New Electric Propulsion missions at SSC: The use of SMART-1 heritage and new lessons learnt

IEPC-2009-053

Presented at the 31st International Electric Propulsion Conference, University of Michigan • Ann Arbor, Michigan • USA September 20 – 24, 2009

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Abstract: Swedish Space Corporation is currently working with new satellite programs where Electric Propulsion has an essential role, such as Small GEO and the SMART-OLEV. This paper describes the two programs, their selected EP subsystem designs and lessons learnt so far. The use and further optimization of SMART-1 heritage in the two programs is also explained. In addition, an update is provided regarding the MEMS based propellant management unit that is in development at Swedish Space Corporation's subsidiary NanoSpace.

I. Introduction

Through the SMART-1 mission, European Space Agency's successful mission to the Moon, SSC (Swedish Space Corporation) gained the position as an enabler of EP (Electric Propulsion) systems. This experience has established SSC as one of few system houses in Europe that together with partners can build missions on the use of this highly efficient propulsion technology. Presently this is the case for the demanding Small GEO and the SMART-OLEV programs. Important lessons[1,2] were learnt from the SMART-1 mission and are now being applied in both Small GEO and SMART-OLEV. Both programs would not be possible without the substantial mass saving and fine control brought by EP.

Additionally, the paper introduces the MEMS (Micro-Electro-Mechanical-Systems) technology based regulation and propellant management concept that is in development at SSC's subsidiary NanoSpace. This concept shows promising capabilities and the aim is to provide enhancements in the current architecture with devices such as a mass saving propellant management unit within the next few years.

II. The early 2000 heritage and the SMART-1 mission

Commercial spacecraft manufacturers got interested in EP in the nineties. Extensive cooperation among the industry made the first commercial applications possible. SSC first experience with EP was SMART-1 (Fig.1 and Fig.2), which used a single HET (Hall-Effect Thruster) that still holds record of the longest Hall effect thruster firing time in space of nearly 5000hrs[3]. This mission initiated the development of several units, such as:

- Pressure regulator
- Thruster pointing mechanism

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It has brought valuable experience related to the in-flight behavior, which now can be used for better flight predictions and wider field of applications:

- Hall effect thruster and flight performances related to Acceptance test
- Performances reliability
- Variable performance settings

The versatility of the EP system, the platform interfaces and the system application have provided SSC with a wide system level experience. The robustness of the system has also been confirmed by major Primes, who have steadily been building a large experience and are now getting new customers on the EP based option of their platform. Models of interactions were also developed for SMART-1 and have been refined in the light of the EP diagnostic data package measurements. These can now be re-used to analyze EP plume interactions on future spacecraft and the effects these interactions have on system level.

Figure 1. Illustration of SMART-1 approaching the moon

Many valuable lessons from SMART-1 will be transferred to future SSC missions:

- Ground operations
- Tank loading
- Final verification of the system
- Tank gauging monitoring
- In-flight characterization

This background is the heritage and backbone of the EP activities presently taking place at SSC together with the team experience gained during previous undertakings.

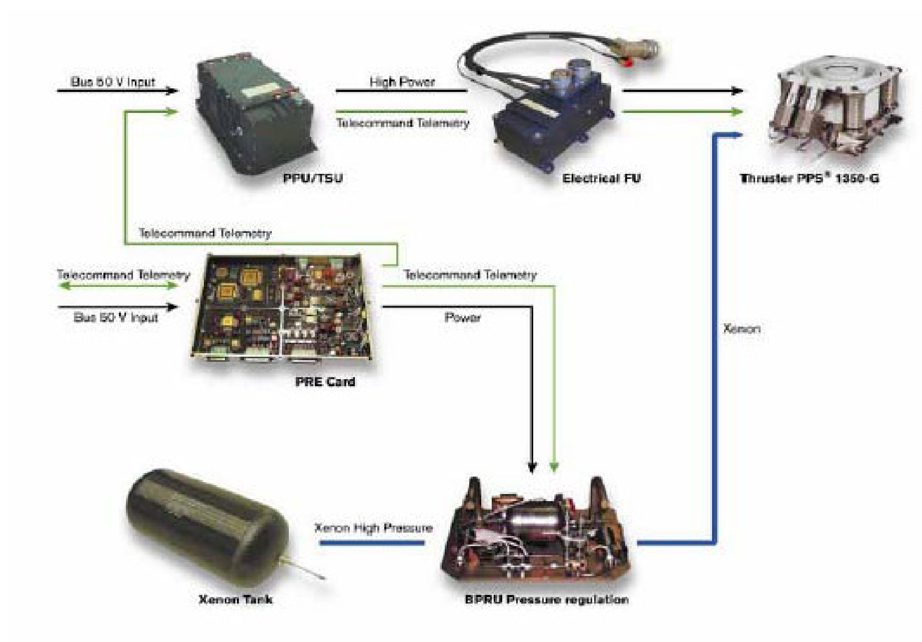

Figure 2. SMART-1 Electric Propulsion architecture

III. The Small GEO mission

A. Introduction

Small GEO (Fig. 3) is a general purpose small geostationary satellite platform that is currently being developed by a consortium led by the German company OHB System, Oerlikon Space, LuxSpace and SSC. SSC plays an important role in this consortium being responsible for the provision of both EP and AOCS (Attitude and Orbit Control Subsystem). The Small GEO platform supports up to 300 kg payload mass, a payload power of up to 3 kW and with a lifetime of up to 15 years. First launch is schedule for 2012.

