The SMART-1 Hall Effect Thruster Around the Moon: In Flight Experience

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Abstract: 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, allowed the capture by the Moon on the 15th of November 2004 and finally the propulsion pushes the spacecraft to the operational orbit around the Moon on 27th February 2005. The total in-flight accumulated hours of the thruster is about 5000 hours. And more than 800 times, the EPS was started. The first comment gained from the in-flight experience is that the EPS availability to perform the thrust function is recorded as 100%. One shall in addition point out that this performance was obtained even during the successive crossing of the Van Allen radiation belts.

The particular orbit followed by SMART-1 to reach the Moon, to be captured and to reaches the operational Moon orbit, has fully confirmed the suitability of the Hall effect thruster to perform such high sensitive orbit maneuvers near the capture.

EPS Contractor, ESTEC, and EPS manufacturer, SNECMA MOTEURS, will present in detail the major's performances of the complete electric propulsion system, with respect to the long life duration achieved.

The main feature of the SMART-1 system is its variable power supply. The PPS®-1350-G Hall Effect plasma Thruster and its Power processing unit, were developed in the frame of the CNES Stentor Program.

Results of the in flight EPS includes the behavior of 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 particular behavior of the floating potential of the thruster with respect to the satellite orbital position and its sun incidence along years.

The successful results obtained support the first technological experience objective of the SMART-1 mission. The performance in term of thrust or total impulse is discussed as well as the main lessons learned.

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.

The mission of the EPS, completed now, ended after performing a one and half month maneuver dealing with the increase of the orbital life by one more year.

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Nomenclature

CRP = Cathode reference potential, see text.

I. Introduction

THE Electric Propulsion Sub-System (EPS) of SMART-1 has been presented in numerous papers[1, 6, 7, 11,12]. The main characteristics of the EPS are roughly described here after and then the behaviour in flight is presented in the second chapter. 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.

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

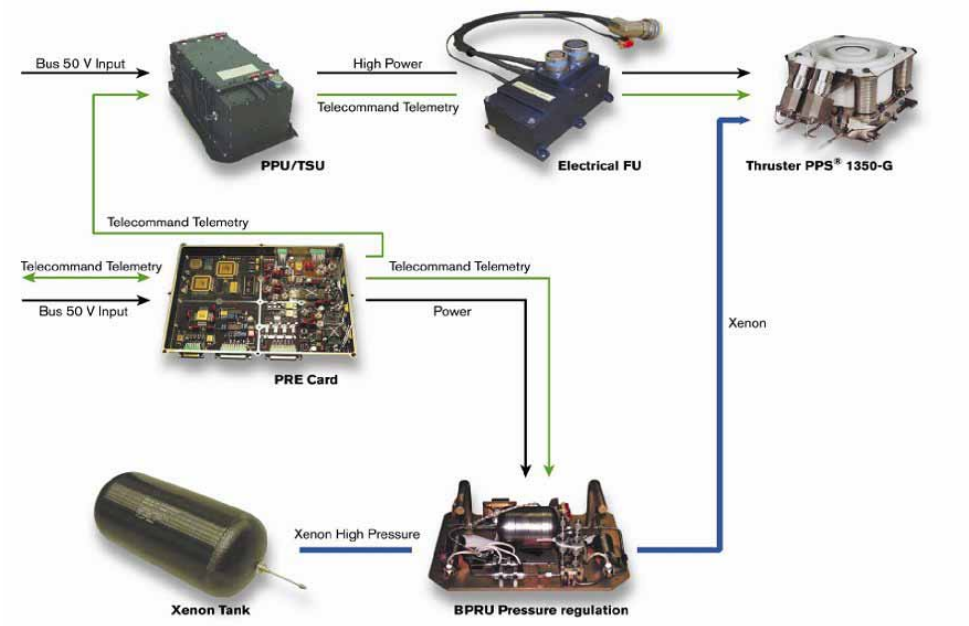

Figure 1. Sketch of the SMART-1 Electric Propulsion subSystem.

