ESA Electric Propulsion Activities

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Abstract: The high specific impulse and high controllability of electric propulsion systems make this technology an enabler for many space missions. The strong competition among telecommunication satellite manufacturers is a major driver for advancements in the area of electric propulsion, where increasing better performance together with low prices are required to provide large propellant savings which can be used to place spacecraft in smaller launchers or extend the life of the space missions. Furthermore, new scientific and Earth observation missions dictate new challenging requirements for propulsion systems and components based on advanced technologies such as microNewton thrusters. Finally, new space missions in the frame of exploration will also require sophisticated propulsion systems to reach planets such as Mars or Venus and in some cases bring back to Earth samples from asteroids or comets. 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, EDRS, Alphabus, LISA, etc. This paper will present the current and future challenges of the electric propulsion in Europe.

Nomenclature

EP	=	Electric Propulsion
ESA	=	European Space Agency
FEEP	=	Field Emission Electric Propulsion
HEMPT	=	Highly Efficiency Multistage Plasma Thruster
HET	=	Hall Effect Thruster
HEPS	=	High Power Electric Propulsion System
MPD	=	Magneto Plasma Dynamic
NSSK	=	North South Station Keeping

I. Electric Propulsion State of the art in Europe

In the last years Electric Propulsion have been successfully employed for a number of science and exploration missions, e.g. Deep Space 1, Smart-1, Hayabusa Explorer, Dawn, and GOCE.

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 larger payload and longer mission duration up to 15

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years. All the major Telecommunication manufacturers (i.e. Boeing, TAS, Space Systems Loral and EADS ASTRIUM) have already implemented EP systems for North-South Station Keeping (NSSK). It is a first step for the penetration of this technology in the Telecom market, even if in some cases the EP systems has been used together with redundant Chemical Propulsion systems. In view of the increasing mass and mission duration of new GEO platforms, the requirements on the Total Impulse to be provided by the electric propulsion systems are constantly increasing. Qualified thrusters, such as the SPT-100 HET, might not be able in the near future to fulfil the Total Impulse specification of future commercial missions. The SNECMA PPS1350 HET fulfils requirement of newly developed large platform ALPHABUS (up to 3MNs). Short and mid term Telecommunication spacecraft will need up to 5MNs at constant power (particularly for larger telecom satellites above 6tons). This may require either a life extension of PPS®1350 or the development of a high power HET (up to 5kW). In the last years, the HEMPT thruster development has been carried out by Thales (Ulm) in the frame of DLR+CNES feasibility studies, DLR consolidation phase, ESA and DLR HEMP technology programs for Small GEO. It has been selected as primary EP system for Small GEO telecom platform; however the 1st flight will start by a demonstration. A very attractive business plan has been presented to ESA. HEMPT might cope with high total impulse demands since it has only negligible discharge channel erosion and thus high life-time prediction (delta qualification could be performed directly after qualification for SGEO mission). European producers of electric thrusters have already initiated development programmes to qualify in the short-term high power version of existing thrusters (up to 5kW). The 5kW QinetiQ T6 high power Ion Engines is undergoing qualification for BepiColombo mission and has undergone pre-qualification for AlphaBus. Hall Effect thrusters and HEMPT with powers up to 5 kW are currently available at breadboard level. Alternatively, high power cluster modules (HEMPT and HET based clusters have been verified within ESA technology programme) would offer straight forward thrust increase at reasonable costs for a delta qualification. Smart-1, GOCE, AlphaBus, Small GEO and BepiColombo will provide a good flight heritage. Furthermore, the capability exists of testing these engines up to 25 kW of electrical power in vacuum facilities at Alta for example. Even if short and mid-term Telecommunication spacecraft uses are concentrated on HET systems, the availability of such new EP thrusters will play a major role in the direction of optimizing the use of EP on the next generation GEO telecoms, when EP operations will be extended to include other functions than NSSK (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 disposal at EOL).

Exploration missions have specific performance requirements, and in particular may require higher specific impulse and total impulse levels currently only available with Ion Engines. Availability of very-high-power HET and/or Ion Engine systems will enhance future robotic exploration missions (such system will provide remarkable mass gain, which can be converted into either additional payload or a reduced launch mass, with acceptable transfer duration). Pre-development activities on 10kW EP systems have already been performed with ESA and National funding. Magneto Plasma Dynamics (MPD) thrusters, although in their early development phase, could enhance such missions even further. Furthermore Helicon Radiofrequency thrusters are currently being developed in Europe by CISAS under EC funding. The HEMPT development in the future should also be directly to higher power leves of operation to allow mission designers to count on the versatility of this thruster.

Another electric propulsion system with a high potential is based on FEEP thrusters that is baseline for scientific ESA missions such as Lisa-pathfinder and LISA. These thrusters will have to provide micro-Newton thrust levels with an accuracy of less than one microNewton and very low noise level. ESA Science and Technical Directorates are jointly developing the flight models.

