SMART-1 Electric Propulsion Operational Experience

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SMART-1 was launched in September 2003, as the first of the European Space Agency's Small Missions for Advanced Research in Technology. After separation from the launch vehicle, the European Space Operations Centre assumed control of the spacecraft. SMART-1's primary mission goal, to demonstrate Solar Electric Primary Propulsion by orbit raising from GTO to the Moon, is now successfully completed. Furthermore, SMART-1 is now starting a one year mission extension after a series of advanced low pressure Electric Propulsion operations were successfully executed. The overall propulsive performance has allowed the mission trajectory to be re-optimised in flight, to produce a faster transfer time, a shorter, less critical, Moon Resonance phase, an improved Lunar Science orbit, and a one year mission extension. This paper presents a summary of the operational experience to date, with particular emphasis on the Electric Propulsion Subsystem, and the final low pressure Electric Propulsion operations. The variation of power available for orbit raising is presented, along with the techniques used to predict and command EP power levels.

I. Introduction

The SMART-1 mission is the first of the European Space Agency's (ESA) Small Missions for Advanced Research in Technology (SMART) and is dedicated to testing new technologies, in preparation for ambitious future cornerstone missions. SMART-1 was launched on September 27th 2003, as an auxiliary passenger on Ariane 5. The primary technology being demonstrated is Solar Electric Primary Propulsion (SEPP). The Electric Propulsion Subsystem (EPS) is tasked with pushing SMART-1 from its Geostationary Transfer Orbit (GTO) starting point, to a polar orbit around the Moon.

A. The SMART-1 Spacecraft

A brief overview of the SMART-1 spacecraft follows. For an in depth description, see Racca et al[1]. SMART-1 is a 3-axes stabilised spacecraft consisting of a central cubic box, of approximate 1m dimensions, and two Solar Array (SA) wings. The complete spacecraft weighs 370 Kg at launch. The central structure is designed around a Xenon fuel tank, of capacity 49l, containing 82.5kg Xenon at launch. A central equipment deck contains most spacecraft units, with the exception of high heat dissipaters. The power system uses GaINP/GaAs/Ge SAs, which are sized to

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deliver 1850 W Beginning of Life (BOL). Split into two wings, of three panels each, the SAs span 14 meters tip to tip. The SAs are positioned on the spacecraft $^+/$-Y panels, and have been designed to be able to rotate. In the orbit-raising phase, this allows the thrust vector and SAs to be optimally pointed at the same time. Power is routed over a fully regulated bus, controlled in three domains, by battery discharge regulators, battery charge regulators and Solar Array Shunt Regulators. Lithium Ion batteries provide power through eclipse phases of the mission, which are sized to support a maximum eclipse length of 2.1 hours (no thrusting). Primary propulsion is performed by the PPS®-1350-G Hall Effect Thruster, which can be gimballed by the EPMEC (Electric Propulsion Mechanism), both to point through the changing spacecraft centre of mass, and to help conserve Hydrazine, in reducing disturbance torques. Attitude control is performed by the Reaction Wheels, with Hydrazine thrusters being used in lower spacecraft modes (e.g. rate reduction at launcher separation), and to de-saturate the Reaction Wheels. Attitude information is obtained through a combination of sun sensors, gyros and star trackers. The data handling subsystem contains cold redundancy, with autonomous Failure Detection Isolation and Recovery (FDIR) software handling any single failures. The main controller, runs on a 32 bit CPU ERC32 Single Chip. The Remote Terminal Units (RTUs) are connected to a Commercial Of The Shelf (COTS) bus (CAN) to interface all units. The On Board Software (OBSW) is designed with a high level of autonomy, such that ground command sequence uplinks are executed nominally once every four days. Normal operation can continue in an absence of ground contact for ten days, and the spacecraft can survive in Safe mode for a period of two months or more.

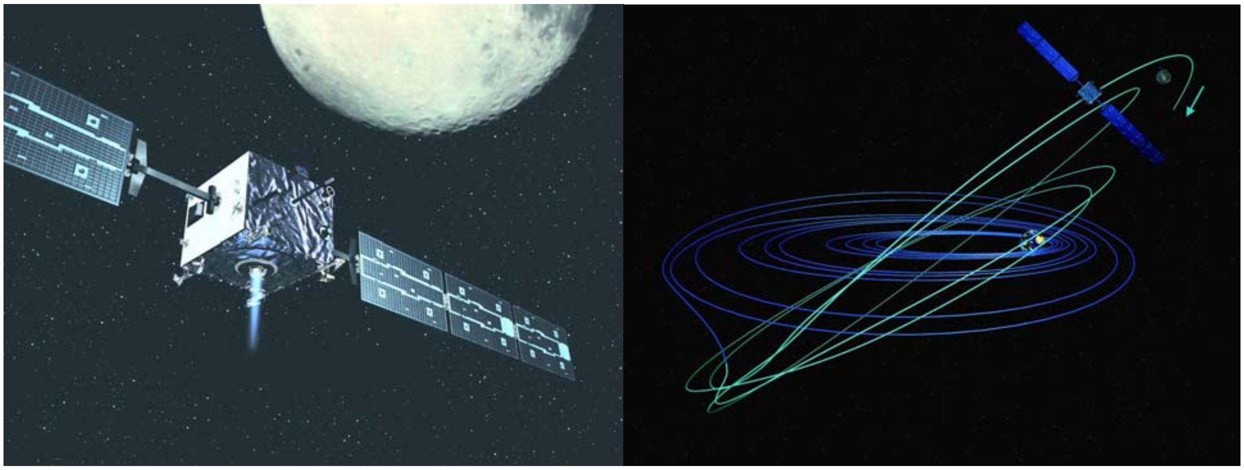

Figure 1 An Artist's Impression of SMART-1 around the Moon (left) and a schematic of the transfer (right)

The basic layout of SMART-1 can be seen in the Artist's impression of Figure 1 (left). The thruster plume is visible pointing in the –Z direction. The SAs are seen to the left and right in the $^+/$-Y faces. The X face contains the Low Gain Antenna (LGA) and several instruments. SMART-1 contains seven instruments in total, used for a combination of lunar and plasma science. The prime contractor for SMART-1 is the Swedish Space Corporation (SSC).

