Electric propulsion Activities at ESA

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Abstract: 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. Furthermore, new scientific and Earth observation missions dictate new challenging requirements for propulsion systems and components based on advanced technologies such as microNewton thrusters.

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.

ESA missions such as GOCE, Smart-1 and Artemis have paved the way for the use of electric propulsion in future ESA missions: Lisa-pathfinder, Bepi Colombo, Small GEO, Alphabus, LISA, etc.

This paper will evaluate the current and future challenges of the electric propulsion field at ESA. The status of the technology and the current and future applications will be also presented.

Nomenclature

EP	=	Electric Propulsion
FEEP	=	Field Emission Electric Propulsion
LISA	=	Laser Interferometer Space Antenna
HEMPT	=	Highly Efficiency Multistage Plasma Thruster
NSSK	=	North South Station Keeping
GEO	=	Geostationary Earth Orbit
EOL	=	End Of Life

I. Introduction

In the last years, the trend in GEO Telecom satellites has consolidated into a considerable increase in electrical power to satisfy the payload needs, an increase in platform size to accommodate the payload and longer mission duration up to 15 years. All the major Telecom manufacturers, as Boeing, Alcatel and Astrium have adopted Electric Propulsion System for north-south station keeping (NSSK)[1]. This can be seen as the first step for the penetration of this technology in the Telecom market, even if in some cases the Electric Propulsion System has been used together with redundant Chemical Propulsion systems. This demonstrates the potentiality of this technology and shows that

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flight heritage and confidence in the Electric Propulsion System are the barriers that this technology has to overcome to be used in all commercial spacecraft.

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 Hall Effect thruster, might 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 initiated development programmes to qualify in the short-term high power version of existing thrusters (5kW). These new thrusters will also play a major role in the direction of optimizing the use of EP on the next generation of GEO telecoms, when EP operations will be extended to include other functions than NSSK: notably full or partial orbit transfer to the GEO orbit, east-west station-keeping, momentum wheel speed control and possibly other attitude control functions and spacecraft de-orbiting at end of life (EOL).

The development philosophy of the electric propulsion systems in Europe is focused on both commercial and scientific applications. Ion engines and Hall Effect thrusters with powers around 5 kW are currently available at breadboard level. Bepi Colombo mission will require ion engines around 5 kW to reach Mercury. The new ESA exploration programme will require high power electric propulsion engines (more than 5kW), capable to bring a significant payload mass to Mars. Therefore, it can be concluded that European systems (Hall effect thrusters, HEMPT and ion engines) are qualified or under development for power levels up to 5 kW. Furthermore, the capability exists of testing these engines up to 10 kW of electrical power. Smart-1, GOCE, AlphaBus, Small GEO and BepiColombo will provide a good flight heritage.

The other electric propulsion system with a high potential is the FEEP thruster that is baselined in scientific ESA missions such as Lisa-pathfinder and LISA. These thrusters will have to provide microNewton thrust levels with an accuracy of less than one microNewton. ESA Science and Technical Directorates are jointly developing the flight models. This propulsion system may also fly in the CNES mission Microscope.

Other electric propulsion technologies that are currently being studied at ESA are: the Magneto Plasma Dynamics (MPD) thruster (Alta and IRS Stuttgart); the small version of ion engines (mini-ion engine) is being developed at Giessen and QinetiQ and a small version of a Hall effect thruster (mini-Hall effect thruster) at ALTA. Thrusters such as Pulsed Plasma Thruster (PPT) and resistojets are also being considered due to their robustness and simplicicity.

Test facilities and standarised test procedures are needed for a proper development and qualification of the electric propulsion systems. European industries and research centers are active in the set up of a network of testing facilities (ALTA, SNECMA, QinetiQ, AEROSPAZIO, Giessen University, etc.) that will be able to offer different facilities to any project requiring a test service. The space community recognized the need of having test facilities ready to be used as back-up when the planned test chamber cannot be used. Furthermore, it is mandatory that the tests performed in different test facilities on the same engine provide congruent results. The possibility of cross-verification of European and non-European thrusters in different facilities world-wide is considered a possibility to speed-up the acceptability of electric propulsion on new missions. Furthermore, this comparability of results is of extremely importance for the developers of microNewton 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.

