EP SYSTEM DEVELOPMENT AND FUNCTIONAL VALIDATION TESTS FOR ELECTRA GEO SATELLITE

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ABSTRACT

The development of the Electric Propulsion sub-system (EPPS) to be used on-board the Electra GEO telecommunication platform for orbit raising and station-keeping applications has involved the development and qualification of key technologies such as: the EP orientation mechanism (THOR), a 5kW Hall-Effect thruster, a 5kW Power Processing Unit (PPU), the xenon flow regulation sub-assembly, and a large capacity xenon tank.

From the hardware development and qualification to the complete sub-system end-to-end test, this paper describes the key development and testing activities performed to validate the EP sub-system of Electra.

NOMENCLATURE

AIT	=	Assembly Integration and Test
AOCS	=	Attitude and Orbit Control System
BOL	=	Beginning Of Life
CGT	=	Cold Gas Thruster
COM	=	Centre Of Mass
CRP	=	Cathode Reference Potential, or coupling voltage (V)
EGSE	=	Electrical Ground Support Equipment
EOL	=	End Of Life
EP	=	Electric Propulsion
EPPS	=	Electric Plasma Propulsion Subsystem
FU	=	Filter Unit
GEO	=	Geostationary Earth Orbit
Id	=	Discharge current (A)
Itt	=	Thermothrottle current (A)
OR	=	Orbit Raising
PPU	=	Power Processing Unit
RS	=	Regulation Subassembly
S/C	=	Spacecraft
SK	=	Station Keeping
XFC	=	Xenon Flow Controller
ΔV	=	Delta-V, or increment of orbital velocity (m/s)

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I. ELECTRA MISSION

In Q3 2016, OHB Sweden was awarded the propulsion system design of the Electra platform program, a public-private partnership aimed at developing an innovative geostationary satellite platform that uses electric propulsion for transfer to GEO as well as for Station Keeping.
OHB System is acting as satellite prime and is leading the Electra platform development. The industrial organization led by OHB System is composed of Luxspace, responsible for the Command Telemetry and Ranging subsystem, and OHB Sweden, responsible for the Attitude & Orbit Control System (AOCS) and the Electric Propulsion Subsystem (EPPS), already proven to be effective during the SGEO program.
The Electra development is currently in phase C/D with the Platform CDR held in mid-2019. The launch date for the first Electra mission is planned for 2022.

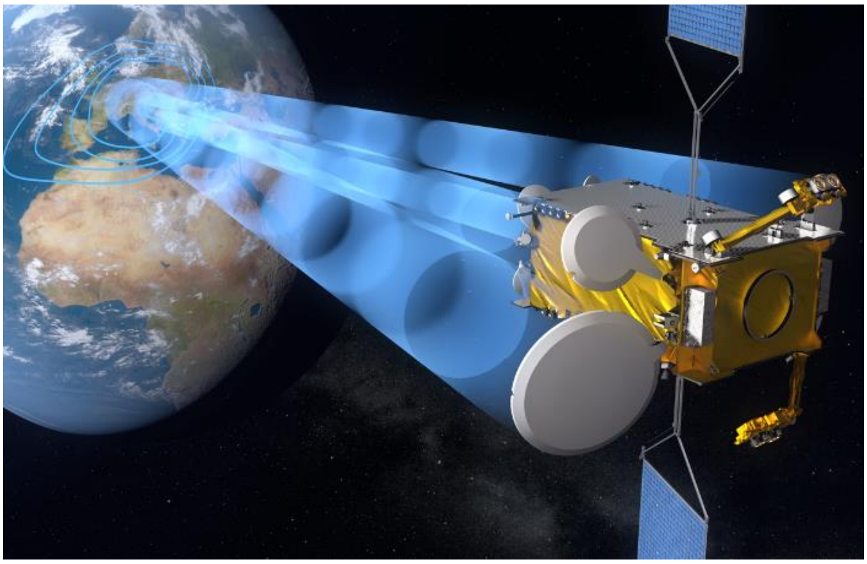

Figure I-1 Electra satellite in GEO (artist impression)

The Electra Satellite platform provides the following key characteristics:

- Payload mass up to 800 kg,
- Payload power consumption of up to 10 kW, 100V bus
- Lifetime of 16 years (including OR),
- Satellite launch mass in 3t class,
- Launchers include Ariane 5 (lower passenger), Soyuz CSG and Falcon 9 among others,
- Three-axes attitude stabilization relying on a set of star trackers and reaction wheels.

On Electra, all propulsive tasks are performed by the EPPS including the transfer phase to the GEO, the final station acquisition and station keeping in GEO as well as repositioning and finally the disposal to the graveyard orbit at end of life. In addition, momentum management during all those phases relies on the EP thrusters. The system is supported by a set of Cold Gas Thrusters (CGT) for de-tumbling of the satellite after launcher injection and to provide attitude control in satellite safe modes when reaction wheels are not available.

II. EPPS ARCHITECTURE

A. Operational modes

The baseline design for Electra involves the use of an Electric Plasma Propulsion Subsystem (EPPS) applying EP thrusters mounted on booms to perform all orbital manoeuvres including the orbit raising from GTO to GEO. In the Electra context, the EPPS includes also the Cold Gas Thruster Assembly (CGTA), given that the operation of EP and CG is closely interlinked and that both share a common Xenon propellant storage and supply.
More specifically, the functions to be performed by the Electra EPPS system will be the following:

Mode	Function	Operations
Cold Gas (CG)	▪ Initial detumble after separation from the Launch Vehicle ▪ Momentum management whenever the EP system is OFF	CGTs are operated at a controlled and constant inlet pressure to provide the thrust necessary (<50mN) to complete the manoeuver within the specified allocated time
EP Orbit raising (OR)	▪ Orbit raising ▪ Transfer to graveyard orbit at End of Mission	During OR, two thrusters - one at each THOR Boom - will fire simultaneously parallel to the velocity direction at 4.5 kW / 300V during sunlit conditions. The thrusters will be completely switched of during eclipse to save platform battery capacity
EP Station Keeping (SK)	▪ Station acquisition & Repositioning ▪ Station-keeping N/S and E/W during 15 years ▪ Momentum management during all phases when EP is ON	During SK, a single thruster will be fired at the south and north ascending nodes respectively, at 3 kW / 375V. The thrusters will be oriented to have their thrust vectors oriented through the nominal S/C centre of mass. The attitude control task of the EPPS, performed by small reorientations of the thrust vector, is limited to dumping of angular momentum (de-spinning of reaction wheels).

