INTRODUCTION TO THE EUROPEAN ACTIVITIES IN ELECTRIC PROPULSION*

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Electric propulsion is being adopted by several scientific and Earth observation missions, where this technology will be used to provide the primary propulsion functions or to perform highly precise control operations. Furthermore, thanks to the mass saving made possible by the use of electric propulsion (EP), significant advantages are created for commercial and scientific missions by increasing the payload, reducing the launcher costs and increasing the mission duration. For all these reasons, the technology area of electric propulsion is in strong evolution and this paper presents an overview of the current European programmes and initiatives in the area of electric propulsion. Specific attention is devoted in the paper to the spacecraft currently in orbit (i.e. ARTEMIS) or ready to be launched (i.e. SMART-1).

The European highlights in the area of Electric propulsion are presented in the following chapters, subdivided by area of application. The information included in this paper update a previous review from the author, prepared in mid 2002.

1. Telecommunication Satellites

1.1 ARTEMIS

The ESA satellite ARTEMIS (Advanced Relay and Technology Mission Satellite), developed by a consortium led by Alenia (I) for testing and operating new telecommunications techniques was launched in July 2001. A malfunction of the launcher's upper stage left Artemis in an elliptical orbit, the apogee being at only 17,500km, far short of the expected GTO orbit parameters.

The extraordinary journey from "total loss" to arrival on station, with several years' useful life, was only possible thanks to a combination of technologies, the most significant being the electric propulsion system, originally intended for North-South Station Keeping (NSSK).

The IPP (Ion Propulsion Package) was developed by Astrium, with a common propellant storage and management system feeding two RITA (Radio-frequency Ion Thruster Assembly) and two EITA (Electron-bombardment Ion Thruster Assembly) systems, mounted in cold redundant pairs on an Austrian Aerospace developed Ion Thruster Pointing Mechanism (ITAM).

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During consideration of potential recovery strategies, 1450kg of chemical propellant was consumed (95% of total) to achieve a safe circular parking orbit of 31,000 km.
Following the last apogee burn and conformation of the new orbit parameters, deployment of the on-board systems was performed, including commissioning of the IPP.
During this commissioning phase, several operational modes beyond the standard IPP mission profile were demonstrated. These included, continuous operation of north and south panel ion thrusters simultaneously and the operation of a RITA1 using the EITA1 neutraliser.

Implementation of the proposed orbit rasing strategy using electric propulsion required extensive modification to the AOCS (Altitude and Orbit Control System) software, to introduce a new flight configuration. In thrusting mode, the S/C was turned though 90° to align the –Z axis tangentially to the orbit. This configuration was maintained for 10 day periods before a rotation back to earth pointing was required for orbit propagator calibration. Reorientation to earth pointing was also performed during satellite eclipse phases, throughout these periods the IPP system was placed into standby mode for attitude control and power conservation reasons. Following spacecraft reorientation to align the ion engine's thrust vector to the orbital plane, two thrusters, each operating at 15mN, were used to gradually increase the orbit radius at the rate of ~15km per day.

In support of the in-orbit activity, both RITA and EITA ground test facilities were made available for validation of new thruster and control software operating modes. This enabled rapid investigation of flight performance observations that were not examined during qualification of the IPP subsystem components. As an example, during S/C IPP operations using EITA and RITA simultaneously, an increase in the RITA neutraliser current was observed. This behaviour is explained by the different grounding schemes employed by the thrusters. To confirm that the higher neutraliser discharge current, would not be life limiting a special supplementary life demonstration was defined by Astrium (D) and executed successfully in the test facility at ESTEC. (The RITA test activity at ESTEC was voluntarily terminated in November 2002 after 20,000 hours.)

By May 2002, the IPP operations had raised the orbit by more than 1000km, demonstrating the post launch developed AOCS software's capability to operate during eclipse seasons with a high degree of autonomy.

