European Space Agency (ESA) Electric Propulsion Activities

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Presentation Overview

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Electric Propulsion Systems

Propellant Storage
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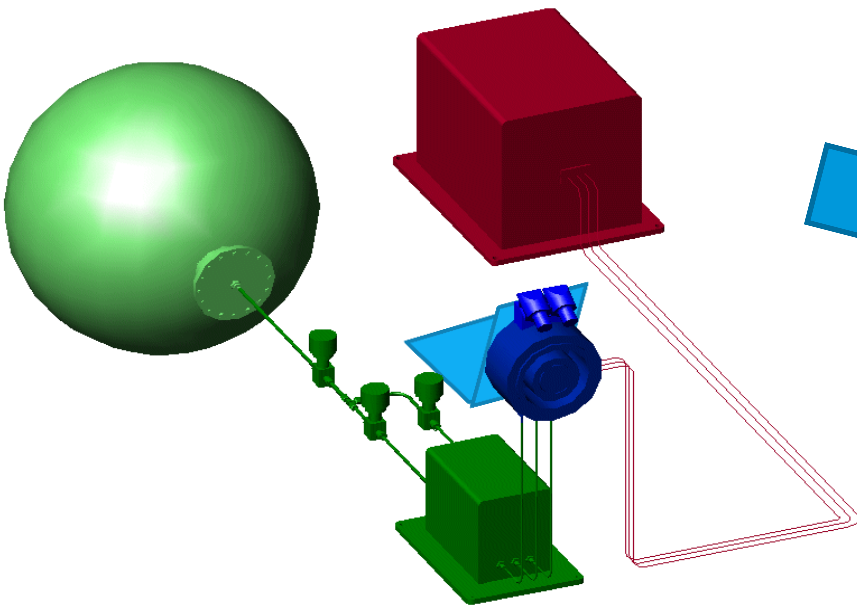
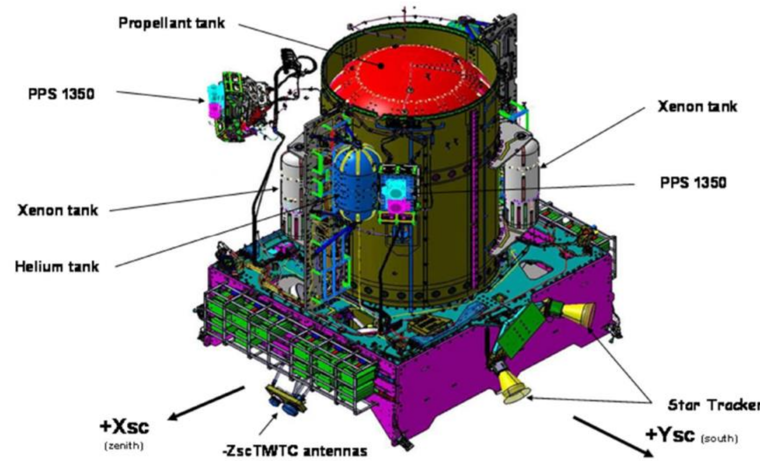
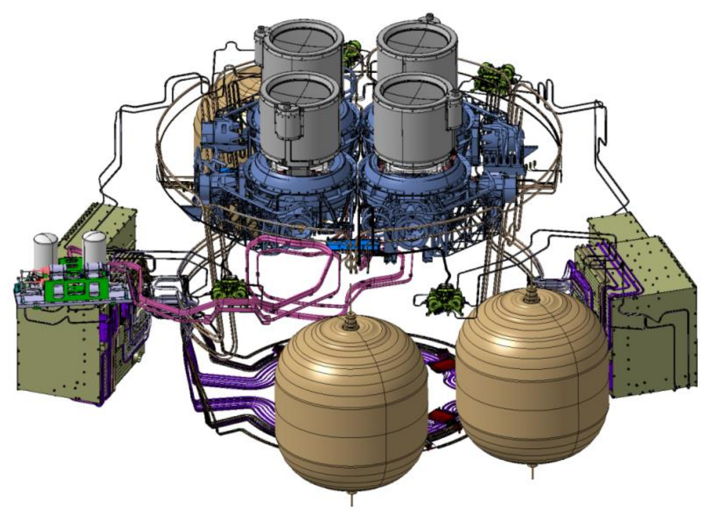
Thruster

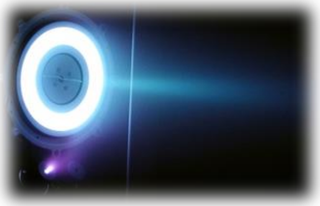






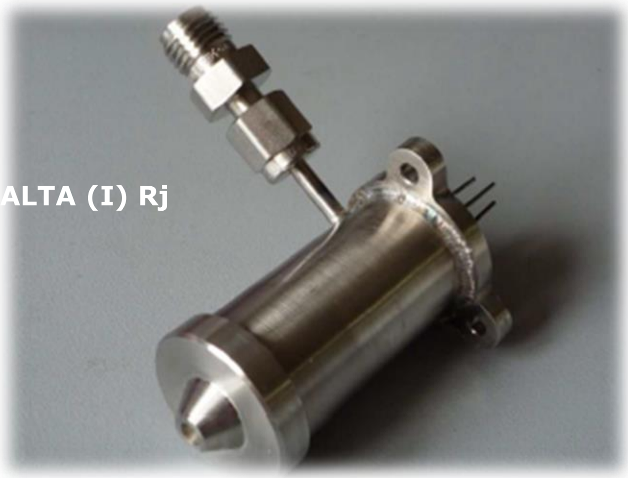
Types of Electric Propulsion

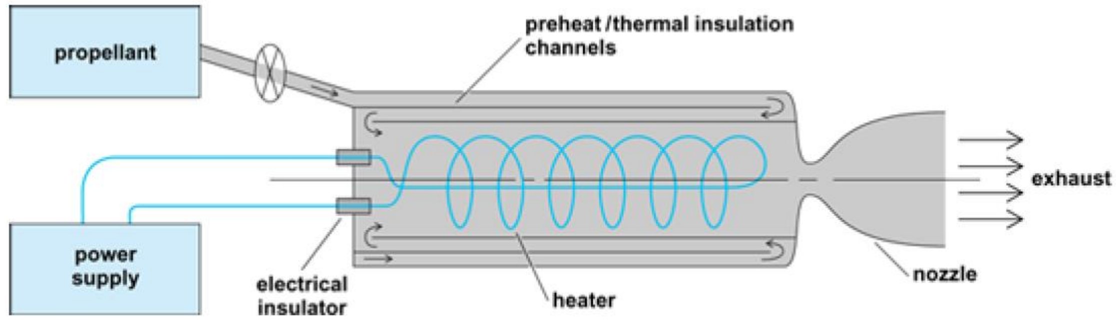
- In general, Electric Propulsion (EP) encompasses any propulsion technology in which electricity is used to produce thrust.
- Electrical energy is used to ionize the propellant from a gas, solid or liquid and accelerate the resulting plasma to very high exhaust velocities (10-40km/s)
- Electric Thrusters are fuel efficient, but provide low thrust.
- 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

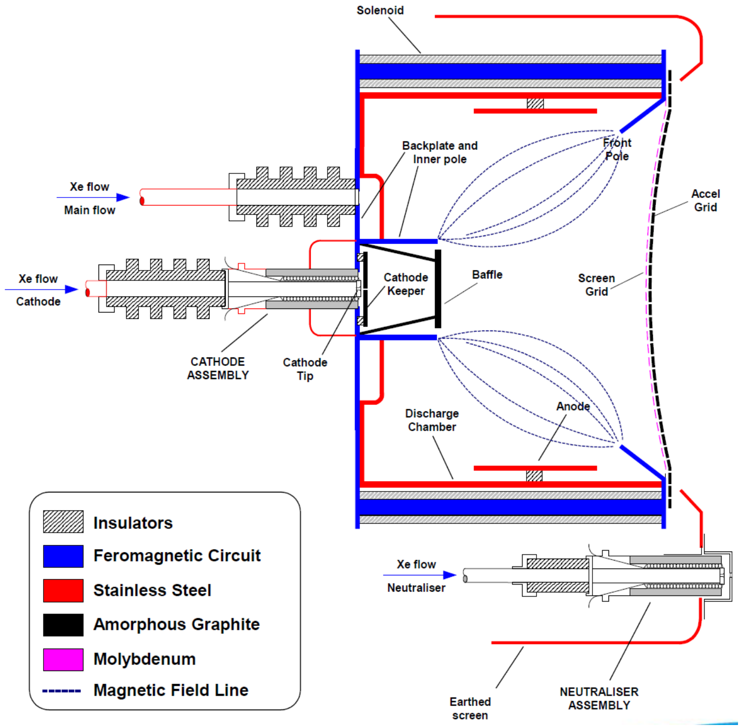


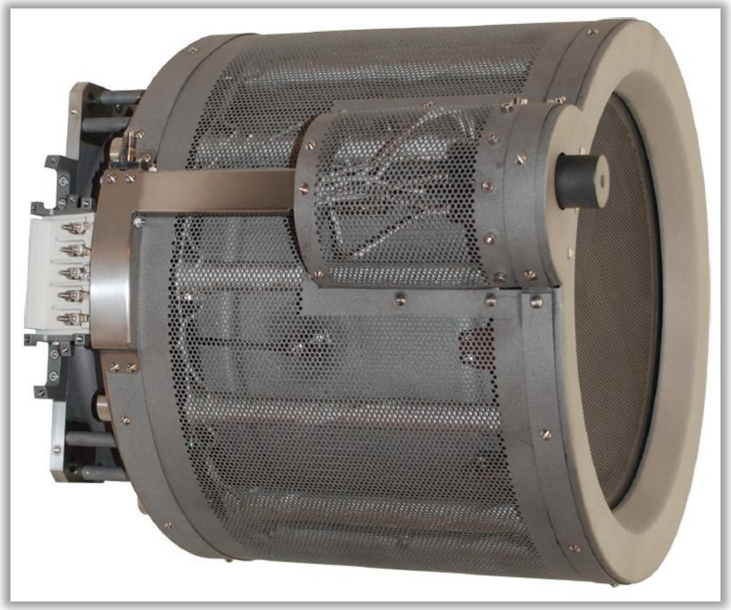


- Resistojets are electrothermal devices in which the propellant is heated by passing through a resistively heated chamber or over a resistively heated element before entering a downstream nozzle.
- The increase in exhaust velocity is due to the thermal heating of the propellant, which limits the Isp to low levels (<500 s).
- Resistojets are simple, low power thrusters (<50W) and can be used as auxiliary propulsion on satellites.

Electrostatic Thrusters
Gridded Ion Engines (GIE)

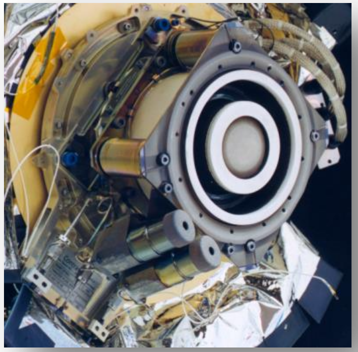
- The Gridded Ion Engine consists of three processes:-
  - Ionization by Electron Bombardment via Radio Frequency or Magnetic Fields
  - Acceleration through ion optics generated by a perforated grid
  - Neutralization of the ion beam using an external electron source (Cathode)

