Electric Propulsion at the European Space Agency (ESA)

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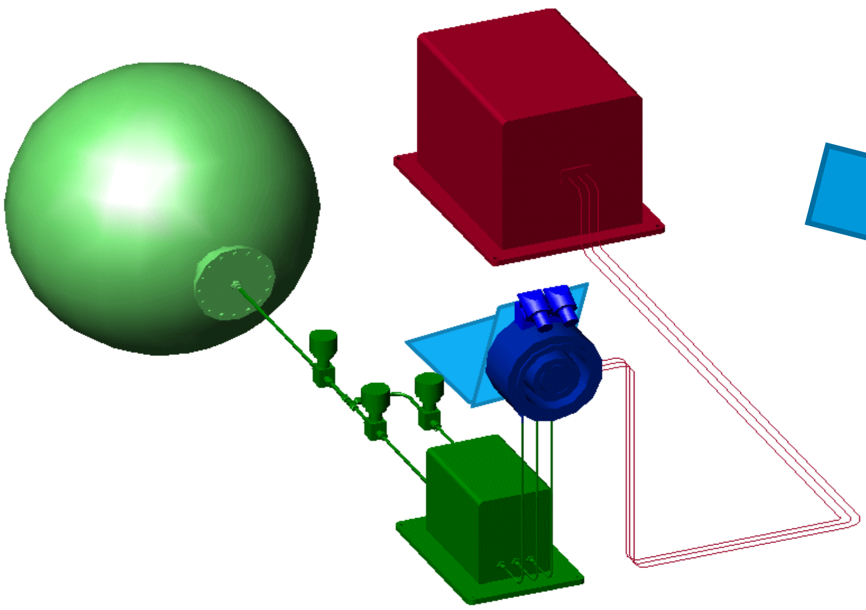
ESA, 30 June, 2020

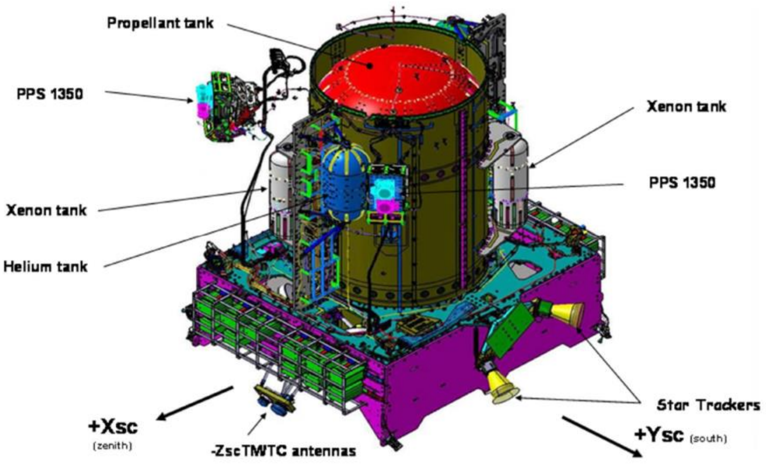
Dresden (Germany)

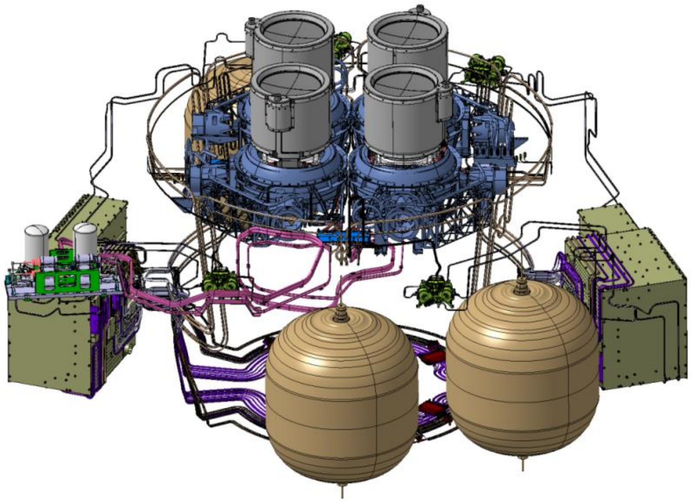
Presentation Overview

Electric Propulsion Systems

Propellant Storage
Fluidic Control
Power Conditioning
Pointing Mechanism
Thruster







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Introduction:
Electric Propulsion

- In general, Electric Propulsion (EP) encompasses any propulsion technology in which electricity is used to produce thrust.
- Electrical energy is used to ionize the propellant (gas, liquid, solid) and accelerate the resulting ions/plasma to very high exhaust velocities (10-40km/s)
- Electric Propulsion is very fuel efficient, but much lower thrust levels achievable than for chemical propulsion.
- Depending on the process used to accelerate the propellant, electric propulsion thrusters fall into three main categories.

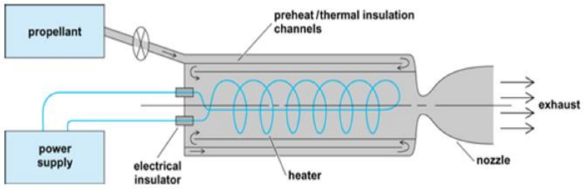
- **Electrothermal**
  - **Resistojets***
  - **Arcjets***

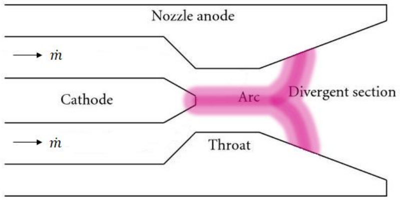
- **Electrostatic**
  - **Gridded Ion Engines (GIE)***
  - Colloid
  - Field Emission Electric Propulsion (FEEP)

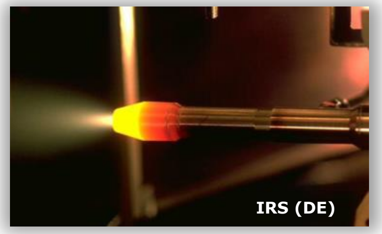
- **Electromagnetic**
  - **Hall Effect Thruster (HET)***
  - **High Efficiency Multistage Plasma Thruster (HEMPT)***
  - Pulsed Plasma Thrusters
  - Magneto Plasma Dynamic Thrusters

***Applicable for GEO satellite propulsion**

Electrothermal Thrusters: Resistojets / Arcjets



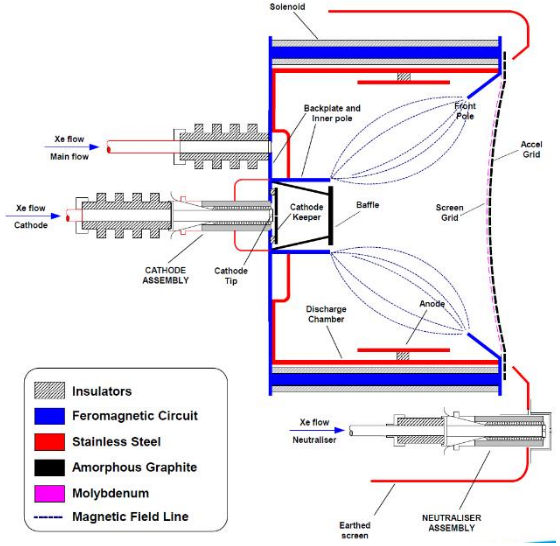


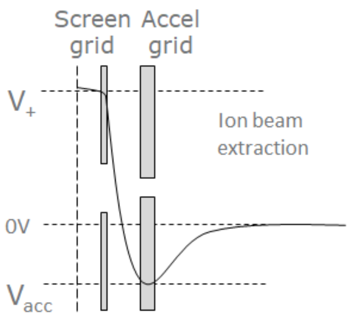


- Resistojets are electrothermal devices in which the propellant is heated by passing through a resistively heated chamber or over a resistively heated element before entering a downstream nozzle.
- The increase in exhaust velocity is due to the thermal heating of the propellant, which limits the specific impulse to low levels (<500 s).
- Resistojets are relatively simple devices and can be used as auxiliary propulsion on satellites.
- The amount of energy added to the flow in a resistojet is limited by the maximum working temperature of the heating element.
- In an Arcjet thruster, an electrical discharge (arc) is generated within the flow between a cathode and anode. This imparts additional energy to the propellant flow, and therefore, higher specific impulse is achievable compared to resistojets.