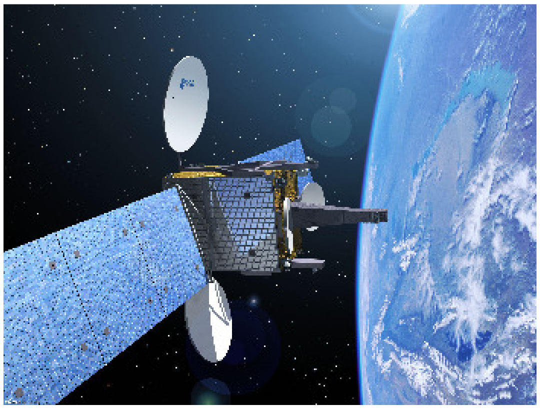

Figure 3. Illustration of Small GEO in orbit

The Small GEO EPPS (Electric ProPulsion Subsystem) will be used throughout the mission, from the early orbital life until the end of life. In short, all the station keeping operations and the graveyard jettisoning will be done with the EPPS, which shows the strong recognition of EP and the technology's maturity by costumers and operators in Western Europe. The lessons learnt from SMART-1, nurtured by complementary ground tests and modelling, have allowed SSC to develop control laws for Small GEO optimized for low thrust and highly repeatable performances of the thrusters. The Small GEO EPPS will be based on extensive reuse of previous EP programs and relying on the expertise of the industrial team led by SSC.

B. EP Operations

SMART-1 heritage has provided a valuable basis for the development of the Small GEO EP and AOCS. The understanding of thruster behaviour (thrust variation, ignition process, repeatability and other EP-related events) has significantly influenced the Small GEO design. Trade-offs have been made for the EP thruster configurations on an early stage resulting in for instance the exclusion of Thruster Orientation Mechanisms as they proved to be unnecessary for this mission.

With SMART-1 as a starting point, a completely new AOCS strategy has been developed with enhanced confidence as the combined orbit and angular momentum control strategy required for Small GEO. This strategy is in turn intimately tied to the orbit determination problem. The SMART-1 heritage was a fundamental source of knowledge and comparison for these developments. For the commanding of the EP thrusters, Small GEO reuses the approach of SMART-1 regarding uplinking of EP commands and attitude profiles. However, the start-up procedures for the EPPS will be simplified with on-board macros.

C. Design description

The EPPS has been broken down in four assemblies according to Fig. 4. These are:

- XTA (Xenon Tank Assembly)
- PSA (Pressure Supply Assembly
- CGTA (Cold Gas Thruster Assembly)
- EPTA (Electric Propulsion Thruster Assembly)

The propellant in form of Xenon is stored in two equally sized tanks that make up the main part of the XTA, shown as the lower grey tanks in Fig.5. The PSA is based on a bang-bang regulator solution similar to the one used on SMART-1 and includes both the regulation feed system and SCE (Support Control Electronics). The PSA interfaces through three different feed lines with the CGTA and the EPTA. The EPTA includes two EP types. The four fixed mounted HEMPT (HEMP 3050) act as the baseline propulsion solution for station keeping operations whereas the fixed mounted four HET (SPT-100) will be a redundant solution. In accordance with their use, the individual HET and HEMPT are accommodated on the spacecraft platform in pairs as seen in Fig. 5 and Fig. 6, one pair in each corner of the spacecraft. The accommodation is based on Yamal experience but allows E/W and N/S station keeping with only four thrusters as opposed to Yamal which has 8 thrusters.

The design of the EPPS permits simultaneous firing of one thruster from each branch as long as the thrusters are not adjacent to each other. This design approach is used for both the individual branches in the EPTA (mass flow of ~5mg/s), but also for the CGCS (mass flow of ~200mg/s) to thereby prevent that pressure spikes influence the subsystem's performance.

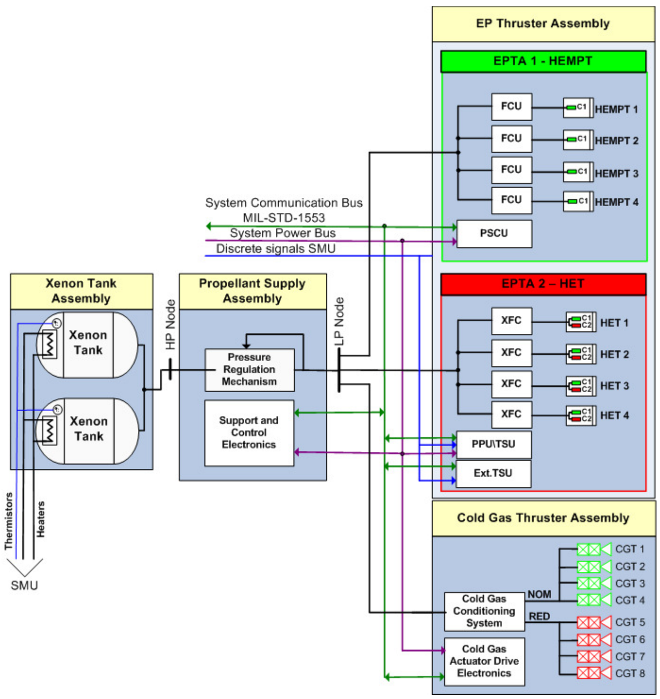

Figure 4. Block schematic of SGEO EPPS Subsystem

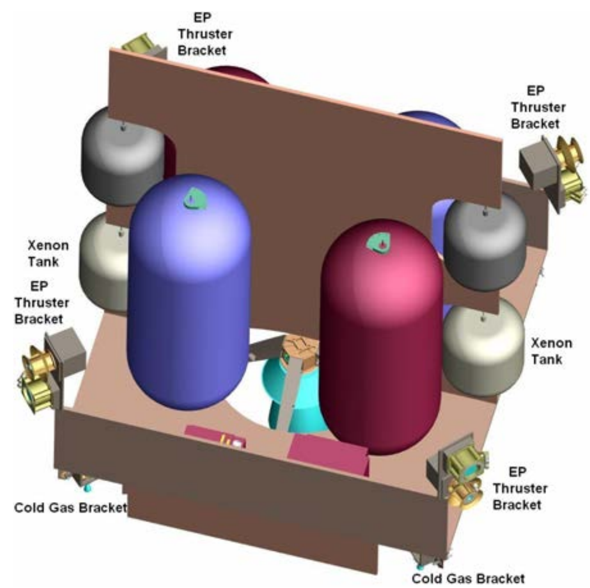

Figure 5. Tank and thruster accommodation (Courtesy of OHB)

D. XTA

The XTA consists of two polar mounted 60 L composite-overwrapped titanium liner tanks. Each tank will house 110 kg of Xenon at 186 bar MEOP. For reasons of volume efficiency the Xenon is stored under high pressure in supercritical conditions. The tanks will be interconnected to the PSA by a shared manifold. This will require a tight thermal control of the tank and SSC has taken the role of thermally equipping them.

