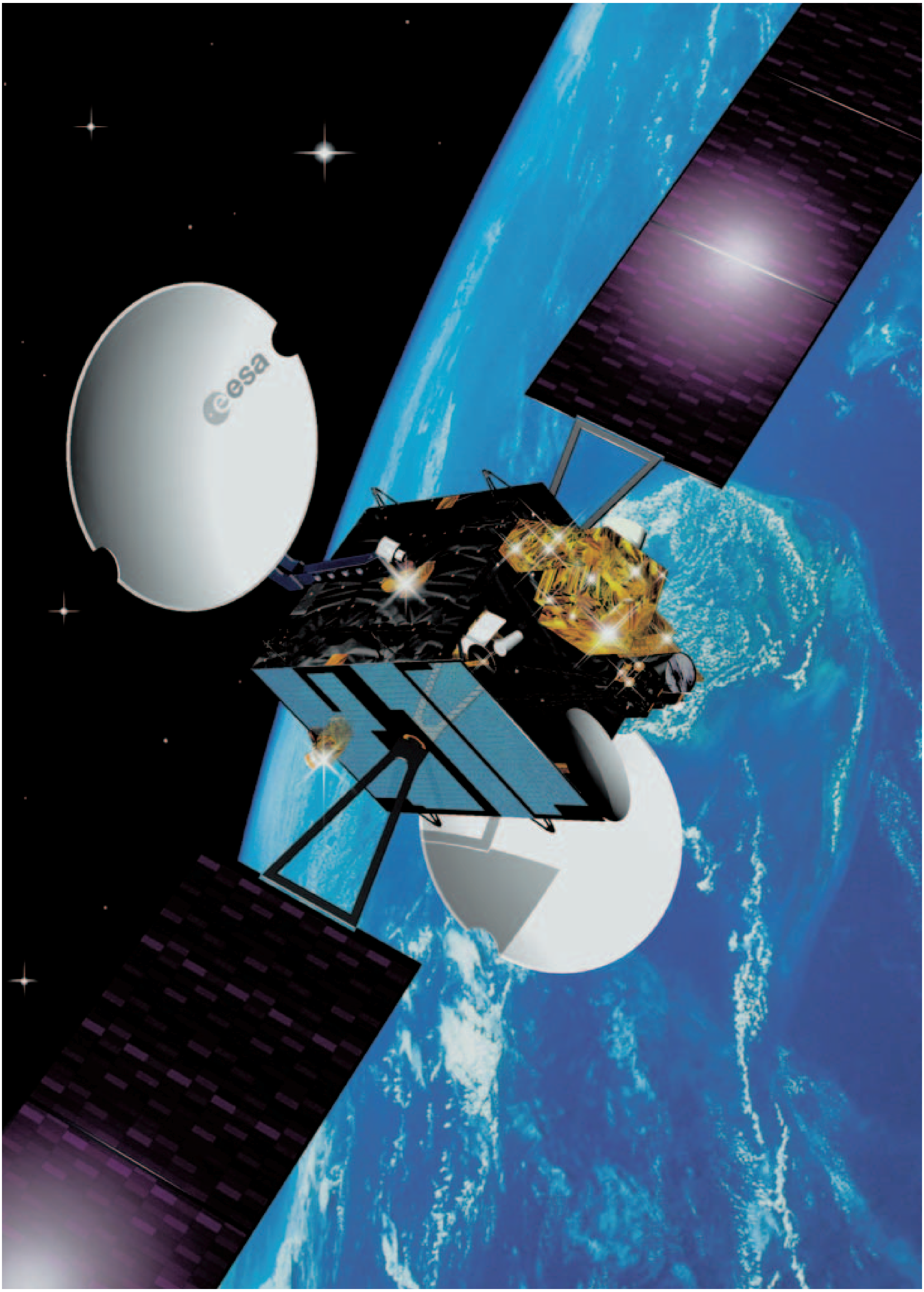

Artemis

– 'A Lost Mission' on Course for a Full Recovery

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Artemis was launched on Ariane flight 142 from Kourou in French Guiana on 12 July 2001. Unfortunately, the second stage of the launcher did not perform to the full, resulting in an abnormal transfer orbit with an apogee of only 17 000 km instead of the nominal 36 000 km. For any other standard communication satellite this would have been the end of the mission. Indeed, for insurance purposes, Artemis has been declared a 'total loss'. However, thanks to the combination of technologies onboard Artemis, a recovery of the mission is possible. At the time of publication, the final phase of recovery has achieved 1100 of the 5000 km needed to reach geostationary orbit.

Introduction

Artemis is ESA's latest and most complex geostationary communication satellite. It carries a number of advanced communication payloads to support new communication services for mobile communication, data-relay and navigation services. In particular its L-band land mobile payload will be used to complement and augment the European Mobile System operated by Eutelsat, its data-relay payloads will provide operational support to Envisat and SPOT-4, and its navigation payload will form an element of the European Global Navigation Overlay Service (EGNOS).

The satellite will also demonstrate the flight-worthiness of a number of new technologies, the most significant being the electrical propulsion system for full north-south station-keeping and the SILEX optical inter-satellite data-transmission system.