B. The Ground Segment

SMART-1 is operated from the European Space Operations Centre (ESOC) in Darmstadt, Germany. This location occupies around 600 people (about $^2/_3$ contractors) and is responsible for operating most of ESA's scientific missions (e.g. Envisat, Mars Express, Rosetta). ESOC also operates some spacecraft for external customers, specialising in Launch and Early Orbit Phase (LEOP) operations. In addition, it holds the development responsibilities for all ESA ground stations, and associated Networks in cooperation with international partners, ESA mission analysis for future missions and all Flight Dynamics operational services. The centre is the home of the Spacecraft Operations Control System also known as "SCOS" used to monitor and control spacecraft in multiple control centres around the world.

For SMART-1, the spacecraft to ground segment interface is based on the Consultative Committee for Space Data Systems (CCSDS) packet telemetry and telecommand standard with two different bit rates for the downlink, 65 Kbps^{-1} (over a medium gain antenna) and 2 Kbps^{-1} through the LGAs. Telecommand uplink is executed at 2 Kbps^{-1}. Four Ground Stations are routinely used to contact the spacecraft, these being; Kourou (French Guyana), Maspalomas (Canary Islands), Perth (Australia) and Villafranca (Spain). The spacecraft on board data handling uses the ESA Packet Utilisation Standard (PUS) for the different services. The spacecraft was designed for a high level of autonomy, in an effort to reduce operations costs. The ground control system and the Flight Control Team (FCT) were designed and sized to operate the platform and payload with just two passes per week of 8 hours duration each. Some innovative operational tools and techniques were developed in the ground segment to reduce operations costs. These included remote TM access and automatic alarming to mobile phones by sms[2]. Summaries of SMART-1 general operations are given by Gestal et al[3] and de Bruin et al[4].

C. Mission Plan

Since SMART-1 was designed to be an auxiliary passenger on Ariane 5, the exact launch date was not known until late into the preparation phase. For this reason the mission trajectory needed to be flexible and be able to cope with all seasonal variations. The mission plan is separated into several sections (7 and 8 being added later).

1) LEOP
2) Van Allen Belt Escape
3) Earth Escape Cruise
4) Moon resonance and Capture
5) Lunar descent
6) Lunar Science
7) Mission Extension re-boost
8) Mission Extension science

LEOP starts at Launch Vehicle separation, and is dedicated to commissioning all the critical platform units required before Electric Propulsion (EP) orbit raising could commence. This was achieved in three days, with two teams working twelve-hour shifts around the clock. Platform commissioning was executed rapidly to allow the EP orbit raising phase to start as soon as possible, thus limiting radiation exposure.

The Van Allen Belts Escape phase used a continuous thrust strategy, initially thrusting along the velocity vector, later thrusting perpendicular to the position vector. This strategy was chosen to quickly raise the perigee radius above a target 20,000 km. After completion of the Van Allen Belt Escape phase, the Earth Escape Cruise phase starts, where thrusting is performed around the perigee only, and the thrust direction is chosen perpendicular to the position vector. As SMART-1 approaches the Moon, Lunar gravity is used to assist the trajectory in a series of resonances, culminating in the critical capture manoeuvre. The thruster is then used to lower the orbit, at which point the Lunar Science begins. The initial lunar orbit was an elliptical polar orbit ~300x3000km. Figure 1 (right) shows a schematic of the transfer. After reaching the lunar orbit the spacecraft was in free drift whilst performing lunar science operations. A mission extension was then planned and executed (see section E).

D. The Electric Propulsion Subsystem

The SMART-1 EPS uses the PPS®-1350-G Hall Effect thruster, developed by Snecma, primarily for North South Station Keeping of Geo-stationary satellites. For SMART-1, the design is similar to the Stentor implementation, with some changes to limit peak inrush power and to be able to operate over a range of power levels (Koppel et al[5]). Koppel and Estublier[6] describe the flight model implementation for SMART-1 in detail. A summary is given below.

The EPS consists of three main sections[7]:

- Xenon system
- Electrical power system and thruster
- Digital interface and communication 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 thruster is controlled and powered by the Power Processing Unit (PPU)[8], built by Alcatel ETCA. 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. An electric filter called the Filter Unit (FU), produced by EREMS (France), is included to reduce the electrical thruster oscillations and to protect the electronics of 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.

In routine operation the EPS has two automatic loops running. One software loop, contained in the PRE Card, regulates the Xenon pressure, in the low-pressure tank feeding the XFC. The PPU hardware applies a power limited voltage source to the anode, selected by the 'nominal power set' command, which also sets the discharge and magnet current levels. The PPU then performs fine control of the thruster discharge current via a signal to the XFC, which varies the mass flow rate accordingly.

To be able to cope with a varying SA power through the mission lifetime, the EPS is designed to be easily throttled over a wide range of input powers. The nominal power set command to the PPU allows 117 different power levels to be set, ranging from 462 W up to 1190 W[9]. The PPU also performs the automatic ignition sequence, which has been designed to limit inrush power at ignition[5]. After the 'Auto exec' command has been executed, the cathode is heated, xenon flow initiated, then the thruster is ignited by application of an ignition pulse.

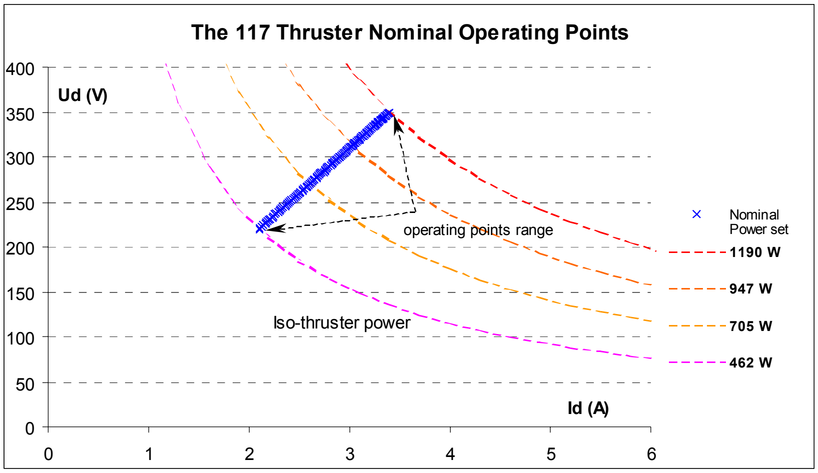

Figure 2. The Nominal Power Set Feature The 117 'nominal power set' steps of the SMART-1 EPS shown in voltage current space.