Compared with standard tanks, the XTA tanks will have dual ports, one in each end. This will ease the process of filling and draining the tanks via an external circulation loop, whose development will be tailored to SGEO needs by SSC and their ground support equipment partners. Such a device will reduce the loading time drastically and keep the preparation cost minimal.

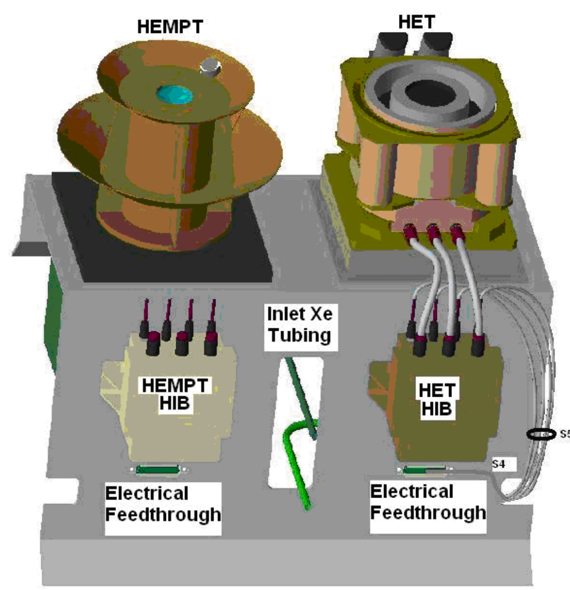

Figure 6. HET and HEMPT pair solution (Courtesy of OHB)

E. PSA

The primary function of the PSA is to decrease the Xenon storage pressure to the operational pressure range required both by the EP thrusters and cold gas thrusters. Towards end of life, the pressure at the high pressure node will decrease down to 2.2 bar. If further operation of the PSA is required beyond this point, the pressure achievable at the Low Pressure Node will be limited by the available Xenon tank pressure.

The outputs to the two EP thruster branches are routed through isolation valves which are open during the operation of the branch in question, and then closed (the same valve type as for the bang-bang operations is envisaged). It was initially intended to use latch valves that would nominally remain open, but as no suitable latch valve was identified SSC's supplier selected a solenoid valve inherited largely from SMART-1 and is now working on actuation profile to minimize the power dissipation. The bang-bang operation is controlled by closed loop regulation performed by the SCE on the basis of the pressure measurements at the low pressure side.

The PSA will be developed largely based on the BPRU (Bang-bang Pressure Regulation Unit) of SMART-1. Compared with the SMART-1's regulator a significantly higher total Xenon throughput will be allowed without exceeding the qualification limit of 1 000 000 cycles per valve. The PSA will be equipped with accurate PT (Pressure Transducers) handled in a dedicated manor to have a highly accurate end of life propellant estimate. The logic inherited from Smart one will allow without any additional hardware to detect the degradation of any valve leak tightness, giving the operators the advance warning and preventing more easily disruption in the spacecraft operations.

The performance of the PSA is driven by the cold gas operational scenario where the average mass flow rate is 200 mg/s during the first part of the mission to support the initial detumbling. The cold gas must be available throughout the lifetime to support Safe Mode though a reduction to 25 mg/s at end of life is acceptable.

F. Propellant distribution system

On SMART-1 several detachable mechanical connections were used between the flow controller and the thruster unit. For mission durations in excess of 5-8 years it is the common practice that tube connections are welded, at least in the high pressure parts. As it is highly desirable to minimize the amount of welding occurring on the satellite (for reasons of safety, accessibility and modularity), the aim is to weld, as far as possible, the EP tubing on a rig, and then to transfer it to the spacecraft.

The EPPS will hydraulically be interconnected according to the below schematic Fig. 7. For mass saving reasons, titanium is preferred to stainless steel that is traditionally used. The tubing and all cross-points will be manufactured and verified in-house at SSC. The EPTA tubing (between XFC and EP thrusters) is provided by the EPTA suppliers and is the only part of the EPPS system that has removable connections. The reason is that the EP thrusters have no internal valves, and all Xenon downstream of the XFC is therefore anyway lost to space after each EP operation.