Electrostatic Thrusters: Gridded Ion Engines (GIE)

- Gridded Ion Engines comprise three main processes:-
  - Generation of a plasma discharge via ionization of propellant by electron bombardment.
  - Extraction of ions and subsequent acceleration to very high velocities across potentials of few kV applied between multi-aperture grids (electrodes).
  - Space-charge neutralization of the ion beam using an external electron source (cathode)





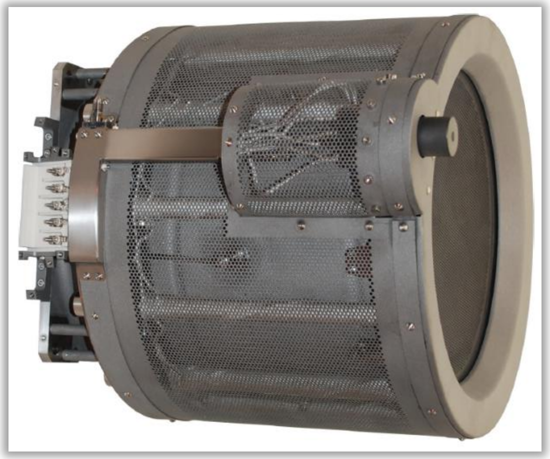


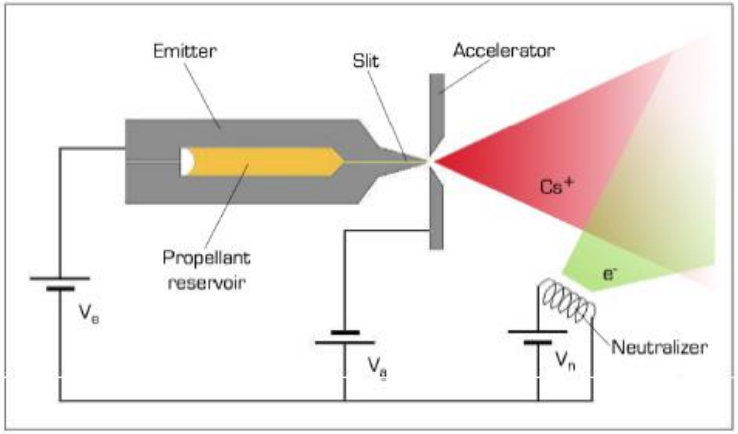
Image: QinetiQ

Electrostatic Thrusters:
Field Emission Electric Propulsion (FEEP)

FEEP is an electrostatic type thruster:

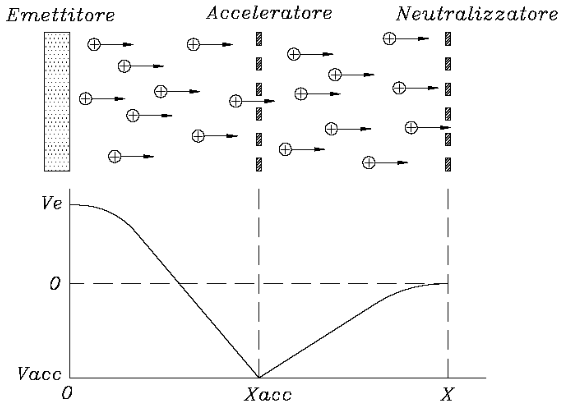
⇒ thrust is generated by ions accelerated by electric fields at high exhaust velocities;

⇒ electrons need to be emitted downstream in the same quantity for charge balancing.



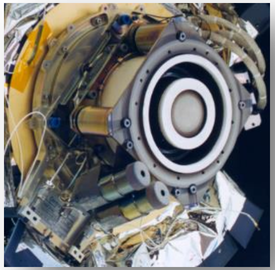
$$qV_e = \frac{1}{2} M v_e^2 \Rightarrow v_e = \sqrt{\frac{2qV_e}{M}}$$

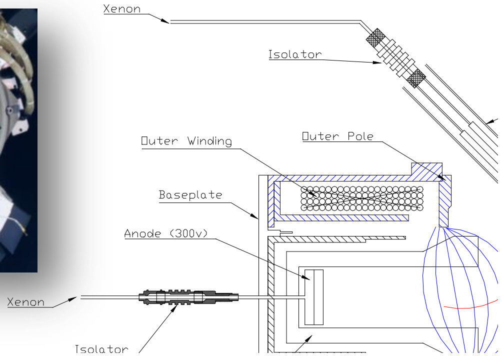
$$\dot{m}_i = \frac{M I_b}{q} \qquad I_b = I_e - I_a$$

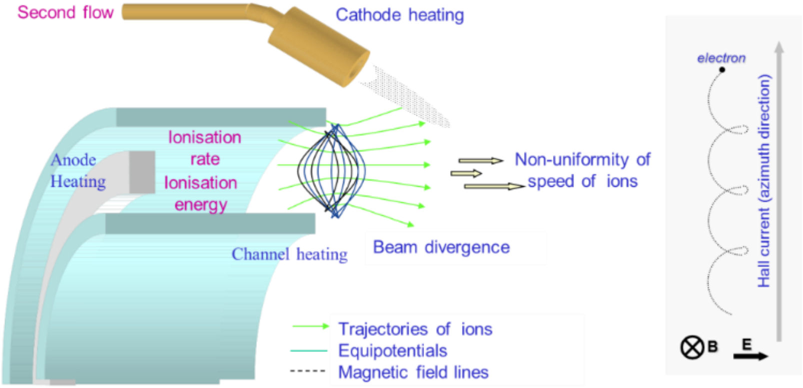


Electromagnetic Thrusters: Hall Effect Thruster (HET)

- Neutral gas supplied to hollow cathode and fed through anode at base of discharge chamber.
- Potential difference applied between cathode and anode.
- Electromagnets generate radial magnetic field in discharge channel.
- Electrons are magnetized; follow field lines and enter discharge channel towards anode.
- E x B field causes azimuthal drift of electrons around axis of thruster → circulating hall current.
- As neutrals diffuse into discharge channel, they are ionized by high energy electrons.
- The more massive ions are not magnetized and are accelerated out of the discharge channel by the electric field.
- Equivalent number of electrons emitted by cathode → space charge neutral plasma plume







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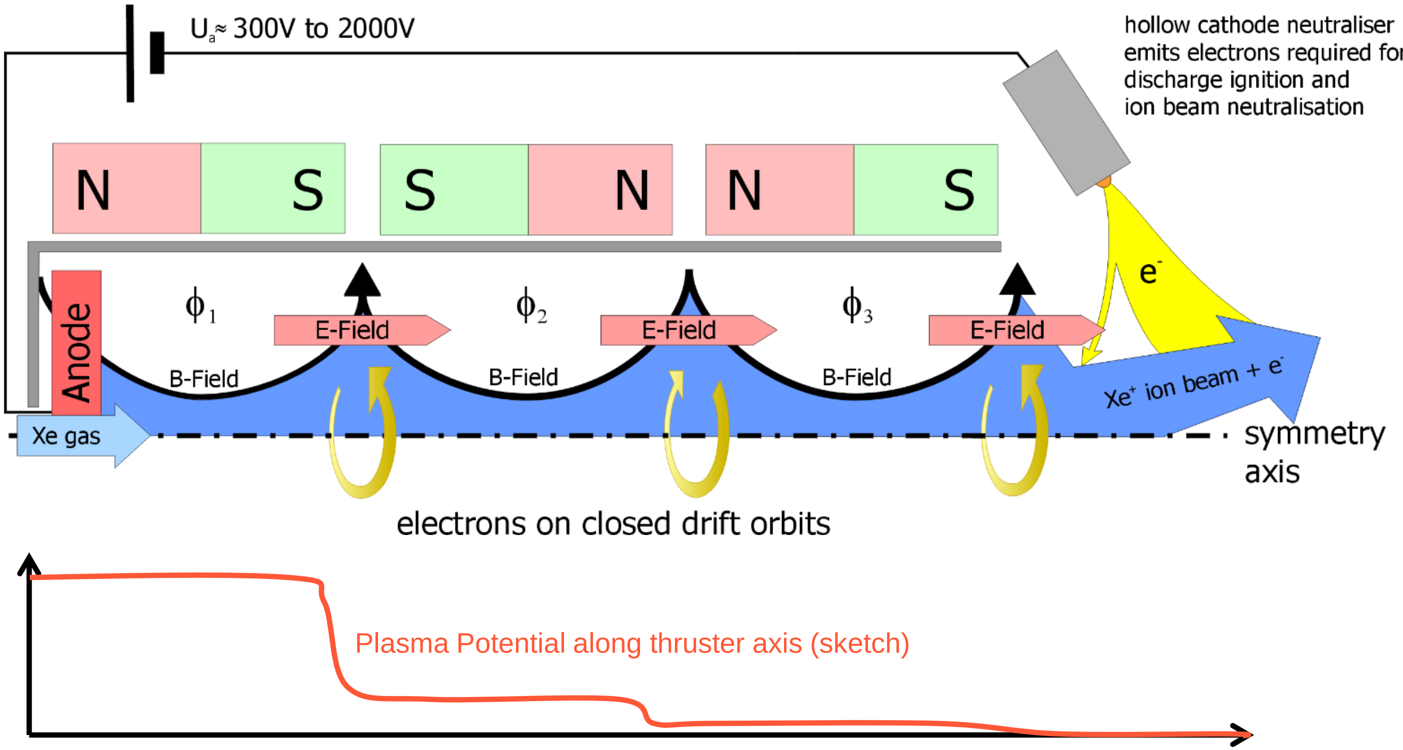
Electromagnetic Thrusters:
High Efficiency Multistage Plasma Thruster (HEMPT)



