Electric Propulsion Thruster Assembly for Small GEO – Status Update

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Abstract: **The European Small GEO platform is currently under development under Artes Element 11, an ESA program to develop the new generation of small platforms for telecommunications satellites in geostationary orbit. In May 2009, Snecma was awarded a contract for the development and procurement of a complete Electric Propulsion Thruster Assembly based on Hall-effect plasma thrusters. This paper provides a status update on the associated development, production and testing activities.**

Nomenclature

F	=	thrust, N
I_d, U_d, P	=	discharge current, A (resp. voltage, V; and power, W)
Id_{osc}	=	discharge current oscillations amplitude, A_{rms}
I_m	=	magnet trim current, A
Isp	=	specific impulse, s
I_{tt}	=	thermothrottle current, A
m_{tot}	=	total mass flow rate, mg/s
U_{CRP}	=	cathode reference potential, V
η	=	thrust efficiency, %

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I. Introduction

SMALL GEO is a general-purpose, small geostationary satellite platform currently under development within the framework of an ESA Artes-11 program.[1,2,3] This development is being carried out by a consortium led by the German company OHB System AG, and including OHB-Sweden AB, RUAG Space AG of Switzerland, and LuxSpace of Luxembourg. The SGEO platform will rely on electric propulsion for most propulsive tasks once in Geostationary Orbit (GEO). It will accommodate payloads near 300 kg in mass and 3 kW in power, for a launch mass into Geostationary Transfer Orbit (GTO) of up to 3 tons depending on satellite version. One version relies on direct injection into GEO by the launch vehicle, whereas another version features an optional MON-MMH chemical Apogee Engine Module (AEM) to transfer the satellite from GTO to GEO.[1,2]

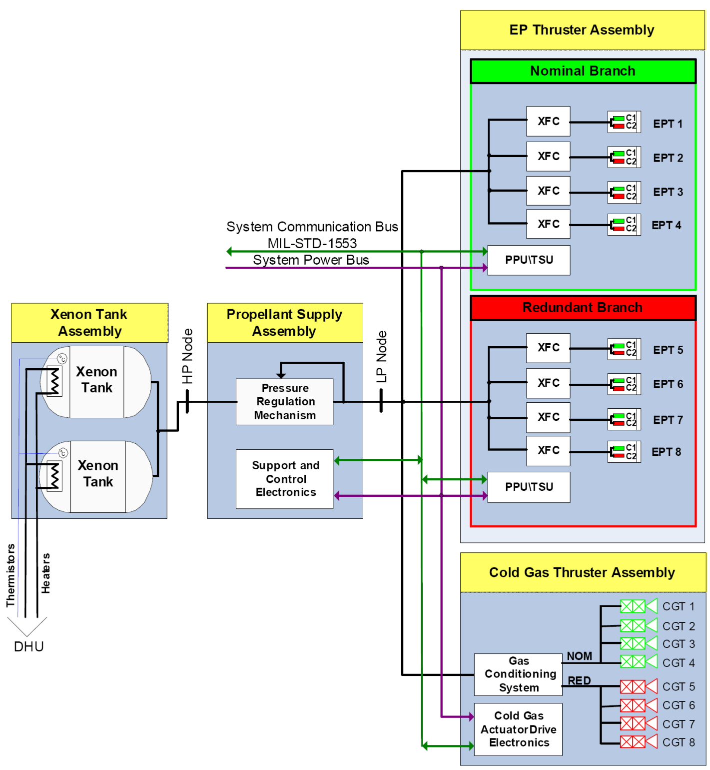

Figure 1. The Electric Propulsion Subsystem for Small GEO.

In the above two versions of the Small GEO platform, all the orbital maneuvers and attitude control will be fulfilled by the Electric Propulsion Subsystem (EPPS) and the reaction wheels. The orbital maneuvers include station acquisition; station keeping for a service life of 15 years; momentum management during GEO mission; intermediate repositioning, if required; and transfer to graveyard orbit at end of life.[1,2,3]

For this purpose, the EPPS baselined on the SGEO platform comprises two independent (redundant) branches of four thruster units each, where the eight thrusters are hard-mounted onto the satellite walls, with no thrust pointing mechanism. This is in similar fashion, for example, to the Russian *GALS*, *Express*, *Sesat*, *Kazsat*, and *Yamal* family of telecommunications satellites, which feature eight SPT-100 or SPT-70 Hall-effect plasma thrusters (HET).[4,5]

