European Space Agency Activities on Electric Propulsion

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Abstract: Interest in using electricity to propel spacecraft dates to the early 20th Century with first successful use in space of Electric Propulsion in 1964. Europe has extensive heritage in developing Electric Propulsion technologies and European players are well positioned in the worldwide landscape. Recent European successes include several GEO Telecommunication platforms like ARTEMIS, AlphaSAT, Eurostar E3000, SpaceBus 4000, SmallGEO, SpaceBus NEO and Eurostar NEO, the ESA's SMART-1 mission to the Moon, the ESA's GOCE Earth Gravity mission and the ESA-JAXA BepiColombo mission to Mercury. Ongoing developments of Electric Propulsion technologies in Europe target application on next generation GEO telecommunication platforms, on several constellations of Telecommunication and Earth Observation small satellites operating in Low Earth Orbits, on Europe's Galileo 2nd Generation Navigation constellation, on Next Generation Gravity missions like NGGM, on Exploration missions like Mars Sample Return and on several Cubesat missions for different applications. Ongoing developments of Electric Propulsion technologies in Europe target application on next generation GEO telecommunication platforms, on several constellations of Telecommunication and Earth Observation small satellites operating in Low Earth Orbits, on Europe's Galileo 2nd Generation Navigation constellation, on Next Generation Gravity missions like NGGM, on Exploration missions like Mars Sample Return and on several Cubesat missions for different applications. Electric Propulsion is considered as a strategic technology in Europe for improving competitiveness in space and to enable emerging space applications. The European Space Agency, the European Commission, the National Space Agencies, and the European Industry are working together to achieve maturation of this technology via on-ground qualification and in-orbit demonstration, to improve performance and reliability, to significantly reduce prices and to increase production volume to establish and retain leadership. Development of innovative and breakthrough Electric Propulsion technologies is also pursuit to enable new applications in Very-Low Earth Orbit for Telecommunication and Earth Observation, namely with use of atmosphere-breathing Electric Propulsion technologies, and for exploration and/or future robotic/human space transportation missions, namely with use of very high-power EP. This paper will report past achievements and state of the art of the Electric Propulsion technology in Europe, elaborate on future mission needs and technology gaps, market perspective, technology trends and opportunities and, finally, it will present the ESA Electric Propulsion Technology Roadmap defined in consultation with the European stakeholders.

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I. Introduction

Electric Propulsion (EP) has been under development since the beginning of the past century. Since the 1970s, EP 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 adopted on Earth observation and navigation missions. More recently, CubeSats and constellations of small satellites operating in Low Earth Orbits with the mass ranging from few to 100 of kgs have started to use EP to enhance their capabilities. Figure II-1 reports the key milestones in the history of EP technology development.

Year	Who	What
1906	Robert Goddard	First known hand-written notes on EP
1911	Konstantin Tsiolkowsky	First published mention of an EP concept
1929	Hermann Oberth	Full chapter on EP in Wege zur Raumschiffahrt
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 HETs on GEO platforms
1998	US	First deep space probe with EP (Deep Space 1)
2003	Europe	First transfer to the Moon with EP (Smart-1)
2009	Europe	First use of EP for drag free control (GOCE)
2015	US	First all-electric communication satellite reaches GEO (Boing 702SP)
2017	Europe	First European all-electric communication satellite reaches GEO (Eurostar E3000EOR)
2018	Europe	Mercury's mission BepiColombo propelled by EP is launched

Figure II-1: EP historical milestones

In Europe, developments have been carried out in all the different areas of electric propulsion over the last four decades. All the thruster types mentioned above have been and/or are being developed in Europe but the level of maturity can vary significantly from early performance evaluation on prototypes to flight ready products.
ESA is leading several development activities on electric propulsion, from basic research and development of conventional and innovative concepts to qualification and flight operation on several European satellites.

The ESA/ESTEC Electric Propulsion team:

- provides expert technical support on electric propulsion to the Agency’s project teams responsible for the development of spacecraft, throughout all the project phases.
- contributes to the preparation of work plans in electric propulsion in the Agency’s technological programs.
- prepares and technically manage Agency contracts for studies, experimental investigations, and qualification of EP technologies.
- manages the ESA Propulsion Laboratory and provide test services.

I. Use of electric propulsion on ESA large GEO telecommunication satellites

Commercial GEO telecommunication represents the largest market for electric propulsion (EP). 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 one week but about 50% of satellite wet mass is propellant. With Electric Propulsion, orbit-raising takes up to six months, but satellite wet mass can be reduced by 40% and 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 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 2001, ESA’s ***ARTEMIS*** (the Advanced Relay and Technology Mission Satellite - Figure II-2) offered the first European flight demonstration of Gridded Ion Engines (GIEs) for orbit raising of GEO Comsats, recovering the satellite to its final orbit following a launcher anomaly.

Figure II-2: ARTEMIS

Starting from the year 2000, Hall Effect Thrusters (HETs) were adopted by an increasing number of satellite manufacturers. In 2010, Lockheed Martin's Advanced Extremely High Frequency (AEHF) satellite after an anomaly with its main Chemical Propulsion system used HETs intended for station keeping to complete its orbit raising.
In 2013, Airbus DS and Thales Alenia Space in partnership with ESA, jointly built ***ALPHASAT*** (Figure II-3), the first European telecommunication platform using the PPS1350 HETs developed and qualified by Safran Aircraft Engines (FR) with the support of CNES and ESA for NSSK.

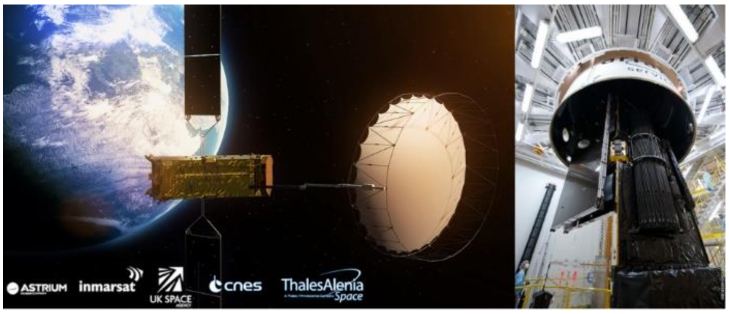


Figure II-3: AlphaSAT

In 2015, Boeing successfully demonstrated the world's first all-electric platform using XIPS Gridded 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.

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

Today all European Primes offer "all-electric" GEO platforms. These platforms are designed to use the European 5kW HET from Safran Aircraft Engines (FR) .

	ARTEMIS	ALPHASAT	NEOSAT
Launch Year	2001	2013	2020
Launch Mass	3,000 kg	6,700 kg	3,000-6,000 kg
Satellite Power	3,000 W	12,000 W	> 20,000 W
Chemical Propulsion	Bi Prop	Bi Prop	Not Required
Electric Propulsion	Ion Thruster	Hall Thruster	Hall Thruster
EP Role	NSSK	NSSK+	Full AOCS Function
EP Power	<800W	~1,500W	3kW+
Thrust	0.018N	0.080N	0.250N (per thruster)

Figure II-4: ESA Telecom platforms growth

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 7 tons launch mass range: Eurostar NEO and SpaceBus NEO. These platforms aim at significant cost reduction thanks to the use of EP for both orbit raising and station keeping. At the time of writing Airbus DS (FR) has 3 all-electric ***EUROSTAR-NEO*** platforms in orbit and additional 6 platforms ordered while Thales Alenia Space (FR) has 7 all-electric ***SPACEBUS-NEO*** platforms in orbit and additional 3 ordered.

In addition, both Airbus DS (FR) and Thales Alenia Space (FR), in partnership with ESA, have started the development of their new medium-size, reconfigurable GEO all-electric platforms named respectively ***ONESAT*** and ***SPACE INSPIRE***, to respond to the fast-changing telecommunication market requiring service reconfiguration, instant in-orbit adjustment to broadband connectivity demand and superior video broadcasting performance.
At the time of writing 6 SpaceInspire and 8 OneSat platforms have been ordered ordered.

OHB (DE), in partnership with ESA, is also developing the ***ELECTRA*** platform to extend their portfolio of telecom satellite platforms, adding a fully electric version to the SmallGEO product line.

The European Space Agency, the European Commission, the National Space Agencies and industries have invested in the development of EP thrusters for the GEO market at SAE (HETs), Sitael (HETs), AGG (GIEs) and Thales (HEMPTs).
ESA's Partnership Projects NEOSAT and ELECTRA have been essential to position European primes and European EP suppliers at the forefront of the global communication satellite market.
ESA is committed to make sure that European 5-7kW EP thrusters are fully qualified and flight ready to accelerate the product adoption level in the global comsats market. The recent geopolitical situation has also revealed the need to ensure dual source of critical EP technologies.