B. EPPS architecture

A 440L tank feeds xenon gas to the flow Regulation Subassembly (RS) which reduces the pressure to both the EP and CG thruster branches and provides necessary protections between high and low pressure sections while also including access ports for testing and fuelling purposes.

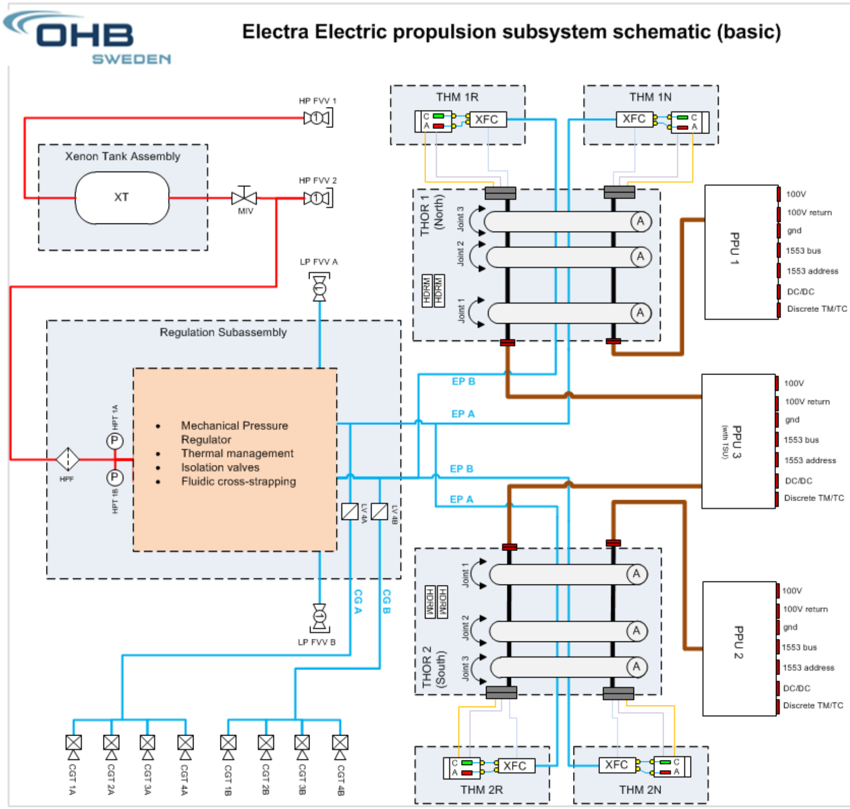

Figure II-1 Electra EPPS architecture

The baseline Electra EP arrangement is illustrated above. It is composed of four EP thrusters mounted pairwise on two Electric Propulsion Boom mechanisms with the product name THOR, all operating with a unified xenon propellant storage and xenon flow Regulation Subassembly (RS).
Since the thrusters mobility enabled by the THOR is a key feature of Electra, the implications on system level (e.g. plume interactions with solar arrays, N/S cant angle during SK firings, lever arm capability) have been optimized taking into account the thruster positioning relative to the spacecraft.

To achieve the required range of motion prescribed by the AOCS design, a three section boom with three axes of rotation is required. This combined with the accommodation of a fully redundant PPS-5000 thruster (baseline) or SPT-140D (option), has led to the physical architecture presented in Figure II-1.

The EP booms are mounted on the lower edges of the North and South radiator panels, close to the anti-Earth panel. This configuration has been extensively analysed and favoured compared to individually gimballed thrusters as it reduces the total number of actuators and thrusters. The THOR system is a triple-arm (triple-hinged) rigid boom deployed and articulated by three actuators.

THOR EP Boom

The three THOR Boom actuators are denoted RA1, RA2 and RA3. Actuator axis 1 and 2 directions are selected to allow decoupling of force and torque in the time critical E/W direction during SK.
During OR, the thruster plumes are directed towards the -Z axis, therefore the plume impingement on S/C surfaces is negligible. During SK the thrusters are positioned such that the angle between the thrust vector and the North-South direction is minimised thanks to the dimension of the boom while keeping any plume impingement impact on the S/C and in particular on the solar arrays within allowable levels. The charged ions can affect the S/C by unwanted forces and torques, thermal fluxes, materials sputtering and contamination.

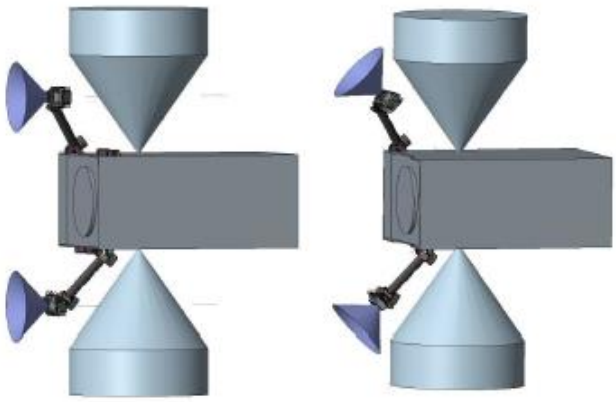

Figure II-2 THOR EP Booms on Electra

This actuator configuration allows applying forces and torques as required for Orbit Raising and Station Keeping as well as covering centre of mass (CoM) shift during the mission. The THOR Boom range of motion covers the lever arm needs for a wide range of spacecraft CoM positions, hence being compatible to the whole Electra platform family with different mission profiles and payloads.