II. Description of the Electric Propulsion Thruster Assembly

The Electric Propulsion Thruster Assembly (EPTA) is one of the four assemblies of the EPPS (Figure 1). The other assemblies are the Xenon Tank Assembly (XETA); the Propellant Supply Assembly (PSA), which electronically regulates the xenon feed pressure to the required 2.2 bar upstream of the Thruster Units; and the Cold Gas Thruster Assembly (CGTA). The CGTA can provide reaction control torques on specific instances where electric propulsion is not available, i.e., during detumbling after spacecraft separation from the launch vehicle; and when the spacecraft enters safe mode.[2]

The EPTA comprises the two redundant branches (EPTA1 and EPTA2), which may be based on two different thruster technologies. A functional schematic is given in Figure 2 and the complete EPTA design accommodation is represented in Figure 3. Both Figures represent the configuration in which the two EPTA branches are based on Hall-effect plasma thrusters. In this configuration, each branch can independently operate one Thruster Unit (TU) at a time using a single Power Processing Unit (PPU). Thruster selection is done *via* a 1-to-2 Thruster Selection Unit (TSU), which is internal to the existing PPU, and a 2-to-4 External TSU (ETSU). Each HET branch thus comprises:

- 1 × PPU including internal TSU;
- 1 × ETSU;
- 4 × TU including Xenon Flow Control (XFC) modules and associated tubing;
- 4 × electrical Filtering Units (FU) with electrical harness and connectors.

Both the PPU and the ETSU are independently powered by the satellite Power Distribution Unit (PDU) *via* a 50-V regulated bus. The PPU communicates with the on-board Satellite Management Unit (SMU) through a MIL-STD-

1553B serial data bus. The ETSU, a much simpler unit, communicates using direct telemetry and direct telecommands.

Apart from the ETSU, all hardware units are preexisting and are flight proven. The ETSU, although it is a new unit, did not require any new technology as it is based on the TSU hardware.

The procurement contract awarded to Snecma entailed the development and delivery of a complete EPTA based on the SPT-100 from EDB Fakel of Russia. The first (PFM) branch will nominally fly on the first Small GEO satellite, whereas the second (FM) branch will safeguard the schedule in case of delays in the development of the HEMPT, which is planned to fly on the other branch. Detailed description of the main EPTA units and heritage have been given in previous papers.[6,7] This paper provides a status update on the EPTA development and production activities as the final, End-to-End test is scheduled at the end of 2011.

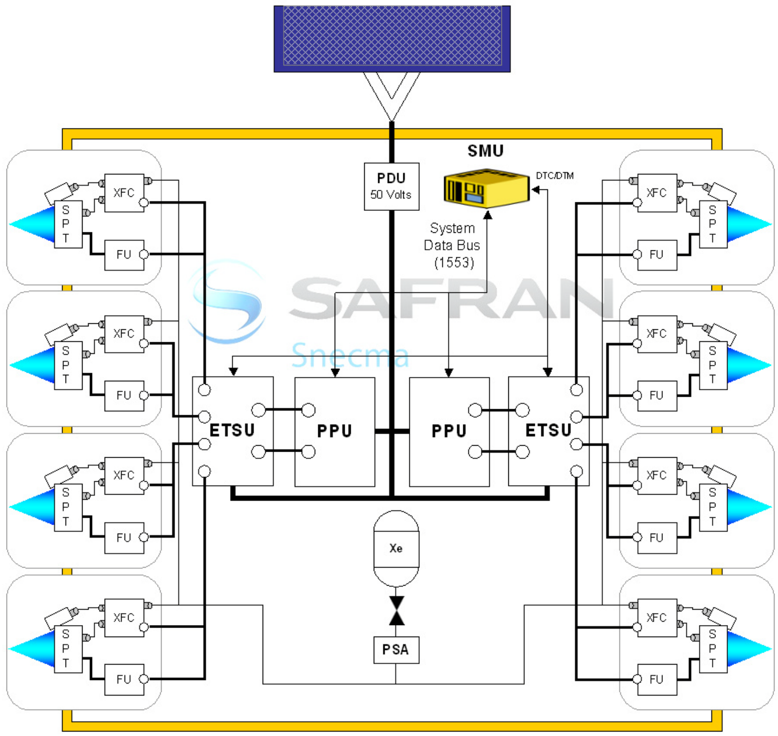

Figure 2. Functional schematic of Electric Propulsion Thruster Assembly in the two HET-branch configuration.

