European Space Agency Electric Propulsion Activities

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I INTRODUCTION

Space mission planners have always tried to reduce the amount of propellant required to bring the spacecraft to the final orbit and reach the required lifetime. Electric propulsion can help them to achieve this goal due to the high specific impulse and in many cases brings huge benefits as in the case of orbit raising manoeuvres for GEO telecommunication spacecraft. Furthermore, the high controllability of these electric propulsion systems enable missions requiring these stringent requirements.

This paper looks at the possible issues and advantages of using electric propulsion in European missions and the electric propulsion systems available in Europe.

The last years have seen many GEO telecommunication spacecraft using electric propulsion for orbit raising and station keeping manoeuvres, together with interplanetary missions that require electric propulsion to reach far planets such as Mercury or Mars. The European navigation constellation GALILEO will also use electric propulsion on their second generation satellites, mainly to perform orbit raising to their MEO orbits. Another important market is the LEO constellations of thousands of small satellites to accomplish many interesting missions such as Starlink, Oneweb, Amazon Kuiper, Lighspeed, ICEYE, etc. (0). These small satellites are making a good use of electric propulsion systems to reach the orbit, keep the satellite in place and deorbit at end of life. These markets have pushed the developers of electric propulsion systems to reduce the price by one order of magnitude that can only be achieved by optimising the design for manufacturing, by large scale production and by changing the way the qualification is performed. Cubesats have also started using very low power electric propulsion systems. The market expectations of hundreds of cubesats in the next 10 years will require in many cases the use of novel electric propulsion systems and several European institutions and SME companies are currently working on the development and maturation of these systems.

The system issues of electric propulsion in small spacecraft are: having small volume and small mass, avoiding electromagnetic interferences, using low power, having the required total impulse and of course having a low price in addition to guarantee a fast time-to-market. These challenges are taken very seriously by the electric propulsion community and new ways of developing and qualifying electric propulsion systems are discussed.

Future trips to Mars and the Moon will require electric propulsion systems to reach their destinations and help the human colonization of the solar system. The use of solar generators and nuclear reactors coupled with high power electric propulsion systems will help to achieve these goals.

This paper also describes the tools that ESA and EC are using to increase the speed of the developments in Europe, to mature technologies and help the European industries to position themselves in the world market.

ESA, through many of their activities in the last 30 years has driven the maturation of electric propulsion in Europe. Several activities on electric propulsion for orbit raising operations were funded paving the way for the commercial adoption of such manoeuvres. SMART-1 was using the PPS 1350 Hall Effect thruster from SNECMA to reach the Moon and later was adopted by the telecommunication primes. Indium FEEPs were

developed in the frame of ESA Earth observation and Science programmes and is now flying in great numbers on cubesats and constellations of small satellites such as ICEYE. Radio Frequency Ion Engines were flown on the ESA ARTEMIS satellite and is now being adopted by telecommunication primes and scientific missions.

II TECHNOLOGY DESCRIPTION

The high specific impulse of electric propulsion systems reduces the amount of propellant required to perform operation in space. These savings allows space projects to use smaller launches or to increase the payload capability.

In the commercial arena (GEO telecommunication and LEO constellations of satcoms), the strong competition among satellite manufacturers is a major driver for advancements in the area of electric propulsion, where increasing performance together with low prices and fast time-to-market 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. Moreover, new interplanetary missions in the frame of exploration will require sophisticated propulsion systems to reach planets such as Mercury or Mars and in some cases bring back to Earth samples from these planets. Space tugs, de-orbiting tugs and re-fuelling spacecraft will make also use of electric propulsion. Also Cubesats have started to use electric propulsion to enhance their capabilities. Finally, electric propulsion systems will be used by the 2nd generation of the European navigation Galileo constellation satellites to perform orbit raising to MEO.

ESA is currently leading several development activities related to spacecraft electric propulsion, from the basic research and development of conventional and innovative concepts to the maturation, qualification and flight operation of propulsion systems for several European satellites. The exploitation of the flight experience is also an important activity at ESA that will help mission designers to implement the lessons learned to the development of novel and innovative propulsion systems. ESA missions such as Artemis, Smart-1, GOCE, AlphaSAT, Small-GEO, Neosat and Bepi Colombo have paved the way for the use of electric propulsion in future ESA missions: NovaCom, Electra, GALILEO 2G, Mars Sample Return, NGGM, LISA etc.

EP thrusters are described in terms of the acceleration method used to produce thrust and are classified into three categories: electrothermal, electrostatic, and electromagnetic. Electrothermal thrusters accelerate a gas by electrically heating and expanding it through a convergent/divergent nozzle. Electrostatic thrusters accelerate an ionised propellant applying an electric field. Electromagnetic thrusters accelerate a plasma applying both electric and magnetic fields.

Electrothermal thruster systems typically consist of a gas storage and management system, a thermal management system and a convergent/divergent nozzle. Electrostatic and electromagnetic thruster systems consist of Power Processing Unit(s), a propellant storage and management system (including tank(s), pressure regulator(s), flow control unit(s), valves, temperature and pressure sensors, etc.), thruster(s) with, when necessary, neutraliser(s) to eliminate charge build-up on the spacecraft and pointing mechanism(s).

EP systems are ideal for travelling long distances or for station keeping of satellites, because they use significantly less propellant than conventional chemical propulsion systems. This results in lower launch cost, extending the lifetime of satellites and enabling additional payload capability. EP thrusters feature high Specific Impulse and this characteristic makes them well suited for medium to high delta-V orbital manoeuvres. In addition, EP thrusters have the possibility of multiple re-ignitions, can operate in pulse mode or at constant continuous thrust and can vary their delivered thrust on demand over wide intervals and with very small incremental steps. On the other hand, these thrusters consume power up to several kWs.

The propellant used in EP system varies with the type of thruster and can be a rare gas (i.e. Xenon, Argon or Krypton), a liquid metal (i.e. Caesium, Indium or Gallium), a solid element (iodine or teflon) or an ionic liquid (a salt in liquid phase like EMI-BF4 or EMI-Im).

The level of development and flight heritage of the different thruster types can vary significantly. In Europe, developments have been carried out in all the different areas of electric propulsion over the last three decades. Gridded Ion Engines (GIEs) and Hall Effect Thrusters (HETs) have emerged as leading electric propulsion technologies in

terms of performance. These thrusters operate in the power range of hundreds of watts up to tens of kilowatts with an Isp of thousands of seconds to tens of thousands of seconds, and they produce thrust levels typically of some fraction of a Newton.

In Hall Effect Thrusters, electrons from an external cathode enter a ring-shaped accelerating channel (discharge chamber) attracted by an anode. Xenon gas is released into the channel. Permanent magnet or coils embedded within the thruster structure generate a magnetic field with a magnitude selected so that only electrons are magnetized and the influence on ions is neglected. The field provides an azimuthal electron Hall current, which causes propellant ionization and ion acceleration when the gas crosses the ExH field. The accelerated ions leaving the channel generate thrust. The electrons from the cathode are also used to avoid spacecraft charge (Fig.1)

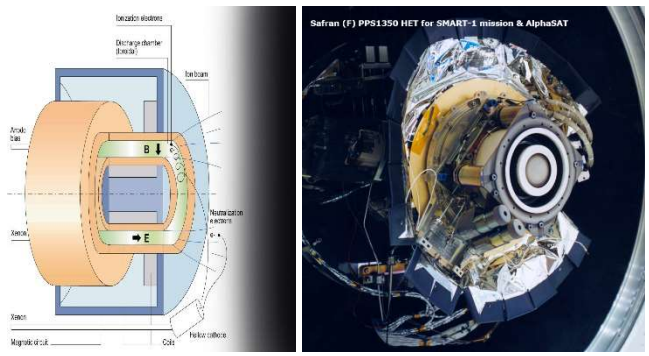


Figure 1: HET working principle (left) and PPS-1350 thruster (right)

In Gridded Ion Engines, Xenon gas is ionized by electron bombardment or through radiofrequency electron excitement and accelerated using high electrostatic potential between a set of grids. A neutraliser is used to avoid spacecraft charge. (Fig 2,3)