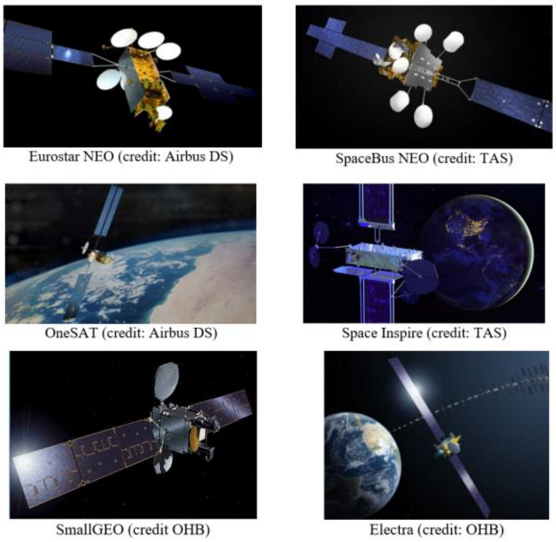


Figure II-5: ESA supported all-Electric GEO Telecom platforms

II. Use of electric propulsion on ESA small LEO/GEO Comsats

The use of the Low Earth Orbit (LEO) is not new to communication satellites (the Iridium satellite constellation has already been running 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 to make a significant impact in the space economy. Small satellites have a unique ability to introduce new products and services in shorter time and at lower cost. Today, several LEO small satellite constellations are under development, namely Starlink, OneWeb, Kuiper and Lightspeed. The satellites of these constellations orbit between 500km and 1200km and use low power (<1kW) EP thrusters to perform deployment and orbit insertion, orbital changes, orbit maintenance, repositioning, collision avoidance and deorbiting at end of life.

ESA, on behalf of the European Commission, is working with European space companies to develop and validate in orbit the ***IRIS^2 constellation*** for secure connectivity. The first satellites and their ground stations are expected to be operational by the end of 2027, based on a contract to be signed in 2024. Electric propulsion is planned to be used on the satellites of this constellation for deployment, orbit maintenance, collision avoidance and deorbiting at end of life**.**

ESA in partnership with Luxspace has developed ***Triton-X*** (Figure II-1), a multi-mission micro-satellite platform designed to give low-cost and fast-track access to space for commercial and institutional applications in low Earth orbit. It is the first generic platform specifically developed for a wide range of applications including telecommunication, Earth observation, in-orbit demonstration and validation, situational awareness, and optical missions. It is tailored to be compatible with the new generation small launchers and rideshare missions. Triton-X embarks the novelly Spaceware MICRO Electric Propulsion System developed by Exotrail (FR) with support of ESA and CNES for in-orbit propulsion.

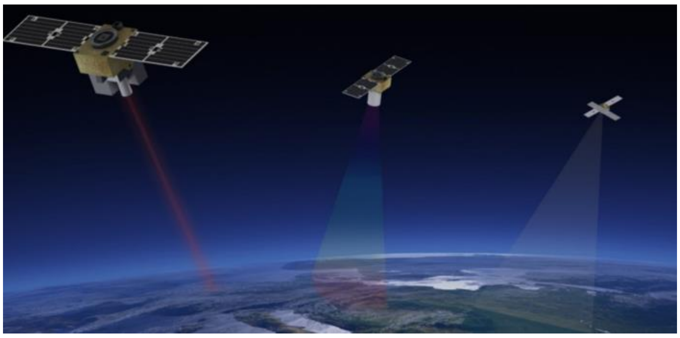


Figure II-1: TRITON-X

ESA in partnership with SWISSto12 is developing a lightweight GEO all-electric platform called ***HUMMINGSAT*** (Figure II-2). This platform is significantly smaller than conventional GEO telecommunication satellites, and therefore benefits from a rideshare launch strategy. Despite its small size, the satellite powers highly capable telecommunications payloads with approximately 2kW of power.

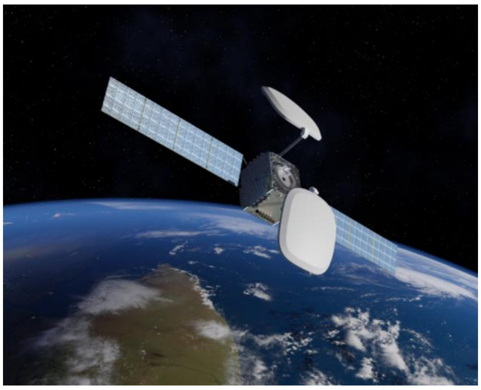


Figure II-2: HummingSAT

The European Space Agency, the European Commission, the National Space Agencies and industries are investing to make sure that European low power (<1kW) and medium power (<3kW) EP technologies will mature and become commercially available to gain and maintain a strategic position in this market.

EP technologies for this market are under development, also with the support of ESA, at:

- Thrusters: Enpulsion (AT), Exotrail (FR), Safran Aircraft Engines (FR), Sitael (IT) and Thales (DE);
- Propellant management technologies: Airbus DS (UK), Air Liquide (FR), ArianeGroup (DE), AST (DE), Bradford (NL), Exotrail (FR), Nammo (UK), Nanospace (S) and Safran Aircraft Engines (FR).
- PPUs: Airbus DS (FR), ASP (DE), TAS (B), Enpulsion (AT), Exotrail (FR), Safran Aircraft Engines (FR), Sitael (IT/GR);
- Pointing mechanisms: BGA (AT), ADS (FR), EHP (BE), TAS (UK), MDA (CA), Exotrail (FR), SENER (ES) and URA (UK).

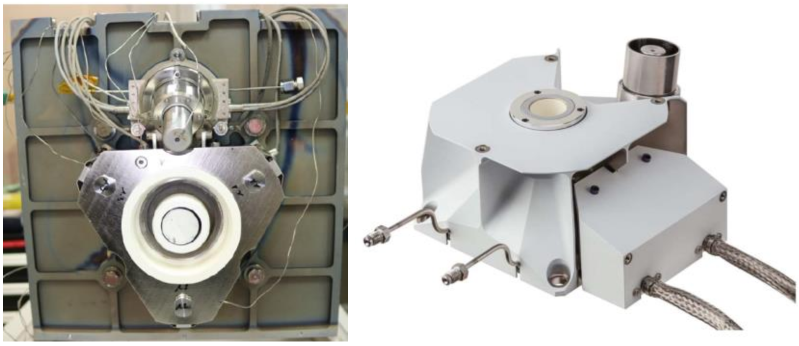


Figure II-3: Safran Aircraft Engines (FR) 200-1000W PPS X100 HET – right - and Thales (DE) 200-700W HEMPT for LEO mega constellations – left.

III. Use of electric propulsion on ESA Navigation satellites

The use of Electric Propulsion for Navigation satellites is mainly associated with the ESA **GALILEO 2ND GENERATION** programme.
In 2021, after several Agency and industry-led feasibility studies, ESA, acting on behalf of the European Commission, signed two contracts to procure the first twelve satellites of the Galileo 2nd generation constellation from two separate Primes: Thales Alenia Space (IT) and Airbus DS (D). The current Galileo navigation constellation consists of 28 satellites in all. All but two of these are positioned in three circular Medium Earth Orbit (MEO) planes at 23 222 km altitude above the Earth, and at an inclination of the orbital planes of 56 degrees to the equator. Initial services became available on 15 December 2016.

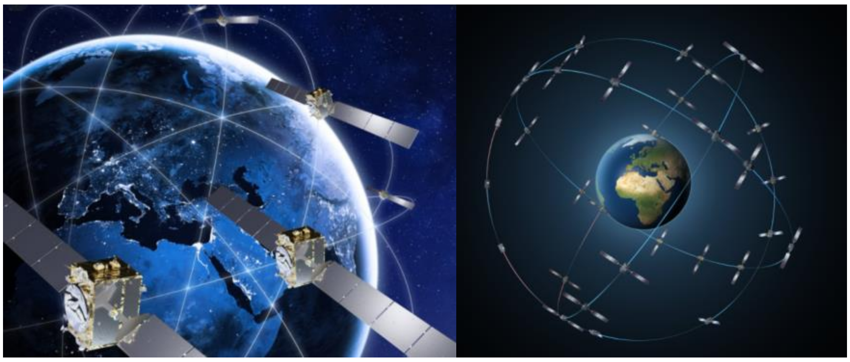


Figure II-4: Galileo 2nd Generation

The 1st generation of Galileo satellites were directly launched into their final orbit. The 2nd generation satellites shall prolong, improve and expand the existing Galileo services, while still providing the first-generation legacy services during deployment.

The Galileo 2nd generation satellites (Figure II-4) will be launched in dual launch configuration by the Ariane 62 and will use 5kW PPS5000 HETs from Safran Aircraft Engines (FR) for orbit raising to MEO.