Low power class Hall Effect thrusters (mini-HET) are currently available at breadboard level. Qualification of such thrusters aims at application on small-medium-size platforms and spacecraft (limited in power) to fulfil the manoeuvre requirements for drag compensation, station keeping, and disposal at End Of Life (EOL).

Miniaturised versions of Ion Engines (mini-Ion Engine) are currently available at engineering level. Qualification of such thruster will enable drag free and formation flying condition.

Pulsed Plasma Thruster (PPT) Resistojets and Arcjets are also being considered due to their robustness and simplicity.

European industries and research centers are active in setting up a network of EP testing facilities (ALTA, SNECMA, QinetiQ, AEROSPAZIO, Giessen University, TAS I-Florence, Thales, ONERA, IRS Stuttgart, etc.) which will allow cross-verification of test results (even between European and non-European thrusters). The possibility of cross-verification of European and non-European thrusters in different facilities could increase the acceptability of electric propulsion systems on new 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. The ESA Propulsion Lab (EPL) at ESA is having an important role in this effort.

New activities on EP systems/spacecraft thruster interaction are being initiated and an effort to standardise the development activities and test procedures is in place with the leadership of ESA

The EP thrusters developed in Europe are the following (see table):

Type	Manufacturer	Model	Technical characteristic				
			Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	I tot. (MNs)	Development Status & Flight Opportunities.
Ion Engine	EADS-Astrium (UK)	UK-10	30	25	3000	1	Operational on Artemis. No longer in production (Obsolete at system level)
	EADS-Astrium (D)	RITuX	Veriable (30-100)	0.050-0.5	300-3000	0.025	Demonstration model tested for 2000 hours, Engineering Model under development with National and ESA funding..
		RIT10	30	15	3300	>1.5	Operational on ARTEMIS since 2003. Life tested for over 20000 hours at ESA Propulsion Laboratory.
		RIT22	35	50-200	4200	>20	Engineering Model developed with National and ESA funding.
	QINETIQ / Uni Southampton (UK)	MiDGITS	40	0.001-1	1500s at 1mN, 90s at 0.012mN	0.040	Laboratory demonstration performed with National and ESA funding.
	QINETIQ (UK)	T5	30	0.6-20	500-3000	>1.5	Operational on ARTEMIS, Operational on GOCE.
		T6	35	150	4400	>20	Qualification in progress: HEEP for GEO comsats and SEP for BepiColombo.
	Mars Space Ltd / Uni Southampton	DS4G	70-90	2-5	14000	TBC	Laboratory demonstration performed with National and ESA funding.
Hall Effect Thrusters & HEMPT	SNECMA (F)	PPS 1350	17	50-88	1650	3	Launched on Stentor, not operated due to launch failure. Operated successfully on SMART-1 (5000 hours). Qualified for Alphasat. Flight opportunity on ConeXpress 2.
		PPS 5000	15-20	230-325	2300-1750	15	Laboratory demonstration performed with National and ESA funding.
		CHEAP	17	15	1400	0.2	Development in progress with National funding.
		PPSNG	18	140	1900	5	Development in progress with National funding.

Type	Manufacturer	Model	Technical characteristic				
			Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	I tot. (MNs)	Development Status & Flight Opportunities.
		SPT100 (*)	17	83	1600	2.9	Over 15 years of on orbit flight heritage on Russian spacecraft. Operational on Intelsat10-02, Inmarsat 4 F1, F2, F3, SS/L satellites. Flight opportunity on Ka-Sat, Yahsat 1A and 1B, Small GEO.
	EADS-ASTRIUM (F)	ROS 2000	19	71-132	1600-1700	2.9	Pre-qualification performed.
	ALTA (I)	HT100	20	2-12	900-1600	0.05	Development in progress with National and ESA funding. Demonstration model tested for 700 hours.
		HT400	20	19 -25	1000-1450	0.2	Development in progress with National and ESA funding.
		XHT 5000	22	230		TBD	Laboratory demonstration performed.
	THALES (D)	HEMPT 3050	20-35	10-70	2000-3500	>4	Development model. Qualification in progress with National, ESA and CNES funding. Flight opportunity on Small GEO, Proba-IP.
		HEMPT 30250	20-35	30-330	2000-3500	>20	Laboratory demonstration performed.
FEEP	ALTA (I)	FT-150	Max power consumption is 75W for 4 thrusters at 0.1mN	0.0001-0.150	>4000	2E-3	Qualification Model. Qualification in progress for LISA Pathfinder (baseline). Performance in life verified during endurance test (more than 3000 hours, 800 Ns). Crucial performance verification such as thrust noise level performed. Additional qualification up to 4000Ns required for LISA.
	EADS-Astrium (D) ARC (A)	In-FEEP	Max power consumption is 112W 4 thrusters at 0.1mN	0.0003–0.100	>4000	0.370E-3	Qualification Model.
Colloids	Queen Mary University (UK)	Array of colloids	TBC	0.01uN /emitter (ion mode) 0.1uN /emitters (droplet mode)	4500 (ion) 600 (droplet)	TBC	19 element laboratory demonstrations performed under ESA funding. Application envisaged on future micro-satellites.

