ARTEMIS ORBIT RAISING IN-FLIGHT EXPERIENCE WITH ION PROPULSION

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Abstract

To demonstrate and promote North/South station keeping (inclination control) using ion propulsion, ESA on July 12, 2001 onboard Ariane 510 launched its most advanced telecommunication satellite: ARTEMIS. Due to a launcher failure the satellite was injected into a useless too low elliptic orbit. The ARTEMIS mission was salvaged by the ALTEL/Astrium/ESA team at Telespazio (Fucino) using in novel modes of operation the on-board chemical and ion propulsion systems provided by Astrium.

By means of the chemical propulsion system provided by Astrium GmbH – Lampoldshausen - the initial orbit, having an apogee of half the targeted altitude, was quickly upgraded to a safe circular parking orbit at 31000 km altitude. The Liquid Apogee Engine was fired in total 8 times to achieve perigee as well as apogee raising.

The final orbit raising to geostationary altitude was performed by means of the ion propulsion system (IPP) applied in a newly designed spacecraft attitude control mode. Alenia Spazio and Astrium, in close cooperation, redesigned all control and data handling software modules affected since the original spacecraft configuration was designed to use the ion thrusters for inclination control only and not to generate thrust with the ion engines in a direction tangential to the orbit. The flexibility of the IPP system consisting of 4 thruster assemblies, provided in its totality by Astrium including the 2 alignment mechanisms for precision thrust direction control, have proven invaluable.

To demonstrate the technologies available in Europe and to enhance reliability, Astrium implemented two different technologies: a Kaufmann type system (EITA) provided by Astrium Ltd. – Portsmouth, and a Radiofrequency Ion Thruster Assembly (RITA) provided by Astrium GmbH – Ottobrunn. Two ion engines of different technology were mounted side by side on one ITAM (Ion Thruster Alignment Mechanism) provided by Austrian Aerospace. A common propellant feed system was used to supply Xe to all thrusters.

This paper, after a brief description of the ion propulsion system, will summarize the results of the qualification life testing as well as of special testing to support the orbit raising. The main part of the paper will address the IPP performance on ARTEMIS in orbit during the orbit raising operations.

1. The ARTEMIS Project

ARTEMIS (Advanced Relay and TEchnology MISsion) is a geo-stationary telecommunication satellite developed by Alenia Spazio as prime contractor for the European Space Agency, as part of the Data Relay Technology Mission (DRTM). ARTEMIS is a three axis stabilized satellite and has a mass of 3100 kg. The main purpose of ARTEMIS is to promote advanced telecommunication technology. ARTEMIS, after a number of delays, was launched on June 12, 2001 on an ARIANE 5 together with the PAS2B satellite. The planned mission duration is 10 years.

In addition the ARTEMIS satellite was selected to demonstrate the advantages of ion propulsion for station keeping of geo-synchronous satellites during a real mission. This is the second use of ion propulsion in Europe, after its first quite short but successful flight demonstration of RITA on-board of EURECA.

2. Ion Propulsion System Description

The Ion Propulsion Package (IPP) for ARTEMIS [1]; [6], was developed under the leadership of Astrium GmbH, to provide the Δv required for North-South-Station-Keeping. For this purpose as shown in Figure 1 one couple of thrusters, consisting of one RIT (Radiofrequency Ion Thruster) and one EIT (Electron-bombardment Ion Thruster), is mounted on an alignment mechanism (ITAM – Ion Thruster Alignment Mechanism) on the north- and on the south panel.

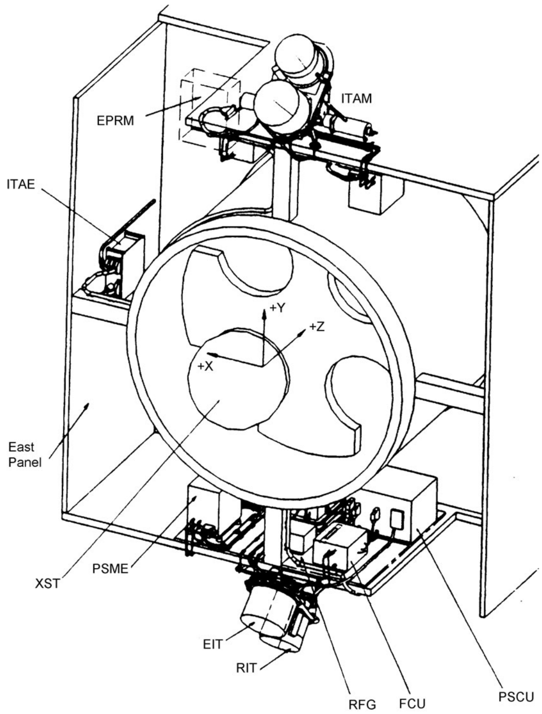

Figure 1: Allocation of IPP on ARTEMIS

To avoid that the fast ions of the beam impinge on the solar cells the thrusters are oriented canted away from the solar arrays as shown in Figure 2. Both EIT and RIT thrusters have very low beam divergence angles, minimising any possibility of interactions with the solar arrays.