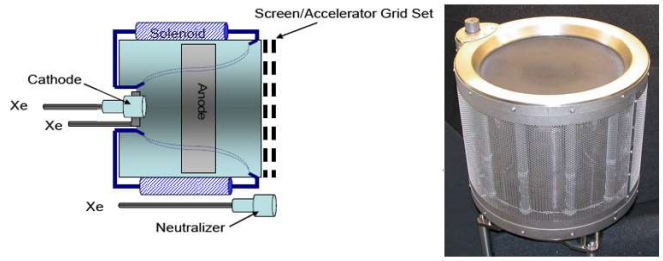


Figure 2: Electro-bombardment GIE working principle (left) & BepiColombo T6 thruster (right)

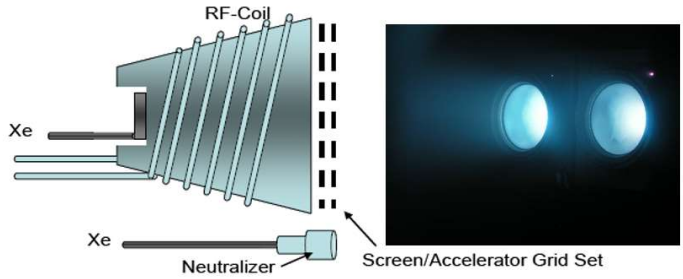


Figure 3: Radiofrequency GIE working principle (left) and RIT2X thruster (right)

III ELECTRIC PROPULSION APPLICATIONS

Electric Propulsion (EP) technologies have been under development since the beginning of the past century when a group of rockets pioneers started to wonder about the use of electricity to propel a spacecraft. Researchers in the US and in the former Soviet Union worked independently on this idea but it took several years to turn what was just a promising concept into a demonstrated technology. After few proof-of-concepts missions of gridded ion engine in US, the first successful operation of EP in space occurred in November 1964 when Pulsed Plasma Thrusters were used on the Russian Zond-2 satellite.

Over the time, EP has made great technological and commercial progress (Table 1). The main driver of this evolution has been the increasing demand for telecommunication satellites, for high delta-V interplanetary missions and, more recently, the commercialisation of space with several constellations being built in LEO to provide global communication services.

Year	Who	What
1906	Robert Goddard	First known hand-written notes on EP
1911	Konstantin Tsiolkowsky	First published mention of the EP concept
1929	Hermann Oberth	Full chapter on EP in Wege zur Raumschiffart
1951	Lyman Spitzer	Demonstration of feasibility of EP
1954	Ernst Stuhlinger	In-depth analysis of EP system
1964	US and Russia	First successful use of EP in space
1980's	US and Russia	Commercial use of resistojets and Hall thrusters on GEO platforms
1998	US	First deep space probe with EP (Deep Space 1)
2003	Europe	First use of EP to escape Earth from GTO (Smart-1)
2009	Europe	First use of EP for drag free control (GOCE)
2015	US	First all-electric platform reaches GEO (Boing 702SP)
2017	Europe	First European all-electric platform reaches GEO (Eurostar E3000EOR)
2018	Europe	Mercury's mission BepiColombo is launched

Table 1: EP historical milestones

In parallel, Electric Propulsion technologies demonstrated the capability to perform a variety of functions and to be used in almost all space applications: from tiny Cubesats, through Earth observation satellites in LEO and telecommunication satellites in GEO/LEO, to remote deep space missions.

Embarking electric propulsion capabilities on-board a satellite can serve multiple purposes:

- Station keeping: satellites shall compensate for perturbations to maintain the desired orbital position:
    - LEO orbits are perturbed by the aerodynamic drag
    - Gravitational fields of the Moon and the Sun affect the inclination of GEO satellites in North-South
    - Non circular shape of the Earth equator causes perturbations in East-West
- Attitude management: to off-load the reaction wheels used for attitude control.
- Orbit transfer/raising from launch orbit to the operational orbit, relocation and disposal at end-of-life.

Since the 1970s, Electric Propulsion has been used on satellites for station-keeping, orbit raising and primary propulsion. It has traditionally had applications for telecommunications and science missions, but increasingly it is being considered for earth observation, navigation and orbit debris removal. More recently, Cubsats and constellations of small satellites with the mass ranging from 1 to few 100 of kgs have started to use EP to enhance their capabilities. (1)

Telecommunication in GEO

Commercial GEO telecommunication represents the largest market for electric propulsion. In the last twenty years, these satellites have become more competitive by the adoption of EP for north-south station keeping (NSSK) and Electric Orbit Raising (EOR). Launchers deliver these satellites into Geostationary Transfer Orbits (GTO) and orbit-raising maneuvers to reach GEO are to be performed by onboard propulsion. With Chemical Propulsion, orbit-raising takes up to 1 week but about 50% of satellite wet mass is propellant. With Electric Propulsion, orbit-raising takes up to 6 months but launch mass can be reduced by 40%. Telecommunication satellites using EP have greater appeal since the propellant mass saved can be used to accommodate larger and more complex payloads. In the last decade, the trend in GEO Telecommunication satellites has consolidated into a considerable increase in electrical power to satisfy the payload needs. The availability of such high power allows for the operation of EP without requiring changes in the platform. On the other hand, the low thrust levels provided by EP systems mean extended firing times and longer transfers to reach the final operational orbit. This implies reduced revenue in the short-term, but important savings in the long-run.
From the mid-90s to approximately the year 2010 the two most prevalent EP technologies for GEO satellites were arcjets and gridded ion engines. In particular, two satellites led this trend: the Lockheed Martin's A2100 and the Boeing's 702. Boeing used XIPS Gridded Ion Engines operated at 0.4 kW to provide 0.018N thrust for North-South station keeping (NSSK).

In 2001, the ESA's **ARTEMIS** (the Advanced Relay and Technology Mission Satellite) offered the first European flight demonstration of EP for orbit raising, recovering the satellite to its final orbit following a launcher anomaly (Fig 4).

Figure 4: ARTEMIS

Starting from the year 2000, Hall Effect Thrusters were adopted by an increasing number of satellite manufacturers like Alcatel Space and Airbus DS. It became clear that, once a satellite manufacturer had invested in integrating a particular EP technology there was a strong incentive to stay with the same technology to avoid repeating the integration investment. This has led to a steady increase in the use of Hall Effect Thrusters on Telecom platforms, a trend that continues to this day.

In 2004, Space System Loral started to use Russian SPT100 Hall Effect Thrusters for station keeping. Operating at 1.5 kW, each SPT-100 produced 0.083N of Thrust for station keeping.

In 2010, Lockheed Martin's Advanced Extremely High Frequency (AEHF) satellite after an anomaly with its main Chemical Propulsion system used Hall Effect Thrusters intended for station keeping to complete its orbit raising.

Boeing (US), and later L3 (US), were the one launching the highest number of EP systems on telecom satellites using the XIPS Gridded Ion Engines.

In 2012, Boeing signed a contract with Asia Broadcast Satellite (ABS) and Satmex for the first four all-electric 702SP satellites and in 2015 delivered the first all-electric satellite with XIPS-25 gridded ion engines for station keeping and orbit raising. This was the first western GEO satellite ever launched without on-board chemical propulsion. All-electric spacecraft have lower mass and enable larger payloads to be carried. It also means that cheaper launchers can be used, or satellites can share a launcher to save costs.

In 2013 Thales and Airbus achieved first flight of Europe's large telecoms satellite, **AlphaSat** (Inmarsat-4A 4F), using a set of four SAFRAN AIRCRAFT ENGINES PPS1350 thrusters for station keeping (Fig 5).