The EPS is a single string system including some internal redundancy. The BPRU valves are duplicated, protecting against single failures in the pressure regulation valve chain. The Power connection, between the EPS and the spacecraft power bus, is also duplicated, as are the thruster hollow cathodes and their appropriate XFC connection. Also included is a redundant BPRU heater. FDIR handling of the EPS uses a combination of internal error detection built into the EPS at subsystem level, and a module in platform OBSW called 'EP Manager'.

II. Operational Experience

At the time of writing, SMART-1 has successfully completed all Electric Propulsion operations, including some advanced low pressure operations for a one year mission extension with improved illumination conditions. The spacecraft is now in free drift in the chosen mission extension orbit, which is presently estimated to be stable until 17th August 2006. The present lunar orbit is polar, with a period of just under 5 hours, a pericentre distance of 2190km and apocentre distance of 4644km. The following sections summarise the various stages of the mission, focussed on the later stages. A more detailed account of the earlier stages (including pre-launch preparation and LEOP) can be found in[10].

A. Van Allen Belt Escape

After launch and the initial LEOP phase, routine operations commenced with the Van Allen Belt escape. In this phase orbit raising was performed by continuously thrusting along the velocity vector, except during the eclipses, when the engine was switched off. The orbital changes are monitored using Doppler and ranging data, which is regularly acquired from ground station passes. This data is then used by the ESOC FD system to update orbit determination, and provide spacecraft acceleration measurements. From this the thrust levels can be accurately measured in space.

Since EP thrusting is the highest spacecraft operational mode, some anomalies can lead to unexpected thruster shut downs. Sensitivity to radiation appeared in three recurring problems, which have all been subsequently solved. Such problems were most visible in the high energy bands of the radiation belts, and were also seen in the large 'Halloween' solar flare, encountered in late October to early November 2003. The first of these problems appeared when the main on-board computer performed autonomous multiple re-boots at the end of the first orbit. The source was tracked down to an error in the memory scrubbing routine on-board, which was not correcting properly detected SEUs in on-board memory. This was resolved by developing and uplinking patches to the OBSW[11]. Later on, the Star Trackers experienced some problems due to a combination of high temperatures and proton flux from a particular energy band[12]. This was also solved by patching, this time to the star tracker's own on-board software. Such platform level incidents induce an EPS shutdown as part of the system level on-board FDIR.

A third unexpected recurrent event, inducing EPS shutdowns, was the Optocoupler Single Event Transient (OSET)[10]. Analysis showed the problem to be radiation induced Optocoupler sensitivity. Simple manual restarts were commanded after the initial OSETs, but since manual re-starts can only be commanded during coverage, an OBSW patch was developed to automatically detect OSETs events, then initiate an autonomous thruster restart. An example autonomous restart is seen in figure 3. Throughout the mission there have been a total of 38 OSETs, the later ones being autonomously corrected on-board. The effect of unplanned shutdowns and small performance variations with respect to the orbit determination is described by Mackensie et al [14].

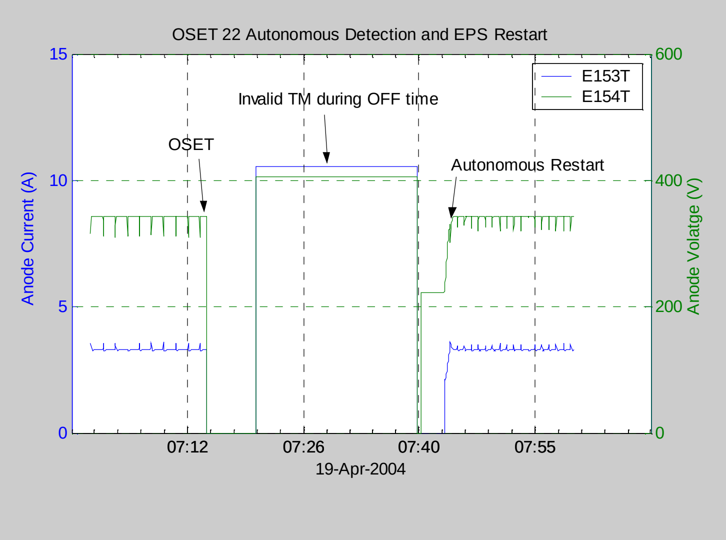

Figure 3 Example Autonomous OSET detection and thruster restart

B. Earth Escape Cruise

Close to the end of the Van Allen Belts Escape phase the thrust strategy was changed to thrust perpendicular to the position vector (in plane). The Van Allen Belt escape threshold was chosen to be a perigee distance of 20,000 km. At this point the apogee distance was 58,575 km. In Mid March 2004, an eclipse season was encountered with the spacecraft passing through the Earth's shadow near the apogee. Eclipses at such altitude are of the longest duration designed for, the maximum duration being 2 hours and 15 minutes. Eclipses times in excess of this value were actively avoided by performing a rotation of the line of apsides, such that the eclipse occurs sufficiently away from apogee to meet the constraint. Later on, the orbit was rotated back to the ecliptic to properly reach the moon. At present, the thrust is again oriented along the velocity vector, contained in thrust arcs around the perigee. The objective of this strategy is to modify the apogee radius. The next strategy to be performed consisted of direction-modulated arcs thrusts in order to also change the inclination of the orbit.