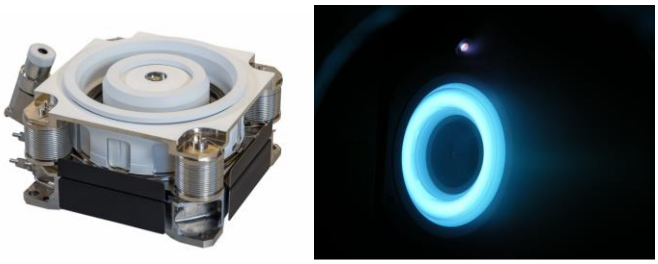


Figure II-5: 5kW PPS 5000 HET for Galileo 2G (credit: Safran Aircraft Engines)

ESA has recently signed two parallel and separate contracts, with GMV Aerospace (ES) and TAS (FR), for the development and IOD of the ***LEO-PNT*** (low Earth orbit positioning, navigation and timing) constellation of ten ~70kg satellites that will fly close to Earth and test the use of novel signals and frequency bands, unlocking exceptional resilience, accuracy and speed in navigation that will enable a long list of new applications and services. The constellation will work in combination with Galileo and other global navigation satellite systems in a multi-layer approach. LEO-PNT will assure signals to overcome vulnerabilities of existing GNSS in medium Earth orbit such as natural phenomena impairments and interferences and provide services to places where today's satnav systems cannot reach, like polar regions, deep urban areas and even indoors. EP is planned to be used on the satellites of this constellation for deployment, orbit maintenance, collision avoidance and disposal.

IV. Use of electric propulsion on ESA Earth Observation missions

Earth Observation missions, like ***GOCE*** (Figure II-6), largely 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 (UK) was operated almost continuously from 2009 to 2013 to compensate aerodynamic drag. The success of the GIE on GOCE has demonstrated the potential of this technology for fine control of satellites flying in LEO and VLEO.

Figure II-6: GOCE

Future ESA Earth's gravity field missions targeting sustained observations at higher resolution, like the Next Generation Gravity Mission **(*NGGM*),** are considering using 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.

ESA and OHB Sweden have built the first ***Artic Weather Satellite*** **(AWS),** Figure II-7, to provide global measurements of atmospheric temperature and humidity with frequent revisit times for improved weather prediction. The AWS mission is a 120kg satellite operating at 600km foreseen for launch in June 2024 and expected to become a constellation to complement MetOp satellites services. Enpulsion (AT) has been chosen to supply an EP system based on 4 NanoR3 indium FEEP thrusters to perform all electric manoeuvres, including de-orbiting.

Figure II-7: Artic Weather Satellite (AWS)

V. Use of air breathing electric propulsion to unlock VLEO orbits

The feasibility of using electric propulsion systems to provide drag compensation at low altitude have been demonstrated already by the ESA's GOCE mission and by the JAXA's Super Low Altitude Test Satellite (SLATS).

Reducing the operational orbital altitudes down to Very Low Eart Orbits, VLEO, between 150km and 250km, can provide a number of benefits:

- For Earth observation, reducing the distance to the ground allows higher resolution and quality of images.
- For communications, the closer the satellite is to the Earth, the better the link budget, the lower the latency (e.g.

enabling high speed internet) and required transmit power. Other benefits include lower interference, improved launcher uplift capability, enhanced revisit over certain locations, low cost, etc.

- Lower altitude orbits are naturally resilient to a build-up in debris due to the effects of drag and therefore have a lower risk of collisions; the same effect of drag ensures that satellites are naturally disposed quickly after their mission is complete or if they suffer a catastrophic failure.
- Launch vehicles can deliver a larger mass into lower altitude orbits, reducing the specific (per unit mass) launch cost.
- The radiation environment is less aggressive and therefore more favourable to the use of COTS components that can reduce cost.

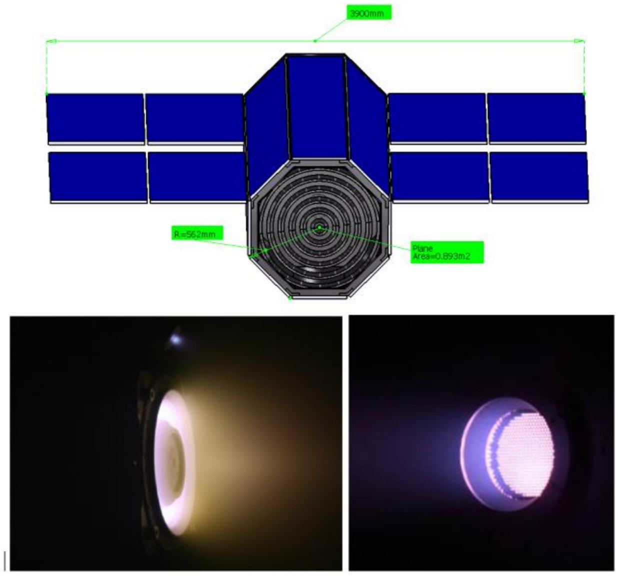


Figure II-8: ESA CDF study concept and HET and GIE operating with N2/O2 mixture

Atmosphere Breathing Electric Propulsion (ABEP), also often referred as "Ram-EP", is considered as the enabling technology for satellites to operate in VLEO. These propulsion systems use atmospheric gas as propellant to provide effective drag-compensation without the limitation of propellant storage on lifetime.
ESA has already invested in developing Ram-EP concepts and 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.
- 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
- 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.

ESA, in consultation with European space entities has defined a technology Roadmap to develop ABEP for VLEO, for Mars or other planetary bodies using the corresponding atmospheric gases as propellant for an extended duration, without using on-board propellant.
ESA is also planning to provide a quick and reliable transition to operational programs through flight demonstration programs targeting in orbit experiments of the Air Breathing electric propulsion concept.

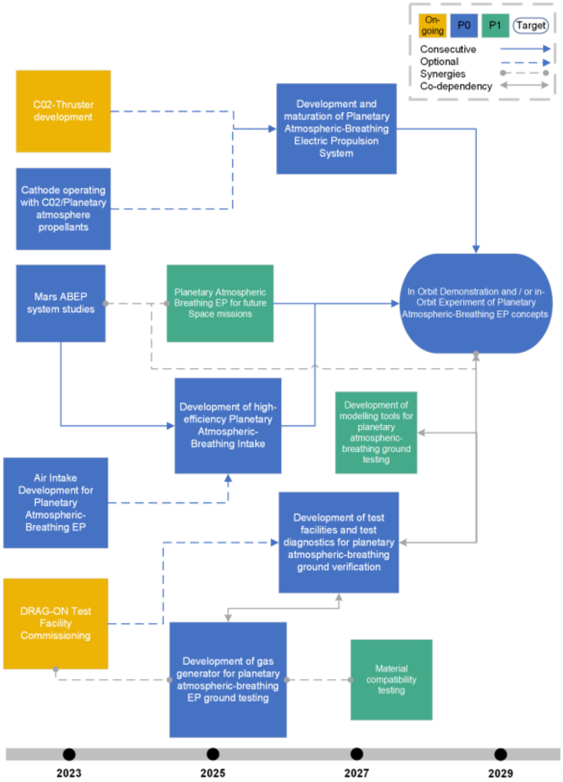


Figure II-9: IP-CCI Atmosphere-Breathing EP Roadmap

VI. Use of electric propulsion on ESA interplanetary missions

Missions such as Deep Space 1, Dawn, Hayabusa, Smart-1 and BepiColombo have all paved the way to the use of Electric Propulsion for interplanetary transfers.

Figure II-10: SMART-1

ESA's first mission to the Moon, ***SMART-1*** (Figure II-10), was launched in 2003 on a shared Ariane-5 ride to GTO. The mission aimed mainly at testing solar electric propulsion for interplanetary navigation, while performing scientific observations of the Moon. One PPS®1350-G HET from Safran Aircraft Engine (FR), powered at 1350W was used to generate a Thrust of 0.07 Newton and propel a 350 kg, 1 m^3 spacecraft to the Moon in 16 months consuming in total only 82 kg of Xenon. The mission ended in 2006 and made history with several notable firsts: first Europe's lunar mission, first European mission with HET as primary propulsion, first spacecraft to undergo a firing end-to-end ground test, first mission using low-thrust trajectories from GTO across van-Allen belt to the Moon, first mission with and integrated plasma diagnostic package to measure plasma potential and ion velocities. In addition, Smart-1 provided direct feedback of flight experience for performance and design parameters and was a powerful demonstration of what extensive flight data exploitation can achieve.

ESA's first mission to planet Mercury, ***BEPICOLOMBO***, was launched in October 2018 and is aiming at providing the best understanding of this planet to date by studying the composition, geophysics, atmosphere, magnetosphere and history of the planet.

