

SGEO Electric Propulsion Subsystem Development Status and Future Opportunities

IEPC-2013-144

*Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 – 10, 2013*

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OHB System's Small Geostationary Satellite (SGEO) is approaching the first flight for Hispasat HAG1 mission. Assembly, Integration and Testing/Validation (AIT/AIV) activities are currently ongoing at satellite level. The electronic units of the electric propulsion subsystem (EPPS) have been integrated on the platform and functional tests have been performed. The development is driving towards the integration of the propulsion module, which includes the tanks, the propellant supply assembly and the cold gas thrusters. The electric thrusters will be mounted in the final stages of the integration phase. The paper gives an overview of the SGEO performance and focuses on the development status of the EPPS. The evolution of the satellite platform towards a full electric propulsion design is outlined.

Nomenclature

AOCS	=	attitude and orbit control system	GTO	=	geostationary transfer orbit
AIV/AIT	=	assembly, integration and testing / validation	HEMPT	=	high efficiency multi-stage plasma thruster
ADE	=	actuator drive electronics	HTA	=	HEMPT thruster assembly
BoL	=	beginning of life	LAE	=	liquid apogee engine
CGTA	=	cold gas thruster assembly	PFM	=	proto flight model
CPPS	=	chemical propulsion subsystem	PPU	=	power processing unit

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FM	=	engineering model	PRP	=	pressure regulator panel
EoL	=	end of life	PSA	=	propellant supply assembly
EPPS	=	electric propulsion subsystem	PSCU	=	power supply and control unit
EPTA	=	electric propulsion thruster assembly	RCT	=	reaction control thruster
ETSU	=	external thruster switching unit	SCE	=	support and control electronics
FCU	=	flow control unit	SPT	=	stationary plasma thruster
FM	=	flight model	XFC	=	xenon flow controller
GEO	=	geostationary earth orbit	XTA	=	xenon tank assembly

I. Introduction

THE Small Geostationary Satellite (SGEO) is approaching the first flight for Hispasat HAG1 mission. The platform is developed in the frame of the European Space Agency's ARTES-11 program. OHB System AG is the prime contractor, supported by the subcontractors OHB Sweden AB, LuxSpace SARL, OHB CGS S.p.A. and Ruag Space AG¹.

The SGEO platform was born to support mainly telecommunication missions, but its modular structure is flexible to accommodate different types of payloads. The actual configuration can board payload mass up to 400 kg and payload power up to 3.5 kW at end of life. The design lifetime of the platform is 15 years, after this time the satellite will be transferred to a disposal orbit. The payload capacity for SGEO is extended by the innovative electric propulsion subsystem, as well as the possible launch opportunities. Indeed the satellite is compatible with the two launch scenarios of a standard geo-transfer orbit and a direct-to-geosynchronous orbit injection.

II. System Overview

Although SGEO is compatible with two different launch scenarios, and therefore the internal accommodation of the propulsion subsystem can be adapted to the mission needs, the envelope of the satellite is independent of the propulsion subsystem. The satellite body dimensions are 2.3 m x 1.9 m base area and 2.5 m of height.

SGEO has been designed and developed with the effort to optimize the payload-to-platform ratio in order to reach commercial cost-effectiveness; this has been achieved with the use of high system performance and new technologies.

The power subsystem is based on a 50 V regulated main bus powered by GaAs triple-junction solar cells disposed on six steerable solar panels. The 9 m solar arrays are deployed after orbit acquisition. The main bus is capable to distribute more than 6.5 kW power at BoL to the spacecraft, roughly divided in 4.1 kW to the payload and 2.4 kW to the platform in nominal mode. At EoL the payload available power reduces to 3.5 kW including margins.

As anticipated, the satellite structure has been designed to be compatible with two different launch scenarios: a direct launch into GEO orbit and a GTO injection with successive transfer phase to GEO. The architecture difference between these two scenarios lies in the implementation of the CPPS for GTO transfer. The EPPS is mainly used for GEO operations; it is based on the combination of the EPTA and the CGTA, both fed with xenon propellant.

The SGEO configuration for GTO transfer foresees the fulfillment of the orbit control functions by using CPPS and EPPS: the CPPS is used for the satellite transfer from GTO to GEO, the EPTA performs the final station acquisition in GEO, the station keeping and repositioning over the satellite lifetime, while the CGTA de-tumbles the satellite after launcher ejection and provides attitude control in satellite safe modes (e.g. reaction wheels not available). The satellite is transferred into the graveyard orbit at end of life using the EPPS.

The station keeping maneuvers consist in activating two thrusters sequentially around each orbital node 6 days per week. Three-axes attitude stabilization relies on a set of reaction wheels, which accumulate the angular momentum further on dissipated by the EPTA or CGTA.