A. 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 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 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[2]. 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 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.

In order to deliver a constant thrust while the Snecma thrusters[8] is firing 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.

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 the PPU/TSU read simply the level of the mean current Id from the thruster 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.

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.

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), all the corresponding points are aligned along a single straight line, which is also roughly the diagonal of that plane.

II. In flight behaviour

Figure 2 present the cumulated hours of the EPS versus the calendar time: the 4958 hours have been reached at the end of the reboost phase, last September 17th. The two cathodes and XFC branches have been used mainly the nominal branch A, and some times on the redundant branch B for Cathode B checks or for using the redundant branch of the XFC.

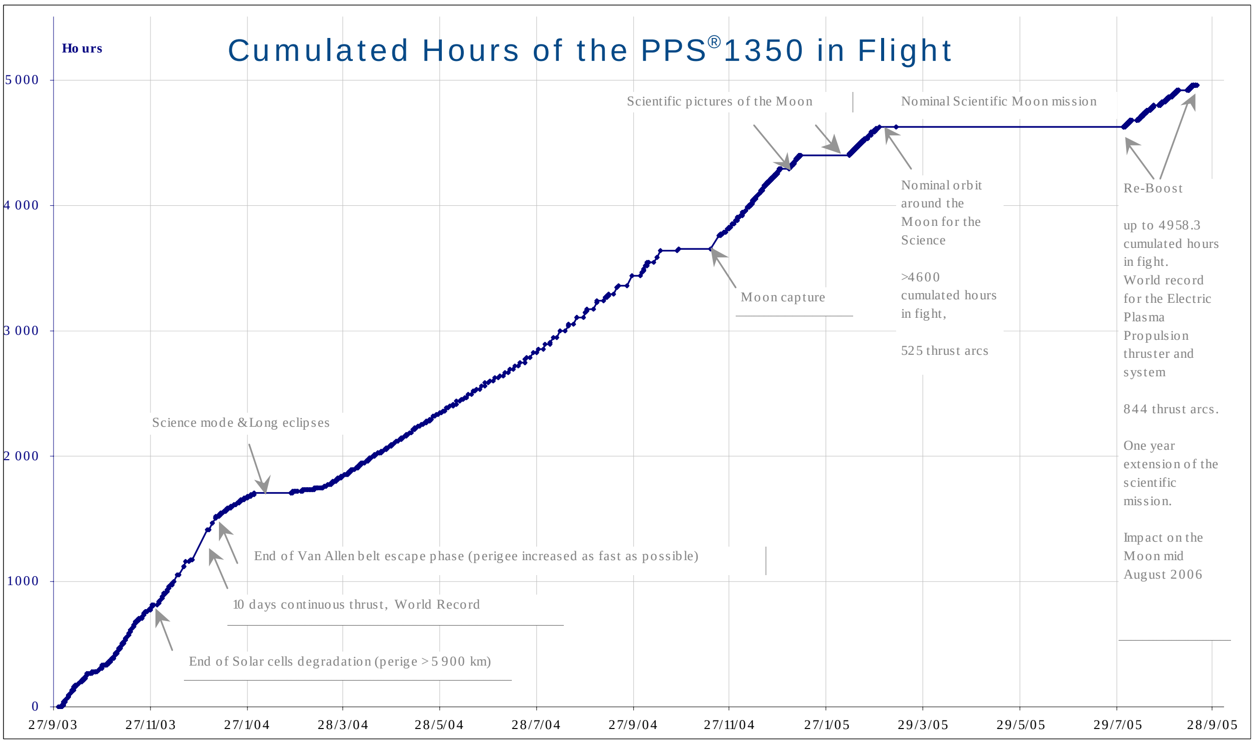

Figure 2. Total thrusting time of the Smart-1 EPS. Since the 30th of September, the EPS was used quasi-continuously. World record for Hall effect thrusters occurs in April 2004 with more than 1700 hours of operation in flight. *The longest continuous firing occurs between December 23rd and January 2nd 2004, for 240 hours(10 days)..*