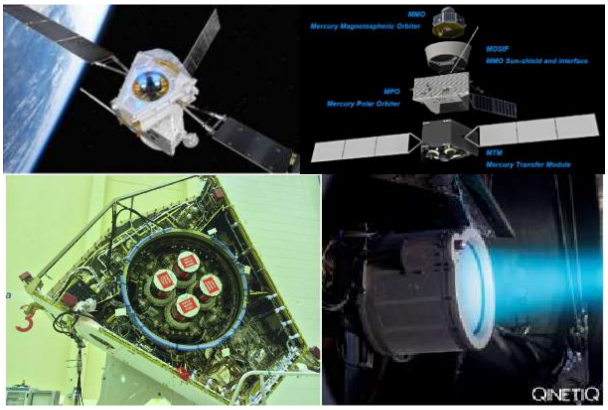


Figure II-11: BepiColombo

BepiColombo will place two independent orbiters around Mercury. These orbiters are transported by the Mercury Transfer Module (MTM) which is propelled by four 5kW T6 gridded ion engines developed by QinetiQ (UK) clustered together. Each T6 GIE of the MTM Solar Electric Propulsion System (SEPS) is mounted on independent gimbal mechanism that allows the thrust vector to be adjusted for the different thruster combinations, S/C CoG migration and momentum wheel off-loading. The MTM Solar Electric Propulsion System (SEPS) also includes 3 xenon tanks to store 580 kg of xenon, a high-pressure bang-bang regulator, four xenon flow control units and two Power Processing Units (PPUs) in addition to all interconnecting harness and pipework. SEPS was fully commissioned in space late 2018 and all thrusters are operating nominally, propelling the spacecraft to Mercury.

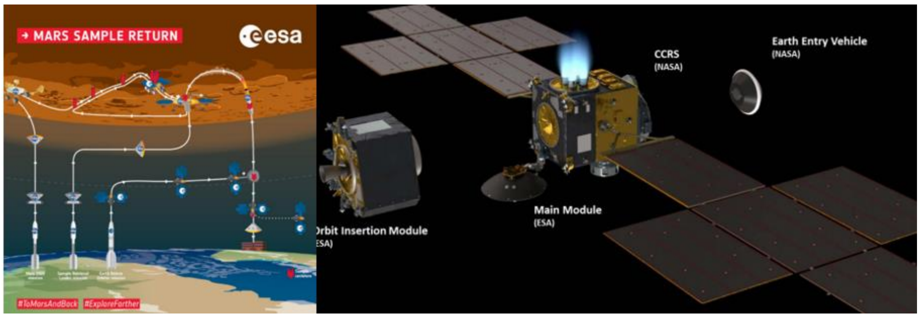


Figure II-12: Mars Sample Return Earth Return Orbiter

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 embarking a cluster of 7.5kW RIT-2X GIE from ArianeGroup (DE) to deliver a total impulse of 45 MNs. Each thruster will be capable to provide thrust between 0.15N and 0.25N with a specific impulse around 4000s.

VII. Use of electric propulsion on ESA space transportation missions

The use of Electric Propulsion is envisaged at ESA also for space transportation missions, especially those targeting last-mile delivery, in-orbit surveillance, in-orbit assembly, in-orbit servicing and life extension and active debris monitoring and removal.

ESA is preparing in-orbit servicing missions for GEO, they will need EP systems.

VIII. Use of electric propulsion on ESA CubeSat missions

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.
Hundreds of CubeSats are launched each year and propulsion capabilities are becoming crucial to enhance utilisation, 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.

To date, only a minority of launched CubeSats have featured propulsion subsystems. However, the portion of CubeSats using propulsion is forecast to increase, especially in response to the increase in CubeSats sizes and to new Space Debris Mitigation guidelines/standards (Figure II-13). This is the reason why CubeSat propulsion is considered by ESA as a strategic technology for the European competitiveness in space.

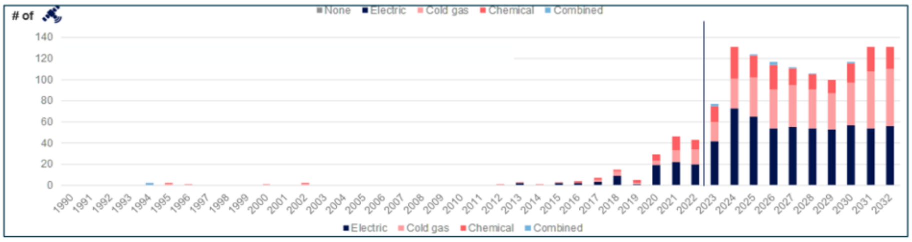


Figure II-13: estimated numbers of CubeSats with propulsion (credi: Euroconsult for ESA)

Several integrated electric propulsion subsystems for CubeSats are available in Europe with different performance and at different level of technology readiness (*Figure **II-14***).
Their compactness, performance and low price are increasingly appealing as the space industry interest in small satellites with mass below 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.

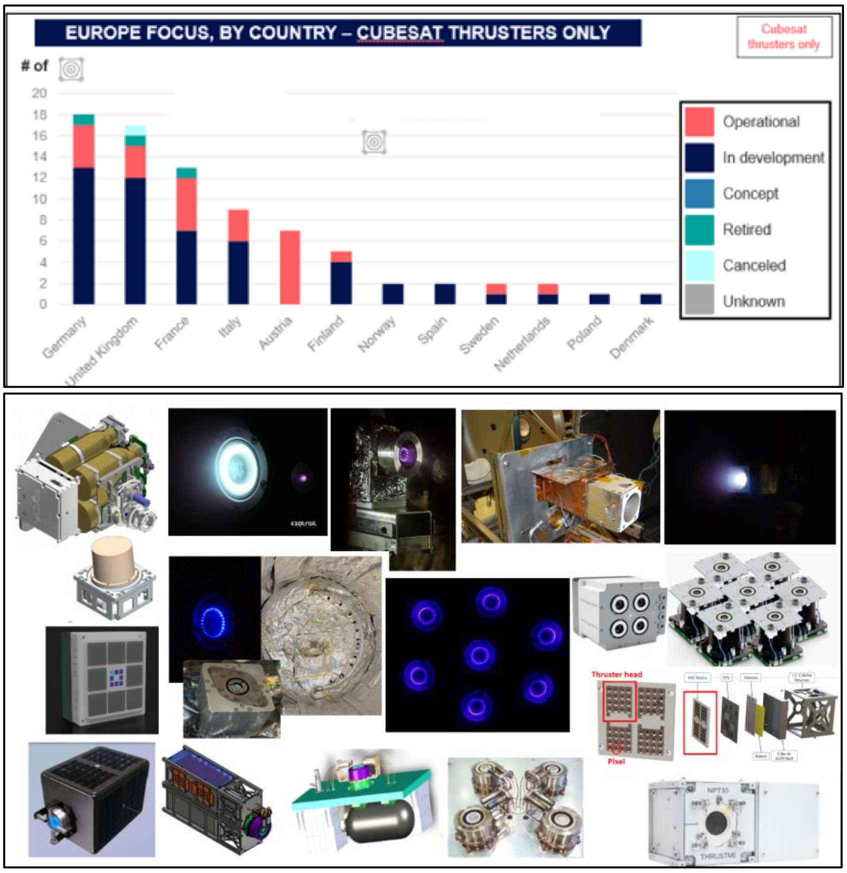


Figure II-14: European Electric Propulsion for CubeSats

Euroconsult has performed a market analysis for ESA and predicted that about 572 CubeSats will use electric propulsion in this decade. This means 861 European electric thrusters estimated to be launched on CubeSats for Earth Observation and IOD/IOV, operated by Commercial or Civil Government operators (Figure II-15).

ESA is constantly mapping the status of the Cubesat electric 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 on ESA Cubesats IOD missions embarking electric propulsion.