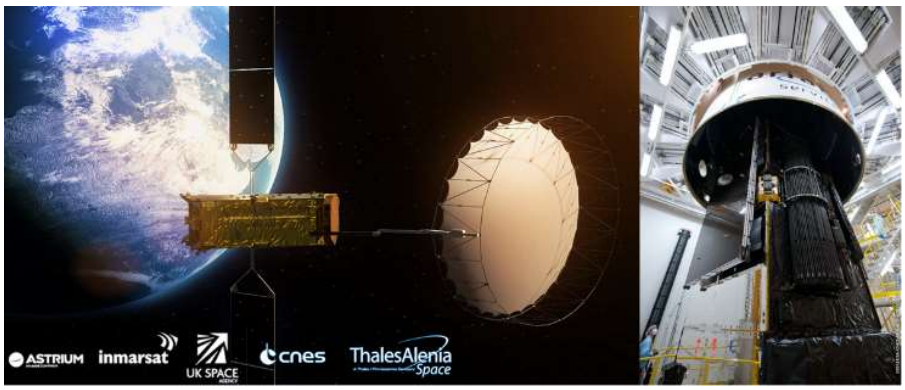


Figure 5: AlphaSAT

In 2014 Airbus wins three orders for E3000 using electric propulsion using HET electric propulsion for orbit-raising.

In 2015, Boeing successfully demonstrated the world's first all-electric spacecraft using XIPS Ion Engines for station keeping and orbit raising. Mass savings allowed two satellites to be launched by one Space-X rocket Falkon 9.

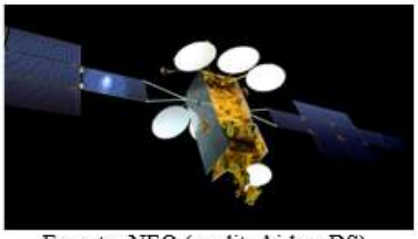
In 2017, the Airbus-built **Eutelsat 172B** became the *first all-electric GEO telecommunication satellite produced in Europe.* This was a modified eE3000 platform using 5 kW SPT-140 Hall Thrusters from Fakel (RU) for orbit raising and all on-station manoeuvres.

The ESA-OHB **SmallGEO** platform was launched in 2017, equipped with 8 SPT-100 thrusters to fulfil all the orbital manoeuvres for 15 years (station keeping, momentum management, repositioning, end-of-life disposal). (2)

European satellite manufacturers have been using electric propulsion for the station keeping of their platforms (Eurostar 3000 produced by Airbus and Spacebus 4000 produced by Thales Alenia Space) for over 10 years accumulating thousands of hours of electric propulsion operations, increasing the confidence in the technology. All of them they are now implementing "all-electric"satellites. By 2022, it is estimated that more than half of all satellites sold will be all-electric or hybrid (embarking both chemical and electric systems). The advent of the "all-electric" platforms corresponded with an increase in platform size (mass and power) and payload capacity (power). The availability of higher platform power led to the use of high power EP thrusters (from 1.5 kW to 5 kW) producing higher thrust to reduce the orbit raising duration.

Today all European Primes offer "all-electric" GEO platforms. These platforms are designed to use European 4.5 to 5kW Hall Effect Thrusters, e.g. the PPS5000 from Safran Aircraft Engines.

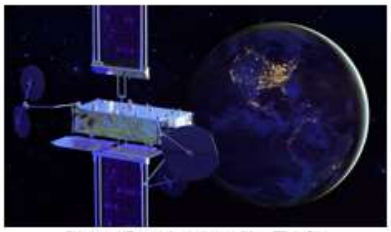
ESA and CNES, through the ARTES Next Generation Platform Programme called **NEOSAT** supported European Primes in developing and qualifying their new all-electric platforms in the 3 to 6 tons launch mass range: Eurostar NEO and Spacebus NEO. These new platforms aim at significant cost reduction thanks to the use of electric propulsion for both orbit raising and station keeping. An important goal of the NEOSAT programme is to build a European supply chain that optimises costs and guarantees on-time delivery. Some units, such as Xenon tanks and Electric Propulsion thrusters, are being developed for both Spacebus Neo and Eurostar Neo to benefit from economies of scale.



Eurostar NEO (credit: Airbus DS)

SpaceBus NEO (credit: TAS)

OneSat (credit: Airbus DS)



Space Inspire (credit: TAS)

SmallGEO (credit OHB)

Electra (credit: OHB)

Figure 6: European GEO platforms

At the time of writing this paper, Airbus DS (FR) has launched four all-electric versions of their Eurostar3000 and sold eight of their all-electric Eurostar NEO platforms. The Hotbird F1 satellite, ordered in August 2018 by the French satellite telecommunications operator Eutelsat, will be the first **Eurostar NEO** platform to be launched. Thales Alenia Space (FR) has launched in 2020 the first of their all-electric **Spacebus NEO** satellites, Eutelsat Konnect, and in 2021, the French government's Syracuse-4, SES-17. TAS has also sold other five satellites: another Eutelsat mission called Konnect Very High Throughput Satellite, Satria which will be operated by the Indonesian operator Pasifik Satelit Nusantara, Eutelsat 10B, Amazonas Nexus for Hispasat and SES ASTRA 1P.

In addition, both Airbus DS (FR) and Thales Alenia Space (FR) have started the development of their new medium-size, reconfigurable platforms named respectively **OneSat** and **Space Inspire** (INstant SPace In-orbit REconfiguration) to respond to the fast changing telecommunication market requiring telecommunication mission and service reconfiguration, instant in-orbit adjustment to broadband connectivity demand and superior video broadcasting performance. These platforms will use off-the-shelf commercial components instead of radiation-hardened ones specially developed for use in space and are designed to meet the highest standards of availability and performance, while cutting equipment costs and assembly efforts. At the time of writing this paper, Thales Alenia Space (FR) has sold five of their Space Inspire satellites (Intelsat-41, Intelsat-44, etc) and Airbus DS (FR) has sold seven of their OneSat satellites (Intelsat-42, Intelsat-43, three Inmarsat, ect).

OHB is also developing its 'all Electric' platform **Electra**, which will make use of 5kW Hall Effect Thrusters for orbit raising and station keeping.

The European Space Agency, the European Commission, the National Space Agencies and industries have invested in the development of electric thrusters for the GEO market at SAFRAN AIRCRAFT ENGINES (Hall Effect Thrusters), Sitael (Hall Effect Thrusters), ArianeGroup (Gridded Ion Engines) and Thales (HEMPTs).

LEO comsats constellations

Low Earth Orbit (LEO) LEO is not a new orbit for satellite communication (the Iridium satellite constellation has already been running a global LEO-system with 66 satellites at 780 km since 1998) but it is recently experiencing a renaissance thanks to the increasing commercialisation of space and to the rapid development of mega constellations of 100-300kg communication satellites. The opportunities provided by small satellites are enabling small companies and startups, in particular, to make a significant impact on the space economy. Small satellites have a unique ability to bring around new products and services at short timescales and for relatively low-cost.

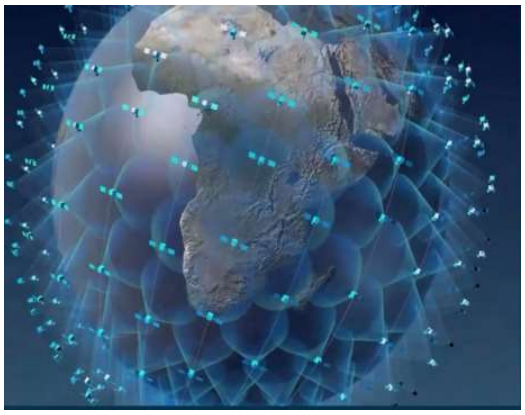


Figure 7: LEO comsats

Small satellites in LEO use of low power (<1kW) EP technologies to perform orbit insertion, deployment to the desired orbital planes, orbit changes, orbit maintenance, repositioning, collision avoidance and deorbit at end of life.

In 2014, two companies, OneWeb and SpaceX, announced plans to build satellite constellations in LEO to provide fast, low-cost internet services to the world. In the following years, other companies have also announced their intention to develop similar constellations. Today, several LEO satellite constellations are in development: Starlink, OneWeb, Kuiper and Lightspeed.

At the time of writing this paper, Space-X (US) has already launched over 1800 Starlink satellites into LEO and aims to have at least 4448 satellites in orbit in near future. Their ultimate goal is to have an operational constellation of around 12000 satellites at 350-550-800 km by 2026. These satellites, of about 300kg each, are built in house and use in-house built, low power, krypton-fed, single Hall Thruster systems to adjust their position in orbit, to maintain their altitude and perform deorbiting at EoL.

