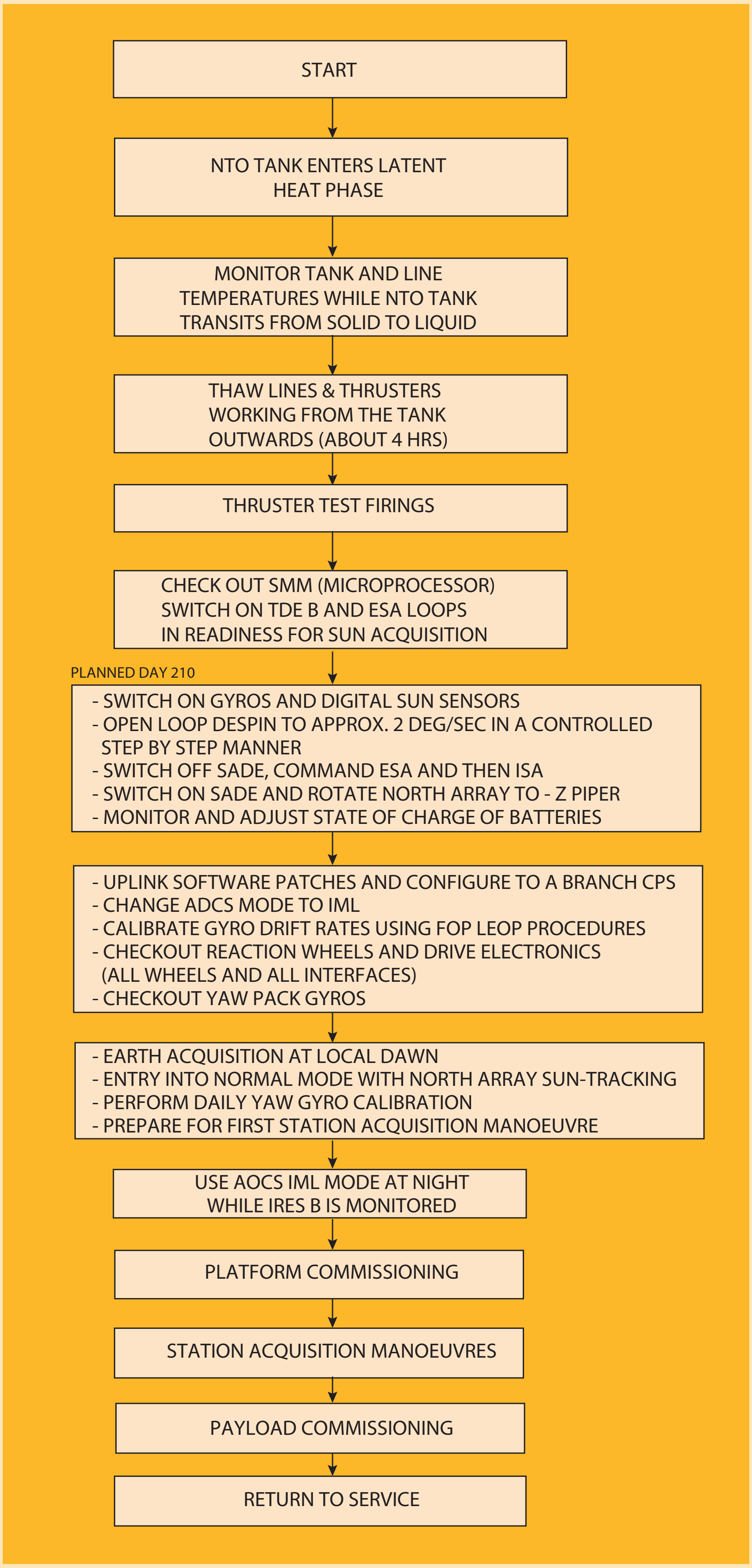
The Olympus launch and early orbit phase operations were conducted from ESOC and control was then transferred to Telespazio's control centre in Fucino, Italy, for the routine operational phase. The spacecraft subsequently suffered from several major onboard failures, including the loss of 50% of its solar-array power and significant performance degradation of its primary attitude-control sensors. Despite all of the problems, the operations team in Fucino managed to keep the communications payloads fully active.

On 29 May 1991, however, the spacecraft experienced further problems and tried automatically to enter its safe mode, but this failed. Attempts by the ground team to regain control of the situation were unsuccessful and 20 hours later, with the spacecraft tumbling through space, all ground control over Olympus was lost. The spacecraft was stranded and drifting eastwards by 5 degrees per day.