C. Moon Resonance and Capture

As the apogee of the orbit increased, its timing was chosen to coincide with the passage of the Moon, which gave some free impulse by 'resonating' with the moon. Initially, it was foreseen to perform three such resonances and three lunar swing-bys, before the capture manoeuvre. Analysis of the on-board propellant and power budgets around the time of the planned lunar capture allowed a new strategy to be developed. The three lunar swing-bys were removed, which had the benefits of reducing transfer time, and the time spent around the operationally critical weak-stability boundary between the Earth and the Moon (see figure 4). The three Moon Resonances were about 27 days apart and their effect was to raise the perigee and to rotate the orbit both in inclination and argument of perigee. On the 11th November 2004, SMART-1 made history with several notable firsts, including being the first Electric Propulsion mission to escape Earth orbit, the first to use Electric Propulsion to enter into orbit around another celestial body, and Europe's first Lunar mission. At the point defined as capture, the spacecraft passed through a position 310,000 km from the Earth and 90,000 km from the Moon in free drift. To achieve this, the thruster had been started 288 times, accumulating 3652 hours firing time, since launch vehicle injection into GTO. Shortly after capture, a 4.5 day continuous thrust braking manoeuvre was executed, to increase orbital stability, and to begin the Lunar decent phase.

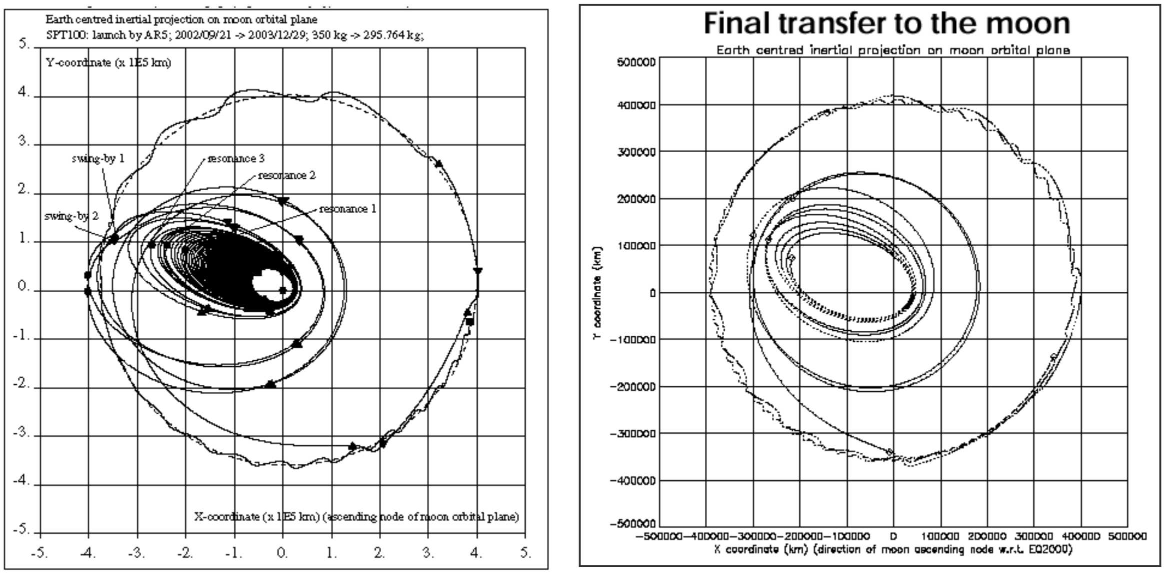

Figure 4 Comparison pre-launch planned (left) and in flight executed (right) Lunar capture strategies

D. Lunar Decent and Science

After the capture manoeuvre, the thruster was used to bring the spacecraft lower until an operational orbit of 2,200 x 4,600 km was reached by February 2005. To achieve this, the thruster performed and additional 236 thrust arcs, adding another 953 hours to the cumulative thrust time. Over the course of the next five months extensive lunar science operations were performed by the instruments on-board. During this time the thruster was not used, apart from routine valve tightness checks. In free drift, the orbital parameters gradually changed due to orbital perturbations, such as the influence of the Earth and Sun, reaction wheel off-loadings and the non-uniformity of lunar gravitation.

E. Mission Extension Re-boost

Due to orbital perturbations, the lifetime of the orbit is limited. Favourable power and propellant budgets, and an efficient transfer strategy, led to the possibility of a mission extension. Without further thrust arcs, the lunar orbit would have gradually degraded in altitude until a lunar impact by the end of September 2005. Studies of possible extensions were performed. At the time it was estimated that around 6.0kg of xenon remained in the main tank, but 1.8kg of this was considered residual (i.e. not useable with existing procedures). Several orbit raising options were discussed. One of the key issues was to obtain good illumination conditions at low altitudes in scientifically interesting lunar locations (i.e. mainly around the lunar south pole), rather than simple perilune boosting.

Flight experience had shown an excellent performance of all the bang-bang valves in the BPRU. In an effort to extend the useable xenon beyond 4.2kg, studies and simulations were performed at ESOC and Snecma to test the ultimate capabilities of the system. Snecma suggested some sequence changes to valve timings which would allow operation to considerably lower main tank pressures. New procedures were written and fine tuned through testing campaign performed at ESOC on the spacecraft simulator[13] (the EP part based on the EcosimPro® software). This analysis identified and validated new procedures that could be used, which with the help of the accurate simulator software, predicted that the tank residual could be reduced from 1.8kg to around 450g.

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GE7008   EPS Discharge Monitor   65296   65535   100325055   52193   2005.200.20.31.11.383
X-GRID INTERVAL      001.00.00.00 AUTO HARD COPY     OFF
NAME     DESCRIPTION        VALUE          UNIT VLDITY SAMPLE TIME           MIN        MAX        LINE
E003T    PREhpt             2.15           bar  VALID  2005.200.20.31.11.383 1.00       4.00
E153T    PPUanodePSDCcurr   1.98           A    VALID  2005.200.20.31.10.386 1.45       3.60
E161T    PPUththPSDCcurr    0              A    VALID  2005.200.20.31.10.386 0.00       2.00
E004T    PRElpt             1.26           bar  VALID  2005.200.20.31.11.383 1.00       2.25
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Figure 5 Predicted Electric propulsion behaviour at very low pressures

Several important thresholds, and the expected behaviour of the thruster at very low pressures, were identified from the simulations. To increase flexibility, the way in which the thruster was commanded was changed to be mission planning based, so that frequent fine tunings could be more easily accommodated. Some important thresholds, with approximate correlation to expected residual xenon mass levels identified by the testing, are shown below.