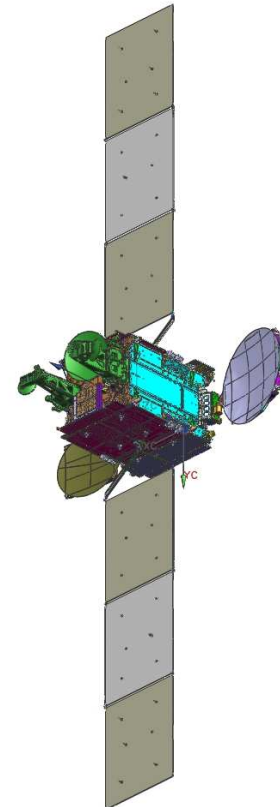
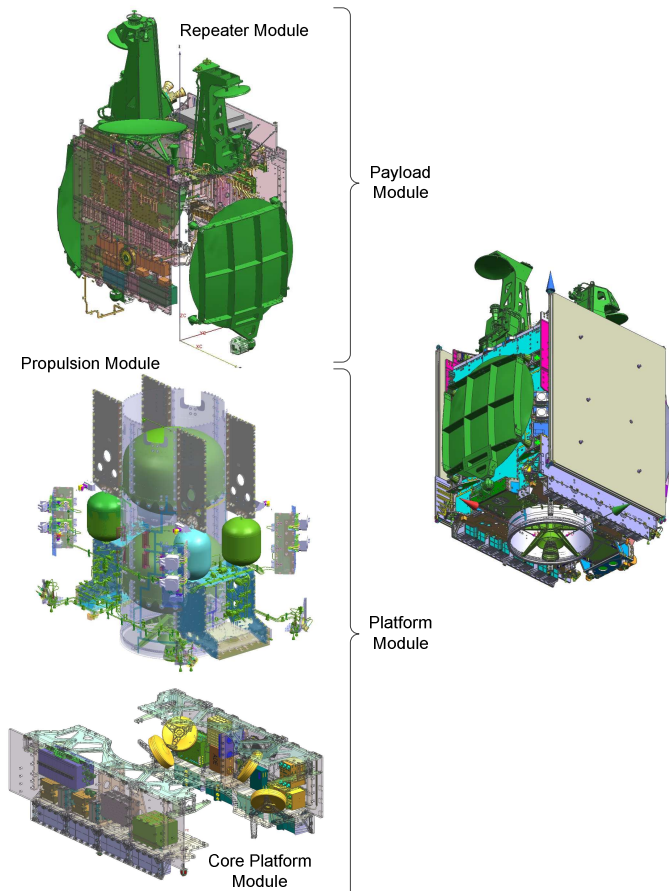


Figure 1 SGEO satellite view in orbit configuration

The HAG1 mission foresees a GTO injection of 1700 kg satellite dry mass. The GTO to GEO transfer is performed by the CPPS at the cost of 1300 kg of propellant mass. The xenon mass for the mission is 200 kg of xenon, used for EPTA and CGTA; therefore the SGEO launch mass is 3200 kg.

A. Architecture and Accommodation

Figure 2 depicts the SGEO modules. The satellite design follows a modular approach: the core platform module, the propulsion module and the repeater module with the antenna assemblies are separately integrated and then mated during the last satellite integration phases.



a 400 N engine, installed at the launch vehicle adapter. It is used to perform the GTO to GEO orbit transfer. The

Figure 2 SGEO modular concept

satellite attitude during LAE firing.

The EPPS is divided in three branches which share the same tank and propellant regulator: two EPTA and one CGTA. The nominal branch of the EPPS is composed of four HEMPT, while four SPT-100 complete the redundant branch. The thrusters are mounted in pairs (one nominal and one redundant) at the edges of the East and West panels, with thrust directions symmetrically oriented around the Nadir vector. In nominal operation, each thruster has thrust vector components in the directions orthogonal to the orbital plane and tangential to the satellite velocity vector in inertial space. This accommodation has been preferred against the complexity of the thruster orientation mechanism as currently used on other telecommunication platforms and has the advantage of providing East/West station keeping control.

The CGTA accommodates eight thrusters (four nominal and four redundant), mounted on brackets close to the RCTs, on the anti-Earth deck of the satellite. The thrusters are placed in pairs in the East and West planes, canted 55° with respect to the x-axis, with an offset from the spacecraft center of mass for de-tumbling the satellite after separation from the launch vehicle.

during the last satellite integration phases.

The payload antennas are deployed from the East and West panels, the boresights are parallel to the positive z-axis (Nadir). The y-axis points to South and the x-axis is oriented positive towards the orbital velocity vector. The apogee engine nozzle protrudes from the negative z-axis (Zenith) side of the satellite.

The repeater module hosts the payload, manufactured by Tesat.