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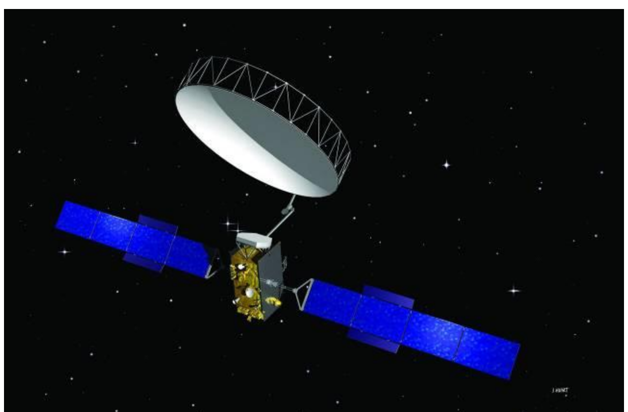
Commercial Spacecraft, ESA initiatives,



1. ESA **Artemis** satellite using 4 ion engines (2 RIT and 2 UK-10) has paved the way for the use of electric propulsion in telecommunication spacecraft.

1. Airbus with several spacecraft launched (4 **Inmarsat,** 1 **Intelsat and 1 Yasat** satellites, …) and many more satellites in construction has the most important experience in Europe in integration of Electric Propulsion Systems.

1. Airbus and Thales have demonstrated their capability to integrate this technology in GEO satellites. The ESA **Alphasat** spacecraft has used PPS1350 for NSSK operations. Alphabus evolution will also consider Electric propulsion for future missions.

2. **Small GEO** satellite has 4 Hall Effect thrusters, SPT-100,

3. **NEOSAT and ELECTRA** will have EP for station keeping and ORBIT RAISING manoeuvres. FULL EP SPACECRAFT (PPS5000). Airbus and Thales will use the HET technology in Eurostar and Spacebus platforms.

Telecommunication Applications
Future Architectures

- The use of Electric Propulsion in the telecommunication space market is essential to improve the position of the European space sector. The announcement of Boeing in 2012 on the procurement of 4 telecommunication spacecraft (platform 702SP) , offered for only 125 million dollars each including launch, thanks to the use of electric propulsion for both NSSK and orbit raising from GTO to GEO, has been noted by European operators and primes. The launch of the first 2 spacecraft took place on the 1 March 2015.

- ESA is now fully involved in the preparation of several telecommunication programmes (**NeoSat, Electra)** that will make use of electric propulsion for all the key maneuvers, paving the way for the commercial use of all-electric platforms by the primes Astrium, Thales and OHB Systems.

- Eutelsat and SES have bought in the last years several spacecraft using electric propulsion as main system for orbit raising and station keeping operations.

- Boeing selected the Falcon 9 for the launch of these spacecraft. Current and future European launchers will need to be capable to optimise their performances, interfaces and operations to offer the best launch options to new all-electric platforms.

Full-EP platforms for EOR & STK

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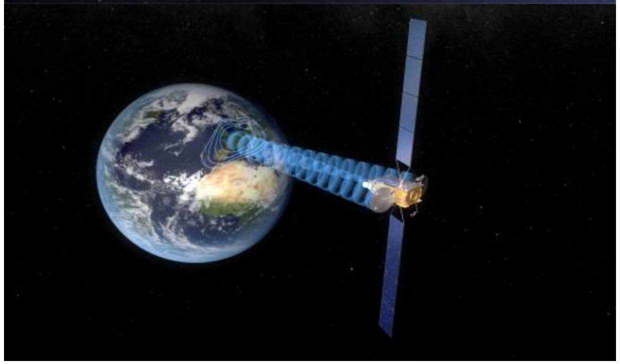
1. HET-based subsystems are currently the preferred choice by European Primes for full-EP telecomm platforms (higher Thrust-to-Power ratio offering reduced EOR duration)

- However other architectures selected by non-European Primes (for example, Boeing 702SP platform used XIPS (GIE); Boeing have also recently selected PPS5000 for a commercial program and are developing a RIT-2X subsystem jointly with ArianeGroup).

- NEOSAT (ARTES-14) → successful sales of Eurostar NEO and Spacebus NEO

- Electra (ARTES-33) → targeting small-GEO platforms



Telecommunication Applications Existing Platforms

With the exception of ESA's ARTEMIS platform all European commercial platforms utilize Hall Effect Thruster Technology.

Platform	Prime Contractor	Status	Platform Mass Range (tonnes)	Platform Power Range (kW)	EP Function	EP Thruster	EP Thruster Type
ARTEMIS	Thales Alenia Space-Italy	Flight Proven	3.0	3.0	NSSK (OR during recovery)	2 X UK-10 (T5) 2 X RIT-10	GIE
Eurostar E3000	Astrium	Flight Proven	4.5 – 6.0	9 - 16	NSSK	4 X SPT-100	HET
SpaceBus	Thales Alenia Space	Flight Ready			NSSK	4 X PPS-1350G	HET
AlphaBus	Astrium / Thales	Flight Proven	6.0 – 6.5	12 - 18	NSSK	4 X PPS-1350G	HET
AlphaBus Extension	Astrium / Thales	Flight Proven	<8.4	12-22	NSSK, Orbit Topping	4 X PPS-1350G 4 X PPS-1350G OPTION T-6	HET/GIE
SGEO	OHB	PFM 2014	3.2	6.5	NSSK, EWSK, Momentum Management	8 X SPT-100 Or 8 X HEMPT	HET
NEOSAT	Airbus/Thales	flying	3-6	15- 25	NSSK, Orbit Raising	4XPPS5000	HET
ELECTRA	OHB	Under Development	3.2	7	NSSK, Orbit Raising	4XPPS5000	HET

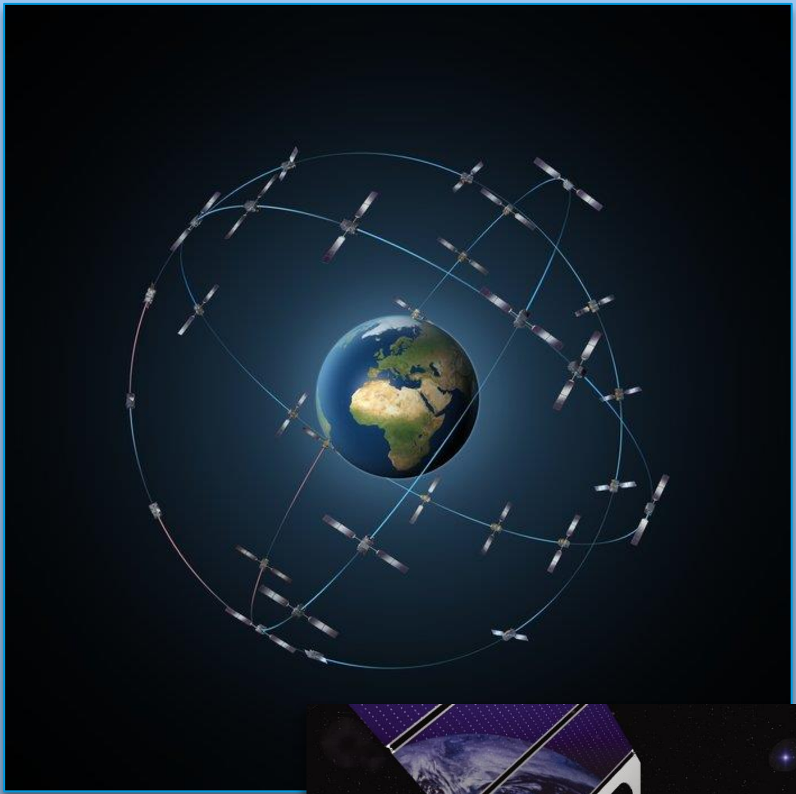
Navigation – Galileo 2nd Generation (G2G)

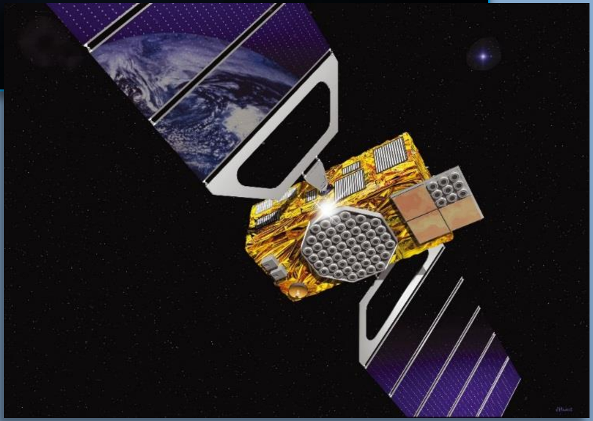
- ESA is preparing the future replacement of GALILEO constellation and is targeting the possibility to increase the Galileo Payload capability without impacting the launch costs (and possibly reducing them).