EP low pressure operational thresholds		
1	Nominal EP on sequence valid until	1.80-1.94kg
2	Under-regulated propellant control at	0.91-0.97kg
3	Under-regulated thrust at	0.73-0.78kg
4	Final shut down	0.44-0.48kg

Table 1 - EP thresholds in terms of Xenon mass

Threshold 1 gives the expected residual tank mass level at which the most efficient sequence in terms of valve timings should be programmed. After this change is implemented, the mass flow rate from the high pressure main tank to the low pressure plenum tank is operating at maximum capacity for a given upstream pressure. This also means that the load on the valves (i.e. frequency of valve activation) is also at a maximum. Since the system is pressure based, temperature changes induced by heater switching cycles, cause some uncertainty as to what exact mass level the thresholds occur at, which explains the mass ranges given above.

At threshold 2, even with the valves operating at maximum capacity, the mass flow rate into the plenum tank falls below the mass flow rate out of the tank (and into the firing thruster) due to the upstream pressure in the main tank being too low. At this point 'under-regulated' propellant loop control occurs, in that the pressure in the plenum tank slowly falls. This means that the upstream pressure seen by the XFC drops with time. The effect can be seen in figure 5 above. The top left plot shows pressure in the main tank, and the bottom right plot shows pressure in the (low pressure) plenum tank. Normally, pressure in the plenum tank is maintained above a target pressure by cycled actuation of bang-bang valves, but as can be seen in the above figure, after a short period, the pressure in this tank begins to fall. Even though the pressure in the plenum tank is falling, the on-board control loop of the XFC is able to compensate for some time. The bottom left plot shows the thermothrottle current. Normally, this is relatively constant around 1.2A, but with falling pressure in the plenum tank, the thermothrottle current drops (the thermothrottle controls mass flow rate by the addition of heat through a warming current). Since the thermothrottle current is reducing, the on-board control loop automatically adjusts, so that mass flow rate to the thruster (and therefore thruster performance) is not affected. This is evident in figure 5 by observation of the thruster anode current (top right), which is unchanged during this under-regulated propellant loop period. Since this type of operation of the thruster was not as originally foreseen, some of the EP FDIR (health checks) in the EP subsystem were disabled to prevent the on-board autonomy from mistakenly initiating a shutdown (i.e. due to under pressure in plenum tank health check triggering). This presented no danger to the subsystem, it merely being a product of the fact that the whole system entered a low pressure state (pressure lower than 0.7 MPa).

Threshold 4 occurs when the XFC becomes saturated, and is no longer able to compensate for the very low upstream pressure. At this point the mass flow rate to the thruster itself begins also to fall, and this affects the anode current, due to lower influx of xenon neutrals. This can be seen in the drop of anode current in the top right plot of figure 5. As anode current drops, so does the thrust produced, although, since applied voltage is maintained, specific impulse is much less affected. Ultimately, when the anode current falls to 1.35A, the software in the PPU detects a 'flame out' and commands the PPU power supplies off and goes to standby mode. According to simulator predictions this would happen in the range of 440-480g residual xenon.

Based on the results of the low pressure EP operations studies, an ambitious re-boost strategy was selected that would use all xenon predicted to be available with the advanced operations (see figure 6). Around seven new procedures were developed for this. On August 2nd 2005, the thrust spirals to achieve the SMART-1 mission extension were initiated. The re-boost phase lasted until September 17th 2005, when the final decision to terminate EP operations was taken. This period included three pauses, totalling a period of around ten days, which were inserted to avoid double star-tracker blinding (i.e. when the field of view of both star trackers are obscured e.g. by the Earth and the Moon). The entire re-boost spiral (including the above pauses) contained 207 revolutions of about 5 hours. The EP power set was programmed at 1325 W (from power budget considerations), which corresponds to a force of ~ 66mN.

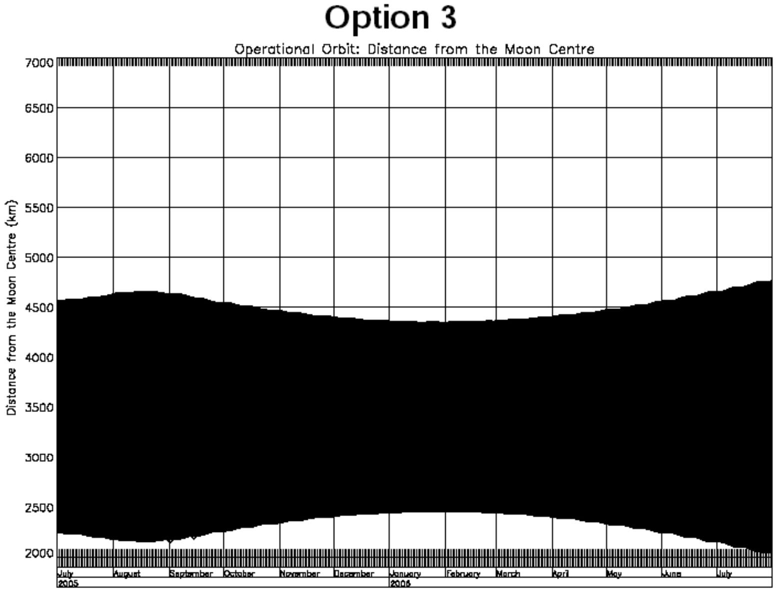

Figure 6 - Operational Orbit selected for Mission extension: Distance from the Moon centre.