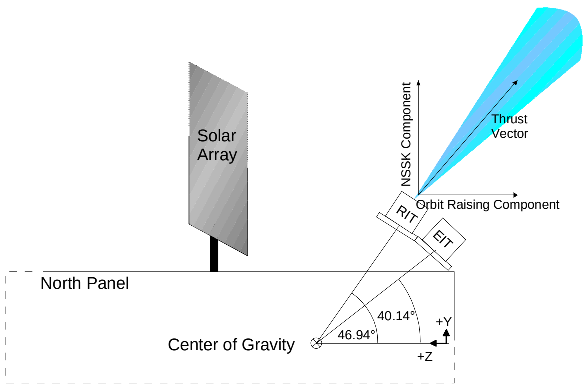

Figure 2: Ion Thruster Orientation ARTEMIS

For NSSK (inclination control) one thruster on the north panel will be operated for 3 hours when the satellite passes the ascending node and one on the south panel 12 hours later, when the descending node is passed. The complete IPP consists of the following assemblies:

- 1 Propellant Storage and Distribution Assembly (PSDA) [Astrium Ltd] including the Xenon Storage Tank (XST) [MAN-Dowty], the Electronic Pressure Regulator Mechanism (EPRM), the Electric Pressure Regulator Electronics EPRE which is physically included in the EITA electronic box, and high and low pressure Fill and Drain Valves (FDV) [Raufoss].

- 2 Electron Bombardment Ion Thruster Assemblies (EITA - Kaufman type), [Astrium Ltd.]. The EITA subassemblies are the thruster EIT, the Propulsion Control and Electronics PCCE, and the Propellant Supply and Monitoring Equipment (PSME). Further details are given in [11] and [12].
- 2 Radiofrequency Ion Thruster Assemblies (RITA) [Astrium GmbH]. The RITA subassemblies are the thruster ERT, the Power Supply and Control Unit PSCU, the Radio Frequency Generator RFG, and the Flow Control Unit (FCU). A detailed description of the RITA is given in [1] to [4].
- 1 Ion Thruster Alignment Assembly, consisting of- 2 Ion Thruster Alignment Mechanisms (ITAM) [Austrian Aerospace] and the Ion Thruster Alignment Electronics (ITAE) [Astrium GmbH], which has a pointing range of > 6° half-cone angle from the nominal orientation.

Figure 3 shows the block diagram of the IPP assemblies. The solid lines demonstrate the Xenon feed line tubes, while the dotted lines represent electrical connections.

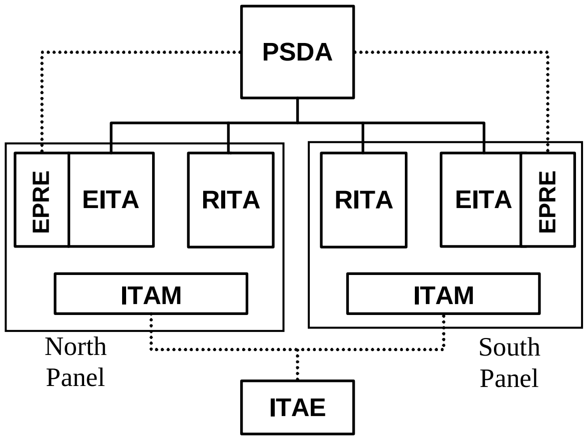

Figure 3: ARTEMIS IPP block diagram

3. Effect of the Launcher Failure

ARTEMIS was launched on July 21, 2001 from Kourou. Due to a malfunction of the ARIANE 5 upper stage, the satellite was injected into a useless too low orbit:

	Perigee	Apogee	Inclination
Orbit achieved	580	17,350	2.5°
Required GTO	810	35,600	2.0°

Although the satellite had been launched with a surplus of 200 kg bi-propellant fuel and oxidizer, this would have been just sufficient to achieve GEO using the bi-propellant system, but as nearly all propellant would have been used up, no meaningful mission would be possible. Immediately after the problem was discovered, the ARTEMIS team (ESA, Alenia Spazio and Astrium) at the TELESPAZIO center in Fucino developed a strategy to bring ARTEMIS into a safe circular orbit and use the IPP for orbit raising which is shown in Figure 4. The goal was to allow a 5 year mission at nominal orbit.

In a first step the apogee height was increased to 31,000 km. For this the 400N main engine, built by Astrium, was operated during 5 successive perigee passages. For each of the perigee maneuvers, starting from sun acquisition the following steps were to be performed: Command earth search, earth capture & acquisition by ground command, start of gyro calibration & drift compensation, acquisition of three axis inertial reference, and orientation of the main thrust engine towards optimal perigee boost direction. To maximize the efficiency the maneuvers had to be performed as close as possible around the real perigee which was inside eclipse (no Sun). In a second step the orbit was circularized at an altitude of 31,000 km (circular parking orbit) with 3 apogee typical boost maneuvers. These maneuvers were performed within a few days to bring the satellite above the van Allen belts.