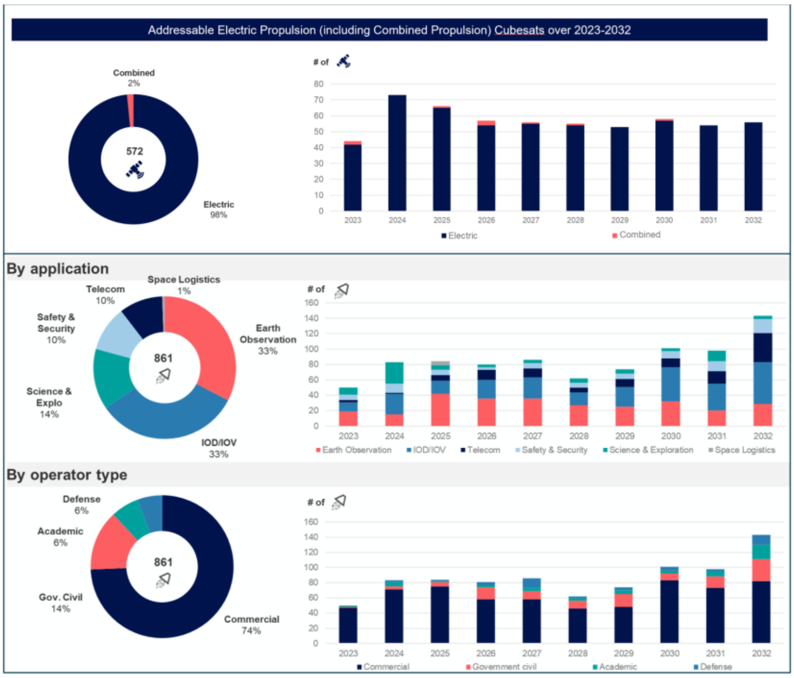


Figure II-15: market analysis of European electric propulsion systems for Cubesats (credi: Euroconsult for ESA)

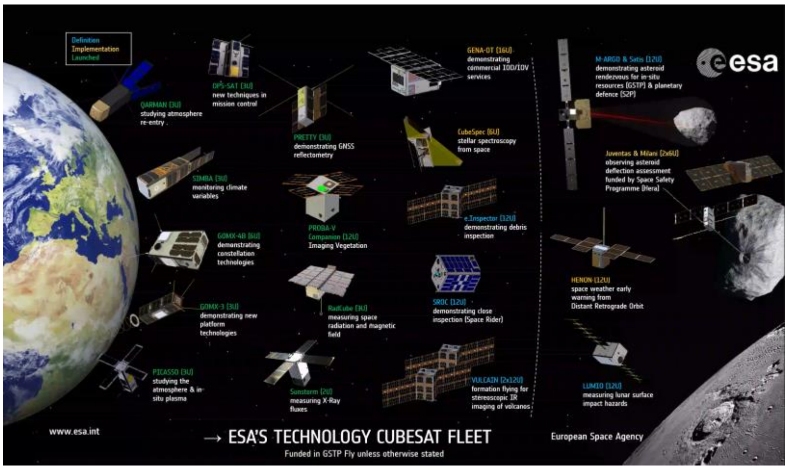


Figure II-16: ESA CubeSat IOD missions

VULCAIN mission aims at flying in formation two 12U CubeSats positioned in a LEO 400 km orbit for stereoscopic imaging of the Earth with relevance to volcanos and coastal areas and demonstrating the possibility of reaching high relative positioning precision and control in very perturbed orbits The use of a 50W REGULUS HPT iodine system is baseline to maintain the formation. The PRR of the mission was completed in November 2023 and PDR is planned for Q3 2024.
GENA-OT 16U CubeSat platform is under development by Orbital Oracle technologies (DE) for IOD/IOV commercial services, including Earth Observation. PDR was completed in October 2023 and Phase C/D is ongoing. The platform uses the Enpulsion NANO FEEP system for Debris Mitigation.

VMMO is an ESA IOD 12U Moon CubeSat mission led by MPB in Canada. It focuses on the acquisition of high-resolution multi-wavelength measurements of the lunar South Pole region. The orbit of VMMO will be such that high-resolution images can be taken (perilune below 75km). Electric propulsion has to ensure orbit acquisition after release from the mother spacecraft and orbit maintenance.

The Miniaturised Asteroid Remote Geophysical 12UXL CubeSat Observer, ***M-ARGO,*** *Figure II-17*, shall demonstrate the capability of a stand-alone deep-space CubeSat to perform rendezvous with a Near Earth Object (NEO) for highly cost-effective in-situ resource exploration. M-ARGO will integrate and demonstrate numerous miniaturised European technologies currently under development, including a high specific impulsive EP and cold gas reaction control system. The spacecraft would be launched to near-Earth escape (e.g. Sun-Earth L2, lunar swing-by, direct escape) by piggybacking on the launch of a larger mission. After separation, the on-board EP system would be used to perform a low-thrust interplanetary transfer over 1-3 years to rendezvous with a suitable NEO target and perform 6 months of close proximity operations to characterise it at high resolution for the presence of hydrated minerals. The M-ARGO propulsion system, called Micro Propulsion System (MiPS), includes cold gas thrusters and a Gridded Ion Engine from MSL (UK). The spacecraft shall be able to generate delta-V of at least 2-3 km/s. The Phase B is ongoing.

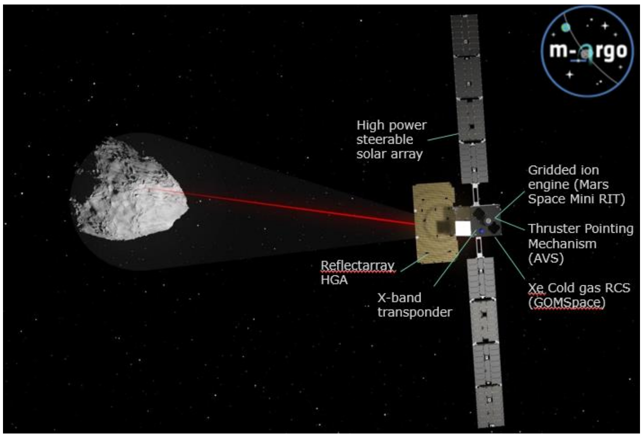


Figure II-17: M-ARGO

The HEliospheric PioNeer for sOlar and interplanetary threats defeNce, ***HENON***, is a pathfinder mission embarking a suit of payloads tailored for Space Weather observations and science. HENON foresees one 12U CubeSat on an unexplored Distant Retrograde Orbit of the Sun-Earth system, so that HENON will spend a long period well beyond L1, allowing for significantly increased warning times. The spacecraft plans to use the same high specific impulsive electric propulsion and cold gas reaction control system of M-ARGO but may include a different quantity of cold gas thrusters. The PDR was successfully completed in November 2023.

SATIS 12UXL CubeSat mission plans to rendezvous with Aphophis two months prior to its close encounter with earth on Friday 13th April 2029 at 315000 km altitude over Atlantic Ocean and to characterise change in physical properties before/during/after close encounter. The spacecraft plans to use the same high specific impulsive electric propulsion and cold gas reaction control system of M-ARGO but may include a different quantity of cold gas thrusters. Phase A study started and PRR is planned for Q3 2024.

E.INSPECTOR 12U CubeSat mission aims at a European debris close inspection, possibly in preparation of future ADR missions. In particular, the main objective of the mission is to inspect a European target and achieving this objective with an imaging payload. The 50W REGULUS-50-I2 electric propulsion system is baseline to perform the transfer to the space debris and cold gas thrusters to perform proximity operation. PDR is planned for May 2024.

IX. ESA Electric Propulsion Technology Harmonisation & Roadmap

Figure II-18: ESA Harmonisation

The process of harmonising and elaborating a future strategy for European space technology was initiated in 2000 in response to the adoption of a Resolution titled "Shaping the future of Europe in Space" adopted at the ESA Ministerial Council in May 1999. The Technology Harmonisation initiative has subsequently been developed to achieve better-coordinated R&D activities among all actors of European space sector and to establish a strong technology base as a key to the worldwide competitiveness of European Industry and to the success of future space missions. It involves establishing a harmonised European Space Technology Roadmap and preparing a European Space Technology Master Plan, through a process of consultation, coordination, harmonisation and agreement between ESA's member states, the European Commission, European Industry and ESA itself.

The main objectives of the Technology Harmonisation initiative are therefore to:

- Fill strategic gaps and minimise unnecessary duplication,
- Consolidate European Strategic capabilities,
- Achieve a coordinated and committed European Space Technology Policy,
- Contribute to continuity and coherence between Technology and Industrial Policies.

The latest Harmonisation process on Electric Propulsion Technologies was concluded in 2023 with the publication of the ESA Technology Harmonisation Dossier on Electric Propulsion reporting the state-of-art of the Electric propulsion technologies, future mission needs, key issues and technology gaps, market perspective and a Roadmap to advance the Electric Propulsion technology in Europe.
In Europe, developments on Electric Propulsion technologies have been carried out in all the different areas of electric propulsion over the last five decades and capabilities exist in all ESA Member States covering conventional and NewSpace market.

Figure II-19 and Figure II-20 provide an overview of he capabilities in Electric Propulsion Technologies in ESA Member states and Figure II-21 provides a global overview of electric thruster supply with Europe focus. 266 electric thrusters are identified at global level, of which 98 are located in Europe

Electric Propulsion has today reached its maturation phase and is increasingly being used in many types of satellites. The most noticeable sign of this trend is the growing inclusion of EP onboard of commercial GEO communication satellites and on LEO mega-constellations of small satellites for orbit raising and all on-station manoeuvres. In parallel, the use of EP is also emerging on satellites for Navigation, Earth Observation, satellites in LEO/VLEO and on science and robotic exploration missions.

