SMART-1 EPS End-to-End Test:

Final Results & Lessons Learnt

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1. INTRODUCTION

SMART-1 is the first version of a new line of small-scale low-cost spacecrafts from the European Space Agency. In addition, the 370-kg SMART-1 spacecraft has the dual objective to bring 17 kg of innovative scientific payloads into moon orbit while performing a flight qualification of a primary electric propulsion subsystem (EPS).

The flight-qualification of the Hall-effect thruster technology developed by SNECMA Moteurs (France) is considered by the Agencies (CNES and ESA who supported financially and technically the development) and the European Primes as the most critical milestone for acceptance of this technology on scientific and commercial platforms. This flight-qualification will not only demonstrate the technology and its robustness in space but also will validate the operational and innovative orbit control aspects from the standard GTO starting orbit, through the commercial GEO orbit, up to the sensitive moon orbit capture manoeuvre.

Furthermore, the SMART-1 EPS is procured directly from SNECMA under ESTEC/TOS responsibility and is provided as a customer furnished equipment from the ESA SMART-1 Project to the Prime Contractor Swedish Space Corporation (SSC Sweden).
These overall constraints have requested a very challenging management interface, test sequence, schedule, and cost to be harmonised between the ESA Project, SSC, and SNECMA.
The recent misfortunes, due to launcher failures in end 2002, of the telecommunication satellite ASTRA-1K (SES + Alcatel) and STENTOR (CNES + Astrium and Alcatel) have further increased the need of the SMART-1 demonstration mission to be successful and provide extensive flight experience of the PPS-1350G subsystem, but also of the multi-junction GaAs solar-cell degradation, and the Lithium-Ion batteries, etc....

2. END-TO-END TEST OBJECTIVE AND JUSTIFICATION

The SMART-1 end-to-end test (18-19 December 2002) has occurred at the end of the environmental test campaign. The main purpose of the end-to-end test was to make possible the operation of the complete EPS including power control and supply, xenon regulation, and data-handling, at subsystem level and also to validate all the interfaces at system-level. Before this test, all the spacecraft functional and EMC tests were performed with either a static or dynamic thruster simulator. Therefore, the filter unit (except EMC), the thruster (PPS-1350-G), the xenon flow control unit (XFC), and the pressure regulation unit (BPRU) were not part of these tests.

In addition, at subsystem level, the xenon chain and the electrical chain were always tested separately due to the complexity and cost of the combined tests that would have otherwise been required. Therefore, the acceptance tests of the thruster were performed with the power processing unit (PPU), filter unit, and XFC, but without the BPRU and its controlling electronics (PRECard); this resulted in an incomplete representativity of the steady xenon mass flow rate into the thruster. Of course, proper analyses were done to quantify these effects and justify that their testing be postponed at the end-to-end test. The actual firing test of the EPS on the spacecraft in an appropriate vacuum chamber was therefore fully justified.

3. THE END-TO-END TEST FACILITY

Before the Large Sun Simulator (LSS) was built at ESTEC, the HBF-3 chamber was the only option for thermal-cycle testing of spacecrafts or satellite subsystems under vacuum conditions, by simulation of the space thermal environment. Since SMART-1 is a relatively small-scale spacecraft, and since there was a lot of concern on the firing of an electric thruster with high-energy particles in the LSS fitted with very expensive optics and black-painted surface, the HBF-3 chamber was preferred.

It is composed of:

- a central 5m-diameter cylindrical test volume covered by a removable lid. The facility can be loaded and the lid closed by means of a 10-ton capacity over-head crane.
- a lower conical part, closed at its lower end by a porthole window.

The SMART-1 spacecraft has been mounted by suspension under the facility lid from a framework mounted with a combination of 4 M22 tapped holes with a maximum load per point of 100 kg. The suspension structure was conceived such as to have the exit plane of the thruster just above the lid interface plane.