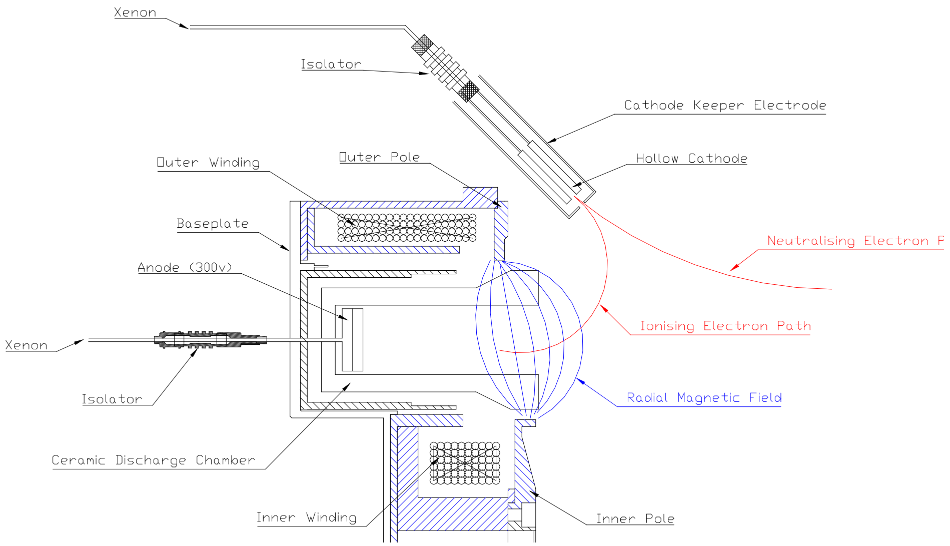


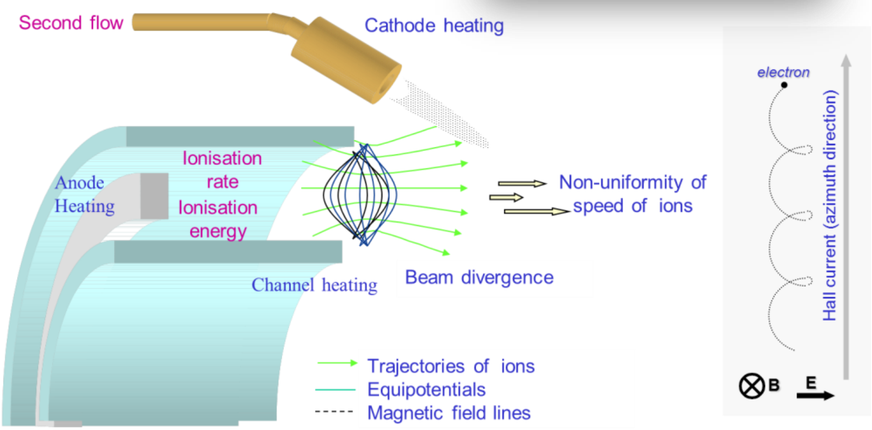


Electromagnetic Thrusters
Hall Effect Thruster

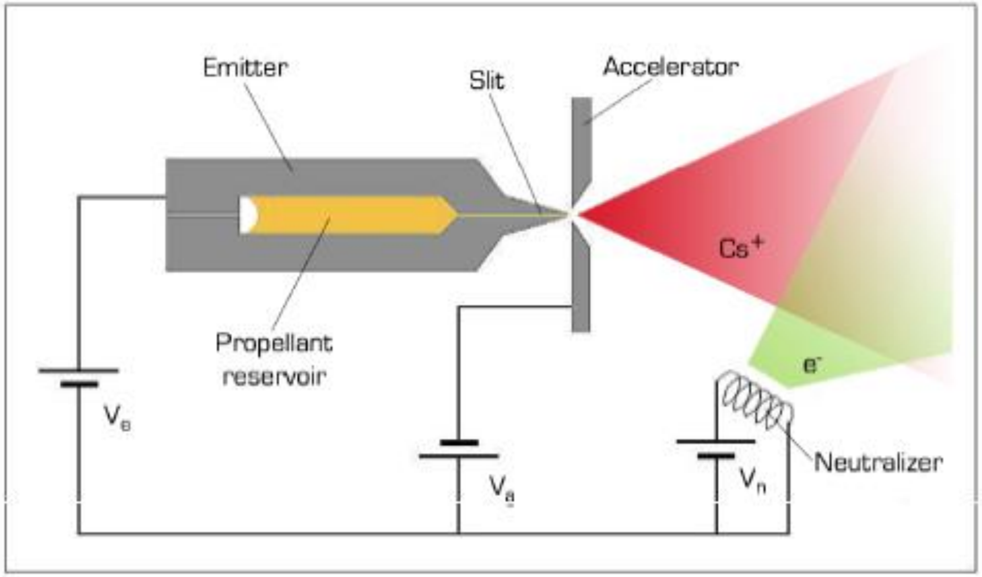
- Propellant is ionized by electron bombardment
- Ions accelerated by electric field
- Electric field established by electron current impediment by magnetic field
- Electrons within the magnetic field follow a closed drift path







European Space Agency



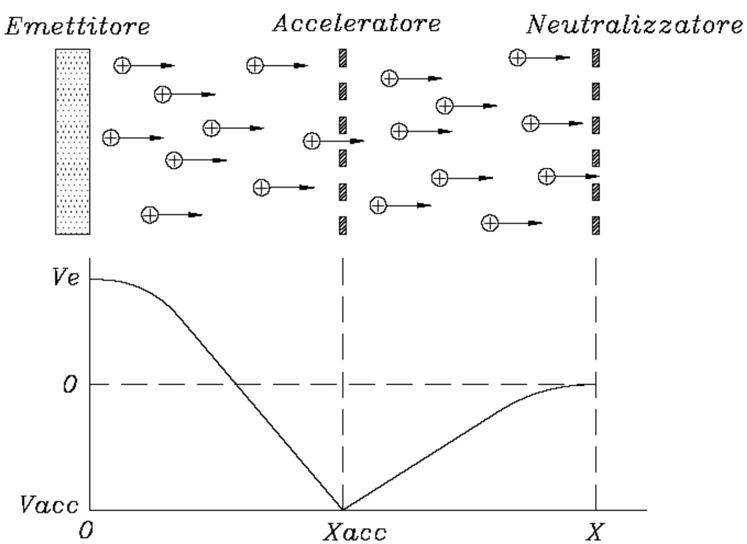
$$qV_e = \frac{1}{2} M v_e^2 \Rightarrow v_e = \sqrt{\frac{2qV_e}{M}}$$

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

FEEP is an electrostatic type thruster:

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

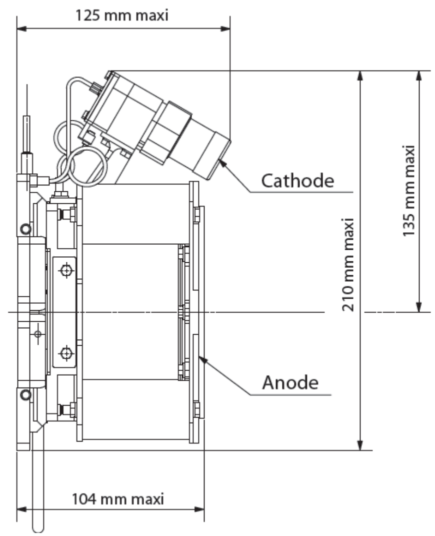
⇒ electrons need to be emitted downstream in the same quantity for charge balancing.



Capabilities in Europe
SAFRAN-Snecma: Hall Effect Thrusters

- **Thruster Performances PPS-1350G (AlphaBus):**
  - Input Power: 1500W
  - Average thrust level during lifetime : 88 ± 3 mN
  - Average Isp during lifetime : 1630 ± 50 s
  - Number of cycles without safety margin : 4680+90 cycles
  - Thruster total impulse without safety margin : 2.23 MN.s (extension to 2.69 MN.s TBC)
  - Longest fire duration :
  - top-up: >1 week,
  - GEO : > 3 hours (worse case 4 hours)
  - Flight Qualified: Agreed qualification factor of 1.3 based on SMART-1 flight experience

- **Thruster Performances PPS-1350E**
  - Input Power: 2500W
  - Average thrust level during lifetime : 140 ± 3 mN
  - Average Isp during lifetime : 1800 ± 50 s
  - Number of cycles without safety margin : TBC
  - Thruster total impulse without safety margin : 2.6 MN.s
  - Under Development (CNES Funding)
  - Intended for dedicated Electric Orbit Topping role (AlphaBus EOR)



Capabilities in Europe
SAFRAN-Snecma: Hall Effect Thrusters

Thruster: PPS-5000 – High Specific Impulse Development (TRP)

Application: Station Keeping / Orbit Topping

Supplier: SNECMA (F)

Status: In development (TRL = 4)

Heritage:

- PPS-1350-G
- PPS-5000 AlphaBus ARTES predevelopment at high discharge voltage
- High-Isp development and test activities within ESA/TRP

On-going developments:

- Development of a high-Isp version of the PPS-5000 with a redesigned discharge channel:
  - Design verification with a short duration lifetime test
  - Operation at 5 kW (1 kV / 5 A) at ~ 200 mN thrust / 3000 s Isp
  - Target total impulse capability of 10 MN.s
  - Activity completion mid 2014

Capabilities in Europe
Thales Electron Devices : HEMPT

Thruster: High Efficiency Multistage Plasma Thruster

Application: North-South Station Keeping & Top-up Functions

Supplier: Thales Electron Devices (D), Astrium (D), Moog Bradford (NL)

Status: Qualification on-going for SGEO (ARTES-11)

Heritage: None

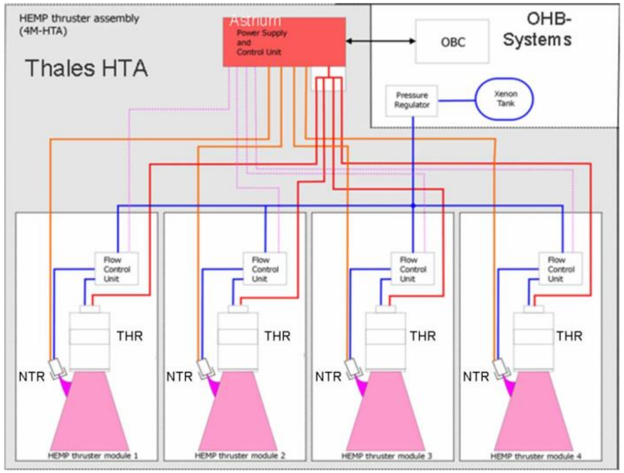
On-going Developments:

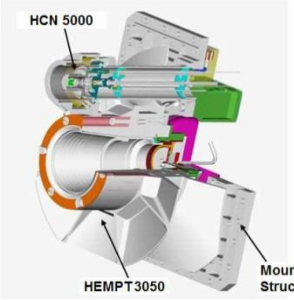
- *SGEO HEMP-TIS (DLR Funded)*
  - *Thruster (ThalesED); FCU (Moog Bradford); PSCU (Astrium)*
  - *Hardware qualification (excluding life-test) expected April 2013*
- Target to improve performance (Thrust, ISP) and reduce complexity and cost.
  - Target performance: 100 mN at 2000 s
  - Reduced cost / complexity PSCU

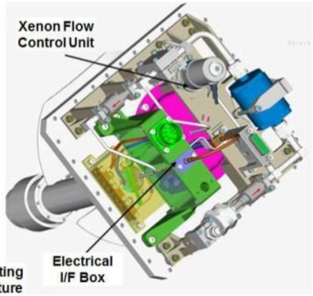
Capabilities in Europe
Thales Electron Devices : HEMPT

Thruster Performances HEMPT 3050 (SGEO):

- Average Thrust Level during lifetime : ≥ 44 mN
- Average Thruster Power during lifetime : ≤ 1380 W
- Average Specific Impulse during lifetime : ≥ 2300 s
- Number of Cycles without safety margin : 6500 cycles
- Operational lifetime without safety margin : 4800 h
- Thruster total Impulse without safety margin : 0.76 x10^6 Ns
- Agreed qualification factor of 1.5 to be demonstrated





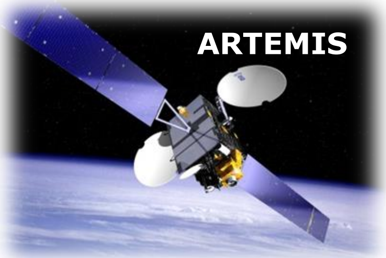


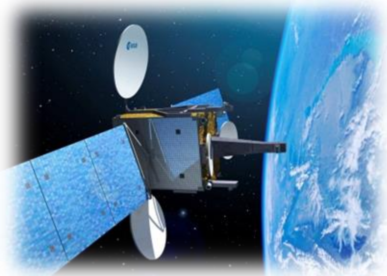
European Space Agency

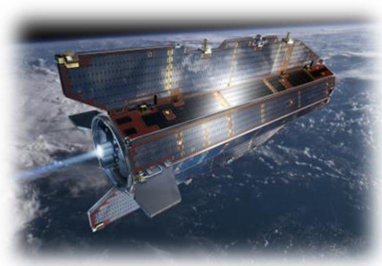
Capabilities in Europe
Advancement of Ion Thrusters

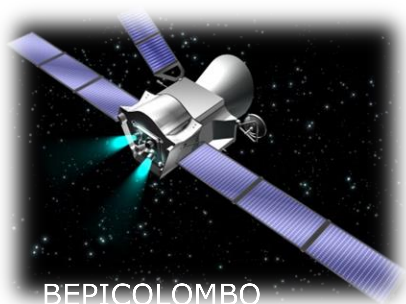
- Whilst there is a current focus on the use of Hall Effect Thrusters in Europe; it is recognized that there exists a very strong capability in the domain of Ion Thrusters.
- It is the view of ESA that given the level of uncertainty of how future commercial and scientific applications will evolve it is important to retain the ability to develop and deliver Ion Thruster based propulsion systems.
- The T-6 Kaufmann Ion Thruster developed for Bepi-Colombo and ARTES High Power Electric Propulsion System provides excellent performance characteristics; but is more optimized for bespoke science missions than commercial applications.
- In particular the specific impulse (Beam Voltage)is too high to compete with the Hall Effect Thruster for applications where high thrust is required to minimize transfer times.
- Transition from the **Kaufmann to Ring Cusp** configuration is seen as the key to ensure that Ion Thruster technology remains viable for commercial applications:-
    - **Increase Performance** (mN/kW)
    - Simplified thruster and power supply design (**Reduced Cost**)
    - **Retention of heritage** (Cathode's & Grid Optics Design Rules)

The ESA Electric Propulsion Fleet Past, Present & Future









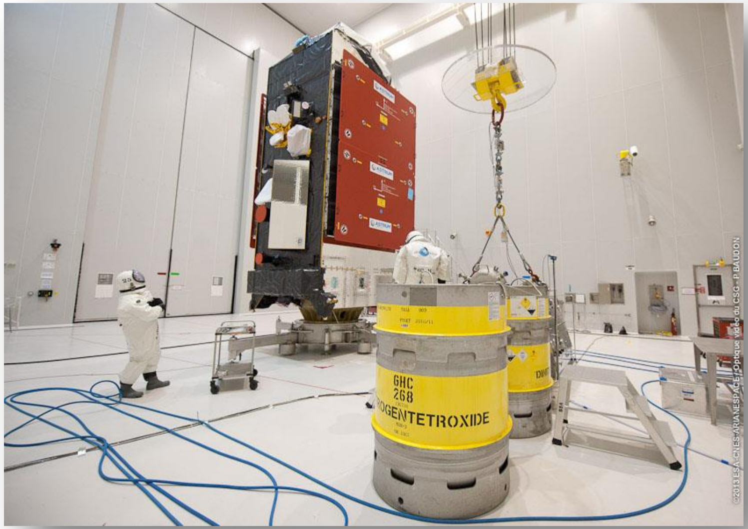
Electric Thrusters
Gridded Ion Vs. Hall Effect

- Between the two technologies, a full range of capabilities are available for candidate applications