The Artemis prime contractor is Alenia Spazio, responsible under contract to ESA for the development, assembly, integration and test, launch operations, and in-orbit operations of the spacecraft. Spacecraft operations from injection until end-of-life are managed by Telespazio from the Fucino Space Centre in Italy.

The choice of a launch vehicle for Artemis was a long and involved process. Initially it was planned to launch on an Ariane-4, but for funding reasons it was later slated for launch on the first, and then the second Ariane-5 APEX flights. When delays in the Artemis Programme made an APEX launch untenable, an agreement was reached between ESA and NASDA for a launch on the new Japanese H-IIA rocket. Following the failure of two H-II launch vehicles, NASDA announced significant delays in the H-IIA programme. In order to launch Artemis in time for its main customers, new funds were made available for a commercial Ariane-5 launch.

From injection to parking orbit

Following launch around midnight on 12 July, the operations team managed to establish TT&C (telemetry, tracking and command) contact with the satellite, despite the non-nominal orbit. The malfunction of the launcher was quickly reported and the first ranging results confirmed the orbit to be non-nominal. In particular, the apogee altitude was 17 487 instead of 35 853 km, the perigee was 590 instead of 858 km, and the inclination was 2.94 instead of 2.0 deg.

The satellite was placed in a safe Sun-pointing mode with its arrays partially deployed, and its systems were checked out. The battery charge cycle was adequate, but due to the relatively long and frequent exposure to the radiation belts in this orbit, a limit of 6 days was set for implementing a recovery .

The first meeting to assess recovery strategies took place on 13 July. The launch vehicle had shown a shortfall of some 500 m/s in injection velocity and it was apparent that, taking uncertainties into account, there was insufficient chemical propellant to reach geostationary orbit (GEO) and provide a useful station-keeping function. Therefore, three mission options were considered, based on making the most of the available chemical propellant, and included the use of non-geostationary orbits. Allowing for uncertainties and residuals, as a first approximation it was considered necessary to retain some 100 kg of chemical propellant for attitude and orbit control in the final orbit. This left about 1420 kg of chemical propellant for orbit recovery, equivalent to 1830 m/s.

The first two options considered were an elliptical orbit and a circular sub-synchronous orbit, respectively. They were aimed at providing a repetitive service coverage opportunity every 3 days by choosing an orbital period of some 18 hours, and were based on the use of chemical propellant only to reach those orbits. It was obvious that these orbits would only provide intermittent visibility of the satellite and would require investment in new ground networks. Moreover, it was quickly appreciated that, for frequency coordination reasons, the main payloads could not be operated in any other orbit than the geostationary orbit at nominal longitude. Consequently, it was GEO or nothing and all effort was concentrated on the practical aspects of achieving that solution.

The essential idea was to reach the nominal GEO by first using chemical propellant to reach an intermediate orbit and then using the ion propulsion system in a new attitude-control mode to transfer to GEO. In principle, the intermediate orbit could be either an elliptical orbit or a circular orbit, but the latter was preferred since the transfer time is shorter. Circular orbits with a radius of 32 000 – 35 000 km and transfer times of 450 – 300 days with ion propulsion were originally considered.

The energy-efficient solution to reach GEO is to provide one or more impulsive thrusts at perigee (correcting for the deficiency of the launcher), thereby raising the apogee to a suitable height, followed by an orbit circularisation (and inclination correction) using impulsive apogee thrusts to arrive at an intermediate parking orbit, from which the ion propulsion can be used to provide a continuous tangential thrust to raise the orbit to geosynchronous altitude. A balance had to be found between the chemical propellant remaining in GEO and the time taken to transfer to GEO using ion propulsion. These parameters determine the height of the parking orbit.

There were several practical problems to be solved in implementing the perigee impulse. It was first necessary to conduct a trial in orbit to verify that the earth sensor would operate at the low altitudes of the sub-standard injection orbit. Furthermore, the control modes for the apogee engine had been designed to operate in sunlight and the perigee was in eclipse. It was therefore necessary to investigate and simulate new mode-switching and operating procedures to operate the engine as close to perigee as possible in the interests of efficiency. It was also necessary to reduce arc loss by using several perigee burns and find a balance between efficiency and overall duration, taking station coverage opportunities into account.

Station coverage was also required to set up the apogee engine-firing attitude prior to perigee pass. This consisted of manoeuvres around apogee to calibrate the gyros and a further manoeuvre to an inertial Sun-pointing attitude to ensure a good state of battery charge. The station coverage constraint gave only two opportunities per day for perigee burns and they had to be executed without delay to avoid solar-array degradation in the radiation belts.

Activities during this difficult period were made easier by the faultless operation of the satellite and the extensive knowledge of the operations teams. Operation of the infrared earth sensor (Officine Galileo) well below its specified altitude was also a critical element in achieving success with these early perigee operations.

These efforts were concluded successfully, and an efficiency loss of only 8% relative to a single impulse was achieved. On 17 July, the final choice of strategy was confirmed.

This stated that the recovery mission would be based upon arriving in geostationary orbit at 21.5°E with a balance between the remaining usable mass of chemical propellant in GEO and the duration of orbit-raising with ion propulsion. Five perigee burns and three apogee burns using the liquid engine were to be used.