Figure 1: SMART-1 attached under the HBF-3 Lid

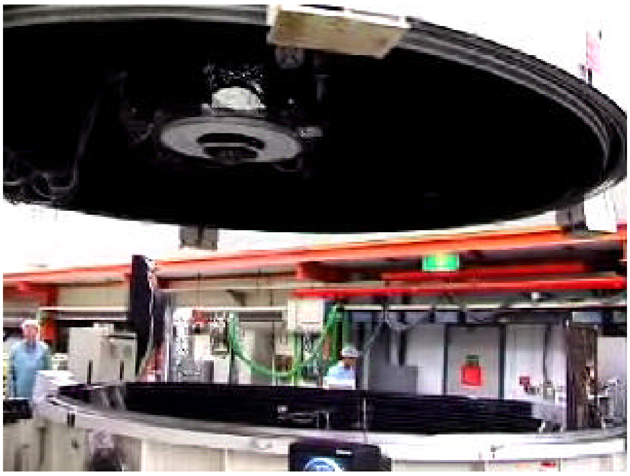


Figure 2: The HBF-3 lid and SMART-1 at Closure

The pumping system can achieve a working vacuum less than 6e-6 mbar and is composed of:

- Three Roots/Rotary fore pumping groups in sequence with 2 times two-stage MPR rotary pumps generate a total pumping speed of 14000 m /h.
- One 15 K Helium gas cryogenic pump in combination with a turbo-molecular pump generates a total pumping speed of 2500 l/s
- Two 20 K cryopumps with a pumping speed 65000 1/s
- one turbo-molecular pump: 2000 1/s

The characteristic pump-down times starting from ambient conditions are:

- one hour down to 2e-2 mbar,
- four hours down to 6e-6 mbar.

To control the thermal environment, the chamber comprises 5 shrouds (absorbtivity: 0.95, emissivity: 0.90) controllable in temperature either by circulation of liquid or gaseous nitrogen in closed pressurized circuits. The shroud temperature is below 100 K when cooled with liquid nitrogen, and between 200 and 373 K by circulation of gaseous nitrogen. The rate of change of the shroud temperature can be up to 2 to 3 K/min.

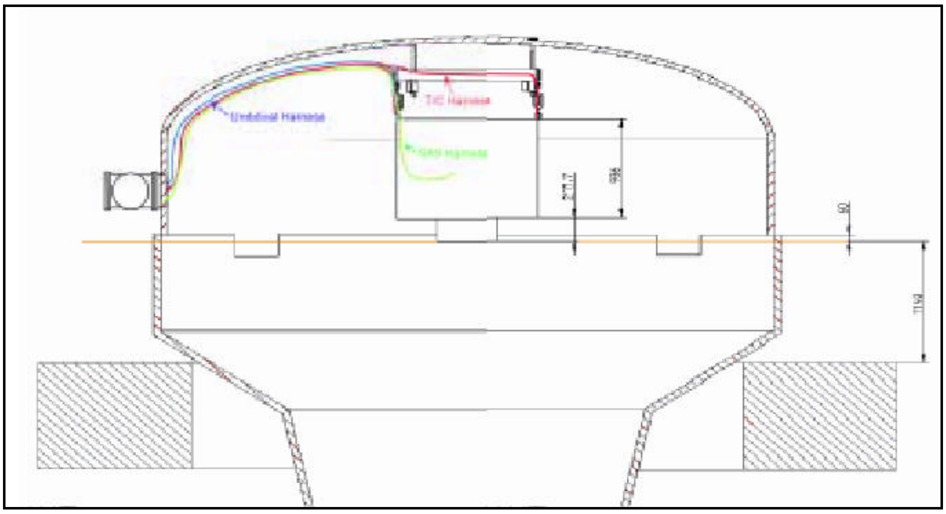


Figure 3: Spacecraft Configuration and Harness Routing in HBF-3

4. END-TO-END SPACECRAFT CONFIGURATION AND TEST SEQUENCE

In order to perform a fully representative functional test, the spacecraft was put into flight configuration as far as feasible in terms of hardware, harness, software, operational procedures, and thermal environment. The end-to-end test was in fact an on-ground spacecraft commissioning with the “first pulse firing” of the EPS in order to test its health. The xenon tank was filled before the vibration test campaign (to be mass-representative for the last test campaign before the E2E test) with 82.5 kg xenon in order to be in BOL pressure conditions (75 bars at 20 C). Previous test fluids used as replacement were PF-5060 (STM campaign), helium (proof and leakage tests), and argon (thermal balance and thermal-vacuum test).

The first EPS test sequence consisted in performing the xenon venting of the BPRU and XFC. This was a four-hour activity with the nominal and redundant valves of the XFC continuously opened. Sequentially, the BPRU nominal and redundant bang-bang valves were activated to perform a filling and emptying of the plenum in order to purge with xenon all the lines. The venting sequence was also the opportunity to confirm that the pumping capability of the test facility could maintain the appropriate vacuum level (1e-3 mbar at 12 mg/s xenon flow rate) and control the spacecraft thermally.

