Spacecraft/thrusters interaction analysis for Smart-1
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Abstract: **The first of the ESA's SMART missions (Small Missions for Advanced Research in Technology), SMART-1, is a small lunar orbiter devoted to the demonstration of innovative and key technologies for scientific deep space missions. A highly innovative and low budget mission to explore the Moon, SMART-1 was launched on the 27th of September 2003 as an Ariane 5 cyclade-like auxiliary payload and uses a Hall thrusters (PPS1350) built by SNECMA. On 13 November 2004, Smart-1 reached the Moon capture point, 60000 km from the lunar surface. The amount of propellant required to transfer the spacecraft from GTO (650 km perigee and 35880 km apogee) to a Moon orbit (300 km over the lunar south pole and 3000 km over the lunar north pole) has been of 75 kg of Xenon. The life of SMART-1 has been extended 1 year until mid 2006. SMART-1 will serve as test-bench for other missions using EP.**

The possible plume interaction effects of the PPS1350 on the SMART-1 spacecraft are being assessed by means of several diagnostics: the Electric Propulsion diagnostic Package (EPDP) and the Spacecraft Potential and Electric fields and Dust Experiment (SPEDE).

The diagnostics on-board any spacecraft using electric propulsion will only give punctual values. Therefore, it is important to develop models that permit to forecast the effects of the use of such thrusters in the whole spacecraft.

The data collected in this flight experiment will be used not only to assess the impact of using electric propulsion on board satellites but furthermore to validate modelling tools which will be employed in a full characterisation of the impact of using this technology in space.

Nomenclature

EP	=	Electric Propulsion
EPDP	=	Electric Propulsion diagnostic Package
SPEDE	=	Spacecraft Potential and Electric fields and Dust Experiment
GTO	=	Geostationary Transfer Orbit
UCRP	=	Cathode Reference Potential

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I. Introduction

Electric propulsion with high specific impulses, one order of magnitude higher than chemical propulsion in some cases, allows huge amount of propellant savings when the deltaV is high enough. On interplanetary missions with high deltaV, replacing or augmenting chemical propulsion with electric thrusters as the primary propulsion system may introduce the following benefits:

- an increase in net payload mass (enable missions otherwise impossible)
- a reduction in flight time with respect to mission based on chemical propulsion and complex gravity assisted operations (reduction in mission operation costs)
- Independence from launch window constraints, which are imposed by the classical gravity-assisted planetary fly-by operations (increase of the mission scientific objectives)
- Possibility to use small/medium launch vehicles (substantial launch cost savings).

SMART-1[1,2] has the Electric Propulsion diagnostic Package (EPDP) and the Spacecraft Potential and Electric fields and Dust Experiment (SPEDE) that monitor the Hall thruster plume interaction effects on the spacecraft [3].

The experiments are aimed to obtain information on the possible interaction of the thruster with the rest of the spacecraft subsystems.

The main possible effects introduced by the operation of the Hall thruster are:

-Physical: erosion, deposition of material on all the surfaces impacted by the plasma and redeposition of eroded materials on the surrounding surfaces.

-Mechanical: perturbation torque due to the beam swirl around the thrusters axis, or due to the impact on spacecraft surfaces and thrust vector variation or divergence of the beam.

-Thermal: increment of surfaces temperature.

-Electrical: surfaces potential changes due to the operation of a plasma beam; electromagnetic effects due to the on-off thruster operation, and RF interference with the spacecraft antennas operation.

Ground testing of these engines requires vacuum chambers. To minimise the influence on the beam characteristics, the chamber has to be big enough and a sufficient low vacuum must be achieved and maintained. In this case, ground measurements have to be carefully interpreted because they do not fully reflect to space conditions. The deviations can be as high as several orders of magnitude. Moreover, ambient space environments (solar winds, LEO, GEO, etc.) or the impact of the full spacecraft geometry on the measurements cannot be simulated in vacuum chambers. Therefore data provided directly from space is needed in order to proceed to a full characterisation of the impact of using Hall thrusters on a spacecraft [1,2]. Modelling and comparison of the thruster and spacecraft/environment interactions is the most complete way to get a deep insight into this problem.