The state at the beginning of the re-boost is given in table 2. The thruster was on in the ascending arc of the orbit for about 68 min between true anomaly 62 deg and 144 deg and it was on in the descending arc of the orbit for about 68 min between true anomaly -144 deg and -62 deg. The coast arcs around the perilune and apolune were symmetric, about 49 min and 112 min respectively. During the ascending arc, the thrust was mainly along the velocity (with an in plane tilt towards the Moon) starting at 29 deg and ending at -11 deg. During the descending arc, the thrust was mainly opposite to the velocity (with an in plane tilt towards the Moon) starting at -11 deg and ending at 29 deg. Both arcs increased the argument of pericentre by about 0.2 deg each, increasing and decreasing the perilune radius by about 3.3km and the apolune radius by about 5.8 km. Due to the symmetric thrusts, the re-boost phase strategy was robust against thruster performance variations.

Initial Conditions	
Radius of Perilune	2172 Km
Radius of Apolune	4634 Km
Inclination	90.264 deg
Right Ascending Node	237.344 deg
Argument of Perigee	243.860 deg
Xenon left	~6.0 kg

Table 2 - State at beginning of EP re-boost phase

Before the start of the re-boost, the valve timing settings of the nominal EP ON sequence were updated with respect to those used at the end of the lunar decent phase, due to coincidently being close to one of the pre-launch defined thresholds (22 bar main tank pressure). This change was also patched into the OSET recovery sequence code contained in the platform OBSW. For the next four weeks of the thrust spiral phase, no more changes were required, and operations progressed smoothly. In order to have good pericentre illumination conditions during the first 6 months of the mission extension, followed by excellent pericentre illumination conditions during the last 6 months, the argument of pericentre at the end of re-boost phase was targeted to be between 290 and 299 deg. (Figure 7).

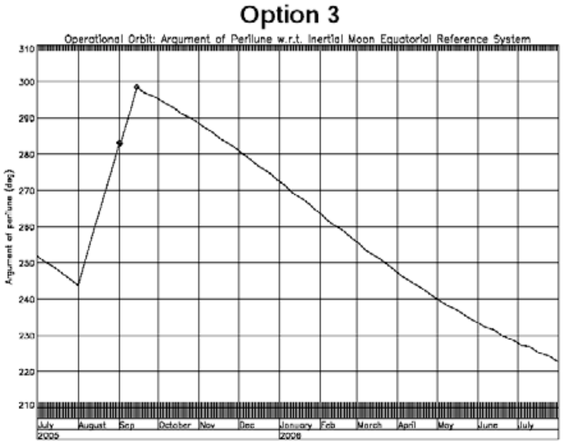

Figure 7 - Argument of Perilune evolution during and after the re-boost phase

During the re-boost, the Flight Control Team closely monitored the pressure in both the main and plenum tanks. With xenon use, the pressure in the main tank dropped quasi linearly with time. Forecasts of the date and time of threshold crossings were periodically tuned based on the performance of the engine. Just before the planned interruption on 6th September, the pressure loop first became under-regulated, as predicted by the simulations. For the first part of this arc, the system was able to regulate the pressure and the LPT (low pressure transducer) reading remained constant (normal behaviour). Shortly before the end of the pulse the plenum pressure started to drop linearly, showing under-regulated propellant loop control. The thermothrottle current (Itt) from the XFC dropped quasi linearly with plenum pressure to compensate, and the thrust delivered by the engine was not affected (see figure 8).

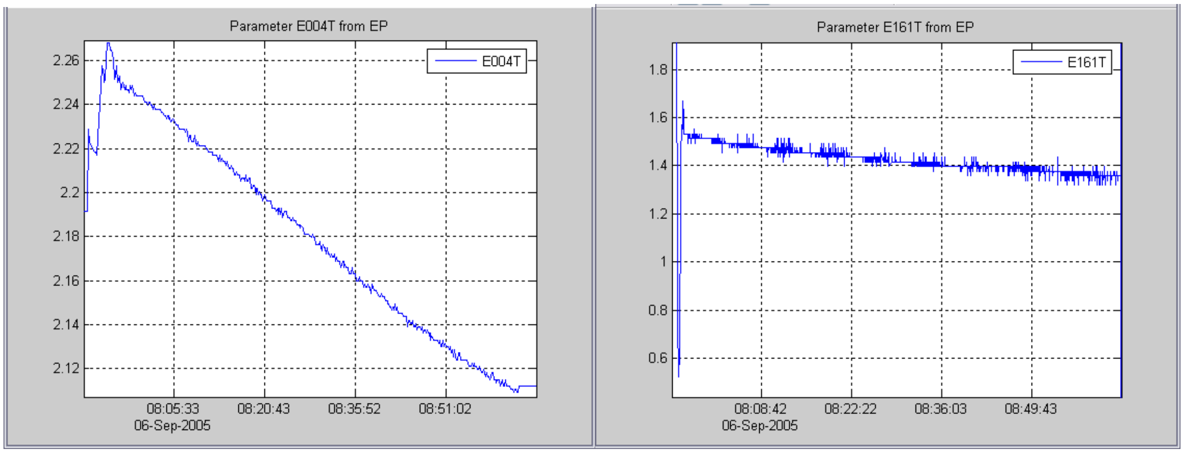

Figure 8 – Plenum pressure (left) and thermothrottle current (right)

At this point some other ideas were considered to further extend the projected lifetime. To increase the time until under-regulated thrust occurs, (predicted at a level of 1.56 bar plenum pressure), a new procedure to boost the LPT between thrust arcs was created and implemented. This procedure powered on and activated only the propellant loop section of the EPS to re-pressurise the plenum tank (no thrust produced and no downstream flow rate). This was called by the mission planning system with execution times selected such that it was active in the parts of the orbit where thrust was not required. The filling of the Plenum Tank was then applied from 12th September.