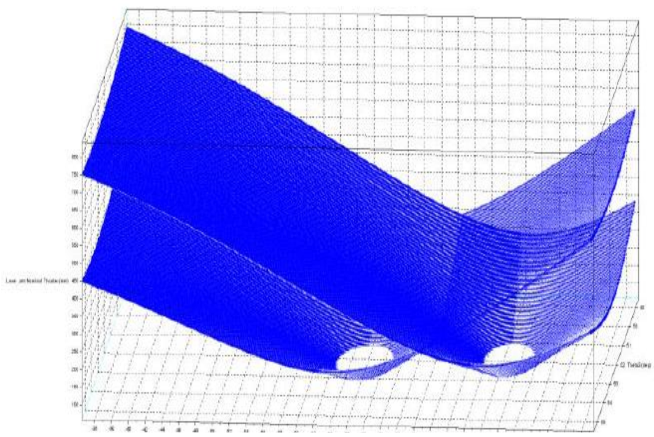

Figure II-3 THOR EP Boom lever arm capability

The lever arm capability of the nominal and redundant thrusters while providing 5degrees East-West thrust component is greater than 80mm, which provides significant margins in the range of motion performances. When no east-west thrust component needs to be applied, a lever arm greater than 225mm is guaranteed for the entire range of the Electra platforms accommodations.

The EP Boom is mechanically designed to cope with a range of launcher environments, to minimize induced shock during initial EP Boom deployment, and to enable a large range of actuation and pointing range to support the mission needs. From a thermal point of view, each EP Boom is designed to support simultaneous firing of two 5kW class EP thrusters.

For Electra, the 5-kW PPS©5000 Hall thruster has been selected and is currently under qualification at Safran [20] [22].

Figure II-4 Safran´s PPS-5000 thruster EQM

The EP thrusters and xenon flow controllers are mounted pairwise on each THOR boom on a rigid baseplate assembly denoted THruster Assembly Module (THAM) designed to provide adequate mechanical and thermal environments to the XFC and Thruster. Flexible harness and tubing are nested inside the THOR boom with the main objectives of minimizing induced resistive torques inside the actuators and limiting power losses due to the cables resistivity. The external position of the THOR boom imposes high radiation requirements, which combined with the mechanical stress imposed by the large number of actuations over life drive the materials selection on the harnesses and other moving parts. Both harness and tubing are pre-loaded during their integration on the THOR boom such that the mechanism actuator performance (backlash, hysteresis) is not impacted by reaction torques from harness and tubing.

Power Processing Units (PPU)

The PPU Mk3 [19] developed by Thales Alenia Space Belgium is selected for the first Electra satellite. The PPU configuration for Electra is shown below and derived from sub-system trade-off. PPU-A and PPU-B interface to one thruster each, while PPU-C can operate either of two redundant thrusters via an internal Thruster Switching Unit. PPU-C thus provides cold redundancy without any performance loss for any single EPPS failure occurring during Orbit Raising or Station keeping. The PPUs are mounted on the north and south platform radiator panels in order to effectively distribute the heat dissipation and minimize the harness length to the EP thrusters.

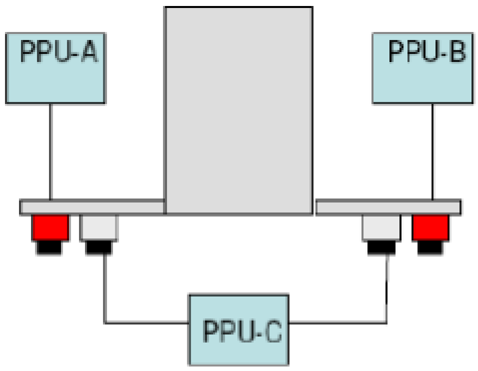

Figure II-5 PPU configuration on Electra

Figure II-6 PPU Mk3 - Thales Alenia Space

Xenon Tank (XT)

The 440L propellant tank developed by MT Aerospace can carry more than 800kg xenon at 186bar and is located inside the spacecraft central tube to help centralising the spacecraft CoG given the large amount of fuel stored.

Figure II-7 440L Xenon Tank - MT Aerospace

Regulation subassembly (RS)

The RS reduces xenon pressure and provides the flow capacity required by both the EP and Cold Gas systems. A too low pressure set-point would cause too low thrust during cold gas operations at 230mg/s while a too high pressure set-point would overstress the xenon flow controller thermothrottle. With the selected pressure set point, the RS can manage flow up to 180mg/s down to 10bar Xenon tank pressure, and flows up to 34mg/s down to 3bar tank pressure. This guarantees >50mN thrust in CG mode for the complete mission lifetime, and >27mN if the mission is extended beyond its nominal duration.

The high flow demand in CG mode imposes that all fluidic hardware in the lines are designed for a minimum pressure drop at high xenon flow.
During operations at 230mg/s, a very large enthalpy drop occurs across the pressure regulator and leads to power losses in the order of 15W. A dedicated thermal management has been designed and validated to compensate for this so-called Joule Thomson effect to enable large flows with stable performances during the whole mission lifetime.

The RS architecture is based on a cold redundant scheme, with a cross-strapping between the two branches such that all EP and CG thrusters remain available even after the loss of one RS branch.

The overall EPPS accommodation on the platform is optimized for a simplified and rapid integration and testing phase of the RS and associated fluidic assemblies.

