Measurements of SMART-1 Plasma Environment with the EPDP Langmuir probe

B. Thiébault [(1)], A. Hilgers [(1)], M. Capacci [(2)], E. Gengembre[(1)], and J. Gonzalez[(1)]

(1) Space Environments and Effects Section (ESA-ESTEC/TEC-EES),
Keplerlaan 1, 2200 AG Noordwijk, The Netherlands
(2) Laben, Firenze, Italy.

Abstract

SMART-1 is the first spacecraft of the European Space Agency using a plasma engine as a main propulsion system. SMART-1 successfully reached a moon orbit in December 2004. It is also equipped with various plasma diagnosis instruments to study the electrostatic environment of the thruster and its potential impact on the spacecraft. Measurements from the EPDP plasma instruments are analysed when the electric thruster is operated and calibration is performed by comparing with other instruments. Characteristics from the charge exchange plasma are presented and it is shown that the spacecraft potential is floating within 10-30 volts negative with respect to the plasma.

1. Introduction

SMART-1 -'Small Missions for Advanced Research in Technology'- is the first mission of the European Space Agency's Science Programme to test new technologies that will eventually be used on larger projects. Its primary objective is to test Solar Electric Primary Propulsion through a mission representative of a deep-space one. The planetary objective selected for the SMART-1 mission is to orbit the Moon for a nominal period of six months. It is the first time that Europe has sent a spacecraft to the Moon. In addition to test the use of solar electric propulsion as a primary propulsion system, the spacecraft will carry out a complete programme of scientific observations in lunar orbit. SMART-1 was launched successfully as an Ariane-5 auxiliary payload on 27 September 2003. The solar electric primary propulsion on-board SMART-1 is a Stationary Plasma Hall-effect thruster, the PPS-1350 developed by SNECMA, France. This is a stationary plasma thruster (SPT) with a chamber diameter of 100 mm, a maximum discharge power of 1.5 kW and a minimum demonstrated discharge power of 480 W. Using the thrust of the electric propulsion system, SMART-1 progressively expanded its orbit, spiraling out from Earth and entered lunar orbit on 15 November 2004, nearly 14 months after launch.

There are some concerns that the use of electric propulsion could give rise to undesired effects such as the contamination of surfaces due to the deposition of sputtered material, and the degradation of surfaces due to erosion caused by ion impingement. Therefore, the prospects for a massive utilization of electric propulsion on present and future scientific satellites have, as a pre-requisite, the necessity to demonstrate mission compatibility with impacts on the spacecraft sub-systems. The main effects of the operation of a Hall thruster are physical, mechanical, thermal and electrical. The plasma can cause erosion and deposition of eroded material on surrounding surfaces. The beam impact on spacecraft surfaces can produce torque and variations in the thrust vector. Surface temperatures can rise. Surface potentials may change and electromagnetic effects can be induced by the on-off operation of the thruster and produce radio-frequency interference to, for instance, the spacecraft antennae. Ground measurements of such effects in vacuum chambers do not fully reflect space conditions and the true spacecraft geometry cannot be simulated. Real space flight data are therefore essential. The Electric Propulsion Diagnostic Package (EPDP) will monitor these effects.

2. Plasma Diagnostic Package, EPDP

The objective of the EPDP experiment on SMART-1 spacecraft is a comprehensive characterisation/evaluation of the "plasma" interactions between the electric propulsion system and the S/C exposed parts/surfaces. Data collected from this experiment are considered essential to assess and confirm the electric propulsion technology full viability, for an extensive utilization on near future European scientific exploration satellites. The package consists of a number of sensors allocated in different boxes. A Retarding Potential Analyzer (RPA) measures the ion energy and current density distribution. The ions that are measured are those of low energy mainly responsible for the backflow contamination. With the resulting data, designers of future space science missions will be able to optimise the position of thrusters and payload instruments for spacecraft of different shapes. A Langmuir Probe (LP) measures the plasma potential and the electron density and temperature. It gives information on the plasma conditions at one side of the spacecraft, whilst another probe (from another experiment, SPEDE) gives similar information on the opposite side. Using single point measurements, 3D representations of the environment will be possible. EPDP also includes a Solar Cell (SC), placed away from the spacecraft's solar array, and a Quartz-Crystal Micro-Balance (QCMB) which is both used as deposition material sensors, providing real data on the extent of contamination. A close view at the EPDP instrument is presented in Figure 1.

Figure 1: Close view of the EPDP assembly including a Langmuir probe and the RPA.

The Langmuir probe is truncated sphere of diameter 7.5 mm mounted on a few centimeters long support (cf Figure 1) and located on a face of the spacecraft perpendicular to the electric thruster plume direction (cf Figure 2).