The electric propulsion systems developed in Europe are the following two tables:

Type	Manufacturer	Model	Technical Characteristics	
			Power (W)	Power to Thrust Ratio (W/mN)
Ion Engine	EADS (D)	RIT-10	600	30
		RIT-XT	5000	35
	QINETIQ (UK)	T5	600	30
		T6	5,000	35
Electro magnetic	SNECMA (F)	PPS1350	1350	20

Thrusters	Thales (G)	PPS5000	5000	22
		HEMPT	1500	25
	EADS (D)	ROS2000	2500	20
	SNECMA (F)	SPT100 (1)	1350	17
FEEP	ALTA (I)		TBD (depending on the application)	60
	ARC (A)		TBD (depending on the application)	80
(1) The SPT is manufactured by Fackel, in Russia, and commercialized in Europe by SNECMA				

Type	Model	Development Status	Flight Opportunities
Ion Engine	RIT-10	Operational on ARTEMIS, Life test for more than 20000 hours done at Electric Propulsion Test laboratory of ESA/ESTEC (NL)	
	RIT-XT	Qualification in progress	Interplanetary and telecommunication missions
	T5	Operational on ARTEMIS,	Operational in GOCE,
	T6	Qualification in progress with National and ESA funding	Candidate for Alphabus evolution and baseline in Bepi Colombo
Hall Effect Thruster	PPS1350	Launched on-board Of Stentor, not operated due to the Launch failure Operational on board of SMART-1	Inmarsat I-4 Alphasat
	PPS5000	Qualification in progress with National and ESA funding	Candidate for Alphabus evolution,
	HEMPT	In development	Small GEO
	SPT-100	On-board of Intelsat-10 and flown on several Russian satellites	Many telecommunication spacecraft
FEEP	ALTA FEEP	(1)	Selected for Lisa-pathfinder and Microscope. Candidate for LISA
	ARC FEEP	(1)	Back-up for Lisa-pathfinder
(1) Once this technology is developed for Lisa-pathfinder, other future missions such as Darwin will use it			

The main issues on Electric Propulsion (EP) for the near future are:

1. Consolidation of the current European products (Hall Effect thrusters, ion engines, field emission thrusters, HEMPT, etc.). In this process the qualification of the EP products is one of the main activities.
2. Utilization of the current flight data (Artemis, Smart-1, GOCE, commercial telecommunication satellites, etc.) to validate the models that will be used by the spacecraft designers in the future.
3. Standardization of engineering processes and testing facilities employed in the design, manufacturing and qualification of the current electric propulsion systems.
4. Preparation for the ultimate goal: the full electric propulsion spacecraft where the benefits of the use of electric propulsion will be maximize by designing the spacecraft around the electric propulsion system.

Electric propulsion community has the technical maturity to face a new era of commercial utilization. To improve the competitiveness of EP on the unique or special missions will require that cost reductions and less complex systems be achieved. In the commercial arena the volume of EP systems produced will be high due to the very nature of the field. However, in the scientific arena there are fewer missions and the missions require a higher level of sophistication. Synergies between these projects and the commercial sector should be sought.

At least one ion engine, one HEMPT, one Hall Effect thruster and one FEEP should be fully developed and commercialise in order to keep Europe at the forefront of the technology and enable new mission with very stringent requirements in controllability and propellant mass availability. Furthermore additional concepts such as mini-ion engines, mini-Hall effect thrusters, resistojets and PPTs should also be seriously considered in the development programmes in order to enlarge the possibilities of the European industries in the competition for new spacecraft (minsatellites, LEO platforms, etc.). Finally, the utilization of MEMS for electric propulsion should be investigated in order to increase competitivity by decreasing mass, volume and power of the different subsystems.