Characteristic	Hall Effect Thruster	Gridded Ion Thruster	Comment
Specific Power	18W/mN	25-35W/mN	Lower number represents improved Orbit Transfer durations for a given power ceiling
Thruster Efficiency	50%	70%	Higher number tends to reduce thermal interface demands for a given power ceiling
Specific Impulse	1500-2500s	2500-4500s	Higher number represents wet mass saving / higher payload fraction
Operating Voltage	300-400V	1000-2000V	Linked to specific impulse, higher voltages are more challenging for power supply design.
PPU Specific Mass	5kg/kW	10kg/kW	Higher number represents increased EP system dry mass penalty
Plume Divergence	45°	15°	Lower number reduces complications of thruster beam interaction with spacecraft appendages (Solar arrays, antennas, deployable radiators etc)
Throttle Range	2:1	10:1	20:1 demonstrated on GOCE (QinetiQ T5) Higher ratio useful for power limited missions (MP-R)

Electric Thrusters
Xenon Propellant

- Xenon is the most common propellant for both HET and GIE thrusters for the following reasons:-
    - Naturally occurring (87ppb in atmosphere) with very low chemical reactivity.
    - Low first ionization potential.
    - High atomic Mass.
    - Gaseous at ambient temperature.
- From a Satellite perspective:-
    - Safe to handle during filling operations
    - No decontamination required
    - Transportable by air
    - Compatible with electron sources
    - Low power consumption to ionize.
    - High thrust efficiency
    - High storage density



AlphaSat Chemical Fuelling: Hazardous Operation

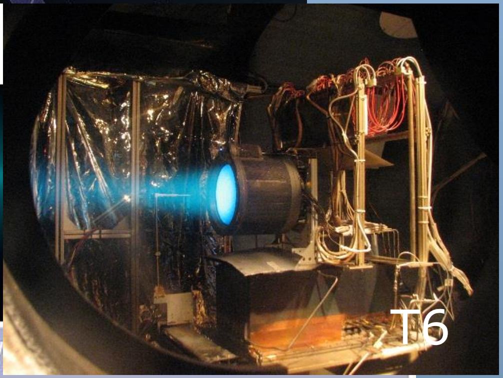
Development Support Requirements
Test Facilities & Diagnostics

- Electric thrusters must be tested in high vacuum environments, this contributes significantly to the cost of electric propulsion systems and places high demands on facilities throughout the development cycle.
- Cryogenic pumping hardware is needed to achieve dynamic vacuum conditions better that $1x10^{-4}$ mb during thruster operation.
- Specialist diagnostic equipment is also required, particularly during the development phase to confirm thruster behavior, a majority of this equipment must also be compatible with operation in vacuum environment for long periods.
- Each type of test places different demands on the test facility and so need to be adapted for specific test activities.
- Qualification life testing is an enormous undertaking with facilities required to operate almost continuously for several years.

Thruster development Phase	Test Duration	Facilities
R&D Testing	~2-8 weeks	Thrust Balances, full plasma diagnostics suite
Engineering/Coupling Testing	~1 month	Thrust Balances, full plasma diagnostics suite, EMI Facilities, Thermal Vacuum
Qualification Testing	~3 years	Thermal Vacuum, limited diagnostics
Acceptance Testing	~1month	Thermal Vacuum, limited diagnostics

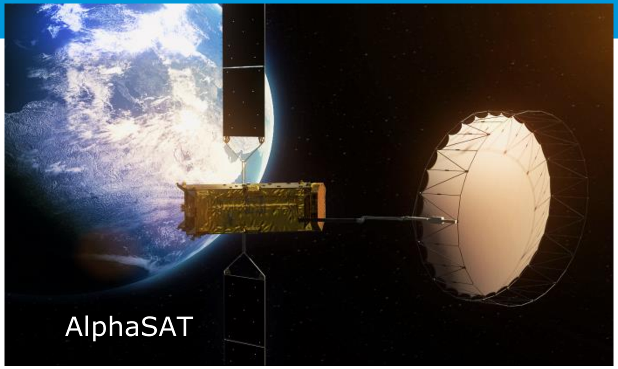
Telecommunication Spacecraft

- existing European platforms use the Fakel (RU) SPT-100 Hall Effect Thruster or the Snecma PPS-1350G Hall Effect Thruster.
- They can not offer significant orbit topping in addition to the baseline station keeping functions.
- **NeoSat (ARTES-14)** and **Electra (ARTES-33)** ,the small to medium class platform. Topping of between 4-8 months, or complete electric orbit raising configurations are expected from these developments.
- The trend to increased use of electric propulsion will continue
- The higher power thrusters (5kW) will be needed to meet both the orbit raising and station keeping needs of future small and large platforms. PPS5000, RIT22, T6, SPT-140,…

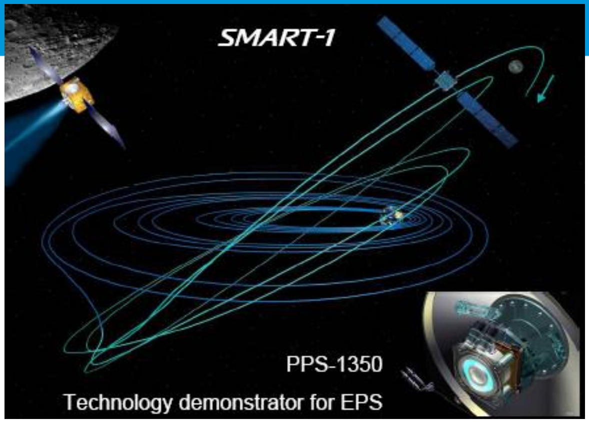


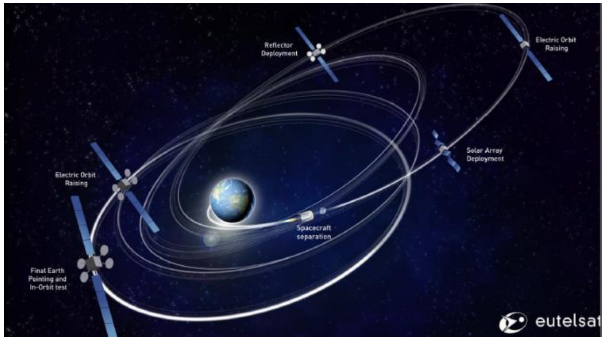
Electric Propulsion for Operational Station-Keeping

- Since the 1980ies EP has been used for station keeping of telecom satellites (US, Ru).
- In 2001, following a launch injection failure, the Artemis mission was saved using its EP station keeping thrusters for partial orbit transfer.
- In 2004, Intelsat 10-02 became the first European developed telecom satellite using EP for station keeping
- Since than several satellites have been built in Europe that feature SPT100 thrusters for station keeping: Astra-1K, Stentor, Intelsat-10, Yahsat 1A & 1B, Inmarsat-4 F1,F2 & F3, Eutelsat 10A & 36B, Yamal 402 & 601..
- In July 2013 AlphaSat became the first European developed telecom using four Safran (F) built PPS1350G thrusters for north/south station keeping.
- Very demanding SK capabilities were achieved on GOCE.
- The new constellations of Space X with 4000 spacecraft or Oneweb with 700 spacecraft using electric propulsion for station keeping and disposal will increase in the next years the already extraordinary flight heritage cumulated by EP thrusters.



Electric Propulsion as a Means for Orbit Raising





- In Europe Orbit raising with Electric Propulsion has already been demonstrated by the SMART-1 lunar probe (5000 hours of almost continuous in space operation) and by Artemis; worldwide by Deep Space 1, Dawn, Hayabusa.
- On telecom satellites orbit transfer to GEO was typically consuming chemical propellant that amount to 40% of the satellite mass and were completed in few days after launch. Using EP, the manoeuvre takes significantly longer (months), but can reduce the propellant consumption by thousands of kilograms, increasing the useful dry mass fraction and reducing the launch cost dramatically.
- Boeing was the first satellite manufacturer to introduce partial EP orbit raising (orbit topping) on their 702HP platform.
- Boeing's announcement in 2012 of sales of 4 of its all electric small platform (702SP), featuring EP for station keeping and full orbit raising, has triggered a revolution in the commercial utilisation of EP.
- In 2015, the Boeing built Eutelsat 115 and ABS 3A became the first all electric commercial satellite demonstrating Electric Orbit Raising.
- The first European built all electric satellite will be launched early 2017 (Airbus Eurostar E3000EOR satellite).
- All the 3 main European Primes are at present developing all electric commercial satellites (Neosat and Electra).
- .

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. AsianSat has already ask for another extra-satellite.

- 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 has bought another spacecraft using EP to Airbus in 2014. SES has just bought in 2015 two spacecraft (Astrium and Boeing) using electric propulsion as main system for orbit raising and station keeping operations.

- Boeing has 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.

- In the short term, the adoption of electric propulsion might offer new opportunities for the heavy lift Ariane 5, that typically offers to launch two spacecraft, one large and one medium. Adding the option of a low mass 702 SP class comsat, Arianespace could accommodate larger primary payloads co-manifested with a single all-electric spacecraft, without exceeding the rocket's total capacity. In the longer term, Ariane 6 will have to be compatible with a new generation of full electric spacecraft

Telecommunication Applications Existing Platforms

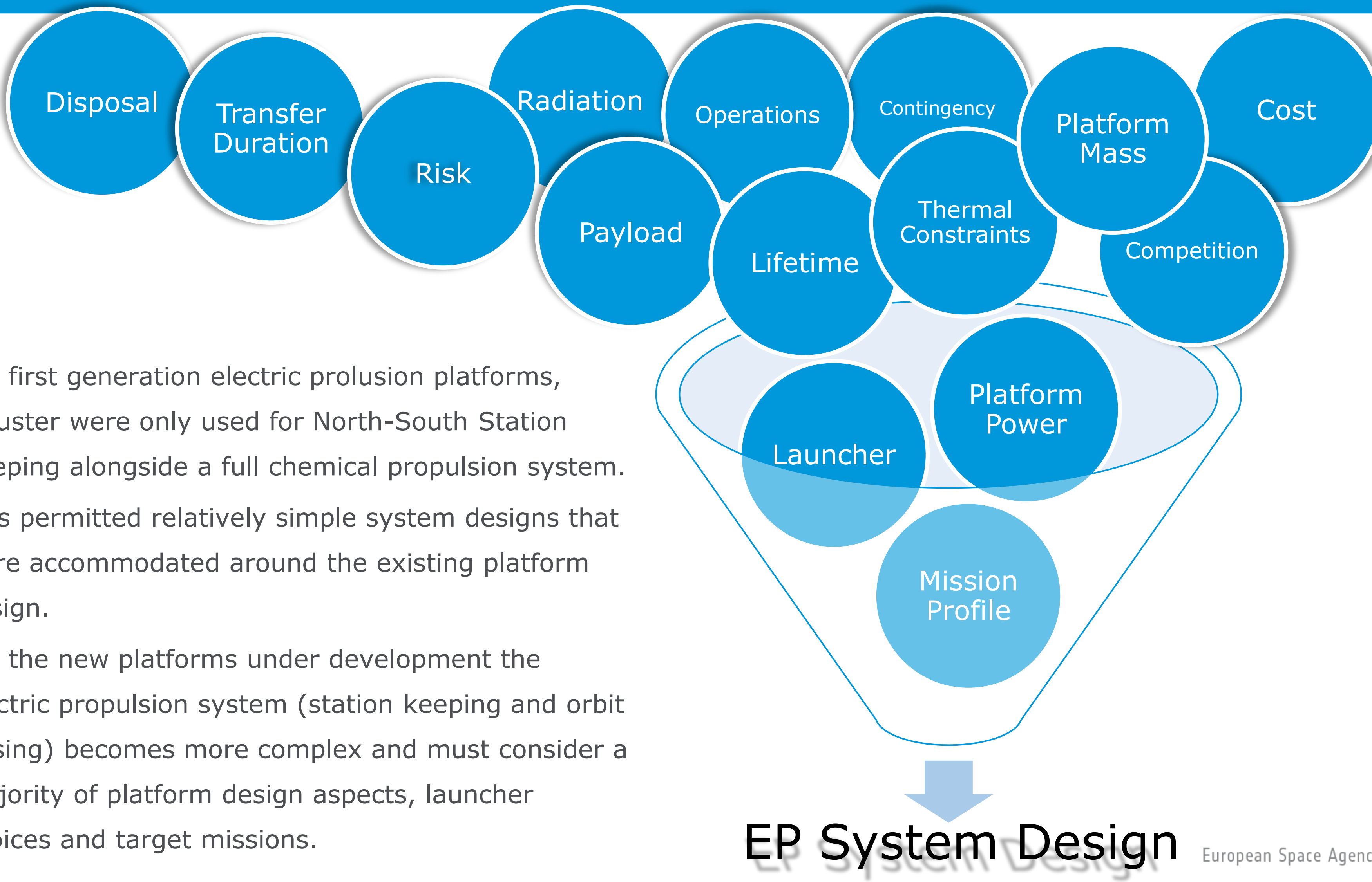
With the exception of ESA's ARTEMIS platform all European commercial platforms utilize Hall Effect Thruster Technology.

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/HEMPT
NEOSAT	Airbus/Thales	Under development	3-6	15- 25	NSSK, Orbit Raising	4XPPS5000	HET
ELECTRA	OHB	Under Development	3.2	7	NSSK, Orbit Raising	4XPPS5000	HET

Telecommunication Applications Future Architectures: More Electric

- Boeing, Loral & Lockheed are offering orbit topping on its large platforms and developing small platforms with 'all-electric' orbit raising and station keeping functions.
- All of the existing European platforms use the Fakel (RU) SPT-100 Hall Effect Thruster or the Snecma PPS-1350G Hall Effect Thruster. Since the total impulse capacity of the both of these thrusters is limited, existing configurations can not offer significant orbit topping in addition to the baseline station keeping functions.
- The European reaction to the changing launcher market and commercial platform developments in the United States is now underway.
- **NeoSat (ARTES-14)** and **Electra (ARTES-33)** are intended to cover the small to medium class platform applications. Significant topping of between 4-8 months, or complete electric orbit raising configurations are expected from these developments.
- It is clear that the trend to increased use of electric propulsion will continue in the telecommunications market and that higher power thrusters will be needed to meet both the orbit raising and station keeping needs of future small and large platforms.
- Eutelsat has bought another spacecraft using EP to Airbus in 2014. SES has just bought in 2015 two spacecraft (Astrium and Boeing) using electric propulsion as main system for orbit raising and station keeping operations.