At the time of writing this paper, **OneWeb** (UK) has already launched 423 satellites and aims to have 682 satellites operational by end of 2022 and 750 by 2025. Their ultimate goal is to have a constellation of around 900 satellites at 1200 km to deliver high speed, low latency global connectivity across the globe. OneWeb uses the low-power SPD-50M Hall Thruster from the Fakel (Ru) to correct the orbit and orientation of the satellite. With a mass of 1.29 kg and a thrust of 16 mN, the service life of this engine is more than 3000 hours and more than 11000 starts. Over 500 Fakel thrusters have already been delivered to OneWeb.

OneWeb has already started to study its 2nd generation of satellite constellation. The trend is towards increasing satellite sizes, from 150 kg to 300kg, in order to increase the capability of the satellites is expected.

Amazon (US) is also planning its own LEO constellation Kuiper. The initial constellation foreseen 3236 satellites orbiting at 350-650 km. These satellites also plan to use Hall Thruster systems to raise the orbit, maintain the satellite on station and for de-orbit.

In February 2021, Thales Alenia Space announced to have been selected by operator Telesat to build the broadband 292-satellites constellation named **Lightspeed.** These satellites, of about 700 kg each, operate in a combination of

polar orbits (78 satellites, 6 planes, 1012 km of altitude) and inclined orbits (220 satellites, 20 planes, 1325 km of altitude) for complete global internet coverage and shall use two 500W krypton-fed HEMPT-EVO thrusters per satellite for orbit raising, orbit maintenance and de-orbit. This constellation plans to be in service starting from 2023.

Navigation

The use of electric propulsion for Navigation satellites in Europe is relatively recent and mainly associated with the **GALILEO 2nd Generation** programme (Fig 8).

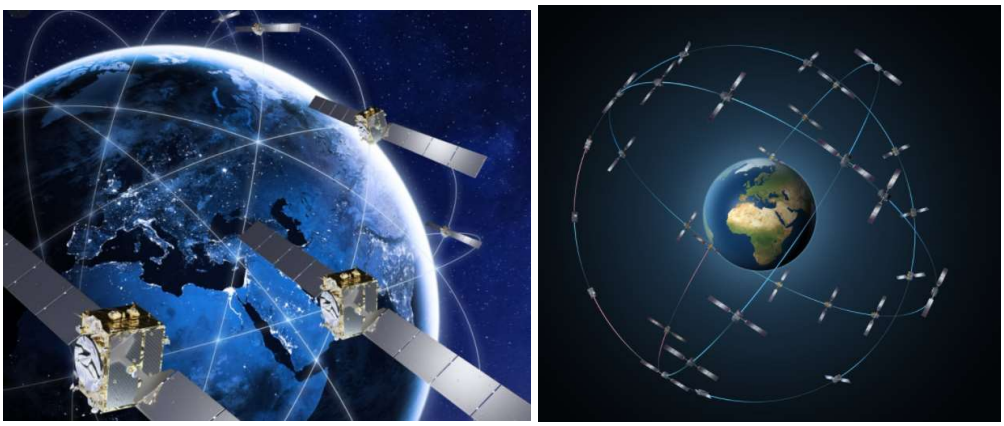


Figure 8: GALILEO 2nd generation

The Galileo navigation constellation comprises an in-orbit set of 24 operational and up to 6 spare satellites in MEO. The second-generation satellites will prolong, improve and expand the existing Galileo services, while still providing the first-generation legacy services during deployment. Galileo Second Generation will be made up of two independent families of satellites meeting the same performance requirements, produced by Thales Alenia Space in Italy and Airbus Defence and Space in Germany. The first satellite of the second generation shall be launched before the end of 2024.

The Galileo second-generation satellites will be launched in single and dual launch configuration by the Ariane 62 launcher and will use 5kW PPS 5000 Hall Effects Thrusters from Safran Aircraft Engines (FR) for orbit raising to MEO in 180 days and EOL graveyarding.

Science & Exploration

The use of electric propulsion for scientific spacecraft is recognised as an important way to enhance mission performances. Replacing or augmenting chemical propulsion with electric thrusters as the primary propulsion system can bring the following benefits:

- an increase in net payload mass
- a reduction in flight time with respect to mission based on chemical propulsion and complex gravity-assisted operations
- independence from launch-window constraints, which are imposed by the classical gravity-assisted planetary fly-by operations
- possibility to use small/medium launch vehicles (providing substantial launch-cost savings).

Specific mission requirements, in terms of power availability, satellite mass and mission profile, dictate the choice of the particular EP technology to be used.

Deep Space 1 was the first use of EP on an interplanetary mission, and its main objectives, the flyby of asteroid Braille and Comet Borrelly, were successfully performed by NASA's NSTAR ion engine in the late 1990s. The JAXA science mission Hyabusa used Japanese ion engines to rendezvous with an asteroid in 2005.

ESA's first Moon mission, **SMART-1**, paved the road to the use of EP on European Science and Exploration missions. The mission was technically and scientifically a success, helping ensure Europe's technology competence in this promising technology and in Lunar exploration. The relatively small satellite, equipped with one PPS-1350G HET from SAFRAN AIRCRAFT ENGINES, required only 82 kg of Xenon to reach and orbit the Moon (Fig 9).

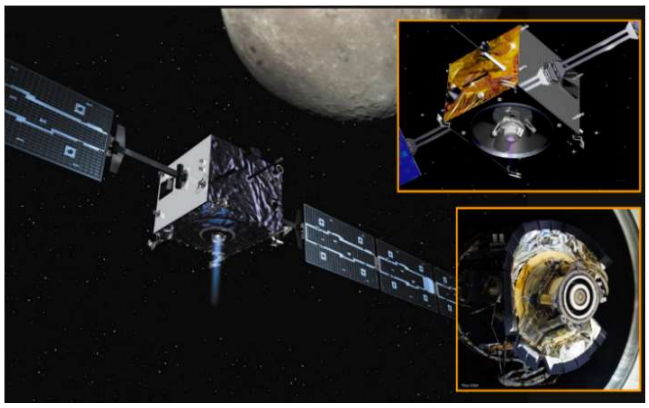


Figure 9: SMART-1

ESA's cornerstone missions **BepiColombo** was launched in October 2018 and will provide the best understanding of Mercury to date by studying and understanding the composition, geophysics, atmosphere, magnetosphere and history of Mercury, the least explored planet in the inner Solar System. BepiColombo is being propelled by a cluster of 5 kW T6 Gridded Ion Engines developed by QinetiQ (Fig. 10).