An artist view of the SMART-1 spacecraft, propelled by its electric propulsion thruster, is shown in Fig.1.

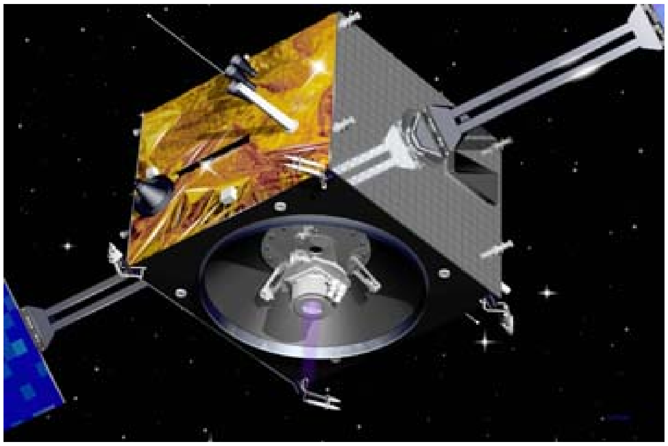

Fig.1 – The SMART-1 Satellite

II. Diagnostic packages in SMART-1

A. EPDP

The Electric Propulsion Diagnostic Package is operating during thruster start-up and during nominal firing. This operation mode at various frequencies allows monitoring the effects on the spacecraft due to the operation of electric propulsion [3].

The location of the EPDP in the spacecraft is of vital importance. The geometrical position where this experiment is placed, at the bottom panel of the spacecraft at about 0.5 m from the thrusters, allows the collection of important data. The EPDP is located in the same plane of the thruster, thus only the backflow will be monitored. This backflow is formed mainly by charge exchange ions. Primary ions with high energy (below 300 eV) will not be directly monitored.

The following sensors compose the EPDP in SMART-1:

Retarding Potential Analyser (RPA):

This sensor measures very accurately the ion energy at the location of the probe and allows the deduction of the plasma potential at the position within the beam where the charge-exhange ions are generated..

This sensor is located parallel to the thruster with its axis oriented towards the thruster, therefore only the ions that reach the sensor are measured. The plasma beam is composed of high and low energy ions. The first ones will not be measured by this sensor because its position is too far from the beam in SMART-1 and these ions **(**300 eV**)** are so fast that they will not come back to the spacecraft. The only way to observe these ions was introducing the RPA inside the beam, but this was not possible in Smart-1.

The ions that are measured with this sensor are the low energy charge exchange ions **(***up to a few tens of eV***)** mainly responsible for the backflow interaction.

The measured current distribution and energy of these ions will allow the investigation on the erosion of surfaces, deposition of the eroded material and electrical effects.

Langmuir Probe (LP):

This sensor produces and current-voltage scan and allow the deduction of the probe floating potential, the plasma potential, and the electron density and temperature.

The charge-exchange ion trajectories will be determined by the potential distribution around the spacecraft created by space charge effects. Therefore it is extremely important to have a measurement of the electron density in a monitored area when the thruster is firing. Most of the present spacecraft/environment models assume a Boltzmann distribution of the electrons (e.g. Samanta Roy, 1996). This flight will allow to analyse the real electron behavior without the constraints of the vacuum facilities and will help to adjust the theoretical models that once validated will be a powerful tool for the spacecraft system designers**.**

Solar cell and Quartz crystal microbalance (QCM)

These sensors will be used as deposition material sensors, providing real data on the amount of material deposited on the sensors. Once the deposition rate of the material is known, then it will be possible to calculate the effect of deposition on thermo-optical and electrical parameters of different materials etc.

Figure 2 shows the position of the EPDP with respect to the thruster.

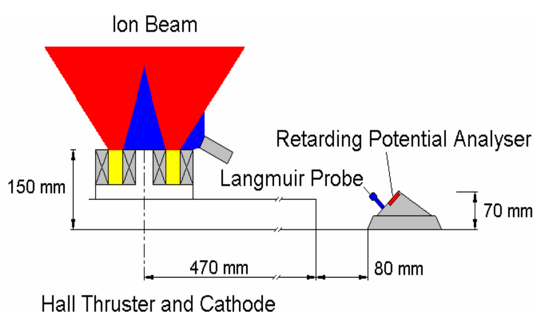

Figure 2-LP and RPA geometrical position.