The only telemetry signal from the stricken spacecraft consisted of a partial frame of 15 seconds of data every 89 secs, but this was insufficient to allow the incoming telemetry to be decoded. It was observed, however, that the duration of the partial telemetry frame was increasing by 1 second per day, suggesting that the solar arrays were progressively getting longer exposure to the Sun and thereby producing more power!

Integration of Olympus with its Ariane launcher in Kourou, French Guiana

Industry successfully decoded the partial telemetry data on 5 June, and this indicated that the spacecraft was stable and spinning slowly about its roll axis. There were major problems, however, in that the satellite's propellants and batteries were frozen. Because of the steadily increasing solar-array power, however, ESA and Industry were optimistic that control of the spacecraft could be recovered and should indeed be attempted. The extent of any



The outline Olympus Recovery Plan

damage to the communications payload was unknown at that point.

A joint ESA-Industry mission-recovery team was established headed by ESOC. The first task was to develop safe procedures to thaw out the frozen spacecraft. Industry conducted ground tests with representative hardware to validate the approach. Operational control was returned to ESOC in Darmstadt, where advantage could be taken of the extensive expertise and facilities available, including ready access to the ESA LEOP ground-station network.

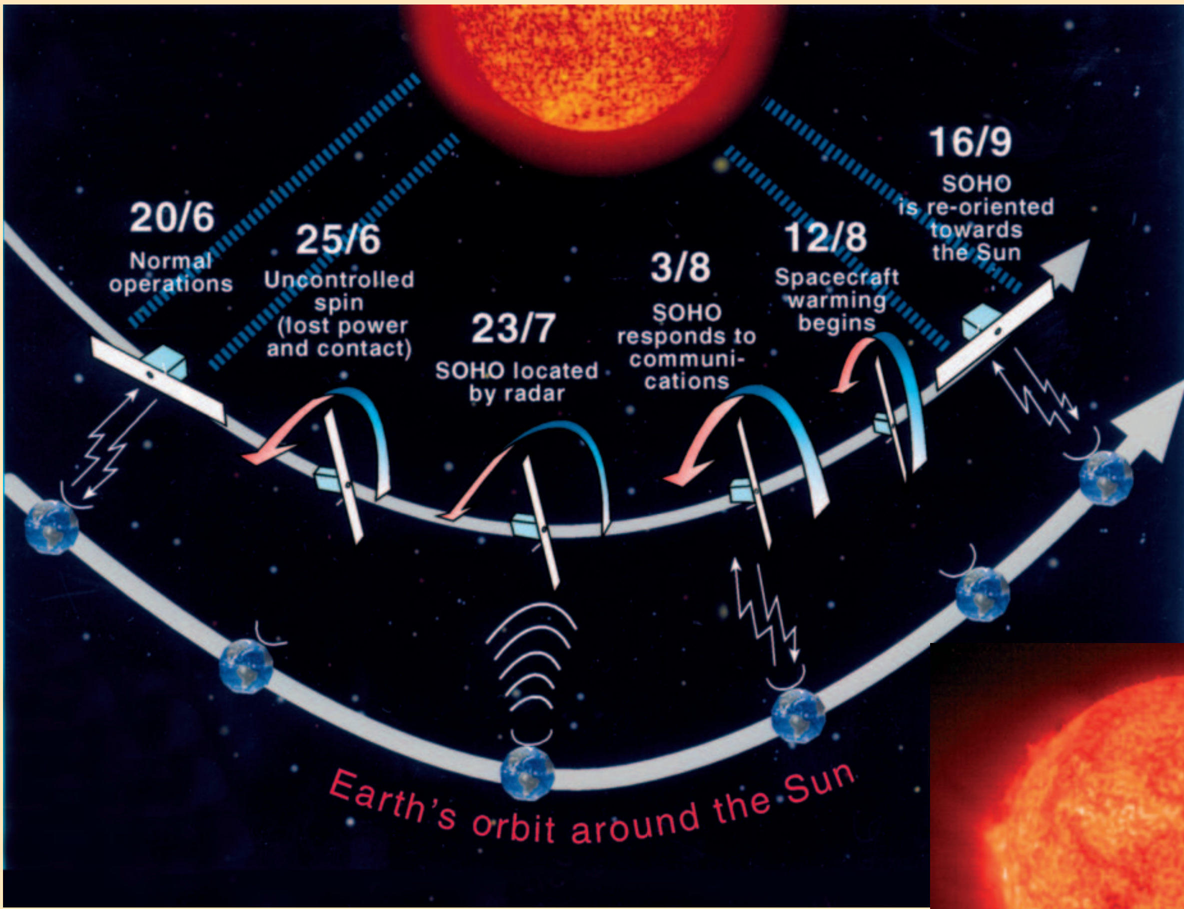
The first telecommand access to Olympus was achieved on 26 June and the ground control team then began thawing out first the batteries and then the propellant tanks, lines and thrusters. Attitude control was regained on 31 July, and by 13 August Olympus was again back on station at 19 degW !

