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The SMART-1 Electric Propulsion Subsystem In Flight Experience

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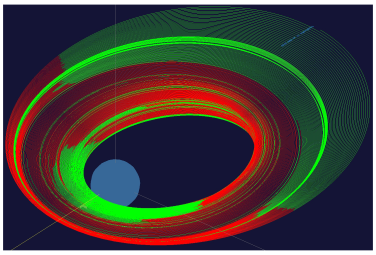
Onboard the ESA SMART-1 spacecraft, (Small Mission for Advanced Research in Technology), the primary Electric Propulsion Subsystem (EPS) operates since the 30th September 2003.



EPS Contractor, ESTEC, and EPS manufacturer, SNECMA MOTEURS, present in detail the major performances of the complete electric propulsion system, with a comparison to the ground tests results.

The PPS®-1350-G Hall Effect plasma Thruster and its Power processing unit, developed in the frame of the CNES Stentor Program, was tested at Snecma facilities. The main feature of the Smart-1 system is its variable power supply. Integrated into the whole spacecraft the electric propulsion system was tested at ESTEC before the in-flight first firing after the successful Ariane V launch.

Results of these main tests demonstrate a good prediction of the in flight EPS behavior including the robust bang-bang xenon pressure regulation for the input pressure and variable electrical power supply. This paper describes the performance results of the PPS®-1350-G firing in space environment. It discusses also the consequences of the Van Allen radiation belt crossing during the first flight phase, particularly the behavior of the floating potential of the thruster with respect to the satellite electrical ground.

The initial successful results obtained supports the first technological experience objective of the SMART-1 mission. These new features of primary electric propulsion subsystem and especially the low-power start-up and variable power features can be also a significant added value for any commercial application using electric propulsion for station-keeping and/or orbit transfer.

I. Introduction

The EPS (Electric Propulsion Sub-System) of SMART-1 has been presented in numerous papers[1, 5, 6]. The main characteristics of the EPS are roughly described here after and then the behaviour in flight is presented in the second chapter. In spite of the fact that at the time of writing, the behaviour is nominal, the second chapter deals also with the presentation of some lessons learned, useful for the improvement of the electric propulsion use in flight.

The Smart-1 power is generated by two GaINP/GaAs/Ge solar arrays panels (1850 W beginning of life) enabling thruster operation at a discharge power of maximum 1190 W at beginning of life.

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In some failure cases, the available power can be reduced to 700 W or less. This is therefore an essential requirement for thruster and PPU to work within a range of pre-set power levels and to be able to follow a dedicated start-up sequence that does not generated power overshoots. This capability is also required for deep-space missions involving variable sun distances.

The whole EPS, fig. 1, is designed for the three following main functions:

- Xenon supply system
- Electrical power supply and thruster
- Digital interface and communication system