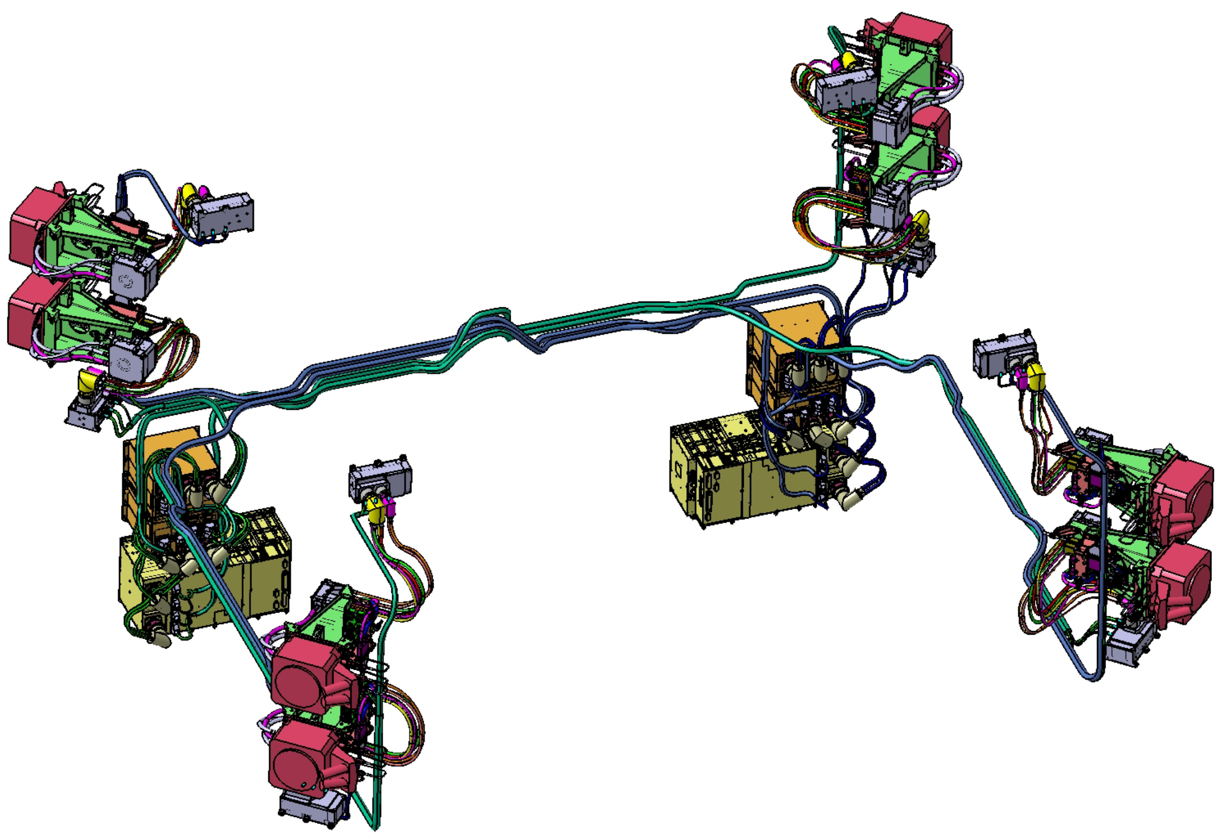

Figure 3. The Small GEO Electric Propulsion Thruster Assembly in the two HET-branch configuration.

III. EPTA Development Status for Small GEO

All EPTA Units, except for the ETSU, have passed Manufacturing Readiness Reviews (MRR) and manufacturing is either complete or nearing completion. The SPT-100U has passed Equipment Qualification Status Review (EQSR) and all eight thrusters for the complete EPTA were delivered to Snecma in 2010. The FU has also passed EQSR, and the PPU, which required minor modifications for SGEO, has passed EQSR and delta-CDR (Critical Design Review). Finally, the ETSU has passed the PDR (Preliminary Design Review), CDR and qualification TRR (Test Readiness Review) milestones, with the EQM (Engineering Qualification Model) about to complete its qualification test sequence. This section provides an overview of the main design and development activities for the units or subassemblies constituting the EPTA for SGEO.