The central tube is the main structural element; the propulsion module is built around it. The CPPS propellant tanks are installed inside the central tube, while the helium and xenon tanks are symmetrically placed around it and as close as possible to the z-axis in order to minimize the excursion of the center of gravity.

All the structure, made of aluminum and composite materials in order to minimize the platform weight, develops from the central tube.

The core platform module accommodates the electronic units which belong to the satellite subsystems and the reaction wheels. Heat pipes run across the north and south panels to remove the heat dissipated by the units. The batteries are accommodated on the anti-Nadir panel.

The propulsion module accommodation is detailed in Figure 3 (a).

The CPPS consists of one LAE and 8 RCTs (four nominal and four redundant). The LAE is (four nominal and four redundant). The LAE is the RCTs provide 10 N thrust, they are located on the base panel and operated to control the

B. EPPS Design Description

The EPPS schematic diagram is shown in Figure 3 (b). The EPPS subsystem, provided by OHB Sweden, is composed of five main assemblies: the xenon tank assembly (XTA), the propellant supply assembly (PSA), the cold gas assembly (CGTA) and the two electric propulsion thruster assemblies (EPTA1 and EPTA2). Four HEMPT and the PSCU compose the nominal (EPTA1) branch, while the redundant branch (EPTA2) contains four SPT-100, the PPU, the ETSU and FUs. The XTA and the PSA are shared with the CGTA.

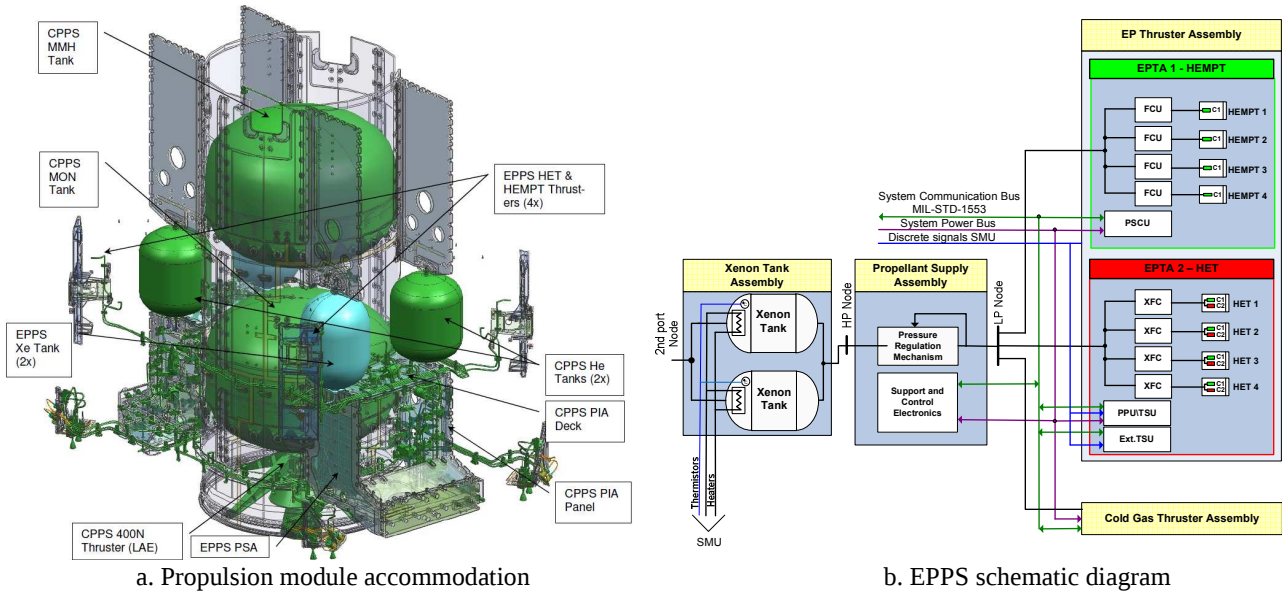


Figure 3 Propulsion module

The XTA is composed of two tanks for the xenon storage: a total volume of 120 l can store 220 kg of xenon at 186 bar and 50°C (BoL). The titanium alloy Ti-Al6-V4 has been used by MT Aerospace for the tank liner. The tanks are accommodated in the propulsion module symmetrically with respect to the central tube. They are mounted in polar configuration, to allow axial elongation while providing translation fixation. To avoid undesirable mass shifting among the tanks, their temperature is controlled by using heaters and thermistors.

The high pressure of the xenon contained in the XTA is decreased to the values required by the thrusters via the PSA. The PSA provides pressure regulation and a central distribution system to multiple thruster branches²; it consists of the fluidic hardware (PRP) produced by IberEspacio and the electronic control unit (SCE) provided by Crisa Astrium. The actual design reduces the propellant pressure from 186 bar (BoL) to 2.2±0.11 bar at the output. The PSA is designed around a bang-bang regulator mechanism to fulfill the different mass flow rate requirements of the propulsion assemblies. The architecture is similar to the one used on SMART-1³.