The EPS and its thruster provided almost continuously the thrust to the spacecraft during the first part of the trajectory. After beginning of January 2004, the perigee altitude being of 14 000 km, the strategy changed, as forecasted, using the EPS only around the perigee. The Moon capture occurs on 15th November 2004. For the propulsion, a long continuous thrust was then performed (4.5 days). The descent to the low polar Moon orbit was performed with two thrust arcs per orbit (a short pulse at apolune and a larger pulse at perilune). The propulsion has been used for 844 times. The remarkable performance of the system is that at every time the propulsion was turned on, the thruster PPS® 1350 starts to work within the scheduled timing and without delay.

With respect to the initial planned trajectory, the realized one was shorter. This is due to the better performance provided by the thruster thanks to the higher power provided by the solar arrays. The deletion of three Moon fly-by allowed to shorter the mission by almost three months at the price of some kilogram of xenon. The total impulse measured in flight is the result of the integration of the thrust measured in flight versus time. The major result is that, even after providing 1 million N.s, the results in flight do not deviate from the forecasted values coming from the laws written into the interface control document, see figure 3 .

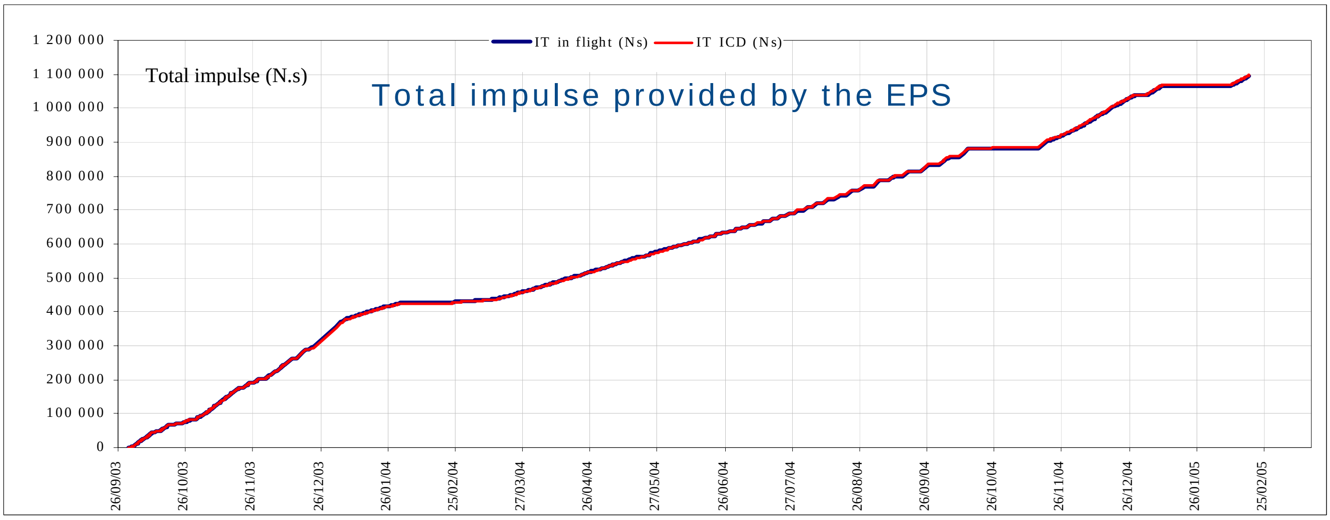

Figure 3. Total impulse comparison, measured in flight and forecasted in the Interface control document (ICD): the data are clearly superposed. EPS provided more than 1 million N.s .

A. The orbit

The orbit in terms of altitude versus time, plotted in figure 4, shows the behaviour of the perigee and the apogee, first with respect to the Earth, and then, after the capture manoeuvre, with respect to the Moon surface. That plot does not include the orbital perturbation of the Moon polar orbit due to the Earth. 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. The same behaviors are applicable to the Moon orbit until the nominal polar eccentric orbit is reached in late February 2005. Contrary to the initial forecast having a final apolune of 10 000 km, the better performance of the propulsion system allow to reach a lower better orbit 300x3 000 km for the scientific observation.