- The increase in payload capability could be achieved by changing the launch injection strategy and by using Electric Propulsion to transfer the satellite from the injection orbit to the target operational orbit.

- The use of the Electric Propulsion system might allow to use small launchers such as VEGA or place more spacecraft in the current SOYUZ and Ariane 5 launchers.

- GIE and HET subsystems are currently considered for the transfer by the selected Primes of Phase A/B1.





Commercial Spacecraft: Constellations

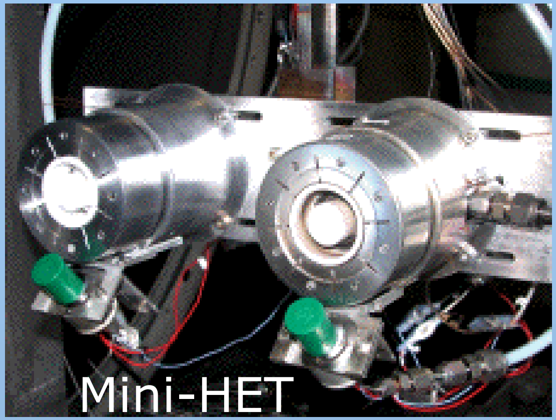
1. Space X: .12000 spacecraft using mini-HET
2. OneWeb: > 700 spacecraft may also use electric propulsion
3. Others (Leosat, etc.)

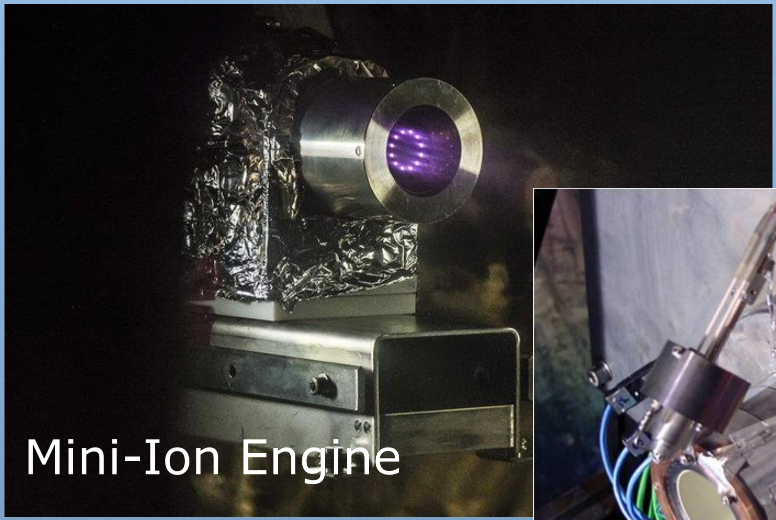
Constellations will use propulsion to perform;

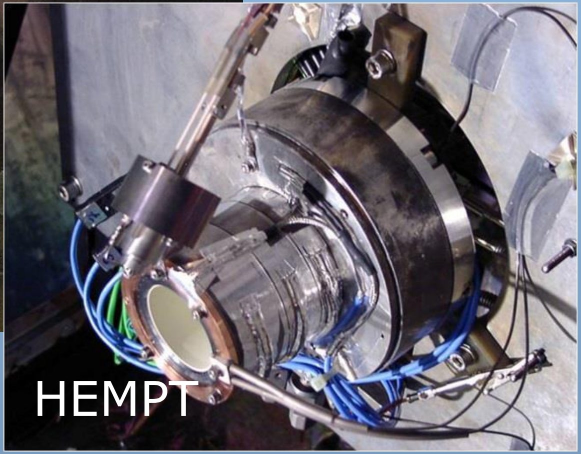
- orbit acquisition, maintenance and de-orbiting from low earth orbit (around 600 -1000km)

Satellites

- ~ 200 kg with
- powers for propulsion ~ 200 W.
- Mini-HET is one of the most interesting options.
- Spacecraft cost around 500 000 $
- the propulsion system (thruster ~15 000 $ and electronics ~25 000 $)