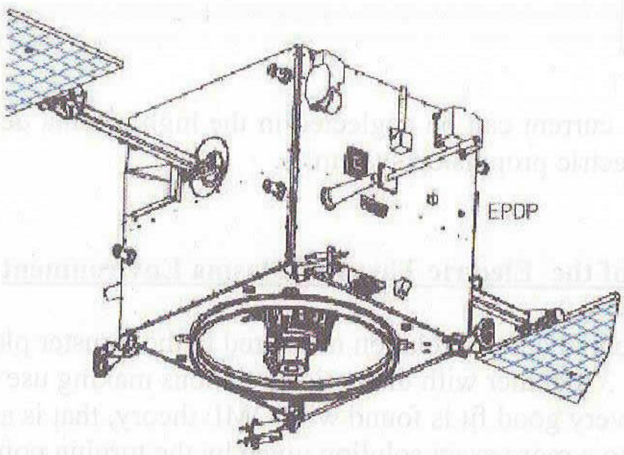

Figure 2: View of the location of EPDP assembly including a Langmuir probe and the RPA.

3. Method for data inversion

The derivation of plasma parameters from EPDP Langmuir probe is based on the determination of the current potential relation. For Langmuir probes it is often possible to use simplified current formulas valid in principle in two limiting cases: (1) the orbit motion limited case (OML) studied by Mott-Smith and Langmuir [1926] and (2) the sheath limiting case studied by Langmuir and Blodgett [1924].

In the two limiting cases mentioned above, the current collected on a spherical conductor from ambient particles of charge q can be expressed as:

$$\begin{cases} q\phi > 0 \Rightarrow I_q = n_q \times V_q \times q \times S \times \exp\left(\dfrac{q\phi}{kT_q}\right) \\ q\phi < 0 \Rightarrow I_q = n_q \times V_q \times q \times S_{eff} \end{cases}$$

where V_e is the electron thermal velocity: $V_e = \sqrt{\dfrac{kT_e}{2\pi m_e}}$ and V_i is can be either the ion thermal velocity or the drift velocity (in a meso-thermal regime) and n_e and n_i are the electron and ion density. S is the surface of the collector and S_{eff} is the effective collection surface.

In the so-called sheath limiting case the effective collection surface is the electrostatic sheath [Langmuir and Blodgett, 1924]. These authors also described an approach to derive an estimate of S_{eff}. In the orbit motion limited regime Mott-Smith and Langmuir [1926] have shown that S_{eff} can be expressed as:

$$S_{eff} = S \times \left(1 - \frac{q\phi}{kT_q}\right)$$

The photo-electron current can be neglected in the high plasma density environment generated by the electric propulsion system.

4. Measurements of the Electric Thruster Plasma Environment

An example of potential current relation measured in the thruster plasma environment is shown on Figure 3 together with theoretical relations making use of Langmuir probe formulas. A very good fit is found with OML theory, that is also shown to be close, in this case, to a more exact solution given by the turning point formalism (cf. e.g. Thiébault et al. [2004]). Plasma parameters corresponding to the best fit are given in Table 1 below.

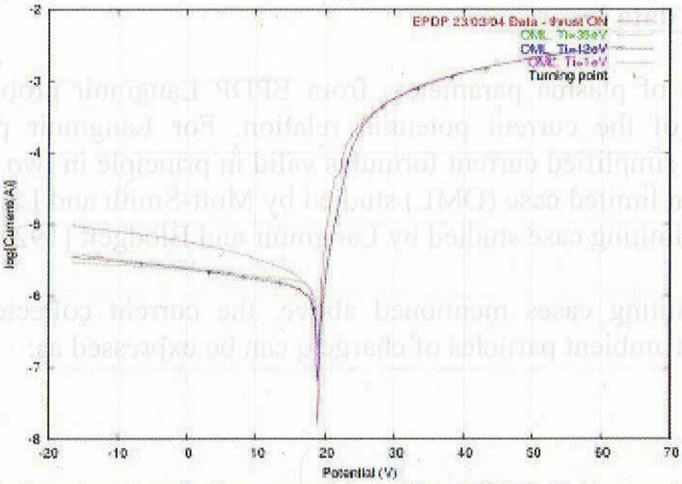

Figure 3: Potential current relation measured by EPDP Langmuir probe in the plasma thruster environment and fitted with OML based theoretical models and the more exact turning point model.

Table 1: Parameters corresponding to the best fit found in Figure 3.