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[9, 11], 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)[3] and Pollard[4], Koppel (7 000km)[5]. 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. This phase of operation was perturbed by the "Optocoupler single event transient." (OSET) already described previously[11]. However, further the first occurrences, at operation level, the consequences of the OSET could be reduced at a minimum thanks to an automatic restart procedure patched to the on-board software of the satellite by ESOC Darmstadt[10]. A total of 38 OSET occurs during the whole mission from the Earth to the Moon, including the reboost phase.

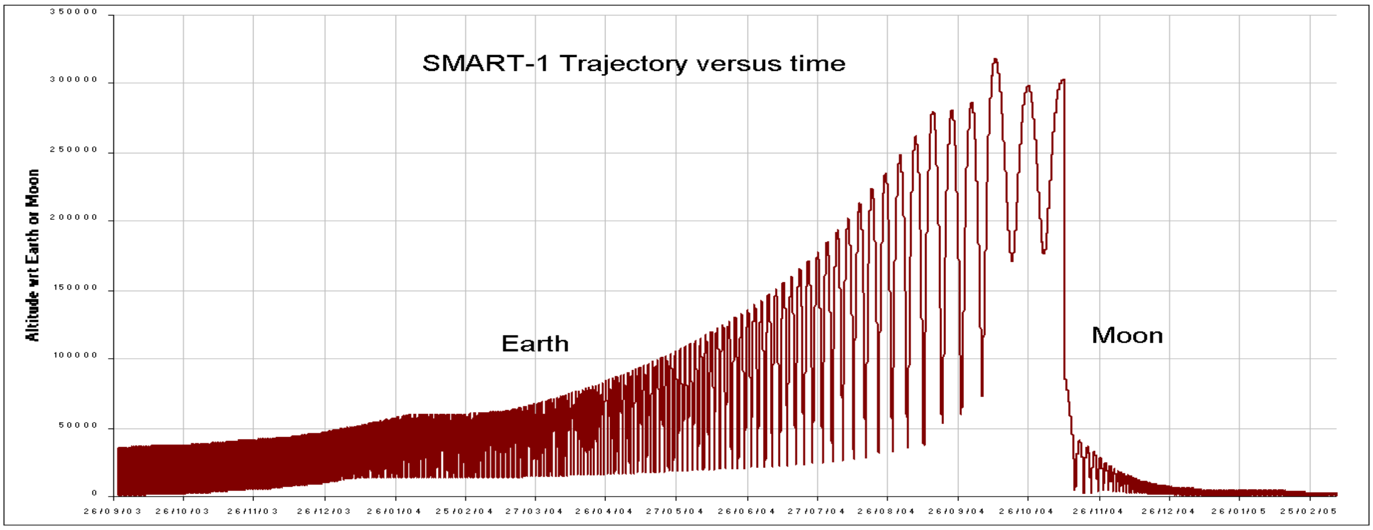

Figure 3. Orbit of the SMART-1 Satellite from Earth to the Moon. *This is the first time that a satellite follows such spiraling trajectory.*

D. Floating potential of the cathode CRP (cathode reference potential)

Among the 51 Gigabytes of data available, one of the interesting behaviour to report here is the behaviour of the floating potential of the cathode CRP.

The cathode reference potential is impossible to record precisely 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 emissive element with respect to the electrical ground of the thruster. 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 5, presents the thruster grounding configuration with the main functional elements.

