Electric Propulsion Activities at ESA

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Abstract: New scientific and Earth observation missions dictate new challenging requirements for propulsion systems and components based on advanced technologies such as microNewton thrusters. New interplanetary missions in the frame of exploration will require sophisticated propulsion systems to reach planets such as Mars and in some cases bring back to Earth samples from these planets. Moreover, in the commercial arena, the strong competition among satellite manufacturers is a major driver for advancements in the area of electric propulsion, where increasing better performance together with low prices are required. Due to all these new space projects, ESA is currently involved in activities related to spacecraft electric propulsion, from the basic research and development of conventional and new concepts to the manufacturing, AIV and flight control of the propulsion subsystems of several European satellites. The exploitation of the flight experience is also an important activity at ESA which will help mission designers to implement the lessons learnt to the development of these new propulsion systems.

EP	=	Electric Propulsion
EPIC	=	Electric Propulsion Innovation and Competitiveness
FEEP	=	Field Emission Electric Propulsion
HEMPT	=	Highly Efficiency Multistage Plasma Thruster
LISA	=	Laser Interferometer Space Antenna

I INTRODUCTION

The use of Electric Propulsion (EP) technologies in the Telecommunication space market is today a key issue to improve the position of the European space sector. European industry was relatively conservative in their adoption of EP technology compared to the US suppliers but nowadays a strong push is given by the European space Agency in this sector with spacecraft such as AlphaSat, Small GEO, Electra or Neosat that will pave the way for the use of this technology in the space telecommunication arena, putting European industries in an advanced position to compete for new telecommunication spacecraft. Airbus and TAS has won several satellites thanks to the use of electric propulsion not only for station keeping but also for orbit raising (Inmarsat 6-F1, SES-17, Comsat, etc.). Since 2002 European Primes have launched many telecommunication satellites that use electric propulsion for station keeping. The platforms retained a full chemical propulsion capability, such that EP was offered as an option to the existing chemical product range, rather than as a separate product line. To data Inmarsat-4 and Intelsat-10 spacecraft have accumulated thousands of hours of electric propulsion operations, increasing the confidence in the technology, and the requirement to include a chemical propulsion backup has been reconsidered.

Electric Propulsion (EP) has today extensive development history, testing, and flight experience (Astra-1K, Intelsat-10, Inmarsat-4, Alphasat, Smart-1, GOCE, Artemis, Alphasat, Small GEO,etc.). Furthermore, the current flight data are proving that expected benefits are real and that future spacecraft missions will enhance their capabilities by using electric propulsion systems (EPS). Nowadays, there are hundreds of spacecraft which had and are using EP for

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station keeping and other operations. The primes of those satellites have obtained huge propellant savings by using EPS operating at specific impulses an order of magnitude higher than conventional chemical propulsion systems.

The European Large Platform Development AlphaBus, an ESA–CNES funded project for future high-capacity geostationary telecommunication satellites, was developed jointly by Airbus Space and Defense, and Thales Alenia Space to enhance European competitiveness in the large telecommunication platform market. For the short-to-medium term needs, the AlphaBus nominal range is defined with a payload power between 12 and 18 kW and a payload mass between 950 and 1300 kg. The use of electric propulsion for North-South Station Keeping (NSSK) is a standard feature of the AlphaBus product, using the Snecma PPS-1350G Hall Effect Thruster. From this product line, Alphasat, Europe's largest and most sophisticated telecommunication satellite was launched into its planned orbit in July 2013. This satellite was preliminary designed to expand Inmarsat's existing global mobile network (Figure 1).

The level of development of electric propulsion systems in the USA (ion engines from Boeing, Hall Effect thrusters (HET) from Aerojet and Russia (SPT-100 and SPT-140 from Fakel) are competing in technical capabilities and price with the European suppliers (HET from Snecma, ion engines from QinetiQ and Airbus Space and Defense, and HEMPTs from Thales). The technical capabilities of the European suppliers have been well enhanced during the last years and now a big effort should be put on industrialisation and cost reduction. ESP is a new European propulsion company sister of Aerojet in USA.

Communication satellites need to generate between 5 to 20 kilowatts of electric power to run its payload. This enables the use of electric propulsion, not only for regular operations in space, but also for actually raising a satellite after separation from the launcher to its geostationary orbit - almost 36,000 km from Earth's equator[1]. This manoeuvre when performed with EP can save thousands of kilos that will allow to manufacture a smaller spacecraft that will cost much less to launch in launchers such as Falcon 9.

The drive to use electric propulsion rather than conventional chemical propulsion has gone on for many years. Chemical propulsion is used to raise a satellite to its orbit after the satellite separates from the launcher, and to perform necessary manoeuvres on the satellite while in orbit. Close to 50 per cent of the launch mass of a geostationary satellite is made up of liquid rocket fuel with most of this propellant used to raise the spacecraft.

Applied for up to several months for orbit raising and a few hours per day for station keeping, the force required is miniscule in comparison to that generated by chemical thruster. The big advantage is that the new electrical propulsion thrusters consume far less fuel than their chemical equivalents. A savings in fuel mass equals a lighter launch mass and therefore potentially smaller launchers could be used to send communications satellites into space providing savings in launcher costs.