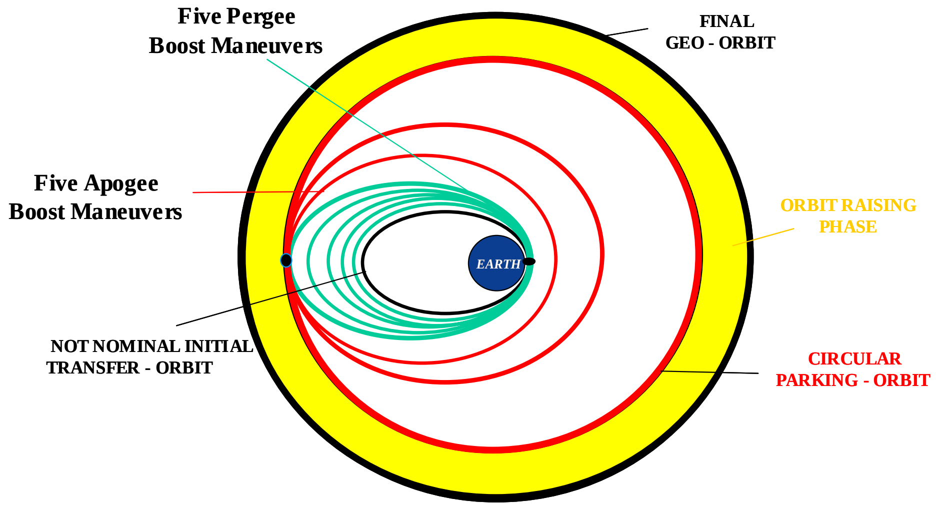

Figure 4: Maneuver Strategy for ARTEMIS Salvage Mission

4. Ion Propulsion System Activation and Early Mission Events

In a third step, after the solar arrays were fully deployed, the IPP was activated and tested. After the initial venting of the feed lines required to get rid of gasses (e.g. O_2, H_2O, ...) which could poison the thrusters' cathodes and neutralizers, the electric pressure regulator (PSDA) was activated and the Xenon feed system pressurized to the required 2 bars regulated Xenon pressure. In a next step the respective electronic boxes of both RITAs and EITAs were checked out successfully and the neutralizers and cathodes were activated. During this process it was discovered that the heater of the RITA1 neutralizer stopped its operation (short circuit) during the activation process. A failure of the heater element due to the higher than expected environmental loads during the early Ariane 5 upper stage operation is regarded the most probable cause. In order to investigate contingency measures and to prepare for the future, the operation of RITA1 using the EITA1 neutralizer was checked. This neutralizer is mounted in roughly 25 cm distance from the RIT. A reproducible ignition of the thruster's discharge could be demonstrated after the thruster inlet pressure for this activity was increased by 15%. The operation of the RIT when using the neutralizer of the other thruster was nominal. This was possible as the RITA system that nominally is operated with automated sequences can be operated in single steps as well for testing and contingency purposes.

To allow a safe operation of the RITA1 with a remote neutraliser that is not part of the RITA1 failure detection algorithms one major issue was to be considered. As the discharge in a RIT thruster, after it was initiated by electrons sucked into the thruster by a positive ignition voltage supplied to the grid, is self sustained, the thruster would keep thrusting, even if the neutralizer of the remote thruster would be off. Sending a continuous ion current of 234 mA into space would result in building up a rapid negative charging of the satellite, which would lead to failures in the electronic system and finally could attract the Xenon Ions back to the satellite causing a massive erosion. In order to protect the satellite with respect to this failure it was decided to switch on the neutralizer of RITA2 as back-up and to implement a new failure algorithm, that in case one of the two neutralizers is switched off will send an alarm to the ground station and in case both are off, immediately will switch off the thruster.

In order to produce a maximum thrust in +Z direction it was planned to use two thrusters operation simultaneously, although by this mode of operation about 9mN of thrust was eliminated by counteracting thrust vector components and the effective specific impulse would be reduces to about 2000 s. As this was not part of the original requirements it was, of course, not tested on ground. Consequently special in-orbit tests were performed to demonstrate simultaneous operation of: EITA1 and EITA2, RITA1 and RITA2, RITA2 and EITA1 and to check for potential interactions. It was found that the RITA2 neutralizer when the thruster was operated together with EITA1 or with RITA1 plus the EITA1 neutralizer delivers a higher electron current as nominal. This indicates that the RITA neutralizer provides electrons for the neutralization the other thruster as well.

The cause for this behavior is that different grounding concepts were used for RITA and EITA. As only the operation of one thruster at a time was specified, there was no need to require identical grounding. The RITA telemetry of the electron current, called neutralizer bias current, has a maximum value of 333 mA (FF HEX).

This value is reached when at nominal thrust levels RITA2 is operated together with another thruster. Unfortunately the EITAs do not provide information on what electron current is emitted. Therefore the real electron current delivered by the RITA2 neutralizer was not known, but based on measurements of how the total electron current is split at lower thrust levels we could conclude that the RITA2 neutralizer delivered about 400 mA which is about 70% higher than during single thruster operation or 30% higher than qualified. To find out whether this operation could have a negative effect on the neutralizer, an accelerated life test of a EQM neutralizer was performed and is described in [9].

To implement the orbit raising a massive update of the satellite's software (AOCS and System) was required. During the time this software was developed, the ion thruster's were used to reduce the inclination. For this the baseline pair of thrusters RITA2 and EITA1 were used. The operation times were increased from the nominal 3 hours around each nodal line passage to 8 hours.

On 29th November 2001, EITA1 failed to recover following a beam-out. A beam out occurs when a high voltage short in the electronics, harness, thruster or plasma is detected by the over-current protection and the high voltages are switched off. Beam-outs due to plasma shorts are normal, particularly during early operations of the thruster whilst some outgassing may continue. The thruster could not be restarted although several attempts were made. Consequently it was decided to use RITA1 and RITA2 for the begin of the orbit raising period until this failure was understood and it could be excluded that the same would occur on EITA2. The failure investigation came to the conclusion that the final inability to restart the thruster, with a high probability, was caused either by a carbonization of the filler material in a Zener-Diode block in PCCE, or due to degradation of the harness between the PCCE and thruster. The diodes are used to limit the anode supply voltage during transient phases (i.e. beam outs). It was assumed that extended heating times applied for the cathode heaters may have caused an overheating of the diodes. But it could not be identified why, during the nominal heating, the anode voltage exceeded the limit, at which the diodes open. Hence, it is considered more likely that the problem resides in the harness.