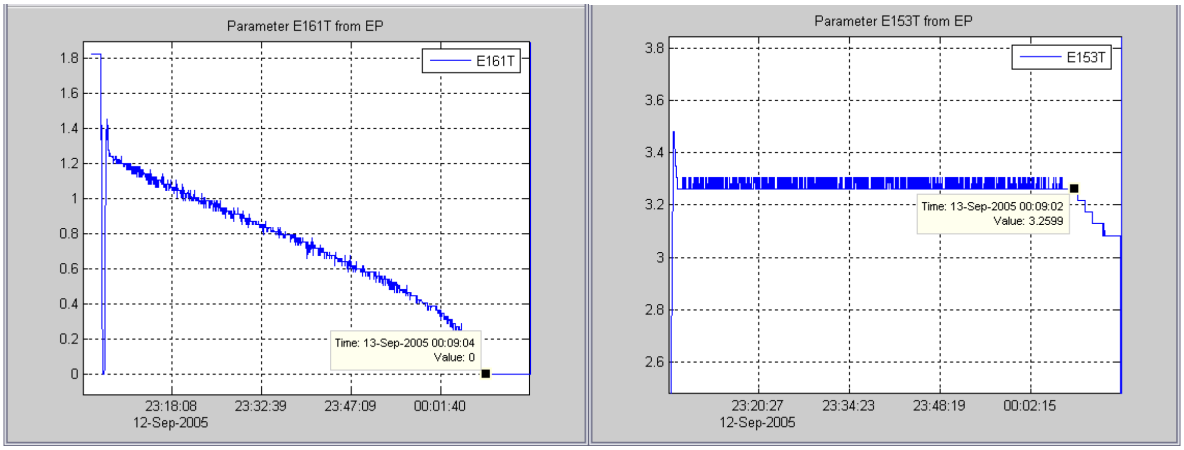

Figure 9 – Thermothrottle current (left) and Anode current (right) at onset of under-regulated thrust

Eventually, even with the above measures, due to the very low upstream pressure, the system becomes unable to maintain a constant anode current, and under-regulated thrust occurs. This happened for the first time on September 13th (see Figure 9). In such conditions, the thrust delivered by the system starts to decrease, and this decrease can be modelled, to a first approximation, as proportional to anode current decrease.

Ultimately, even with plenum filling procedures inserted between thrust arcs, the pressure at the beginning of the thrust arc becomes lower than the nominal preset level, and a fine tuning to the current (Itt) applied to the thermothrottle at ignition (capillary tubing integrated into the Xenon Flow Control valves) is required. Reduced pre-ignition 'warm up current' (applied to the XFC) was executed for the last thrust arcs. This strategy was used from 14th September and the value of Itt was adapted according to the maximum available pressure in the plenum tank. As this maximum pressure dropped with each subsequent arc, eventually no current was applied.

When the anode current falls below 1.35A, the PPU software turns off the thruster power supplies and flags a "Flame-out" in telemetry. The first occurred on 15th September about 10 minutes before the thrust arc was due to end. From this time onwards, the pulses became shorter and shorter until the last thrust arc on the 17th September sustained thrusting for only 10 minutes.

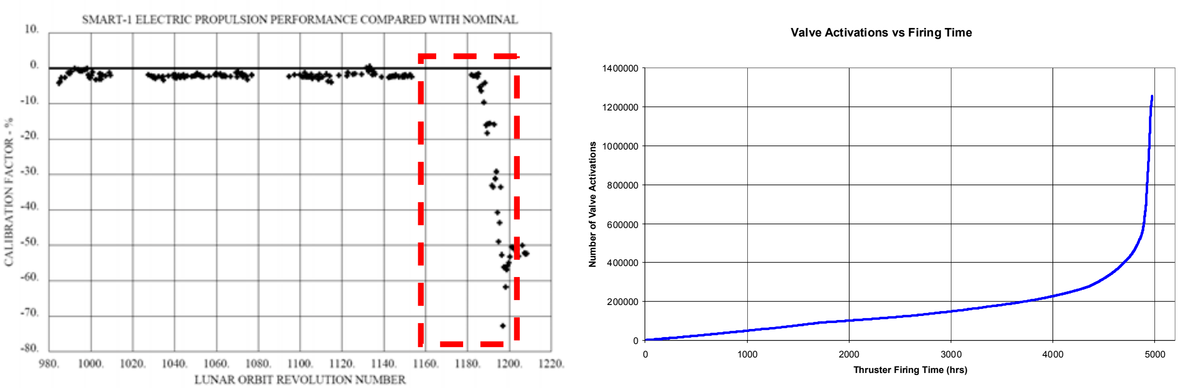

Figure 10 – Thrust calibration factor (left and cumulative valve activation count (right)

The thrust performance during the re-boost, measured by orbit determination, can be seen in the left of figure 10. Up until around lunar orbit 1160 it can be seen that the thrust is fully nominal. To the right hand side of this figure can be seen the effect of operating in under-regulated thrust mode. This reduced thrust was expected from the testing and is merely a product of the extreme operating conditions. The right hand plot in figure 10 shows the cumulative valve activation count from the beginning of the mission (plotted against thruster firing time) for thrusting alone. The exponential growth to the right is a product of working at very low pressures. For the plenum filling sequences, the redundant valves were used due to very large number of activations commanded. A cumulative count of 1.3 million activations was approached on the nominal chain alone, with no signs of leakage even at this very high number (beyond qualification limits).

After the last thrust arc on 17th September 2005, Flight Dynamics made a new orbit determination computation. After a complete analysis it was decided not to continue the EP thrusting, since further thrusting would become very challenging and the targeted orbit range had been reached. A summary of the mission is shown in the table below.

SMART-1 EPS in numbers	
- Number of Pulses	844
- Total number of hours fired	4958.3 hours
- First Pulse	30/09/03 12:25
- Last Pulse	17/09/05 18:45
- Number of nom. BB activations	1.256.505
- Xenon at BOL	82.5 kg
- Remaining Xenon	~280 grams
- Useable Xe of the remaining in the tank at 17/Sep/2005	~60 grams
- EP Power set range used during the mission	649 W / 1417W
- Number of OSET	38
- Total of Flight Operation procedures created	45
- Total of EP sequences created	98

Table 3 – SMART-1 EPS figures

From October 1st 2005, the science phase resumed. The 300 km perilune altitude, important for the science phase, will be reached on 8th June 2006 and the moon impact will be on 17th August 2006.