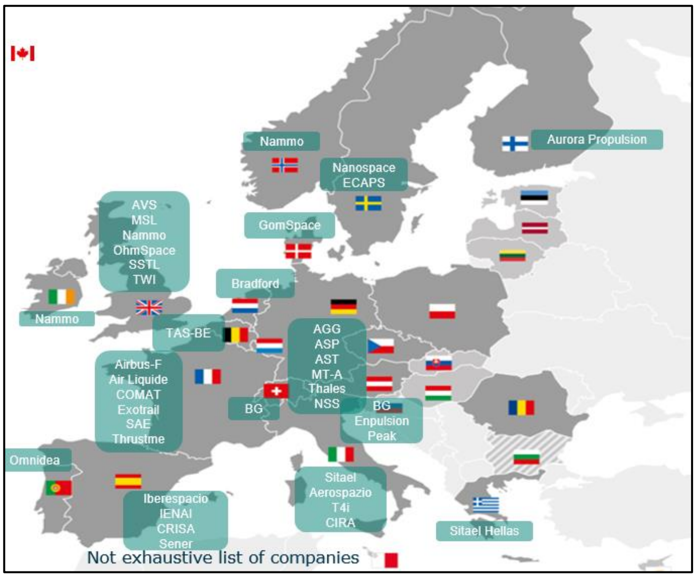


Figure II-19: Suppliers of Electric Propulsion technologies in ESA Member States

The estimate of the European Electric Propulsion market addressable by European suppliers over the decade has been conducted by Euroconsult for ESA. According to this market analysis a total of 1,664 satellites are estimated to be addressable by European suppliers of Electric Propulsion technologies, i.e. 10% of the total market of 17,045 satellites. Over half of addressable satellites (63%) are for satcom (mainly due to OneWeb & Telesat being addressable) and about a quarter (24%) are for Earth observation (driven by smallsat constellations). Satcom and EO combined account for 87% of the EP market (in number of satellites with EP), while the remaining 13% is mainly shared between Science & Exploration, Security, Technology Demonstration (IOD/IOV).

The 1,664 addressable satellites that are electric or hybrid represent a total of 2,600 electric thrusters, of which about three quarters (74%) are known or estimated (i.e. the model/name of the thruster is known or has been assumed), totaling 1,935 known thrusters. Another quarter (26% or 665 thrusters) have yet to be identified and remain unknown, most of them being in the later part of the decade. *Figure II-22* depicts the known/estimated 1,935 thrusters in the various power categories. The additional 665 thrusters that have yet to be identified could be part of any category, and thus represent upside to the figures presented here.

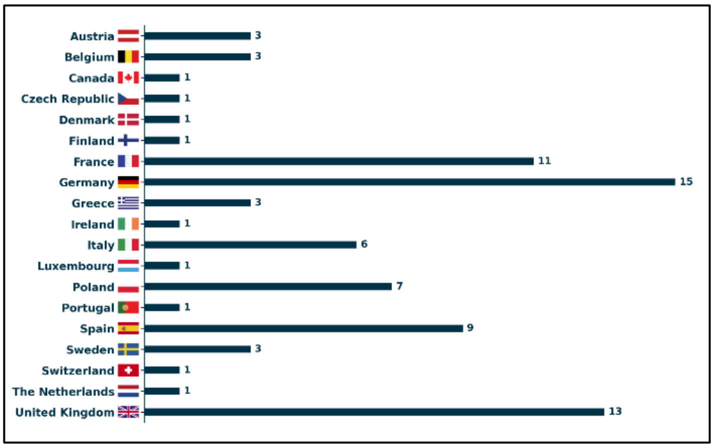


Figure II-20: Number of European entities with confirmed capabilities in Electric Propulsion Technologies

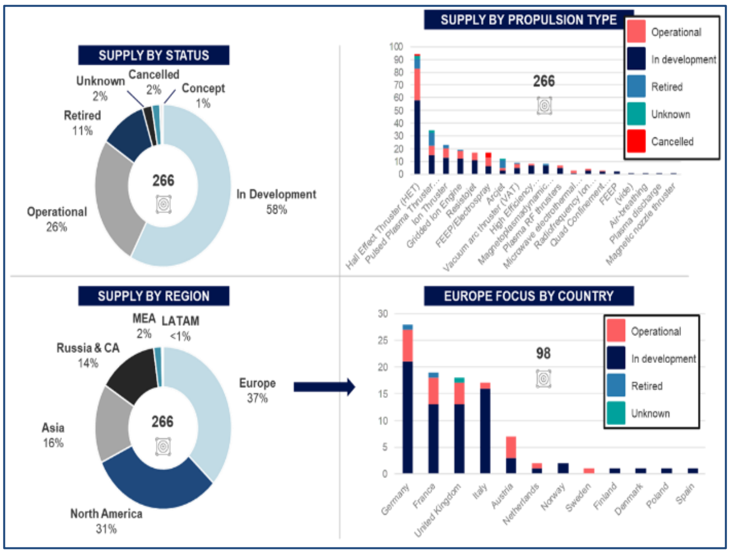


Figure II-21: Mapping of the European Propulsion products (Worldwide vs Europe)

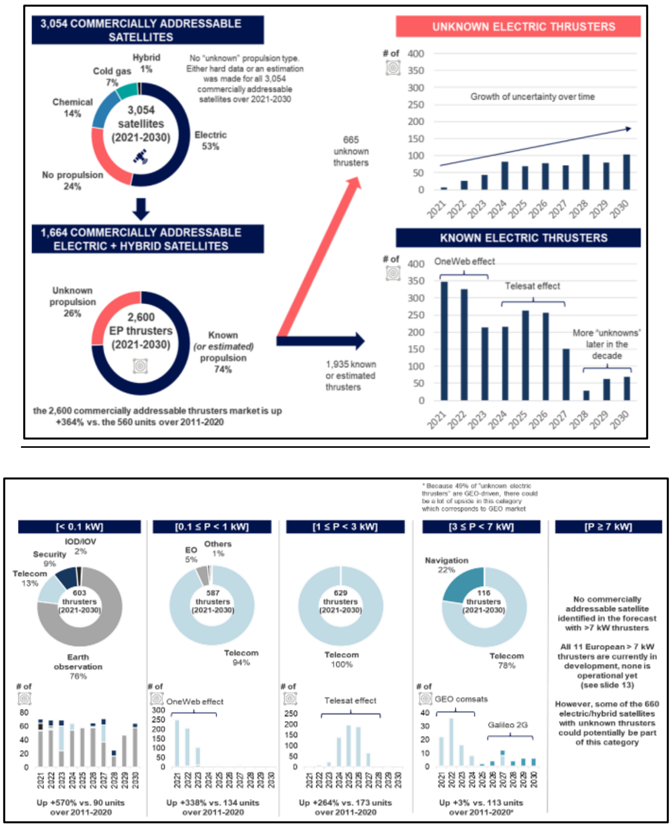


Figure II-22: Market analysis (credit: Euroconsult for ESA)

Taking into account the needs of user programmes and industry and in line with the market analysis results and with ESA general targets driving technology development (Figure II-23), the ESA THAG Roadmap has been defined with the main objectives to:

- Continue on-going developments of European EP technologies targeting performance improvement and on-ground qualification;
- Foster development of innovative, disruptive, cost-effective and mass-producible EP technologies from New Space or Conventional suppliers;
- Increase competitiveness of European EP technologies by ensuring:
    - Low cost

- High performance
- High quality and reliability
- Short time-to-market
- Mass-production
- Demisability

- Guarantee European independence;
- Explore novel test techniques and test methodologies for verification purpose to shorten time-to-market;
- Support technology in-orbit demonstration or in-orbit experiment to complement (not to replace) on-ground qualification.

The 2022 THAG Roadmap proposes 95 new activities, including development of very-low (<100W) to very high (>7kW) electric propulsion thrusters, Power Processing Units, fluidic components and pointing mechanisms, in addition to models/codes, MAIT facilities, GSE, diagnostics, and IOD and flight data exploitation studies for generation of lessons learnt.

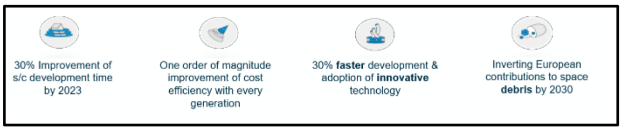


Figure II-23: ESA technology targets.

X. ESA R&D ACTIVITIES ON ELECTRIC PROPULSION

ESA, through its various technology development programs (e.g. TDE, GSTP, Incubed, ARTES, etc..) is supporting European Industry in developing and maturing innovative and disruptive electric propulsion technologies having the potential to enable new missions.

Figure II-24: Implementation of ESA Roadmap into Technology Programs Workplans

ESA short/mid-term priorities identified in the Harmonisation Roadmap are addressed in TDE, GSTP Compendia and ARTES AT Workplans and are complemented by ESA Projects-led developments, GSTP Element 1 (Develop) & Element 2 (Make) & Element 3 (Fly/IOD Cubesats) programs, ARTES C&G & Pioneer programs, Incubed program, HE/NAV Workplan.