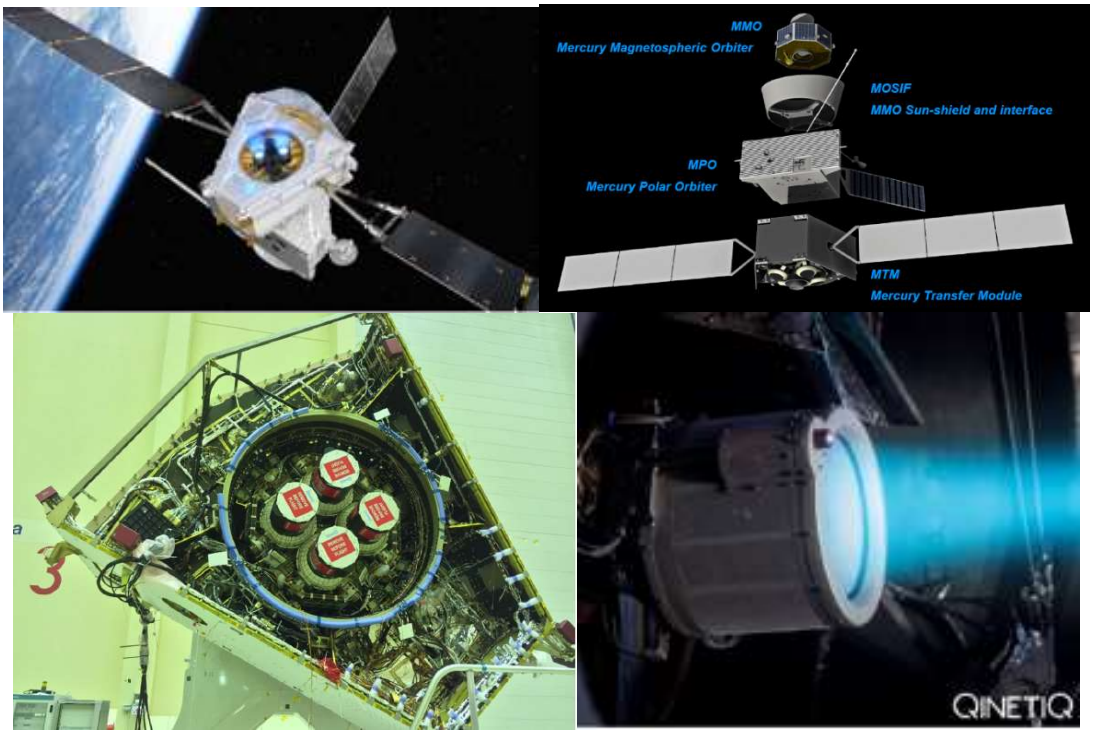


Figure 10: BepiColombo and T6 integrated and firing

ESA and NASA are currently working together on the **Mars Sample Return** mission which is aiming to return the first samples of Martian rock and dust directly back to Earth. ESA is responsible for the **Earth Return Orbiter** (ERO), an EP/CP hybrid spacecraft foreseen for launch in 2026. ERO will embark an EP Subsystem made of a cluster of 7.5kW RIT-2X Gridded Ion Engines from ArianeGroup (D) to deliver a total impulse of 45 MNs. Each thruster shall be capable to provide thrust between 0.15N and 0.25N with a specific impulse around 4000s (Fig 11).

Figure 11: Mars Sample Return - Earth Return Orbiter

Since several years, ESA has also been investing in the development of a 20-25 kW high-power Hall Thruster from Sitael (IT) initially through the TDE programme, soon followed by a HRE (Cislunar activity reaching completion) for a prototype, then a GSTP activity (still ongoing) for technology maturation and long test, and finally the EU Horizon 2020 EPIC programme with the CHEOPS I predevelopment until PDR (now completed) and afterwards with the **ASPIRE** development started in April 2021 in order to reach qualification readiness. All these activities have allowed the development, up to various TRL's, of different versions of the 20 kW HET propulsion subsystem, as well as the progressive upgrade of a large test facility capable of testing in steady state at 20 kW and perform all the necessary performance measurements in terms of thrust, plume, and channel erosion. The different versions of the 20 kW HET include the capability of using either xenon or krypton, the possibility to drive the thruster without power supply directly from the solar-arrays, the capability to have a high-thrust or a high specific impulse mode of operation.

Future scientific missions such as **LISA** (Laser Interferometer Space Antennas) will require electric microthrusters as very fine control actuators to insure operation under drag-free conditions. These thrusters should also have a long lifetime and FEEP, colloidal thrusters and miniaturized ion engines are main candidates to this kind of missions (Fig.12). LISA will also use Hall Effect thrusters to bring the spacecraft to the right orbit.

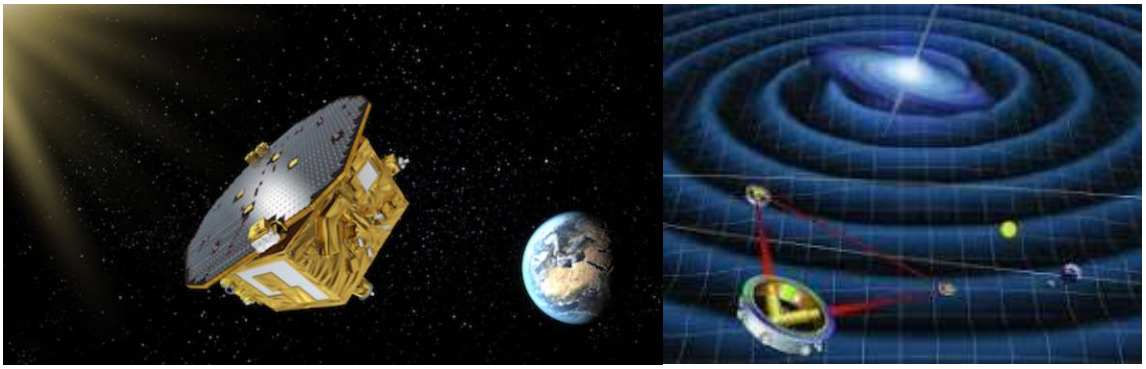


Figure 12: LISA

Earth Observation

Earth Observation missions, like **GOCE** (Fig 13), also benefitted from the use of EP. The main aim of the GOCE mission was to provide unique models of the Earth's gravity field and its geoid to high spatial resolution and accuracy. The T5 GIE system from QinetiQ was operated on GOCE almost continuously from 2009 to 2013 to compensate aerodynamic drag. 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. (3)

The success of the Gridded Ion Engines in GOCE demonstrated the use of EP for drag free control in LEO. Future ESA Earth's gravity field missions targeting sustained observations at higher resolution, like the Next Generation Gravity Mission (NGGM), are considering to use EP for continuous drag-free control during the measurement of the Earth's gravity field over long time span, possibly covering a full solar cycle.

Figure 13: GOCE

In addition, ESA is cofounding via the InCubed program, the development of the MultiSpectral Companion Mission (also referred as **MSCM**) by the Belgian company AerospaceLab. It will be the first in-orbit demonstration satellite of a future constellation that aims to generate commercial multispectral data products to support Copernicus Sentinel-2 datasets with daily global coverage. Exotrail (FR) has been chosen to supply an Electric Propulsion system (ExoMG) based on the HET technology providing a thrust level between 4 and 16 mN.

Furthermore, ESA has signed in March 2021 a contract with OHB Sweden to build the first **Artic Weather Satellite** planned for launch in 2024. It is based on the previously developed Inosat platform. The objective of the mission is to provide global measurements of atmospheric temperature and humidity with frequent revisit times for improved weather prediction. The Arctic Weather Satellite mission is a prototype satellite but is foreseen as an eventual constellation to complement MetOp satellites. It embraces the New Space approach by proving new concepts in a cost-effective and timely manner. Enpulsion (AT) has been chosen to supply an Electric Propulsion system based on 4 NanoR3 indium FEEP thrusters to perform all electric manoeuvres, including de-orbiting (Fig 14).

Figure 14: Artic Weather Satellite

The European Space Agency, the National Agencies and industries have already started investing in the development and qualification of traditional and novel European electric propulsion technologies to serve the EO market at:

- Enpulsion (A), Exotrail (FR), ThrustMe (FR), T4i (IT) mainly based on the New Space approach
- Mars Space (UK) and Aerospazio (I) for more traditional systems.

Furthermore, the use of small ion engines, small Hall Effect thrusters, FEEPs or helicon plasma thrusters would enable operation of earth observation satellites at much lower altitude orbits.

There has been studies and development programs considering the use of the gases in the atmosphere as propellant for electric thrusters (RAM-EP) to enable continuous operation at altitudes lower than 200 km. ESA has already invested in developing Ram-EP technologies:

- in 2007, a CDF study on RamEP concluded that to compensate the drag of a satellite operating at altitudes as lower as 180 km, a ram-EP concept could be a feasible solution.
- In 2010, a TRP contract with Sitael (IT), SAE (FR) and University of Giessen demonstrated via test the capability of an HET thruster and a RIT thruster to operate with nitrogen, oxygen and their mixtures but identified the need to consider appropriate materials to minimise corrosion/erosion.
- In 2017, a TRP contract with Sitael (IT) and Quintescience (PL) demonstrated for the first time the Ram-EP concept in a relevant environment, by simulating the atmospheric flow with a specially designed particle flow generator and providing evidence that the propulsion system was able to generate a measurable thrust.
- In 2022, a TDE contract with ASTOS (DE), IRS (DE), Von Karman Institute (BE) and T4i (IT) is on-going, implementing the design of a RAM-EP mission based on a cathodeless electric propulsion thruster, including the system level PDR and demonstrating, via test, the plasma flow model and the RAM-EP system
- In 2022, a GSTP contract with Von Karman Institute (BE) is on-going with the aim to develop a computational model to simulate the performance of an intake for a RAM-EP application; a test facility, including a prototype intake and a particle flow generator, is being implemented as part of this contract in VKI dependencies as a model verification tool

Finally, constellation of thousands of satellites are currently been developed. These satellites are launched in cluster and need low power EP to reach their operational orbit, stay there and be disposed at the end of the mission. Cheap and versatile electric propulsion systems will be required as the cost of the system shall be one order of magnitude lower than current prices.