This design, based on a multiple cavity system, allows to adapt the mass flow rate to the requirement of the active propulsion system. The introduction of a plenum volume has been necessary to stabilize the pressure during the bang-bang valves activation.

The top level architecture of the EPTA1 branch is depicted in Figure 4 (a). The EPTA1 is based on the HEMPT system: this is a new development in the frame of the DLR project HEMPTIS (HEMPT In-orbit-verification on SmallGEO)⁴. The HEMPT assembly (HTA) consists of three main components: four HTM, including the thruster, the neutralizer and the FCU, the PSCU and the internal harness. Thrusters and neutralizers are developed by Thales Electronic Systems GmbH Ulm, the FCU is produced by Bradford MOOG, while the PSCU is provided by Astrium Germany. The FCU controls the propellant flow through the neutralizer and through the thruster anode, while the PSCU provides electrical power to the HTM. This configuration permits to connect together all the anode lines, avoiding the use of switching units. The thruster activation is performed by applying propellant flow to the neutralizer and the anode of the selected thruster. During the assembly and integration activities, the HTM will benefit from its compact design, obtained by mounting the HEMPT and the neutralizer on one side of the support structure, the FCU on the opposite side.

The layout of the EPTA2 branch is shown in Figure 4 (b). The branch is composed of four units: the thruster module (SPT-100 and XFC) delivered by Snecma, the FU produced by EREMS, the ETSU and PPU provided by ETCA Thales Alenia Space⁵. The thruster modules are powered by the PPU: this includes a switching unit to select between two thrusters operation. The ETSU is a pure switching unit designed with the same structure of the PPU switching unit, which allows the selection between additional two thrusters. To avoid the re-qualification of the existing PPU, the ETSU has been designed with a separate discrete control of the switching functions and status monitoring, which is provided directly by the satellite management unit. The combination of ETSU and PPU allows the selection of one thruster out of four. The FU acts as an electrical inductive-capacitive line filter, to facilitate the discharge ignition and to decrease the perturbations conducted from PPU to thruster and vice versa. Due to its flight heritage, the SPT-100 is considered to be a safe and robust backup solution in case of failure of the newly developed HEMPT. Since the thruster module, the FU and the PPU are already qualified and operating in space, only the ETSU underwent a full qualification, ended in 2011. The EP thruster brackets will hold all the thruster assemblies for easy insert and removal during platform assembly, integration and testing phases. The thermal radiation into the baseplate is kept as small as possible to prevent overheating of the flow controllers located on the opposite side of the thrusters bracket.

The CGTA is provided by Thales Alenia Space, Italy⁶. It consists of eight cold gas thrusters in cold redundancy, controlled by the ADE. The conditioning module (fluidic hardware) provides interfaces to the low pressure side of the PSA and also provides insulation from the upstream propellant when the cold gas thrusters are not operating.

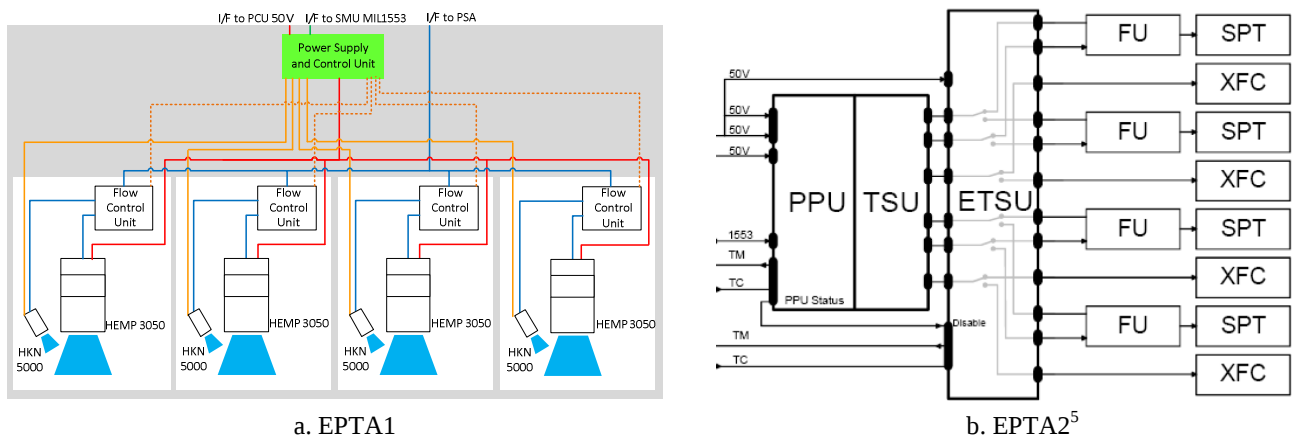


Figure 4 EPTAs schematic diagrams

C. Development Status

The EPPS development is complete and all hardware has been delivered. The tank QM has been qualified in 2011 and the FMs have been delivered and accepted in January 2012. Currently, the tanks are integrated in the propulsion module.