Electric Propulsion Systems
System Trade-off Considerations



- For first generation electric prolusion platforms, thruster were only used for North-South Station Keeping alongside a full chemical propulsion system.
- This permitted relatively simple system designs that were accommodated around the existing platform design.
- For the new platforms under development the electric propulsion system (station keeping and orbit raising) becomes more complex and must consider a majority of platform design aspects, launcher choices and target missions.

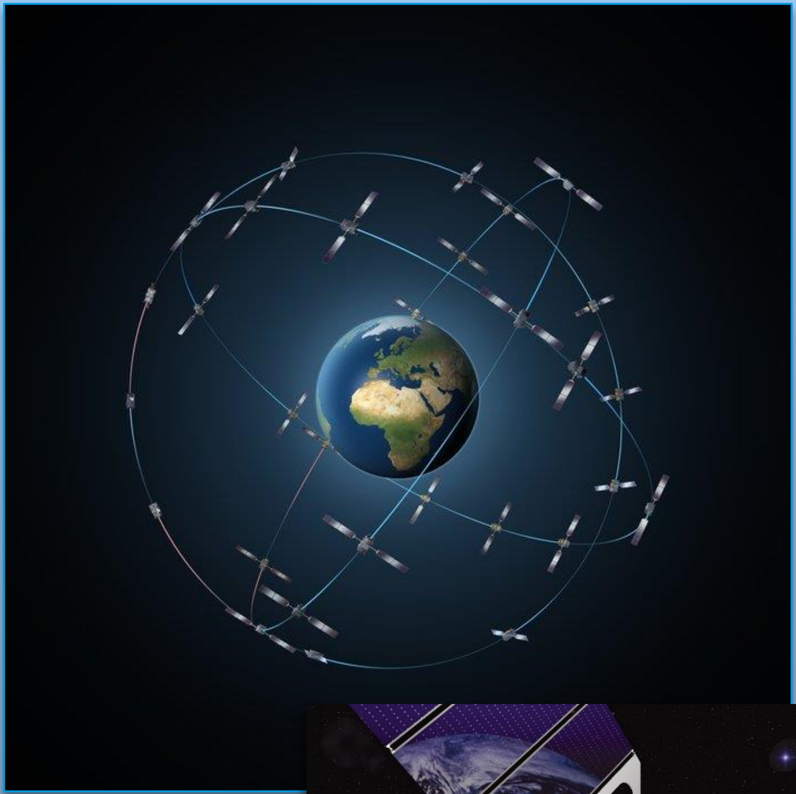
Navigation – Galileo 2nd Generation (G2G)

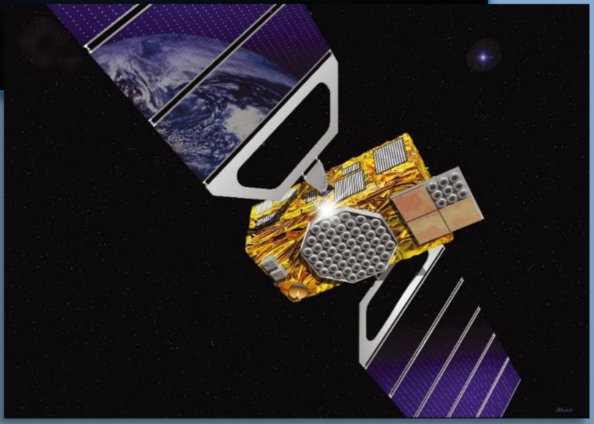
- ESA is preparing the future replacement of GALILEO constellation and is targeting the possibility to increase the Galileo Payload capability without impacting the launch costs (and possibly reducing them).

- 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 Applications:

Application Area: Telecom, Navigation

Technology Subject: ***Electric Propulsion for Orbiting, Deorbiting, Orbit control***

2023- …

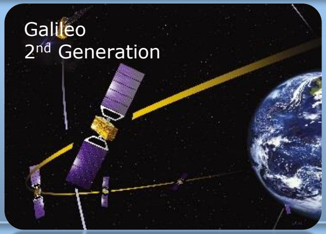
Further Minimizing Transponder to Orbit costs

Further Mass Saving
Further Mass Reduction

Further Minimizing of Time to Orbit (mission scenarios)

2018-2023

Commercial Exploitation



2013-2017

Development for Commercial Exploitation

Xenon market evolution and availability

LEOP(Launch early Operation) costs

Electric propulsion driven recurring and non-recurring prices for Design to Cost options

Industrialization and production chain

5KW Propulsion Systems

Commercial Spacecraft

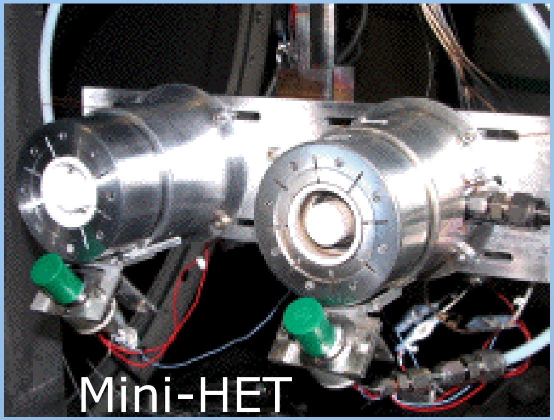
1. Space X: ~5000 spacecraft using mini-HET
2. OneWeb: > 675 spacecraft may also use electric propulsion
3. Others (Leosat, etc.)

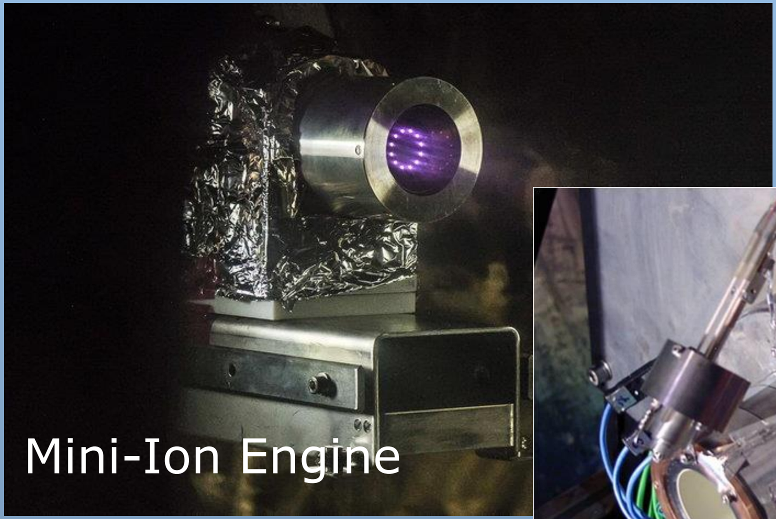
Constellations will use propulsion to perform;

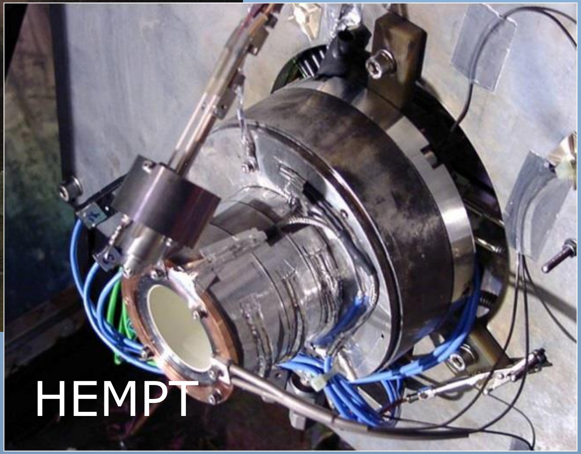
- orbit acquisition, maintenance and de-orbiting from low earth orbit (around 600 -1000km)

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 $)