A. Thruster Subassembly

The Hall-effect plasma Thruster Unit selected for SGEO is the Russian-built SPT-100U (Figure 4). Two operating points were defined in the early stages of the program, to fit within the power constraints of the small platform, corresponding to thrust levels of 40 mN and 75 mN.

In order to keep the startup current in-rush on the power bus below acceptable limits, a low-power startup condition was also defined, drawing from the experience of operating the PPS®1350-G from Snecma on the small *Smart-1* spacecraft.[8,9] On SGEO, thruster discharge will be ignited near 900 W and 250 V of discharge power and voltage, respectively. The PPU will then automatically ramp up the discharge voltage to the nominal 300 V, at which point the SMU will take over to throttle the engine to the desired thrust level by adjusting the (regulated) discharge current set point. The low-power startup throttle condition, as well as the two SGEO nominal operating points, are represented in Figure 5.

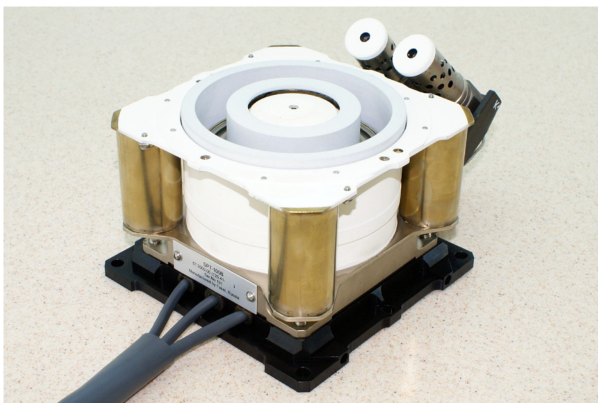

Figure 4. One of the SPT-100B modules for the SGEO EPTA PFM branch.

Table 1 provides a summary of the thruster control and performance parameters at Beginning of Life (BOL) for the two nominal thrust levels required for SGEO. In this Table, I_{tt} is the thermothrottle current controlling xenon flow rate;[7] I_m is the magnet trim current; I_d, U_d and P are the discharge current, voltage and power, respectively; Id_{osc} is the amplitude of discharge current oscillation; m_{tot} is the total xenon mass flow rate; U_{CRP} is the cathode coupling voltage; F is the thrust; Isp is the (total) specific impulse; and η is the total thrust efficiency. The need for magnet trim current I_m at low discharge current comes from the fact that the electro-magnet coils are electrically connected in series with the main discharge, so that lowering the discharge current to throttle the engine to low power also means that the magnetic induction field strength is lowered. The magnet trim supply in the PPU provides the possibility of adding the current I_m to the discharge current I_d into the electromagnet coils.

Table 1. SPT-100 reference performance at Beginning of Life for both Small GEO throttle points.

I_{tt} A	I_d A	U_d V	Id_{osc} A_{rms}	m_{tot} mg/s	F mN	U_{CRP} V	I_m A	Isp sec	P W	η
1,79	4,22	300	0,23	5,04	75,2	19,85	0,00	1521	1265	44,3%
3,65	2,31	300	0,13	3,09	40,1	22,20	1,00	1321	693	37,5%