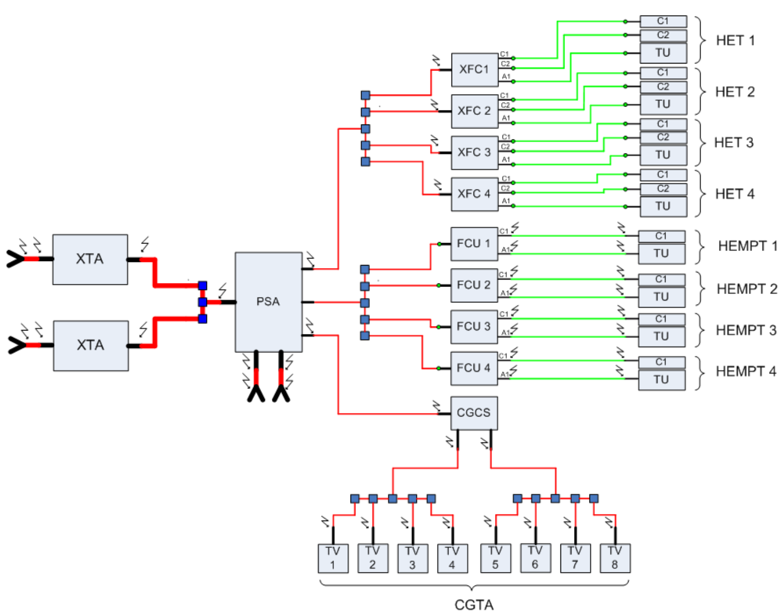

Figure 7. Welding schematic

G. EPTA 1 – The HEMP branch

Performance characteristics for the HEMP-T, both given Small GEO requirements and expected values, are given in Table 1 below. Figure 8 shows a cross section of the HEMP 3050 thruster with three permanent magnetic rings around the thruster ceramic cylinder. The magnetic configuration of the thruster will be optimized to decrease the plume divergence angle in an iterative design loop in which SSC is performing the erosion evaluation and acting as a coordinator.

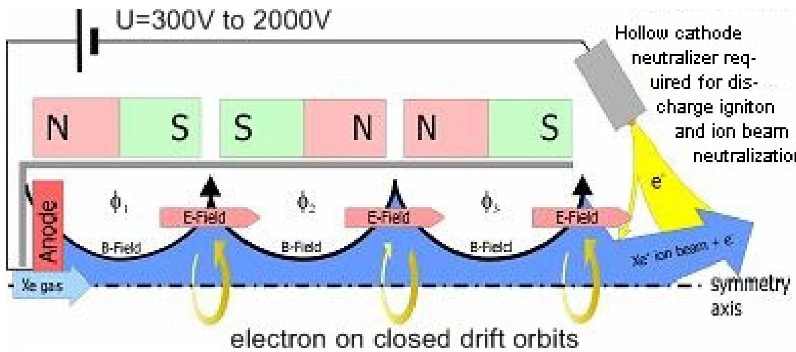

Figure 8. The cross section of the HEMP-T

The power unit for the HEMP system is denoted the PSCU (Power Supply and Control Unit). It is inherent to the HEMP branch design as shown in Fig. 9 that several thrusters can operate off a common anode power supply, thus eliminating the need for any thruster switching. Instead, the control and thruster activation is done by applying propellant flow to the anode and cathode of the selected thruster. For this purpose, each thruster has an FCU (Flow Control Unit) that is used to control the propellant flow through the anode. This activates the thruster by providing a discharge path (ionized Xenon) where current can flow. When no propellant is flowing, the thruster is OFF.

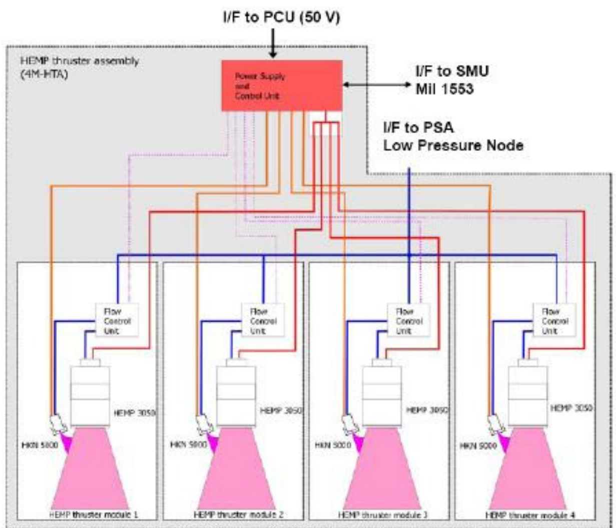

Figure 9. The design of the HEMP-T branch (Courtesy of Thales Electron Devices)

Table 1. The T-3050 performance characteristics

Performance	Expected	Requirement
Nominal Thrust	45 mN	>37 mN
Average Isp	2500 s	≥2000 s
Discharge voltage	1000 V	-
Xenon flow rate	<17 sccm	-
Total Impulse	3.0 MNs	0.9 MNs
Operational duration	>18000 h	5463 h
# restarts	TBC (Thermally stressing. No erosion expected)	8356
PSCU Input Power	1529 W (not including margin)	1500 W
Beam Divergence	<45°	<45°

H. EPTA 2 – The HET branch

From the Stentor development, the PPU (Power Processing Unit) has an internal TSU (Thrusting Switching Unit) allowing selection between two thrusters. The Small GEO requires however the possibility of switching between four thrusters within a thruster branch. An additional ETSU (External Thruster Switching Unit) has therefore been added to the HET EPTA branch as demonstrated by the design schematic in Fig. 10. To avoid re-qualification of the existing PPU,

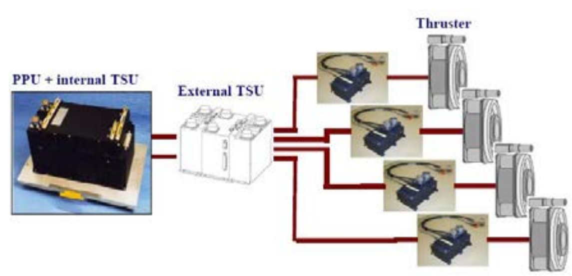

Figure 10. The design of the HET branch

the ETSU will have separate discrete control of the switching functions and status monitoring that will be provided by the SMU (Satellite Management Unit).
The nominal thrust of a HET thruster in the Small GEO application has been set to 75 mN, as a mean to limit the overall power consumption at PPU level to 1500 W. The HET thrusters are however capable of operating at different set points compared with the nominal one. A thrust as low level as low as 40mN is considered and the SPT-100 magnetic configuration is being optimized to allow this thrust level.