Space Transportation

Based on growing maturation of electric propulsion systems and increasing capabilities of such propulsion devices, 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 (e.g. Electric-Vega);
- Space Tugs for LEO/GEO servicing, LEO/MEO Debris Removal, LEO/MEO to GEO tugs and Moon cargo delivery.

CubeSats

Owing to their inherent characteristics of low cost, rapid development time and ability to incorporate advanced technologies, CubeSats have given universities, research establishments and private companies the opportunity to put small payloads into Low Earth Orbits (LEO). Initially intended for educational purposes and technology demonstrations only, the industry has matured rapidly and CubeSats are increasingly becoming attractive to institutional and commercial users for applications such as Earth observation, communications and even space exploration.

Today, hundreds of CubeSats are launched each year and propulsion capabilities are becoming crucial to enable mobility and to enhance performance and utilisation potential of future CubeSats, permitting tasks such as satellite deployment, orbit changes, drag compensation, station keeping, formation flying, proximity operations, collision avoidance, end-of-life disposal and even interplanetary transfers. This is the reason why CubeSat propulsion is considered by the European Space Agency as a strategic technology for the European competitiveness in space.

Numerous EP micro-propulsion systems for Cubesats are currently under development in Europe to allow mobility and enhance the performance of CubeSats (Fig 15). Their compactness, good performance and low price are increasingly appealing as the space industry interest in small satellites with mass ranging from 1 to few 100 of kg

grows all over the world. These satellites, often in constellation, could provide commercial services such as global internet coverage and monitoring of air and sea traffic or Earth observation to broadcast weather and monitor the response to natural disasters.

Figure 15: European Cubesat Propulsion technologies

There are over 100 European electric propulsion systems for CubeSats already in space, from few suppliers. Enpulsion (AT) is leading the market with over 100 IFM FEEP Nano systems (Fig 16) in space followed by ThrustME (FR), Exotrail (FR), T4i (I) and Morpheus (D) but there are also several announced plans for IODs and numerous new electric propulsion systems under development or in research status.

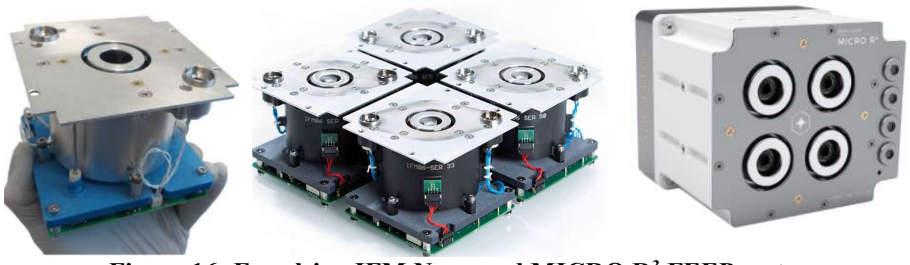


Figure 16: Enpulsion IFM Nano and MICRO R^3 FEEP system

ESA is constantly mapping the status of the Cubesat propulsion technology and is supporting the European Industry by financing and technically managing several R&D activities targeting maturation of innovative electric propulsion technologies through ground verification, qualification and In-Orbit Demonstration (11) on ESA Cubesats IOD missions like M-ARGO, GOMX-5 and VMMO.

M-ARGO (Miniaturised Asteroid Remote Geophysical Observer), led by GomSpace (LU) with Politecnico di Milano (I), aims at demonstrating the capability of a stand-alone deep-space 12U CubeSat to perform rendezvous with a Near Earth Object for an highly cost-effective in-situ resource exploration. The M-ARGO propulsion system, called Micro Propulsion System (MiPS), includes cold gas thrusters and a single radiofrequency gridded ion thruster from Mars Space Limited (UK), both using xenon as propellant and sharing the same tanks and feeding system. The spacecraft shall be able to generate delta-V of at least 3300 m/s. The ion thruster shall generate thrust in the range of 0.8 to 2mN and a total impulse higher than 90kNs while consuming power below 130W.

GOMX-5, led by GomSpace (DK), aims at demonstrating next generation constellation related technologies for 12U CubeSat platforms. A core technology to be demonstrated is the NPT30 electric propulsion system from ThrustMe (Fr) for large orbit transfers in LEO.

VMMO (Volatile & Mineralogy Mapping Orbiter), led by MPB Communications Inc and Surrey Space Center is a 12U lunar orbiter, planning to use two FEEP electric propulsion systems from Enpulsion (AT) to map lunar surface minerals and frozen volatiles including water ice to 10 m resolution using a 'laser radar' lidar able to peer into shadowed regions at the poles.

Figure 17: ESA IOD missions with EP , from left to right: M-ARGO, GOMX-5 and VMMO

ESA has also prepared in collaboration with National Agencies, European Commission, Euroconsult and European Industry a Technology Development Roadmap on Cubesat propulsion (11).

IV EPIC

The European Commission is currently contributing "*to guarantee the leadership of European capabilities in electric propulsion at world level within the 2020-2030 timeframe*" via their H2020 grant titled "Electric Propulsion Innovation and Competitiveness", in short EPIC. The grant is structured along the two lines of Incremental Technologies and Disruptive Technologies. ESA is the coordinator of this project where the team is formed by several space agencies and industrial entities.

Incremental Technologies are the most mature technologies having flight heritage, with the physical principal well understood, and with established performances. They are the Hall Effect Thruster (HET), the Gridded Ion Engines (GIE), and the High Efficiency Multistage Plasma Thrusters (HEMPT). Under EPIC, these Incremental Technologies shall improve their current performances and reduce their cost in order to increase their competitiveness in the global market.

Disruptive Technologies are very promising EP concepts which could disrupt the propulsion sector by providing a radical improvement in performance and/or cost reduction, leading to become the preferred technology for certain applications/markets or enable new markets or applications not possible with the existing (Incremental) technologies.

The selected Incremental Technologies contracts are: CHEOPS on HET; GIESEPP on GIE and HEMPT-NG on HEMPT technologies.

The selected Disruptive Technologies contracts are: GaNOMIC on PPU innovative Technologies; HiperLoc-EP on Electrospray Colloid EP System and MINOTOR on Electron Cyclotron Resonance Accelerator thrusters.

A new batch of disruptive and incremental technologies is currently being pursued:

Disruptive: AETHER (Air Breathing electric propulsion); EDDA (European Direct Drive Architecture); HIPATIA (Helicon Antenna Thruster); NEMESIS (Novel Electric Material); Plasma Jet Pack; iFACT (Iodine Fed Advanced Cusp field thrusters),

Incremental: ASPIRE (20 kW HET); CHEOPS low power; Cheops medium power; GIESEPP medium power; HEMPT-NG2.

V ESA PROPULSION LABORATORY (EPL)

Activities of the ESA Propulsion Laboratory

The main purpose of the EPL is to provide test services to ESA projects which require independent and fast assessment of propulsion technologies and related topics, including performance and possible failures. Projects among which Bepi Colombo, Lisa Pathfinder, M-ARGO, NGGM, GAIA and EUCLID, among others, have been or are currently using EPL capabilities. For example, a subsystem test with the Ion Engine T6 was conducted in June-August 2018 in the CORONA Vacuum Facility at the EPL in the frame of the launch phase of the Bepi Colombo mission. The test objective aimed at verifying the results achieved by the lifetime test conducted in parallel in QinetiQ facilities in Farnborough (UK).