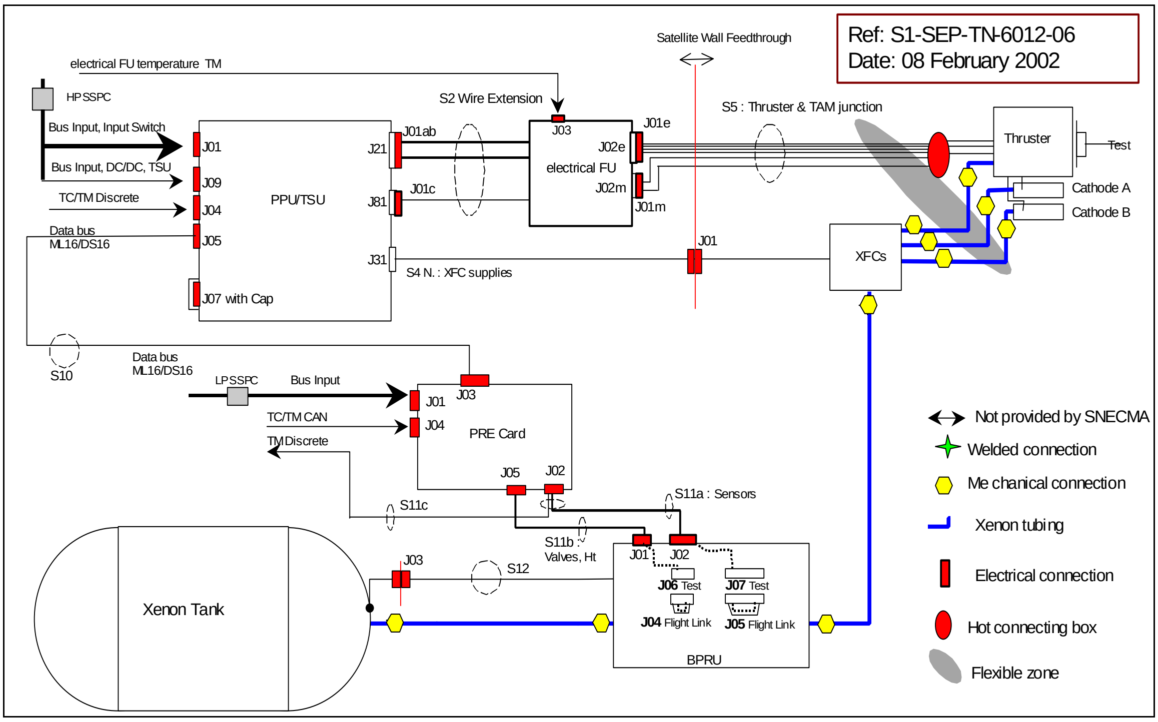

Figure 1. EPS functional diagram: the xenon system feeds the thruster cathodes and anode.

A. The xenon system

The xenon is stored in the main Xenon Tank, 82.5kg at launch, under high pressure (up to 150bar). A pressure regulator called the Bang-Bang Pressure Regulation Unit (BPRU), designed by Snecma Moteurs and Iberespacio (Spain), regulates the xenon down to a constant low pressure (around 2bar). The low-pressure xenon is then fed into the adjustable flow regulator, called the Xenon Flow Controller (XFC). A simple and robust control loop algorithm, located in the Pressure Regulation Electronic Card (PRE Card), controls the constant pressure delivered by the BPRU. The XFC then provides fine control of xenon mass flow rate to the thruster anode and cathode. The flight hardware is shown in figure 2.

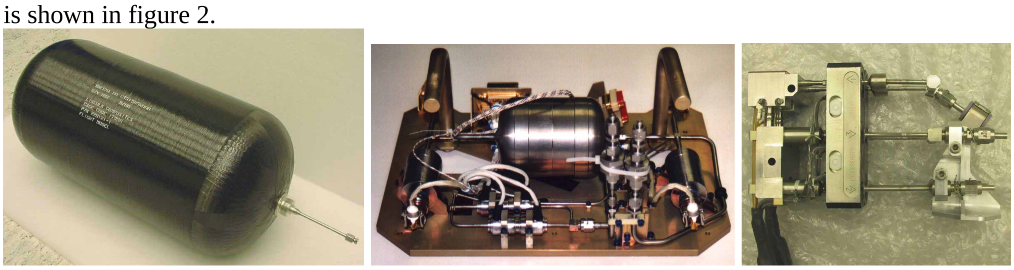

Figure 2. Flight model hardware: tank, BPRU and XFC.

The intrinsic concept of Bang-Bang regulator introduce a very regular fluctuation of the “constant regulated pressure”: each time the measured pressure become lower than the target pressure, the bang-bang valves are activated and a small positive step in the pressure of the plenum volume occurs[10]. This characteristic, as the heart of the system, is visible on about all the tele-measured functional parameters of the EPS. The telemetries available from that system are the main parameters: Pressure and temperature of the tank (called HPT and Ttank), Pressure and temperature of the plenum volume (called LPT and Tplenum) and other housekeeping parameters.

B. Electrical power supply and thruster

The electrical power supply and thrusters, fig. 3, is composed of a main power transformer called Power Processing Unit / Thruster Switch Unit designed by ETCA (Belgium) which transform the electrical voltage delivered by the satellite, 50 Volts DC, into the voltage required by the thruster (from 220 up to 350 Volt DC). Between the thruster anode / cathode, and the PPU/TSU, an electric filter called Filter Unit (FU) produced by EREMS (France) is designed to reduce the electrical thruster oscillations and to protect the electronics of the PPU/TSU..

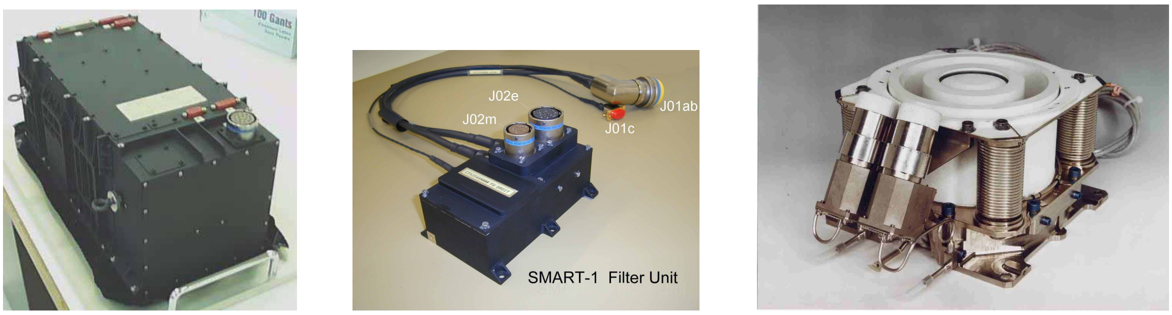

Figure 3. Flight model hardware: PPU, FU and thruster PPS®1350-G.