ESA's Artemis telecommunications satellite was Europe's first experimental use of electric thrusters to raise a satellite to its intended orbit. Artemis proved that electric thruster-based systems are capable to perform the same task as chemical propulsion with up to a 90 per cent savings in fuel mass over conventional chemical thrusters. Since Artemis ESA and European industry have worked together to further develop electric propulsion technology. Europe has invested in electric propulsion technologies at SNECMA (Hall Effect Thrusters), QINETIQ (ion engines), ASTRIUM (ion engines) and THALES (HEMPT)[2] and these technologies are now competing with American and Russian systems. Europe needs to keep the independence on this technology which is strategic for the future commercial telecommunication market, especially considering the ITAR restrictions of American products.

Space science plays a prominent role within Europe's space programme, and has been at the core of ESA's activities since the early 1960s. Activities in space science effectively underpin ESA, building European industrial technical capacity, and bringing together European national space programmes.

Interplanetary missions such as Deep Space 1, Hayabusa and Smart-1 have paved the road for the common use of EP systems for Science and Exploration missions. Smart-1 required only 82 kg of Xenon to propel a 350 kg spacecraft to the Moon from GTO. The huge savings in propellant enables by EP will allow missions such as BepiColombo to reach objects far away from Earth in reasonable time. Planned for launch in 2018, the BepiColombo mission is now in the implementation phase, and has selected a solar electric propulsion system, based on the QinetiQ T6 GIE, to perform the transfer to Mercury. A dedicated propulsion module is being developed to transfer the two orbiter spacecraft to Mercury. It is anticipated that the BepiColombo propulsion module will be suitable for the transfer propulsion needs of future science missions. Re-use of technology in this way will offer the science programmes considerably reductions in costs and development risk.

Earth observation also benefits from the use of EP technology. The GOCE main aim was to provide unique models of the Earth's gravity field and its geoid (reference equipotential surface to high spatial and accuracy). GOCE also performed advance research in the field of steady-state ocean circulation, physics of the Earth's interior and leveling systems. The launch of the satellite took place in 2009. The GOCE satellite was a low-Earth orbiting spacecraft (275 km) that had a small cross section of approximately 1 m^2, and was totally symmetrical to minimise the influence of external forces. The design configuration maximised the use of available volume under the launcher fairing by using fixed solar panels. There were no deployables or mechanisms to produce shocks. There was no sloshing effects as all the thruster propellant is gas. The actuators for orbit maintenance and along-track drag control were a pair of ion thrusters.

The primary function of the ion engine on GOCE was to provide variable thrust for compensation of the drag force in flight direction throughout the satellite measurement phases. In addition the ion engine supported instrument calibration and satellite maintenance phases by providing sufficient thrust for orbit raise maneuvers and atmospheric drag compensation. The Ion Propulsion Assembly (IPA) of GOCE is made up of the following subsystems: 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 was provided by QinetiQ (UK); Bradford Engineering (NL) has been appointed as the supplier for the PXFA and CRISA (E) was in charge of the IPCU. The IPA has been operating almost continually since the launch in 2009 and the end of the mission in November 2013 . Consequently, a firing time in excess of 30.000 hours was demonstrated on the primary ion thruster. The success of the ion engine in the GOCE spacecraft has demonstrated the potential of this technology for fine control of satellites flying in LEO.

A new post GOCE mission is being designed at ESA. This mission will be based in the assessment of a current study on a Next Generation Gravity Mission (NGGM) for monitoring the variations of the Earth Gravity. This mission is composed of two small satellites flying in formation in a very low orbit. Primary drag compensation would be carried out by the same QinetiQ T5 thrusters used on GOCE. The mini-ion engine from Astrium (D) and University of Giessen and the FOTEC (Austria) field emission microthrusters are being considered for compensation of the very small cross track drag forces. These flying formation missions in Earth Observation have similar requirements to science missions such as LISA (Figure 1), thus the thrusters required for this kind of missions are similar (FEEP, mini-ion engines, mini-Hall Effect thrusters, etc.)

Exploration future missions could also benefit of the use of this high and very high power and specific impulse technology as it has been stated in assessment of ESA and NASA studies on the subject.

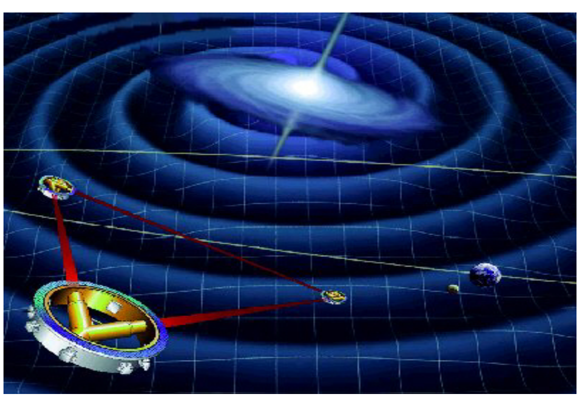

Figure 1: Laser Interferometer Space Antenna (LISA)

II Telecommunications

The commercial telecommunications satellites market is nowadays the more important market for EP. The market has evolved in recent years, and it is continuing to evolve, based on a range of developments in launch services, platform technologies and operator requirements. This market is dominated in the west by a small number of US and European suppliers, namely Boeing, Space Systems Loral (SSL), Airbus Space and Defense and Thales Alenia Space, who are all offering large platforms (6.5 tons class). SSL, Airbus Space and Defense and TAS currently offer a conventional approach with launch into GTO and a chemical propulsion transfer from GTO to GEO transfer and either chemical propulsion or electric propulsion systems for station keeping. Boeing offer an alternative approach with launch into Sun Synchronous Transfer Orbit (SSTO) with a combination of electric propulsion and chemical propulsion transfer to GEO, utilising the more efficient inclination change maneuvers possible at the high apogee of the SSTO. All station keeping is then performed with electric propulsion.