In July 2002 the final orbit raising configuration was established, using only the RITA2 thruster, incorporating an additional spacecraft roll bias to make efficient use of the single thrust vector. The operational thruster performed flawlessly throughout the final eclipse season in October 2002, during final drift correction manoeuvres and up until arrival at geostationary altitude. As most of the orbit raising was performed by RITA2, a specific switch-down procedure was prepared, this allowing for a characterisation of the thruster after 6000 hours of operation.

On the 2nd of February 2003, the Ion Propulsion Package (IPP) was shut down as Artemis made a final insertion manoeuvre into its orbital slot at 21.5° east.
Although unplanned, in terms of thruster "on-time", the utilisation of electric propulsion for the recovery of Artemis has resulted in almost 7 years normal use, to be achieved in just 18 months.
Despite anomalies having occurred within the ion propulsion package resulting in restricted operations, this unique spacecraft salvage mission was successful, with full payload operations expected to start by March 2003.

This experience has undoubtedly increased the exposure of electric propulsion and provided EP developers with invaluable experience of "in-flight" operations, which in other circumstances would have taken many years to accrue. With the support of extensive ground testing and flight performance data, the lessons learnt from Artemis are already being applied to enhance the functionality, reliability and performance of future electric propulsion systems.

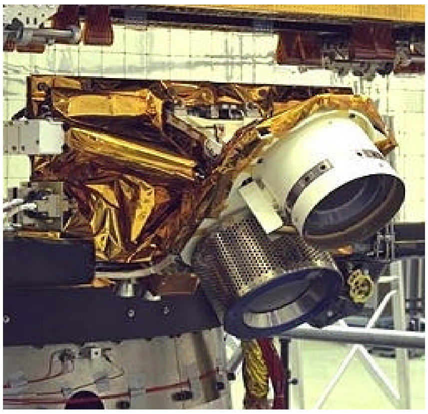

Fig. 1: The RIT-10 and UK-10 Thrusters on the North Panel of Artemis

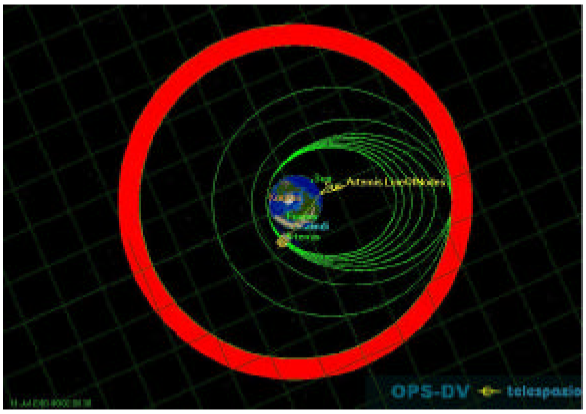

Fig.2: The Artemis Recovery Strategy

By concept and design, this mission was going to be ground breaking, with the role of demonstrating newly developed and innovative technologies. The implementation of electric propulsion, provision of UPS propellant backup, flexibility of the AOCS and teamwork from all those involved has allowed Artemis to achieve a number of world firsts during its salvage from the grave.

1.2 Other activities for GEO Telecoms

Under the pressure of international competition the two European Telecom manufacturers (Astrium and Alcatel) are now offering enhanced versions of their geostationary platforms (Eurostar 3000 and Spacebus 4000 respectively) which offer the option of using Hall-Effect thrusters for NSSK operations. As from the year 2000 several new satellites have been sold by ALCATEL and ASTRIUM to European and American customers, using Hall-effect thrusters for the North-South Station Keeping operations. This important result is the consequence of years of development efforts at spacecraft and subsystem levels, which made possible the establishment of an excellent European background in the EP technology field. On the other hand the confidence on this technology among the satellite producers is put under question by the lack so far of flight heritage in the Western countries, dramatically confirmed by the loss of the CNES technology demonstration satellite STENTOR and of the Alcatel ASTRA 1K spacecraft, both fatally lost due to the failure of their carrying launchers at the end of 2002. This unfortunate situation contributes to increase the conservative attitude by the insurers towards new spacecraft technologies not sufficiently space proven, including electric propulsion. Several initiatives are being undertaken in Europe to enhance the confidence on electric propulsion by operators and insurers, including collection of flight data from Russian experience and a detailed recording from the Artemis successfull experience. Furthermore, the increasing use of Electric Propulsion (EP) on modern spacecraft introduces different operational requirements on the launcher than for conventional spacecraft. These requirements involve issues such as:

- Injection strategies
- Ground operations and control
- Relaxation of launch windows.