Type	Manufacturer	Model	Technical characteristic					
			Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	I tot. (MNs)	Development Status & Flight Opportunities.
	EPFL (CH)	Array of colloids	20	2.5uN/m m2	2500	TBC	Laboratory demonstration performed. Application envisaged on future micro-satellites.
Arcjets	IRS Uni Stuttgart (D)	ATOS (NH_3)	7	115	480	0.4	Lifetime tested (1010 hours including 1010 activations) and qualified with national funding. Flight on AMSAT-P3D. Flight opportunity on TALOS (Stuttgart Small Satellite Program)
		MARC 5kW				TBD	Laboratory demonstration performed.
		HIPARC 100kW (H_2)			2000 (1000s at 1kW 1500s at 10kW)	TBD	Laboratory demonstration. Flight opportunity on Perseus and Lunar Mission BW1 (Stuttgart Small Satellite Program).
Hollow Cathode	QinetiQ / Uni Southampton (UK)/Surrey	Xe 30 A	320	2	1000	TBD	Laboratory demonstrations performed.
Resistojets	ALTA (I)	XRJ50 (xenon)	2	10-50	65		Laboratory demonstration.
	Ampac ISP (UK)	Xenon Nitrogen NH_3 others	2	10-50	45 150 158	0.05	Laboratory demonstration.
	SSTL (UK)	Xenon Nitrogen Nitrous Oxide	2-5	20-100 125	42 100 127	0.038E-3	Flight heritage. Flight opportunity on PROBA2.
MPD	ALTA (I)	SF-MPD	TBD	10k-70k	10000		DM
		SF-MPD with heated cathod	TDB	50k	2000		DM
		HPT	TBD	Up to 14k	Up to 2500		DM
		AF-MPDT	TBD	2000	2500		Under development with ESA and Internal Funding

Type	Manufacturer	Model	Technical characteristic				
			Power to Thrust Ratio (W/mN)	Thrust (mN)	ISP (s)	I tot. (MNs)	Development Status & Flight Opportunities.
	IRS Uni Stuttgart (D)	AF MPD ZT1 10kW (argon)	40	250	3000	TBD	Laboratory demonstration. Basic research, thruster optimization.
		AFMPD ZT2 100kW (argon)	40	2500	3000	TBD	Laboratory model in development.
		ZT and DT thrusters 500kW	19	26000		TBD	Laboratory demonstration. Basic research. Investigation on plasma instabilities.
PPT	IRS Uni Stuttgart (D)	ADD-SIMPLE X		1.5		TBD	Engineering model. Flight opportunity on Perseus and Lunar Mission BW1 (Stuttgart Small Satellite Program).
	Uni Southampton (UK)	HFB				TBD	Laboratory demonstration.
(*) The SPT is manufactured by Fackel, in Russia, and commercialized in Europe by SNECMA							

The Electric Propulsion components developed in Europe are as follows:

Type	Manufacturer	Model	Technical characteristic				
			Media	Mass (kg)	MEOP (bar)	Flow rate range (mg/s)	Development Status & Flight Opportunities.
Mechanical Pressure Regulators	Ampac ISP (Ir)	HPR	Xe / N_2 / He		150 (Xe)	10	Qualification in progress for Alphabus (ARTES 8)
	Ampac ISP (Ir)	MEMS PRM	Xe / N_2	0.45	150 (Xe) 310 (N_2)	10 (Xe)	Mechanical regulator will fly in N_2 cold gas application on PRISMA. MEMS component version under development for Proba-3.
	Astrium (UK)	XMRS	Xe	7	120 (Xe)	10	Operational on Intelsat10-02.
Electronic Pressure Regulators	Astrium (UK)	XRFS	Xe / He	6	120 (Xe)	10	Operational on Inmarsat-4 F1, F2, F3, satellites. Flight opportunity on Ka-Sat, Yahsat 1A and 1B,. Delta-qualification in progress for BepiColombo.
	Snecma (F)	BPRM	Xe	2.75			Operated successfully on SMART-1 (5000 hours).
	IberEspacio (E)	PSA	Xe	5.3	150	< 200	Under development and qualification for SGEO.