The PSA EM has been qualified in 2011. The PSA FM has been integrated in OHB Sweden in the propulsion module. The SCE is integrated in the core platform module in Bremen, already tested with the platform equipment.

The CGTA EM has been qualified in 2011. The cold gas thrusters FMs are integrated in the EPPS part of the propulsion module, the ADE is integrated in the core platform module and already functionally tested.

The QM ETSU has passed the qualification in 2011. The FM units are integrated in the core platform module and tested. The PPU, SPT-100 thruster module and the FU, off-the-shelf units, did not undergo qualification, but only acceptance tests. The PPUs are integrated on the core platform module and have been successfully tested with the ETSUs.

Both PSCU EQM and FM have been delivered to Thales. The PSCU EQM will undergo a lifetime qualification test with the HTM QM, while the PSCU FM will undergo the end to end test with the HTM FMs in the following months. The HTA is heading towards the Critical Design Review close out. The EM HTM successfully underwent a life-test of nearly 8000 hr⁷. In the following months, two QM HTM will start a full SGEO mission life-test: one will be subjected to a real mission thermal environment and operation, the other will undergo the life-time test with

accelerated thermal cycles and operation. Both QMs will be subjected to environmental tests. Four FM HTMs will be delivered to OHB after the end to end (acceptance) test.

Since the EPTA1 branch is composed of new development units, the schedule risk of the development has been

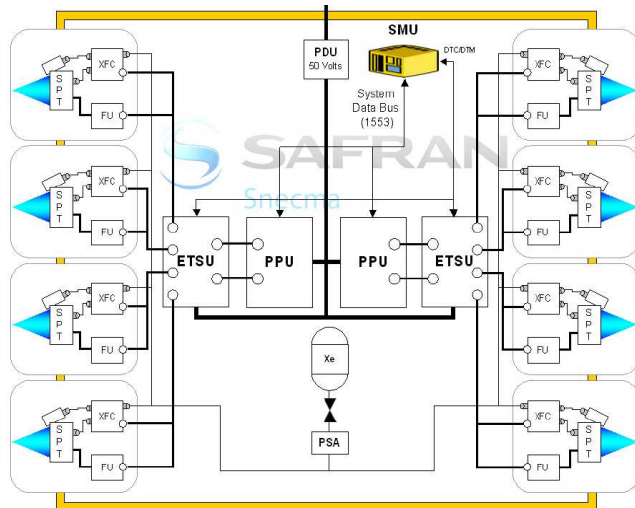


Figure 5 Full SPT-100 configuration schematic diagram⁵



Figure 6 Xenon tanks integrated on the propulsion module

considered high. In order to prevent undesirable delays on the satellite overall development, a mitigation solution has been implemented in the early development phases of SGEO. Due to the high versatility of the platform, it was possible to implement a backup solution, which foresees the use of two identical EPTA branches, equipped with the SPT-100. Thus, Snecma has been awarded the contract to deliver a second EPTA branch, which constitutes the backup solution. The full configuration of EPTA1 and EPTA2 branches is reported in Figure 5. In this case the SGEO platform versatility, even in course of Critical Design Review, can be appreciated for two main points: accommodation of the units and flight operations. The former is a main advantage of the system modular design approach, reflected in the assembly and integration activities. The accommodation of a second PPU and a second ETSU (instead of the HEMPT PSCU) has been performed without major modifications of the platform, including the structure and the harness routing. A minor redesign has involved the thruster brackets and the thrusters fluidic interfaces, while the fluidic interfaces of the PSA, designed for the HEMPT subsystem, will be connected to the SPT-100 branch. Finally, the SMU is capable to implement the modification of the I/O signals to be transmitted to the additional PPU and ETSU.

The flight operations will not be affected by this modification, since the EPTA 2 branch has been already considered in the mission analysis. Moreover, the mission propellant budget already accounts for full SPT-100 operation: this scenario has been analysed as a failure mode (HEMPT failure) and it represents the worst case propellant consumption, covered by margins. The consequences on the thermal and power budgets have been considered negligible, since the operating parameters of the units are slightly different.

The SGEO development is currently in phase C/D. In 2010 the Preliminary Design Review was successfully completed, while the Critical Design Review was held in autumn 2011. The Qualification Acceptance Review of the platform is planned at the end of 2013, while the preliminary qualification acceptance reviews for each subsystem are undergoing. In August 2013 the EPPS qualification acceptance review has been successfully held.