Launch services for the large commercial platforms are dominated by Proton and Ariane-5. These launchers have high prices for heavy payloads despite aggressive pricing strategy by Proton since 2013. Smaller platforms (< 3.5 tons) may be launched as dual payloads on Proton and Ariane-5 or as single payloads on Falcon 9. The possibility to launch dual payloads on Falcon 9 has emerged with Boeings announcement of its small 702SP platforms (2 tons class). The development of re-ignitable upper-stages has introduced flexibility in to the launcher market and allows a range of sub- and super-synchronous transfer orbits to be offered, reducing the overall velocity increment requirement on the spacecraft bus, and enabling electric propulsion to be considered for orbit topping / raising as well as station keeping.

Recent developments in platform technologies have been aimed at increasing the available payload fraction and accommodating larger, more powerful payloads. These developments have focused on the power subsystems and thermal control systems necessary to accommodate higher payload power. This has the advantage that more power can be made available for electric propulsion, especially during orbit transfer phase when the payload is not operational.

With respect to operator requirements, there is a sustained request for lower cost-per-transponder, coupled with a demand for larger transponder capacity and longer operational lifetimes. Despite the need of a higher capital investment many existing operators continue to be attracted by larger, higher-power spacecraft. However, in emerging markets where capital investment may be limited, smaller spacecraft may be more appealing. The telecommunications market is expected to continue to be dominated by the large spacecraft class, but with increasing interest in smaller platforms for expansion into emerging markets.

The described developments and trends in spacecraft and launchers are driving the total impulse requirement of electric propulsion to increasingly large values. Existing systems, with their limited total impulse capability, will not be capable to meet the future needs, so that development of higher power variants is becoming increasingly urgent.

Boeing’s announcement in 2012 of sales of four of its new all electric small platform (702SP) has produced significant interest in the commercial telecommunications market. Their aggressive approach to reduce satellite mass and allow dual satellite launches on the Falcon 9 launcher can lead to very significant reduction in operator costs. Although many of the satellite suppliers appear to be skeptical about the Boeing approach, they are all now reviewing their offerings with a view to increase competitiveness by increasing their use of electric propulsion.

It is clear that the trend to increased use of electric propulsion will continue in the telecommunications market and that higher power thrusters will be needed to meet both the orbit raising and station keeping needs of future small and large platforms.

For telecommunication platforms a largely independent market exists in the United States, over the past decade commercial (and institutional) missions have taken the lead in exploiting the potential offered by electric propulsion. Both Space Systems Loral and Boeing represent a significant threat to European commercial platform products and have each developed platforms using electric propulsion.

Boeing is the market leader, having already developed two generations of platforms using electric propulsion. Their 601HP platform was the first western commercial telecommunications bus to fly electric propulsion in the form of the XIPS-10 gridded ion engine. Their current generation bus 702HP uses its high-power capacity (up to 18kW) to take full advantage of electric propulsion technology. The satellite is equipped with four 4.5kW XIPS-25 gridded ion thrusters that feature high power orbit raising and low power station keeping modes. Once on station, the ion thrusters are used to perform all station keeping and spacecraft momentum control functions.

Space Systems Loral (SS/L), through an agreement with Fakel (RU), have incorporated the SPT-100 Hall Effect Thruster into their LS-1300 platform. The four SPT-100 thrusters provide impulse for on-orbit inclination and eccentricity control as well as momentum control functions.

Since 2002 European Primes have launched eight telecommunications satellites that use electric propulsion for station keeping. These platforms have retained a full chemical propulsion capability, such that electric propulsion was offered as an option to the existing all chemical product range, rather than as a separate product line. To date Inmarsat-4 and Intelsat-10 spacecraft have accrued thousands of hrs of cumulated electric propulsion operations, increasing the confidence in the technology.

The European Large Platform Development AlphaBus (Figure2), an ESA–CNES funded project for future high-capacity geostationary telecommunication satellites, was developed jointly by Airbus Space and Defense and Thales Alenia Space to enhance European competitiveness in the large telecommunication platform market. For the short-to-medium term needs, the AlphaBus nominal range is defined with a payload power between 12 and 18 kW and a payload mass between 950 and 1300 kg. The use of electric propulsion for North-South Station Keeping (NSSK) is a standard feature of the AlphaBus product, using the Snecma PPS-1350G Hall Effect Thruster.

Although orbit topping is feasible with the PPS-1350G it would provide only a very small fraction (50 to110 m/s) of the needed transfer velocity increment (1.5 km/s). This option may be attractive on the smallest of the AlphaBus range when the spacecraft mass budget is marginal for one of the smaller launcher. For the nominal AlphaBus range work has started on incorporating an Electric Orbit Raising (EOR) capability to improve competitiveness and capability. These improvements are based on the extension of the PPS-1350E Hall Effect Thruster performance to enable orbit raising at a higher power operating point.

Both Airbus Space and Defence and Thales Alenia Space have extended the capabilities of their existing Eurostar and SpaceBus platforms.

In the case of Airbus Space and Defence, they have taken the decision to embark electric propulsion on their smaller platform configurations. These modifications reuse the flight demonstrated electric propulsion system, based on the Fakel (RU) SPT-100 thruster, currently offered as an option on the larger platform variant. This activity is solely targeted at achieving compatibility with emerging low-cost launchers, with the electric propulsion system only used to meet NSSK requirements.