Electron temperature	Te	1 eV
Electron density	N_0	$1.55\ 10^7\ cm^{-3}$
Ion drift energy	Ei	12 eV
Spacecraft potential	F	-23 V

It can be noted that the electron density found is close to what is predicted by numerical methods (cf e.g., Hilgers et al. [2005]). The ion drift energy is due to the acceleration of the charge exchange ions by the electric field in the plume where the ion is generated. The spacecraft potential is a priori shielded by the plasma with a short distance (of a few millimeters). However, since the RPA is on the spacecraft wall one can expect that ions will be detected with a total energy of 32 eV. It can be verified on Figure 4 where RPA are shown that there is a peak in energy around 30 eV.

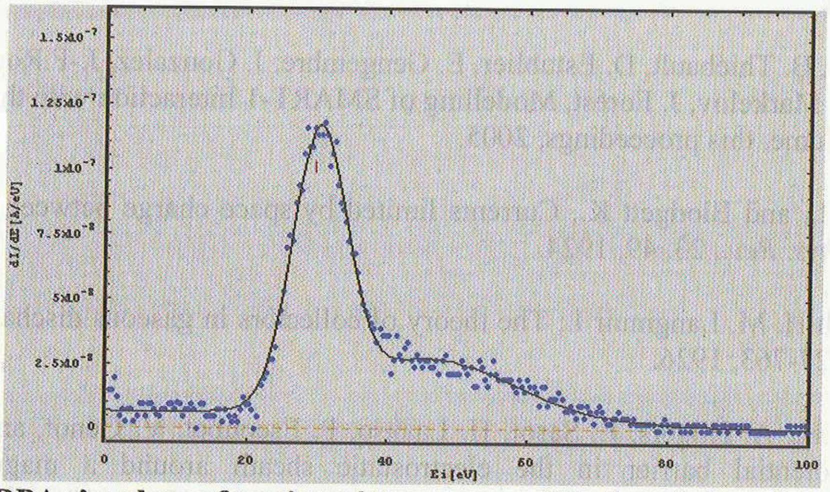

Figure 4: RPA signal as a function of the energy of the ions detected and showing a peak in energy around 30 eV.

RPA data can be analysed for systematic study of the plasma parameters. An example of time series analysis of the spacecraft potential is shown on Figure 5 below. It can be seen that the spacecraft potential varies considerably in the range from –10 to –30 Volts.

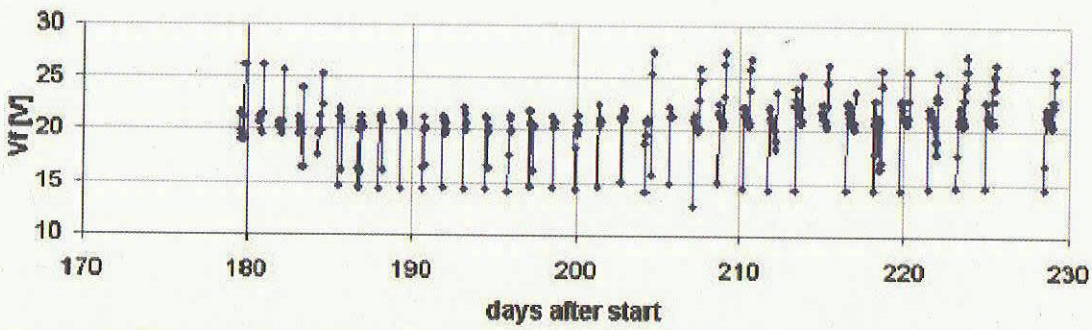

Figure 5: Time series of the absolute value of the floating potential on SMART-1 as a function of time spent in orbit. The actual values are negative.

5. Conclusions

Plasma measurements made by the plasma diagnostic package EPDP have been examined to characterise the charge exchange plasma generated by SMART-1. It is shown that the spacecraft potential is floating within 10-30 volts negative with respect to the plasma.

Acknowledgments

This study has been performed in the frame of the Spacecraft Plasma Interaction Network in Europe (SPINE) activities (cf. www.spis.org). We acknowledge useful discussions with the participants of the 8th SPINE workshop (December 2004).

References

Hilgers, A., B. Thiébault, D. Estublier, E. Gengembre, J. Gonzalez, J.-F.Roussel, M. Tajmar, G. Markelov, J. Forest, Modelling of SMART-1 Interaction with the Electric Thruster Plume, this proceedings, 2005.

Langmuir I., and Blodgett K., Currents limited by space charge between concentric spheres, *Phys. Rev.*, 23, 49, 1924.

Mott-Smith H. M, Langmuir I., The theory of collectors in gaseous discharges, *Phys. Rev.*, 28, 727-763, 1926.

Thiébault, B., A. Hilgers, E. Sasot, H. Laakso, P. Escoubet, V. Génot, and J. Forest (2004), Potential barrier in the electrostatic sheath around a magnetospheric spacecraft, *J. Geophys. Res.*, *109*, A12207, doi:10.1029/2004JA010398.