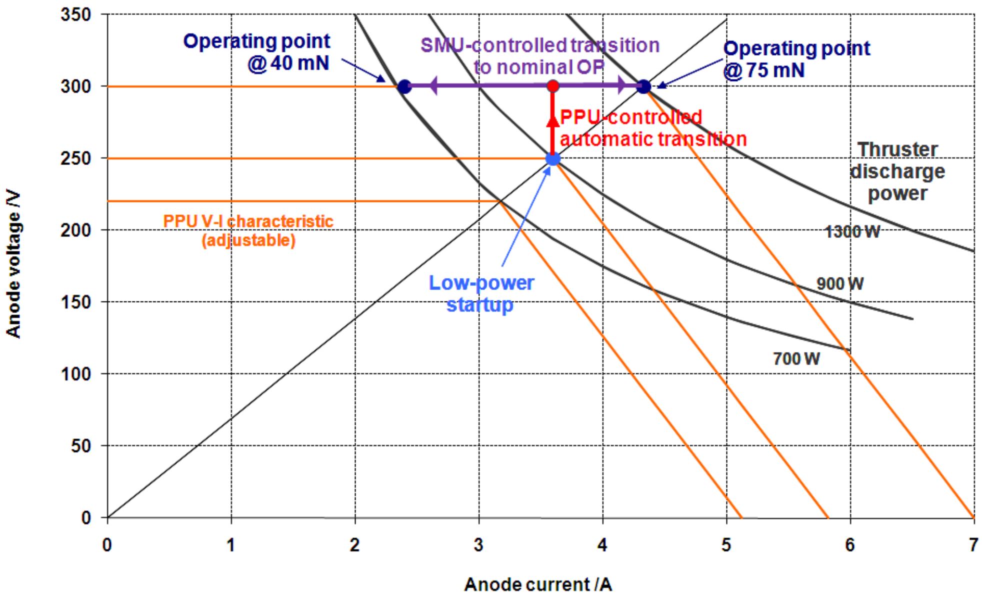

Figure 5. Low-power startup, and thruster operating points for SGEO.

Each SPT-100U thruster unit comprises a SPT-100B thruster module including two redundant cathodes, and a XFC assembly constituted of two redundant XFC-100B modules (Figure 6). Each thruster unit is integrated into a thruster subassembly, along with the necessary xenon tubing, ancillary mechanical supports, electrical interconnections and harness. Because each of the eight electric thrusters has a fixed direction of thrust in the SGEO architecture, there is no mobility requirement on the electrical harnesses and xenon tubing, and the thruster subassemblies can be hard-mounted onto the satellite walls.

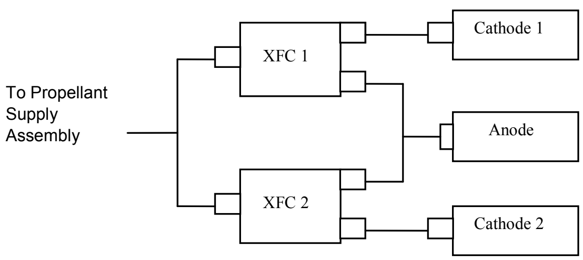

Figure 6. Block diagram of SPT-100U thruster unit.

The design of the thuster subassembly for SGEO draws maximum heritage from the Snecma Thruster Module Assembly (TMA)[10,11] experience. Indeed, a total of 16 TMAs have been produced at Snecma to date, and since the launch in 2004 of the first TMA on board Intelsat X-02,[12,13] TMAs have cumulated over 47 years of flight experience and over 14,000 hrs of total firing duration. The thruster subassembly for SGEO, represented in Figure 7, thus features removable xenon lines downstream of the XFCs to simplify Acceptance, Integration and Testing (AIT) operations, and highly reliable electrical connections without potting. The thruster subassemblies are under final integration and will be ready for delivery before the end of 2011.

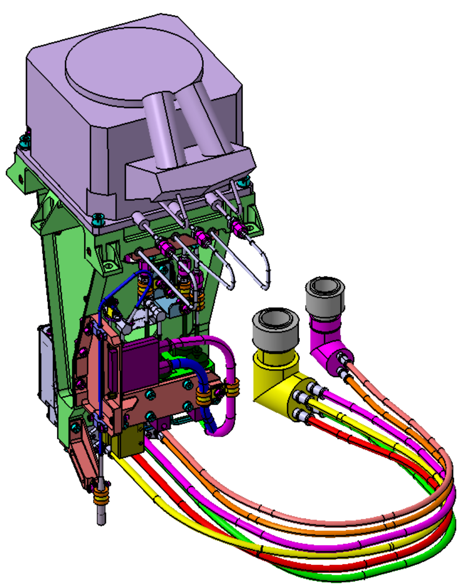

Figure 7. Small GEO EPTA thruster subassembly.

B. Power Processing Unit and Thruster Selection Unit

The main PPU functions are to supply the necessary discharge and auxiliary power inputs to the thruster, to regulate the discharge current *via* a closed-control loop acting on the xenon flow rate, and to ensure most of the Telemetry and Telecommand (TM/TC) interface between the SMU and the EPTA. In addition to this, the PPU also has thruster selection and cathode/XFC branch selection functions. It also sequences all thruster operations such as, e.g., automatic startups and shutdowns. A functional schematic of the PPU is given in Figure 8.

The PPU is provided by Thales Alenia Space ETCA of Belgium. This Unit comprises five internal mechanical modules:

the primary module, the anode module, the HIM (Heater Ignitor Magnet) module, the upper module (sequencer and XFC drive), and the TSU (Thruster Selection Unit) module. The PPU for SGEO is based on the extensive flight heritage already accumulated on this design[6,13,14] with already 34 flight models produced to date. A complete overview of the heritage and future developments is given in Ref. 15.