Surprisingly the spacecraft had suffered very little damage as a result of the extremely low temperatures that it had encountered, and following recommissioning of the payload it was returned to service and operations were transferred back to Fucino. The mission was eventually terminated in August 1993.

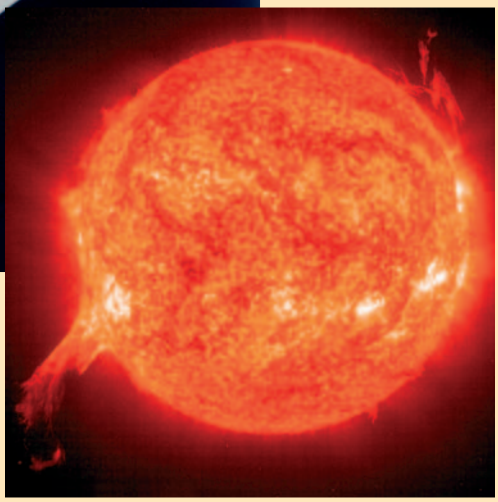
SOHO

The ESA/NASA SOHO scientific spacecraft was launched in December 1995, with day-to-day operations being conducted from NASA's Goddard Space Flight Center (GSFC) in Maryland, USA. On 25 June 1998, the spacecraft entered its back-up emergency Sun re-acquisition mode. During the subsequent return to normal operations, attitude control was lost. Five hours later all contact with SOHO was also lost.

ESA and NASA engineers believed the spacecraft was spinning about a fixed axis with its solar panels edge-on to the Sun and therefore not generating any power. If that were indeed the case, the solar arrays



Some of the key events in SOHO's recovery



SOHO continues to provide an unprecedented view of the Sun and its interior

would become progressively more illuminated due to the seasonal variation in SOHO's orbit, and ESA and NASA therefore concluded that a recovery operation should be attempted. A SOHO recovery team was therefore established which included several ESOC staff.

ESOC had itself not been directly involved in the SOHO operations, but it immediately joined the search for a signal from the spacecraft using its S-band tracking stations at Redu (B), Villafranca (E) and Perth (W. Aus.). On 3 August, after 6 weeks of silence, signals from SOHO were finally detected by Perth and by NASA's Goldstone station. The signal 'spikes' lasted between 2 and 10 seconds, but these bursts of data were insufficient to allow the telemetry to be decoded. A complex telecommand sequence was therefore established and uplinked in the blind to increase the length of the data bursts, but this proved unsuccessful and so ESOC's data-handling experts proposed a modified sequence. This one worked and the first telemetry was received on 8 August. The recovery team based at GSFC then developed and executed a complex plan to recover the spacecraft, and by 25 September SOHO was back in its normal operating mode.

Following the recovery of SOHO's attitude control, however, the short-term predictions of the evolution of the satellite's orbit were proving to be very inaccurate. A leaking thruster was feared, although there was no such evidence from the attitude dynamics. ESOC was again contacted to help explain the mystery, and within a few days came up with a logical explanation: since no tracking had been possible during the SOHO outage, the orbit-determination process needed to be re-initialised with carefully selected parameters. After this was done, SOHO operations returned to normal.

ERS-2

ERS-2 was launched in April 1995, four years after its almost identical predecessor ERS-1. Although ERS-1 had been flying without any major operational difficulties, ERS-2 began to suffer successive failures in its six gyroscopes, starting in February 1997. Since the original onboard attitude-control algorithms required at least three healthy working gyro units for accurate three-axis attitude control of the satellite, the chronology of these failures caused concern that the mission might not last much beyond January 2001 without upgrading the onboard attitude-control system.

Soon after the first failure, the ERS Project asked Astrium SAS to study, with ESOC's support, the feasibility of autonomous three-axis attitude control with fewer than three gyros. In February 2000, a new control mode using a single gyro for payload operations was patched onboard and successfully commissioned. In 2001, a zero-gyro attitude control algorithm was introduced, which allowed the mission's dependence on gyroscopes to be significantly reduced and the precious remaining working gyros to be reserved for backup and orbit-control modes.