Thales Alenia Space has opted to reinstall electric propulsion on the SpaceBus platform as a first step to establish an electric propulsion station keeping capability (system architecture identical to AlphaBus nominal range). Thereafter, a stepwise evolution is planned whereby dedicated orbit topping thrusters are added, these being fixed and only employed for orbit raising. The final evolution plans to introduce high power thrusters (5kW Class Hall Effect Thruster) to perform orbit topping and Station Keeping Functions using an advanced thruster pointing mechanism to perform the reconfiguration.

OHB's Small GEO platform[3] has been designed from the start to use Electric Propulsion. With eight fixed thrusters mounted in pairs on the East-West-North-South edges of the spacecraft, North-South and East-West station keeping and momentum control functions can be performed simultaneously. Auxiliary propulsion (Xenon cold gas) is available to provide emergency attitude control functions. 2x4 electrical thrusters mounted on the E/W/N/S edges. The satellite is operating very well and a lot of flight data is being analysed.

In the US it is expected that Boeing will continue to market its large 702HP platform, using the XIPS-25 gridded ion engine system for the orbit topping and station keeping functions, toward operators seeking to replace or expand their existing fleets. In addition, following the announcement in 2012 of the first orders for their small 702SP 'All Electric' platform, it is expected that Boeing will target this platform at emerging markets, where the potential of low cost dual launch on Falcon 9 could significantly reduce capital investment cost for new markets.

The Boeing 702SP is a 2 ton/ 7.5 kW class platform which uses a common electric propulsion system, based on the XIPS-25 gridded ion engine, for full orbit raising and all station keeping and momentum management functions.

Space Systems Loral, are known to be engaged in qualifying the Fakel (RU) 5kW SPT-140 Hall Effect Thruster. Once mated to a wide range deployment and positioning mechanism, developed by Loral, this will offer a complete orbit raising and on orbit control capability using electric propulsion.

Faced with such competition it is reasonable to expect that the "market" will over time demand that European platform providers match the worldwide competition, by offering orbit topping on its large platforms and developing small platforms with 'all-electric' orbit raising and station keeping functions. All of the existing European platforms use the Fakel (RU) SPT-100 Hall Effect Thruster or the Snecma-Safran PPS-1350G Hall Effect Thruster. Since the total impulse capacity of the both of these thrusters is limited, existing configurations cannot offer significant orbit topping in addition to the baseline station keeping functions.

For the AlphaBus extended range, the situation was even more difficult. This platform range is targeted at for a maximum launch mass of 8.8 tonnes (maximum Ariane-5 ECA capability to LEO) and power extension to 22 kW. In this situation the total impulse capability of existing 1.5 kW thrusters (PPS1350/SPT-100) is marginal to perform the station keeping role. In order to maximize the payload mass fraction in this scenario, even relatively modest top-up durations will exceed the thruster capability. Whilst there is a potential to employ dedicated orbit raising thrusters, this de-optimises the propulsion system, thus requiring the availability of thrusters with a higher total impulse capability.

OHB Systems are working in partnership with SES-Astra and the ESA to develop a small 'all-electric' platform, named Electra (ARTES 33). The intension is to produce a small platform in the 2 – 2.5 tonne class which can compete with the Boeing 702SP by offering low cost launch options. The baseline design considers a four thruster configuration (2 + 2) with each pair of thrusters mounted on a boom mechanism to allow repositioning between orbit raising and station keeping functions. The requirement for orbit transfer duration to be less than 200 days necessitates the use of 4.5 kW class thrusters for orbit raising. At this stage of the project has selected Hall Effect thrusters which have the longest flight heritage.

High-power electric propulsion is therefore needed to cover this range of large Telecom applications within the AlphaBus frame. High-power electric propulsion is also needed to compete in the worldwide Telecom market and provide a substantial orbit-topping capability for the whole platform range. The AlphaBus extended-range platform will be designed to provide up to 90-days orbit-topping (with a maximum 200 m/s velocity increment), requesting an additional 1 MNs for the thruster total impulse capability.

In the longer term high power thrusters will be needed to extend the total impulse capability of the electric propulsion systems and to increase the thrust available for orbit raising, so that larger fractions of the orbit raising function can be performed using electric propulsion while maintain an acceptable orbit transfer duration.

High-power electric propulsion is needed to save a larger fraction of the chemical propellant within the specified transfer duration and to extend the total impulse capability to be able to perform both orbit-topping and station-keeping with the same thrusters. Therefore a double operation point for this thrusters will optimise the output of the mission, high specific impulse and for station keeping and lower power to thrust ratio for orbit raising will be required. With the increased thrust capability of the high-power thruster, wet mass savings are much more significant and the limitation of the maximum platform dry-mass is removed. In addition, novel thruster orientation mechanisms enable the operation of 2 thrusters in parallel with small thrust vector losses, rendering orbit transfer even more attractive. Hall Effect thrusters, ion engines and HEMPT systems are the main candidates for these operations.

The European reaction to the changing launcher market and commercial platform developments in the united states is now underway. Both NeoSat (ARTES-14) (Figure 3) and Electra (ARTES-33) are intended to cover the small to medium class platform applications. Significant topping of between 4-8 months, or complete electric orbit raising configurations are expected from these developments.

In parallel both Airbus Space and Defence and Thales Alenia Space are working on extended versions of their existing developments, these being based on the availability of 5kW Hall Effect Thrusters and fully deployable thruster gimbals.