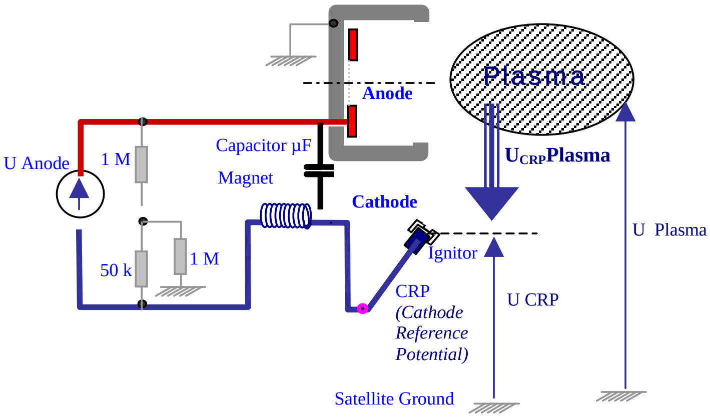

Figure 5. Sketch of the simplified electrical circuit of the EPS Smart-1. *The Cathode potential with respect to the electrical ground of the satellite is called CRP.*

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 6, shows the overall data along the whole mission (24 months).

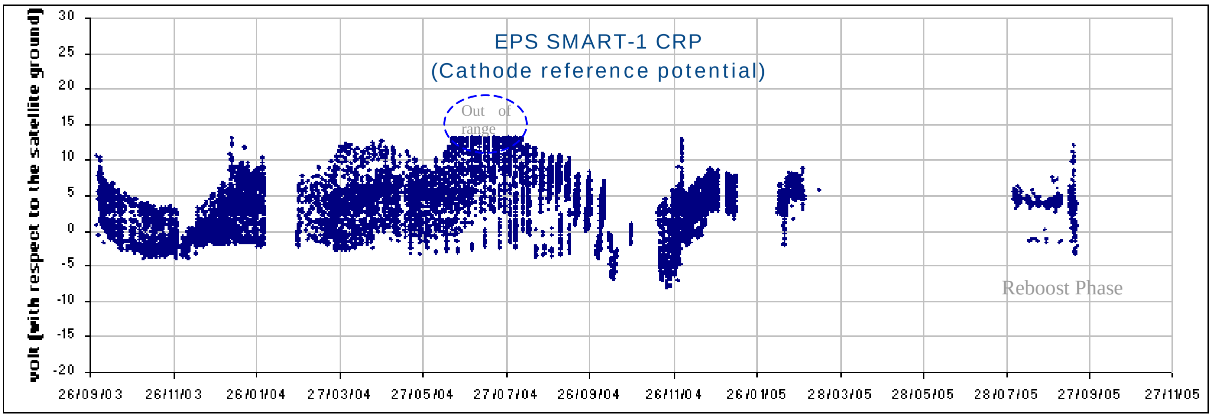

Figure 6. Long term (24 months) Cathode potential with respect to the electrical ground of the satellite.

The second plot, figure 7, 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. 8, presents the correlation between the measured values of plasma floating potential (shifted by 19 volt) and CRP: the correlation, clearly visible, indicates that for the cathode in flight, the plasma of the thruster plume plays the same role as the electrical-ground of the test facility during the ground tests. This interesting result, learned from the SMART-1 EPS in flight, was for the team in charge of the understanding of the plasma propulsion in flight a confirmation of number of theories[16, 17].

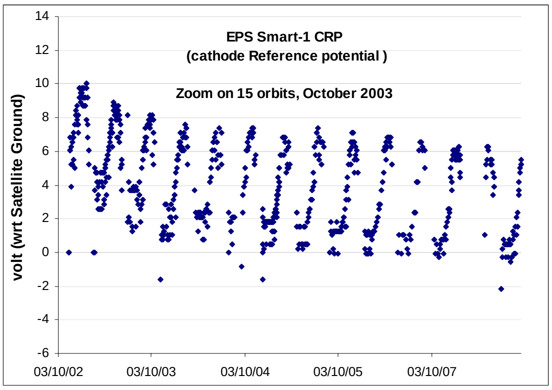

Figure 7. Zoom on 15 orbits, Cathode potential with respect to the electrical ground of the satellite.