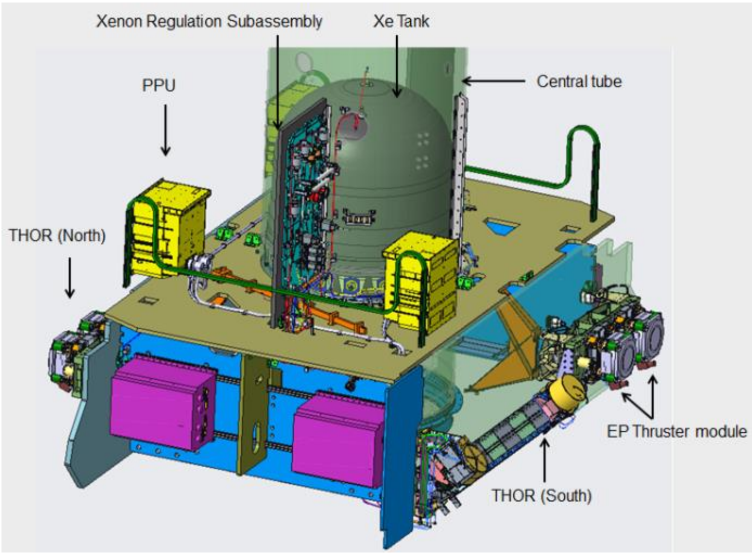

Figure II-8 EPPS accommodation on Electra

III. EPPS VALIDATION TESTS

A. THOR development logic

Being a key technology of the EP sub-system development, the THOR Boom was initially submitted to thermal stress tests using 1 STM and 1 TM thrusters simulating firing at 4.5kW each. The test confirmed the accurate thermal control of the xenon flow controllers, and ensured sufficient margins to perform dual-firing at maximum power on one THOR Boom. The proper sizing of the heating system to be used in cold cases was demonstrated.

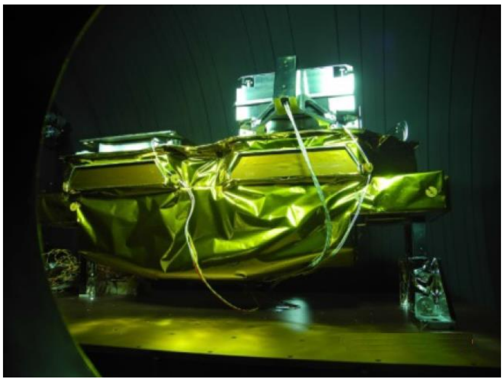

Figure III-1 THOR THAM thermal test

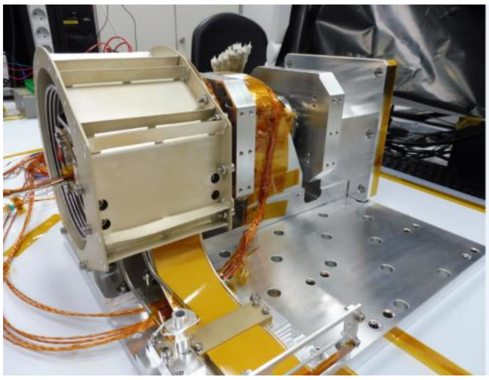

Figure III-2 THOR QLTM cycle life test

A rotary actuators engineering model equipped with tubing and harness was then submitted to a full cycle life test and design iterations have permitted to minimize backlash and hysteresis behaviour on the whole operational thermal range.

The Qualification Model (QM) currently being manufactured benefits from well demonstrated building blocks to minimize risks during the assembly and qualification campaign.

B. Regulation Subassembly (RS) and Cold Gas thruster compatibility test

The performances of the fluidic assembly have been verified in Q3 2018 during a test involving the flight tubing configuration, a flight representative regulation subassembly and cold gas thruster. As expected, the RS can support the low flow required for EP operations and regulated pressure stability was demonstrated at 34mg/s (dual firing case) down to 3bar tank pressure. The critical part of the test is the validation of the high mass flow (230mg/s) condition since this corresponds to the case of maximum pressure drop, hence to the maximum Joule-Thomson cooling effect that will occur during the initial and crucial spacecraft detumbling operation with CG thrusters.

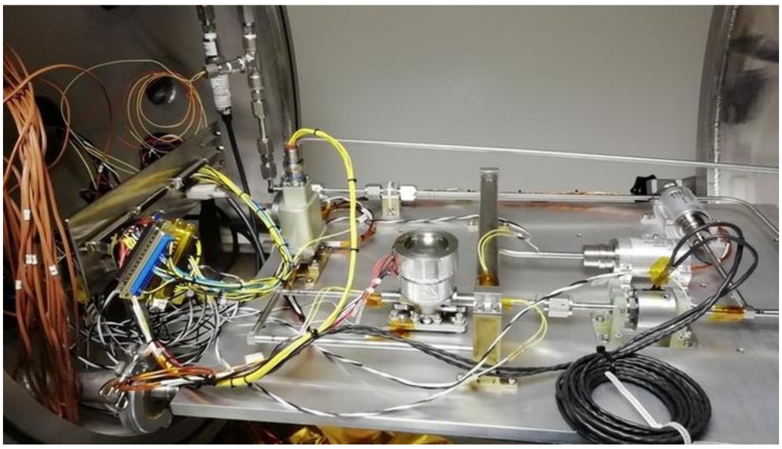

Figure III-3 Regulation Subassembly in TVAC - OHB Sweden

Figure III-4 Cold Gas thruster in TVAC

As seen on figure III-5, the test has successfully shown pressure and mass flow stability to ensure >50mN CG thrust in the detumbling phase for up to 2.5hrs. The test actually demonstrated a thrust level of 67mN. The thermal control of the pressure regulation system only consumed 13W in average thanks to the efficient thermal design of the heated areas.

During the tests, the heaters located at the pressure regulator inlet tubing were used to increase the margin to the high pressure xenon liquefaction point (~17C) in operation since this would cause phase change hence pressure and flow instabilities during the gas expansion.