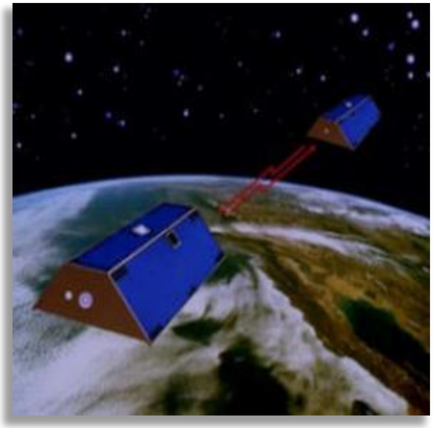




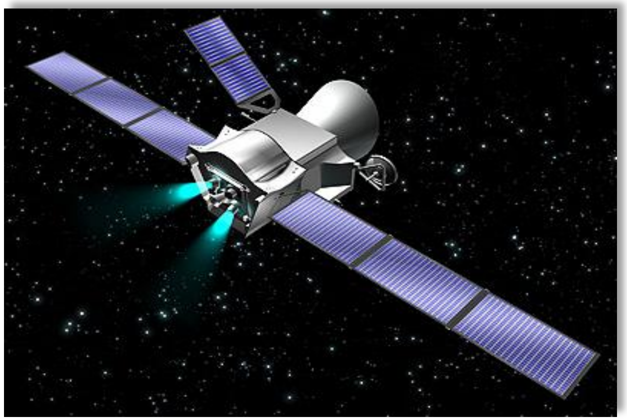
Science & Earth Observation

GOCE

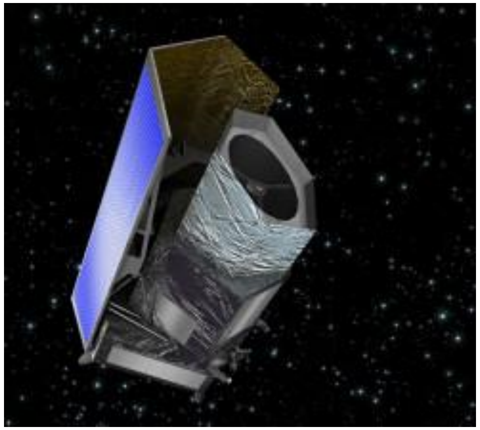
Smart-1



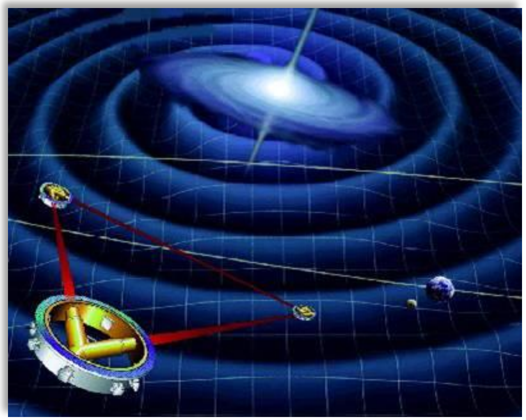
NGGM



Bepi-Colombo

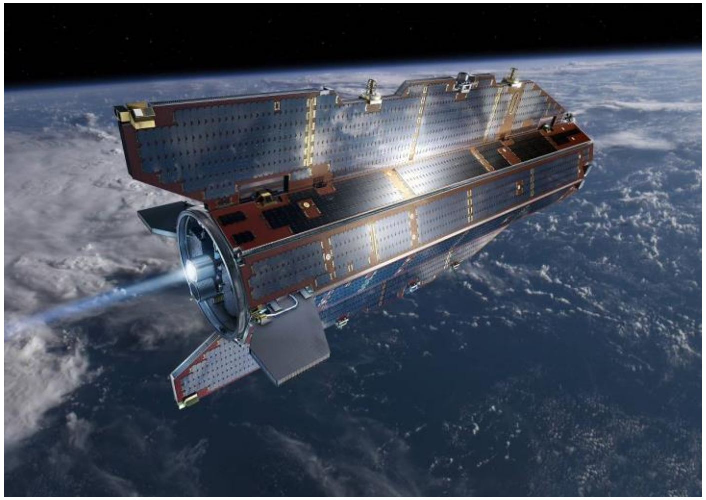


Euclid



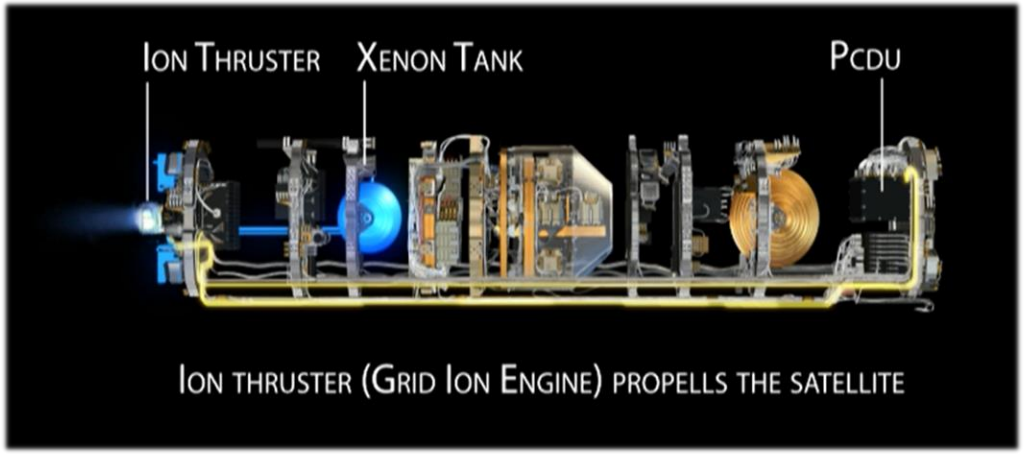
LISA

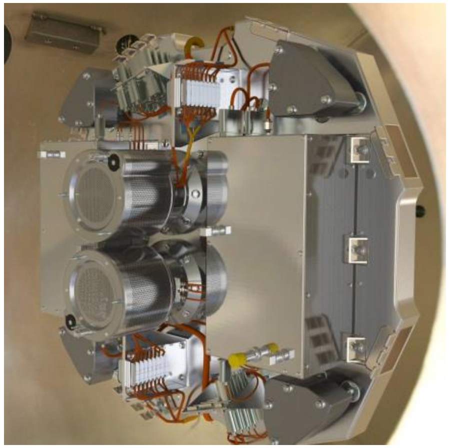
GOCE: 'Ferrari of space' Mission Complete



After nearly tripling its planned lifetime, the Gravity field and steady-state Ocean Circulation Explorer – GOCE – completed its mission in October 2013

In mid-October, the mission came to a natural end when it ran out of fuel and the satellite began its descent towards Earth from a height of about 224 km.



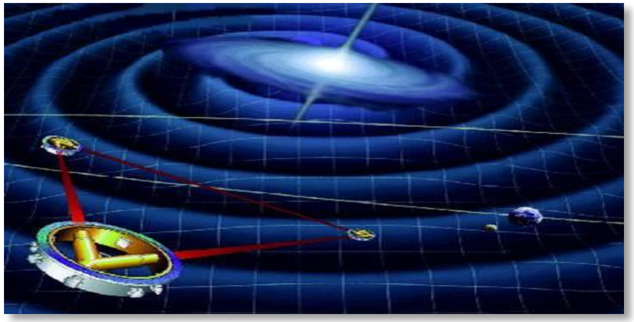


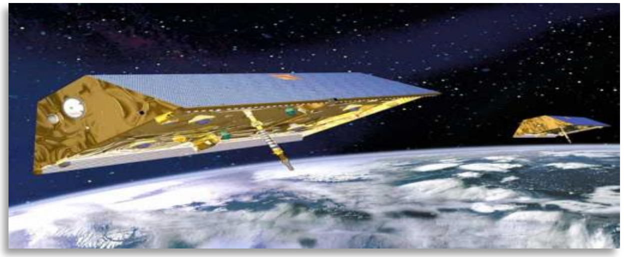
Air-Breathing Electric Propulsion: History ESA developments

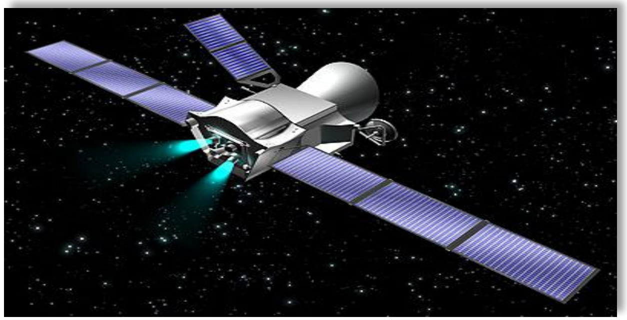
1. In 2007, an high level ESA-CDF feasibility study concluded that to compensate the drag of a spacecraft operating at altitudes as lower as 180 km, a ram-EP concept, could be a feasible solution. As such lift-times can become far longer than with conventional electric thrusters today.

2. In 2010, under TRP contract, two test campaigns were carried out on Snecma's PPS1350 Hall Thruster and on RIT-10 ion engine for performance characterization with atmospheric propellants:
    a. HET and RIT technologies are compatible with N2/O2 mixture, which is of interest for RAM-EP applications in LEO (200-250 km).
    b. The thruster lifetime and lifetime prediction are strongly affected by corrosion/erosion phenomena. However, with the appropriate choice of materials, the lifetime can still be in the 1000-10000 hours range.

Science & Earth Observation



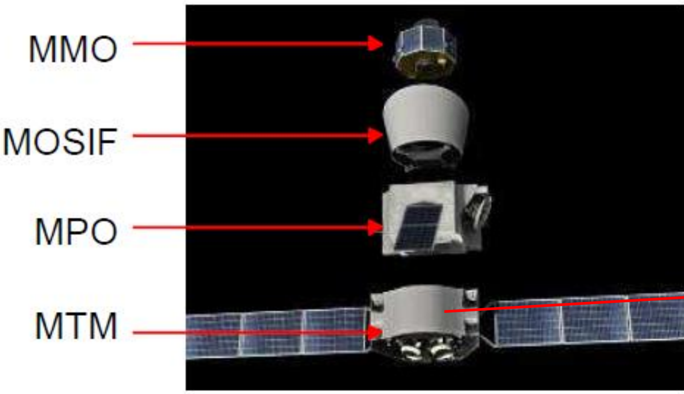


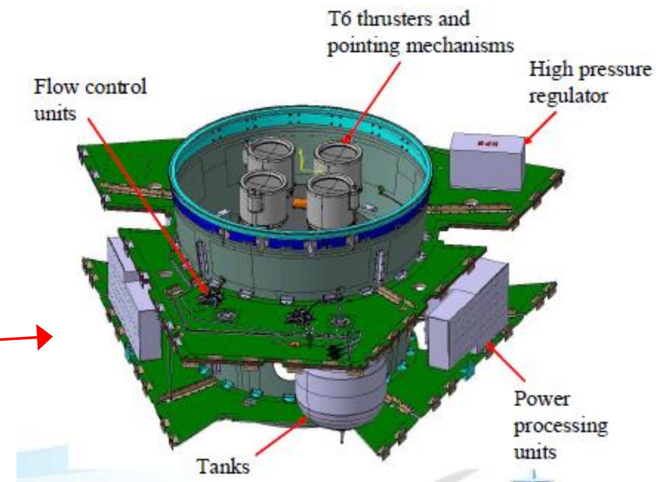


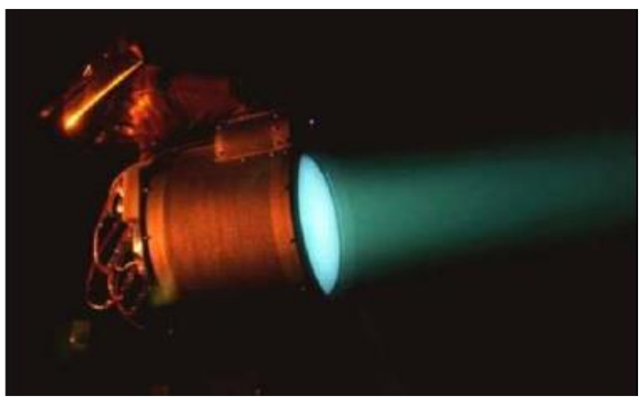
Future Needs

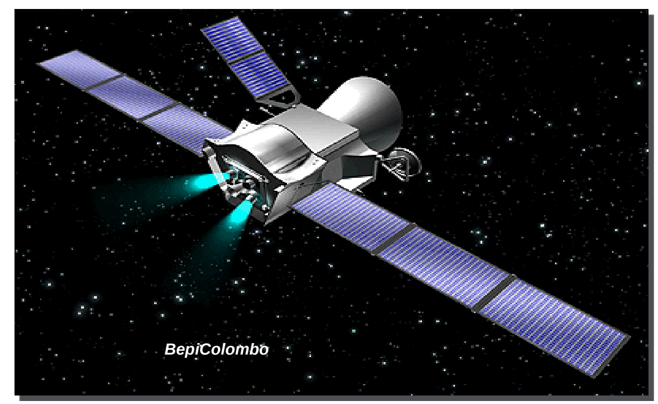
- Next Generation Gravity Missions, NGGM, will require Mini-ion Engines and micro-field emission thrusters to provide drag compensation and formation control.
- LISA class missions will require micro thrusters for ultra-fine formation control. Mini-ion engines, cold gas and field emission engines are the main candidates.
- Future asteroid, rendezvous or planetary missions will require high ISP thrusters for cruise to the target object.
- Remote sensing and science missions using formation flying will need electric propulsion for formation control.