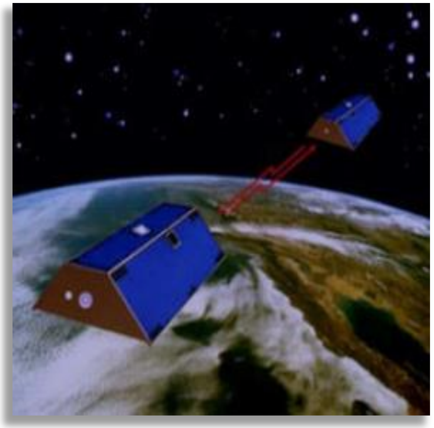




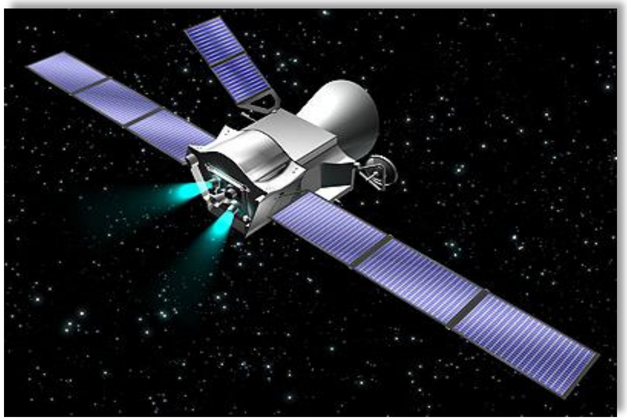
Science & Earth Observation

GOCE

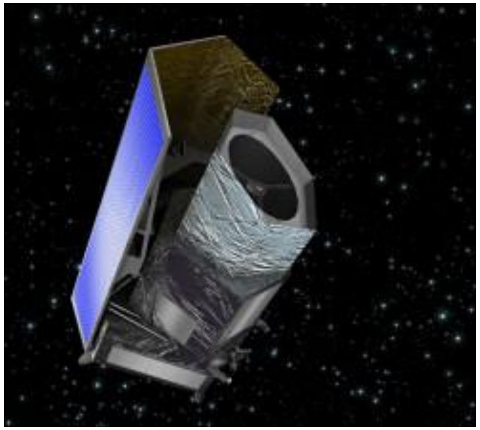
Smart-1



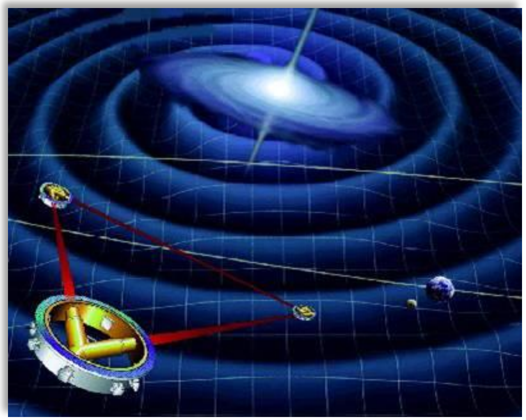
NGGM



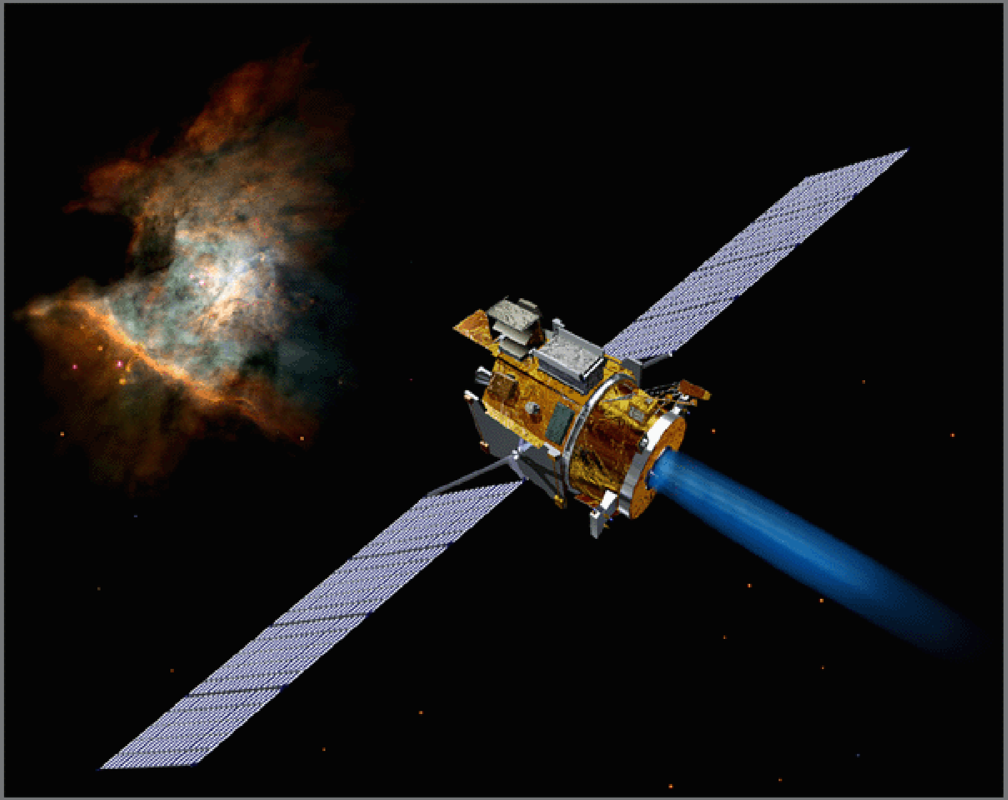
Bepi-Colombo



Euclid

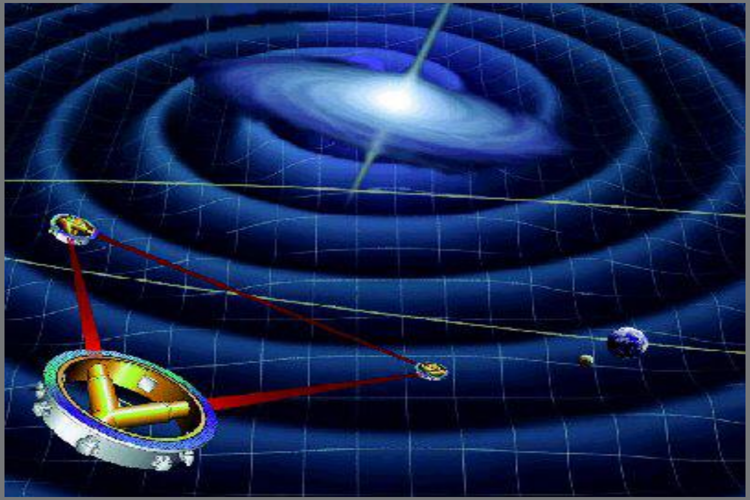


LISA



Interplanetary Missions

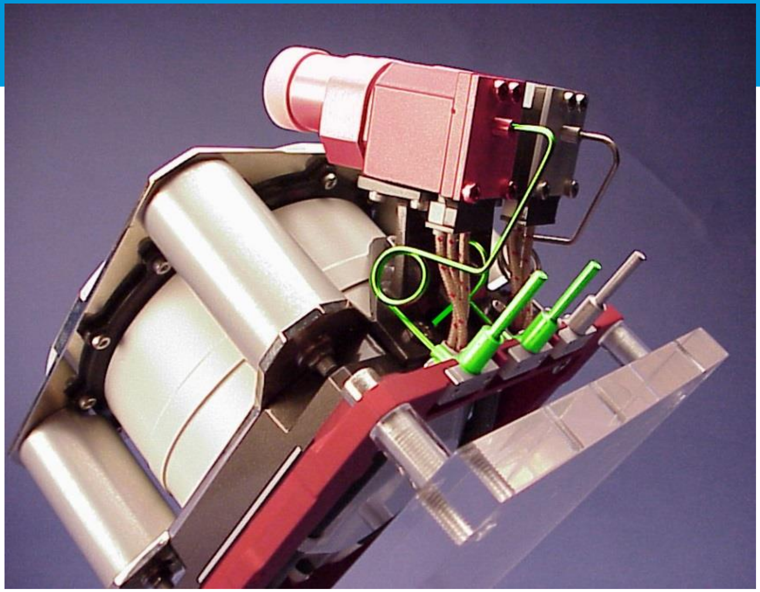
- More scientific payload
- Shorter trip time
- Reduced launch window limitations

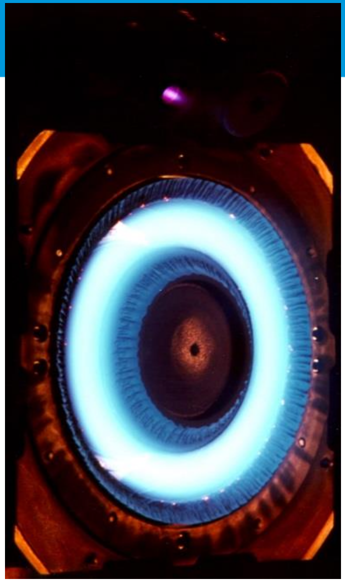


High Precision Pointing Missions

- Space interferometry
- Sintetic aperture observatories
- Formation flying

The SMART-1 Thruster

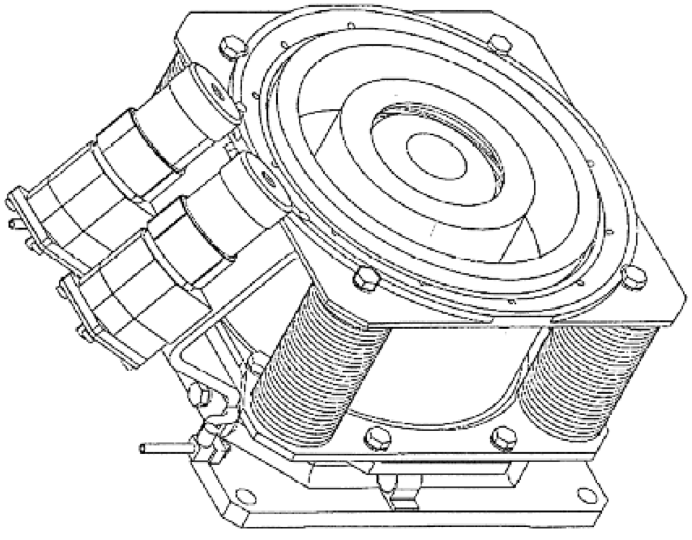




On SMART-1, Electric Propulsion is used as Primary propulsion system.

The thruster selected for this mission is the

PPS-1350 (SNECMA - F).



The PPS-1350 thruster is a derivative of the qualified Russian SPT-100, with increased performance in terms of thrust and specific impulse.

The PPS-1350 has been qualified for a 15 years mission for the NSSK of a large GEO Telecom. An EP diagnostic package (EPDP) was flown to assess the spacecraft thruster interaction

1. Goal for the technology experiment (EPDP) in SMART-1:
2. *"understanding the local environment of an spacecraft using Hall Effect Thrusters (erosion, deposition, torque perturbations, thermal and electric behaviour)"*

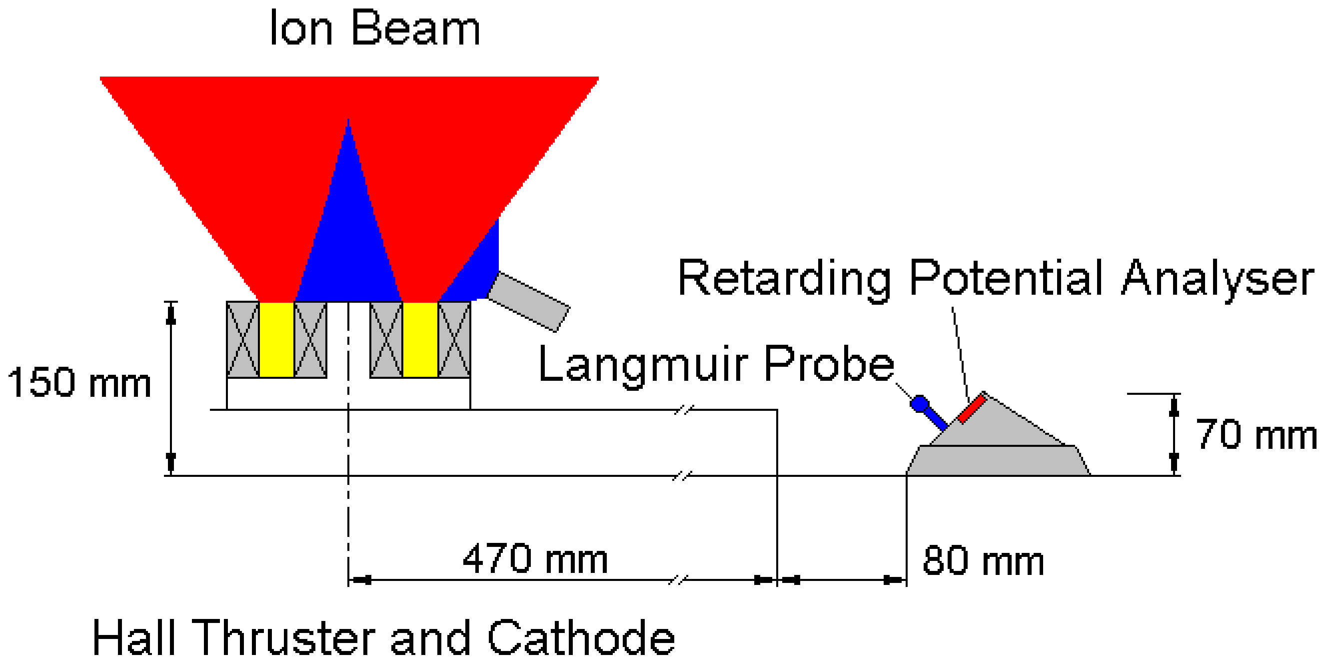
3. Working Approach:
4. - Flight measurements with the EPDP and SPEDE
5. - Ground laboratory measurements for correlation
6. - Models based on physical principles and mechanisms

EPDP: Plasma Diagnostic Package instrument

Summary of Estimated Parameters (derived quantities):

- LP Sensor:
  - Plasma Density, Plasma & Floating Potential,
  - El. Temperature, Ion current density
- RPA Sensor:
  - Ion Energy Spectrum, Ion current density
- QCM Sensor:
  - Mass deposition
- SC Sensor:
  - Open,Short,Load circuit effective resistance (for further post-processing not in LABEN

Layout of the experiment



EPDP findings

European Space Agency

1. EPDP has provided important data which has been used together with the cathode reference potential to derive the plasma reference potential

2. U_{CRP} takes values varying between −5 V and + 10 V during thruster operation, compared to −20 V during ground testing. There is a relationship between the cathode potential and the solar array angle. The floating cathode potential is maximum when the solar cells are exposed towards the thruster backflow.

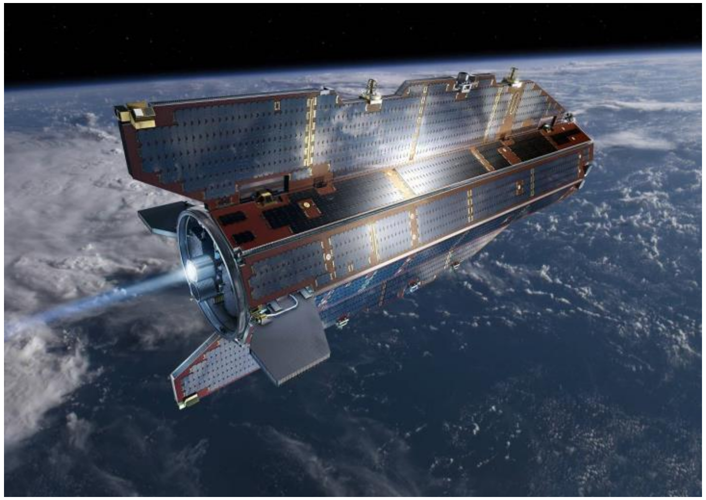
3. Local plasma is the real reference for the cathode operation and the whole propulsion system is floating w.r.t. this reference with a value that has been correlated.

4. The two peaks in energy obtained with the RPA of the EPDP are now well explained. The first peak around 35 eV is well understood at space and ground. The second peak at higher energies (around 65 eV) may be explained by the existence of double charge exchange ions accelerated at higher velocities.

5. The data coming from the solar cell and the QCM demonstrate that the amount of eroded material is very low. The degradation of the cell is lower than expected as was also seen at the main solar arrays

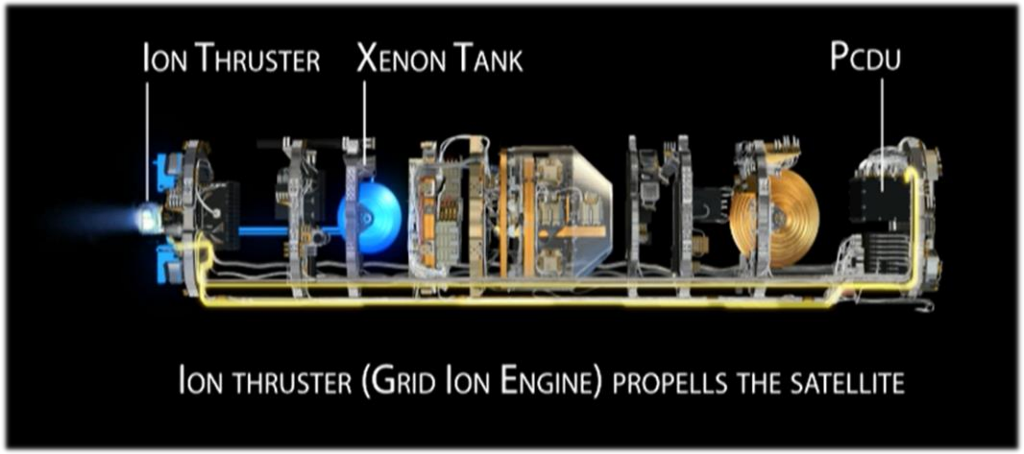
6. The modelling tools used during this process have allowed to understand better the phenomena involved and will be used for spacecraft designers in the development of future EP satellites.

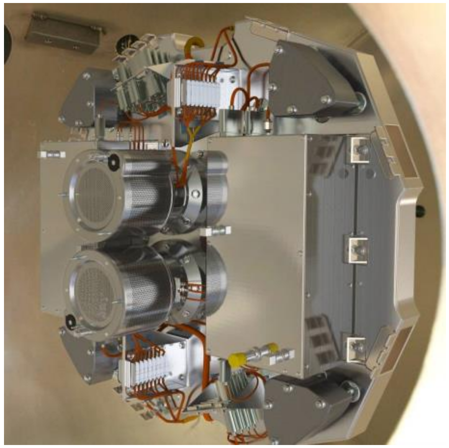
GOCE: ‘Ferrari of space’ Mission Complete



After nearly tripling its planned lifetime, the Gravity field and steady-state Ocean Circulation Explorer – GOCE – has 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.





European Space Agency

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.