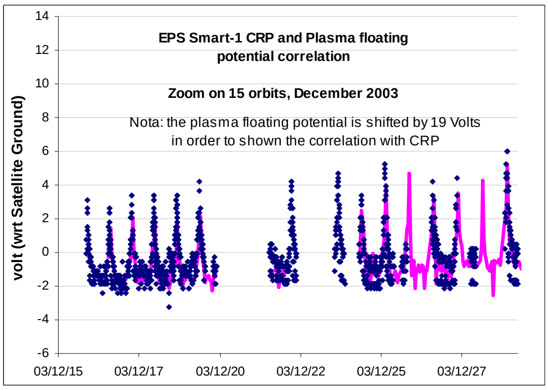

Figure 8. Correlation of the Cathode potential with the plasma potential.

E. In-flight characterisation of the thruster

In order to compare the ground tests with the in flight behaviour, two campaign of characterisation has been programmed, the first one when the satellite was out of the Van Allen belts (thruster cumulated ON time being 1500 hours), and the second one was performed after capture by the Moon (thruster cumulated ON time being 3800 hours). The results of one of those tests are shown in figure 9 with the additional magnet current and the magnet voltage in raw units. The magnet current (a current injected into the coil of the thruster 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 for each tests. The comparison with the ground tests results shows also the existence of functional modes with low and very low FUoscillation[13]. 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 behavior. The two tests performed shows very similar behaviors without indications of thruster ageing

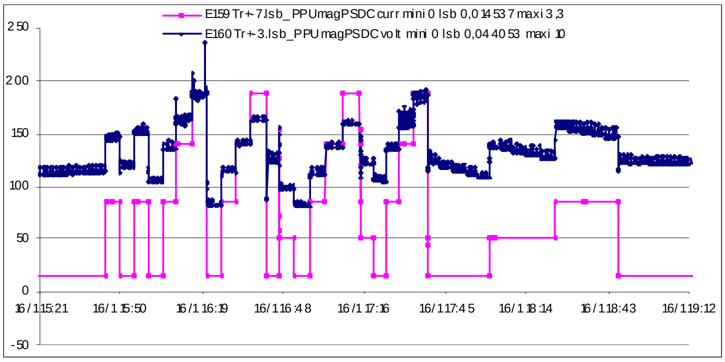

Figure 9. Magnet current during a characterisation test sequence of the EPS Smart-1 in flight.

F. Reboost phase

The extension of the mission for one year started on August 2nd 2005. The phase was mainly characterised by the use of the EPS and the thruster up to the limits of the system[14,15]. The main results are that it has been possible not only to fulfil the extension mission requirements, but also to quantify the unusable xenon mass in the system. The results are remarkable: the remaining xenon mass is 0.28 kg (including a usable xenon mass of 60 g). The unusable xenon mass ratio of the order of less than 0.4 %, much less, much better than the initial forecasts of about 2%.

III. Conclusion

The paper presents the behaviour of 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 as a Main Propulsion System.

The Electric propulsion system has cumulated more than 4 958 hours of thrust in flight. With 82 kg of xenon throughput the ideal velocity (delta V) imparted to the spacecraft reached of 3.9 km/s.

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: for the cathode, the plasma of the thruster plume plays the same role as the electrical-ground of the test facility during the ground tests.

The unusable mass of xenon can be set to the order of 0.4% only for future next missions.

After the nominal mission of 6 months around the Moon, the reboost phase has been completed successfully. The natural touch down of the Moon surface has thus been delayed by one more year. Moreover, the nominal orbit around the moon is also 3 times lower than originally foreseen (with a perilune of 300 km instead of 1000 km). The extension of the mission and the achievement of a better observation orbit were made possible thanks to the very good resistance against the degradation of the solar cells providing more electrical power after crossing the belts. And this allowed operating the electric propulsion sub-system powered by a Hall effect thruster at a better performance level.

The very high total impulse demonstrated on one single thruster in various operating and environmental conditions, is the clear evidence of the robustness of the SMART-1 EPS design, and of the capability of this thruster to achieve a wide range of space missions, including scientific and commercial ones. For example, the SMART-1 experience allows considering scientific mission with higher deltaV needs (up to 10 km/s) without major changes in the SMART-1 size.

Acknowledgments

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