The final target height of the parking orbit was selected to be 31 000 km just before the final perigee kick, corresponding to a remaining chemical propellant after liquid-engine firings of 70 kg and an orbit-raising duration of 200 days with ion propulsion. The reduced transfer time with ion propulsion was due largely to the improved efficiency obtained with the perigee strategy and a revision of remaining chemical propellant to the bare minimum. The total impulse imparted during perigee and apogee burns was 1885 m/s and 1449 kg of chemical propellant was used during this phase.

In view of the non-nominal parameters of the injection orbit (inclination 2.9 deg, argument of perigee 151 deg), there was a limit to the inclination correction that could be made during circularisation at apogee. In fact, a parking orbit with a residual inclination of 0.8 deg was achieved. Some or all of this inclination can be reduced using the ion-propulsion thrust during the orbit-raising phase. This will, however, increase the overall duration of this phase by a few months.

The result of the overall strategy is illustrated in Figure 1, where the effect of the five apogee burns and three perigee burns, and the remaining band of altitudes to be served by ion propulsion is shown.

Shortly after the last apogee burn and confirmation of the new circular parking-orbit parameters, it was decided to proceed with the deployment sequence as foreseen for the nominal mission. Following battery and attitude-control system checks, the solar arrays, L-band reflector and S/K-band antenna arm and reflector were deployed. The two ion-thrust alignment-mechanism platforms, which allow the ion thrusters to be directed through small angles, were also released and the unified propulsion subsystem blow-down mode commanded, isolating the liquid-apogee engine and high-pressure tanks. The satellite was later commanded from Sun-pointing mode to Earth-acquisition, wheel spin-up and normal mode entry. This was followed by the initiation of the SILEX terminal's deployment and software loading.

All subsystems of the satellite performed excellently during the transfer-orbit operations. The solar-array outer panels, which provide 25% of the total power, have suffered some degradation due to radiation, but this amounts to only 2% of overall performance and is within the end-of-life margins.

Orbit-raising phase

New station network

Following the successful LEOP (Launch and Early Orbit Phase) recovery actions, Artemis was left in a safe condition in a parking orbit of some 31 000 km altitude and 0.85 deg inclination. Under natural perturbations, the semi-major axis and eccentricity of this orbit do not change significantly, but the inclination increases steadily. In this orbit, the drift rate of the satellite seen from a ground station is about 70 deg/day: the satellite is visible for about 3 days from an equatorial station every 5 days.

The original LEOP tracking network was no longer available to support Artemis long-term operations, so the first important activity was to arrange for a new network. Thanks to Telespazio's policy of deploying their own TT&C baseband equipment at the stations, a new network providing global coverage was rapidly set up. By September, a four-station network consisting of Fucino (Italy), Dongara (Australia), Southpoint (Hawaii) and Santiago (Chile) was fully operational.

So far this network has proved to be rather reliable, with only a few planned gaps in station availability of typically a few hours and a few communications outages of some minutes. However, there is no station redundancy and coverage is not guaranteed. This factor has led to the need for increased spacecraft autonomy as part of the new control concept.

New attitude-control mode

There are four ion thrusters on Artemis mounted in redundant pairs to provide north