Type	Manufacturer	Model	Technical characteristic				
			Media	Mass (kg)	MEOP (bar)	Flow rate range (mg/s)	Development Status & Flight Opportunities.
	TAS (I)	HP-RIV	N_2Xe	< 0.2	150		EPR Proof of Concept (based on HP-RIV) successfully tested within ARTES 8 contract
Latching Valves	Ampac ISP (Ir)	HPLV	Xe		150 (Xe)	< 12	Qualification in progress for Alphabus (ARTES 8).
Proportional Flow Control Valves	TAS (I)	LP-RV	N_2Xe	< 0.2	< 5 bar		Under qualification for GAIA (cold gas thruster application).
	Bradford Engineering (NL)		N_2		< 5 bar		Pre-qualified in the frame of GAIA.
	Ampac ISP (UK)	MPT	N_2	0.276	< 5 bar	2	Pre-qualified in the frame of GAIA.
Solenoid Flow Control Valves	Ampac ISP	SV06-01	Xe	0.075	< 5 bar		Qualification in progress for Alphabus (ARTES 8)

Type	Manufacturer	Model	Technical characteristic				
			Media	Mass (kg)	MEOP (bar)	Flow rate range (mg/s)	Development Status & Flight Opportunities.
Pressure transducers	Bradford Engineering	SAPT / HAPT	Xe, N_2, He, H_2O	0.25	1 - 1000 bar	N/A	Qualified product. Flight experience from Rosetta, ATV, GOCE. Will fly on PRISMA, Proba-2, ADM-AOELUS.
	Presens	1560	Xe, N_2, He, H_2O	0.075	1 - 250	N/A	Under development. Will fly on PRISMA.
	SNECMA	SAPT	Xe, He, MON, MMH, N2H4	0.28	1-310	N/A	Flight Proven with Spacebus and Proteus; baseline fro @sat/@sat EP
Mass Flow Sensors	TAS (I)	MFS	Xe, N_2	< 0.05	< 5		Under qualification for GAIA (cold gas thruster application).
	Bradford Engineering (NL)	XMFS	Xe	< 0.2	< 5	< 1	Qualified and flying on GOCE in Ion Propulsion Feed Assembly.
	Bradford Engineering (NL)	XFM	Xe	< 0.2	< 150	1 - 10	Under development for Telecommunications S/C propellant gauging applications (ARTES 5)

Type	Manufacturer	Model	Technical characteristic

			Media	Mass (kg)	Discharge current range (A)	Flow rate range (mg/s)	Development Status & Flight Opportunities.
Hollow Cathodes / Neutralisers	QinetiQ (UK)	5A	Xe	0.09	< 5	< 0.45	Flight qualified in the T5 Ion Thruster Assembly on GOCE. Tested with mini HET at ESA facilities. Original T5 cathode also fully life qualified for and flown on Artemis IPP .
	QinetiQ (UK)	20A	Xe	0.15	< 20	< 1	Qualification in progress for T6 SEPS application on BepiColombo and HPEPS application for GEO telecoms. Pre-qualified for application on the PPS-5000. Qualified for application on the ROS-2000 HET
	QinetiQ (UK)	30A	Xe	0.18	<50	<1.5	Laboratory demonstration completed using internal funds
	Snecma (F)	SPT-100 Cathode	Xe	?	< 5	< 0.5	Operational on Intelsat10-02, Inmarsat 4 F1, F2, F3, SS/L satellites. Flight opportunity on Ka-Sat, Yahsat 1A and 1B, Small GEO.
	TAS (I)	HCA	Xe	0.15	4.5	< 0.5	Pre-qualification for the PPS-1350.
		Feep Neutraliser					FM status achieved for LISA and Microscope.
		HP HCA	Xe	0.25	< 15	< 1	Pre-qualified under ESA funding for possible application with large Ion Engines and Hall Effect Thrusters.

Type	Manufacturer	Model	Technical characteristic				
			Media	Mass (kg)	Discharge current range (A)	Flow rate range (mg/s)	Development Status & Flight Opportunities.
		Mini-HET Cathode	Xe	0.15	<2A	0.1-0.2	Development in progress, based on the LP HCA of ARTEMIS.
	THALES (D)	HCN 5000	Xe	0.086	0.1 to 5	0.1 per A	Engineering model, TRL6 under qualification for a small GEO HEMPT system. Successfully operated with RIT22 (EADS)
Helicon Radio Frequency	CISAS	HPH.com	Ar	1.5	N/A	0.1	To be qualified within 2011

II. Competitiveness and Benchmarking

Ion Engine:

The ion engine technology in Europe is currently developed by two European companies, EADS-Astrium (RIT-10 in Artemis, mini-ion development for future flying formation and drag free missions) and QinetiQ (UK-10 in Artemis, T5 in GOCE and T6 in the future Bepi Colombo). The advantage of this product comes from its high specific impulse capabilities (4000 sec). This technology is best suited for:

- interplanetary missions (very high deltaV)
- missions where the operation time of the engine is not a constraint (NSSK operations),
- orbit topping and orbit raising,
- Formation flying missions (post-GOCE) where high controllability is required (micro-Newtons to several milli-Newtons).

In USA, L-3, the successor of Boeing's old generation electric propulsion activities, produces electric thrusters and is able to provide this product at a very competitive price [1].