The integration of the core platform module is complete, functional and performance tests are ongoing. The CPPS tanks have been integrated into

the propulsion module in Avio and received in Bremen. Figure 6 depicts the xenon tanks and tubing system of the CPPS integrated in the propulsion module. The tubing system, the cold gas thrusters and the PRP have been integrated in OHB Sweden AB, as depicted in Figure 7, on a mechanical support structure which simulates the spacecraft interfaces. The propulsion module and the core platform module will be mated in the next months to form the platform module.

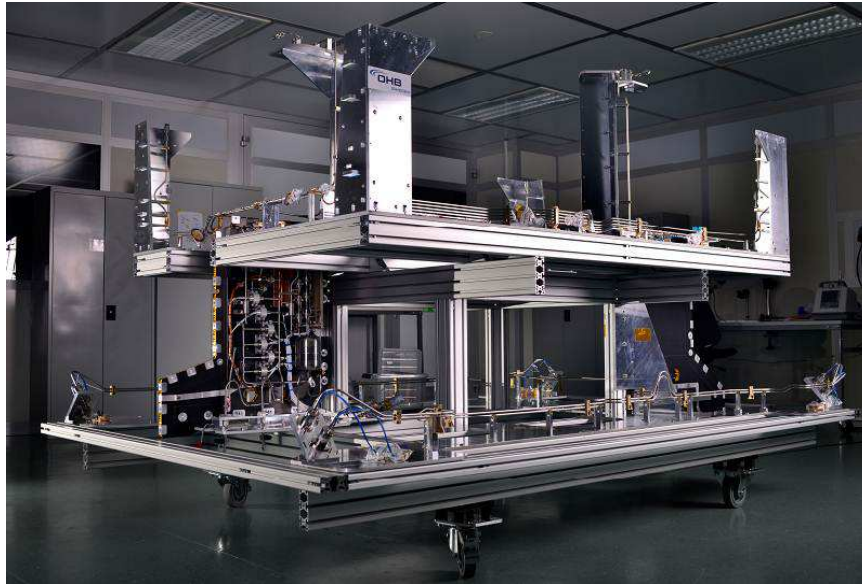


Figure 7 Integration jig for EPPS tubing, PRP and cold gas (OHB Sweden)

The EPPS testing at system level is divided in three main activities: the core platform level testing, the verification tests after the mating between the core platform module and the propulsion module (platform level) and a final verification after integration of the payload. The core platform module testing foresees mainly functional tests of the electronic units. After having been integrated, the units undergo bonding and isolation tests, followed by interface and functional tests. The telemetry and commands are verified with the on board software and the operative modes of the units are tested. Figure 8 shows the test bench of the core platform module: the first units on the left side are the PPU and the ETSU of the EPTA.



Figure 8 Core platform module on the test bench

The EPTA branches have been tested with the thruster simulators, which simulate the thruster impedance, using the flight harness. Selection of the thruster has been checked and the command to operate the thruster has been sent to the PPU, which delivered the required power to the simulator. The redundancy of the telemetry and telecommands has been checked. A mission simulation will be performed in coordination with the AOCS testing. The test will simulate the spacecraft operation from separation from the launcher to the station keeping maneuvers, including the detumbling (cold gas operation) and colocation into GEO orbit. The platform level testing is performed after the mating of the core platform and the propulsion module. Therefore, after the integration and welding of the tubing assembly, functional tests of the fluidic hardware will be performed. These include leak tests, proof pressure tests and pressure regulation tests. The full functionality of the PRP and of the cold gas will be tested. Finally, after the mating of the platform module with the payload, the EP thrusters will be integrated. Leakage and proof pressure tests will be performed to verify all the tubing assembly of the subsystem, then the xenon flow controllers of the thrusters will be tested. All the described activities are planned to start by the end of this year, before the satellite environmental campaign which will start next year.

Pressure and leakage tests, as well as functional tests of the units will be repeated during the environmental test campaign, to verify correct performance of the subsystem before and after the satellite tests.

III. SGEO Flex Configuration: an Introduction to Electra

Although solely electric propulsion orbit raising has been contemplated since 2000s, only nowadays this possibility is becoming a real alternative to the impulsive transfer for commercial telecommunication applications. Despite the saving on the propellant mass obtainable with the use of electric propulsion, so far the telecommunication market has given a higher weight to the weakness of this solution: the low thrust. Indeed, this weakness calls for a very long transfer time, typically from 100 to 300 days, depending on the thruster type and the satellite mass. During this time, the satellite has to face thermal control issues and the multiple crossing of Van Allen radiation belts.