In order to deliver a constant thrust while the Snecma Moteurs thrusters7 is firing, fig. 4, a simple and robust algorithm loop is integrated into the PPU/TSU and generate the analogical control signal to the XFC. The telemetries available from that system are the main parameters: Discharge current (mean value and ripple value – ie the RMS value of the AC waves called FUoscillation-), discharge voltage, voltage between the Cathode emissive crystal and the ground satellite – so called Cathode Reference Potential (CRP) - and other housekeeping parameters.

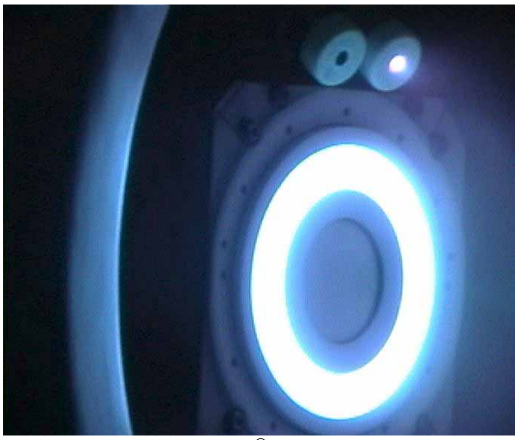

Figure 4. Thruster PPS®1350-G FM during acceptance tests Firing sequence.

C. Digital interface and communication system

The digital interface and communication system is composed of one main interface located into the PRE Card designed by Atermes (France). All Telemetry (TM) and Telecommands (TC) are interfaced to the EPS through the PRE Card. Commands reaching the PRE Card are either executed by the PRE Card (if relating to the BPRU control) or passed to the PPU.

Both the PRE Card and PPU contain software with “automatic mode” subroutines. These routines reduce the number of commands that need to be routinely sent to the EPS. With such feature, the ignition of the thruster requires only a few set of TC: first, a selection of the main or redundant branches and initialisation parameters, then it is needed to sent the TC “automatic exec” in order to perform automatically the xenon pressure regulation algorithm loop and the thruster ignition sequence and after its ignition, the further xenon flow control algorithm loop.

That last loop is performed also automatically by the PPU/TSU in the following way: the target for Smart-1 is to maintain almost constant the power consumed by the thrusters. This is almost equivalent to maintain almost constant the thrust delivered by the thruster.

However, it has been shown that it is sufficient to keep constant the Discharge Current, abbreviated “Id” , in order to keep the thrust constant.

On the other hand, it has been shown that the current Id vary quasi linearly with the xenon flow. A device called thermothrottle (a capillary tube able to be heated when connected to a current source) integrated into the XFC acts as a xenon mass flow regulator: the xenon mass flow depends mainly on the current delivered to the thermothrottle (current abbreviated “Ith”) and depends slightly on the xenon feed pressure.

Thus the thrusters-XFC-PPU loop is the following, fig. 5: the PPU/TSU read simply the level of the mean current Id from the thrusters and the PPU algorithm compute the required xenon flow and generate the required current Ith to be sent to the XFC.

The telemetries available from that system are the status parameters of the logic and other housekeeping parameters.

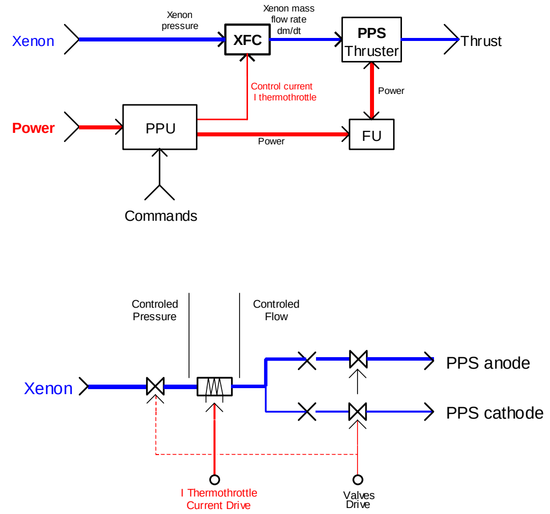

Figure 5. Xenon flow regulation loop and Xenon flow Controller functional diagram.