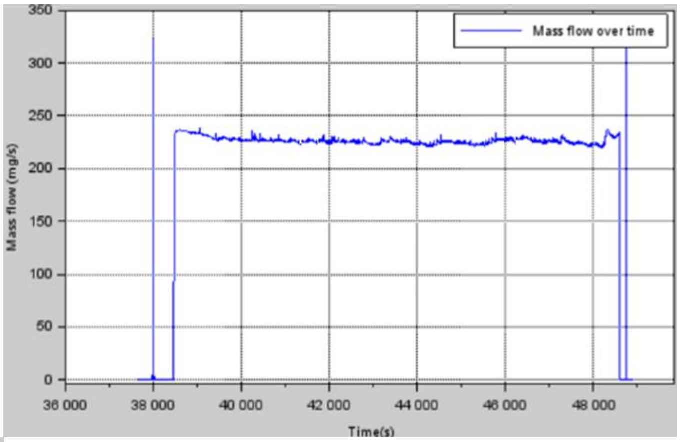

Figure III-5 Mass flow stability at max flow conditions (CG)

Performance in CG thruster pulse mode was tested to characterize transient's behaviour and justify the minimum total impulse bit at sub-system level.

The test results in figure III-6 demonstrate nominal CG thruster performances (>50mN) down to 10bar xenon tank pressure. At EOL, the CG system can still provide 27mN thrust during safe mode and sun acquisition.

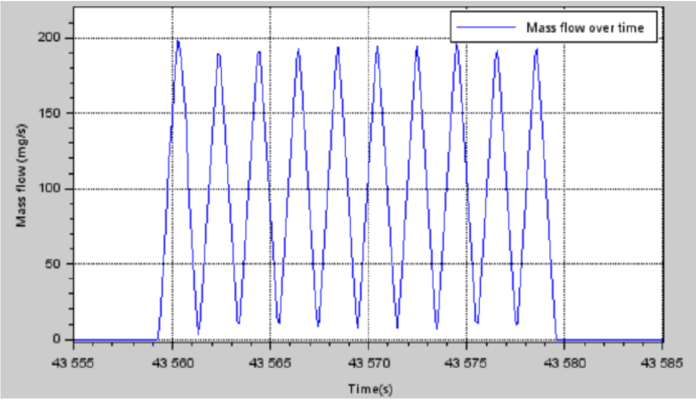

Figure III-6 Cold gas thruster in pulse mode

C. EPPS end to end test

The test was performed in Q1 2019 at Aerospazio MVTF-4 test facilities in the beautiful town of Rapolano Terme. The objectives of the EPPS end to end test were to:

- Demonstrate the functional performances and compatibility of RS, PPU, XFC, Thruster, Tubing, Harness, THOR boom harness, THOR tubing, and electrical interconnections
- Validate the PPU settings (Start-up, protection thresholds, thermothrottle control loop) selected for Electra
- Validate all flight scenarios (initial venting, initial hot outgassing, orbit raising at 4.5kW, station keeping at 3kW, BoL, EoL) using the step-by-step operational EPPS software sequences
- Test operating point throttling capability during a burn

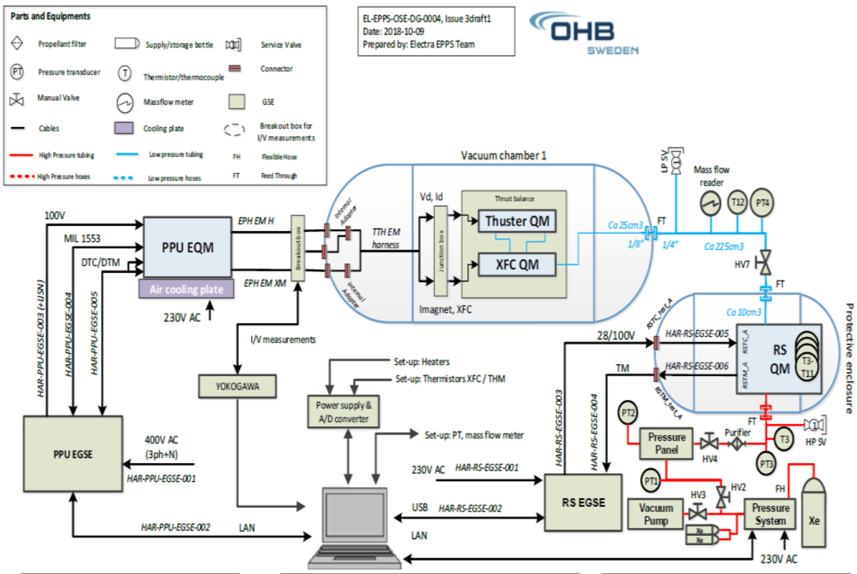

Figure III-7 EPPS end to end schematic

For this purpose, a complete functional branch was used in the test , i.e., the RS EQM unit, a Thruster/XFC EQM units, a PPU EQM, flight xenon tubing and flight representative harness (internal and external along the THOR boom). The test was performed with a Line Impedance Network Stabilizer (LISN) representing Electra´s bus impedance. The tested validates fluidic, electrical and thruster performances all above analysis predictions.

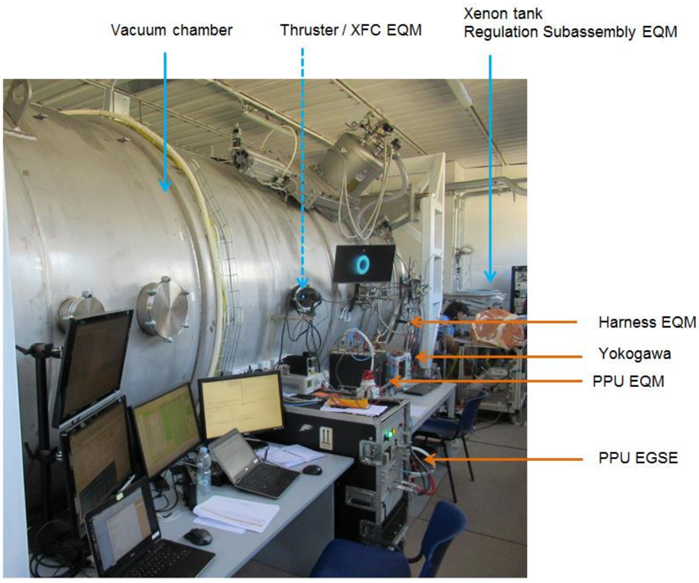

Figure III-8 Electra EPPS end to end test setup

Figure III-9 PPS-5000 during the Electra EPPS end to end test

The performances obtained at the different operational points are summarized below:

Test	Operating point	Thrust (+/- 2%)	Isp (+/- 4%)
Hot outgassing	4.5kW @300V	274.4mN	1718s
Orbit raising #1	4.5kW @300V	271.1mN	1655s
Station Keeping #1	3.0kW @375V	159.5mN	1734s
Orbit raising #2	4.5kW @300V	269.7mN	1700s
Station Keeping #2	3.0kW @375V	160.0mN	1809s

Figure III-10 Electra EPPS performances at 500hrs of operation in OR and SK modes

The anode discharge current to thermothrottle current control loop was demonstrated to be stable under all conditions with no overshoot, even during a hot throttling as shown below during a transition from 3kW at 300V to 4.5kW at 300V.

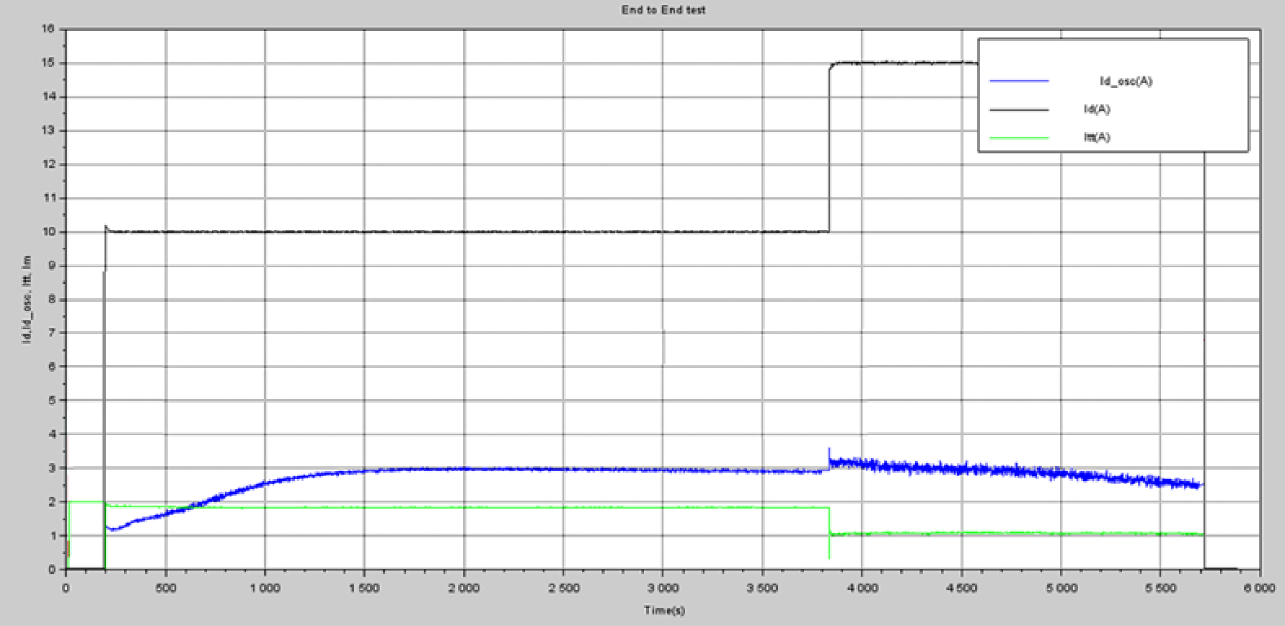

Figure III-11 Electra EPPS firing test at 3kW/300V and 4.5kW/300V

The selected thruster soft start-up method confirmed no overshoot on the in-rush current at thruster ignition.

Unexpected extinctions occurred during the initial hot outgassing test where single events caused by back-sputtered material are prone to occur. The flight settings have been consequently updated to increase the robustness to these events and avoid such abort in flight.
Measurement of the discharge current was performed up to 1MHz to characterize the oscillation current and analyse the discharge mode stability over time for the two operating points selected.

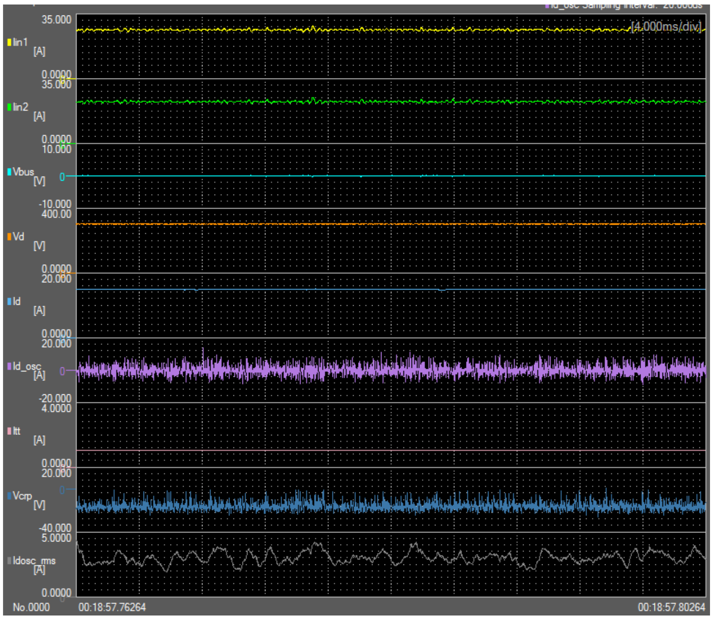

Figure III-12 High frequency acquisitions at 4.5kW/300V

D. Spacecraft level validation

An inherent limitation of using EP thruster technologies is that is does not enable a full validation of the functional chain once integrated on the spacecraft since EP thrusters can only be operated in high vacuum environment. Although EP firing is not possible, the complete electrical and functional aspects can be verified on Electra thanks to a complete set of Electrical Ground Support Equipment (EGSE) developed by OHB Sweden in support of Flatsat and Spacecraft AIT to alleviate to above mentioned restrictions. The set of EGSE presented below also simplifies greatly the scheduling of tests and allows having a complete electrical representation of the EPPS sub-system for Flatsat electrical testing, Software and FDIR validations.