Minor changes have been brought to the original *Stentor* PPU designed to Snecma specifications in order to meet the SGEO technical requirements and include lessons learned from past programs. First, the maximum output power level of the anode supply was adjusted to ensure that even in worst-case conditions, a maximum PPU input power of 1500 W; imposed by satellite power constraints, cannot be exceeded. Second, as was the case on *Smart-1*, the output voltage may be commanded by TC, from 220 V up to 300 V. And third, a low-power start-up sequence has been implemented to meet the maximum inrush current requirements specification. Minor parts obsolescence has also led to reviewing some of the hybrid boards.

All PPU versions, to the exception of the *Smart-1* PPU, include a (internal) TSU that permits the selection of one out of two thrusters, and of one out of two cathodes per thruster. Because only one thruster was present on *Smart-1*, the TSU was simplified to include only the capability for cathode/XFC branch selection. The capability to select one out of two thrusters, normal on the recurring units, has been implemented in the PPU configuration for SGEO.

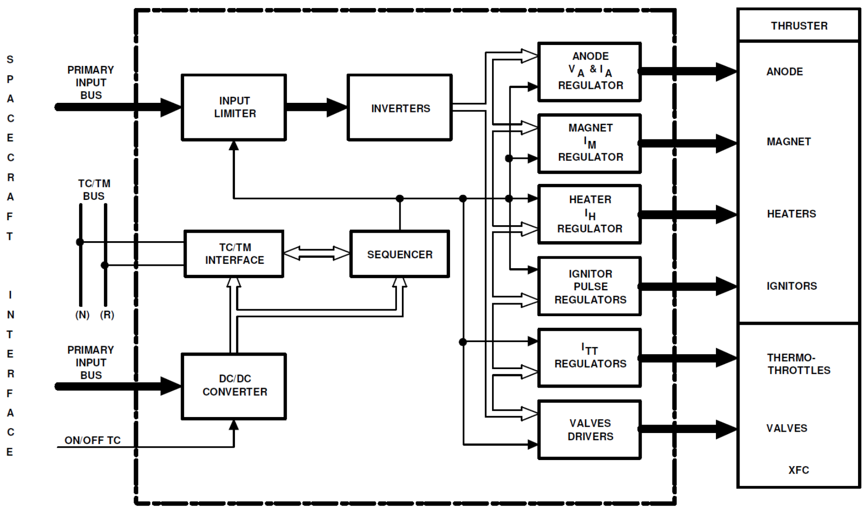

Figure 8. Functional diagram of recurring PPU for Hall-effect plasma thruster applications.

Because the PPU includes the sequencer software, which was adapted to match specific SGEO needs, a Software Requirement Review (SRR) and a Software Qualification and Acceptance Review (SQAR) were held successfully in 2010. After successful close-out of the CDR in June 2010, the two SGEO flight PPUs have entered the acceptance testing phase.

C. External Thruster Selection Unit

The architecture selected for SGEO comprises two PPUs, where each one must be able to drive any one out of four thrusters. One solution would have been to extend the PPU functions with two supplemental TSUs. This, however, would have required significant internal modifications to circuit boards, to the internal TSU structure, and would eventually have lead to deep modifications of the entire PPU structure. The qualification and flight experience would have been lost as a result.

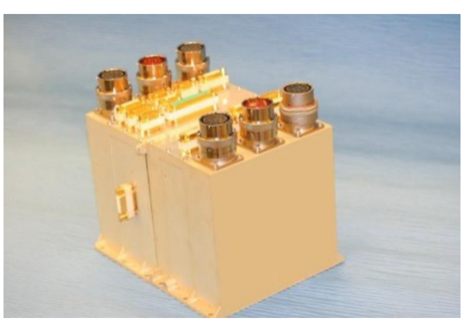

Figure 9. ETSU for 1:4 thruster switching capability. *EQM model.*

In order to provide this overall 1:4 switching capability without inducing undue development risk and cost, another solution involving a separate (external) unit was preferred, as shown in Figure 2 and Figure 10. With an ETSU, the PPU is structurally exactly identical to the models possessing flight heritage. The ETSU reuses the structure of the internal TSU module within the PPU, a simple structure much easier to analyze. The connection is ensured by latching relay contacts, with capability to switch 32 inputs to 64 outputs. Practically, the 4-way ETSU is based on 2 TSU switching modules. The Engineering Qualification Model (EQM) is shown in Figure 9.