B. SPEDE

SPEDE experiment has two electric sensors of cylindrical shape mounted on the ends of two 60 cm. booms. Each sensor can work either in a Langmuir (LP) mode or in an electric field (EF) mode. When operated in an EF mode, the sensor is current-biased, and both the spacecraft potential and wave electric fields can be monitored. Large variations in the spacecraft potential affect the charge exchange ions distribution. These measurements will aid the analysis of possible contamination detected by the solar cell sample and the QCM.

Using the potential measurement of an EF sensor and the electron temperature from the EPDP Langmuir probe, we can estimate the charge-exchange ion density.

In an LP mode, the sensor is voltage biased to monitor the variation of electron flux. An increase of the electron flux would also indicate the presence of charge exchange ions in a quasi-neutral plasma. The relative position of the booms with respect to the thruster and to the neutralizer has been an important issue that has been assessed during the data analysis exercise.

III. Data Analysis

A. Plasma effects

The low energy plasma environment of any spacecraft is determined by several factors including the ambient plasma environment, the number of photoelectrons from the spacecraft surface, the spacecraft surface potential and the size of the spacecraft compared to the Debye length. For a spacecraft with electric propulsion, additional contributions have to be taken into account: high energy primary ions of the plasma beam and a low energy charge exchange ion population (in the order of tens of eV).

When the electric thruster is turned on or off, variation of the floating potential on the spacecraft surface and possible transients may occur. As a spiral orbit raising phase in the Earth's magnetosphere is part of the mission, different ambient plasmas may vary the spacecraft potential. This influences the impact energy of charge-exchange ions on the spacecraft surface.

Important parameters to be monitored are: the spacecraft potential and the plasma environment. The EPDP package provides information on the plasma environment near the thruster while SPEDE diagnoses the plasma on the opposite side of the spacecraft.

Part of the slow charge-exchange ions flow back to the spacecraft due to the potential distribution in front of the thruster. The impact of high energy beam ions on the ceramic discharge surface create sputtered material (metals or ceramics) which go into the plume. Both propellant and non-propellant effluents can cause contamination of optical sensors, multi layer isolation blankets, solar arrays etc and is a potential concern when using electric propulsion systems.

In Hall thruster systems such as PPS-1350, the contamination due to charge-exchange ions is far dominant. Assuming that all sputtered discharge wall material is charged, the resulting current would be three orders of magnitude below the beam ion current. Hence, the present analysis neglects non-propellant contamination.

B. LP and RPA information analysis

In the vicinity of the thruster exit, the thruster plume will dominate the spacecraft environment by many orders of magnitude. The EPDP is placed in the same plane of the thruster, thus only the backflow will be investigated, primary ions with high energy will leave the spacecraft and will not be monitored directly by the diagnostics on board. The measurements of the current density and ion energy near the thruster by means of the RPA will allow us to characterize the backflow in this region of the spacecraft. If the energy of the charge exchange ions is high enough could sputter the materials where they impact.

C. Deposition sensors information analysis

The final goal of all EPDP contamination analysis is not to evaluate the mass deposit on the spacecraft surfaces but rather to estimate their effects on the surface properties. The main contamination surface effects are:

- Modification of the thermo optical properties of surfaces.
- Degradation of mechanical properties such as cratering of the surface, mechanical and chemical erosion etc.
- Modification of electrical properties of surfaces.
- Output power reduction for solar cells.

A solar cell placed away from the solar panels monitors the deposition rate of various contaminants. The housekeeping data from the two main spacecraft solar generators are also monitored and compared with the data coming from the solar cell. The data are used to assess the impact of using a Hall thruster in different areas of the spacecraft. In order to be able to distinguish between the effects coming from thruster operation and the normal cell degradation due to radiation, a thorough study of the solar cell degradation on other spacecraft not using electric propulsion must be carried out. Several models of solar cell degradation at ESTEC are used to assess this issue.