The laboratory also enables fast access to qualification and lifetime tests which are long and expensive in nature. For instance for the Artemis mission the EPL hosted the lifetime test of the Radio Frequency Ion Engine RIT-10 which accumulated about 22,000 hours[3]. Another example is the involvement of the laboratory during the development and the acceptance of the propulsion system for the NGGM mission. Since several years, the EPL is providing support in testing several technologies that are available in Europe in order to provide a solid performance analysis to the mission. (4)

The EPL provides support to ESA Research and Development programs as well. It performs technologies assessment and explorative internal R&D work on new ones proposed by Industries and/or Research Centers. In the last few years, several tests devoted to the development of new engines such as mini-Hall Effect thrusters that will be the baseline for constellations have been and will continue to be hosted by the laboratory. Many other miniaturised thrusters have been tested before their implementation on small satellites to verify performance, such as a miniaturised Resistojet from TNO (NL) and the 600W Helicon Plasma Thruster from Sener (ES).

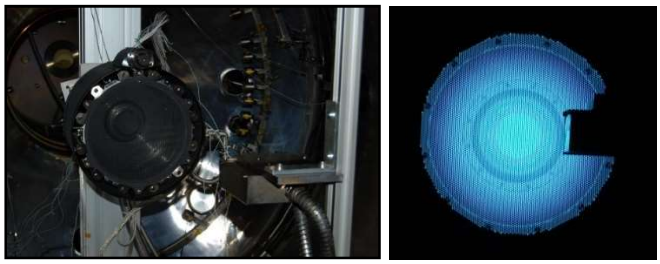


Figure 18: QinetiQ T6 Thruster firing test at the EPL

The EPL is today a reference for all the propulsion companies in Europe mainly in the field of electric propulsion testing and provide them with on demand technical. For example, in 2019 a 6-DoF Cold-gas Thruster designed to be operated with Butane and developed by NanoSpace, Sweden, was characterized in the EPL. Moreover, EPL is involved in the preparation of the network of electric propulsion facilities put it place in the last years. In collaboration with industry bodies, the objective is to standardize the way electric propulsion technologies are tested. This will allow any customer to change testing facilities in case of logistics or technical problems, minimizing schedule and cost impact on the activities. The EPL helps in procedures definition and contributes actively to propose alternative solutions to the problems found in this field.

In addition, EPL has recently submitted an internal plan to become the **ESA Test Center for CubeSat Propulsion** to provide ESA with an opportunity to support and nurture future R&D activities. EPL plan is incremental with test capabilities being deployed in steps, starting from 2022 with the commissioning of a Cubesat Test Platform, the upgrade of one existing test facility to fire electric propulsion systems during thermal cycling also when integrated on a CubeSat and the upgrade of one existing test facility to make it compatible with iodine propellants.

Several tests on electric propulsion systems for Cubesats have been performed at EPL starting from 2021, mainly as part of the multiple ESA TDE contracts on Innovative Propulsion systems for Cubesats (11).

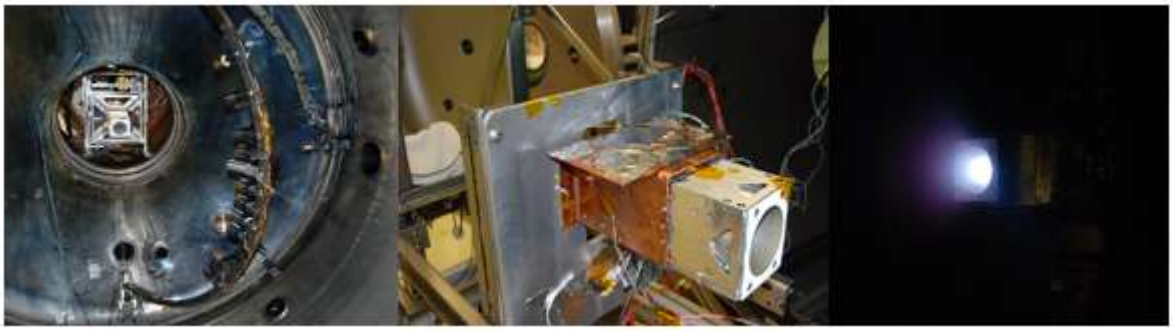


Figure 19: T4i REGULUS-150-Xe MET system under test at EPL

The REGULUS-150-Xe system from T4i (IT), the REGULUS-150-Xe system underwent a performance characterisation in the EPL CORONA test facility to verify its performance in the power range of 50-150W followed by an endurance test of 300 hours.

The NANO AR3 electric propulsion system from Enpulsion underwent a performance characterisation in the EPL SPF test facility to verify its capability of achieving thrust vectoring within a cone of 12.5 degrees (12).

The Cube de ALPS (CubeSat Deorbiting ALl-Printed Propulsion System) from the University of Southampton underwent a performance characterisation to verify the propulsive performance and an endurance test of over 3 million pulses (13).

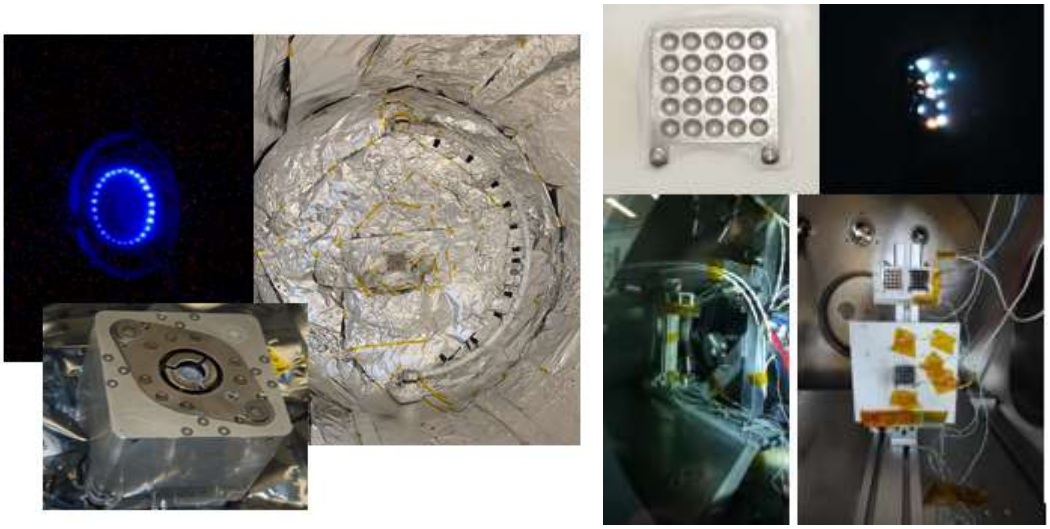


Figure 20: ENPULSION NANO AR3 FEEP system (left) and University of Southampton printed VAT system under test at EPL

The EPL is also expanding its activities towards generic propulsion activities. As example, a test is being prepared to perform a characterisation of a miniaturised bi-propellant thruster for CubeSat applications. In 2018, a facility was built within the laboratory to perform compatibility tests between tank materials and green propellants. In addition,

the flow bench keeps being updated in line with the requirements from the industry, and was recently used by Airbus UK to qualify the fluidic system of the MTG spacecraft with respect to the requirements on high-pressure resilience.

Organisation of the ESA Propulsion Laboratory

The EPL is managed by the EPL manager with the support of the EPL infrastructure and quality manager. The EPL manager is the person in charge of the normal operation of the laboratory. The operation, maintenance and procurements are under the monitoring of the Head of the Propulsion and Aerothermodynamics division. The justification for investments (mainly for facilities, diagnostic packages and data acquisition systems) is performed by the EPL management together with the customers of the laboratory who are frequently consulted via a steering board. This board assesses the work performed within one year and design the strategy of EPL in investments and activities for the next year. For every test performed, a test team is formed. A senior test manager is in charge of the test and the team composed by senior and junior engineers. This organization helps not only to perform the test but also to train junior engineers who can therefore learn directly in the field under the supervision of the senior members.

The ESA Directorate of Technology, Engineering and Quality (TEC) to which the EPL belongs has passed an ISO 9001 certification process carried out by NQA. Therefore the procedures and reporting outputs are exposed to the demanding quality requirements of the accreditation body.