One of the major perception challenges faced by EP is the potential interactions of the energetic plasma with the spacecraft concern with implementing EP is the interaction of the energetic plume on spacecraft surfaces and payload. This was a concern for SS/L which uses EP for NSSK. The plume of the thruster impinges on the spacecraft solar arrays which are mounted on the north and south panels. This causes the solar array anti reflective coating to be eroded from the cell cover glass over the course of the mission. Predictions of solar array degradation due to EP plume impingement were made to size the solar arrays for EOL requirements and, after nearly four years on-orbit, solar array performance tracks these predictions. Up to date the models used to assess the possible spacecraft thruster interactions are validated with ground data. Some customers require more confidence on the results which can come from additional validation of such models with flight data. This issue has been recognized on Europe with a special effort to incorporate plasma diagnostics into telecommunication satellites. Validation of ground tests with the flight data will continue to demonstrate that these issues are understood and can be addressed.

II. European Missions with Electric Propulsion

A. Science and Exploration:

ESA scientific missions such as Lisa-pathfinder and LISA require FEEPs as very fine control actuators for the drag free systems and the constellation control maneuvers. Interplanetary missions to Mercury, Mars, etc. will require high power ion engines, HEMPT and Hall effect thrusters as primary propulsion systems. Earth Observation missions such as GOCE are making use of the large controllability of the ion engines to compensate the variable drag along the orbit. 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.1)**, foresees for the electric propulsion options an ion propulsion system with high specific (>4200 sec) and high total impulse capability.

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 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 in phase B and C/D. A lifetime test will also take place in due course.

Figure 1. Artisti view of the Bepi-Colombo spacecraft

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 MICROSCOPE, **LISA pathfinder**, LISA, and DARWIN. These missions will make use of mini-ion engines, Field Emission microthrusters and 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.

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 ultra 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.2)**. 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.

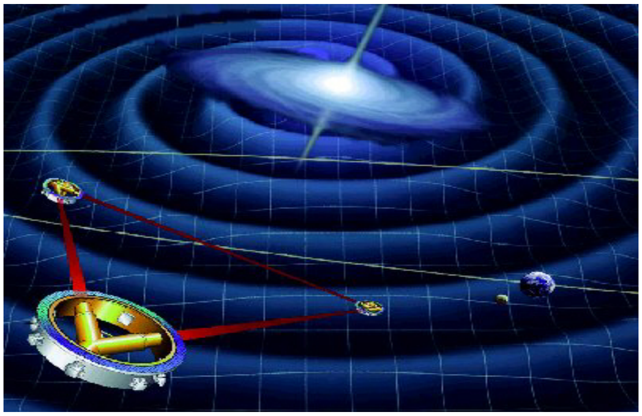

Figure 2. The LISA Mission Concept

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.

Space Interferometry was identified in the ESA long-term program 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 several spacecraft flying at distances ranging from 100 to 500 meters. The spacecraft will work together to detect Earth-like planets in other solar systems and also to analyze their atmospheres in search for signs of life. The Darwin mission will carry in total six infrared telescopes located on several spacecraft. Using interferometry the six telescopes will suppress or 'null' the bright light of the central star, while enhancing the emission from the small, opaque orbiting planets. During the initial design studies of Darwin, two competing satellite designs were evaluated: 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. The position of each individual spacecraft will be controlled with the use of FEEP thrusters or mini-ion engines.

Both LISA and Darwin 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 is developing colloid thrusters that will also be included on the mission as a backup system for providing the drag-free operations.

The scientific objective of the MICROSCOPE mission is the verification of the Equivalence Principle between the inertial mass and the gravitational mass of two different bodies. This requires a precision better than 10^{-15} m/sec^2 more than what can currently be verified on ground. The mission is funded by CNES and is based on a standard CNES microsatellite bus. The sophisticated Attitude and Orbit Control System (AOCS) requirements for this mission will be fulfilled by a FEEP propulsion system. The Microscope FEEP Electric Propulsion System (FEPS) is provided by ESA according to an ESA/CNES agreement.

The development of the FEEP system is vital to the ESA science program. In order to reduce risk, two industries are currently developing different concepts for the FEEP system, one by Alta which has been selected as main candidate in Italy and one by ARC of Austria that is currently a back-up solution. An important aspect of the development is the characterization and lifetime performance of these thrusters.

B. Earth Observation

The main aim of the GOCE mission [3] 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 enable advanced research in the field of steady-state ocean circulation, physics of the Earth's interior, and leveling systems. The satellite has been launched launched on the 17 March 2009 .