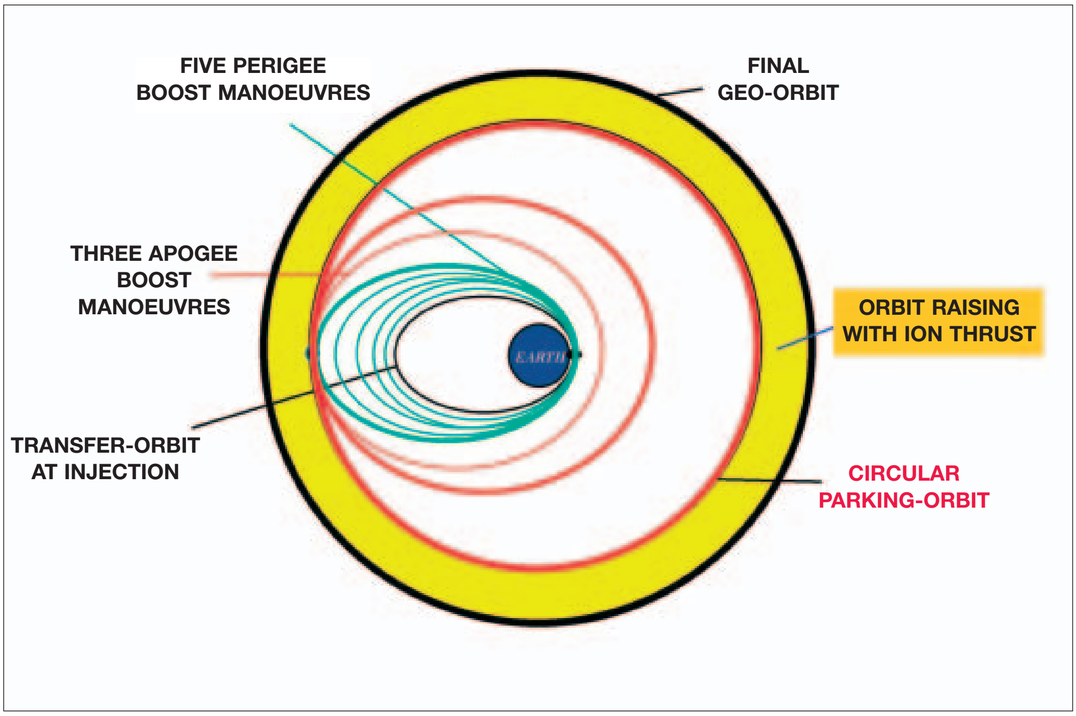


Figure 1. Overall manoeuvre strategy for Artemis recovery

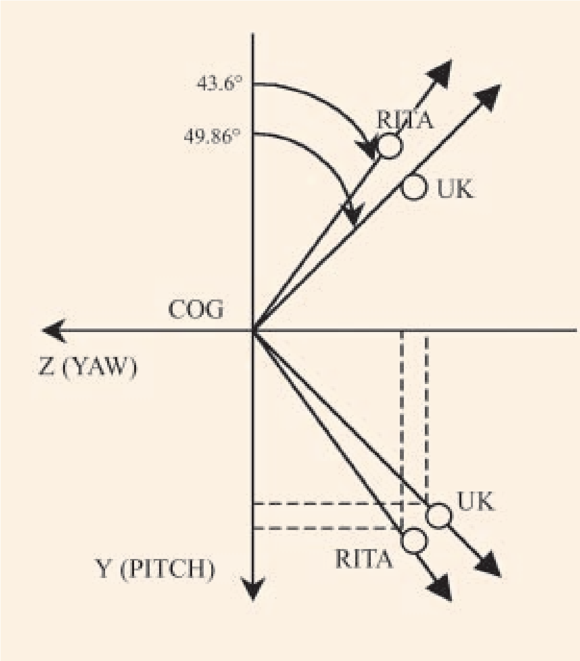


Figure 2. Ion-thruster orientation

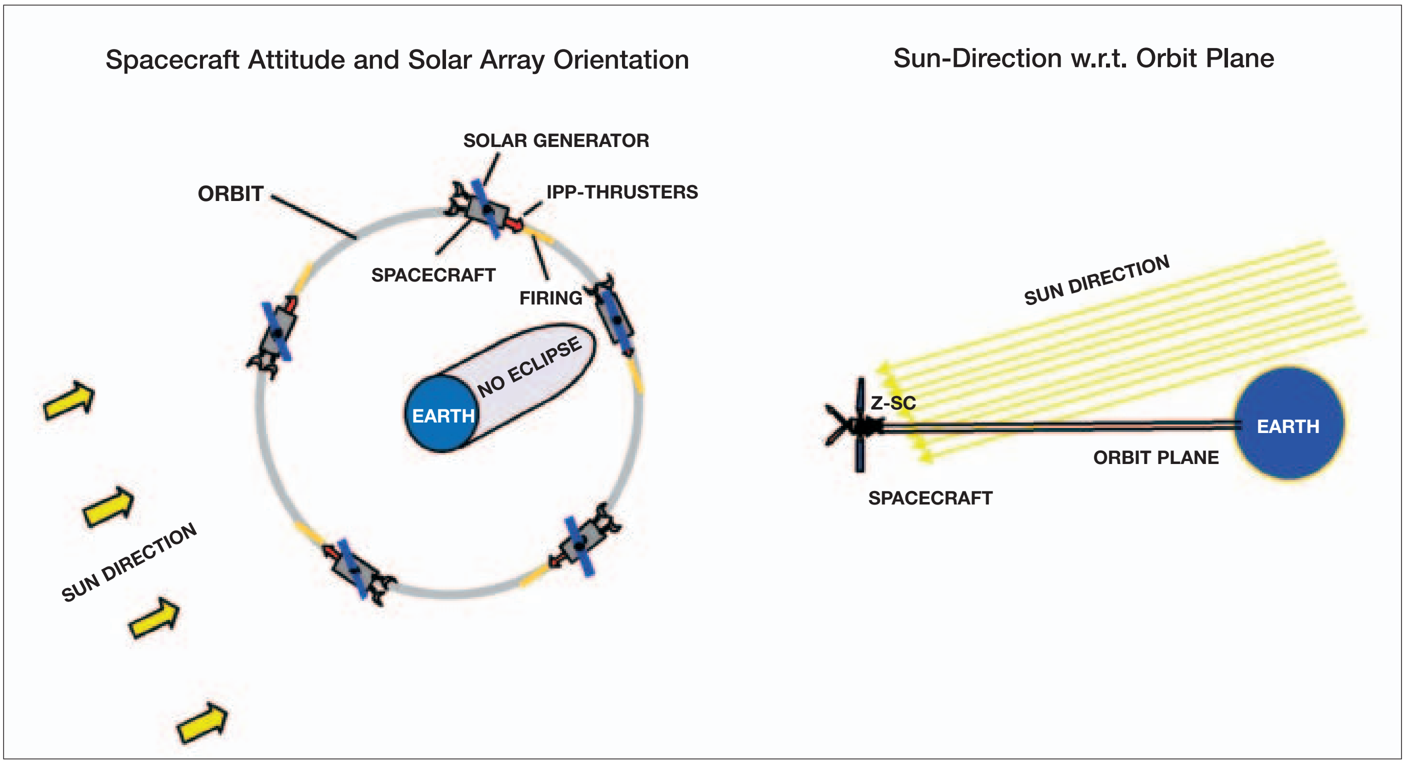
and south thrusting for inclination control in GEO (Fig. 2). Due to their location, and because their thrust has to be directed through the spacecraft's centre of mass, there is a large (70%) thrust component along the spacecraft's z-axis, which points towards the Earth. During normal GEO operations, this component is unwanted and is cancelled by the alternate operations of north and south thrust arcs on opposite sides of the orbit. However, this is the very component required for orbit raising. By re-orientating the spacecraft's z-axis from being Earth-pointing to point along the direction of motion of the orbit (Fig. 3), the thrust will augment the orbit velocity and gradually lead to an increase in orbit radius.