Hall Effect Thrusters:

This technology in Europe is represented at the moment by SNECMA PPS1350 that has been operating successfully in SMART-1 and has been qualified for Alphasat. EADS has another Hall effect thruster (ROS2000) with a Russian design, but the level of development is much lower. Lower (HT400, 400W-800W) and higher (P > 5 kW) power Hall Thrusters are being jointly developed by a group formed by SNECMA (F) and Alta (I). An even lower power Hall Thruster (HT100, 100W) is being qualified by Alta (I).

This technology:

- Offers a well proven robustness (MBSAT, Intelsat X02, Inmarsat 4F1 and F2, F2,F3, Kasat, Yahsat 1A/1B Thaicomsat 4, etc. and SMART-1 mission) and baselined on AlphaBus today
- Has specific impulse around 1500-1700 sec
- Allows lower power consumption than ion engines due to the higher power to thrust ratio (20W/mN)

- Is capable of accomplishing missions in lower time due to its higher thrust density
- It is best suited for NSSK and orbit topping operations (power levels below 12kW) and interplanetary missions where the power to thrust ratio is critical

In USA this technology is well developed in companies such as Aerojet or Busek. SS/L is flying HET on about half of its recent S/Cs

HEMPT

Europe has a unique expertise in this technology which is being developed at Thales Germany (Ulm). This technology:

- Has a nominal specific impulse around 2300 sec, can be varied from 2000 to 3000 sec
- Allows a lower power consumption than ion engines due to the lower power to thrust ratio (20-30 W/mN)
- Will be able to accomplish missions in lower time due to its higher thrust density
- Has presumably very high life capabilities due to negligible erosion of discharge channel
- Can be operated in clustered configuration with one common anode supply line from the PSCU and has therefore maximum modularity and minimum system complexity.
- Offers a good solution today for NSSK and in the future also for orbit topping operations (will be flying on the Small GEO satellite of ESA)

FEEP

This technology has been developed only in Europe. FEEP performance in terms of thrust level, noise, thrust accuracy, quantization step etc. is unique. There are two Companies providing this technology but using different concepts and propellants, ALTA (Italy) and ARC (Austria)

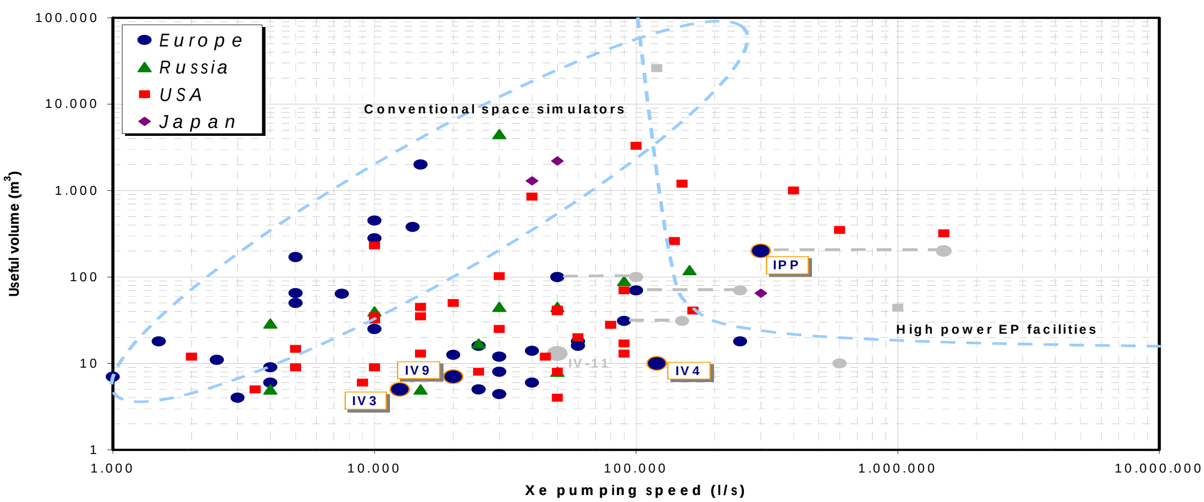
The American technology that could match FEEP in some performance parameters is the colloid thruster that has a lower level of development.

FEEP technology:

- has unique performances
- is baselined in several ESA missions (Lisa-pathfinder and LISA) and one CNES spacecraft (Microscope)
- Qualification status still to be confirmed for the mission

Test Facilities

Test Facilities and standardisation of development processes and testing procedures are fundamental for the competitiveness of Electric Propulsion Systems. A European network is currently being set-up by Industry and research centres to increase the cost/benefit ratio of these systems. ESA is actively promoting this initiative. Europe shall consider developing its own EMI measurement facility to test Electric thrusters. The PPS 1350 had to be tested in the USA EMII facility at Aerospace. HEMPT, T6 (QinetiQ) and mini-HET engines (SNECMA / ALTA) will need these tests too. The status of European and world wide test facilities is reported in figure 1.