The impact on the launcher is even more relevant in the case of a dual launch, when only one of the spacecraft makes use of EP.

Following discussions with European industry (in the launcher, spacecraft and propulsion areas) and with Arianespace, ESA is taking the initiative to promote an European Working Group on the mentioned issues, involving all the interested parties, including the satellite operators. A first workshop on the subject took place at ESTEC in September. An industrial study, to be performed in the frame of the General Study Programme, will complement the work to be performed by this Working Group in the period 2003-2004.

In view of the increasing mass and mission duration for the new GEO platforms, the requirements on the total impulse to be provided by the electric propulsion system are constantly increasing. As a result, the currently qualified thrusters, such as the SPT-100, will not be able in the near future to fulfil the total impulse specification for the future commercial missions. It is for this reason that the major European producers of electric thrusters have initiated development programmes to extend the operational capability of the current Hall-effect thrusters (PPS-1350) or to qualify in the short term new thrusters with a higher impulse capability, such as the ESA sponsored ROS-2000 thruster developed by ASTRIUM (UK).

Further to work on the evolution versions of their current platforms, ALCATEL and ASTRIUM have joined the efforts to design and develop together the next generation of European GEO platforms, which is planned to be offered on the market after the year 2005. This new platform, called @BUS, will offer a very high power payload capability (up to 25 kW) and will optimise the use of EP, because the EP operations will possibly be extended to include other functions than NSSK, notably full or partial orbit transfer to the GEO orbit and other functions. New, high thrust EP systems are needed for this new platform and all the major European EP thruster suppliers are currently initiating these developments. In particular, SNECMA (F) has announced the development of a high thrust version of their PPS Hall-effect thruster, called PPS X000, while ASTRIUM (D) and Quinetik (UK) are involved in the development of new, high thrust gridded ion engines, respectively the RIT-XT and the T6 thrusters. Pre-development activities in the area of European high thrust EP systems for application on @BUS are being funded by ESA in the frame of the ARTES-8 programme. The final selection of the EP system(s) for @BUS will be performed on a competitive basis in 2003.

2. Scientific Satellites

On interplanetary missions, replacing or augmenting chemical propulsion with electric thrusters as the primary propulsion system usually brings significant benefits.
The specific mission requirements, in terms of power availability, satellite mass and mission profile, dictate the choice of the EP technology to be used. Some of these advantages are also relevant to Earth orbiting scientific missions, which therefore shall benefit from the development in the EPS field.

2.1 Interplanetary Exploration Missions: SMART-1, Bepi Colombo

The first of the ESA's SMART missions (Small Missions for Advanced Research in Technology), **SMART-1** (Fig.3), is a small lunar orbiter devoted to the demonstration of innovative and key technologies for scientific deep space missions. A highly innovative and low budget mission to explore the Moon, SMART-1 has formally been approved by ESA's Delegations in 1999. The most important technology to be flown on the 350-kg spacecraft will be solar electric propulsion. This will constitute its primary propulsion to escape the Earth's gravity, for its 17-month cruise to the Moon and to stay in lunar orbit for six months. It will be the first time that Europe uses EPS as primary propulsion of a scientific satellite. SMART-1 will serve as test-bench for future European missions using EPS.

Figure 3. The SMART-1 spacecraft (left) and its plasma propulsion system (right). (Courtesy Swedish Space Corporation)

Due to the mass limitation of the spacecraft and the consequent limitation in the electrical power (1.4 kW available for the EPS at the beginning of life in orbit), the thruster to be used on SMART-1 is a scaled-down version of the thrusters which will eventually be used on future operational missions. The PPS-1350 thruster, developed by SNECMA, has therefore been selected with the additional advantage of being already qualified for GEO telecoms, although a characterization of its performance in a variable low power mode (480-1220 W) was needed for this application.