Bepi Colombo mission to Mercury









Science and Earth Observation Electrical Propulsion Developments and Challenges

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Where are we today?

- Electric propulsion has taken us to the Moon (**SMART-1**) and is allowing us to measure the Earth's gravitational field with unprecedented accuracy (**GOCE**).
- Electric propulsion is planned to take us to the planet Mercury (**BepiColombo**)
- Small constellations such as **ICEYE** are going to use the FOTEC-ENPULSION field emission thrusters (FEEP) IFM Nano to keep the constellation in orbit and de-orbit all the satellites when the life is finished. This thrusters are already flying since beginning of 2018.

Required on-going & future developments

- Mini-ion engines system and micro-field emission thrusters are in development to satisfy the needs of future gravity missions and other science missions such as **NGGM and LISA**.
- Mini-hall thrusters system are in development to satisfy the needs of future mini/micro-satellites to perform SK and disposal maneuvers in **constellations**.
- Micropropulsion for ***Nanosatellites*** and microsatellites (*NEW MARKET*)
- **Large Electric Propulsion Systems** must be developed to meet the needs of future asteroid or planetary exploration missions. Cargo missions to Mars will also make a good use of these systems. Space Tugs (*NEW MARKET*)

Space Tugs

Space Tugs are currently under discussion at all three European LSIs. Electric propulsion is considered as one of the key technologies for Space Tugs due to the relatively low propellant consumption compared to chemical propulsion. At the moment four different use cases are foreseen for Space Tugs:

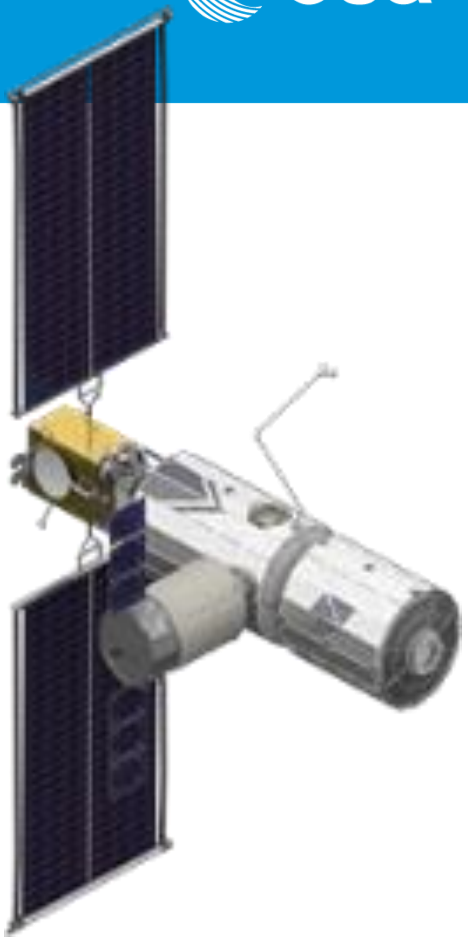
a. GEO Servicing
b. LEO/MEO Debris Removal (Mega constellations, SSO debris removal)
c. LEO/MEO to GEO tugging (for telecommunication satellites, 60 kW tug would be required)
d. Moon cargo delivery (high Isp operation would be of interest)

A clear need has been identified for the development of high power (~15 kW-20kW), long lifetime Hall effect thrusters in the frame of discussions concerning future Space Tugs.

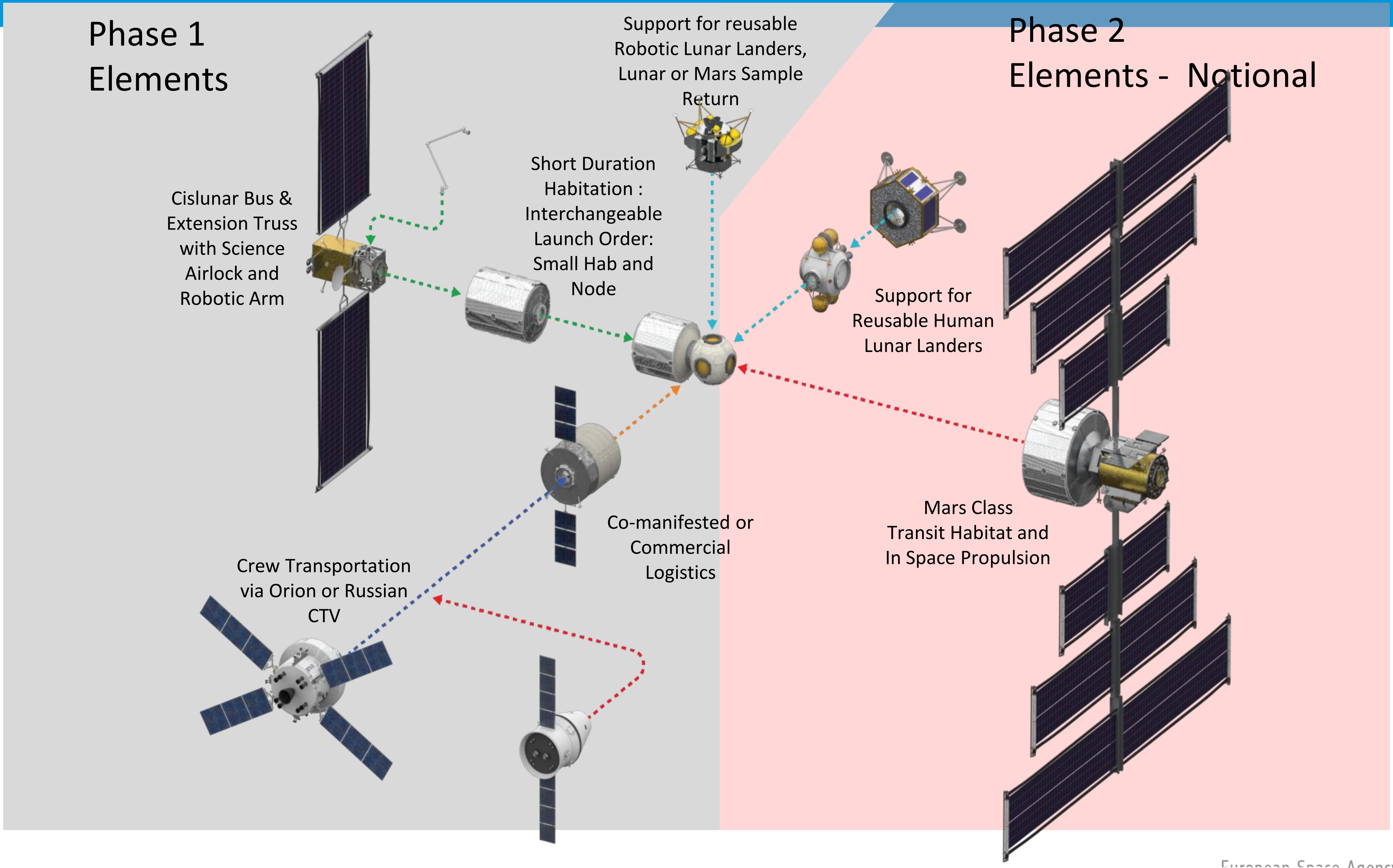
Several meetings have been performed to identify possible commonalities in terms of technology development between Space Tug applications and e.Deorbit.