Facilities and capabilities of the ESA Propulsion Laboratory

The testing of propulsion systems (Fig.10) requires facilities capable to simulate space conditions and which are designed for this scope (Fig.11). In some cases such as electric propulsion components (thrusters and neutralizers) the vacuum conditions must be better than 10-9 mbar. The European Space Agency has invested in the ESA Propulsion Laboratory to allow the Agency to assess the special characteristics of the electric and cold gas propulsion thrusters and components in the last decades. Lately, the laboratory has expanded its fields of application to other chemical propulsion activities such as testing of propulsion components (valves, injector, etc).

Figure 11. CORONA Vacuum Facility in EPL

The domain of competence of the EPL includes procedures for the direct and indirect measurements of thrust, mass flow and electrical power related to propulsion systems operation in specific ranges which have been extensively tested and proved reliable and repeatable.

Features of testing facilities at EPL:

- Certification of ISO 9001 (General Requirements for the competence of testing and calibration laboratories)
- Cleanroom ISO Class 8 capability (eq. to class 100,000)
- Seismic block for background noise isolation
- 7 vacuum facilities dedicated to space propulsion testing
- Vacuum chamber reproducing space environment with pressure down to 10-9 mbar
- Beam target and diffuser reducing on-ground testing disturbances
- High speed high resolution data acquisition systems

- 1 flow bench (accepted for water-hammer tests)
- 1 sloshing bench
- 1 green propellant test bench
- Calibrated commercial measurement instruments
- Various electronic equipment for measurements from 1 μV/1 nA to 35,000 V / 20 A
- Mass spectrometers for residual gas analysis
- Infrared Thermocamera
- Pyrometer
- 5 thrust balances for thrust measurement from microNewton to Newton ranges
- 3 beam diagnostics systems for beam divergence and energy distribution measurements

Specific diagnostic systems available at the EPL include two Mettler-Toledo high precision (0.1 mg resolution) electronic load cells customized for micro and milliNewton thrust measurement of cold gas thrusters, two specifically designed thrust balances for milliNewton range electric propulsion thrusters. The design and manufacturing of very specific diagnostics is usually realized in collaboration with external entities. For instance, among others, two balances and several diagnostics (Faraday probes, Retarding Potential analyzers, etc.) were developed by Sitael S.p.A; ICARE designed and developed a retarding potential analyzer and its electronic system able to measure energies of primary and charge-exchange ions, and more recently, developed an ExB probe and its electronics for the measurement of the ion velocity distribution function; the University of Stuttgart is developing a Langmuir Probe. Nevertheless the EPL has independent capabilities to carry out this kind of activities: internally designed single-Langmuir probe and emissive probes are being successfully used in the laboratory to determine the plasma parameters in a Hall Effect Thruster plume. Currently, the EPL is performing an activity to assess the calibration of Faraday Probes with an Ion Engine to path the way towards the standardisation of EP testing.

The EPL is capable of designing, preparing and executing performance characterization and endurance tests of low and medium power electric propulsion thrusters and components in its automated vacuum facilities. EPL has also demonstrated its capabilities to perform spacecraft-thruster interaction tests in the past. Performance of components for chemical propulsion may also be measured. The last few years a green propellant test bench was commissioned in the EPL for assessing the compatibility between tank material and multiple new propellants. Tests with calibrated orifices (flow restrictors) were successfully performed allowing demonstrating the limitations of the bench.

The EPL is evolving to provide test service to future CubeSats adopting electric propulsion. The Cubesat Test Platform (CTP) has been developed by the Politecnico di Torino (I) for EPL. The CTP can interface a wide range of new miniaturized electric propulsion systems and assess their impact and the interactions with CubeSat technology and vice versa. The CTP features an Al-alloy 6U structure, in which a Propulsion Box hosts the propulsion system (up to 4U), and a Service Module contains the on-board avionics (1U), and battery packs (1U). The avionics systems are in-house developed electronic boards representative of the CubeSat technology. The avionics box is constituted by the Propulsion Interface System (PIS) that manages the data and power exchanges with the propulsion system and a basic CubeSat module made of the Command and Data Handling board, the Electrical Power System (PCDU and battery), and the communication module (UHF for housekeeping and experiment data transmission). The Propulsion Interface System (PIS) provides the interfaces of CTP towards the propulsion system and the instruments and devices to measure the parameters for assessing the interactions between the CTP and the propulsion system. Two main parts constitute PIS: the Data Logging System (DLS) and the High-Power Management System (HPMS). [RD6]. The CTP is a valuable instrument to increase the level of readiness of a new propulsion technology. This platform can support functional and operational tests, gathering information about electromagnetic compatibility, thermal environment induced by the operations of the propulsion system and power consumption

The commissioning of the Cubesat Test Platform was successfully completed at EPL during CW7 of 2022 using a REGULUS electric propulsion system provided in kind by T4i. The collaboration with Politecnico di Torino will be extended in time to improve the system further on with EMC and EMI capabilities.

Figure 21: PoliTO CubeSat Propulsion Test Bench commissioned at EPL

A thermal system is under procurement from Aerospazio Technologies (IT) to enable thermal cycling of CubeSats of size up to 16U with firing electric propulsion in the existing EPL SPF test facility.The thermal system has recently undergone an ESA led design review and it is planned to be commissioned at EPL in 2022.

VI CONCLUSIONS AND OUTLOOK

Since the 1970s, Electric Propulsion has been used on satellites for station-keeping, orbit raising and primary propulsion. It has traditionally had applications for telecommunications and science missions, but increasingly the use of EP is being considered for earth observation, navigation and space transportation.

More recently, constellations of small satellites are being deployed using electric propulsion systems to perform the transfer to the operational orbit and other functions. Thanks to the mass savings made possible by the use of electric propulsion, fewer launchers are needed to place the constellation in orbit, thereby allowing a major cost reduction for the service being offered. The use of EP is also capable to enhance the services offered by CubeSats. (5), (6), (11).

Europe has excellent capability in the area of Electric Propulsion, which has stemmed from decades of research and development and exemplified by the success of ESA missions such as ARTEMIS, SMART1, GOCE, AlphaSAT NEOSAT and BepiColombo that have paved the way to the use of electric propulsion on European commercial telecom satellites such as Electra, Novacom and ESA institutional missions such as GALILEO 2G, Mars Sample Return and NGGM.

A big effort is now being made on industrialisation and price reduction to guarantee the competitiveness of European EP products in the global market. The first positive result is the over 100 orders and 47 delivery of PPS5000 from SAFRAN AIRCRAFT ENGINES (F), the several orders of RIT2X from ARIANEGROUP (D) and the 100 in space and over 200 delivery of IFM Nano FEEP systems from Enpulsion (AT). (7)

ESA is strongly involved and committed in this technology area, both as an initiator of electric propulsion system developments and a user of this technology for its new missions. The goal is to maintain the competitiveness of European industry by ensuring the availability of qualified, cost-effective and reliable EP systems, and to make new and challenging scientific missions possible. The ESA Propulsion Lab at ESA is an important tool to help the development of electric propulsion in Europe. Furthermore, the European Commission is currently contributing "*to guarantee the leadership of European capabilities in electric propulsion at world level within the 2020-2030 timeframe*" via their H2020 grant titled "Electric Propulsion Innovation and Competitiveness", EPIC. (8)

ESA activities in the field of micro propulsion for CubeSat's are paving the way for the use of these systems in a market of more than 3000 satellites in the next decade. The activities on Radiofrequency ion engines and Hall Effect thrusters are today very important to promote and improve the competitive standards of the European actors in this field that will allow commercial telecommunication spacecraft and navigation primes and operators using European Electric Propulsion technology. Constellations of satellites are today using electric propulsion systems and ESA is contributing to enhance the European capabilities in this domain through many of their initiatives. ESA Scientific missions such as LISA, NGGM or Mars Sample Return will make use also of European Electric technology.

Furthermore, the colonization of the solar system will only be able to take place by the use of high power electric propulsion engines for cargo missions to planets like Mars. (9), (10)

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