The second EPS test sequence consisted of 2 firing tests. The first firing test was using the high-power distribution and protection system of the spacecraft (HPSSPC) from the lowest (start-up power, 10 min), to intermediate (20 min), to maximum power setting (1420 W input, 1200 W discharge, 20 min).

The second firing (15 minutes long) used the power distribution through a relay (PPIM) with redundant BPRU, cathode, and XFC lines. The power was immediately ramped up at the 6.25 W/s rate from the low-power standard start-up to the maximum power level.

After the firing tests, the spacecraft was left under vacuum conditions until the thruster mechanical interface had recovered its initial temperature from before the test. The HBF-3 vacuum was then broken with nitrogen flushing in order to slowly recover ambient pressure conditions. After chamber opening, all the contamination samples were inspected as well as all the spacecraft optical properties.

5. PREVENTIVE MEASURES AGAINST RISKS AND UNCERTAINTIES

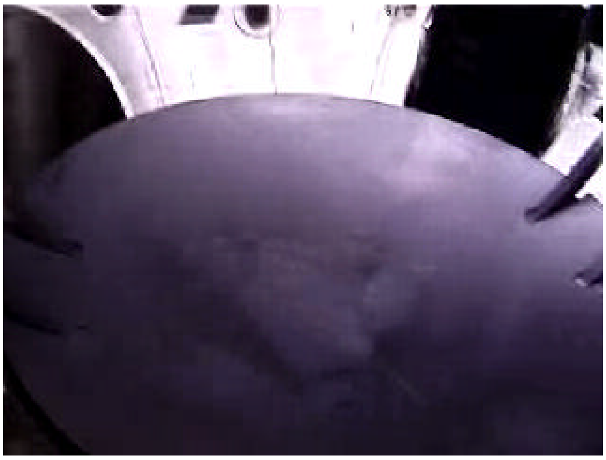
The most critical concern about the end-to-end test was the fact that it had to work properly at the first trial in a vacuum chamber that had never been used before for any electrical thruster test. This test had to be performed directly with flight equipment. Consequently, all possible preventive measures have been taken to ensure a successful test and no damage to the satellite equipments.

The end-to-end test has required to organise new investigations in the domain of spacecraft test facilities: simulation of primary electric propulsion, xenon thermodynamic behaviour, capability of the existing pumping systems of extracting xenon, high-energy beam interaction with chamber surfaces, back-sputtering, optic contamination, EMC contamination, surface charging, and spacecraft + facility grounding.

It was originally thought to combine the thermal test in the LSS with the end-to-end (E2E) test. But this option was abandoned in favour of two separate test campaigns. The HBF-3 chamber was chosen for the E2E test because of the eventual risk of contamination of the LSS sun optics and damage to the black paint. In addition, a special thruster switching unit would have been necessary in order to select either the static simulator or the thruster. The very long thrusting sequences needed during the thermal tests are not feasible with the FM thruster. The end-to-end duration was limited to around one hour: this was sufficient for functional tests and limited the eventual risks mentioned before.

Additional vacuum gauges have been installed in order to have a two-level protection in case of leakages. A first warning was set at 8e-5 mbar and the shutdown value was set at 2e-4 mbar (maximum limit for operating the thruster). For visual monitoring, a video camera was installed with the proper field of view such as to allow real-time thruster observation and tape recording of the cathode and of the beam stability. One chamber window situated under the test floor was used for this purpose. The other available window was on the test floor, and served for direct visual inspection and additional movie and picture taking.

A special target was manufactured to protect the test facility and avoid back-sputtering. The target had a hemispherical shape of 2 meters radius and a 90-degree total cone angle. It was sprayed with Aquadag E, which is a water-based colloidal graphite coating. Several sample were made before and tested at different beam positions to validate the amount of sputtered carbon after 1 hour of firing. Both the analyses and the measurements (with large scattering) were confirming the very low values of a few centigrams of carbon sputtered throughout the firing test. To trap the maximum of sputtered material, the target was placed just in from of the LN2 cryopanels.



In order to confirm these predictions, measurements of emission and absorption coefficients were performed on the radiator white paint on each of the + / –Y panels and on the thermal skirt behind the thruster orientation mechanism. A comparison with measurements after the end-to-end test will demonstrate whether the optical properties of the white surfaces have been altered by the thruster firings. During the test, contamination was monitored using quartz crystal microbalance (QCM) and witness plates.