D. Variable Power Feature

As a main feature of the Smart-1 program, the thruster is able to be started and continuously used with a variable input electrical power. The reasons of such feature are related to the satellite solar arrays cells performance evolution as well as to cover a failures-case.

The user can sent, at any time, a “Nominal power set” parameter tele-command to the EPS in order that the thruster use more or less electrical power and to produce more or less thrust. Such command is taken into account by the PPU/TSU to fix its output characteristic. The transient between two settings points is performed by the PPU/TSU in an automatic fashion at a rate of change of about 15 Watt per second. The range of power at thruster level vary from 462 W up to 1190 W.

Taking into account the natural losses into the PPU/TSU as well as comfortable power margins, the range of the Nominal power set parameter is varying from 649.3 W to 1417.8 W. The exact power used by EPS is slightly lower than the Nominal power set parameter. Thus, the user is able, after in-flight characterisation, to sent the maximum “Nominal power set” command to the EPS even if the available power is less than 1417.8 W, in order to get the maximum thrust and performance from the EPS.

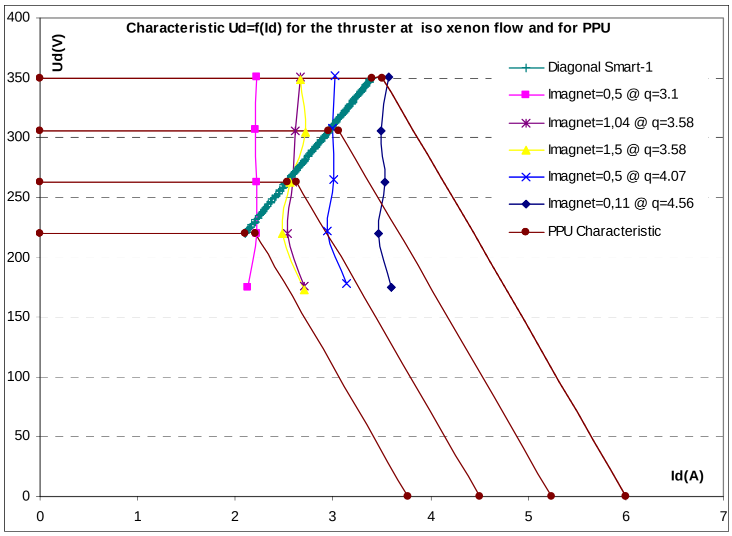

Figure 6. The diagonal with the 117 steps of the variable power feature of Smart-1given by the Nominal Power Set parameter. *The EPS Power at thruster level is of course **Ud*Id.** Thruster characteristics at iso-mass flow and only 4 of the 117 characteristics provided by the PPU/TSU are shown.*

The lowest value is the software default Nominal Power set value. It is used to perform the thruster ignition in automatic mode. There are 117 steps of Nominal power set parameter available, i.e each step of Nominal power set is equal to 6.625 W. In the common electric characteristic plane of the thruster (plane Ud, Id, see fig. 6), all the corresponding points are aligned along a single straight line, which is also roughly the diagonal of that plane.

II. Acceptance Tests

The SMART-1 units acceptance tests have been performed at their manufacturing plants by each sub-contractor. Special attentions were taken w.r.t. the tank environmental tests with fluid simulating the real xenon gas, and the protoflight PPU/TSU which was not completely considered as an off-the-shelf component due to the new features added to it (mainly the variable power feature). The pressure regulation unit BPRU, composed of off-the-shelf components, has been protoflight acceptance tested by Iberespacio (Spain) at the Madrid INTA facilities. Before, a BPRU characterisation-mapping campaign with xenon has been performed with the support of a detailed modelisation using the powerfull software EcosimPro. The test results showed the very good predictive accuracy of the mathematical model. The Electronic PRECard Flight Model (FM), fig. 7, has been fully acceptance tested (including shock test and thermal vacuum campaign performed by Swedish Space Corporation in Solna, Stockholm, Sweden).

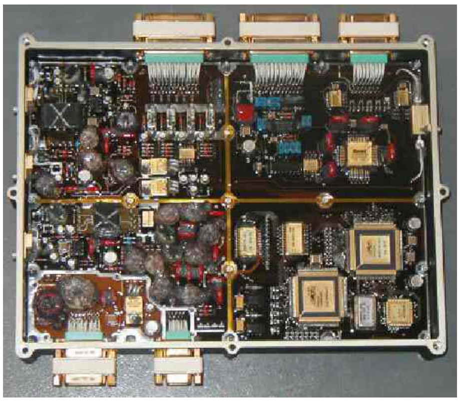

Figure 7. Atermes PRECard Flight-Model.