Widely used for station keeping manoeuvres, in the last decade the electric propulsion technology proved to be ready for orbit raising applications.

The SMART-1 mission⁸, primed by OHB Sweden, showed the ability to perform long transfers using electric propulsion: the spacecraft went from GTO to the moon using only a single Snecma PPS-1350 thruster. Today, this achievement represents, together with ARTEMIS spacecraft⁹, the only European orbit raising manoeuvre performed by using electric propulsion. These two missions have paved the way for the technical feasibility and offered a proof to the market, highlighting the existence of a choice between hall-effect and ion thrusters. Indeed, the qualification of Snecma PPS-1350, or the on-going qualification of QinetiQ T6 for Bepi Colombo mission, declare the availability of European thrusters capable to fulfill the requirements for such a transfer. Moreover, the robustness and extreme endurance showed in Hayabusa¹⁰, Deep Space 1, Dawn and GOCE missions increased the consideration for ion thrusters, while the Advanced Extremely High Frequency mission with BPT-4000, Snecma exploratory work on PPS-5000 and SPT-140 qualification lead to consider the attractive power to thrust ratio of the Hall effect thrusters class.

In late 2011, SES-Astra presented a study about end-to-end optimization for mission cost and orbital life, by combining launcher and spacecraft performance models into a single set¹¹. The paper deals with the use of smaller launchers and lower injection orbits, where instead a larger delta-v to GEO could be provided by an on-board EP system. This revealed that the concept of significantly longer transfer time to GEO was now being proposed by one of the main telecom satellite operators.

At the beginning of 2012, in the frame of a joint venture between Asia Broadcast Satellite (ABS of Bermuda and Hong Kong) and Satmex of Mexico, Boeing announced the development of four full electric propulsion satellites based on XIPS. At the same time, Space Systems/Loral (SSL) declared that a similar project has been studied for a few years, as the use of electric propulsion for GTO to GEO transfer decreases the launch mass of the spacecraft roughly by a factor of two. Therefore, the use of electric propulsion for orbit raising and the selection of cheap, small launchers has become a real alternative.

In late 2012, SES announced its participation to the ARTES-33 program Electra of the European Space Agency (ESA). Under the Electra program, ESA, SES and OHB System will establish a public-private partnership aimed at developing a full-electric propulsion small/medium sized satellite platform designed, developed and manufactured in Europe. Specifically, the project aims to develop, implement, launch and commercially operate an innovative geostationary satellite platform that uses electric propulsion for transfer into geostationary orbit as well as on orbit station keeping. Thus, the satellite platform can take advantage of smaller launch vehicles or dual launch

capabilities, while carrying payload capabilities equivalent to current mid-sized satellites in terms of power consumption and number of active transponders.

OHB System will lead the Electra platform development and will act overall as satellite prime under contract by SES who will lead the ELECTRA project in respect to satellite customer requirements definitions and will act as mission prime contractor towards ESA. The industrial organization led by OHB System will be composed of Luxspace responsible for the subsystem Command Telemetry and Ranging (CTR) and OHB Sweden for Attitude Orbit Control (AOCS) and Electric Propulsion Subsystem (EPPS)¹², already proved to be effective during the SGEO program.

A. Electric Propulsion Subsystem Overview

Electra will be the first European all-EP telecom satellite. The launch date for the first Electra mission is planned for 2018-2019. The first Electra satellite will take advantage of the flexibility of the SGEO platform: it will have a launch mass in the range 2-3 t including a payload up to 700 kg and 8 kW at end of life. This performance will place the platform in the same category as current mid-size telecom satellites with typical launch masses around 5 t.

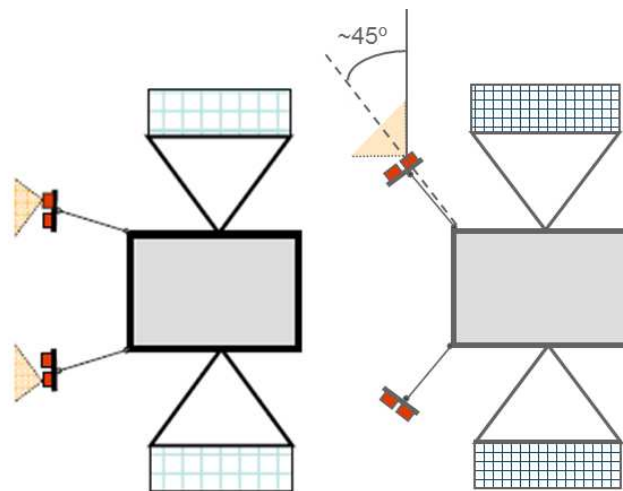


Figure 9 Orbit raising configuration (left) and station keeping operation (right)

The use of electric propulsion also for the orbit raising phase allows to reduce the launch mass for Electra to the range 2-3 t, thereby placing it within the capabilities of several low-cost launch alternatives.