The SMART-1 spacecraft is now fully developed and ready for flight.

December 2002 has been fully devoted to the successful completion of the environmental test campaign on the spacecraft in ESTEC. Further to the “classical” tests on the spacecraft and its subsystems, the EPS system was fire-tested in its completeness (xenon distribution + power processing) with the spacecraft (end-to-end test). The real difficulty about this test was that there was no possible pre-test and no second chance to make it right. The test facility (HBF-3) had never been used for that purpose before. There was no possibility to test a thruster in stand-alone since the chamber was not instrumented for power and xenon supply. Fortunately, the end-to-end test was a complete success beyond all expectations (Fig.4): the test facility behaved as planned, the vacuum level was as computed, there was no detectable contamination on the thruster and on the spacecraft sensitive surfaces. The thruster started at the first pulse and was very stable immediately. There was no shutdown induced by the spacecraft for temperature of power reasons.
In January, the spacecraft software is undergoing a functional and performance test campaign that cover all the subsystems and all mission phases.
The launch of SMART-1, originally planned for Spring 2003 as an Ariane V secondary payload, has now been postponed due to the difficult situation on the new version of Ariane V.

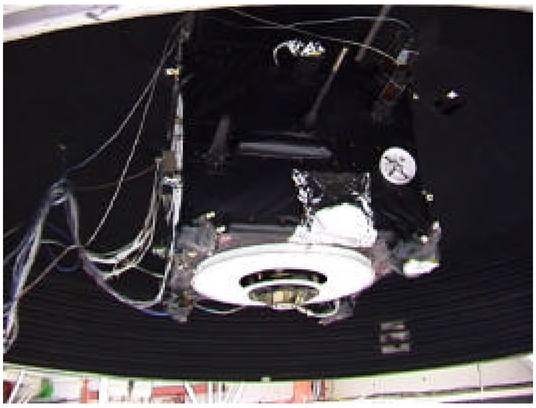

Figure 4. The SMART-1 spacecraft mounted in the end-to-end test facility at ESTEC (left) and the PPS-1350 thruster firing during the test (right)

The ESA Cornerstone mission to the planet Mercury, **BepiColombo**, currently undergoing a new assessment phase, foresees for the electrical options an ion propulsion system with high specific (>4200 sec) and high total impulse capability ($1x10^7$ Ns).

The BepiColombo Solar Electric Propulsion Module will be propelled by a cluster of high-power (in the 5-6 kW range) gridded Ion thrusters providing a maximum thrust of 200 mN each. The system architecture philosophy will maintain one complete propulsion unit (Thruster, PPUs and FCU) in cold redundant status.

For the ESA Technology Development Activities supporting the BepiColombo programme, the British T6 electron bombardment ion thruster has been selected. During 3000 hours of thruster characterisation test a single and twin configuration (see Fig.5) will be investigated. Thruster characterisation with one single neutraliser in twin thruster configuration and a test at high temperature will also be performed. Analysis on the lifetime capability of the thruster (ion optics and components) will provide suitable data for the improvement of the design and of the thruster reliability in phase B and C/D.

An ESA TRP activity currently ongoing will also support the BepiColombo programme through the development and manufacturing of new Ion optic systems. New materials assessment, new design configuration and ion optic characterisation are needed for the realisation of ion thrusters with high performances. Both the radiofrequency RIT-XT ion thruster by Astrium GmbH and the electron bombardment T6 QinetiQ ion thruster will be used to test the new grid design. Two parallel contracts have been placed to QuinetiQ and Astrium GmbH tocompare the grid technologies and to reinforce the European competitiveness in this field. The program is also developing ion optics capable of very high specific impulse capability and operation of ion thrusters in dual mode in synergy with the @bus programme.