The PRECard qualification test campaign performed by Atermes, France, has shown a complete compatibility with the SMART-1 environmental specifications.

The SMART-1 PPS® 1350-G Flight model has been submitted to two acceptance test campaigns. First, a common acceptance test campaign including magnetic field measurement, start ON and performance measurement, environmental tests,… has been performed in order to confirm the manufacturing quality.

Secondly, a coupled test campaign was performed with the PPU-FM and the FU-FM. The test sequences (at different power levels) were fully checked during that campaign, as well as the right behaviour of the FM devices in real conditions (with the real thruster instead of the usual thruster simulators). The results of that campaign are considered as the Reference State of the EPS.

III. The End-to-End Test Campaign

The EPS tank was filled in xenon thanks to a dedicated xenon loading equipment in November 2002. The completion of this task by the Snecma Moteurs team allows to perform the so called “End-to-End” test. The main purpose of the SMART-1 end-to-end test (ESTEC, 18-19 December 2002) was to operate 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 Electro-Magnetic Compatibility (EMC) tests were performed with either a static or dynamic thruster simulator. 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 an incomplete representativity of the steady xenon mass flow rate. 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.

Figure 8. Thruster mounted on the spacecraft, End to End test first thruster firing.

The first EPS 4-hour test sequence consisted in performing the xenon venting of the BPRU and XFC in order to purge all the lines from any oxygen. The second EPS test sequence consisted of 2 firing tests at various power levels for a total firing time of more than one hour, fig. 8.

The good behavior of the spacecraft power system was verified with the FM 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.

The SMART-1 end-to-end test was the first time for Europe electric propulsion was fired successfully at spacecraft-level. 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.

The EPS remain full of xenon up to the launch with Ariane 5 (V62) from Kourou (French guyana) which occurs on September 27th 2003.

IV. In flight behaviour

At the time of writing the figure xx present the cumulated hours of the EPS versus the calendar time: the 2000 hours have been reached last April 16th. The two cathodes have been used mainly the nominal cathode A, and a few times (7 times) on the redundant Cathode B for checks. On the contrary, the cumulated hours on cathode B is still very low with only 20 hours, fig. 9.

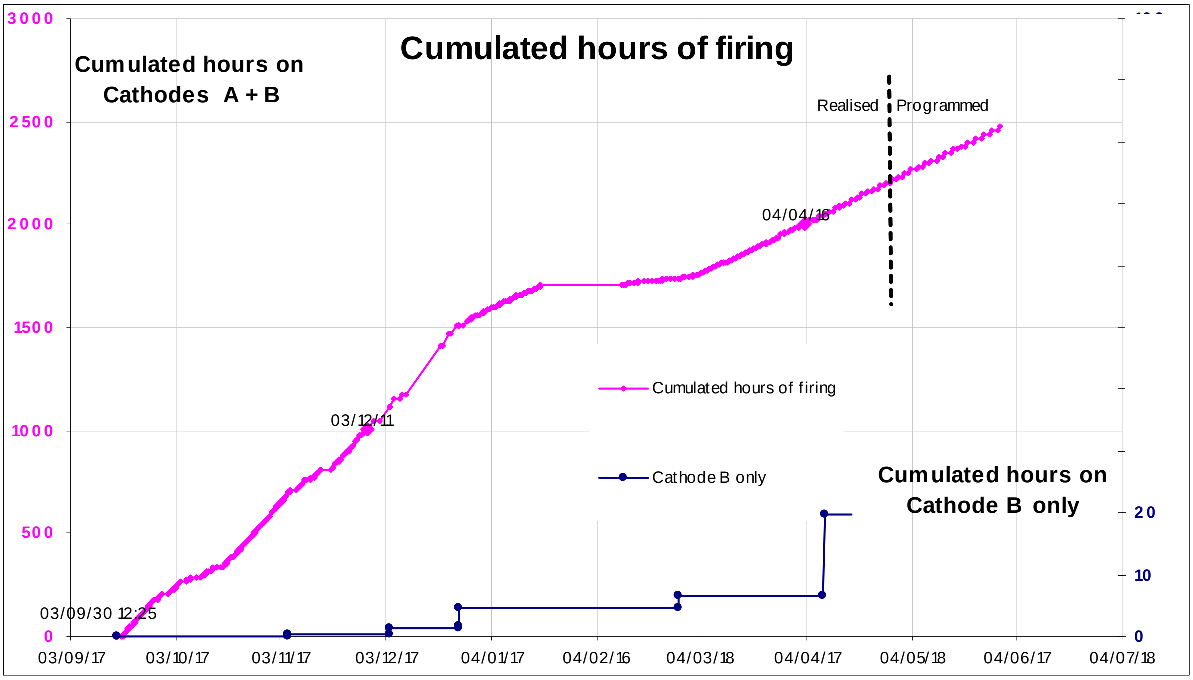

Figure 9. Total thrusting time of the Smart-1 EPS. Since the 30th of September, the EPS was used quasi-continuously. Thousand hours occurs on 11th of December and two thousand of hours occur the 16th of April. *The longest continuous firing occurs between December 23rd and January 2nd 2004, for 240 hours(10 days).*