The GOCE satellite (see Fig 3.) has a small cross section (approximately 0.9 m^2), and is totally symmetrical so as to minimize the influence of external forces. The satellite will operate in a low-Earth orbit of 240-270 km. The design configuration maximizes 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 because the EP system uses a gas propellant. The EP systems on this mission are a pair of ion thrusters which are used for drag compensation and orbit maintenance. The ion engines are provided by QINETIQ of the UK. These thrusters can provide variable thrust for compensation of the drag force in flight direction throughout the GOCE satellite measurement phases. In addition, the ion engines also support instrument calibration and orbit raising maneuvers. 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 mission imposes stringent requirements in terms of thrust range (1 to 21 mN with quantization steps of 12 microNewtons), noise, and stability on each of the subsystems of the IPA. The ITA is provided by QinetiQ of the UK. An endurance test of 5000 hrs has been performed successfully on this engine.

Future Earth observing missions are anticipated to fly at low altitudes and these will also need milli-newton propulsion system in a range up to 20mN to compensate for drag. The high specific impulse of electric propulsion systems, together with their high controllability, will enable these spacecraft to fly lower than classical missions using chemical thrusters. For missions such as A-SCOPE, which has as a primary payload a LIDAR instrument, it is important to fly low at relatively low altitudes in order to reduce the mass, volume and power of these devices. Small ion engines and small Hall effect thrusters are candidates for these types of missions.

Figure 3: The GOCE spacecraft

A. Telecommunication:

Among the European spacecraft vendors, Thales and Astrium have incorporated EP systems from Snecma of France for their Eurostar and Spacebus platforms. The communication spacecraft using these systems are: Astra 1K, Intelsat 10, Inmarsat 4-F1, F2 and F3 and more recently Ka-Sat, Yahsat 1A and 1B and Alphasat. Among the European spacecraft vendors, Thales and Astrium have incorporated EP systems from Snecma of France for their Eurostar and Spacebus platforms. The communication spacecraft using these systems are: Astra 1K, Intelsat 10, Inmarsat 4-F1, F2 and F3 and more recently Ka-Sat, Yahsat 1A and 1B and Alphasat..

ESA Alphasat will be a collaborative adventure between Thales and Astrium and will fly the PPS1350 from SNECMA. This thruster has already been flown by Smart-1 successfully in its trip to the Moon, now in Alphabus will be fully qualified for a commercial telecommunication mission.

An ESA telecommunication satellite, called **Small GEO (Fig.4)**, will also use EP systems to perform station keeping operations. In this case EP decreases the launched mass by several hundred kilograms. This difference will enable Small GEO satellite to have a total mass of less than 4000 kg which in turn allows it to be launched on a Soyuz launcher and thereby reducing launch costs to ½ of what they would be had the mission be implemented chemically and launched on the required Ariane 5. SPT-100 and HEMPT[4,5] thruters are baselined for this mission.

Figure 4: The Small GEO spacecraft

III. Conclusion

Electric Propulsion systems are baselined in several ESA missions that will be launched before 2015 (Alphabus, Small GEO, Bepi Colombo, GOCE, Proba 3, Lisa-pathfinder, etc.). Furthermore, future missions such as LISA, Darwin, Alphabus evolution, A-Scope, post-GOCE, etc. will require also EP systems to achieve stringent requirements. The symbiosis between the commercial world and the institutional one is very successful and ESA is making a good use of the background and infrastructure placed in industry due to the commercial push. Telecommunication missions such as Astra 1K, Intesat 10, Inmarsat 4-F1, F2 and F3, Ka-Sat, Yahsat 1A and 1B and Alphasat fly or will fly electric propulsion systems that later on could be used for scientific missions. The last ESA missions using EP, Smart-1, GOCE and Artemis, are providing flight data that is used to improve future designs of EP systems in Europe. Ion engines, Hall Effect thrusters, HEMPTs and FEEPs are the main candidates for all these missions.

European industry and academia are collaborating actively with ESA in the research, development and industrialization of European Electric Propulsion systems that are flying in commercial and institutional space missions successfully.

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