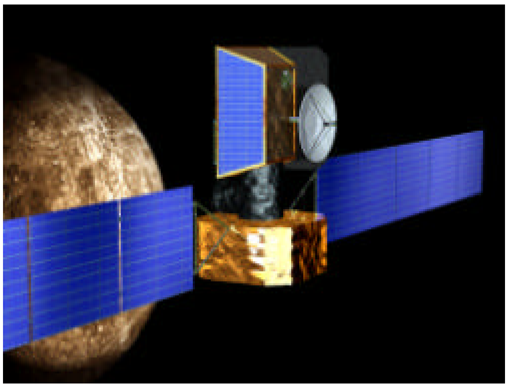

Figure 5. A candidate configuration for the BepiColombo spacecraft to Mercury and two T6 candidate Ion Thrusters undergoing twin firing test at QinetiQ (UK).

2.2 Earth Orbiting Scientific Missions: GOCE

The main aim of the **GOCE** mission is to provide unique models of the Earth's gravity field and its geoid (reference equipotential surface) to high spatial resolution and accuracy. GOCE will also perform advance research in the field of steady-state ocean circulation, physics of the Earth's interior and leveling systems. The eventual launch of the satellite is expected to be at the beginning of 2006.

The GOCE satellite will be a low-Earth orbiting spacecraft (240-270 km) which will have a small cross section of approximately 0.9 m2, and be totally symmetrical to minimise the influence of external forces. The design configuration maximises the use of available volume under the launcher fairing by using fixed solar panels. There will be no deployables or mechanisms to produce shocks. There will also be no sloshing effects as all the thruster propellant is gas. The actuators for orbit maintenance and along-track drag control are a pair of ion thrusters. Smaller, proportional micro-thrusters are used for attitude control.

The primary function of the ion engine on GOCE is to provide variable thrust for compensation of the drag force in flight direction throughout the satellite measurement phases. In addition the ion engine supports instrument calibration and satellite maintenance phases by providing sufficient thrust for orbit raise manoeuvres and atmospheric drag compensation

The Ion Propulsion Assembly (IPA) is made up of the following subsytems: the Ion Thruster assembly (ITA), the Ion Propulsion Control Unit (IPCU), the Proportional Xenon Feed Assembly (PXFA) and the Xenon Storage Tank (XST). The stringent requirements in terms of thrust range, noise and stability impose severe constraints on each of the subsystems of the IPA. The ITA is provided by QinetiQ (UK); Bradford Engineering (NL) has been appointed as the supplier for the PXFA and CRISA (E) is in charge of the IPCU. The Preliminary Design Review for the QinetiQ ion engine is currently taking place and will be finalised within April 2003.

2.3 Nuclear-Electric Propulsion for Space Exploration Missions

During the past year the interest of the space community on nuclear propulsion and power has grown significantly, in particular on Nuclear Electric Propulsion (NEP). The use of nuclear propulsion has the potential to greatly improve the capability, sophistication and reach of future science and exploration missions.
Nuclear Electric Propulsion (NEP) or the use of nuclear reactors to generate heat, which is converted into

electrical power for high-performance electric thrusters, can add significant benefits to space missions:

- NEP will enable much faster and more frequent planetary investigations with greater science capabilities "anywhere, all the time" mission design;
- NEP enables a revolutionary change in approach to outer Solar System exploration;
- Drive spacecraft directly to the planets in ways not possible today, and perform complex orbital manoeuvres once there;
- Provide ample electrical power to operate advanced scientific instruments and transmit the resulting data to Earth at a very high bit rate;

Enable multi-destination missions capable of entering into orbit around one body, conducting observations, and then departing to a new destination.

ESA, through the Propulsion and Aerothermodynamics Division has been actively involved in the past year in the preparation of future activities in nuclear propulsion by participating to the an International Academy of Astronautic (IAA) workgroup set up to prepare an international position paper on nuclear power and propulsion in space, following a direct request from the NASA Administrator. The workgroup includes people from academy, space agencies and industry. ESA has also, preliminary and on a technical basis, agreed on a common explorative approach with the CNES on this subject, by defining exchange of information on work carried out and to be performed in the future.