Special attention was put on the grounding aspects in order to avoid that any electrical anomaly could be damageable to flight equipments. The objective was to organize the overall grounding loop with the thruster, spacecraft, and test facility in an approach identical to the way the thruster is tested in stand-alone in the SNECMA vacuum chambers. The beam target was connected mechanically to the test facility, which was itself electrically grounded to the local facility ground. The thruster was well electrically coupled to the spacecraft structure (measured during thruster integration test), which was connected to the clean local ground. Contrary to what is needed for satellite test without electric thruster firing, this local ground had to have a very low isolation with respect to local facility ground, in order to avoid surface charging due to an eventual electrical beam coupling between the spacecraft external power supply and the target.

6. EMC MEASUREMENTS

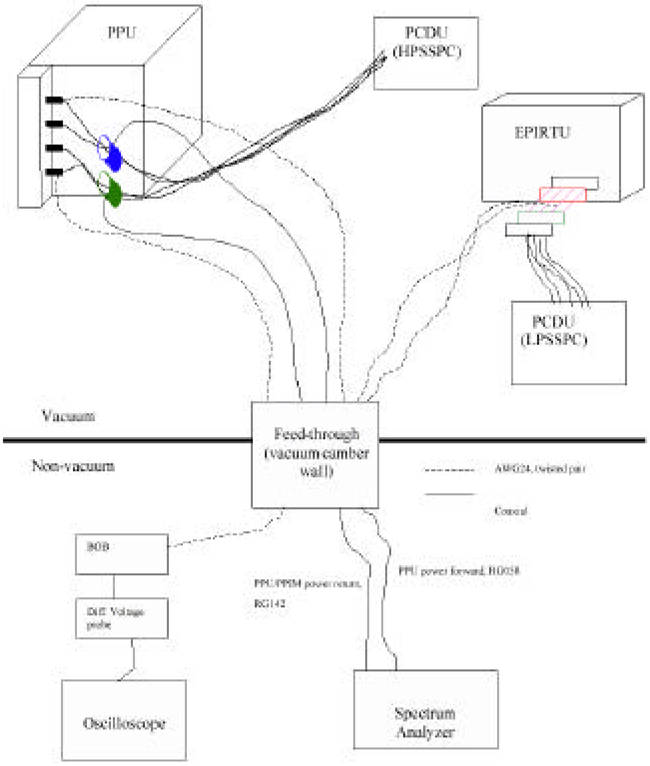


Figure 4: Conducted EMC Test Setup for EP

All previous EMC measurements had been performed during unit qualification tests and subsystem acceptance tests. The satellite EMC test campaign was run with the dynamic thruster simulator DS-100M to provide an electrical load to the S/C power system. It was therefore a unique opportunity to verify the EMC characteristics of the whole spacecraft were well understood.
In particular, at EPS level, forward and backward currents were monitored with oscilloscopes and spectrum analysers between the PPU and the PCDU and between the PRECard and the PCDU.
The measured currents were thereafter compared with the system EMC data to verify their coherence.