The deposition of material in solar cells can be especially troublesome, and accurate computation of the degradation in power output is non trivial. The solar absorptance of the deposit is a factor as well as the reduction in transmittance due to the deposit and reflections at the interface between cover slip and deposit layer. Absorptance by the deposit raises the temperature and reduces the efficiency of the solar cell. Once the deposition material quantity for a specific period of time in a defined geometry is known, it is possible to calculate the amount of material that will be deposit in any part of the spacecraft and to deduce the changes in performance characteristics of solar cells, thermal coats etc.

A QCM sensor will add direct information on the deposition rate at the instrument area of the spacecraft.

D. Complementary information sources analysis:

ACS (Attitude Control System). These ACS measurements will include contribution from many factors: thrust misalignment with spacecraft's center of mass; thruster plume instabilities and plume impingement on any spacecraft's appendages (if any); AOCS thrusters operation; variation of the spacecraft's centre of mass and solar array rotation. It will be part of the analysis to distinguish between the contribution to the ACS telemetry coming from the thruster operation and the other effects.

-Telemetry of the on board antennas will be analyzed to monitor possible perturbation of the communication signal when the thruster is on and off. The plasma density around the spacecraft during the use of electric propulsion may be high enough to disturb the signals. Signal phase shifts, if any, can be calculated from electron density profiles obtained by Langmuir probes and then correlated with the telemetry monitored during SMART-1 operation.

-Payload data obtained during the operation of the thruster may also be analyzed to study possible disturbances due to thruster operation.

-Thruster telemetry will be analyzed to monitor possible thuster behaviour due to different environment such as solar wind plasma, eclipses, etc.

-Thrust profile can be deduced using the radio science experiment by calculating the orbital parameters.

-Thermistors telemetry is used to assess the thermal behaviour of the spacecraft during the thruster operation and its operational transients.

E. Mathematical Models

As the measurements of the diagnostics at Smart-1 are always punctual, it was necessary to develop some tools that would allow understanding the whole spacecraft thruster interaction. ESA together with Snecma, Proel, ARC, FMI, Alta and CNES are currently developing several models to assess the plasma environment around the spacecraft. Mathematical models devoted to the electric propulsion plume-spacecraft interaction have been developed and are currently being used to assess all the issues by ARC, Alta, ESA and CNES[4].

These models are being validated with data coming from space and also from ground tests done at Pivone and Laben facilities. The comparison between the data on ground and in space will allow us to tune the models and understand better the differences between space and ground.

F. Thruster behaviour:

The thruster has accumulated almost 5000 hours of operation at the date of writing. The parameters are all correct and are well within specifications. However, several OSETs (Optocoupler Single Event Transients) have caused unexpected but harmless thruster power supply shutdowns [5,6,7]. The optocoupler is one of the isolation components present in the power electronics, needed for the SMART-1 variable power function. A software patch has been uploaded on SMART-1 in February 2004 to automatically detect OSETs and restart the EPS. The lesson learned is that, in the case the variable power feature is needed, a minor change in the software logic is required for that power conditioning unit in order to become insensitive to the consequences of the optocouplers S.E.T.

Since the beginning of the mission, a very low discharge oscillation in the anode current has been observed on SMART-1; its magnitude is 10 times smaller than what is measured during lifetesting in a vacuum chamber. Furthermore, its evolution along life shows a very different behaviour than observed during ground testing. Possible reasons for this effect could be related to:

-The presence of lower discharge power on Smart-1 than during lifetime tests
-The absence in space of deposition of sputtered materials from the vacuum chamber onto the ceramic discharge channel walls.

Nevertheless, these arguments need to be confirmed by specific studies since the influence of deposition, operating point etc. on the evolution of thruster characteristics along life is far to be fully understood. Comparision with flight data from other spacecrafts using the same technology will also be made.

These low oscillations levels have a beneficial impact in the thrust, and needs to be forecasted by the spacecraft control system in order to define the right thrust profile required to fulfill the mission propulsion requirements. This effect has pointed out the need of having means of deducting the instantaneous thrust at spacecraft level.

A variation of the rms-value of the discharge current oscillations has been observed during the thruster life. This variation induces modifications of the position of the ionization zone within the thruster channel, which in turn slightly affects.the energy of the charge exchange ions..A preliminary correlation with the energies of the charge exchange ions measured at the EPDP has been done. This work is ongoing in the frame of one of the two working groups set at ESA to assess the flight data of Smart-1.