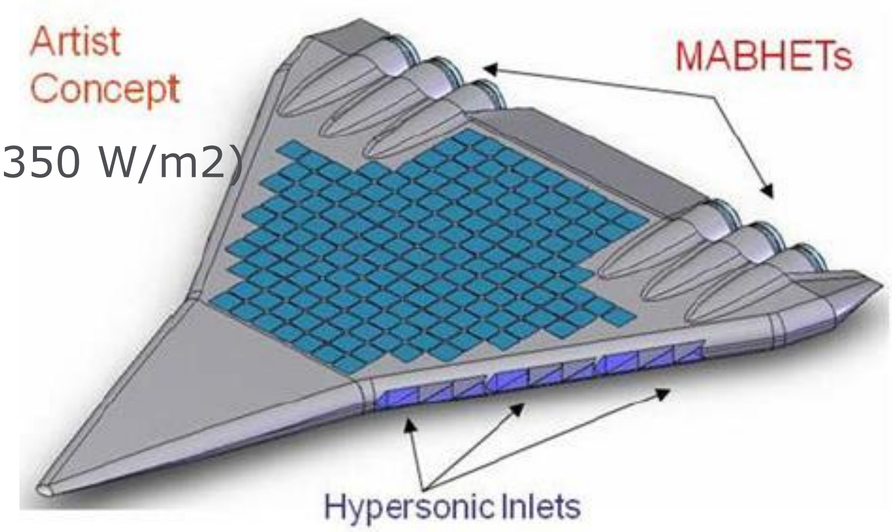
Air-Breathing Electric Propulsion: history ESA developments

1. Currently industrial efforts carried out by SITAEL with support of QuinteScience and coordinated by ESA, are devoted to demonstrate experimentally the feasibility of such a concept in a ground facility.

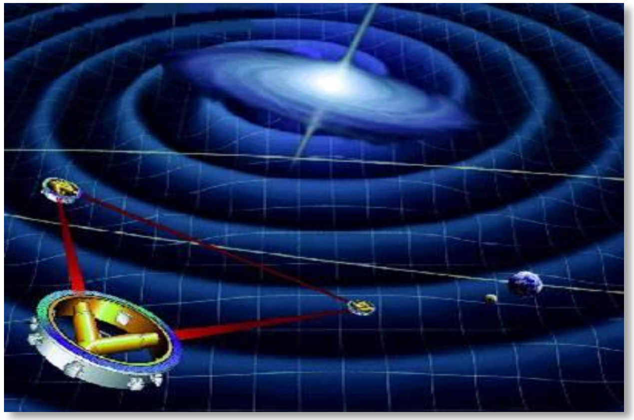
2. The breadboard system, to be tested in a vacuum chamber, is composed of
    a) a particle flow generator,
    b) a particle collector system,
    c) a propulsion thruster (to generate the required thrust) and
    d) a measurement system to characterize the flow and to obtain the forces. This paper reports on the status of the activity.

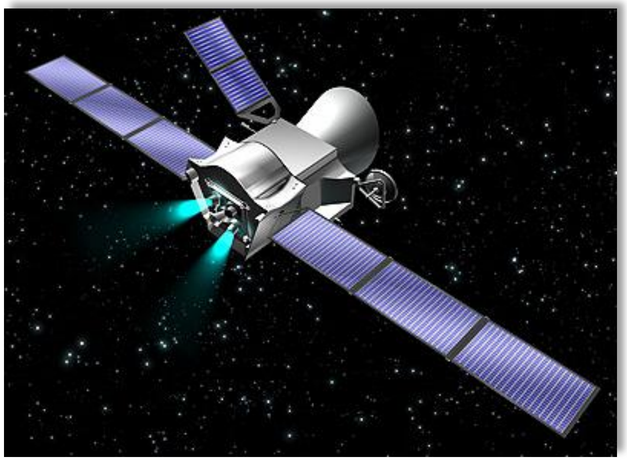
Martian Atmosphere Breathing Hall Effect Thruster (MABHET) by Busek & NASA : Extremely Long Mission Capabilities

1. Concept studies by BUSEK / Nasa Glenn: (**K.Hohman, V. Hruby, H. Kamhawi)**
2. Solar Electric Power Orbiting Spacecraft that ingests Mars Atmosphere, Ionizes a Fraction of that Gas and Accelerates the Ions to High Velocity
3. Mars atmosphere is thin and composed mainly CO_2
4. The altitudes of interest are 120-180km due to drag and power requirements
5. The orbital velocity is around 3.4km/s
6. Solar Flux is about 584 W/m2 (Earth ~1350 W/m2)



Science & Earth Observation

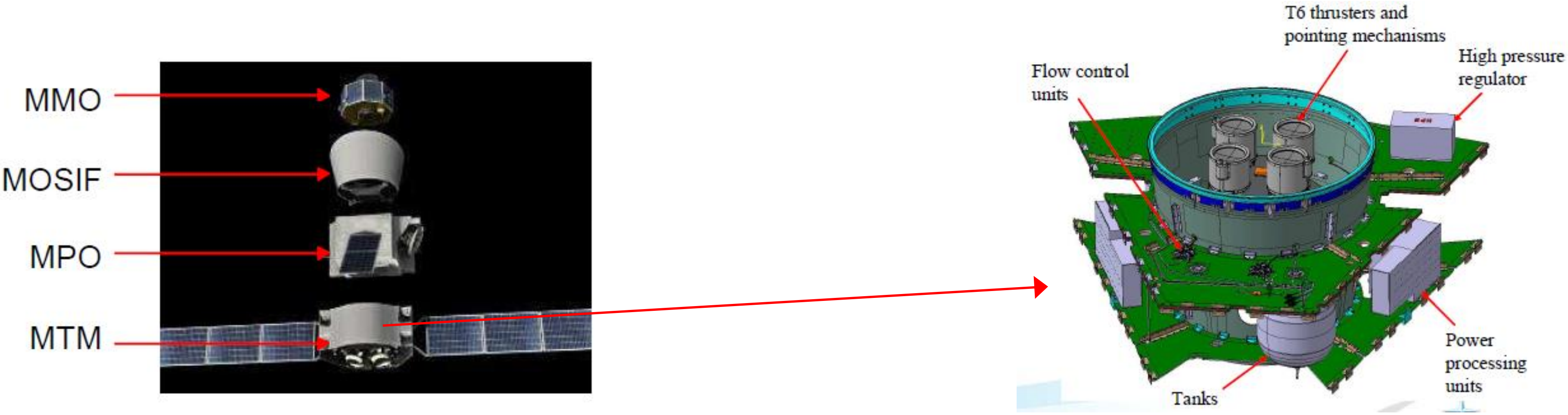


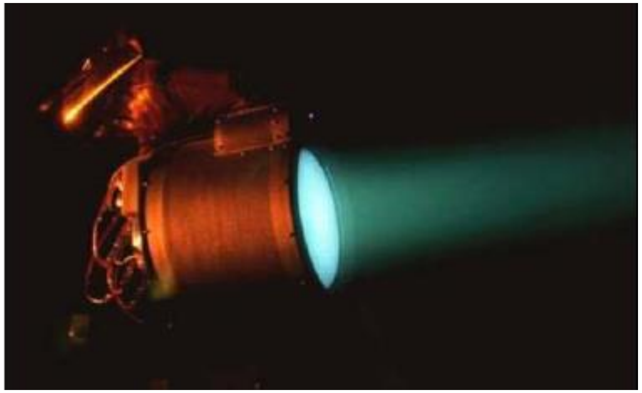


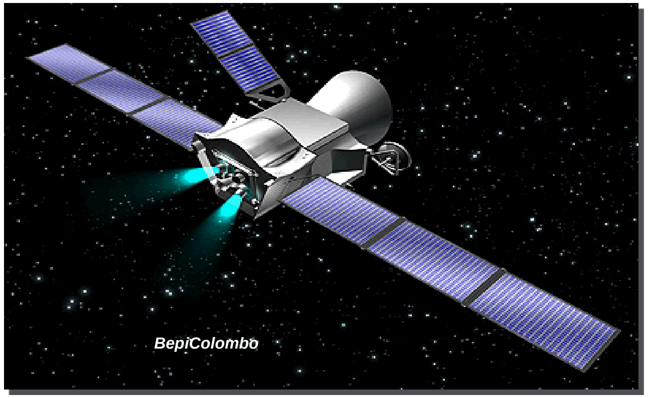
Future Needs

- Next Generation Gravity Missions, NGGM, will require Mini-ion Engines and micro-field emission thrusters to provide drag compensation and formation control.
- Euclid is looking at Mini-ion Engines as back up for the proportional cold gas thrusters.
- 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



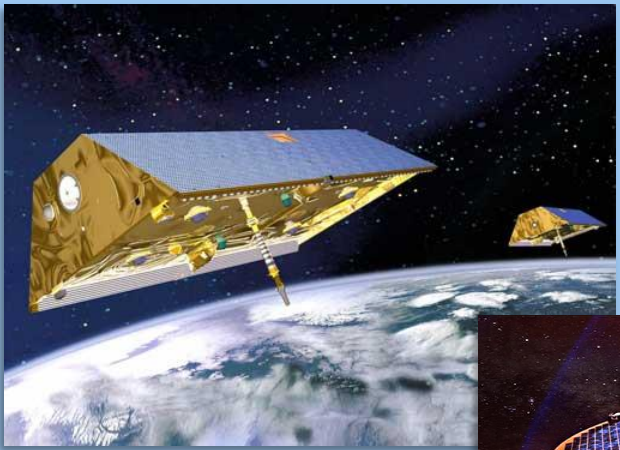


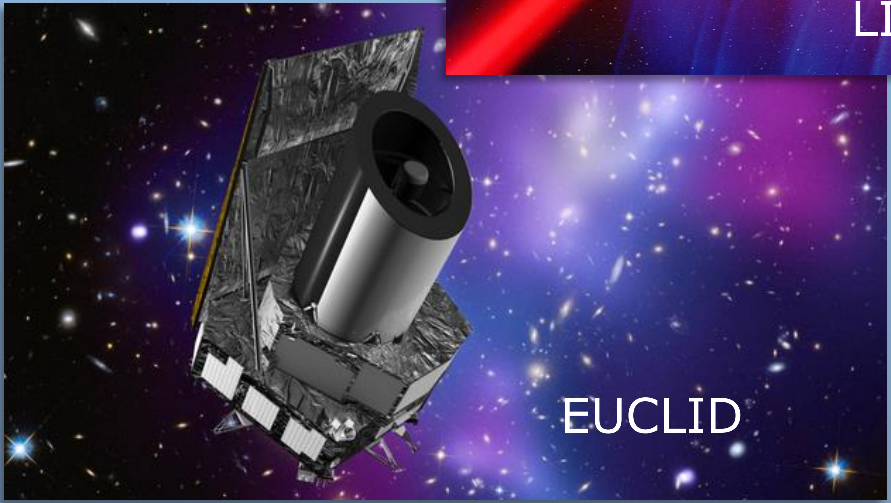


Science and Earth Observation

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 Euclid.
- Mini-hall thrusters system are in development to satisfy the needs of future mini/micro-satellites to perform SK and disposal maneuvers.
- Large Ion Engines and Hall Effect Thrusters 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.





Science and Earth Observation Electrical Propulsion Developments and Challenges

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) and will allow us to investigate the existence of gravitational waves (LISA).

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 Euclid.
- Mini-hall thrusters system are in development to satisfy the needs of future mini/micro-satellites to perform SK and disposal maneuvers.
- Large Ion Engines and Hall Effect Thrusters 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.

EO and Mega Constellations:

Technology Subject: ***Electric Propulsion for Orbiting, Deorbiting, Orbit Control fine Attitude control, Drag Compensation***

2020-2024

High Resolution From GEO(EO)

Next Generation Gravity Mission(EO)

2018-2020

Propulsion Subsystem:
- Low cost (constellation)
- Low Power Consumption (EO and Constellation)
- Light (EO and Constellation)
- High thrust controllability (EO)
- Manufacturing Capability(Constellation)

2013-2017

Alternative propellants for Mini, Micro, Nano Satellites

Power

Micro/Mini Propulsion

Nano/Microsatellite Applications

Scientific Research, Technology, EO, Education, Military, Astronomy

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)

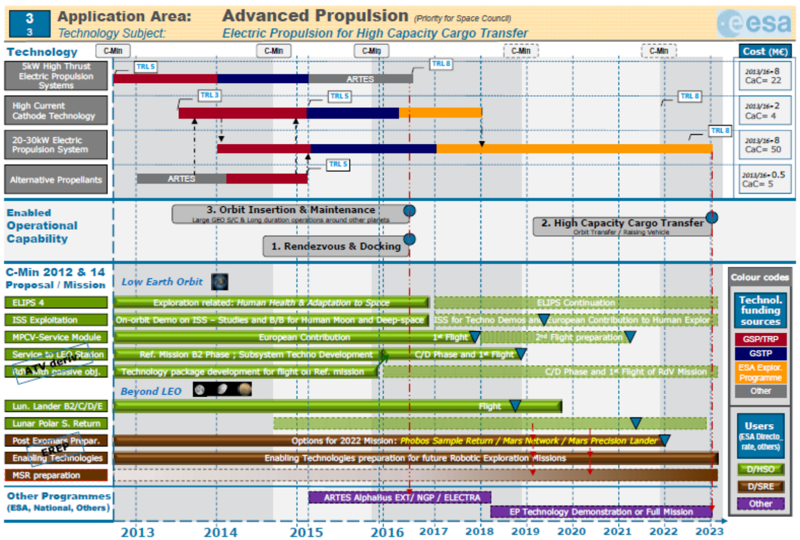
A clear need has been identified for the development of high power (~15 kW-20kW), long lifetime Hall effect thrusters in the frame of discussions concerning future Space Tugs.