F. Power budget and EP throttling

Throughout the mission the power budget has been closely monitored on ground. The goal is to maximise the commanded nominal power set parameter, to provide better thrust and specific impulse, without consuming more power than is available. In the initial stage of the mission there were two predominant effects driving this analysis, these being radiation exposure in the Van Allen Belts and the seasonal variation of the Earth to Sun distance. Figure 11 shows the measured SA power (left) and effect of the radiation belts (right). The plot on the right hand side uses the same measured data but subtracts out the seasonal effect due to changing Earth-Sun distance ($^{+}$/- 3%).

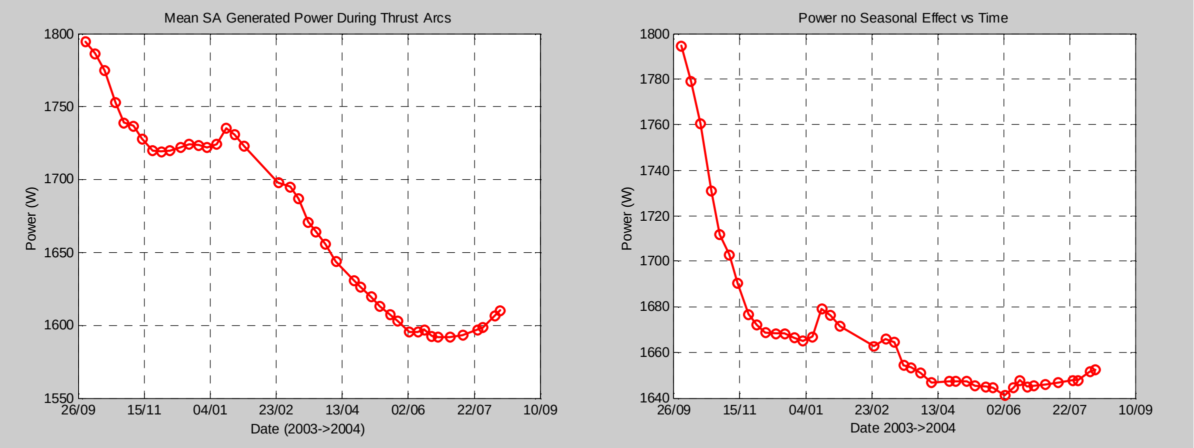

Figure 11 SA power in the first year of operations

These results show a reduction in SA generated power of ~8% due to Van Allen belt passage, which includes the effect of a very large X-class 'Halloween' solar flare in October 2003. After moon capture, the trend becomes a little more complex, as the lunar orbit superimposes a higher frequency modulation to the spacecraft-sun distance. This can be seen in the figure below, where the purple line is the modelled trend and the blue points show spacecraft data (unfiltered). This type of analysis was used to select appropriate power levels for the thrust, which were then used by flight dynamics team to propagate the orbit.

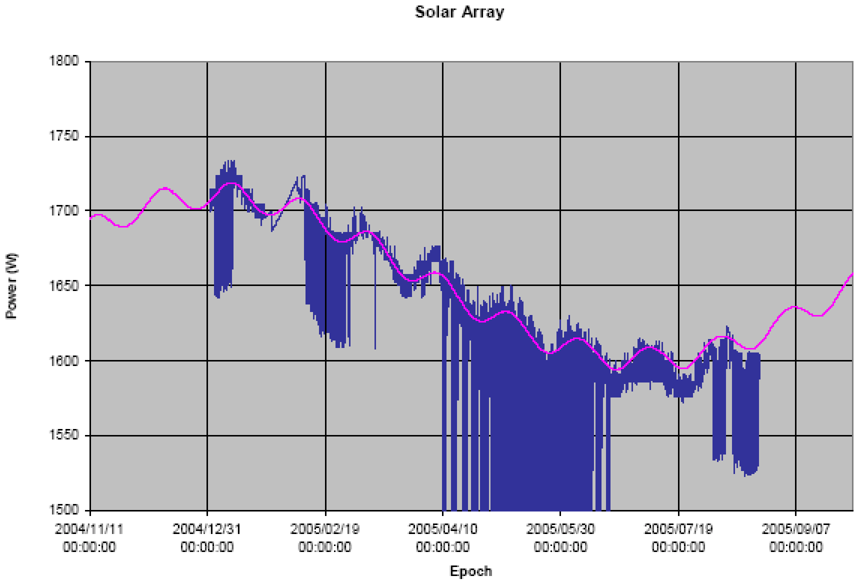

Figure 12 Predicted and measured SA power

III. Conclusion

Due to favourable thruster and power subsystem performance, and an efficient orbital transfer strategy, the SMART-1 mission trajectory was fine tuned in flight to produce a shorter transfer time, an improved lunar science orbit and a mission extension (via an additional re-boost phase). On the 11th November 2004, SMART-1 passed into the primary influence of the moon and made history with several notable firsts, including being the first Electric Propulsion mission to escape Earth orbit, the first to use Electric Propulsion to enter into orbit around another celestial body, and Europe's first Lunar mission. SMART-1's primary mission goal has been successfully achieved, and in addition to this, a set of advanced low pressure Electric Propulsion operations were developed and executed which enabled the residual xenon mass to be reduced from 1.8kg to only ~280g. This has made possible a mission extension of excellent altitude and illumination conditions for Lunar science. In achieving these goals, the engine has performed at total of 844 ignitions, firing for a total accumulated time of 4958 hours. The longest continuous thrust, of 240 hours, was performed in the Van Allen Belt Escape phase, when the initial eclipse season ended. The accumulated thrust time and maximum pulse length are both records for this time of thruster. SMART-1 is the first mission to use primary electric propulsion to orbit raise through the Earth's radiation belts. This was executed in conjunction with an improbable occurrence of a major solar flare at the end of October. The measured reduction in generated power caused by radiation belt passage was found to be around 8%. Even under these challenging conditions, operation of an SEP spacecraft orbit raising through the radiation belts has been successfully demonstrated. On 17th September 2005, SMART-1 Electric Propulsion operations were terminated, bringing to an end the EP aspect to a highly successful mission. The mission extension lunar science operations are now being executed, up until a lunar impact predicted to occur on 17th August 2006.

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