I. Lessons learnt

1. Mass shift analysis

The pressure of supercritical Xenon is strongly dependent on the Xenon temperature. With the chosen EPPS design, Small GEO will host two separate Xenon propellant tanks compared with SMART-1's single tank that was placed along the spacecraft's central axis. Analyses have shown that even moderate differences in the tanks temperatures can cause significant mass transfer between the tanks. To avoid inadvertent propellant transfer between the two tanks during flight, without introducing isolation valves between the tanks and the PSA, the temperature difference between the tanks will be carefully controlled by the use of heaters attached to the outer tank surfaces and thermal feedback from thermistors mounted on representative tank parts. Performed analysis has demonstrated the non-linearity of the mass shift, which depends on the nominal pressure. However, with tight tank temperatures control, the effect on the S/C centre of mass shift will be maintained within allowable limits.

2. Sputtering analysis

It is a well-known fact that surfaces will erode over time when exposed to incident ions. The consequence of the thruster plumes eroding the silver strings interconnecting the solar arrays over 15 years were therefore identified as a potential risk at an early stage. The consequences of ion plume sputtering on the solar panels have carefully been simulated by using TdNTriaX[4]. The performed analyses show that the silver strings will suffer less erosion if the strings are laid out along the length of the solar panel (Case 1) compared with a layout along the width of the solar panel (Case 2) as given by Fig. 11.

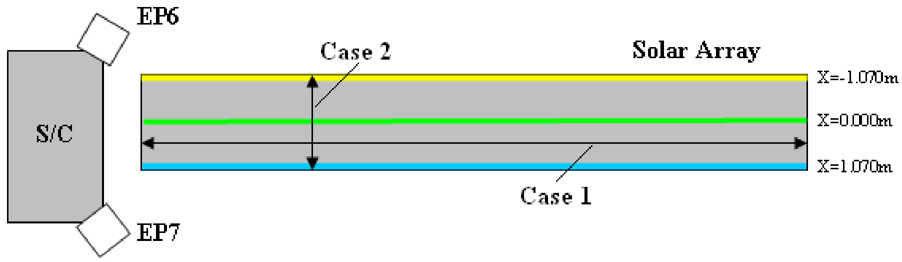

Figure 11. Principle of silver string layout

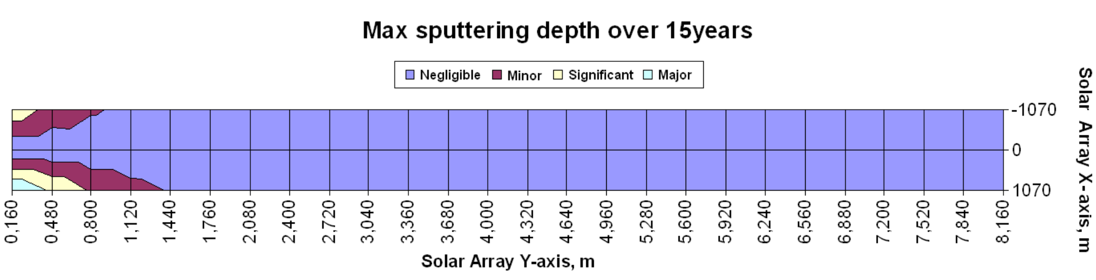

Figure 12. Max sputtering depth on strings at X-1.070m, X0.000m and X1.070m

With the silver strings mounted as in Case 1 the sputtering analyses still showed a significant amount of erosion over 15 years when using the EP thrusters assuming a plume divergence angle of 45°. The firing durations of the thrusters and used maneuvers were optimized as much as possible with respect to the SADM (Solar Array Drive Mechanism) rotation angles to minimize the total erosion. This approach and the arrangement of silver strings have brought the erosion back to the design capability of the array and the work is continuing with refined plume characterization testing.

Figures 12 below show the accumulated sputtering effect generated by HEMPT EP6 and HEMPT EP7 on three selected silver strings located at X=-1.070 (yellow), at X=0.000m (green) and at X=1.070 (blue) on the solar panel. Each string is approximated as a half cylinder with the flat backside attached to the panel. The used label "local silver string angle" in the figures describes the curved upper surface of the string cylinder.

The sputtering depth is at a maximum on the string at X=1.070 showing erosion levels regarded as major near the spacecraft, but also the erosion on the string at X=-1.070 is considerable. Meanwhile the sputtering across the central string is negligible. Based on the performed analysis, steps are being taken to reduce the erosion over 15 years to below 5µm on all strings. Optimization of the HEMPT magnetic configuration (and thereby reduce the plume divergence angle) and a reduction of the applied thruster voltage from 1000V to 900V (and thereby reduce the ion energy and divergence angle) are two potential ways to limit the total erosion further.

IV. The SMART-OLEV mission

A. Introduction

SSC, together with its partners Kayser-Threde (Germany) and Sener (Spain) is developing the SMART-OLEV life extension satellite. The service, whereby the SMART-OLEV docks with GEO communications satellites at the end of their propellant life and provides attitude and orbit control functions for up to twelve additional years, is marketed through Orbital Satellite Services.