Either two thrusters are fired together, in which case a maximum in-plane thrust component is achieved, giving orbit raising only, or a single thruster is activated, in which case both in-plane and out-of-plane components provide orbit raising and inclination control together. The current baseline strategy consists of switching between one- and two-thruster operations over four arcs of the orbit. With the correct choice of arc, the residual inclination (by now some 0.95 deg) can be removed at the same time as the orbit radius is increased to the geostationary value.

A similar scheme involving the modulation of thrust levels is under consideration. This would avoid switching between thruster combinations and relieve the operational workload. More powerful thrust steering strategies are also being analysed, involving spacecraft attitude changes as a function of orbital position.

The new attitude control mode (referred to as NM-ITN, or Normal Mode Ion Thruster Navigation) is similar to the Earth-pointing normal mode in geostationary orbit, in that it is based upon fixed momentum perpendicular to the orbit provided by a spinning momentum wheel. As the Earth is no longer visible, the attitude-

Figure 3. Principles of orbit raising when there is no eclipse



control reference in roll and yaw is provided by the Precision Sun Sensor (PSS) and the Rate Integrating Gyro (RIG). This is an entirely new mode, which has not been used on a spacecraft before, and it is thanks only to the re-programmable control concept (Integrated Control and Data Handling System, ICDS) that it is possible to implement it on Artemis.

The new control concept includes other additional attitude-control applications: a special orbit propagator to give the Sun reference direction in the new orbit; an automatic gyro drift observer-estimator; and a closed-loop system for the continuous pointing of the ion thrusters, using the Ion Thruster Alignment Mechanism (ITAM).

As the new mode relies upon the Sun for an attitude reference, during eclipse seasons the spacecraft has to return to Earth-pointing and ion thrusting has to be interrupted, for those arcs of the orbit in the Earth's shadow. This sequence is illustrated in Figure 4.

A number of the standard operational functions of Artemis have been designed under the assumption that there is permanent TT&C contact between spacecraft and ground, allowing ready evaluation and response from the Operations Control Centre (OCC). Due to possible TT&C outages during the orbit- raising phase, a number of the more critical functions have had to be upgraded or re-designed for autonomous onboard control. These include:
– ion-propulsion subsystem management
– battery-charge management
– solar-array pointing and drive management
– eclipse entry and exit management, including automatic return to Earth-pointing
– orbit propagator and gyro calibration
– closed-loop ion-thruster pointing control
– fault surveillance, detection and recovery.

In addition, new telecommand, telemetry and data-handling interface functions for the above have been implemented.

In all, about 20% of the original ICDS (Integrated Control and Data Handling) software has been modified. These modifications have been effected by uplinking software 'patches' to the satellite amounting to 15 K-words, the largest ever for a telecommunications satellite.

Undoubtedly, the effort required for the design, development, test, integration and production of operating procedures was underestimated. But with so much at stake and with some early setbacks, it was considered prudent not to take shortcuts and make the most of the test models available. As it is, the new software has not been tested to the same level as existing functions and we are proceeding cautiously with activation of each sub-mode.

Nor has the development time for the new software been wasted at satellite operational level. The platform and payload functions have been commissioned and valuable in-orbit experience has been gained with the ion