Several meetings have been performed to identify possible commonalities in terms of technology development between Space Tug applications and e.Deorbit. No commonalities have been identified in terms of electric propulsion since e.Deorbit is baselined to use chemical propulsion. However developments in the frame of e.Deorbit could be of interest for the AOCS thrusters (chemical propulsion) and the auxiliary propulsion system required for collision avoidance manoeuvres.

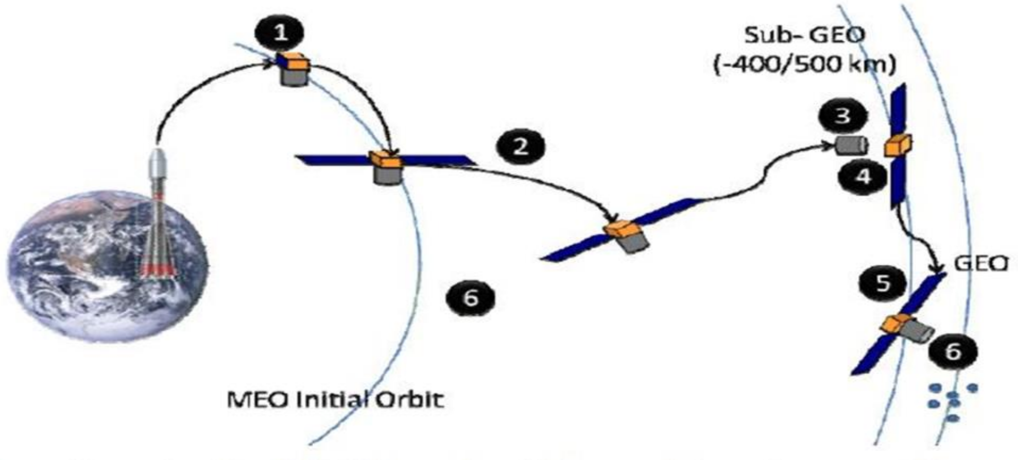
Exploration

ESA has initiated a reflection period on Exploration.

- Space Tugs to the Moon and Mars .
- Exploration roadmaps have been published in 2012 and reviewed in 2015.
- The main idea is to have technology missions that prepare the way to Exploration, taking into account the different needs of these missions on propulsion.
- R2D3 and Complex are technology missions with Electric Propulsion (10kW engines)
- The roadmaps for the technology needed for Exploration were harmonised with industry in 2015.



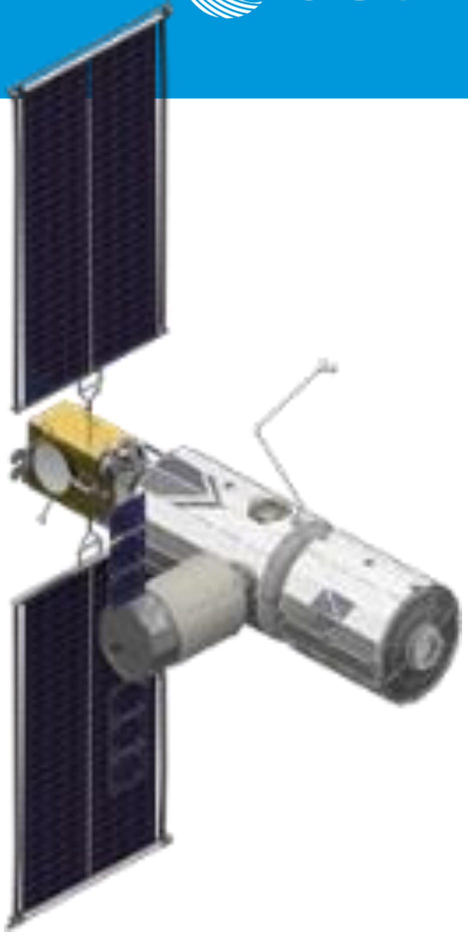
Technologies for Space Exploration Roadmaps



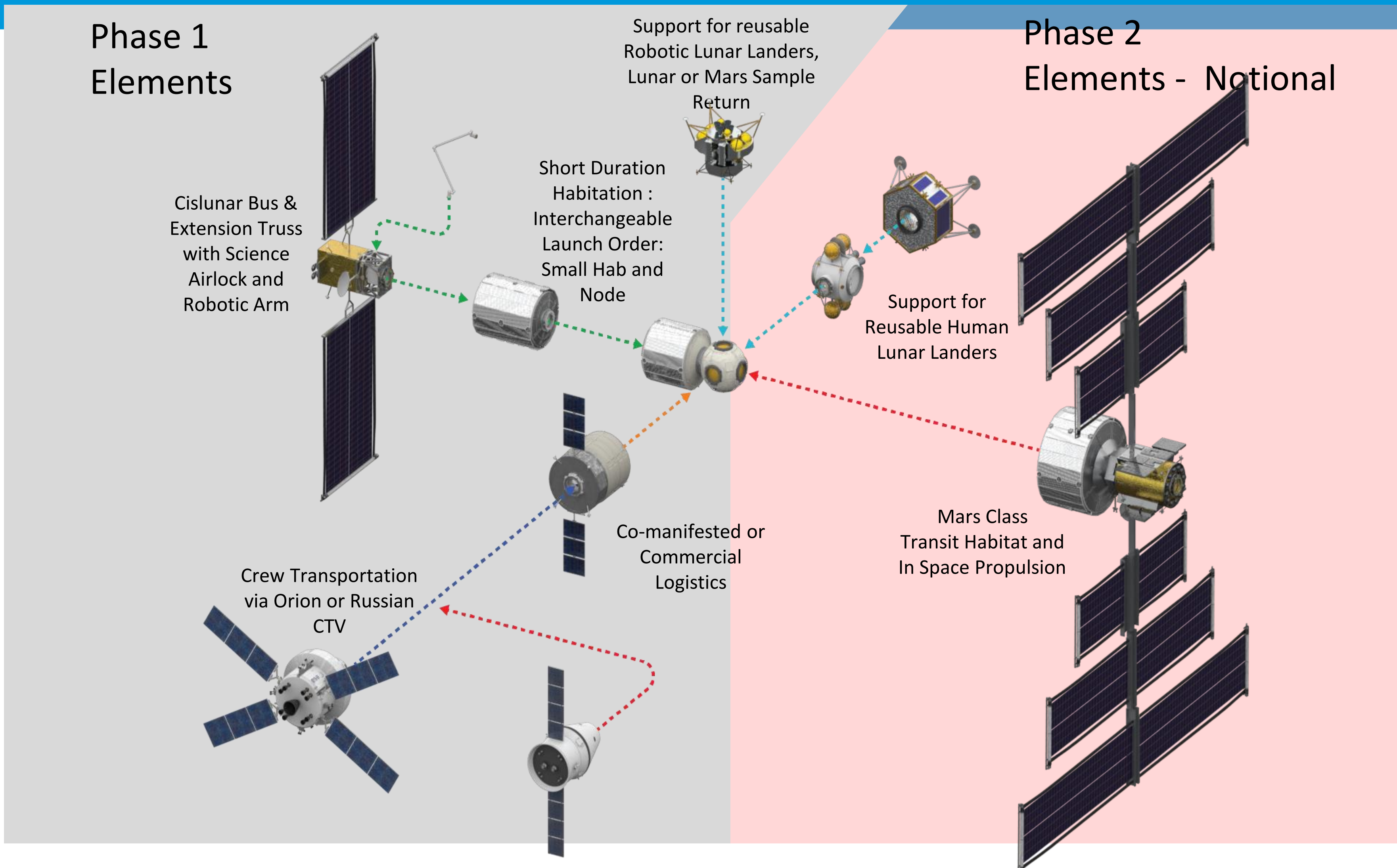
European Space Agency

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

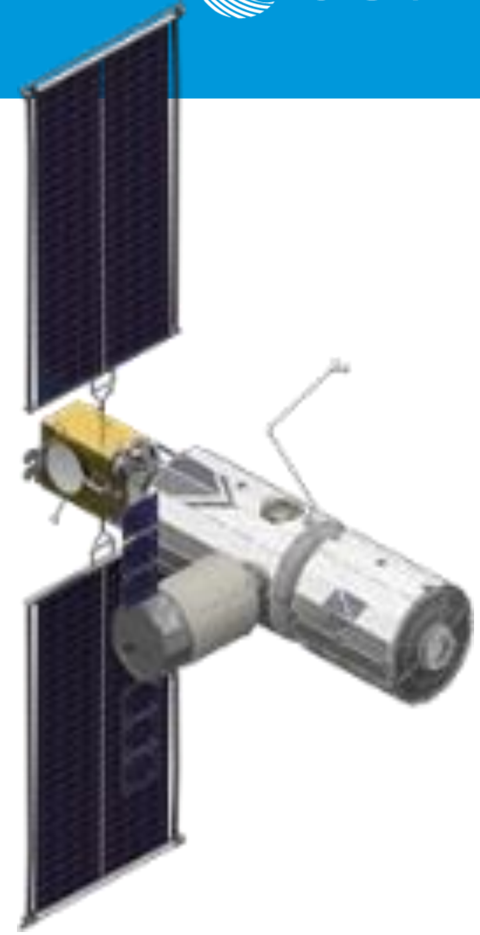


Cislunar Infrastructure – Possible ESA contributions

NASA and ESA are studying possible options to define ESA's role and responsibilities in the Phase 1 of the CTH development and operations. It is expected that the ESA contribution may initially include:

- Transportation elements (improved/evolved Orion European Service Modules
- A habitation module (including sub-systems and life support)
- Contribution to the CTH service module, with data, navigation, communication subsystems and electric propulsion for orbit maintenance and support to orbit translation missions
- Role in module/logistics transportation with an electric propulsion tug (TBC)
- Operations and ground control center

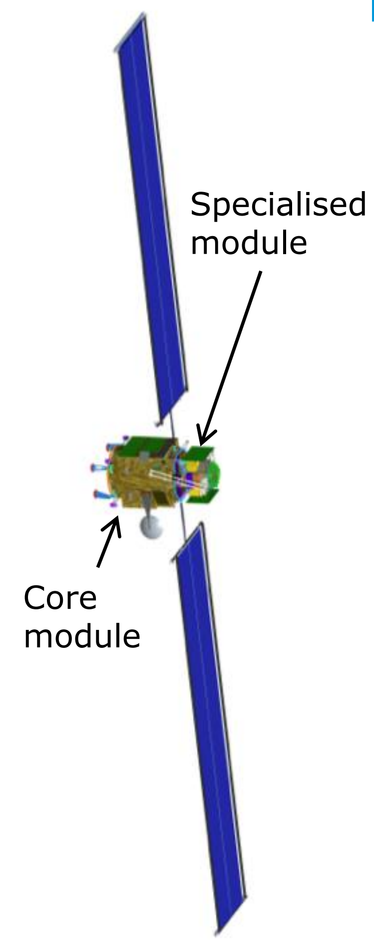
- Specific Phase A/B1 activities will start after C-MIN 2016 to further define the ESA selected contribution to Cislunar.
- Several European Industries (Airbus, TAS, OHB, RUAG) are supporting ESA in this activity.



15-20 kW HET

For the Cislunar service module NASA is considering a large re-use of the Asteroid Retrieval Mission (ARM) bus (core module).

- As a potential ESA contribution to the Cislunar service module ESA is considering to provide:
  - The specialised module with coms, main bus avionics, scientific airlock, RVD sensors, docking, etc,
  - A 15-20 kW HET string (thruster, thrust vector control, power processing unit) in addition to the NASA 12.5 kW HET units (4).
- The business case for a SEP thruster (class 40-60 kW) is not demonstrated yet, but would use the same thruster.
- High power SEP is becoming more and more interesting for various applications:
  - Large satellite transfer to GEO
  - Interplanetary missions
  - Cislunar Phase 2 and Mars transfer
  - Spacecraft servicing



Exploration:

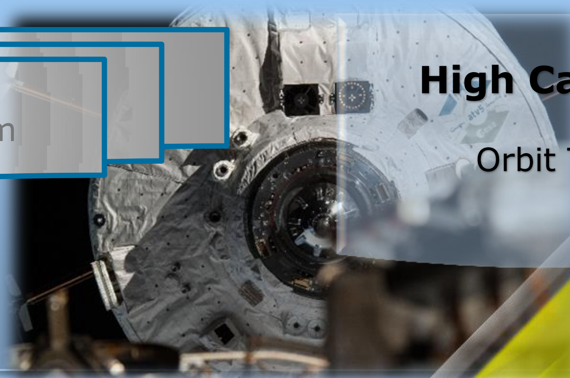
Application Area: Advanced Propulsion *(Priority for Space Council)*

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

esa

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

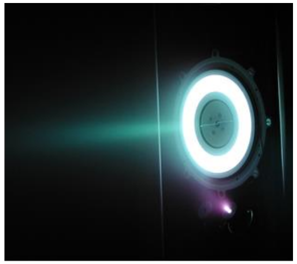
High Current Cathode Technology

5KW Propulsion Systems

Technology Developments

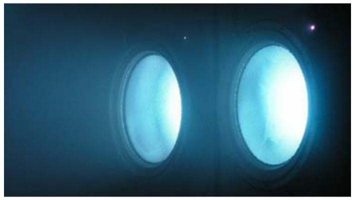
Thrusters

- Higher and lower power versions of current engines (HETs, Ion Engines, HEMPT). 5-20 kW power
- MEMS, Helicon Antenna Thrusters, thrusters, Micro-PPTs, QCTs, ERC, etc.
- Mini-ion engines, mini-Hall Effect thrusters, FEEPs



Components (emphasis on cost reduction)

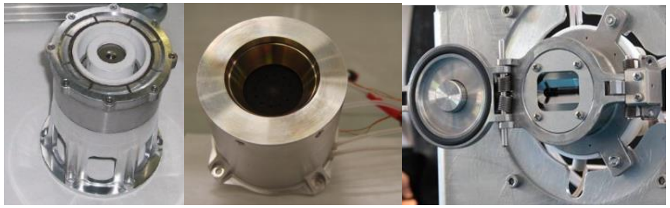
- Xenon storage, regulation and flow control systems
- Cathodes and neutraliser
- Power electronics



Electric Propulsion in-flight Diagnostic Packages

Verification Tools and techniques

- Advanced plume characterisation tools and models
- Electric Propulsion EMC - EMI validation facilities
- EP system design and performance verification models



EP Implementation Support

- Assessment of Flight data from missions in-orbit
- Optimisation of systems configurations

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 (Germany and Italy) 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. Power levels around 5 kW or higher. 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.).