Perspective for Cislunar Infrastructure

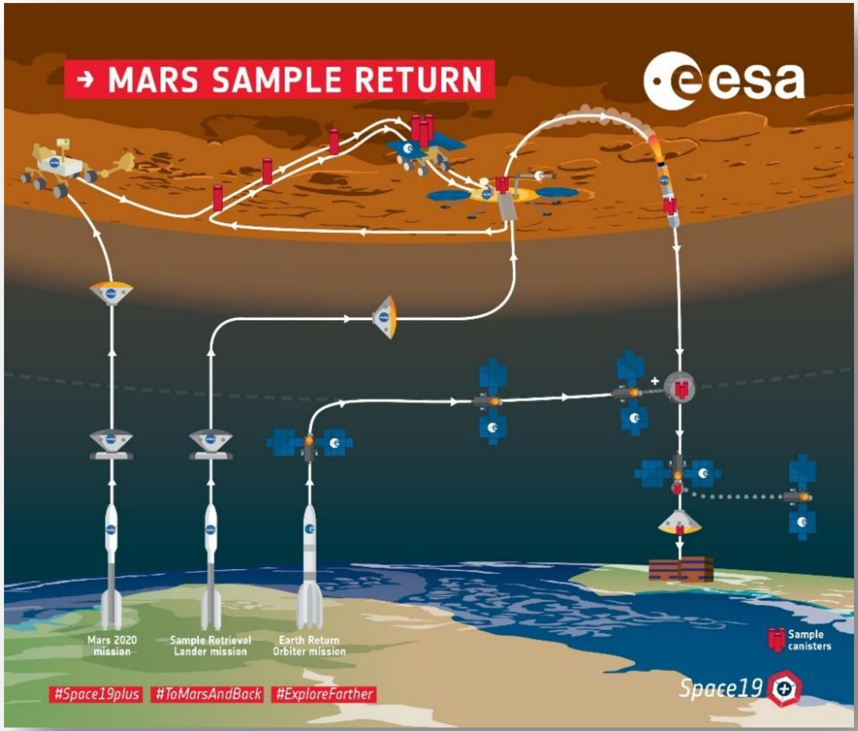
1. ESA and the ISS Partners are discussing plans for beyond LEO activities, considering a small man-tended infrastructure in Cis-Lunar orbit, known as evolvable Deep Space Habitat or Cis-Lunar Transfer Habitat (CTH).
2. This is the first enabling step to a sustainable access to the Moon surface and will be assembled and serviced using excess launch mass capability of NASA's SLS/Orion.
3. During Phase 1 (2023-2026) such an infrastructure shall support up to 90 days of crewed operations and robotics surface missions.
4. During Phase 2 (2026-2030) it shall support up to 300 days of crewed operations and Moon robotics and crewed surface missions. Then part of the CTH may go to a crewed trip to Mars.
5. Phase 2 will see the arrival of a larger habitation module and resource/propulsion service module



Cislunar Phase 1 and 2



Exploration:
Potential Near-Term Future Applications – Mars Sample Return



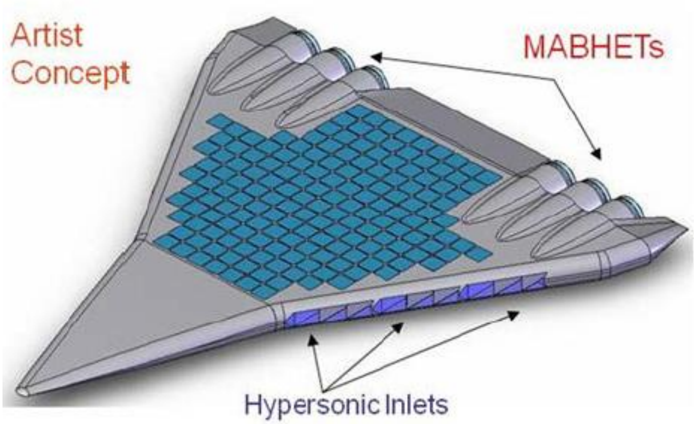
Mars Sample Return would represent a cornerstone in the exploration of the Solar System. The MSR overall architecture is based on three different missions as an international effort.

ESA is leading industrial studies for the Earth Return Orbiter (ERO) mission.

Solar Electric Propulsion (SEP) is considered for cruise phases (transfers) and orbit lowering/raising at Mars.

Exploration:
Potential Far-Term Future Applications – RAM-EP

1. Concept studies by Busek / NASA Glenn:
2. **(K. Hohman, V. Hruby, H. Kamhawi)**
3. Solar Electric Power Orbiting Spacecraft that ingests Mars Atmosphere, ionizes a fraction of that gas and accelerates the ions to high velocity.
4. Mars atmosphere is thin and composed mainly of CO_2.
5. - The altitudes of interest are 120-180km due to drag and power requirements.
6. - The orbital velocity is around 3.4km/s.
7. - Solar Flux is about 584 W/m2 (Earth ~1350 W/m2) .



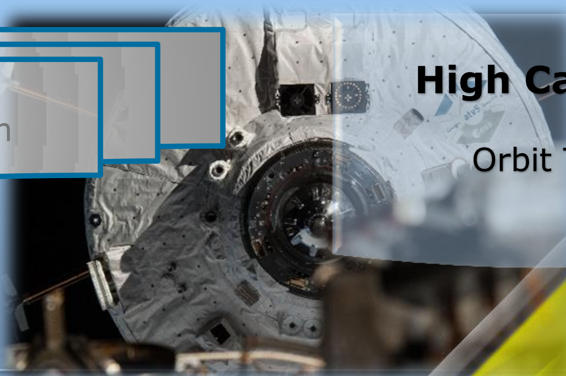
Exploration:

Application Area: Advanced Propulsion *(Priority for Space Council)*

Technology Subject: ***Electric Propulsion for High Capacity Cargo Transfer***

2020-2023

20-30kW Electric Propulsion System



High Capacity Cargo Transfer

Orbit Transfer / Raising Vehicle

2018-2019

20-30kW Thruster Testing Facilities

20-30kW System Components

Orbit Insertion & Maintenance

Large GEO S/C & Long duration operations around other planets

Orbit Insertion & Maintenance

Rendezvous & Docking

2013-2017

Alternative Propellants

High Current Cathode Technology

5KW Propulsion Systems

Future Developments

- **HALL EFFECT THRUSTER:** Extension of lifetime via magnetic confinement and double operation point (higher thrust during orbit raising and higher specific impulse during NSSK). TELECOMMUNICATION, Navigation and Science and Exploration missions will benefit from these developments. Power levels around 5 kW or higher. System activities, cost reduction and industrial production issues should be assessed.

- **ION ENGINE:** Reduction of the power to thrust ratio via the cusp design . TELECOMMUNICATION, Navigation and Science and Exploration missions will benefit from these developments. Power levels around 5 kW or higher. System activities, cost reduction and industrial production issues should be assessed.

- **HEMPT:** High power HEMPT with high lifetime and different operation points to adapt the thruster output t the power of the solar array of the spacecraft. TELECOMMUNICATION, Navigation and Science and Exploration missions will benefit from these developments. System activities, cost reduction and industrial production issues should be assessed.

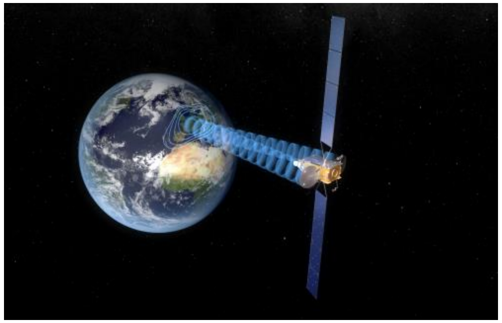
- **Mini-ion engines, FEEPs and mini-Hall effect thrusters** will be used for science and Earth observation missions. Thrust levels from micro-Newtons to some milli-Newtons. Lifetime will be a special issue to be assessed.

- **Testing facilities:** The utilisation of High power engines will pose strong requirements in acceptance testing facilities. The standardisation of testing methods will also be required to reduce cost and risk of these developments.

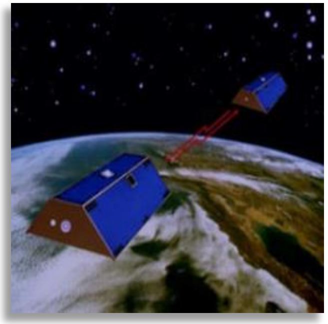
- **New High Power Electric Propulsion** Concepts evaluation (Helicon Antenna Thruster, Electron Cyclotron Resonance thruster, MPD, E-Imapct thruster, etc.). MICROPROPULSION and VERY HIGH POWER EP

Current and Future ESA missions with EP

Neosat

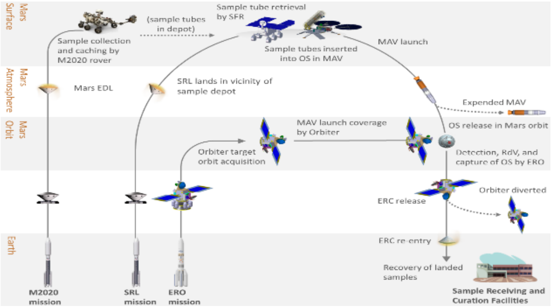


Electra

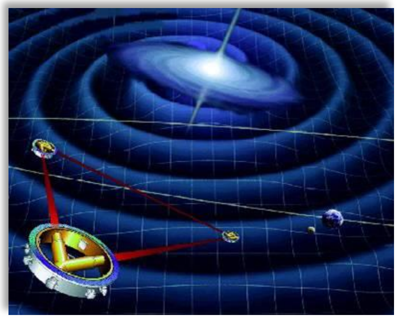


NGGM

Navigation



Exploration (Cislunar, Mars, Sample Return)



LISA

EPIC: H2020 SRC for Electric Propulsion

- Electric propulsion has been identified by European actors as a Strategic Technology for improving the European competitiveness in different space areas.
- **The European Commission (EC)** has set up the "In-space Electrical Propulsion and Station-Keeping" Strategic Research Cluster (SRC) in Horizon 2020 with the goal of enabling major advances in Electric Propulsion for in-space operations and transportation, in order to contribute to guarantee the leadership of European capabilities in electric propulsion at world level within the 2020-2030 timeframe.
- The SRCs will be implemented through a system of grants connected among them and consisting of:
  - 1)"Programme Support Activity" (**PSA**): The main role of this PSA is to elaborate a roadmap and implementation plan for the whole SRC and provide advice to the EC on the calls for operational grants.
  - 2) Operational grants: In future work programmes (2016 and 2020), and on the basis of this **SRC** roadmap and the PSA advice for the calls, the Commission is expected to publish calls for "operational grants" as research and innovation grants (100%) and/or innovation grants (70%).