Figure 4. Principles of orbit raising during the eclipse season

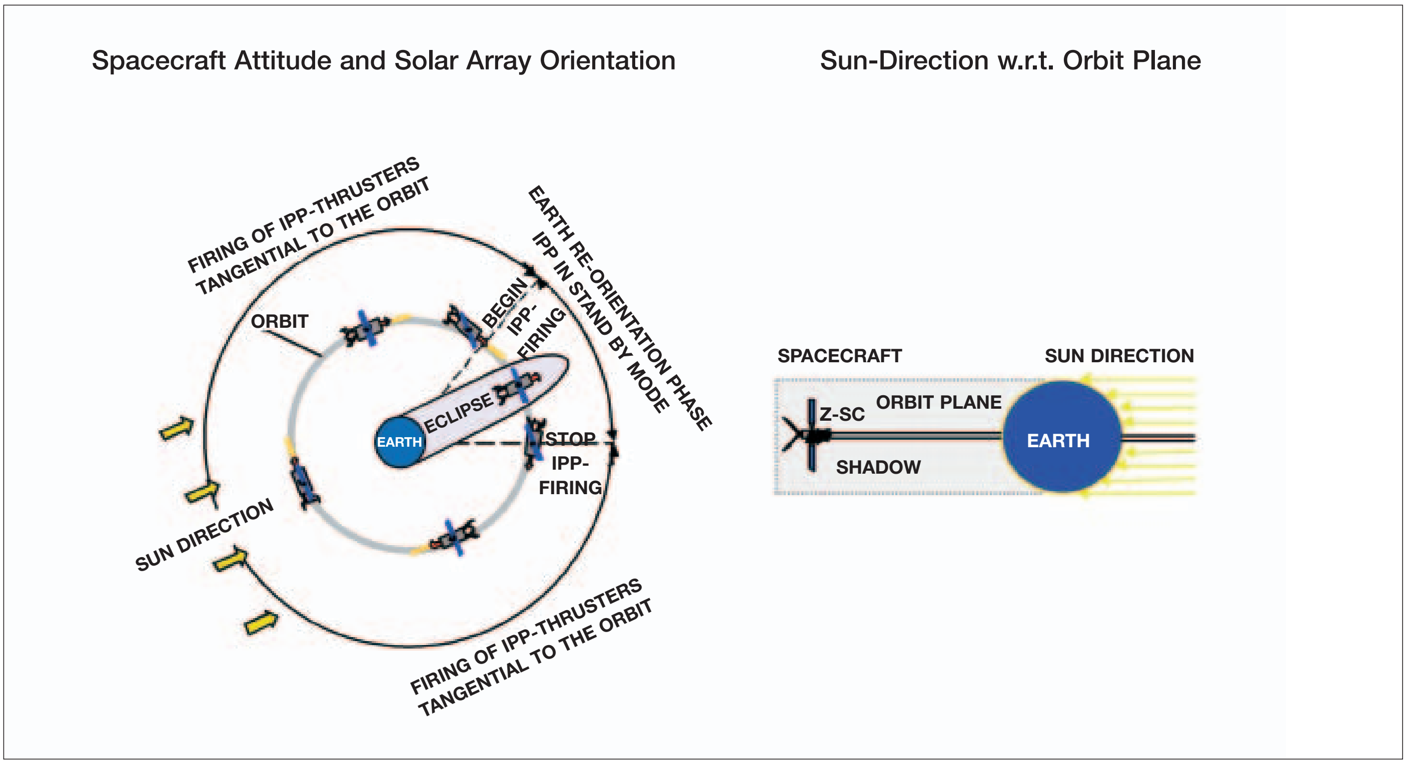
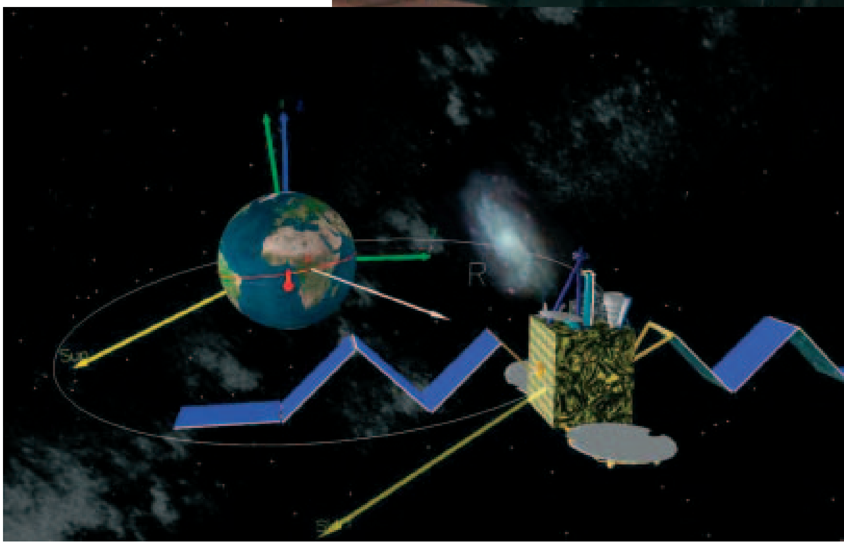


Figure 5. Telespazio's LEOP Control Centre, with the dynamic satellite visualiser (inset)



propulsion systems and ITAM control. During this same period, other operating modes of the satellite and the new ground facilities have also been exercised extensively. Moreover, very little propellant has been consumed during this phase.

Now the new mode is operational, but much observation and adjustment remains to be done in orbit. The eclipse season (which in this orbit starts around 22 February and lasts for some 50 days) will prove to be a testing time for the onboard autonomous functions and the operations team will be required to be vigilant around the clock.