G. spacecraft and plasma potential:

The plasma and floating potentials of the cathode are monitored by means of the EPDP (Langmuir Probe) and the Cathode Reference Potential (CRP) of the thruster and both sensors detect similar variations:

- The plasma potential is always a rough constant value above the cathode potential
- On ground test, the test facility electrical ground is always a rough constant value above the floating potential of the cathode (this constant depends on the discharge voltage of the thruster)

The main conclusion is that the plasma potential in flight plays the same role as the test facility electrical ground for the ground test.

The floating potentials on the cathode vary from negative to positive along the orbit (from –5V to +10V). On ground this potential was always negative (-20V). A possible explanation for this variation is an interaction of the solar array interconnectors with the plasma. This contribution of the solar panels with solar cells interconnectors (biased at 50V) in the presence of a plasma and their impact on the spacecraft potential is also being taken into consideration as a possible explanation when analyzing the variation of the plasma potential along the orbit. The relative position of the solar array to the thruster plasma governs the electron current collected by the spacecraft. The variation of the magnitude of the collected electron current then determines the floating potential.

The modeling results of ARC confirm that the solar array side at 50V will collect more current when this side is looking at the thruster backflow than when this side looks at the opposite direction. This is due to the fact that the electrons will be attracted by the solar array interconnectors. When the solar array side at 0V faces the thruster backflow, this side will collect a lower electron current.

Another important fact to be considered on this issue is that the thruster is mounted on a thruster alignment mechanism that is currently changing around 4 degrees to keep the spacecraft center of gravity. This information should be taken into account when analyzing the charge exchange ions density distribution and the variation of the plasma potential because the density of charge exchange ions will change depending on this variation.

On the other hand the in-flight data shows generally that the spacecraft potential with respect to the cathode starts to decrease when the cathode heater start to heat the emissive element (LaB6 crystal) about one minute before ignition; the explanation is the electron thermo-emission (the discharge voltage, 220 V, is applied between anode and cathode 170 seconds before ignition). This effect could induce a better starting potential at spacecraft level previous thruster ignition. The group will investigate this effect that could give information for a new strategy for thruster ignition.

EPDP has observed a drop in the floating potential of 10 V from eclipse to sunlight. Nevertheless a lot of work should be performed to extract the right plasma and spacecraft potentials for the different mission phases. During this assessment is very important to have the right thrust performances characteristics correlated with the EPDP and SPEDE acquisitions.

Due to the operational range of the experiment, SPEDE can only see plasma potential variations bellow +-14 eV. Nevertheless this is a good approximation to the upper limit of the plasma potential observed until now by other means.

It has been observed that the current in the –X panel probe is higher than the one in the +X panel. The current obtained by the probes depends on the probe potential. SPEDE team now is trying to correlate the EPDP measurements of the plasma potential and the cathode reference potential at the thruster in order to understand their influence on the current at the SPEDE probes. On ground and in space it is clear the existence of a difference in current between the two probes. The position of the cathode more closed to one of the probes could be the reason for this difference. In case it is demonstrated that this is the case, we could conclude that more electrons will go to the probe that is closer to the cathode.

Finally, it has been observed that the plasma potential and the floating potential increase when rising the power of the engine.

H. Backflow: charge exchange ions

A typical RPA profile from EPDP shows that there are two species of charge exchange ions with energies around 35eV and 65 eV (see figure 3). The first ones are dominant and are the ones that were expected; the second group is presumably due to double charged ions although several explanations can be proposed for its existence (accelerated double charge ions or product of collisions between several species of charge exchange ions).