The EPS and its thrusters provide almost continuously the thrust to the spacecraft during the first part of the trajectory. After beginning of January, the perigee altitude being of 14 000 km, the strategy changed, as forecasted, using the EPS only around the perigee. This remains true up to today, except an interruption of the thrusting period in February (for science commissioning) followed by short thrusting periods due to the eclipse duration constrains.

A. The orbit

The orbit in terms of altitude versus time, plotted in figure 10, shows the behaviour of the perigee and the apogee. That plot includes the forecasted orbits up to June. The first part of the orbit transfer is clearly visible on that plot because the altitude of the perigee is increasing first (as well as the apogee). The change of thrusting strategy is also clearly visible because the perigee altitude does not vary too much on the contrary; the apogee altitude is widely increasing.

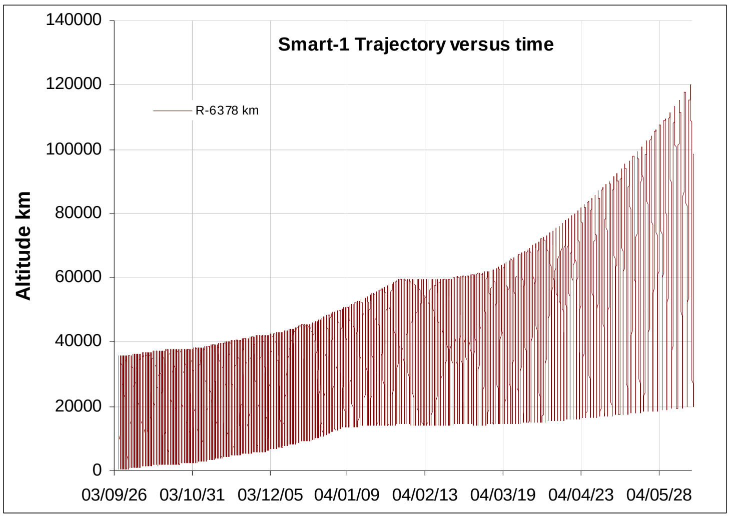

Figure 10. Orbit of the Smart-1 Satellite. *This is the first time that a satellite follows such trajectory.*

B. Van Allen Belt Altitude

This is the first time in the world that satellite follows such trajectory. The lessons learned, already published in a previous paper[8], about the behaviour in the Van Allen Belt shows that the end of the radiation effects on the solar arrays occurs for Smart-1 at an altitude of 5 900 km only. This is a rather low altitude compared with many assumption published everywhere in the world, the most conservative values of the altitude reached 15 000 km, while the most optimistic altitude one were from Spitzer (8 622 km)[2] and Pollard[3], Koppel (7 000km)[4], even if most of the scientific literature on the Van Allen Belts mention a upper limit for the "protons belt" of 5 000 km . In fact the value provided by Smart-1 takes into account the X5 Halloween solar flares that occurs in the middle of the Smart-1 passage in the Van Allen Belt, so, we can foresee that the Smart-1 value of 5 900 km may be considered as a consistent value. This is a first lesson learned from the Smart-1 EPS in flight, and this is of course to be confirmed by the next spacecraft that will follows the Smart-1 route.

C. First use of the thrusters in space

The objective of the Launch Early Orbits Phase (LEOP) was the commissioning of the EPS. The reference state of the EPS into the Satellite being the end-to-end test of December 2002, it was planned to operate the EPS in a similar way.

The first EPS test sequence consisted in performing the xenon venting of the BPRU and XFC in order to purge all the lines from any oxygen. Contrary to the end-to-end test, it was here in space possible to point the thrusters toward the sun in order to warm up itself and its xenon lines. So increasing the performance of the oxygen purge, the duration of the venting phase could be slightly reduced. The second EPS test sequence consisted of 2 firing tests at various power levels for a total firing time of 56 minutes. The first firing pulse of 50 minutes uses the nominal branch of the EPS (nominal branch of the bang-bang valves of the BPRU and nominal branch of the XFC and Cathode of the thrusters). This first pulse was a complete success showing all the functionalities of the EPS.