Over 120 R&D activities dedicated to electric propulsion technology development were approved in the period 2017-2022 for a cumulative budget of almost 130 M€. Most of those activities targeted development and qualification of electric propulsion technologies for GEO telecommunication platforms and Exploration.

Ongoing developments target application on next generation GEO telecommunication platforms, on constellations of Telecommunication and Earth Observation small satellites operating in Low Earth Orbits, on Europe's Galileo 2nd Generation Navigation satellites, on Next Generation Gravity missions like NGGM, on Exploration missions like Mars Sample Return and on several CubeSat missions for different applications.

Priorities are given to developments targeting:

- Ground qualification of **5-7kW HET/GIE systems** for GEO Telecom, Navigation, Space Transportation and Exploration missions,

- Ground qualification of **<1kW EP systems** for LEO constellations,
- **Non-dependence** and **dual source** for critical/strategic technologies,
- Maturation of **CubeSat Electric Propulsion systems** for 6 DoF and high dV,
- Maturation of Air-Breathing Electric Propulsion (**ABEP**) systems for VLEO application,
- Development of Electric Propulsion systems operating with **propellants alternative** to costly xenon (iodine, krypton, argon, etc..),
- Design for **demise** to comply with new Space Debris Mitigation.

XI. EPIC

The European Commission has heavily invested in Electric Propulsion and contributed "*to guarantee the leadership of European capabilities in electric propulsion at world level within the 2020-2030 timeframe*" via their HORIZON 2020 grant titled "Electric Propulsion Innovation and Competitiveness", in short EPIC.

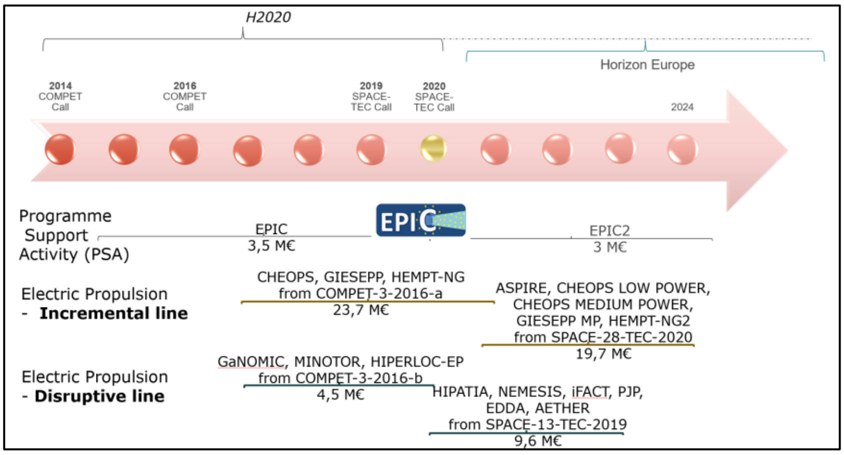


Figure II-25: EPIC Timeline

EPIC, recently completed, was coordinated by ESA and partners were from main National Space agencies and associations representing the industry. EPIC prepared the Strategic Research Cluster (SRC) on Electric Propulsion roadmap and accompanied the Commission in preparation of Call topics and in follow up of operating grants results. The SRC objective was to strengthen the European EP scene and run two lines of development: Incremental line (HET, GIE and HEMPT technologies), and Disruptive line (all other thruster concepts and new supporting technologies). Projects from the Incremental line (HET, GIE and HEMPT) targeted to reach TRL 6-7 by 2023-2024 for the Low and the medium power ranges, and TRL 5-6 for the High Power. The timeline and budget of the EPIC grant is depicted in Figure II-25.

The following disruptive grants were recently completed:

- HIPATIA – Helicon Plasma Thruster
- NEMESIS – new electrical material for cathodes
- iFACT – Advanced Cusp Thruster on iodine
- PJP – 30W Vacuum Arc Thruster
- EDDA – Direct Drive architecture for HET & HEMPT-based systems
- AETHER – Air breathing HET/GIE sub-system.

The following incremental grants are under completion:

- ASPIRE – 20kW HET system with direct Drive Power Unit
- CHEOPS LP – Low Power up to 1kW HET
- CHEOPS MP – Medium Power HET – Dual mode for orbit raising (5-7kW) and Station keeping (3kW)
- GIESEPP MP – Medium Power Gridded Ion Engine – Dual mode OR & SK up to 5kW
- HEMPT-NG2 – High Efficiency Multistage Plasma Thruster – 700W Low Power class.

XII. INNOVATIVE PROPULSION CROSS CUTTING INITIATIVE (IP-CCI)

The Innovative Propulsion Cross Cutting Initiative (IP-CCI) responds to the directions set by the Agenda 2025 and ESA's Technology Strategy to foster disruptive propulsion technologies and systems. Under this premise, the IP-CCI follows past and ongoing cross cutting initiatives at ESA by focusing on particular themes of interest for the future of the space industry, taking into account the needs of user programs and industry and exploiting the potential of innovative propulsion technologies across the complete R&D life cycle.
The objectives of the IP-CCI are:

- To identify and support the strategic interest of ESA member states, industry and academia.
- To stimulate the propulsion ecosystem of the ESA member states.
- To formulate roadmaps establishing the steps needed to increase the Technology Readiness Level (TRL), to implement IOV / IOD missions, to foster research, development and testing capabilities and to demonstrate applications and services.
- To provide an increased visibility (internal and external) on innovative propulsion activities for space.

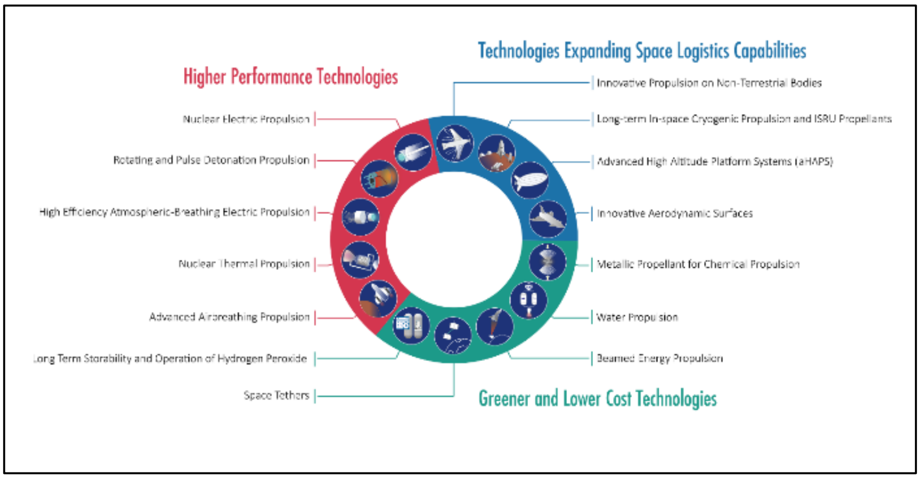


Figure II-26: IP-CCI technologies

The **IP-CCI targets three technology groups of higher performance technologies, greener and lower cost technologies and technologies expanding the space logistic capabilities. Belonging to any of these technology groups, an overall of 14 technologies are identified which, by definition, do:**

- Bring a significant positive benefit in terms of mass, performance, cost and flexibility.
- Are at low TRL yet enough (>TRL2) to be engineered and demonstrated in a medium term.
- Enable new missions or applications.
- Facilitate the creation of new markets.
- Enhance the reliability and competitiveness of European propulsion and flight vehicle products.

Out of the total 14 technologies, 3 electric propulsion technologies are addressed by the IP-CCI:

- High Efficiency Atmospheric-Breathing Electric Propulsion to enable operation in Very Low Earth Orbit (VLEO) at altitudes in the [150, 250] km range for an extended duration without using on-board propellant,
- Space Tethers for de-orbiting, orbit raising and interplanetary transfer,
- Nuclear Electric Propulsion for crewed or cargo deep space missions and/or Earth-Moon / Earth-Mars space tug.