Another important market is Constellation of satellites required for internet operations, OneWeb, LeoSat, Space X, etc will need thousands of spacecraft that will use electric propulsion systems to reach the right orbit, stay there and perform de-orbiting operations at the end of the mission. Cheap and versatile electric propulsion systems will be required and the cost of the system will need to be one order of magnitude lower than current prices. The way the test are done, the materials used, the geometries considered will be key points to achieve such savings. Small constellations such as ICEYE will use the FOTEC field emission thrusters to keep the constellation in orbit and de-orbit all the satellites when the life is finished.

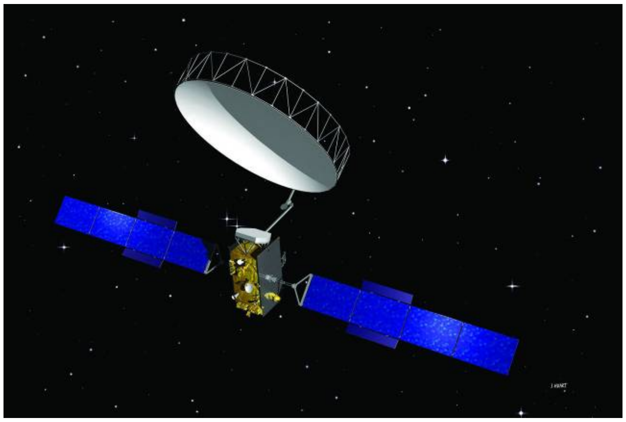

Figure 2: AlphaBus.

Figure 3: Neosat.

III Navigation

The Galileo 2G programme is targeting the possibility to increase the Galileo Payload capability without impacting the launch costs (and possibly reducing them). The need to increase the size of the Galileo Payload (mass and power) is deriving from system needs, which are considered to become essential in a new scenario of Galileo.

Today, there are no margins in the Galileo platform to allow an increase in the payload capability, due to mass and power limitations established by the adopted launch strategy (Soyuz, dual launch, direct injection). Therefore, any increase in payload would lead to a single Soyuz launch, with a negative impact on costs.

Several ESA studies concluded that the increase in payload capability could be achieved only by using Electric Propulsion to transfer the satellite to operational orbit and by changing the launch injection policy.

Electric Propulsion, used to transfer within 12 months each satellite from the injection orbit (LEO or GTO) to the target orbit (MEO or IGSO), would allow to:

- increase the Galileo payload capability;
- make the Galileo platform compatible with any launcher of the Arianespace's launcher family;
- reduce the launch costs by increasing the number of satellites per launch, with the goal to launch:
    - o $\geq$ 4 satellites in Ariane 5 shared launch into standard GTO, leaving a co-passenger mass $\geq$ 3000 kg
    - o $\geq$ 3 satellites in Soyuz ST dedicated launch
    - o $\geq$ 1 satellites in Vega dedicated launch.

The ESA studies have considered the use of several Electric Propulsion SubSystems (EPSS) from different European suppliers. In particular three Electric Propulsion technologies were assessed: Gridded Ion Engines, Hall Effect Thrusters, HEMPT. ESA is currently funding the European sector to adapt these engines to Galileo evolution.

IV Science and Exploration

Scientific missions such as LISA require microthrusters (field emission, mini-ion engines, colloids, etc.) as very fine control actuators for the drag free systems and the constellation control maneuvers. Interplanetary missions to Mercury, Mars, Asteroids, etc. will require high power ion engines, HEMPT and Hall effect thrusters as primary propulsion systems. Earth Observation missions such as GOCE made use of the large controllability of the ion engines to compensate the variable drag along the orbit and future gravity missions will also employ electric propulsion systems to compensate the drag at low Earth orbits. Furthermore, the use of electric propulsion such as small Hall Effect thrusters will allow lower altitude orbits than chemical propulsion due to the higher specific impulse of the electric systems, and in this altitude the payload mass (SAR, RADAR, optical instruments, etc.) will be reduced.

The ESA Cornerstone mission to the planet Mercury, BepiColombo (Fig.4), foresees for the electric propulsion options an ion propulsion system with high specific (>4000 sec) and high total impulse capability.

The BepiColombo Solar Electric Propulsion Module will be propelled by a cluster of high-power (in the 2.5-4.5 kW range) gridded Ion thrusters providing a maximum thrust of 143 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 QinetiQ T6 electron bombardment ion thruster has been selected. During 3000 hours of thruster characterisation test a single and twin configuration has been investigated. Thruster characterisation with one single neutraliser in twin thruster configuration and a test at high temperature has also been 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. A lifetime test will also take place in due course.

Very accurate pointing requirements for missions such as Laser Interferometer Space Antennas (LISA) [2] as well as other low disturbance requirements such as imaging applications require propulsion systems to operate in the micro-Newton region. Drag free and flying formation missions also require very low and accurate thrust. Only propulsion systems that can deliver both high specific impulse and ultra precision controllability are capable to fulfilling the stringent requirements on these types of missions. In many cases EP is enabling for missions such as LISA. These missions may use mini-ion engines, Field Emission microthrusters or micro colloids systems. The engines developed in the frame of Bepi-Colombo, the Qinetiq T6, and high power Hall Effect thrusters such as the Snecma PPS5000 will also be candidate for exploration missions to different planets of the solar system.