The ignition of the second pulse using the redundant branch was also successful, and the 3 minutes before the planned end of the commissioning pulse, an unwanted shut down of the propulsion occurs. The signature of the shut down is a flag called "flame out" into the PPU software. The cause of this phenomena came one month later after correlating the behaviour of the propulsion and the X5 Halloween solar flares. It was founded it was due to a single event transient (S.E.T.) on a fast optocoupler device (specific to the SMART-1 PPU) that resets the anode power supply output voltage setting for 100ms. This behaviour is specific to the SMART-1 PPU that has the capability to adjust the anode supply output voltage.

The consequence of a S.E.T. on that optocoupler is a loss for a while (100 ms) of the anode voltage. A specific short test campaign confirmed that in such condition the thruster is shut down and do not restart itself when the anode voltage is again applied. Hence, a lesson learned from the Smart-1 EPS is that because ground tests of S.E.T. are not really feasible at system level, one shall carefully considers a specific deep analysis on the consequences of S.E.T. on the system.

However, at operation level for Smart-1, the consequences of a so-called "Optocoupler S.E.T." abbreviated "OSET" are reduced at a minimum thanks to an automatic restart procedure patched to the on-board software of the satellite by ESOC Darmstadt[9].

D. Floating potential of the cathode CRP

Among the 15 Gigabyte of data available at the time of writing, one of the interesting behaviour to report here is the behaviour of the floating potential of the cathode CRP which is impossible to record on earth facility due to the intrinsic space vacuum characteristics, presence of the sun and its solar wind, presence of the earth magnetic field and the Van Allen belts, dimension of the plasma bubble around the satellite not compatible with the size of the ground facilities… The CRP is the Potential of the cathode with respect to the electrical ground of the thrusters. The electrical ground of the thrusters is connected through a very low resistance -some milliohm- to the electrical ground of the satellite. The sketch, figure 12, presents the thruster grounding configuration with the main functional elements.

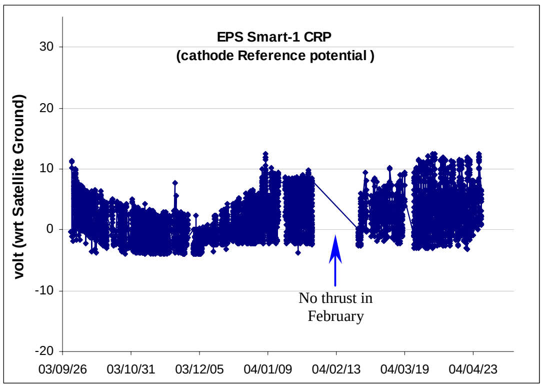

Figure 11. Long term (7 months) Cathode potential with respect to the electrical ground of the satellite.

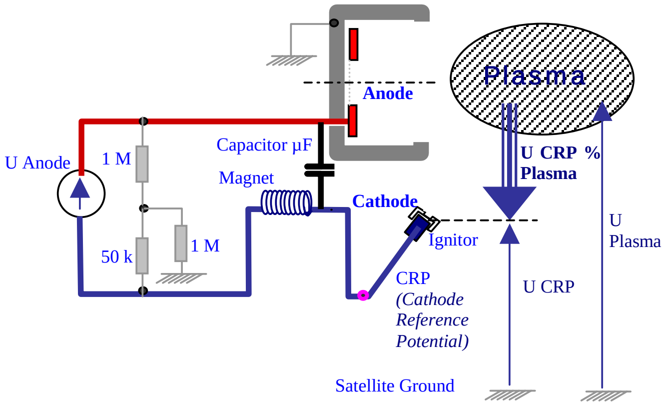

Figure 12. Sketch of the simplified electrical circuit of the EPS Smart-1. *The Cathode potential with respect to the electrical ground of the satellite is called CRP.*

The CRP is recorder in flight to values between –5 and +12 volts. This is by far different from the values recorded on the ground facility that is always, for the same discharge current, around -20 volts. The first plot, figure 11, shows the overall data along the eight first month of the mission. The second plot, figure 13, shows a zoom of the data for few orbits only. Because on Smart-1, the instrument EPDP (electric propulsion data package) produced by Laben (Italy) can measure the plasma potential thanks to a Langmuir probe, a correlation between CRP and plasma potential has been performed with the available data of EPDP in December 2003. The third plot, fig. 14, presents the correlation between the measured values of plasma floating potential (shifted by 19 volt) and CRP: the correlation, clearly visible, indicates that in flight, the plasma plays the same role as the test facility during the ground tests. This interesting result, learned from the Smart-1 EPS in flight, is for the team in charge of the understanding of the plasma propulsion in flight a confirmation of number of theories.