Moreover, ESA, in the framework of the **Aurora** exploration programme issued an industrial study in 2002 on NEP: "Assessment of Electric Propulsion Systems for Exploration Missions: Comparison Between Solar Electric and Nuclear Electric Propulsion Systems". The aim of the activity is to design different NEP systems, based on state of the art technologies, and define the operational envelope of NEP vs. SEP (Solar Electric Propulsion). This Study is the first ESA funded activity on Nuclear Propulsion, and an important step in defining the technologies and funding required for an eventual Agency program in this area. It is important to note that there is a strong and wide spread industrial interest in nuclear propulsion, reflected by the proposals received. Technology developments for a NEP system, if initiated in Europe, would involve at least the 6 European major countries and several companies.

2.4 High Precision Scientific Missions: LISA, Darwin, GAIA, SMART-2, MICROSCOPE

The Laser Interferometer Space Antenna (**LISA**) mission's goal is to detect gravitational waves, distortions of space-time thought to be generated when a massive body is accelerated or disturbed. To achieve that goal the relative position of several solid blocks placed in different spacecraft, 5 million kilometers apart, will be constantly monitored with a high accuracy using laser-based techniques. A gravitational wave passing through the spacecraft will cause these bodies to vibrate, changing the separations between them (Fig.6). But the changes will be so subtle that in order to perceive them the position of each satellite must be controlled up to the nanometer level. Also, scientists need to be completely confident that the vibrations of the solid blocks in each spacecraft are indeed caused by a gravitational wave and not by other phenomena, such as the solar wind.

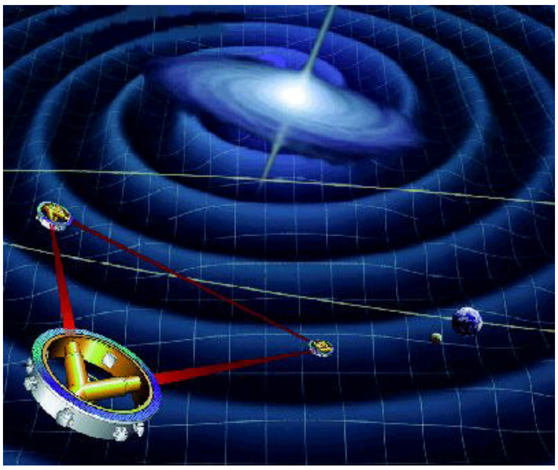

Figure 6. The LISA Mission Concept

The success of the mission is based on the performance of such a sophisticated accelerometer concept, which must work under drag-free conditions. The drag-free control of the spacecraft will be provided by FEEP thrusters. Higher thrust EP systems could be used for the orbit transfer phase of this mission. The control torques and forces for the attitude and drag-free control during the operational phase are provided by the FEEP thrusters by providing a controlled thrust in the range of 1 to 100 µN, with a noise below 0.1 µN. LISA is envisaged as an ESA/NASA collaborative project. LISA is aimed at a launch in the 2011 time frame.

Space Interferometry was identified in the ESA long-term programme for science as a potential candidate among space projects planned for after the turn of the century. In the framework of this science technology area, the "InfraRed Space Interferometry Mission" IRSI-DARWIN or **DARWIN** for short) is a candidate ESA cornerstone mission. The DARWIN mission consists of a flotilla of seven spacecraft flying at distances ranging from 100 to 500 metres. They will work together in a coordinated way with the aim of detecting Earth-like planets in other solar systems, and of analysing their atmospheres in search for signs of life as we know it. An eight satellite will act as the master communications spacecraft. On the whole, Darwin will carry six infrared telescopes located in different spacecraft. By interferometry the six telescopes will manage to suppress or 'null' the bright light of the central star, while enhancing, instead, the emission from the small, opaque orbiting planets. The mission feasibility study has been performed by Alcatel Space.
During the initial design studies of Darwin, two designs of satellite were considered: the 'free-flyer' model, and the structured model. Since that time, the free-flyer model, has been agreed upon. The model consists of five or six individual telescopes mounted on separate spacecraft. Each individual spacecraft could by moved around by FEEP thrusters.