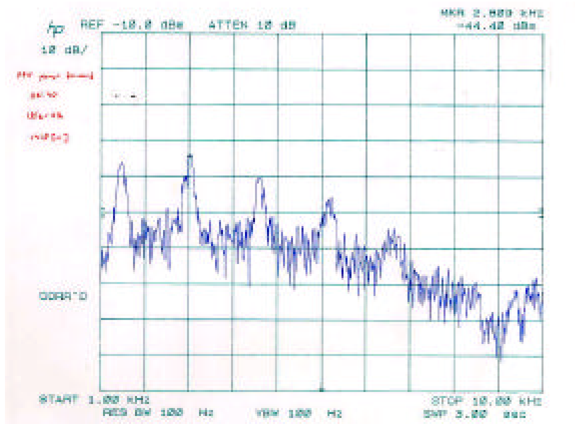


Figure 5: PPU, 1-10kHz, 1200 W discharge

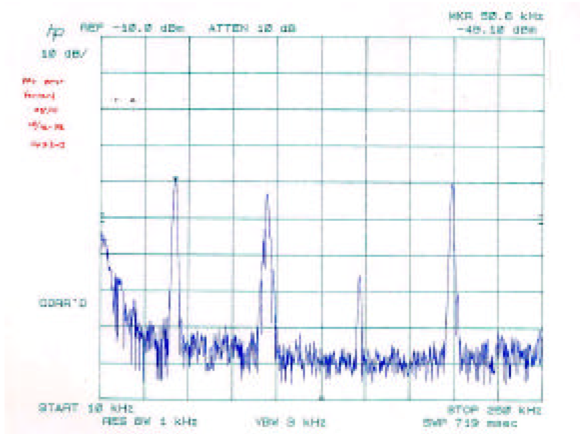


Figure 6: PPU, 10-250kHz, 1200 W discharge

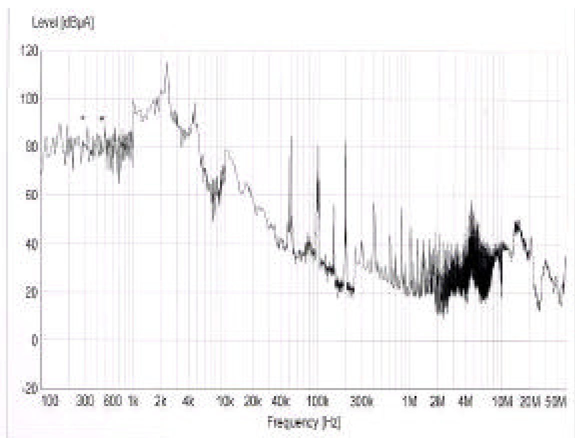


Figure 7: PPU, 100Hz-50MHz, 1200W system EMC

7. PAYLOAD, PLASMA PROBES, AND ANTENNAS OPERATION

The scientific payload was also tested during thruster operation to investigate eventual signal perturbation.

Current density measurements were taken during thruster operation by the SPEDE plasma probes consisting of two 50-cm rigid booms on opposite vertical panels. All the thruster operation phases were clearly detected with the sensor current varying in real-time with the discharge power level. No cumulative plasma effect could be observed. High-resolution sampling allowed the capture of the effect of valve actuation on the discharge current. The plasma perturbation induced by a thruster single-event occurring during the second sequence is also clearly visible.

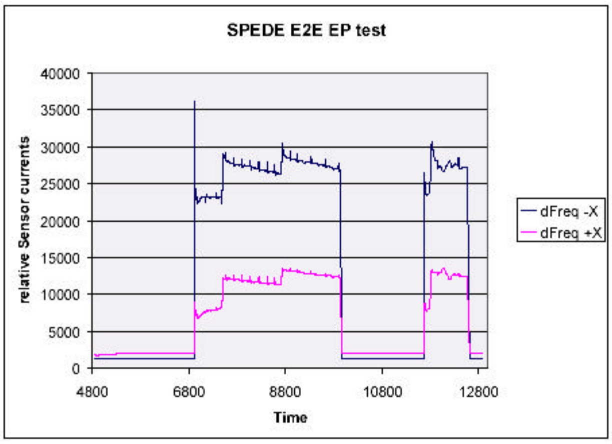


Figure 8: Plasma Probe Currents during E2E

For communication, the proper operation of the low-gain S-band antenna was also verified.