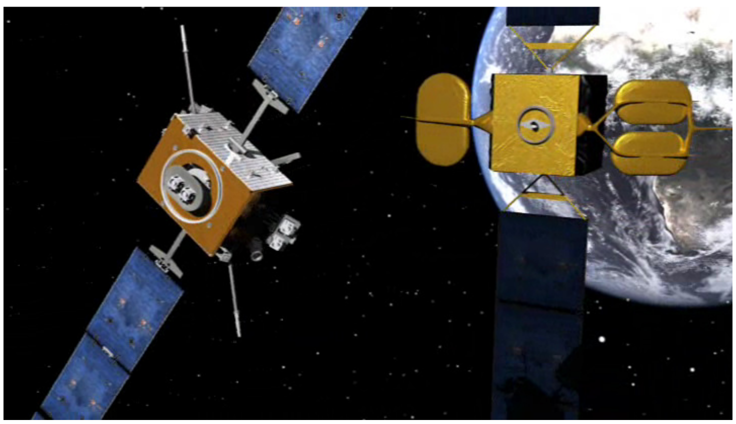

Figure 13. Illustration of SMART-OLEV approaching a client communication satellite (courtesy of OSS)

The SMART-OLEV spacecraft (Fig. 13) will use the EPS (Electric Propulsion System) for all transfer and orbital maneuvers with the exception of the rendezvous and docking for which the RCS (Reaction Control System) will be used. More specifically, the functions to be performed by the EPS are listed below. The two configurations referred to, solo and mated, are stating if SMART-OLEV is free flying (solo) or if it is docked to the client spacecraft (mated).

- Orbit raising from GTO to GEO (solo)
- Station-keeping (solo or mated)
- Inclination change (solo or mated)
- Node rotation (solo or mated)
- Relocation along the GEO arc (solo or mated)
- Transfer to a disposal orbit (mated)
- Return from the disposal orbit to GEO (solo)
- Angular momentum dumping of momentum/reaction wheels (solo or mated)

B. Design description

The SMART-OLEV EPS shown in Fig. 14 includes:

- XSS (Xenon Storage System)
- PRU (Pressure Regulation Unit) with related propellant distribution network
- Three TOM (Thruster Orientation Mechanism) supporting the EP payload
- EP-E (Electric Propulsion Electronics)

The XSS is based on four 60 L tanks configured around the spacecraft central axis. The PRU with related high-pressure and low-pressure tubing is regulating the pressure and distributing the propellant to the thrusters. Furthermore, three TOM accomondate the three pairs of EP thrusters, each providing an assembly called TMA

(Thruster Mechanism Assembly). The EP payloads are supervised by the EP-E consisting of power, control and thruster switching electronics.

Of the three TMA, two are identically and are labeled STMA (Station keeping Thruster Mechanism Assembly) whereas the third, the TTMA (Transfer Thruster Mechanism Assembly), is designed somewhat different due to its use in the transfer phase to Geostationary orbit. The main differences between the STMA and TTMA are the mobility range, thermal design and mounting structure to the SMART-OLEV platform. The concept of thruster mobility was also used on SMART-1 and this experience has proven essential in terms of functionality and design approach. The heritage has also influenced steps taken to improve later stages when the TMA will be qualified, implemented and finally operated in-orbit. Compared with SMART-1's thruster mechanism, the three TMA will be more advanced by for instance housing two thrusters, allow dual thruster operation (TTMA) and provide larger mobility range (STMA).

It shall be noted that the EPS does not provide the cold gas system, the RCS, with a low-pressure interface like in Small GEO, but instead a high-pressure interface. The very high maximum mass flow rate of more than 1g/s required by the RCS (required to execute the so-called Collision Avoidance Maneuver, e.g. docking abortion during the final approach of a client spacecraft) is far greater than the maximum 11-12 mg/s needed for dual SPT-100 operation by the EPS. Therefore separated regulator units have been chosen as the design baseline.

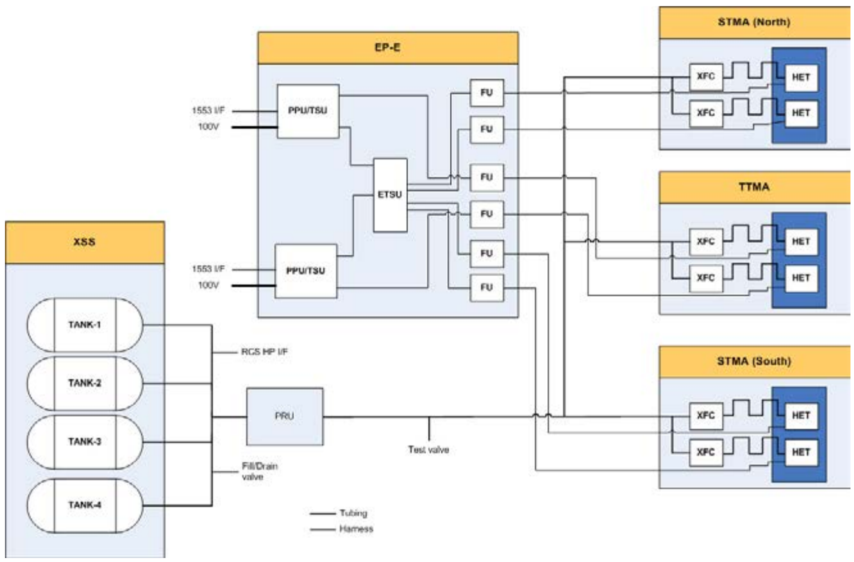

Figure 14. Simplified schematic of the EPS

C. XSS

The four 60L tanks will together be pressurized to a baseline MEOP of 150bar housing 400 kg of Xenon in total. Their design will however allow for a top up to a MEOP of 190 bar thus allowing a total propellant mass of 440 kg. The four tanks will be arranged around the spacecraft central axis and thereby contribute to a centralized CoM. Isolation valves between the tanks and the PRU are not a part of the design. Therefore the thermal control of the tanks will be essential due to the Xenon mass shift. Heaters attached on the tank surface, thermistors mounted at the tank outlet and other representative parts and MLI wrapping will be used to ensure a stabile tank temperature within 37 °C to 42 °C for each tank.

D. PRU and propellant distribution

The PRU is a stand alone unit housing two internal pressure regulation branches. It will be design for an input MEOP of 190 bar though the baseline MEOP is set to 150 bar. The PRU will regulate the pressure to a stable low-pressure output to the EP payloads at about 2.55 bar. One of the main drivers of the PRU is the large mass throughput required.