As further insurance, a mono-gyro attitude-control algorithm for those backup and orbit-control modes was also patched and commissioned onboard during the last quarter of 2001. From that point onwards, active control of the orbit's inclination, which had been suspended a year before after the third full gyro unit failure, could be resumed.

ESOC and ESTEC, with active support from Industry, had therefore managed to steer the mission away from a nearly certain premature end and secure many extra years of mission lifetime for the Earth-observation user community.

The ERS-2 spacecraft being readied for launch

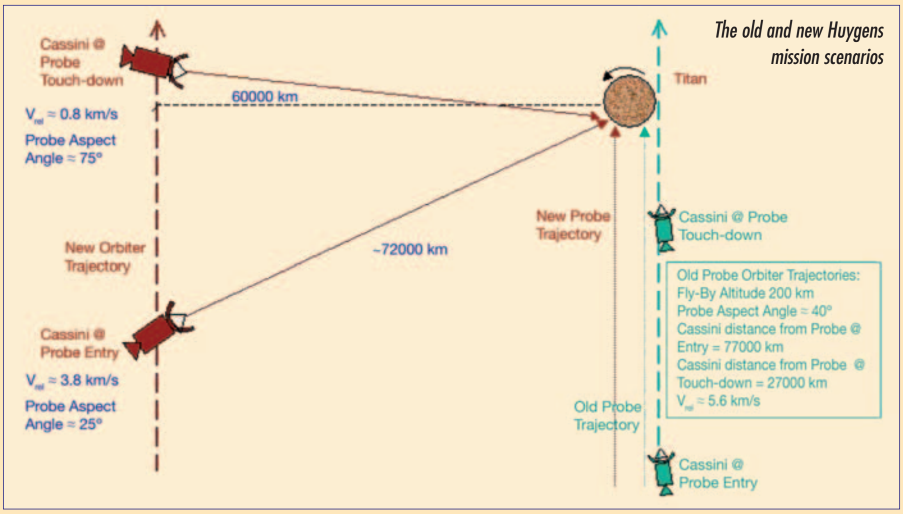
Huygens

Since its launch on 15 October 1997 as a passenger on NASA's Cassini mission to Saturn, the Huygens probe has undergone regular 'health checks' on its payload. Although these checkouts mimic as closely as possible the sequence of events during the probe's actual descent onto Saturn's moon Titan in 2005, the Huygens-to-Cassini radio link is simulated through an umbilical.

To check the radio link itself, special tests were conducted after launch in which ESOC simulated the probe's radio signals, using a NASA Deep-Space Network antenna to transmit to Cassini's high-gain antenna a signal equivalent to the one that the probe will send during its descent onto Titan. During the first such test in February 2000, ESOC discovered a major anomaly in that the Huygens telemetry receiver onboard Cassini was not performing as planned and would not be able to receive data with the degree of Doppler shift to be expected during the probe's descent phase. As a consequence, a very large percentage of the Huygens scientific data could be lost!

Further probe relay tests, complemented by several very comprehensive test campaigns on the Huygens engineering model housed at ESOC, were a major factor in understanding, characterising and resolving this anomaly. They showed that the problem could only be solved by a combination of actions:

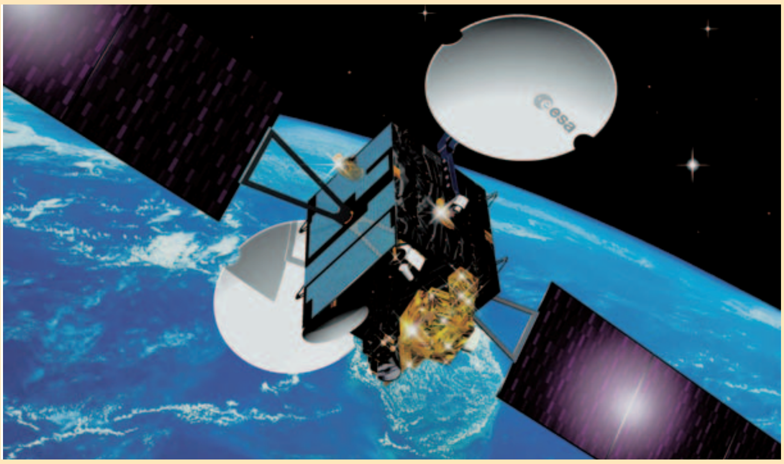
- A new Cassini trajectory that minimises the radial component of the probe-orbiter relative velocity. This involves increasing the Cassini-Titan flyby distance from 1200 to 60 000 km and reducing the Cassini orbiter delay time from 4 hours to 2 hours.
- A probe pre-heating strategy, which will slightly reduce the transmitted data stream frequency, thereby providing greater margins. It requires specific changes to the probe and payload onboard software, which have been thoroughly tested and validated using to the Huygens enginee-ring model.