Pressure Regulators
Astrium (UK and Germany) are currently developing these items for Bepi Colombo and Eurostar. Iberspacio is also developing a bang bang pressure regulator for Small GEO. Furthermore, Thales/Alenia (I) and Ampac (UK) are also developing electronic pressure regulators based in proportional valves. Bradford (NL) was involved in the development of the pressure regulator system for GOCE.
In mechanical pressure regulator systems, Astrium (UK) develops systems based on USA mechanical pressure regulator. Ampac (IR) is also developing mechanical pressure regulator to provide an European alternative to the USA components.

Latching Valves
At this moment all these devices are USA components. This is an important area for Europe to develop these systems. Ampac (IR) is developing this type of components within Alphabus programme.

Solenoid Flow Control Valves
These systems are all using USA components. Ampac (UK) are qualifying these systems for Alphabus. Bradford (NL) and Astrium (Germany, UK) have also capabilities in this sector.

Pressure Transducers
Bradford (NL) is the most important supplier in Europe although USA components are often used. Presence and Snecma are also active in this field.

Mass Flow Sensors
Thales/Alenia(I) and Bradford (NL) are developing these systems for monitoring and propellant gauging applications.,

Cathodes / Neutralisers
Qinetiq (UK), Thales electron (Germany),Thales/Alenia (I) and Snecma (F) have strong capabilities in this field for the medium power range. Small and high power cathodes need further development to fulfill future missions.

Special Materials for EP thrusters. Tecnalia (Spain) has developed in the last year an important infrastructure in ceramic materials for Hall Effect thrusters.

III. Application of EP to Space Missions

A. TELECOMMUNICATION MISSIONS

The Telecommunication market requires a qualified product, life test demonstrated, EMC characterized, and in orbit demonstrated. EP systems with Hall Effect Thrusters have demonstrated good performance in orbit. The main challenge is now competitiveness. The cost of the overall system (thrusters, power supply and mechanism) must be competitive against the extra price on launcher or extension of bipropellant tanks. Today the launcher market pricing structure by steps, and the too high price of available European EP systems are such that European Telecom Primes have to stay with extended Bi Propellant system, up to the moment when the competition on Launcher is too small (over 6 Ton), and then EP is used. Consequently EP today is used as an optional add-on package. This currently results in limited opportunities (few per year), but might enlarge in the future as payload increase Power and Mass. Hall Effect Thrusters, ion engines and HEMPTs can be used for primary propulsion and allow both orbit transfer and station keeping.

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)

Further to work on the evolution versions of their current platforms, Thales-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 in the near future. This new platform, called @BUS (see Fig.1), will offer a very high power payload capability (up to 12 kW in the short term and higher power in the long term) and will optimize the use of EP, because the EP operations will possibly be extended in the future 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) is carrying out the development of a high thrust version of their PPS Hall-effect thruster, called PPS 5000, while QuinetiQ (UK) are involved in the development of new, high thrust gridded ion engines, the T6 thruster. 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 PPS1350 has been selected as main candidate for the short term. For the @BUS evolution (up to 20 kW), the T6 will be a perfect candidate.

Small GEO satellites will be capable to carry a payload of around 300 kg in a spacecraft of less than 4000 kgr and fitting in SOYUZ. Hall Effect thrusters and HEMPT technologies will be in charge of performing attitude and orbit control. EDRS (European Data Relay Satellite) may also have HEMPT to perform NSSK operations [4].

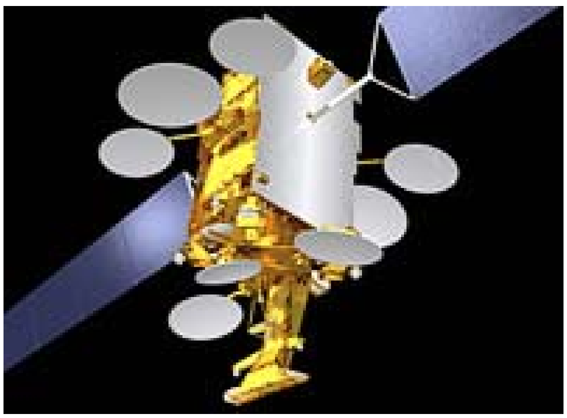


Figure 1. The Alphabus platform

B. SCIENTIFIC MISSIONS

1. Interplannetary exploration missions: Smart-1 and Bepi Colombo

Electric thrusters as the primary propulsion system for these missions will introduce several benefits: Increase in net payload mass (enable missions otherwise impossible); Reduction in flight time with respect to mission based on chemical propulsion and complex gravity assisted operations (reduction in mission operation costs); Independence from launch window constraints, which are imposed by the classical gravity-assisted planetary fly-by operations (increase of the mission scientific objectives); Possibility to use small/medium launch vehicles (substantial launch cost savings).

Smart-1 demonstrated clearly all these advantages after a successful mission in space.