To start the orbit raising as soon as possible, it was decide to use both RITAs plus the EITA1 neutralizer. Due to the fact both EITAs used the same telecommand addresses, an operation of the EITA1 neutralizer in parallel with a complete EITA2 initially seemed to be not feasible. However, Astrium Ltd. later developed software modifications that subsequently allowed this operation.

5. Reconfiguration of the Avionics System for the Orbit Raising Phase

The 3-axis attitude control and the orbit raising strategy using ion thrusters for the Artemis Spacecraft Salvage Mission will be described in this chapter. Especially during the boost phase only inertial 2-axis attitude measurements from the Sun sensor and two axis rate measurements from the gyro assembly are available for attitude determination. In contrast to the nominal operation, where the attitude is controlled with respect to a fixed orbital Earth pointing reference frame, large-angle time-varying rotations have to be performed to orient the ion-thrusters into the fuel optimal boost direction. The design consist of a new attitude estimator / propagator, an adaptation of the orbit propagator, a continuous 3-axis wheel unloading method during firing and a nonlinear decoupling & tracking controller. The orbit raising strategy is designed to govern all possible combinations or single use of the IPP-thrusters and control as far as possible inclination and eccentricity under the Artemis specific constraints like Field of View (FOV) of sun-sensors, available electric power, thermal aspects, and limitations of the wheel configuration. A detailed description of the strategy and the approach for the new pointing control mode is given in [10].

The new orbit raising mode consists of two phases:

1) Earth pointing phase when infrared earth sensor (IRS), Precision Sun sensors (PSS) and two gyros (skewed and along z - axis) are available for measurement.
2) Orbit raising phase when only PSS and the two gyros are available for measurement. In this phase the IPP will be used for delta -V generation. The ion thrusters are placed on steerable platforms (ITAM's) on the anti earth panel of the satellite but tilted in such that they can provide thrust for N/S orbit corrections. However there is also a component in the + z-direction which will be used for raising the orbit. For this purpose the satellite must first be rotated in pitch by about 90°, so that the thrust vector is tangential to the orbit.

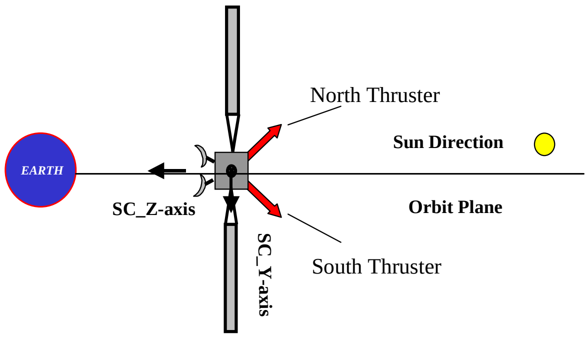

Figure 5: Principle Configuration of Ion Propulsion Thrusters

The ion propulsion thrusters are mounted canted by about 40° (for EITA) and 47° (for RITA) w.r.t. the +Z direction. Consequently when using two thrusters, one on each panel for orbit raising the +y and –y components of the thrust vector a compensating each other. This leads to an effective thrust in the +z direction of 27 mN when using both EITAs and 21 mN for the RITAs, but in both cases reduces the effective specific impulse.

Other general constraints for the orbit raising are:

- Continuous high electric power demand during thrust generation (available, as payload is switched off)
- Nominal thrust orientation is the flight direction
- Large time depending rotations in two axis perpendicular to the nominal thrust direction for ground controlled final spacecraft positioning
- Minimization of ground operation support
- Almost continuous operation of ion-propulsion system until to final orbit
- Maximum use of existing AOCS - SW for the new operational conditions
- Development period of operational control mode must be compatible with the overall schedule
- Generation of maximum thrust in SC z-axis and minimum disturbance torques by selection of optimal ITAM–angles by ground investigations

Based on these the main design drivers were:

- Availability of Ion Propulsion Thrusters (RITA & EITA)
- Thruster Configuration 1
  two RITA or two EITA or a mixed configuration of one EITA and one RITA on the corresponding ITAM‘s both continuously operating
- Thruster Configuration 2
  combined configuration of one EITA and one RITA on the corresponding ITAM’s but operating alternately
- Thruster Configuration 3
  Use of one ion propulsion thruster
- Acquisition of three axis reference with optical Earth & Sun measurements followed by a orientation of the S/C towards the required thrust direction
- Continuous change of orbital parameters and autonomous eclipse management
- Pointing accuracy of thrust vector w.r.t. to optimal flight direction to be better than +/- 5° half cone average value over one orbit => 0.996 efficiency
- Autonomy without ground contact of 10 days
- Orbit Raising during Eclipse periods will reduce the orbit raising phase of 30 days or 60 days when two IP-thrusters are used or when only one IP-thruster can used respectively

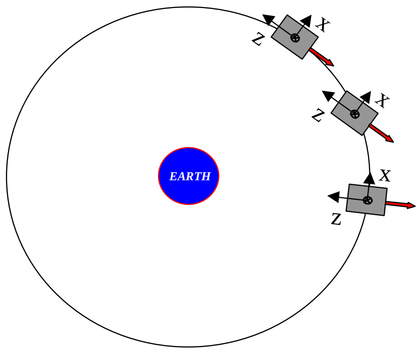

Figure 6: Change of satellite orientation from earth pointing to orbit raising attitude

For the orbit raising the satellite, designed to operate earth pointed, has to be turned such that the Z-axis is tangential to the orbit. Therefore the S/C, as show in Figure 6, has to be turned by 90° by a pitch rotation around angle theta. The S/C's AOCS software was modified such that the orbit raising can be performed quasi automatic, controlled by a orbit propagator, using the sun sensor of the solar array for reference.