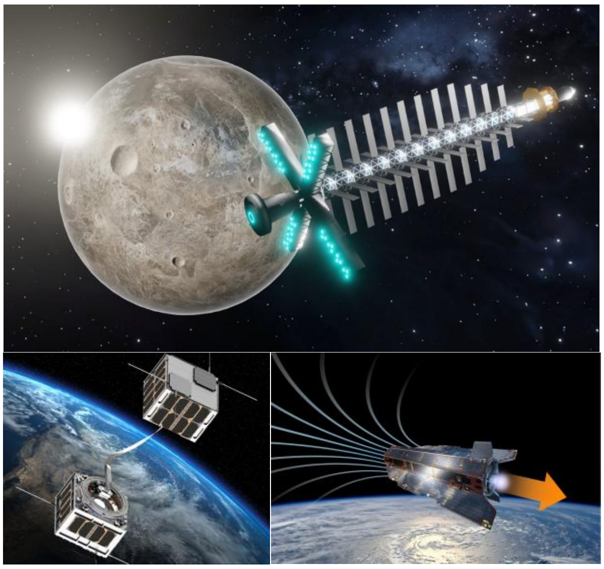


Figure II-27: IP-CCI EP technologies (Nuclear Electric Propulsion, Space tethers and ABEP)

The IP-CCI is implemented by an IP-CCI core team of the Propulsion, Aerothermodynamics, and Flight Vehicles Engineering Division in the ESA's Directorate of Technology, Engineering and Quality (TEC-MP).
During 2023 and 2024 the IP-CCI progressed in three phases. In a first phase, a draft of a white paper was elaborated by the core team upon consultation with experts from ESA user directorates. In a second phase, workshops were held around each identified innovative propulsion technology with participants from industry (suppliers & users), academia, research institutes / centers and National Agencies from ESA Member States.
In a third phase, a compendium to the GSTP work plan specific to innovative propulsion technologies is prepared and reviewed by the application programs, the Delegations from the GSTP Participating States and their industries.

XIII. Handbook on Cubesat Propulsion

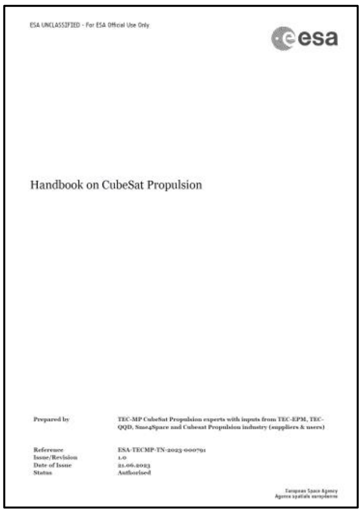
ESA has setup an internal CubeSat Propulsion Working Group composed by chemical & electric propulsion experts with the objectives to generate tailoring of existing ECSS Engineering standards for operational, demonstration & educational CubeSat mission types and to generate Engineering Guidelines for CubeSat Propulsion.
An Handbook on CubeSat Propulsion has been prepared by this Working Group with inputs collected during the Workshop organized by ESA in 2021 on Propulsion4Cubesats, and provided by Sme4Space and by several European CubeSat Propulsion Space Entities (suppliers and users).

The Handbook is intended to provide guidance and recommendations for how the engineering work should be carried out, particularly to help external entities in reducing/eliminating known technical problems/issues/risks from occurring/recurring during the development of Propulsion Systems for CubeSats, and to outline how they can meet ESA's expectations as customer/technical manager of the projects.

More specifically, the scope of the Handbook is to highlight best practices specific to CubeSat propulsion developments for the following aspects:

- Requirements Definition: main requirements to include in the CubeSat Propulsion System Technical Requirement Document (TRD)
- Design Definition and Consolidation: critical elements for design process, margins and design outputs (for ESA reviews)
- Analysis: scenarios to be analysed, models, assumptions, analysis outputs (for ESA reviews)
- Inspection: methods and outputs.
- Testing: test objectives, test sequence for qualification and acceptance test, test models, setups, GSE, facilities, test data outputs, approach to life verification (for ESA reviews)
- Recommendations for Materials and Components Selection
- Recommendations for Propulsion AIT activities on CubeSats
- Recommendations for Management of ESA Reviews: reviews to be held, list of deliverables per review and content of deliverables.

The Handbook on Cubesat propulsion has been made available to all European space entities.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Handbook on CubeSat Propulsion

Prepared by	TEC-MP CubeSat Propulsion experts with inputs from TEC-EPM, TEC-QQD, Sme4Space and Cubesat Propulsion industry (suppliers & users)
Reference	ESA-TECMP-TN-2023-000791
Issue/Revision	1.0
Date of Issue	21.06.2023
Status	Authorised

European Space Agency
Agence spatiale européenne

Figure II-28: Handbook on CubeSat Propulsion

XIV. ESA Propulsion Laboratory

The ESA Propulsion Laboratory (EPL) is located at the European Space Research and Technology Center (ESTEC) in Noordwijk, the Netherlands.

Figure II-29: ESA Propulsion Laboratory

The main purpose of EPL is to provide test services to ESA projects that require independent and fast assessment of propulsion technologies, including performance characterisation and endurance testing. ESA projects like BepiColombo, Lisa Pathfinder, M-ARGO, NGGM, GAIA and EUCLID have used or are currently using EPL test services.
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. Another example is the involvement of the laboratory in the development of the electric propulsion system for the NGGM mission. In addition, EPL provides support to ESA R&D programs by performing test aiming at early validation of performance of propulsion systems and equipment.
In the last few years, several tests devoted to the development of new thrusters for LEO smallsat constellations have been and will continue to be hosted by the laboratory. Several test have been performed also on novel electric propulsion systems for CubeSats and MicroSats.

EPL features:

- Certification of ISO 9001
- Cleanroom ISO Class 8 capability (eq. to class 100,000)
- Seismic block for background noise isolation
- 7 vacuum facilities dedicated to electric propulsion testing, 1 compatible with iodine propellant
- Beam targets reducing on-ground testing disturbances
- High-speed, high-resolution data acquisition systems
- 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
- 1 Cubesat propulsion Test Bench
- 1 thermal shroud for End-to-End thermal cycles of Electric propulsion systems for Cubesats in operation.

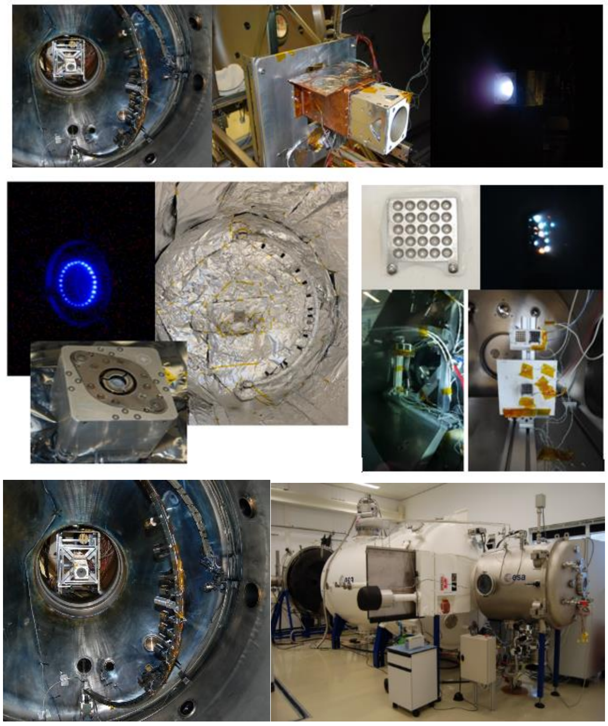

Figure II-30: recent test at EPL

XV. Conclusion

Electric Propulsion (EP) is considered by the European Space Agency strategic technology for improving the European competitiveness in space and to enable emerging space applications.

Europe has extensive heritage in developing EP technologies and European players are well positioned in the worldwide landscape. European EP successes include several GEO Telecommunication platforms like ARTEMIS, AlphaSAT, Eurostar E3000, Spacebus 4000, SmallGEO, Spacebus NEO and Eurostar NEO, the ESA's GOCE mission, the ESA-JAXA BepiColombo mission and the ESA's SMART-1 mission.

Ongoing developments of Electric Propulsion technologies target application on next generation GEO telecommunication platforms and on several mega-constellations of communication and Earth Observation satellites being launched to Low Earth Orbit, on Europe's Galileo 2nd Generation navigation satellites, on Next Generation Gravity Missions and on exploration missions like Mars Sample Return.

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.

Europe has excellent capability in Electric Propulsion. However, European suppliers must achieve maturation of their products via on ground qualification, significant reduction in prices and increase in production volume to build and retain leadership in the future.

Development of innovative and breakthrough Electric Propulsion technologies are also pursuit to enable new application in Very-Low Earth Orbit for communication and Earth Observation (e.g. with use of air-breathing EP) and for exploration and/or future robotic/human space transportation (e.g. with use of very high-power EP).

The ESA Propulsion Laboratory (EPL) is an important tool to aid the development of electric propulsion in Europe.

The ESA Roadmap on Electric Propulsion technologies has been defined with all European stakeholders to answer the need:

- To mature strategic EP technologies via on ground qualification,
- To increase competitiveness by ensuring low price, high performance, high quality and reliability, fast time-to-market, mass-production, demisability,
- To develop innovative, disruptive, cost-effective and mass-producible EP technologies from New Space or Conventional suppliers;
- To guarantee European independence of supply chain and dual source of strategic elements,
- To explore novel test techniques and test methodologies for verification purpose to shorten time-to-market;
- To support technology in-orbit demonstration or in-orbit experiment to complement (not to replace) on-ground qualification.

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