EPIC: H2020 SRC for Electric Propulsion

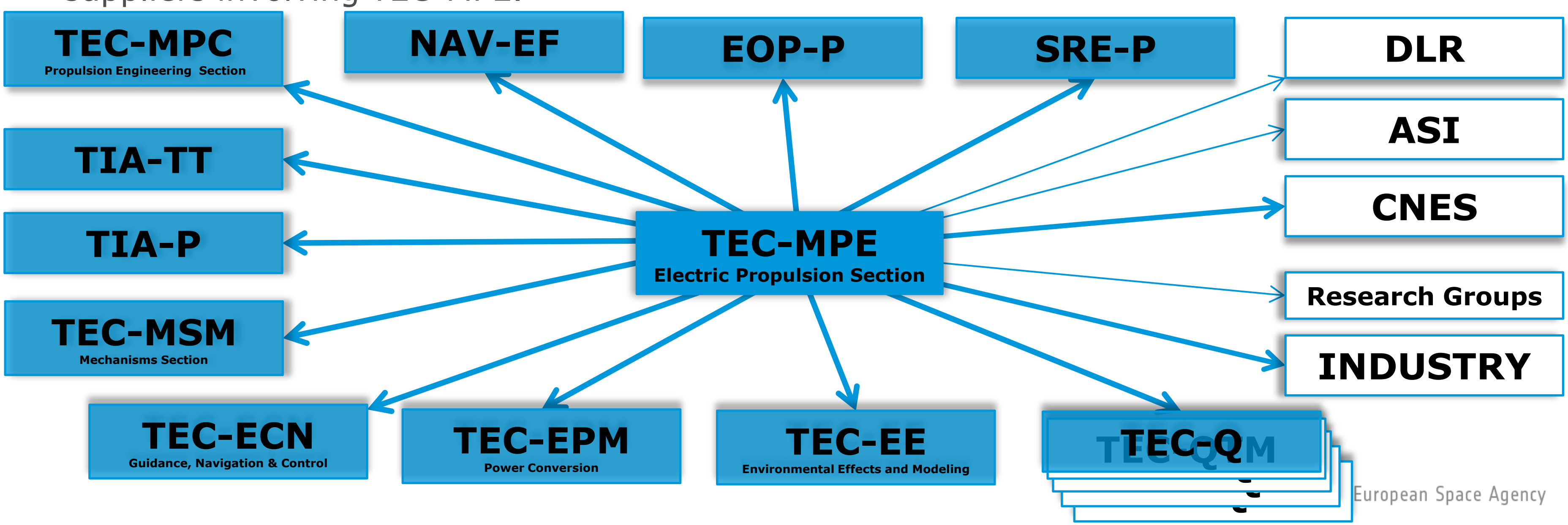
- Electric propulsion has been identified by European actors as a Strategic Technology for improving the European competitiveness in different space areas.
- **The European Commission (EC)** has set up the "In-space Electrical Propulsion and Station-Keeping" Strategic Research Cluster (SRC) in Horizon 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%).

EPIC PSA

- The European Commission (EC) has funded, as part of the Horizon 2020 Space Work Programme 2014, a Programme Support Activity (PSA) for the implementation of the **Strategic Research Clusters (SRC) on "In-Space electrical propulsion and station keeping"**.
- The "**Electric Propulsion Innovation & Competitiveness**" **(EPIC)** project is the PSA for the Electric Propulsion SRC funded as response to the H2020 Space COMPET-3-2014 topic.
- It has been initiated in October 2014 and has a duration of **5 years**, during which it is meant to support the European Commission on the definition and successful implementation of the SRC in Horizon 2020, in order to achieve the objectives set for it and subsequently for Europe on this increasingly relevant technology area at worldwide level.
- **The EPIC PSA aims at providing advice to the EC preparing Roadmaps, drafting call texts and assessing results of the SRC operational grants.**
- The R&D work will come in the SRC as a part of future Calls made by the EC, open to all EU Member States and H2020 participants, and will be selected and supported through the normal Horizon 2020 grant procedures
- **EPIC PSA Partners: EPIC – ESA (coordinator), ASI, BELSPO, CDTI, CNES, DLR, UKSA, Eurospace, S4S**

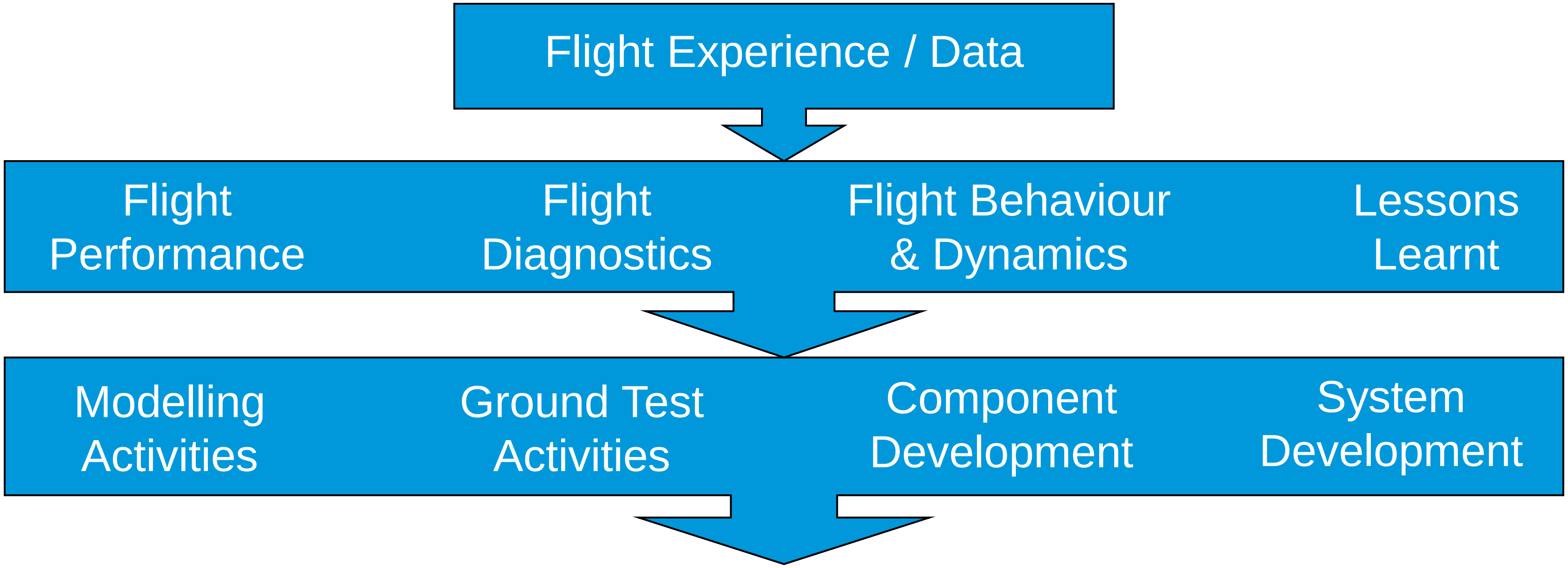
Capabilities in ESA D-TEC

- Within ESA; the Directorate of Technical & Quality Management (D-TEC) permits a close cooperation between the many disciplines that are needed to support new technologies, through to implementation of **flight ready systems**.
- D-TEC provide direct support to telecommunication, Earth Observation, Science, Exploration and Navigation directorates and programmes.
- Function of TEC-MPE, is entirely dependent on an excellent working relationship with all European entities involved in the commercial exploitation of the technology.
- Below an indication of regular interaction between specialist disciplines, customers & suppliers involving TEC-MPE.



Capabilities in ESA Flight Experience Activities

- Coordinated by TEC-MPE, dedicated activities are implemented to ensure maximum return on experience from Flight Programs, both institutional and commercial.



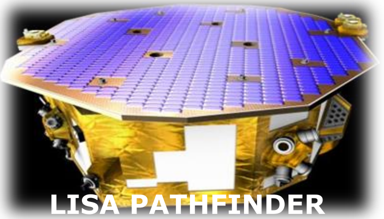
Verification of current designs

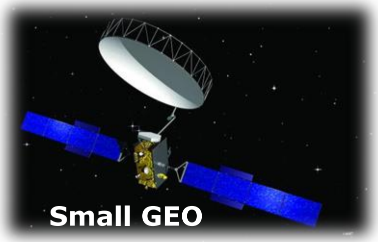
Securing confidence in technology

Next Generation of EP Systems / Applications

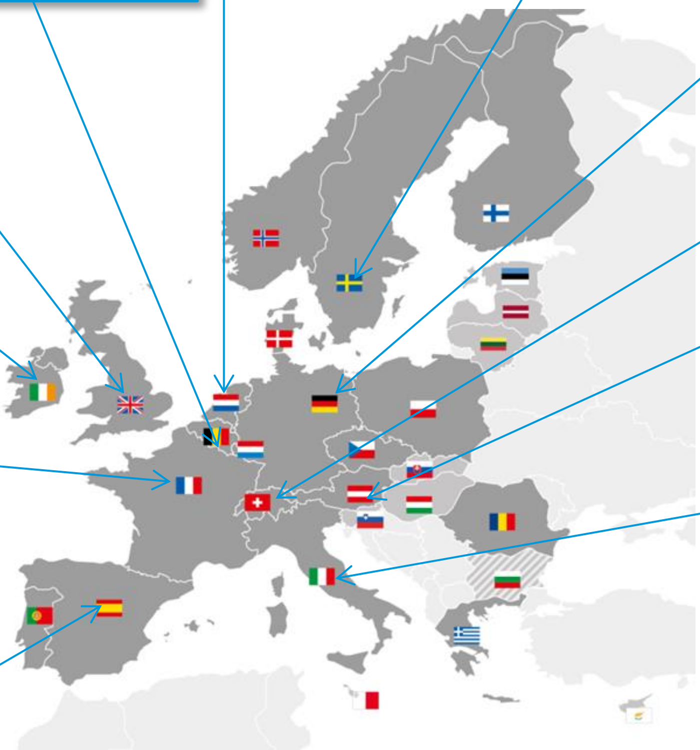
3. EPL Activities

- 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 Europe



Coverage of EP technologies in Europe

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

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.
- 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

- *Consolidation of the current European products* (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.
- *Utilization of the current flight data* (Artemis, Smart-1, GOCE, Inmarsat 4F, Intelsat 10, Astra 1K, Alphabus, etc.) to validate the models that will be used by the spacecraft designers in the future.
- *Standardization of engineering processes and testing facilities* employed in the design, manufacturing and qualification of the current electric propulsion systems.
- *Preparation for the ultimate goal: the full electric propulsion spacecraft* where the benefits of the use of electric propulsion will be maximize by designing the spacecraft around the electric propulsion system.

ESA Activities

- *System studies are required to address all potential uses of EP.*
- *Systematic analysis/exploitation of available flight data from existing operational missions is required.*
- *Ion Engines Development for Telecomm (NSSK, orbit topping, deorbiting, etc.), Earth Observation and Scientific Missions (formation flying and drag free control) and space exploration (interplanetary missions).*
- *Hall effect thrusters and HEMPT (current base line for Neosat, Electra): Continued development for future applications including, commercial, Earth Observation, science and exploration.*
- *Microthrust development for science and Earth observation missions. Nanosata are also included.*
- *Test facilities (EMI, lifetime,…) and procedures standardisation is needed to prepare all these technologies for space applications.*
- *Technology/product evolution, new concepts and flight experiments are needed for future applications (mini-ion, mini-Hall,, Helicon Antenna Thruster, MEMS colloids, micro-PPTs, etc.).*

Technology Challenges

1. Microthruster development and measurement of microthrust levels are very challenging.
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
3. Qualification through long lifetime testing such as Bepi Colombo.
4. EP Cost reduction exercise at system level specially for Constellations
5. Spacecraft thruster possible interactions.
6. Flight opportunities, Bepi Colombo, Small GEO, Neosat, Electra, NGGM, etc.
7. Nanosatellites with propulsion.

Conclusion

- Exploitation of Electric Propulsion in Europe has reached the end of the beginning, with mission success demonstrated for Telecom, Science and Earth Observation programmes.
- **High power EP (5kW) medium term applications**: telecommunication will be able to make an immediate use of these technologies or on obit control and full or partial transfer.
- Later, Navigation, Science (interplanetary missions) and Exploration (the Moon, Asteroids and Mars) will require such systems.
- In order to improve European access, it is important to retain a capability to deliver alternative 5 Kw technologies The power for these engines is around **5kW**.
- ESA is also developing micro thrusters such as **mini-ion engines, FEEPs, mini-Halls**, etc. with capability to fulfil stringent Science and Earth Observation requirements (LISA, NGGM, Euclid, microsatellites etc.). Airbus, ALTA, FOTEC, etc. are busy with these developments where lifetime will have to be assessed.
- Galileo 2nd Generation programme, **EGEPT**, is planning the use of electric propulsion to perform orbit raising from LEO/GTO to MEO.
- The Next evolution of the current engines developed today for high power (5kW) will have to provide higher LIFETIME, lower power to thrust ratio, higher specific impulses and be more efficient. These are the main challenges. **10 and 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.