The spacecraft attitude with fixed pitch rotation (Q = p/2) and time dependant roll biasing and control of solar generator orientation during n/2 orbit periods are shown in Figure 7 for the outside eclipse season. To update and recalibrate the orbit propagator the S/C has to be turned to earth pointing every ten days.

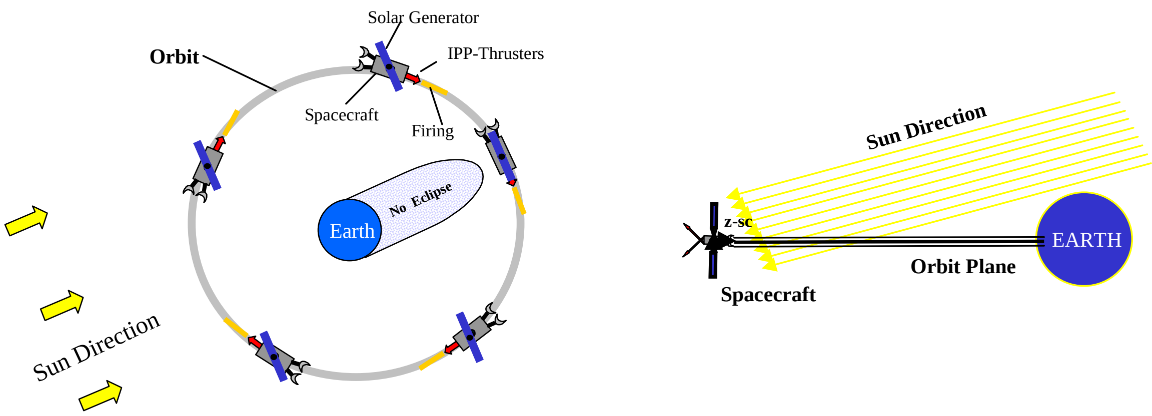

Figure 7: Satellite during orbit raising during off-eclipse season

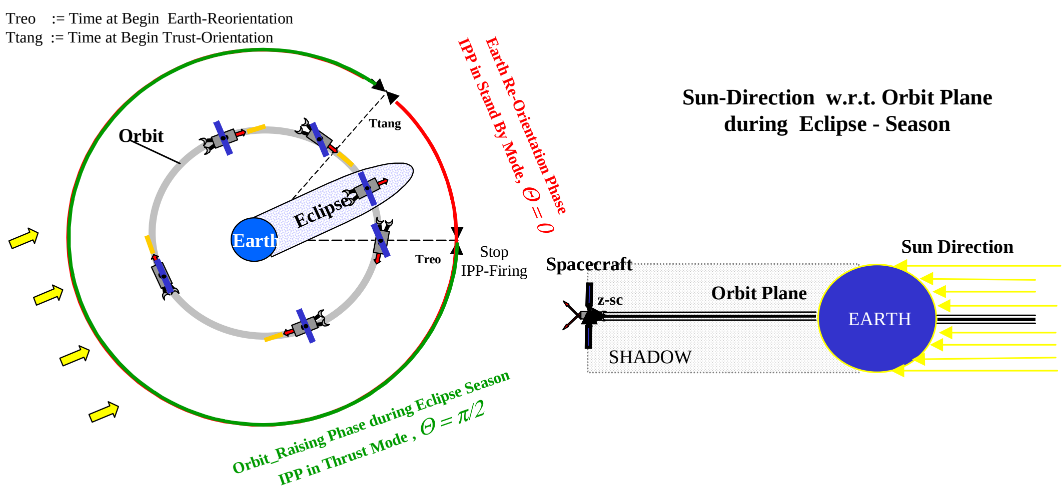

Figure 8: Principle Configuration of Ion Propulsion Thrusters

During eclipse phases the orbit raising is performed identically with the one difference that before entering into the earth's shadow the thrusters are turned into standby and the satellite is turned to earth orientation in order to maintain celestial reference by using the earth sensor. For this purpose the roll bias has to be set to zero before commanding to earth reorientation and IPP-thrusters in have to be switched off or commanded into standby. This is required to provide zero force components and reduced el. power consumption during eclipse. This principle is shown in Figure 8.

6. Electronic Pressure Regulator Performance

As indicated above, the ARTEMIS IPP is equipped with an Electronic Pressure Regulator (EPRM) that provides Xenon at a constant pressure of nominally 2 bar to the respective flow regulator of the RITA and EITA systems. This unit has supported all IPP operations since the start of the mission (for both EITA and RITA activities), and during a cumulated operation time of more than 6700 hours has performed flawlessly. Figure 9 below shows an example of the pressure telemetry provided from this unit. The drift in high pressure is due to temperature variations in the tank; the cycling of the low pressure is a feature of "bang-bang" regulation method employed, and shows excellent repeatable performance within specification.