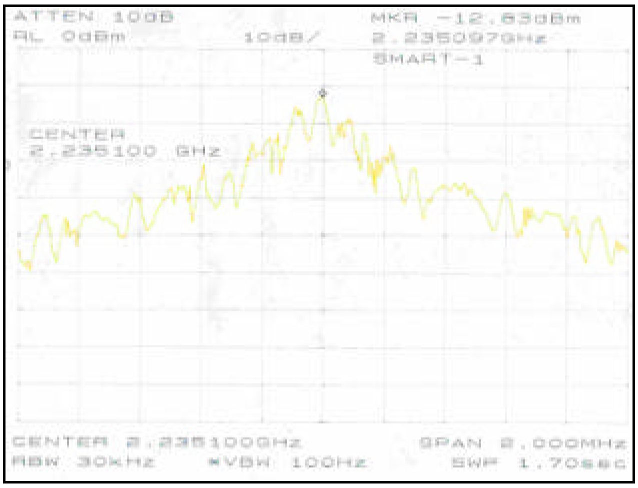


Figure 9: Downlink spectrum during venting phase

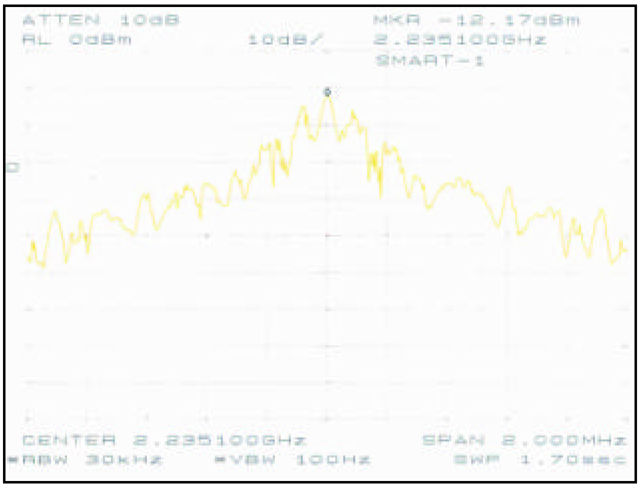


Figure 10: Downlink spectrum during EP full power

In the very high-frequency communication range (Ka-band), the SMART-1 payload KaTE was operated during thruster firing. No corruption of the Ka-band KaTE packets (down-converted to 70 MHz) was observed when the thruster beam was ON.