To save time during system integration, the PRU and tubing will be provided by the subsystem responsible as a fully welded and verified assembly ready for system integration. This will limit the number of system level welds to be carried out by SSC to only the tank interfaces, the RCS interface and the three TMA interfaces.

E. EP-E

The EP-E is a network of two PPU, one ETSU and six FU (Filter Unit) providing the means to control and power the EP payload. The design of the EP-E network will ensure that the two thrusters on the TTMA will be able to operate simultaneously. The use of an ETSU limits the number of PPU needed, which lowers the cost and improves the mass budget. Each PPU will be connected to the regulated 100 V power bus via a fused protected interface and to the DHS (Data Handling System) via a tailored MIL-1553 interface.

F. TMA

Each TMA contributes of a TOM (Thruster Orientation Mechanism) with the housed EP payload. EP payload consists of two identically SPT-100 thrusters located on the TOM mobile platform and the supporting equipment mounted on the fixed TOM structure. The main objective of the TOM is to provide the thrusters with correct position and orientation, ensuring that the thrust vector passes through the centre of mass both when solo and when in mated configuration with a client. This will be achieved by applying a stepper motor configurations that is able to maneuver the TOM mobile platform in two dimension of freedom, shown in Fig. 15 as angle span alpha and beta.

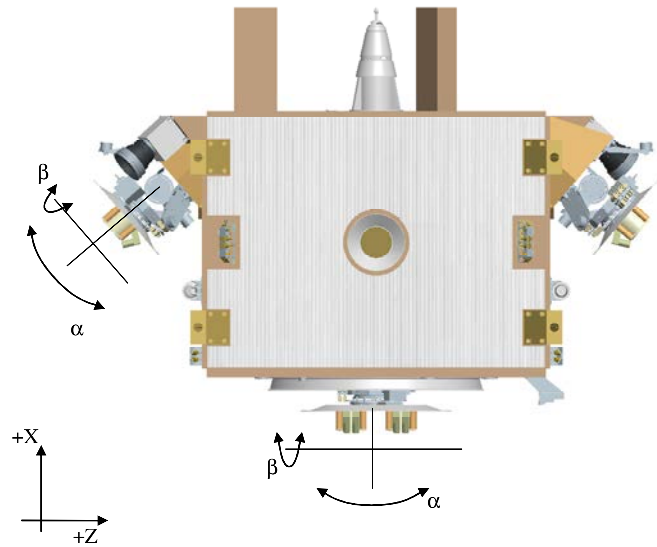

Figure 15. SMART-OLEV TMA mobility

The mobility of the STMA is mainly driven by the distance *L* between SMART-OLEV CoM and the client CoM, where the smallest client and largest client in the foreseen client fleet define the STMA angle range. The large alpha range will be the most demanding. For the TTMA a smaller angle range than for STMA is required. However, a Xenon mass shift analysis has showed that even a few degrees temperature difference between the four Xenon tanks can cause a shift of the CoM in the range of a few centimeters. This has been considered when stating the angle range requirements. Thus the design will cover for normal TTMA operations with an additional safety margin to the foreseen tank temperature interval of 37 °C to 42 °C.

For all transfer operations, including orbit rising from GTO to GEO, the thrusters on the TTMA will be operated simultaneously. This drives the thermal design of the TTMA. For the STMA, operation of only one thruster at the time will be necessary. Another design driver for the TTMA is the transfer duration to GEO. During this period the TTMA EP payload will be in constant use when the solar arrays are powered by sunlight. Performed analysis has showed that a small angle adjustment (typical less than <0.5°) every 5 minutes will be needed by the TTMA to sustain a stable transfer orbit which is inline with SMART-1 experience.

G. EP Payload

Each EP payload consists mainly of two SPT-100 thrusters with the supporting XFC (Xenon Flow Controller), flexible tubing and flexible harness. In all, thee EP payloads will be carried by SMART-OLEV with a total of six SPT-100 thrusters with a required lifetime average performance of 81.5 mN and 1520 s.

An important part of the EP Payload is the flexible tubing between the SPT-100 thrusters on the TOM mobile platform and the XFC mounted on the fixed TOM structure. The tubing will have to withstand significant stress loads due to the mobility of mobile platform. The same applies to the harness routed between the thrusters and the two electrical FU caring the 4.5 A at 300 V.

H. Lessons learnt

1. TMA concept

The TMA is similar to what was used on SMART-1, but SMART-OLEV brings the mobile thruster platform concept to a new dimension in terms of thermal design and mobility. It has been the initial approach to gain as much as possible from the similarities between the STMA and TTMA when setting up the roadmap for design, development, qualification and implementation of the two TMA types.

2. Simultaneous operation of two SPT-100

Simultaneous operation of two SPT-100 thrusters with floating grounding has yet not been used in-orbit. The consequences of interactions between the plumes are therefore difficult to foresee. Tests performed by University of Michigan[5] and ALTA[6] with similar thrusters show that the thrusters most likely will operate as normal or even have improved performance together compared to their individually sum. The thrusters' simultaneous performance and joint characteristics will be carefully tested on ground with a dedicated test campaign. With the same test set-up the thermal design of the TTMA will be confirmed.

3. Thermal balance of the Xenon tanks

As explained for Small GEO above, the Xenon mass shift due to thermal unbalance between the tanks can be considerable and even critical to the mission. Performed analysis has however showed that with a careful thermal control design the relative tank temperatures can be kept within 5 °C and thus keep the CoM shift to less than 25 mm at any time. Steps of precaution have however been taken to ensure that the TTMA can support a significantly larger CoM shift.

V. Other in-house EP related activities

A. NanoSpace

One of SSC's subsidiaries, NanoSpace, is developing a miniaturized Xenon flow control system capable of delivering Xenon from a high pressure storage tank, to the mini-ion engine at the required flow rates and with high accuracy. NanoSpace has already delivered cold gas thrusters manufactured with MEMS technology for the Swedish formation flying mission Prisma to be launched early 2010.