Fabrication of the EQM at Thales Alenia Space ETCA was completed in April 2011. After initial system testing at EPTA level performed at the premises of OHB System AG in Bremen, Germany, the EQM is currently undergoing mechanical and thermal environment qualification testing (vibration, pyro-shock and vacuum cycling). Electro-Magnetic Compatibility (EMC) tests and Electro Static Discharge (ESD) tests have already been completed in the spring of 2011. Manufacture of the flight units has progressed in parallel, and the flight hardware is expected for delivery by the end of 2011.

D. Filter Unit and electrical harness

The main functions of the electrical inductive-capacitive line Filter Unit (FU), placed between the PPU and each thruster, are to facilitate discharge ignition and to insulate the PPU electronics from any conducted noise generated by the thruster. It therefore filters out the perturbations and allows the thruster to be compliant with usual EMC requirements. Each FU interfaces with one thruster and its electrical supply system, as represented in Figure 10. The electrical harnesses connect the PPU to the ETSU, the ETSU to the FU and XFC, and the FU to the thruster.

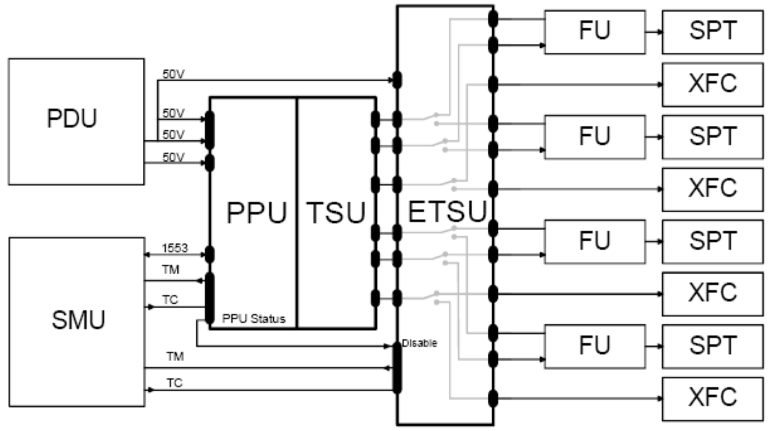

Figure 10. Schematic diagram of EPTA Units and electrical interfaces with the satellite power bus (PDU) and management unit (SMU).

An important flight heritage also exists on the electrical harness and FU manufactured by EREMS of France, selected for SGEO. To date, a total of 46 FMs have been delivered, with the additional 8 units for SGEOnearing completiong. The qualification and flight heritage is described in Ref. 6.

After final harness and FU configuration freeze in April 2011 (Figure 11) for the first SGEO satellite, manufacturing has progressed well and the PFM units will be delivered in October, 2011.

Figure 11. Electrical Filtering Units (right and left configurations).

E. End-to-End Testing

Final functional verification of the EPPS design and manufacture will be performed with two End-to-End (E2E) test campaigns in immediate succession at Snecma. The first test will implement the EPTA PFM branch units: PPU, ETSU, FU, thruster units along with the flight harness and xenon tubing. A laboratory xenon supply stage will be used. The second test will see the replacement of the laboratory xenon supply by the EM model of the Propellant Supply Assembly (PSA). Thus, the compatibility of the complete PSA plus EPTA chain will be verified against the behavior predicted by analyses.