The ESA Cornerstone mission to the planet Mercury, BepiColombo, will make use of the ion propulsion system with high specific (>4200 sec) and high total impulse capability. Qinetiq has been selected to provide the T6 for this purpose (see fig.2).

The BepiColombo Solar Electric Propulsion Module will be propelled by a cluster of high-power (in the 5-6 kW range) gridded Ion thrusters, T6, 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.

Once, this engine is developed for BepiColombo, the recurring cost of the engine will be reduced and other interplanetary missions requiring high delta-V will make use of this technology in the future.

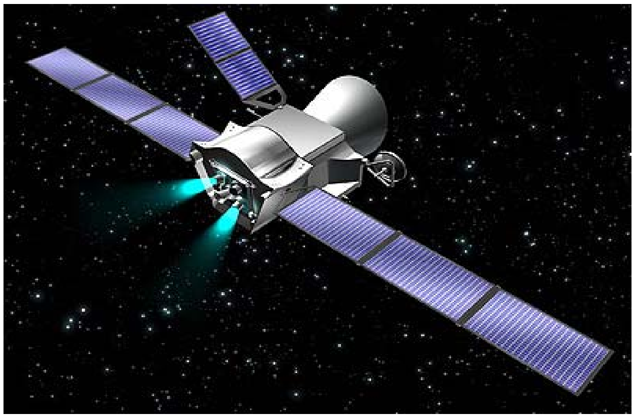


Figure 2. The Bepi Colombo Mission Concept

2. High precision scientific missions: Lisa-pathfinder, LISA, Darwin, Microscope

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 in different spacecraft, 5 million kilometers apart, will be constantly monitored with a high accuracy using laser-based techniques [2]. A gravitational wave passing through the spacecraft will cause these bodies to vibrate, changing the separations between them (Fig.3). 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.

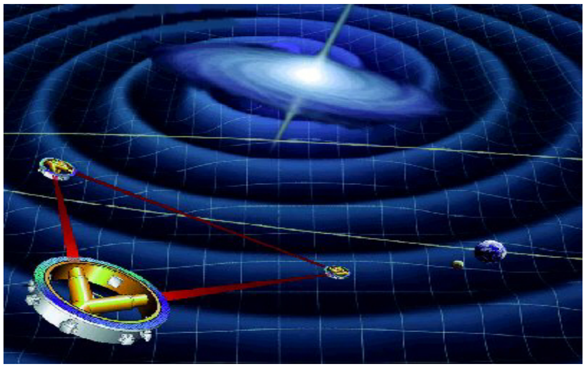


Figure 3. The LISA Mission Concept

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 given 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. Mini-ion engines could also fulfil these requirements.

LISA will 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 Lisa-pathfinder (see Fig.4) mission. Lisa-pathfinder is the technology demonstrator for LISA. Lisa-pathfinder will verify, among other things, the drag-free system, i.e. the accelerometers (inertial sensors) and the micronewton electric propulsion (FEEP, Colloid Thruster). The FEEP is designed to operate during the drag-free mode and the cold gas 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.

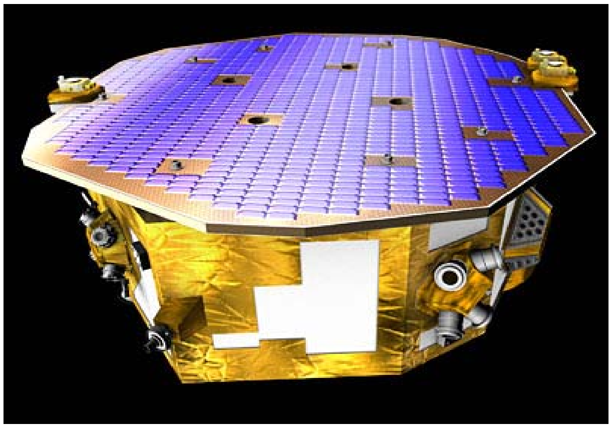


Fig.4 LISA-Pathfinder Concept

C. EXPLORATION

Missions such as Mars Sample Return and Mars Next Landers will benefit of the use of electric propulsion systems for the transfer of such spacecraft to Mars. High power EP engines such as T6 (Qinetiq) and PPS 5000 (SNECMA) may be good candidates for these missions.

ESA is currently studying the future evolution of the Exploration programme. It is clear that 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.

D. EARTH OBSERVATION

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 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 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 [3].

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 has been 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.

Fig.5. The GOCE Spacecraft

A special activity at ESA on flight data analysis of GOCE will be carried out during 2010 by Qinetiq.

IV. European Strategic Interest

A. Telecom Market

As main customer, telecom market is the driver / pathfinder to develop robust / efficient / competitive EP systems. NSSK and orbit topping maneuvers requirements can be fulfilled by EP thrusters. The availability of high total impulse Hall Effect thrusters, ion engines and HEMPT will allow Europe to compete worldwide in the telecommunication market. Competitiveness improvement of European EP systems is the main challenge for this market. Development of high power EP systems such as the Snecma PPS 5000 and the QinetiQ T6 may enlarge application of EP behind NSSK.