Both LISA and Darwin rely on technologies that have never been tested in space, including the FEEP system, so neither of them could be built without a previous space demonstration. This is the objective of the **SMART-2** and possibly **SMART-3** mission. SMART-2 is the technology demonstrator for LISA. It is scheduled for launch in 2006 (Fig.7). Darwin technology could be tested in the SMART-3 mission, which is still under discussion at ESA. For LISA, SMART-2 will verify, among other things, the drag-free system, i.e.the accelerometers (inertial sensors) and the micronewton electric propulsion (FEEP, Colloid Thruster and µResistojet). The FEEP is designed to operate during the drag-free mode and the µResistojet for all the other AOCS functions. Colloid thrusters are included to perform the drag-free mode with the DRS inertial sensor provided by NASA, added in parallel to the ESA inertial sensor.

The scientific objective of **MICROSCOPE** is the verification of the Equivalence Principle between the inertial mass and the gravitational mass of two different materials, with a precision better than 10-15, more than what it has been possible to verify on ground so far. This mission is funded by CNES and it is based on a standard CNES microsatellite bus. The sophisticated AOCS requirements for this mission will be fulfilled by a FEEP propulsion system. The Microscope FEEP Electric Propulsion System (FEPS) is provided by ESA, as a result of an ESA/CNES agreement. Following the results of a competitive tender, the contract for the supply of FEPS has been awarded to the company ALTA S.p.A. (I), with Carlo Gavazzi Space (I) and CAEN Aerospace (I) as subcontractors. During the first phase of the activities, a trade-off between nominal and redundant configurations for the FEPS is being performed, together with a full characterization of the FEEP performance in the mission requirement range. A full lifetime test qualification of the FEEP thrusters is included in the contractual frame for the FEPS. The launch of MICROSCOPE is planned for 2006.

GAIA is the successor of the ESA's Hipparcos satellite and will be the next ESA Cornerstone after Bepi-Colombo. Its main objective is to perform a global astrometric survey of the whole sky, with unprecedented accuracy. GAIA will be a 1.5-ton spacecraft. It will go to a station 1.5 million km out on the dark side of the Earth, at Lagrange Point No. 2 (L2) where the gravity of Sun and Earth combine to create a place of rest relative to the Earth. GAIA is expected to operate for about five years. The satellite will employ interferometers to measure distances and motions of tens of millions of stars throughout our Galaxy. Electric propulsion (FEEP) thrusters at millinewton level are currently baseline as actuators for the attitude and orbit control system of the GAIA spacecraft

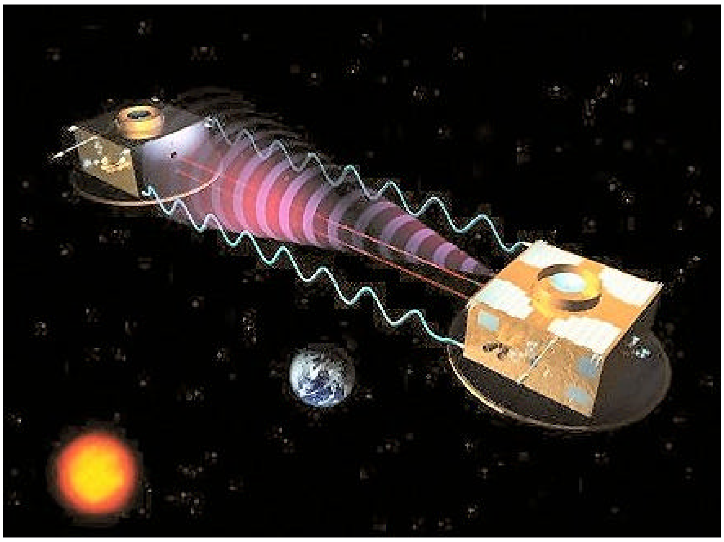

Figure 7. The SMART-2 Mission Concept

5. Acknowledgments

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