Depending on the strategy and thruster combination used, we expect orbit raising to last about 200–250 days, representing an increase in orbit radius of about 20 km per day. Artemis carries two different ion-propulsion technologies – RITA and EITA – delivering slightly different thrust levels. The duration also depends upon the extent of inclination control applied during the raising process. In all cases, the xenon consumption is the same, about 16 kg or the equivalent of 4 years of normal north-south control in geostationary orbit. The last few hundred kilometres of orbit adjustment is expected to be made using chemical propellant with the small east-west station-keeping thrusters. When the drift rate is less than 3 deg/day, it is more efficient in terms of resources and interference with other users of the geostationary ring.

Spacecraft commissioning

Several months have passed between Artemis' arrival in parking orbit and the start of the orbit-raising manoeuvres. This period has been used to carry out commissioning and payload-performance verification.

Coming after the hectic transfer-orbit operations, platform commissioning was a relatively straightforward affair. Indeed, thanks to the many satellite reconfigurations needed during the LEOP operations, nearly all equipment and many spacecraft modes had already been exercised. It merely remained to test a few thermal configurations and initialise and configure payload equipment.

Payload performance testing was a more difficult matter. It required bi-directional RF links to be established between the spacecraft and the test and monitoring earth stations at ESA's Redu site in Belgium. Owing to the drift rate in parking orbit, link opportunities were limited to some hours every 5 days and special test methods and procedures were required. Moreover, use of the allocated radio frequencies is only allowed from the nominal orbital position at 21.5°E. This limitation was strictly respected for the 12 GHz band (Ku-band), which are widely used in the vicinity of Artemis' nominal position. For the Ka-band, there was more freedom to operate over the orbital arc from 10°W to 20°E in coordination with the relatively few Ka-band users in this region.

In order to cope with these constraints, a novel technique for performance measurement was devised to minimise transmit time and potential interference. This involved using very-low-power signal levels and rapid channel switching with computer-automated measurement and data logging on the ground synchronised with spacecraft switching operations.

The correct functional operation of all payloads was demonstrated, and payload performance was confirmed with satisfactory accuracy.

Two demonstrations are worth highlighting here. To establish a data link between with a user satellite in LEO, the 3 m SKDR steerable antenna on Artemis has to be pointed with high accuracy towards the user for the duration of the data transmission. Pointing can be performed in two ways:

– by programmed (open-loop) tracking: in this mode of operation, the antenna pointing angles are calculated using the orbit parameters of both Artemis and the user spacecraft and are updated every few seconds to maintain the required pointing accuracy
– by radio-frequency (RF closed-loop) tracking: in this mode of operation, the antennas of both Artemis and the user spacecraft are first pointed in open loop towards the partner; after an acquisition process both antennas track on the communications signal from the partner spacecraft.

Both modes of operation were demonstrated by maintaining antenna pointing and the communications link towards the earth station at Redu, with Artemis drifting in its parking orbit at a rate of 3 deg per hour.

Most impressive was the demonstration of the optical data-relay system SILEX between Artemis and SPOT-4, and as a preparatory exercise, between Artemis and the optical ground station in Tenerife (E). The art of establishing the optical data link consists of pointing a laser beam so accurately that the partner satellite is illuminated. The laser beam

The Principles of Ion-Engine Operation

EITA and RITA are both are ‘gridded’ ion thrusters, providing an impulse of about 3000 sec (approx. 30 000 Ns/kg) specific impulse, and for both engines the ion-beam neutralisation is provided by electrons delivered by a so-called ‘neutraliser’ electron source. Two separate developments have been pursued with industry to avoid the possibility of the incorrect application of a single technology jeopardising the future utilisation of electric propulsion in European space programmes.

The Electron-bombardment Ion Thruster Assembly (EITA) is a so-called ‘Kaufmann engine’, where the ionisation is performed by a DC discharge in a main cathode (Fig. 6a). The ions are focussed by means of magnets (solenoids) and accelerated in an three-grid system made of molybdenum. In contrast to other designs, the Astrium/DERA thruster utilises an inward dished grid. The innermost grid has the highest temperature and therefore due to the material expansion caused by the operating temperatures the dish will increase most for the hottest grid and less for the next grid. Thus the spacing between the grids increases when the thruster is operating, reducing the danger of a direct contact between grids.

With the Radiofrequency Ion Thruster Assembly (RITA), the ionisation is performed by a 1 MHz alternating field, induced by a coil surrounding the discharge chamber (Fig. 6b). Thus no main cathode or magnets are needed. The ions are again accelerated in a three-grid system, but the middle electrode ‘acceleration grid’ is made of graphite, providing greater resistance to material loss due to sputtering effects caused by the ions. Due to the relatively high specific resistance of graphite compared to metals like molybdenum, a potential graphite bridge between two grids is cleared by a substantially lower current than is required to clear a metal bridge.