B. Scientific Mission

Microthrust propulsion systems will enable scientific missions requiring very fine control and will allow Europe to deploy state-of-the-art scientific spacecraft. High power ion engines and Hall Effect thrusters will allow efficient interplanetary cruise.

C. Exploration

High Power Electric Propulsion Systems are one of the technologies that need to be developed to enlarge the frontiers of space exploration. Therefore specific exploration requirements should be defined. Enlarging the frontiers of space exploration suggests planetary applications. This may require larger thrusters, new propellants, higher onboard power systems and different materials, all of which shall be investigated.

D. Earth Observation

Based on the successful operation on GOCE, assess the use of Electric Propulsion systems for future missions is taking place at ESA. The post-GOCE mission has baselined mini-ion engines for this mission.

The main challenges for Electric Propulsion (EP) system for near future are [6]:

- Improving the access price to overall EP system, starting with Hall Effects Thrusters, Ion Engines and HEMPT.
- Qualification of HEMPT, diversification of this technology to other thrust and specific impulse ranges, exploration of clustering capabilities
- Qualification of FEEP for Scientific missions, Earth Observation, dual missions and formation flying.
- Increase competitiveness of the current European products (Hall Effect Thrusters, ion engines, FEEP, HEMPT, Helicon Radiofrequency thruster, etc.). In this process the qualification of the EP products is one of the main needs.
    - HET is now at TRL 9 and short term priority should be put on competitiveness
    - T5 is now at TRL 9 and short term priority should be put on competitiveness
    - T6 is in process of qualification on BepiColombo.
    - HEMPT is being qualified on first SmallGEO missions; a delta qualification for other platforms should follow.
- Use of the current flight data (Artemis, Deep Space 1, Dawn, Smart-1, GOCE, commercial telecommunication satellites, etc.) to validate the models that will be used by the spacecraft designers in the future. The EP community would benefit significantly from better use of existing flight data:
    - Fund activities for data analysis and model validation
    - Ensure data access to all participants involved in the program
- Standardization of engineering processes and testing facilities employed in the design, manufacturing and qualification of the current electric propulsion systems.
- Preparation for the ultimate goal: the full electric propulsion spacecraft where the benefits of the use of electric propulsion will be maximized by designing the spacecraft around the electric propulsion system.
- Increase EP autonomy: it should be of general interest to assess how at system and EP sub-system level the autonomy can be increased for EP use for long duration mission.
- In the commercial market 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 they usually require a higher level of sophistication: synergies between these projects and the commercial sector should be reinforced.
- Ion Engines, HEMPT, Hall Effect Thruster and FEEP should be fully developed and commercialised in order to keep Europe at the forefront of the technology and enable new missions with very stringent requirements in controllability and propellant mass availability. Additional concepts such as mini-ion engines, mini-Hall effect thrusters, Resistojets (Xenon), Arcjets, mN-FEEP, Colloids and PPTs should also be seriously considered in development programmes in order to enlarge the possibilities of the European industries in competition for new spacecraft (minisatellites limited in power and/or mass, LEO platforms, etc.). MPD and Helicon-Antenna thruster should be developed for a long term Exploration scenario.
- Extended research on non conventional propellants (e.g., Ar, N_2, or gas mixtures containing Xe, O_2, CO_2, a.s.o.) and new materials for extending life capabilities of EP engines should be considered
- Consider the use of MEMS components for electric propulsion in order to increase competitiveness by decreasing mass, volume and power of the different subsystems.
- A sufficient amount of dedicated test facilities and standardization of test procedures is needed in Europe to accomplish a successful development and qualification of the electric propulsion systems, including EMI.
    - Generally, care needs to be taken in adopting a “one size fits all” test approach
    - Each large facility in Europe is significantly different, and whilst there may be some perception that common procedures can be implemented, it is unlikely that facility diagnostics can be standardised in a cost-efficient way.
    - the development of a European certified calibration facility for diagnostics and probes could be the answer.

V. Conclusion

Electric Propulsion has flown successfully in commercial spacecraft and several ESA satellites (Artemis, Smart-1, GOCE) and will fly in future ESA missions (Alphabus, Small GEO, EDRS, Lisa-pathfinder, LISA, Bepi-Colombo, post-GOCE, etc.).
The next challenge for EP is to reduce the cost of the technology to improve the competitiveness at world level.
All the flight data that is available today should be carefully evaluated to extract lessons learned and inject them in the new programmes.
Scaling up and down of the current EP designs and future concepts need to be pursued. In particular, the high power EP version for Exploration should be pursed.
To avoid ITAR restrictions, European companies should develop capabilities in components that today are mainly developed at USA.
An effort on standardisation of testing of Electric propulsion systems is required in the near future. The ESA Propulsion Lat at ESA is very active in this field [7].

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