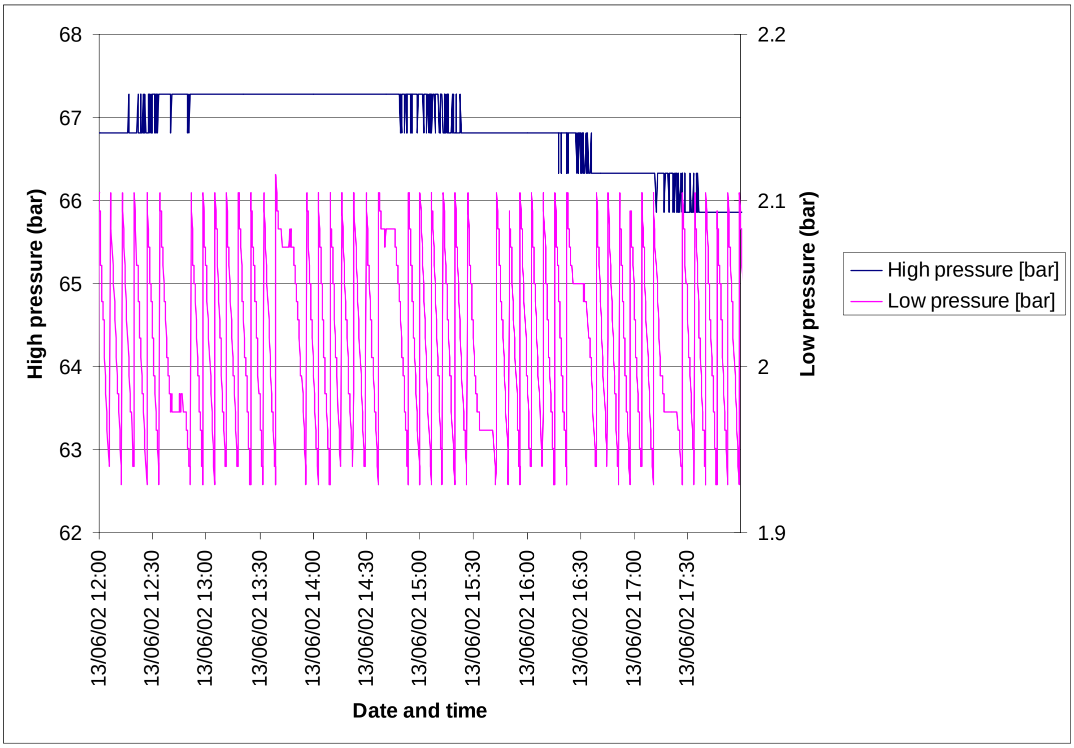

Figure 9: EPRM Telemetry

7. Results of Orbit Raising

The orbit raising, after the new software was uploaded and a few initial tests were completed, was started on 4 April 2002. As described above the raising maneuver was started with both RITAs firing simultaneously. On September 23, the orbit was increased to a semi-major axis of 40,000. During the early mission phase it was found that the beam outs were more frequent than expected, but the number decreased with time. In addition the accel drain current, resulting from the orbits (21 to 24 hour) thermal period, showed a sinusoidal variation with the same period and phase as the FCU temperature. By this the thermal environment for a ion thruster during orbit raising is more complex than e.g. during deep space missions, as in the later case the solar incidence angle is nearly constant over a long time. In the case of ARTEMIS due to the roll biasing the thruster is subject to a continuous variation of the solar radiation thermal input.

The RITA performed as expected, regarding the not specified operation regime. In Figure 10 the orange line shows the temperature variations of the FCU, while the pink line is the temperature of the ITAM platform for a period of 7 orbits. The red (upper) line shows the accel drain current (INHV) and the beam current is shown as blue line. The variation of the INHV is caused by two effects. As can be seen there is long period variation of about 22 hours, caused by the thermal environment during one orbit. A 2nd order variation, having a period of about one hour is caused by the Xenon load cycle of the FCU which has a regulation bandwidth of about 100 mbar.

It can be seen easily that all graphs have the same period, but only the phases for the FCU temperature and the INHV (= accel. drain current) co-incide. This is due to the fact that the thruster inlet pressure and by this the flow rate varies with the FCU temperature. The interruptions are eclipse phases when the thruster was switched to standby and the satellite was in earth to keep reference and update the orbit propagator.

On May 31 the orbit raising was interrupted and the RITA's were switched off, to test the new software that should allow to operate the EITA1 neutralizer together with EITA2. After the software upload was completed and RITA1 was to be switched on again, a blockage of the Xenon flow in the feed system to the thruster was detected. The blockage is believed to be caused either by a valve stuck close due to mechanical or electric reasons or due to a blocked flow restrictor. The causes are still under investigation and measures are investigated to achieve a better understanding and if possible to find a work around.