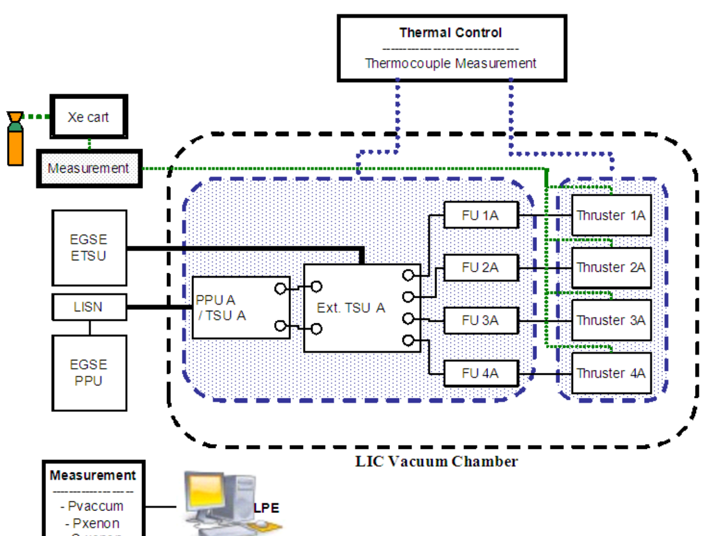

Figure 12. General test setup for the EPTA, and EPTA+PSA E2E test campaigns

For the E2E tests, all four thruster subassemblies for the EPTA PFM branch will be placed under vacuum and tested, along with the PPU and ETSU. The PPU and ETSU will be driven *via* Electrical Ground Support Equipment (EGSE) and through a Line Impedance Stabilization Network (LISN). The general setup is represented in Figure 12.

In preparation for this campaign, all mechanical, electrical, fluid and thermal interfaces for the LI-C test facility in Vernon, France, have been commissioned in July 2011 (Figure 13). The EGSE and LISN have been fabricated, and final commissioning tests will be performed in the fall 2011 using the ETSU EQM and PPU EM. The tests are expected to begin at the end of 2011, after delivery of all the EPTA PFM branch hardware.

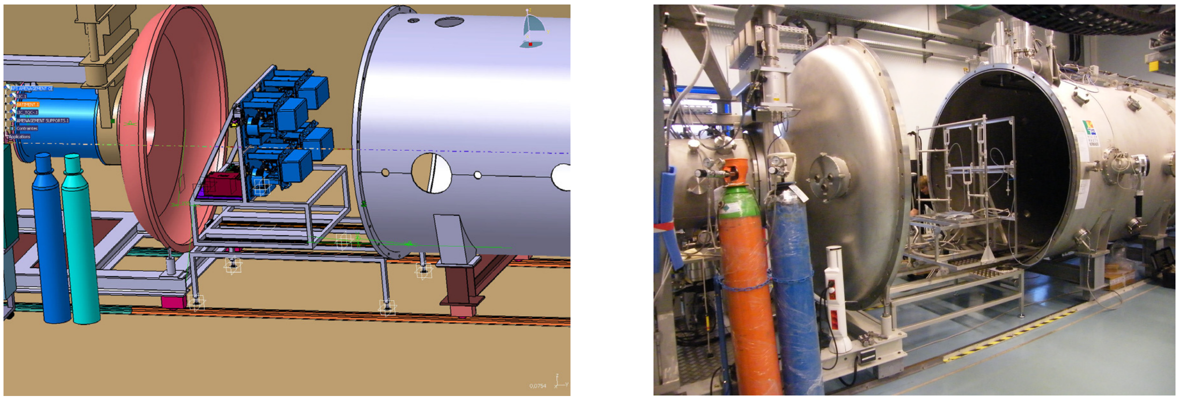

Figure 13. Integration of EPTA PFM branch into LI-C test chamber at Snecma, Vernon operations.

IV. Conclusion

Significant flight-program heritage on Snecma Electric Propulsion modules or subsystems has been cumulated on the ESA *Smart-1* technology demonstration mission, on *Eurostar* commercial platforms based on the original *Stentor* program, and on the *Alphabus* program. Based on this heritage, the new product line for Small GEO is being qualified and readied for flight with high confidence. This product line is constituted by the EPTA, which includes two fully redundant branches, each comprising one PPU, one ETSU, four FUs and four Thruster Units. The thrusters are hard-mounted onto the satellite walls, i.e., with no thrust orientation mechanisms.

The EPTA thus reuses most of the units, technology and processes developed and demonstrated on previous programs. All thruster units have been delivered to Snecma in 2010. The PPU hardware is based on the *Stentor* configuration, and the PPU software is based on the more recent *Alphabus* software, with only minor modifications brought to both PPU hardware and software. The ETSU is the only new Unit, and a qualification model is currently under environment qualification testing. The first (PFM) EPTA branch will undergo a complete subsystem test at Snecma where the PSA will be implemented along with all EPTA branch units, xenon tubing, and electrical harnesses placed under vacuum. All four thrusters will be fired in sequence during this subsystem test. After contract signature in mid-2009, both EPTA flight branches remain slated for delivery by the end of 2011.

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