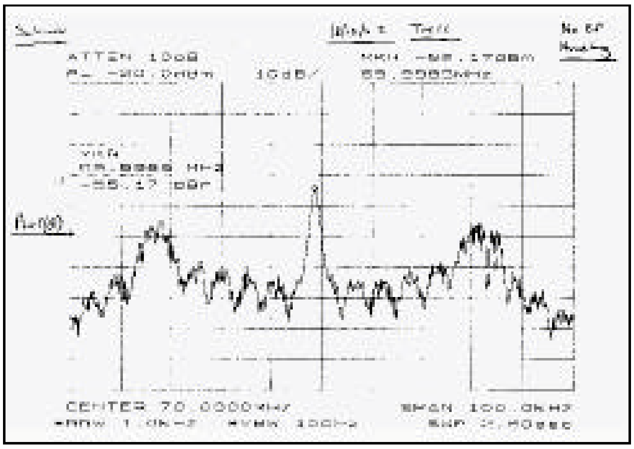


Figure 11: EP OFF: TM sub-carrier with modulated data - Low data rate

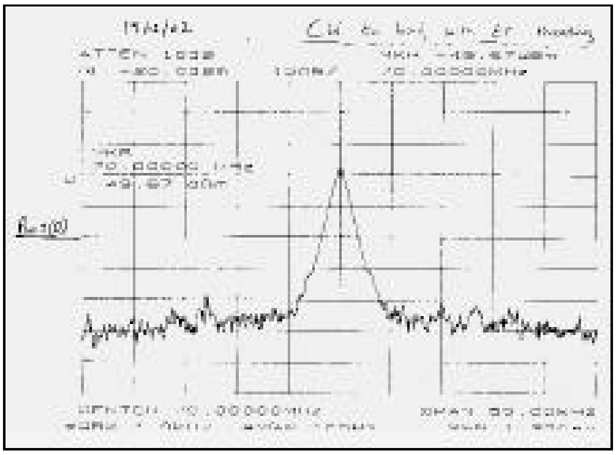


Figure 13: EP ON: Ka band carrier only - No modulation

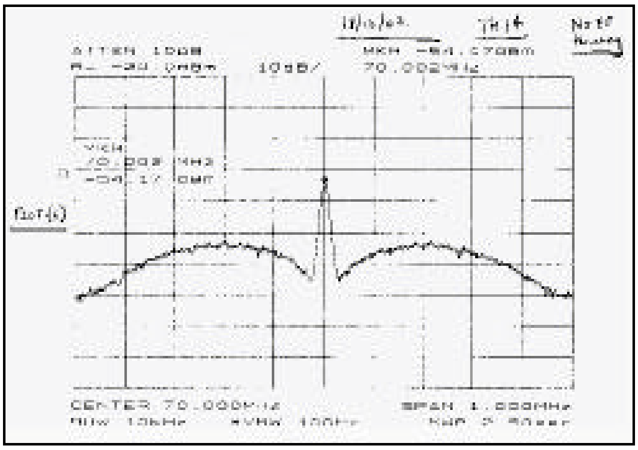


Figure 12: EP OFF: TM data modulated directly on carrier - High data rate

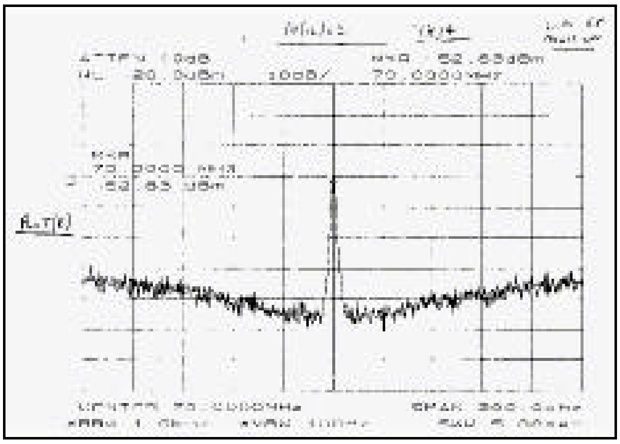


Figure 14: EP ON: TM data modulated directly on carrier - High data rate

8. SMART-1 EPS END-TO-END TEST RESULTS

The good behaviour of the spacecraft power system was verified with the real Hall-effect thruster (tested with the static simulator before). No overshoot of power was detected during start-up and during operation even though it was the first pulse. After storage in ambient conditions, the thruster is expected to have substantial outgassing and single events (inducing current overshoots). An overshoot of power lasting more than 10 ms above the nominal-power-set send by telecommand would have led to the activation of the FDIR EPS shutdown sequence.

The performed EMC measurements confirmed the previous results knowledge of the EPS. There are spikes present at 50kHz, 100kHz, 150kHz etc. The levels of these spikes are as anticipated and correspond with the measurements performed within the frame of the System EMC Test. The susceptibility margin of 6dB used at system-level EMC test has successfully been confirmed by the measurements made during the E2E test. Also both the S-band and Ka-band antennas have operated according to specifications during the E2E test.

The thermal aspects were again verified during this test; the previous comprehensive thermal test took place in the LSS with argon instead of xenon and with the thruster simulator. All the EPS units have an operating environment limited between 20 and 50 C to avoid the presence of liquid xenon and stay below the maximum operating pressure of 150 bars. The onboard software and failure detection system (FDIR) do not allow EPS operation if this temperature environment is not guaranteed. During the venting, it was discovered that the high-pressure xenon pipe between the tank and the BPRU did not reach a sufficiently high temperature in particular at the bracket positions. This demonstrated that the xenon lines were not sufficiently insulated and that this particular pipe required the installation of three small heaters of minimum 0.25 W each.

Obviously, the EPS functional aspects were thoroughly scrutinised. Especially, the effects of the xenon bang-bang pressure regulation on the discharge and thermothrottle currents were compared to the previous estimates. The PPU loop between the thermothrottle and the thruster discharge fulfils its regulation task during the transient opening of the bang-bang valves and during the slow decrease of plenum pressure. The overall effects of pressure regulation on the discharge power are very minor (slightly above one percent).