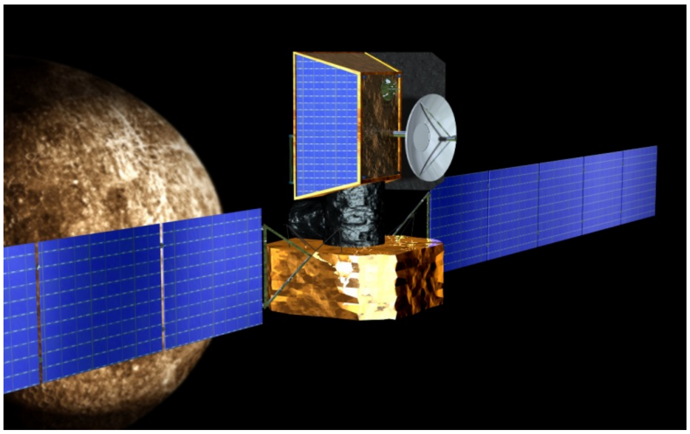

Figure 4. Bepi-Colombo spacecraft

The Laser Interferometer Space Antenna (LISA) mission's goal is to detect gravitational waves, distortions of space-time occurring when a massive body is accelerated or disturbed. To achieve that goal, the relative position of several solid blocks placed on different spacecraft 5 million kilometers apart will be constantly monitored with very high accuracy using laser-based techniques. A gravitational wave passing through the spacecraft will cause these bodies to vibrate, changing the separations between them. Gravitational wave induced changes will be so subtle that in order to perceive them the position of each satellite must be controlled down to the nanometer level.

The success of the LISA mission will depend on the performance of a sophisticated accelerometer concept working under drag-free conditions. The drag-free control of the spacecraft will be provided by FEEP thrusters. The control torques and forces provided by the FEEP thrusters for the attitude and drag-free control during are in the 1 to 100 µN range, with a noise below 0.1 µN. LISA is envisaged as an ESA/NASA collaborative project. .

LISA mission will rely on advanced technologies that have never been demonstrated in space, one of those technologies is the FEEP system. In order to reduce mission risk, a space demonstration is planned for the unproven technologies. This planned demonstration mission is called LISA-pathfinder. The ESA FEEP thruster is being developed to implement the drag-free operation on LISA pathfinder and NASA has developed colloid thrusters that will also be included on the mission as a backup system for providing the drag-free operations.

ESA has assessed the use of electric propulsion systems for interplanetary trajectories to Asteroids. The Marco Polo mission has been internally at the ESA Concurrent Design Facility (CDF). This study had the objective to design a mission that returns a sample from a near Earth asteroid of a primitive class, while providing context information on the Asteroid itself. The Marco Polo mission was a Cosmic vision M-class candidate and was first studied in the CDF in 2008 using chemical propulsion, the cost of the mission was too high and the only way to reduce the cost bellow 400 ME was to use electric propulsion which by reducing the mass could allow to launch in a smaller launcher. Ion engines and Hall Effect thrusters are main candidates for the propulsion system of such a mission.

ESA is currently studying the future evolution of the Exploration programme. It will be very expensive to engage in a complex mission to Mars directly, especially in the frame of the current economic crisis. Instead of thinking on unrealistic missions due to their high cost, ESA is reflecting on proposing a technology mission that allows to test all the future technologies required for exploration missions. Any mission to Mars or any planet in the frame of exploration will require lifting weight to LEO, then assemble different structures and send this spacecraft to interplanetary trajectory, at that point the spacecraft will need to orbit the planet, descend, collect samples or bring astronauts and ascend again before coming back to Earth. High Power Electric propulsion (>10kW) could be a perfect candidate for performing interplanetary cruise and will need to be considered during this technology mission that could pave the way to future and more ambitious missions.

V Earth Observation

The main aim of the GOCE mission was to provide unique models of the Earth’s gravity field and its geoid (reference equipotential surface) to high spatial resolution and accuracy. GOCE also performed advance research in the field of steady-state ocean circulation, physics of the Earth’s interior and leveling systems. The launch of the satellite took place in 2009. The GOCE satellite (see Fig5.) is a low-Earth orbiting spacecraft (275 km) that has a small cross section of approximately 1 m^2, 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 are no deployables or mechanisms to produce shocks. There is 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. The primary function of the ion engine on GOCE was 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 [4].

Fig.5. The GOCE Spacecraft

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. An endurance test of 5000 hrs was performed successfully on this engine.

The success of the ion engine in the GOCE spacecraft has demonstrated the potential of this technology for fine control of satellites flying in LEO. A new post GOCE mission is being designed at ESA. This mission is composed of two small satellites flying in formation in a very low orbit and is considering the mini-ion engine from EADS and University of Giessen to compensate very small drag forces. Milli-Newton In thrusters (FOTEC) are also candidates for this mission.

One of the major limiting factors to extend LEO mission's duration and to lower the operational altitude is the mass of propellant required to perform drag compensation. The possibility to use the external residual atmosphere as propellant for a conventional electric propulsion system is being explored by ESA since 2007. In a first GSP study (*CDF Study Report Advanced Electric Propulsion for Very Low Earth Orbit Missions*), it was investigated the collection from the atmosphere the gas needed to feed an electric propulsion systems. The activity was followed by a TRP study (*Completion of HET and RIT characterization with atmospheric propellants*) that successfully demonstrated the ability to operate a Hall-Effect-Thruster (HET) with a very high content of oxygen (about 50%). A final step was undertaken in a recent experimental activity aimed to demonstrate that a RAM electric propulsion system (RAM-EP) could effectively be realized. The demonstration, carried out by SITAEL (IT), was funded by the ESA TRP study *Assessment of Key Aerothermodynamics Element for a RAM-EP Concept*.