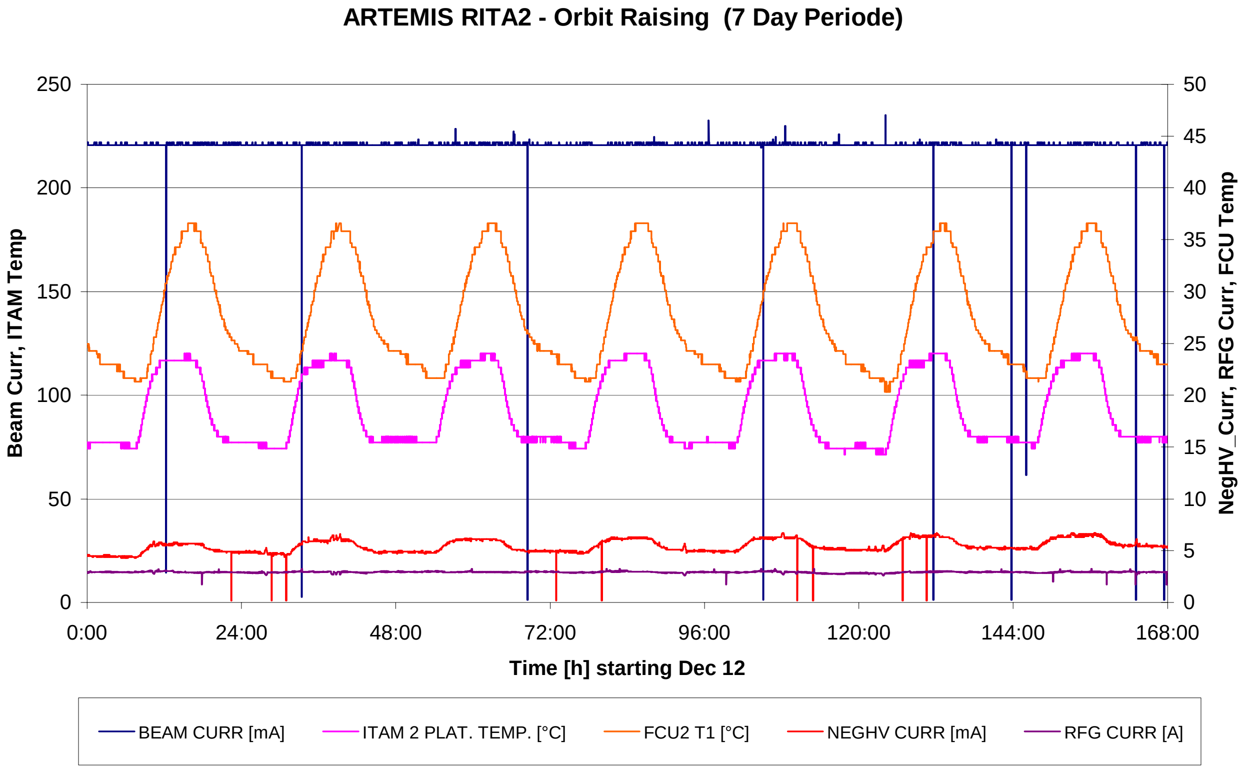

Figure 10: RITA Thermal Effects during 7 days of operation

In order to continue with the orbit raising EITA2 was kept in operation. After 10 days of nominal operation on June 12 the telemetry for the INHV nominally at 1.6 mA showed the full scale (FF hex) value read as 13.65 mA. As the full scale value should be 26 mA it has to be concluded that a telemetry conversion failure is occurring and the nominal INHV value was about 3.2 mA. As all other performance values were nominal, the anomaly was regarded a telemetry problem. During the subsequent days the full scale INHV was present for long periods and sequences of beam outs (inner thruster short circuits) occurred, during which the PCCE was not able to reinitiate thrust, requiring the operators to switch on the thruster manually. On 27 June the EIT operation was terminated, as the ITAM platform (see Figure 11) reached the maximum allowable temperature of 130°C.

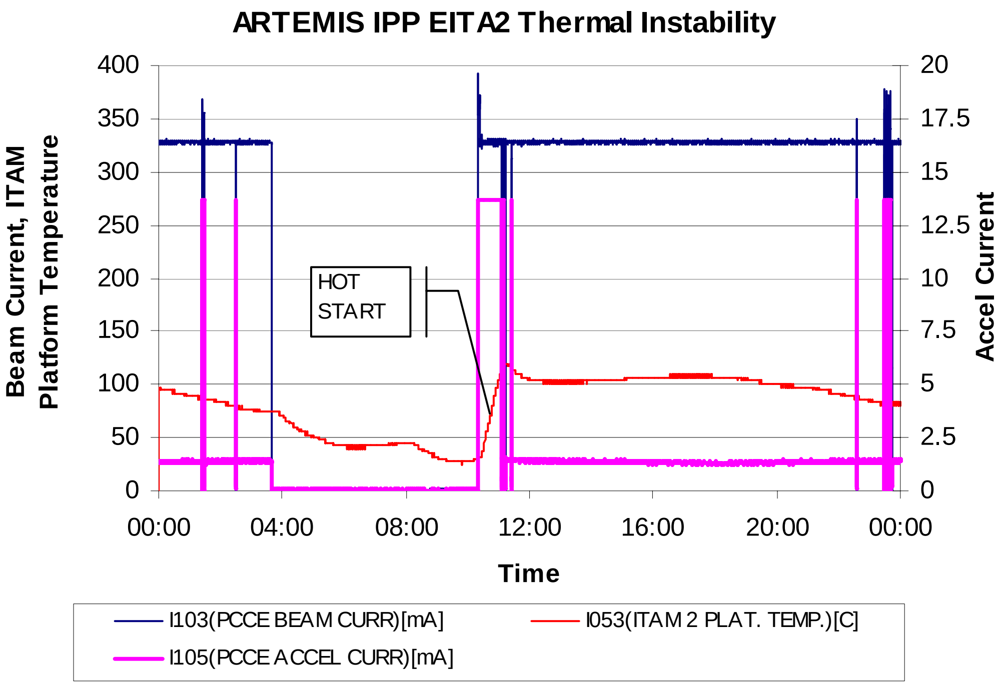

Figure 11: EITA Thermal Instability

A detailed data analysis revealed that since June 18 during most of the restarts, following a long manually restarted beam out period, a thermal instability occurred that caused a rapid increase of the temperature measured on the quite remote ITAM sensor as show in Figure 12.