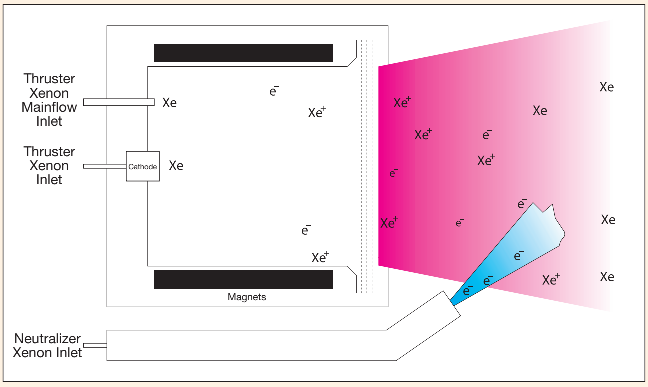


Figure 6a. Principles of EITA thruster operation

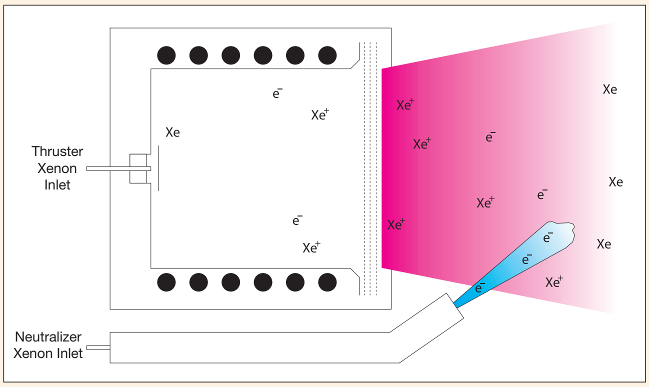


Figure 6b. Principles of RITA thruster operation

has a width of only 300 m after travelling 40 000 km through space while the LEO satellite has a relative velocity of several km/s.

Up to now, we have attempted to establish 26 optical links and all of them were successful. Once the link was acquired it was always maintained for the pre-programmed time, and no loss of link has ever occurred.

The communication link quality is remarkable. Quality measurements for the overall link, including the feeder link from Artemis to Redu, resulted in a Bit Error Rate (BER) of better than 1 in 10^9, i.e. when transmitting 1 billion bits, only one was erroneously received.

SPOT-4 image data has been relayed in real-time via Artemis to the data-reception centre in Toulouse. The picture quality was almost perfect, providing a convincing demonstration of the advantages of a data-relay system.

Outlook

The Artemis project has suffered many significant delays, initially for programmatic reasons and later due to an uncertain launch scenario. Now the rescue operation has added to this overall delay. Nevertheless, considerable progress has been made towards recovery. If the experimental ion propulsion system performs as planned, we expect the spacecraft to arrive on station in geostationary orbit in the latter half of this year and with sufficient propellant (chemical propellant and xenon) to support a nominal GEO mission for 5 to 7 years.

In parking orbit, the correct functioning of the communication payloads has already been demonstrated and Artemis will be able to provide its main services as planned:
– the L-band mobile communication payload will be used commercially by Eutelsat
– EGNOS will use the navigation payload, first experimentally, and later operationally
– SPOT-4 will use the SILEX optical data-relay payload for at least 5 orbits per day
– Envisat will use the Ka-band data-relay service for at least 3 hours per day.

It is to be hoped that Artemis will continue to stimulate European data-relay services, with the Space Station and other users who have shown an interest in this potential.

A lost mission is on course for a unique recovery. In terms of a reversal of fortune, it bears comparison with the earlier rescues of ESA's Olympus and Hipparcos missions. It will set new standards for the use of ion propulsion and re-programmable data-handling and attitude-control systems.

Acknowledgements

With operations of this kind, it is common to stress the need for teamwork. In this case we can honestly say that the team skills and close cooperation of Alenia and its subcontractors, Telespazio and ESA were essential for all aspects of this novel recovery mission. Astrium, Fiat Avio, Officine Galileo and Vega deserve special mention for their vital support during the critical LEOP activities. We would also like to pay tribute to the inspiration of Alenia and Astrium (D) engineers in conceiving of the new attitude- control mode and their perseverance during its development and testing. The ground operation teams, Telespazio with Alenia project support, have exhibited a command of procedures, facilities, flight dynamics and knowledge of the satellite that has been exemplary. We would also like to thank ESOC's flight-dynamics personnel for their timely and spontaneous advice, and the ESOC network team for extending LEOP services.

The spacecraft itself has performed well beyond its normal design specifications in many critical areas, and the accompanying panel provides a list of the major industrial participants in its realisation.

The industrial organisation for Artemis

– System		Alenia Aerospazio (I)
– ICDS		" "
– Thermal Control		" "
– Structure		Casa (E)
– Power Subsystem		Fiar (I)
– Solar Array		Fokker (NL)
– Solar-Array Drive Assembly		Astrium (UK)
– Batteries		Saft (F)
– Unified Propulsion System		Fiat Avio (I)
– Ion Propulsion:	RITA	Astrium (D)
	EITA	Astrium (UK)
– LLM Payload		Alenia Aerospazio (I)
– SKDR Payload		" "
– IAPS/IOL Antenna		" "
– Forward Repeater		Alcatel Espace (F)
– Return Repeater		Bosch Telecom (D)
– TT&C and Comms.		Alenia Aerospazio (I)
– OPALE (SILEX)		Astrium (F)
– System MGSE		ORS (A)
– System EGSE		Laben (I)
– Parts Procurement		TOP-REL (I)
– Ground Segment and Operations		ALTEL (I), INDRA (E), RYMSA (E), Laben (I), Vega (UK), GMV (E), ESOC