The old and new Huygens mission scenarios

The Cassini spacecraft, with the Huygens probe mounted on the left side, being lowered onto its launch-vehicle adapter at Kennedy Space Centre (photo NASA)

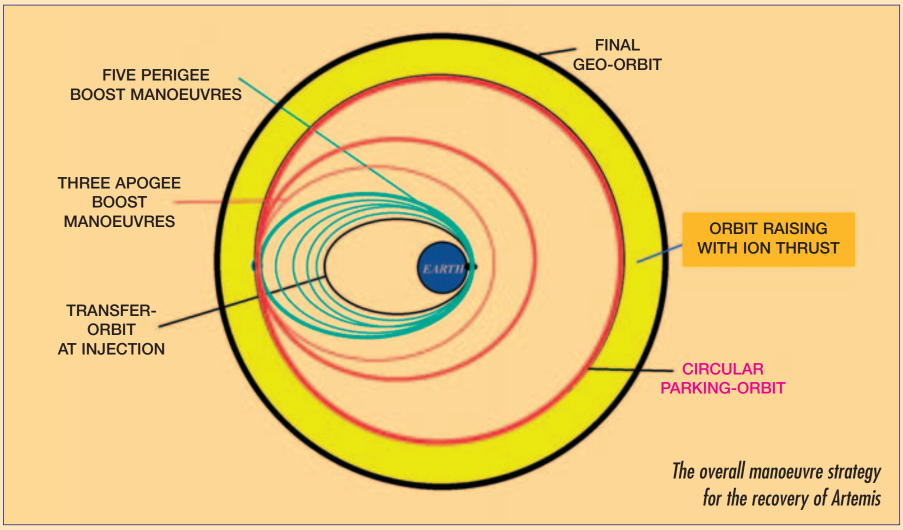
The baseline recovery mission was finalised in September 2003 and is now being implemented by the ESA Huygens (ESOC, ESTEC and Industry) and NASA Cassini teams.



Artist's impression of Artemis in orbit

Artemis

ESA's Artemis spacecraft was launched by an Ariane-5 in July 2001. Telespazio was in charge of the operations, but ESOC had a role as adviser to the ESA Project Team, with one of its staff present in Fucino (I) as an observer. A launcher underperformance problem resulted in the Artemis orbit having an apogee radius of only 25 700 km, instead of the intended geostationary apogee radius of 42 164 km. In addition, the plane of the orbit was not correct.



The overall manoeuvre strategy for the recovery of Artemis

Although not directly participating in the launch and early orbit phase (LEOP), ESOC was informed, quickly made an analysis of the situation, and developed a recovery plan. The essential steps in this plan were to use chemical propulsion to put Artemis into a circular orbit about 5000 km below geostationary radius by first raising the spacecraft's apogee and then its perigee. The electrical propulsion system onboard would then be used to raise the orbit to geostationary altitude.

The use of the electrical propulsion system for orbit raising required a major reprogramming by Industry of the satellite's on-board attitude and orbit control (AOCS) software, as it had been designed only for inclination-correction manoeuvres.

The plan was successfully implemented by Telespazio, albeit with some delay due to difficulties resulting from the heavier than foreseen use of the electrical propulsion system, and Artemis is now fully operational.

Support to Other Agencies

As in the case of Artemis, ESOC has also provided emergency support to several other spacecraft operators in times of need. In late1997 and early 1998, for example, the Centre provided emergency support to NASDA for its ETS-VII and COMETS missions.

ETS-VII was launched at the end of November 1997 and full telemetry, tracking and command (TTC) support from Kourou (Fr. Guiana) and Perth (W. Aus.) was originally foreseen only for the first days after launch. However, because of contingency situations the full TTC support from Kourou and Perth was extended first by a week, then until the end of December 1997, and finally it was provided until the beginning of February 1998.

COMETS was launched at the end of February 1998, but a launcher malfunction meant that the spacecraft did not achieve the target geostationary-orbit apogee altitude, reaching only about 1900 km. ESOC was asked to provide full TTC support from Kourou and Perth for the necessary orbit-raising manoeuvres during the months of March, April and May.

Acknowledgements

The authors would like to acknowledge the professionalism and dedication of their colleagues in ESOC who have contributed so much to the Centre's success in ensuring that many missions that would otherwise have been lost have been recovered and have thereby been able to accomplish most of their planned objectives. The support of European Industry has been of paramount importance throughout.