Regulation subassembly emulator

The RS Emulator contains a series of electric loads and generators aiming at reproducing the electric behavior of the real RS. It contains representative loads for latch valves, heaters and pressure transducers and delivers back to RTUs analog signals representative of the thermistors and pressure transducers. The RS emulator is not remote controlled and proposes instead a set of switches to allow for several telemetry levels.

The RS EGSE allows the command (Latch valve, Heaters), the supply (Pressure Transceiver) and the readout (Latch valve switch position, thermistors, pressure regulator output signal) of the RS devices from a computer. All operations are scripted to reproduce the flight sequence.

Figure III-13 Regulation subassembly emulator

PPU emulator and PPU EGSE

A PPU emulator is used to simulate PPU operations (in terms of power supplies and sequencing) during validation and tests of the Thruster emulators (same device developed for both SPT-100/MK1 and PPS-5000/Mk3 operations).

A PPU EGSE (TAS-B PPUs MK1 to 3) was developed to power and control actual PPU EQM or FM. It can power PPUs in 50V (Mk1) or 100V (Mk2 and MK3), read TM / send TC from / to PPUs, and send Milbus-1553 commands to the PPU (which is used as remote terminal) according to the user manuals and ICDs from TAS-B. The PPU EGSE is controlled from RAMSES (an OHB Sweden developed network based GSE environment) which proposes a visualization and logging of all PPU telemetries (both direct and 1553) and power supplies status (voltage and current delivered to PPU, etc.) as well as a scripting tool enabling easy parametrization of the EGSE and the PPU

Figure III-14 PPU Emulator

Figure III-15 PPU EGSE

Thruster emulator

THM emulators (TEM) are being developed by OHB Sweden to support Flatsat testing activities and Satellite TVAC functional tests. The TEM is able to reproduce all main electric characteristics of a Hall Effect Thruster: anode discharge (start-up, steady state and oscillation current, shutdown), magnet coils, cathode heater and ignitor / keeper, xenon flow control valves and regulation controller. The main features of the emulator are to adapt the discharge current as a function of the xenon flow (thermothrottle current in the present case) and to respect the ignition sequence decided (soft start or normal start). All TEM parameters are set from a control computer which allows monitoring and logging during firing emulation. The TEM can also emulate several thruster failures in order to verify PPU reaction to flame out, absence of ignition, etc. Ultimately, using a thruster or a thruster emulator becomes transparent for the PPU.

Figure III-17 Thruster emulator

Figure III-16 THOR EP Boom emulator

THOR emulator and check-out equipment

A check-out equipment (SCOE) is developed to support the qualification and acceptance testing of the THOR Boom as well as flat-sat and spacecraft level testing. The THOR SCOE can be used to drive and monitor a real THOR Boom or the THOR Boom emulator shown below. The SCOE commands Ruag´s SA-15 actuator, the hold-down and release mechanism, and thermal control hardware. It can also monitor the actuators current consumption as well as thermistors, potentiometers, and position switches telemetries.

The THOR boom emulator electrically represents the complete functions of the north and south booms. It provides means for electrically load the spacecraft interfaces as well as feeding back values in both open and closed loop control. The position, and thermal conditions of all THOR Boom parts can be defined by the user, and are used to validate on-board software, AOCS control-loop and system FDIR.

IV. OTHER EP ACTIVITIES: HEINRICH HERTZ SATELLITE

The OHB Sweden design approach and test activities described in the sections above are also applied for the development of the Heinrich Hertz satellite (H2Sat). The H2Sat mission is a German satellite project aiming to demonstrate new telecommunication technologies in the geo-stationary orbit and to deliver telecommunication capacities to the German Federal Armed Forces. The mission/the project is being implemented by the Space Administration of the German Aerospace Center (DLR) on behalf of the Federal Ministry for Economic Affairs and Energy (BMWi) with participation of the Federal Ministry of Defense (BMVg).

The EPPS used on-board the 3400 kg H2Sat platform has a design similar to what shown in Figure II 1 and it consists of four main functional parts: the xenon tank assembly (XTA), the propellant supply assembly to provide pressure regulation from the XTA to the thruster assemblies and two EP thruster assemblies (EPTA). EPTA-1 is the nominal assembly and consists of two HEMP thrusters [22] with their flow controllers and power unit and it is handled by OHB Sweden as customer furnished item. EPTA-2 is the redundant assembly and consists of two HETs and their flow controllers and power unit.

OHB Sweden AB and their industrial partners are completing the majority of the qualification activities and functional testing at sub-system level.

As per Electra, the use of Electrical Ground Support Equipments (EGSEs) is necessary to enable early system level electrical and communication interfaces validation. Similarly to what presented in section D, EGSEs designed and validated by OHB Sweden in the frame of H2SAT include a dedicated dynamic EP thruster simulator, a PCDU EGSE to operate the Power Processing Unit and a xenon flow regulation subassembly electrical emulator.