The design configuration will be finalized mid of 2014 during Phase B1, leading to a Platform Preliminary Design Review (P-PDR). The preliminary EP configuration is based on a 4 high-power-thruster configuration. The thrusters are mounted in pair on two articulated EP booms. The EP booms are placed in at the edges of the anti-Earth panel. This configuration has been extensively analysed and found to have advantages with respect to competing configurations using thrusters mounted individually on pointing mechanisms. The thruster orientation during orbit raising and station keeping is depicted in the Figure 9.

It is planned to operate two thrusters at the same time during the orbit raising phase, with a total available power for the EPPS of 9.6 kW. The station keeping will be performed using one thruster at time at each orbital node, with a maximum allocated power for EP operations of 3.2 kW. This means that the EP thruster has to be capable to operate at two different operative points.

The use of EP thrusters mounted on booms represents advantages with respect to the SGEO configuration in terms of thermal control management and payload interaction. The risk of electro-magnetic interferences between thrusters and satellite are e.g. strongly decreased by the boom length. Moreover, the interaction of the thrusters sputtering with the solar arrays and the optical reflector is effectively decreased (cf. sputtering analysis of SGEO as shown in Figure 10¹)

An additional difference and complexity with respect to SGEO satellite, taken into account in the Electra EPPS design, is brought by the different mission profile. Indeed, the orbit transfer which will face Electra satellite increases the time spent in the radiation belts. The exposure of the S/C to the total non-ionizing dose (TNID) will increase considerably for the range of transfer orbits envisaged as compared to a traditional CP mission, in particular

for sub GTOs with initial apogee altitudes in the order of 10000 km. The major impact is the degradation of the solar cells, which is accounted for in the design. The total ionizing dose (TID) for the range of transfer trajectories will be significantly less than the 15-year on-station dose. The total dose is mainly caused by electron radiation. The influence of the lower proton belt on the total ionization dose is not very high since it is for internal equipment relatively easy to shield for protons.

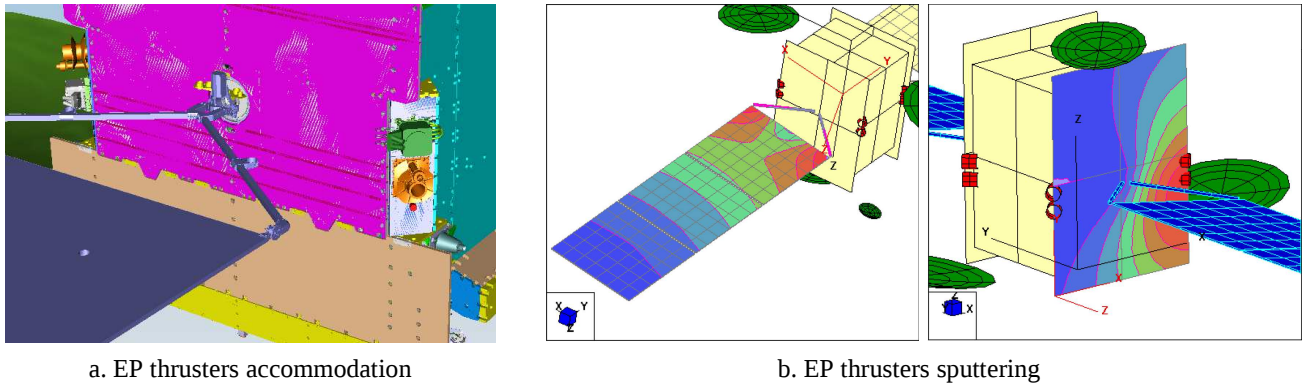


Figure 10 SGEO thrusters accommodation and sputtering results

IV. Conclusion

Designed for a 15-years mission, the SGEO platform is a highly flexible geostationary platform that can accommodate payloads in the range of 400 kg and 3.5 kW. The payload capability and the launch opportunities can be extended to 700 kg at 8 kW by the use of the electric propulsion subsystem. Moreover, a direct injection in GEO can be chosen, instead of GTO to GEO transfer, whereby all orbital maneuvers are performed with the electric propulsion. In the course of the SGEO development, the modular design of the platform proved to be an asset, giving the possibility to modify the subsystems accommodation and to define straight assembly, integration and testing activities. The Electra mission will benefit from the SGEO platform design: the modular architecture, the flexibility of the design and accommodation are the base of the Electra design as well. The enhanced all-EP platform will be the first European telecommunication satellite to use electric propulsion for all orbit phases.

Acknowledgements

The authors acknowledge the support of ESA, DLR and the work of OHB, LuxSpace, OHB Sweden AB and RUAG Space AG design teams and the industrial consortium members.

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