To carry out the test in a ground facility, it was necessary to upgrade a vacuum chamber with a flow generator. A 5kW class HET thruster fed with a particular mixture of $1.27N_2+O_2$ (a composition equivalent to the atmosphere at 200km) was used to produce a 8km/s flow motion inside the chamber. The tested RAM-EP consisted on a dummy spacecraft equipped with an intake (or collector) numerically designed for the conditions of the chamber, to feed a two-stage HET thruster. Due to the very low gas density achievable at the intake, the ionization of the atmospheric gas represents a critical issue. The solution adopted was to use a double stage thruster, characterized by an ionization stage placed upstream of the acceleration stage of a common HET thruster. Such configuration allows for a high enough density and for a satisfactory collisional ionization process. At the same time, the magnetic field allows for the drift of the ions towards the acceleration stage and, at the thruster exit, for the acceleration of the ionized gas.

The experimental campaign was composed of three main phases:

- The validation of a particle flow generator, able to provide a suitable and representative flux to the RAM-EP system,
- The validation of a double stage HET thruster using representative propellants, and finally,
- The concept validation of a full-integrated RAM-EP System.

The tests, carried out in the time frame 26/04 – 05/05, successfully demonstrated for the first time in the space history the realization of a RAM-EP concept (s. figure6). The RAM-EP was able to start and operate in stable form during the test using as fuel the air ingested through the collector. This is a milestone worldwide, that open the door not only to future low altitude Earth observation spacecraft (a kind of GOCE second generation) but also to new type of exploration missions, and in-orbit servicing missions. In particular, for this last application, it enable in huge dimensions the realization of the reusability concept and therefore to realize missions with low level of space debris.

Figure 6 (airbreathing Electric Propulsion, RAM-EP)

Next steps will be the maturation of the technology by dedicated technology development activities for the characterization and optimization of the collector and the two-stage thruster, as well as for the investigation on the scalability of the concept.

VIII Space Transportation

Based on growing maturation of Electric Propulsion Systems and increasing capabilities of such propulsion devices (power rising), possible applications to space transportation vehicles have gradually been studied with a more and more detailed level of analysis.

It is possible today to gather the different classes of applications around the two following families of concepts:

- Electric kick stages for launchers to increase performance capabilities;
- Service module of Orbital Transfer Vehicles (OTV) for inter-orbital missions (servicing, cargo transportation beyond LEO, towing of asteroids, etc.)
- New injection strategy missions for possible new institutional missions (transfer from LEO) and commercial missions (on orbit servicing, …)

Several ESA studies have already been performed to increase the performances of launchers by adding an electric kick stage to a conventional architecture chemically propelled. For instance, this is the case for the Vega launcher with an electric kick stage composed of a cluster of five HETs, each of them delivering a 0.3 N thrust with a 5 kW power requirement. Another possibility was studied by CNES for implementation in Ariane launchers (EASE concept) and provides significant increase of performance that can be appreciated for liberation missions for instance. The first study was also performed with a cluster of 5 kW HETs.

Globally speaking these architectures clearly offer to launchers significant gains of performance for a limited cost. This gain is especially important when the thrust is increased. Beyond the increase of launchers' performance the perspective is the intention to offer the payloads a generic service for directly injecting them on their operational orbit.

Moreover there are many in-progress activities on service modules of orbital transfer vehicles, based on the use of EPS such as Chaser for Active Debris Removal, asteroid Retrieval mission (from NASA), etc.
It is also necessary to mention several industrial initiatives (Airbus DS, OHB, …) to identify potential commercial markets with OTV architectures

This very quick overview of the different applications demonstrated an important potential for EPSs for future missions. The already promising results would be greatly improved if more powerful engines were available. It is the reason why such potential applications are looking for more powerful electric thrusters to limit the number of engines to be assembled in a cluster. With the EC FP7 HIPER project background, which allowed testing a 20 kW HET electric thruster (1 N of thrust with 2400 s Isp), Europe has gained capabilities to better address the first class of missions.

Some of these new missions will require important electric power. Today photovoltaic panels are very good products to generate some tens (satellites' scale) or hundreds of kW (e.g. in space infrastructure).Technology is mature and flight proven with in progress activities to still improve performances. A number of activities are in progress in order to identify, study and mature alternative means to generate great amount of electric power in space (some hundreds of kW and more).

High power PPU's at low recurring cost are required in a strongly competitive market environment.
Power Processing Units (PPU) are a significant cost drivers and can make easily half of the development cost and recurring cost of an EP subsystem. European PPU's at high TRL (8-9) level are currently only available at 1.5 kW and 2.5 kW power for HET, and at 2*1.4 kW for HEMPT . However all these products may need a further iteration of industrialization to improve their cost competitiveness including impact of delta-qualification. Addressing higher

power needed for orbit raising would require clustering of units with compatible thrusters. For GIE 6.8 kW based on 5 high power modules are available for science missions at TRL8, but only TRL5 for telecom (here 5.1kW by 4 modules). Capabilities to supply 5kW class of thrusters is targeted by several European PPU suppliers expected to be achieved within the next 2-3 years. It has to be mentioned, that all these new near term developments for higher power will end up with a first result, which typically needs a further cycle of industrialization, which duration can be 3-5 years year in addition to improve cost. Furthermore the first 5 kW class thrusters is/will be supplied by PPU which generate the high power out of parallelized high power modules, where the block size is in the order of 2.5 kW, however a bock size of 5kW would allow further mass and cost optimization. Multiple-operation (variable/configurable working points) has not been specially addressed today. Furthermore, todays PPU allow only limited range of adaptation to different thruster. The increase of modularisation of PPU is a trend which is expected to help for cost improvement. There is also the expectation that new types of electrical components (semiconducters), materials (PCB's) and processes (packaging) may help to improve the power per module capabilities and/or provide cost reduction. Direct drive concepts may make sense for space transportation with EP as the spacecraft power system is anyway then dedicated to supply the EP system and could allow therefore simplification of PPU and PSCU architecture, presuming that the availability of high voltage solar arrays is given.