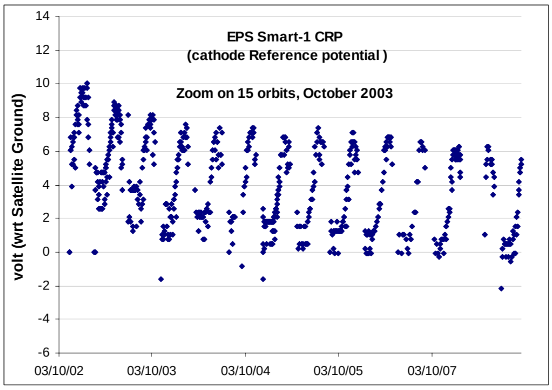

Figure 13. Zoom on 15 orbits, Cathode potential with respect to the electrical ground of the satellite.

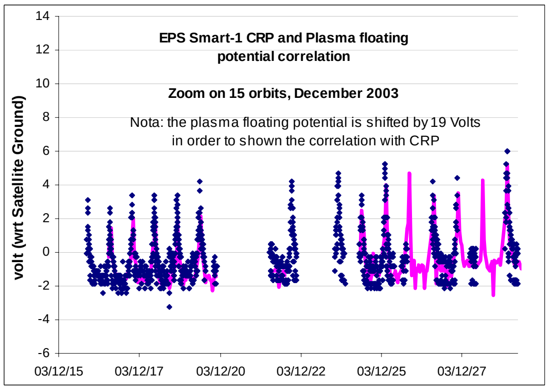

Figure 14. Correlation of the Cathode potential with the plasma potential.

E. In-flight characterisation of the thruster

In order to compare the ground tests with the in flight behaviour, a campaign of characterisation has been programmed when the satellite was out of the Van Allen belts. The results of the tests are shown in figure 15 with the additional magnet current and the magnet voltage in raw units. The magnet current (a current injected into the coil of the magnet added to the main discharge current, to produce an increasing value of the thrusters discharge magnetic field) was changed for different operational points. A total of 31 tests points were performed. The comparison with the ground tests results shows also the existence of functional modes with low and very low FUoscillation. On the same plot, one can see that the magnet voltage provides also a mirror of the pressure steps injected into the low pressure side of the system (ie at each time the low pressure of xenon reaches its lower target, the Bang-Bang valves opening produce a positive pressure step). Hence, the duration of each tests points was determined in order to get a minimum number such transient behaviour. Those transients enhance the check of the thruster behaviour.

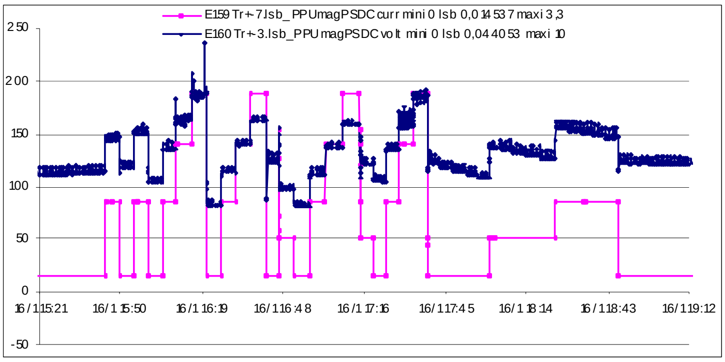

Figure 15. Magnet current during a characterisation test sequence of the EPS Smart-1 in flight.

V. Conclusion

This paper presented the SMART-1 EPS Flight Model in flight. Based on the various SMART-1 test campaigns, the thruster PPS® 1350-G and the EPS have demonstrated the capabilities of a Main Propulsion System.

After more than 2 230 cumulated hours of thrust in flight, the behaviour of the Electric propulsion system is nominal.

The lesson learned from the Smart-1 EPS in flight is first the quantification of the altitude at which the performance of the solar cells is no more affected by the Van Allen belts radiations. This altitude is surprisingly quite low with only 5 900 km. One shall mention in addition that it takes into account one very large solar flare.

A lesson learned, generic to all systems, deals with the immunity to the Single Events Transients for which, ground tests are not really feasible at system level, and thus should imply a specific deep analysis on the S.E.T. consequences in the system.

For electric propulsion, an interesting confirmation of number of theories has been achieved with the Smart-1 EPS in flight: the plasma potential play in flight the same role as the electrical-ground of the test facility on ground.

Acknowledgments

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