Figure 16. MEMS-based fluid control components developed by NanoSpace. Total MEMS chip mass is about 10 grams.

Miniaturization is a key element in this work in two respects. In one sense miniaturization means a significant reduction in mass and volume of the subject Xenon flow control system compared with existing systems. The second meaning of miniaturization is that a flow control system shall serve mini-Ion engines and their most demanding requirements of low and precisely controlled flow rates. The introduction of MEMS technology will provide a design solution small in size and mass and at the same time solve the fluidic control problem in microscale. MEMS technology is all about electromechanical parts, with sometimes extremely small feature sizes, manufactured using processes inherited from the semiconductor industry.

The task taken on by NanoSpace is to design, manufacture and qualify a flow control system, distributing Xenon from a high pressure (150 bar) storage tank and feed a number of Ion thrusters with a precise flow rate at low pressure (2 bar). A conventional xenon feed system does normally consist of discrete components such as valves, pressure regulators, filters, etc connected by tubing in a rather complex system. These kind of conventional feed systems are normally heavy, in many cases several kilograms. SMART-1, as an example, had a feed system weighing about 8 kg. The NanoSpace's flow control system will weigh far less than 1 kg.

The common situation on a satellite is that a single high pressure storage tank, normally located near the centre of gravity, is used to supply multiple Ion thrusters, located near edges or corners of the spacecraft. This fact leads to a concept with two major mechanical subassemblies:

- A pressure regulation module (PRM), and
- A Xenon flow control module (XeFCM).

Figure 17 shows the schematic of the complete XeFCS. Functional components in blue colour are MEMS devices, while yellow components are "conventional" components.

The target of this work is to develop an engineering model XeFCS by 2009 with the following main characteristics:

- Mass: 1 kg (maximum)
- Power: 20 W (maximum, at max flow)
- Flow rates: 0 – 10 mg/s main flow with proportional control, and fixed low rate for secondary flow.

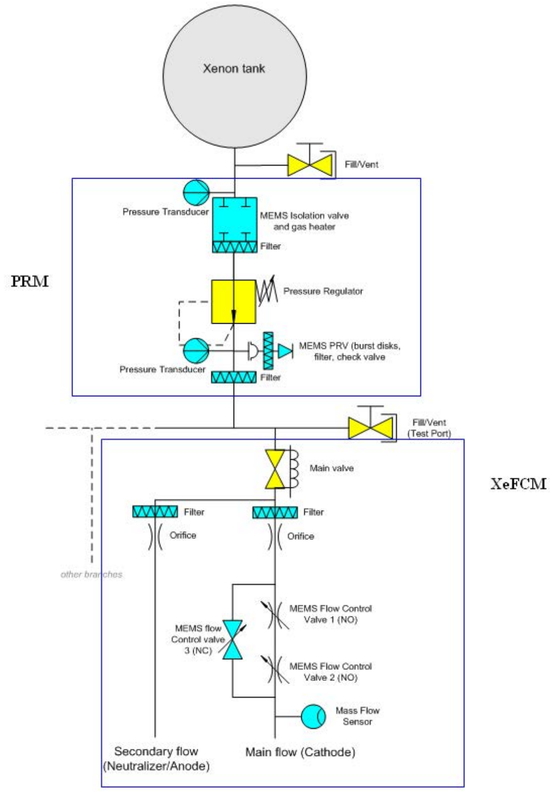

Figure 17. Schematic showing the complete Xenon flow control system (XeFCS).

B. SPIS Modelling

SSC has since 2007 the in-house expertise[8] to use and perform detail SPIS (Spacecraft Plasma Interaction System)[7] models for 3-dimensional EP plume interaction analysis using PIC (Particles-in-Cell) and MCC (Monte Carlo Collision). The same tool has been used for preliminary spacecraft charging analysis for the Cross-scale mission. SPIS, together with TdNTriaX mentioned previously for the Small GEO sputtering analysis, strengthen SSC understanding of EP operation on system level adding EP plume interactions to the in-house expertise.

C. EcoSimPro Modelling

SSC is using the European Space Agency promoted simulation tool[9] at its latest version together with their partners to verify before the testing stage that performances are achievable. The tool is also used to generate test predictions. It has been found very flexible and useful.

D. Manufacturing of hydraulic parts in Titanium

The tubing and couplings for Small GEO will be manufactured, cleaned, welded and proof pressure tested in-house.

VI. Conclusion

Swedish Space Corporation (SSC) was founded in 1972 and is today a well-reputed, comprehensive and innovative company. The company expertise covers a wide field, from the definition of new business concepts and space projects to the development, test and operation of subsystems and systems.

Knowhow and experience of Electric Propulsion (EP) was first gained by SSC during ESA's lunar mission SMART-1 for which SSC was the prime contractor. The heritage from SMART-1 has proven essential in terms of ground operations, system verification and the understanding of EP applications on system level. Today this knowledge is being introduced in the new and challenging satellite programs, Small GEO, SMART-OLEV, Proba3 and others. For these missions, EP is essential. SSC has growing engineering skills in the EP field thanks to the developments undertaken in the past and at present time and the in-house manufacturing capabilities that also are applied to chemical propulsion.

SSC is developing a growing network and relationships with international partners. Based on SSC's wide experience and knowhow, from development and the understanding of the end user needs, to in-orbit operations through integration and testing, SSC brings many key elements to the partners and has a central enabling and motivating position.

SSC as an innovative company is looking forward to future commercial and institutional development of EP missions, new partnerships and new projects on an economically viable basis.

Acknowledgments

The authors wish to thank Christophe Koppel for his kind help and good support to the work undertaken using the two software TdNTriaX and EcoSimPro.

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