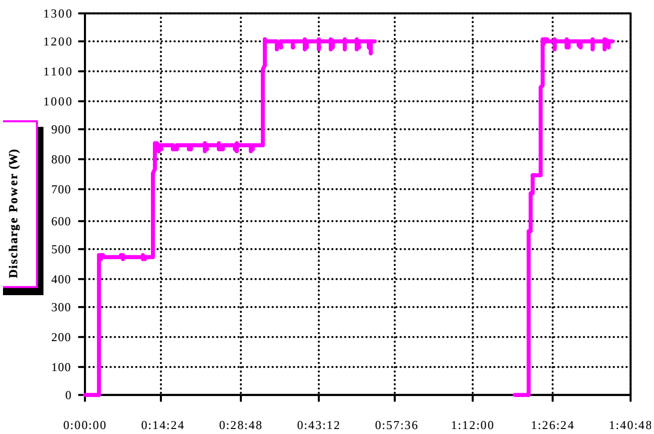


Figure 15: Discharge Power Variations during E2E

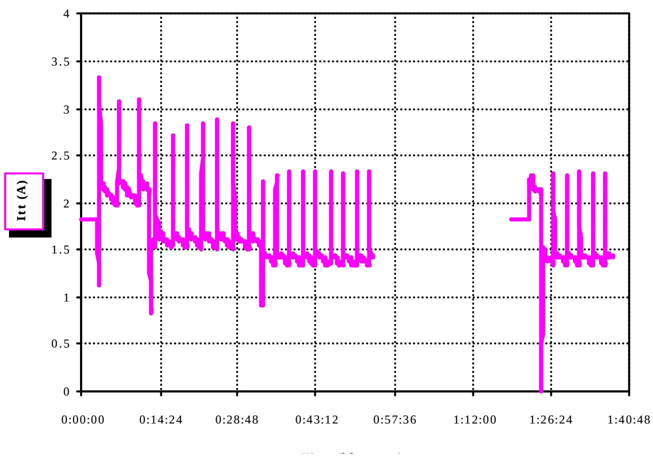


Figure 16: Thermothrottle Current during E2E

There were a total of 25 bang-bang valve actuations over the two firing tests, with the plenum pressure varying continuously between 2 and 2.2 bars (10% range). The frequency of activations depends on the xenon tank pressure (which varies extremely slowly with mass flow rate but depends also on the tank temperature controlled with heaters and thermistors) and is proportional to square-root of the selected discharge power level (variable xenon mass flow rate and discharge voltage):

- 215 s at the minimum discharge power of 470 W,
- 170 s at intermediate discharge power of 850 W,
- 144 s at maximum discharge power of 1200 W.

Valve actuation frequency can be used to correlate the effective mass flow rate evolution during the thruster life.

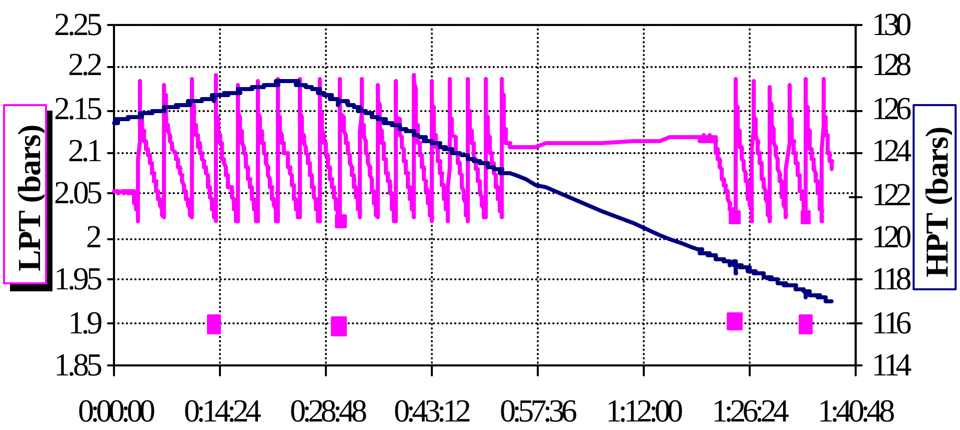


Figure 17: Tank and Plenum Pressures during E2E

Outside the tiny perturbations generated by the valves, the discharge power is superbly steady. Through the chamber's window, an expert eye could immediately notice the perfectly stable thruster operation:

- The PPS-1350-G thruster started both times at the first ignitor pulse in a very sharp way without oscillations,
- The beam was immediately stable,
- No simple event could be visually captured by the recording instruments, but a couple of them could be identified after analysis of the thruster operating parameters,
- The cathode had its characteristic blue-violin coloration.
- Both thruster shutdowns were also very sharp.

9. CONCLUSIONS

The SMART-1 end-to-end test was the first time for Europe electric propulsion was fired successfully at spacecraft-level, and this for more than one-hour duration. For hall-effect thrusters, this test is worldwide the first in its category.
This test has turned out to be extremely successful and useful not only functionally at EPS and spacecraft level, but also with respect to the traditional areas of concern for all Customers: the EMC and contamination aspects. This test has proven that, even for a relatively small size vacuum facility, a firing test of around 1 hour does not generate measurable back-sputtering and contamination if nominal preventive measures are taken.
For EMC, the conducted part is very well filtered by the FU and PPU. The radiated part has not generated for SMART-1 any perturbation of the S-band and Ka-band antennas.

Based on these results, the concept of an end-to-end firing test at spacecraft level turns out to be much more attractive in terms of "fine-tuning" functional validation since the thruster operation is little disruptive for the test facility and for the spacecraft under test.
With an increasingly popular low-cost approach for satellite environmental and functional test campaign, the end-to-end test as performed on SMART-1 might have a promising future. We must however be very cautious to take too many shortcuts during test campaigns under the argument that these specific aspects can be covered during the end-to-end test. Since it is the last test of the campaign with flight models, the discovery of a major functional mismatch at this point could become catastrophic in terms of cost and planning.
Because of the heavy schedule and cost constraints of SMART-1, it was particularly important to very well balance an early interface validation with the last resort of the end-to-end test verification.