V. CONCLUSIONS AND ACKNOWLEDGMENT

The EPPS design activity was supported by a series of test activities aimed at validating the critical functional parts and technologies of the sub-system. The xenon flow regulation assembly was proven to be compatible with the auxiliary cold gas propulsion system and the thermal management used to cope with the Joule Thomson effect was demonstrated to be very efficient. The THOR EP boom was thermally validated to perform simultaneous firing of two thrusters at 4.5kW each while ensuring a smooth thermal environment to the xenon flow controllers. A cycle life test of a rotary actuator confirmed that the actuator design and mechanism margins could cope with the resistive torques from the harness and tubing even at EoL after a very high number of activation cycles.

The complete sub-system was then successfully validated in Q1 2019 during a firing test at Aerospazio facilities using qualification models of the regulation sub-assembly, PPU, thruster, XFC, harness and tubing.

To validate the EPPS design and interfaces at system level, a complete set of EGSE simulating the functional chain (RS; PPU, Thruster, THOR) was developed and manufactured by OHB Sweden.

The same design approach and test activities are also successfully applied for the development of H2Sat, a German satellite project employing EP.

The authors acknowledge the support of ESA, OHB System, and the industrial consortium members.

VI. REFERENCES

[1] Perez G, et al: “Overview of OHB System’s Navigation and Telecommunication Satellites Capabilities”, IAC-17-B2-2.5, 68th International Astronautical Congress, Adelaide, Australia 2017

[2] Chasset C, et al: “SGEO AOCS In-Flight Results”, 10th International ESA Conference on Guidance, Navigation & Control Systems, Salzburg, Austria 2017

[3] Luebberstedt H, et al: “Electric Propulsion Applications in the SmallGEO Product Line”, Deutscher Luft- und Raumfahrtkongress, Augsburg, Germany, 2014

[4] Rayman M. D.: “The Successful Conclusion of the Deep Space 1 Mission: Important Results Without a Flashy Title”, Space Technology 23, Nos, 2.3, p.185, October 2002

[5] Kuninaka H., et al.: “Explored Powered by Ion Engines on the way to Earth”, IEPC-2009-267, 31th International Electric Propulsion Conference, University of Michigan, Ann Arbor, Michigan, September 2009

[6] Garner C. E., et al.: “The Dawn of Vesta Science”, IEPC-2011-326, 32nd International Electric Propulsion Conference, Wiesbaden, Germany, September 2011

[7] Wallace N., et al.: “The GOCE Ion Propulsion assembly – Lessons Learnt from the First 22 Months of Flight Operations”, IEPC-2011-327, 32nd International Electric Propulsion Conference, Wiesbaden, Germany, September 2011

[8] Killinger R., et al.: “ARTEMIS Orbit Raising In-Flight Experience With Ion Propulsion”, 38th AIAA/ASME/ASEE Joint Propulsion Conference and Exhibit, Indianapolis, Indiana, July 2002

[9] Milligan D., et al.: “SMART-1 Electric Propulsion Operational Experience”, IEPC-2005-245, 29th International Electric Propulsion Conference, Princeton University, New Jersey, October 2005

[10] Azrie M., “A Rescue Story”, MilsatMagazine, April 2012, URL: www.milsatmagazine.com /2012/MSM_Apr2012.pdf

[11] De Selding P. B., "SpaceX Launch Positioned Eutelsat, ABS Satellites For Faster Start," Space News, May 14, 2015, URL:http://spacenews.com/spacex-launch-positioned-eutelsat-abs-satellites-to-enter-service-sooner/

[12] "EUTELSAT 117 West B all-electric satellite fully charged and now in commercial service," Eutelsat Press Release, Jan. 16, 2017, URL: http://resources.mynewsdesk.com/ image/upload/t_attachment/nteip3xrv2bd8tp1e7vg.pdf

[13] “Airbus-built full electric EUTELSAT 172B satellite reaches geostationary orbit in record time”, Airbus Press Release, Oct. 11, 2017, URL: http://www.airbus.com/content/dam/corporate-topics/publications/press-release/Press-Release-SPACE-SYSTEMS-11102017-EN.pdf

[14] Rathsman P., et al.: “Electra – The Implementation of All-Electric Propulsion on a Geostationary Satellite”, IAC-13-C1-7.4, 64th International Astronautical Congress, Beijing, China, 2013

[15] Letizia F., et al., “Optimisation tool for low thrust orbit raising based on the Sequential Gradient Restoration Algorithm”, IAC-17-C1-6.9, 68th International Astronautical Congress, Adelaide, Australia 2017

[16] Schäff S., Low-Thrust Multi Revolution Orbit Transfers in Space Engineering: Modeling and Optimization with Case Studies, Giorgio Fasano, János D. Pintér, Eds., Springer, 2016.

[17] Luebberstedt H., et al., “Solely EP based Orbit Control System on Small GEO Satellite”, Proceedings of the 30th International Electric Propulsion Conference, Florence 2007, IEPC-2007-274

[18] Laube J., et al., “EP plasma plume: Modelling, validation status and way forward”, Space Propulsion, Seville 2018, SP2018_156

[19] Bourguignon.E, Fraselle S., “PPU Mk3 for 5kW Hall Effect Thrusters”, International Electric Propulsion Conference, Atlanta 2017, IEPC-2017-171

[20] Duchemin O., et al., “Development status of the PPS®5000 Hall Thruster Unit”, International Electric Propulsion Conference, Atlanta 2017, IEPC-2017-171

[21] Lubberstedt H., et al., “EP Boom operations concept on the Electra satellite for GEO applications”, Space Propulsion conference, Sevilla 2018, SP2018-420

[22] Weis S et al, “Overview, Qualification and Delivery Status of the HEMP Thruster based Ion Propulsion System for SmallGEO” IEPC-2017-197, 35th International Electric Propulsion Conference, Atlanta Georgia, USA, 2017

[23] Duchemin O., et al., “Qualification Status of the PPS®5000 Hall Thruster Unit” IEPC-2019-906, Vienna, Austria, 2019