The degradation in performance has been progressive, with the following sequence in order of the first appearance:

- Unexplained ADA software exception events
- High Accel+Decel Current which did not influence any other parameters, accompanied by a higher incidence of beam outs
- Clusters of Beam-outs
- Electron back-streaming causing a high thermal dissipation, resulting in an excessive thermal load on the grid and on the ITAM platform

The initial degradation in performance, resulting in high Accel and Decel current, has been most likely to be caused by an intermittent leakage path between the Accel supply and ground. This could originate in the thruster, the harness or the PCCE. Calculation and many hours of testing make it extremely unlikely that inter grid material could be the cause. Currently, Astrium considers the most probable cause is an intermittent harness problem, and further in-orbit investigation is required once Artemis is on station.

Due to the high thermal impact of the EIT-thruster on the ITAM platform, as also to prevent any possible further failure propagation with EITA2 until the problem could be properly investigated, it was decided to avoid further operation of EITA2, as the high thermal impact could cause problems either to the platform or to the RIT next to it (see Figure 12).

Consequently the orbit raising was completed with RITA2, which worked flawlessly since than and on January 31 was switched off, when the ARTEMIS has reached its final positioning. In total RITA2 until end of orbit raising was operated 5863 hours in space.

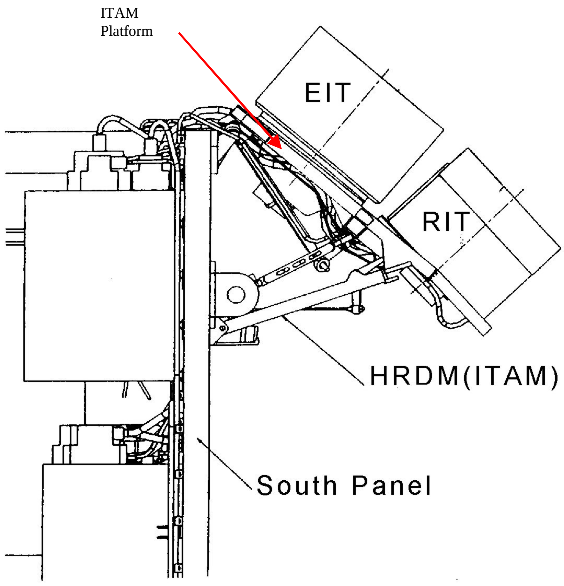

Figure 12: ITAM Assembly with Thruster

8. Conclusion

The experience gained so far during the ARTEMIS mission shows the value of such a flexible propulsion architecture using bi-propellant and ion propulsion, which allows to react even on nearly mission catastrophic launcher failures. After about 10 months of continuous ion thruster operation ARTEMIS on January 31, 2003 has reached its final position. The table below summarizes the actual performance of the IPP during the ARTEMIS mission:

	RITA1	RITA2	EITA1	EITA2
Total Ontime	**698.1 h**	**5863.0 h**	**182.3 h**	**521.0 h**
Total Mass	**1.28 kg**	**10.76 kg**	**0.40 kg**	**1.15 kg**

Table 1 IPP Thruster Life Log

The very successful adaptation of the AOCS software, designed for a GEO telecommunication satellite – earth pointed – application, with respect to orbit raising purposes proves that an orbit raising with ion propulsion, although in this case, due to the low thrust level, it will take several months, can be performed cost effective by applying a nearly autonomous strategy.

The data collected during the initial inclination reduction phase and the orbit raising to date are in good compliance with the ground test results.

The RITA ion thruster assembly for ARTEMIS, after an initial problem caused by the test environment which was reported in [5] and [6], since more 2.5 years show excellent and stable performance with data significantly better than the specification. It has successfully completed the 15,000 hours life verification and in fact is demonstrating a significant higher life capability. The test was terminated at 20,000 hours of successful operation. Inspections in combination with a grid erosion model and electron back streaming measurements indicate a substantially higher life capability at an "EOL = 15000 hour" specific impulse of 3370s (average of 3420 s) which is substantially higher than the required 3000 sec.

Prior to the EITA anomalies this thruster system was shown to be extremely stable with far less thruster beam-outs than expected. The software contained in the PCCE allowed for extremely flexible operations and could be adapted easily.

Similarly, the EIT thruster has completed 2000 hours of life testing, which has shown considerably less erosion of the grid system than originally forecast (this is considered to be the life limiting item for the thruster). The thruster behaviour during this life test exhibits excellent repeatability compared with the in-orbit operation. Electron back streaming effects at EOL are to be confirmed by an additional test using a grid set manufactured at EOL conditions. Additionally, the EIT cathodes have been subjected to a full life test.

The ARTEMIS experience shows the value of the flexible AOCS system using a combination of chemical propulsion with a high specific impulse ion propulsion system.

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