Capabilities in Europe

System Design
Fluidic Management
Thruster Design
Test Facilities
R&D
Advanced Materials
Modeling

Power Supply, Mechanisms

Fluidic Management

Fluidic Management

System Design
Fluidic Management
Tanks
Thruster Design
Test Facilities
R&D
Modeling
Flight Dynamics

Fluidic Management
Thrusters assembly

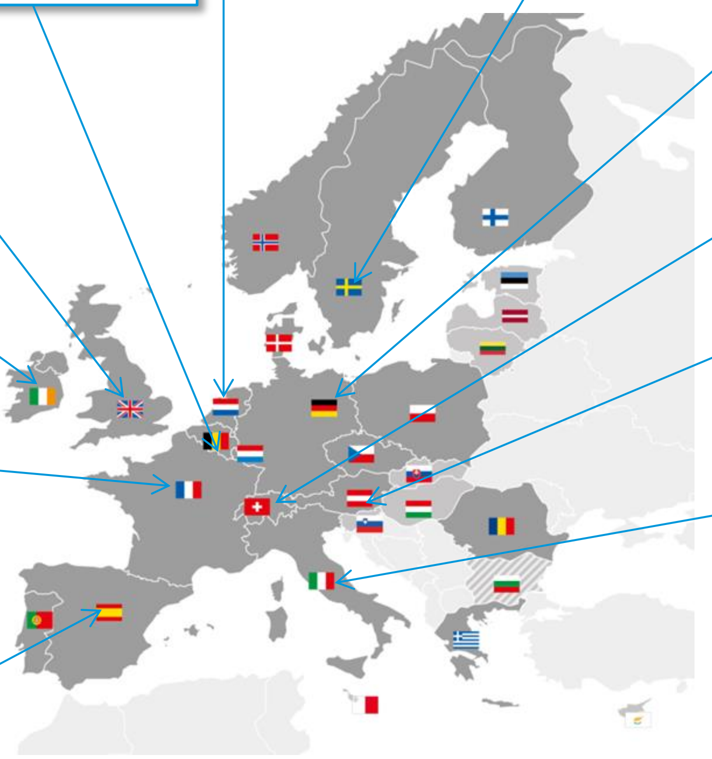
Mechanisms

System Design
Fluidic Management
Tanks
Thruster Design
Test Facilities
Mechanisms
R&D
Modeling
Flight Dynamics

Mechanisms
Electronics
Microthruters

Fluidic Management
Tanks
Thruster Design
Test Facilities
R&D
Modeling

Electronics
Flight Dynamics
Advanced Materials
thrusters
facilities



Coverage of EP technologies in European

Capabilities in ESA
ESA Propulsion Laboratory

- ESA Propulsion Laboratory (EPL) located in ESTEC, The Netherlands.
- Provide test services to the Propulsion and Aerothermodynamics division of the European Space Agency, which is responsible for the technical support to ESA projects and the R&D activities in the areas of chemical propulsion, electric and advanced propulsion, and aerothermodynamics.

CORONA

Micro Newton

Small Plasma Facility

FEEP

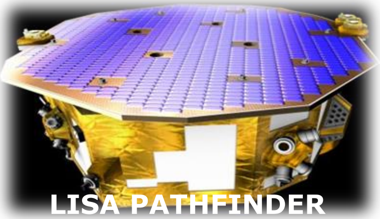
GIGANT

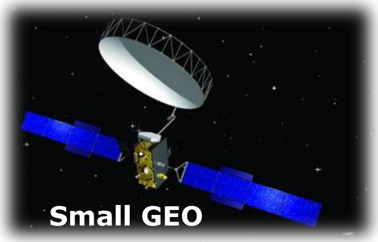
ELECTRON

GALILEO

3. EPL Activities

- Support to ESA projects
  - Independent performance assessments
  - Quick answers to specific questions
- Support to R&D Activities
  - Technology assessment for ESA R&D programs
  - Explorative internal R&D work on new technologies
  - International scientific/technical cooperation
  - Patent exploitation
- Support to European Aerospace Industry
  - Reference for standardization of testing methods and tools
  - Joint testing for cross verification of performance





Capabilities in ESA
ESA Propulsion Laboratory

- EPL today provides independent assessment on EP thrusters & propulsion components performances.
- Tests are mainly focussed on low power EP propulsion and cold-gas system and space propulsion subsystems.
- Future improvements are aiming at enabling measurement of thrust and thrust noise in μN regime for science and earth observation application (NGO, Euclid, NGGM) and at characterising mid-high power thrusters for science, navigation and telecommunication applications (>2kW).
- Planning and execution of performance characterization of electric thrusters (HET, GIE, FEEP, Resistojets), cold gas thrusters & propulsion components.
- Design, manufacturing and validation of diagnostics (thrust balances, data acquisition systems, beam probes) in collaboration with European industries/research centers.
    - ISO 17025 certification of thrust, mass flow and electrical power:
    - Force: 1 μN – 500 mN
    - Mass flow: 1 μg/s – 300 mg/s
    - Power: 1 mW – 2 kW

- ***<u>Consolidation of the current European products</u>*** *(Hall effect thrusters, ion engines, field emission thrusters, HEMPT, MPD, etc.). In this process the qualification of the European products is one of the main activities together with the European autonomy in components. ESA aims to have full European systems where not only the thruster is European but also components such as pressure regulators, feeding systems, neutralizers, etc.*
- ***<u>Utilization of the current flight data</u>*** *(Artemis, Smart-1, GOCE, Inmarsat 4F, Intelsat 10, Astra 1K, Alphabus, Small GEO, etc.) to validate the models that will be used by the spacecraft designers in the future.*
- ***<u>Standardization of engineering processes and testing facilities</u>*** *employed in the design, manufacturing and qualification of the current electric propulsion systems.*
- ***New electric propulson systems****: higher and lower power (space tugs, nanosatellites …).* ***MICROTHRUSTERS and VERY HIGH POWER EP***

Technology Challenges

1. **Microthruster** development and measurement of microthrust levels are very challenging. **Micropropulsion Systems for Nanosats**.

2. **High power thrusters** (5kW, 15-20kW) capable of operating at high specific impulse with a low power to thrust ratio (orbit raising and interplanetary transfer). Double operation mode for telecommunications and Space Tugs.

3. **Qualification through long lifetime** testing such as Bepi Colombo.

4. **EP Cost reduction** exercise at system level specially for Constellations, in particular for de-orbiting. Use of COTS

5. **Spacecraft thruster possible interactions**.

6. **Flight opportunities**, Bepi Colombo, Neosat, Electra, NGGM, ICEYE...

Conclusion

- **Telecommunication market** will be able to make an immediate use of these EP technologies for on obit control and full or partial transfer. **5kW** engines with low power to thrust ratio and high specific impulse will be very important. Dual mode and long lifetimes will be important.
- **Navigation**, **Science** (interplanetary missions) and **Exploration** (the Moon, Asteroids and Mars) will require EP systems.
- **Mini- ion engines, FEEPs, mini-Halls**, **electrosprays** with capability to fulfil stringent Science and Earth Observation requirements (LISA, NGGM, Euclid, microsatellites etc.). **MICROPROPULSION FOR NANOSATELLITES will be a new market. Constellations such as ICEYE are flying mini-satellites with EP thrusters (FOTEC-ENPULSION).**
- **Very High Power** Electric Propulsion for Exploration and Space Tugs. **10-20 kW engines** will have to be developed.
- **Constellations of satellites** may make use of EP systems at very low prices due among several reasons to the large quantities. Low power engines for constellations.
- ESA, Space Agencies and Industry have participated to the **EPIC** proposal within the European Community Horizon 2020 programme. ESA has been the coordinator of this proposal. EPIC is the winner of the H2020 programme and work is ongoing.