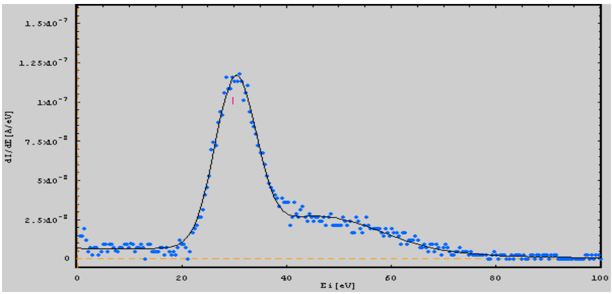

Figure 3: species of charge exchange ions

It was also concluded that we should look at the variation of the charge exchange ions thrust density with different thrust levels. This will permit to observe any possible change of mass efficiency with thrust. Furthermore, any change of ion energy should be correlated with the variation of thruster voltage to assess the possible explanation of accelerated charge exchange ions coming to the RPA at different ion energies.

about The second peak can have several possible sources, which are currently being investigated. This can be explained by the fact that the RPA reference potential is given by the satellite floating potential and in fact accelerates the incoming ions by a corresponding amount before collecting them. The primary peak of CEX energy within the plasma plume is therefore to be considered around 18 V, consistently with the results from preliminary simulations [8], that had the satellite floating potential set to 0 V (Figure 4).

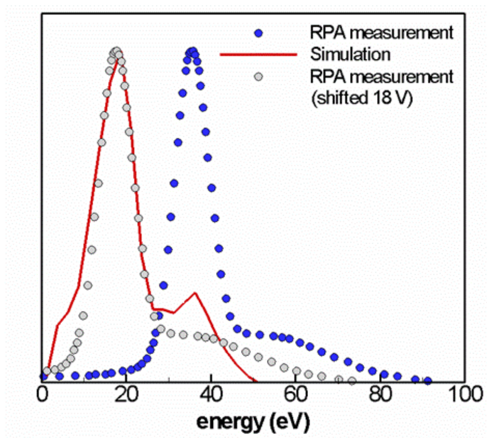

Figure 4: comparison between simulated RPA and measured values

According to an ALTA model the magnitude of the secondary peak depends on the assumption on double charged ions percentage as well as the reference electron temperature if an adiabatic expansion model for electron is used. As the computed plasma voltage depends on the assumptions on satellite potential, and plasma potential at the exit of the acceleration channel, it is clear that all the models should investigate these phenomena using the same assumptions to allow a good comparison. Further work should be performed to extract the right plasma and spacecraft potentials for the different mission phases. During this assessment is very important to have the right thrust performances characteristics correlated with the EPDP and SPEDE acquisitions.

Fits of the EPDP Langmuir probe current-potential relation were found meaningful even when the thruster was switch-off (but only for the electronic branch of the current-potential curve). The approach applied to the determination of the particle density, temperature and spacecraft potential are consistent with findings from Alta using a complete 3D code with particle ions and electrons and suggest that the probe is located in the sheath region with a slight imbalance of ion and electrons.

The values of the backflow electron temperature vary from 0.5 to 0.7 eV. The electron density is in the range of 1.5 to 2 $*10^{13}$ m^3. The ion density is between 6.5 and 7 $*10^{13}$ m^3. These values are within the forecasted values.

The value of the QCM and the solar cell will be analyzed in more detailed during the following months. A historical data acquisition will allow a clear picture of the sputtering and deposition effects. The effects observed up to now demonstrated that very little deposition material coming from the erosion processes has been found.

IV. Conclusions

The main results highlighted during the assessment of the data coming from Smart-1 are the following:

-EPDP and SPEDE have provided important data which has been used together with the cathode reference potential to derive the plasma reference potential.

-UCRP takes values varying between –5 V and + 10 V during thruster operation, compared to –20 V during ground testing. Solar array interconnectors interaction with the environmental plasma contribution is the main effect that can explain the periodic variation of the spacecraft potential.

- Local plasma is the real reference for the cathode operation and the whole propulsion system is floating w.r.t. this reference with a value that has been correlated.

- The two peaks in energy obtained with the RPA of the EPDP are now well explained. The first peak around 35 eV is well understood at space and ground. The second peak at higher energies (around 65 eV) can be explained by the dynamics of double charge exchange ions. The difference with respect to the foreseen values is due to RPA ground potential which coincides with the floating potential. At these energies some materials could be eroded.

- The data coming from the solar cell and the QCM demonstrate that the amount of eroded material is very low. The degradation of the cell is lower than expected as was also seen at the main solar arrays

- The modelling tools, validated with space and ground data, used during this process have allowed understanding better the phenomena involved and will be used for spacecraft designers in the development of future EP satellites.

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