As a summary final goal should be to get a clear identification /validation of the capabilities of the existing concepts, to identify their limitations and to build a work plan for high power (> 30 kW) conditions

VII EPIC

The Electric Propulsion Innovation and Competitiveness (EPIC) project mainly aims at producing a clear integrated roadmap and master plan for its implementation through the European Commission Horizon 2020 Space Strategic Research Cluster (SRC) on In-Space Electrical Propulsion and Station Keeping.
The roadmap and its complementing documents, when implemented through the SRC Operational Grants will support the achievement of the overall SRC goal of enabling major advances in Electric Propulsion (EP) for in-space operations and transportation, in order to contribute to guarantee the leadership through competitiveness and non-dependence of European capabilities in electric propulsion at world level within the 2020-2030 timeframe, always in coherence with the existing and planned developments at national, commercial and ESA level.

The EPIC PSA also intends to provide advice to the Commission for the SRC calls documentation for Operational Grants, contribute to the assessment of the progress and results of the Operational Grants and support the Commission and REA on the general SRC implementation.

The EPIC objectives will be measurable through the immediate deliverables and milestones of the project.

EPIC project is coordinated by ESA and the team is composed by several space agencies (CNES, ASI, UKSA, DLR, CDTI, Belspo) and Eurospace and SMI4Space.

VII CONCLUSIONS

The main trends in Telecommunication and Navigation, clearly indicate the importance of the use of high power (5kW) ion engines, Hall Effect thrusters and HEMPT. European suppliers have successfully developed and qualified Electric Propulsion technology that is capable to support existing and medium term applications. Suppliers from across Europe can provide a majority of the components required at electric propulsion system level. It is however noted, that these equipment's have a difficulty to compete with those coming from Russia and US with respect to recurring price.

In order to assure access to electric propulsion technology to support medium to long term Telecommunication applications, Europe has to proceed with the development of High Power Electric propulsion systems (5 kW) to match the current challenges in the telecommunication arena.

For missions that permit orbit topping durations of around 6 months, this will require the availability of 5 kW Hall Effect Thrusters, with a dual-mode (throttling capability) and sufficient total impulse capability to cover transfer and station keeping needs. Due to the uncertainty as to if certain important areas of the commercial market will permit significant orbit topping durations, High Power Ion Engines (GIE/HEMPT) need to be ready to provide mass efficient station keeping functions. These thrusters would also be strong candidates if the launcher market evolves to permit direct injection strategies. Whilst European knowhow and initial development activities are today underway, due to the long process of development and qualification, these activities must be accelerated and provided with sufficient support for the non-recurring effort. Above all, the development activities must be focused from the earliest point on producing a market competitive products.
SNECMA-SAFRAN PPS5000 , QINETIQ system (T6 and new ring cusp system), ASTRIUM (RIT-22) and HEMPT (5 kW) systems are the European candidates. FAKEL SPT-140 and Aerojet BPT4000 are the main competitors outside Europe.

The use of lower power Hall Effect thrusters and HEMPT (1350 W) in clusters is also an important alternative for some missions. The reduction of the cost of the European systems is today mandatory to compete with American and Russian systems which are today cheaper and in some cases more matured.

The trends in Science and Earth Observation shows that micro Newton regime will be very important for flying formation missions, gravity missions and space telescopes. Therefore, systems such as mini-ion engines, mini-hall effect thrusters and field emission micro-thrusters will have to be developed.

System studies, flight data exploitation and spacecraft thruster interaction studies will have to be carried out together with new mission analysis and orbit trajectory optimisation assessments taking in consideration the low thrust produce for electric propulsion systems.

In the long term, the use of high power electric propulsion systems will be used by exploration missions to inner and outer planets making use of high power sources such as nuclear space reactors or powerful solar arrays. The development of high power versions of the current Electric Propulsion systems such as Hall Effect Thrusters, Ion engines , MPD, HEMPT or Helicon antenna thrusters will allow to achieve high delta v missions such as cargo missions to Mars.

New applications such as the de-orbiting of thousands of satellites forming part of future space constellations is an important issue that has to be resolved in the near term. Furthermore, once many satellites, upper stages and other objects are in space, we will have to clean the space and initiatives on space tugs acting as cleaners by going to these objects grabbing them and send them to lower orbits to permit the re-entry or higher orbits in the case of GEO objects will have to be carried out in the future. Electric propulsion systems of low, medium and high power are main candidates for these missions.

EP testing facilities are requested for long duration tests and acceptance testing. In addition the space community recognizes the need of having test facilities ready to be used as back-up when the planned one cannot be used. Furthermore, it is mandatory that the tests performed in different test facilities on the same thruster provide congruent results. This comparability of results is of extremely importance for the developers of micro-Newton thrusters (FEEPs, colloid, mini-ion engines) due to the need of such developers to clearly demonstrate that their engines are capable of controlling the thrust at such low regimes.

European Commission Horizon 2020 Space Strategic Research Cluster (SRC) on In-Space Electrical Propulsion and Station Keeping is a clear exponent of the importance of the EP technology for Europe. ESA is the coordinator of this project wher the team is formed by several space agencies and industrial entities.

ESA is actively developing all the technologies required for all these missions with the support of the ESA Propulsion Lab[5,6].

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