Modelling of SMART-1 Interaction with the Electric Thruster Plume

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Abstract

Results from SMART-1 plasma measurements indicate that the spacecraft is in general floating 10 to 30 Volts negative with respect to the ambient plasma. An analytical model based on the interaction of the charge exchange plasma with the spacecraft and the solar panels is shown to be in good quantitative agreement with most of the observations. Progress for simulating the overall interaction between the thruster plume and the spacecraft by the use of PIC simulation codes is also presented.

1. Introduction

SMART-1 is the first mission of the European Space Agency to flight an electric propulsion system as a main engine. SMART-1 was launched successfully as an Ariane-5 auxiliary payload on 27 September 2003 and entered lunar orbit on 15 November 2004 after nearly 14 months spiraling out from Earth. 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.

SMART-1 was equipped with a plasma diagnostic package to especially investigate the impact of electric propulsion on the spacecraft surface (cf Thiébault et al. [2005]).

2. Observations

Onboard plasma measurements reported e.g. by Thiébault et al. [2005] in this conference gives evidence that SMART-1 ground potential is usually in the range between –10 and –30 Volts. It has been shown that the variation is well correlated with the solar panels orientation with respect to the thruster flow direction. The potential being most negative when the solar array is facing the direction of the electric thruster. The ambient particle environment has also been measured. Typical plasma parameters as measured in the vicinity of the spacecraft surfaces perpendicular to the thruster direction are reported in Table 1 below [cf Thiébault et al., 2005].

Table 1: Plasma parameters measured on surfaces perpendicular to the EP flow.

Ni	~10^{13} m^{-3}
Ne	~10^{13} m^{-3}
Ei	~12 eV
Te	~1 eV

2. Model

2.1 Phenomenology

It is suggested here that this potential fluctuation is mainly due to a 'wake' effect of the solar array in the back-flow of the charge exchange (CEX) plasma. The main elements of this model is sketched on Figure 2 below.

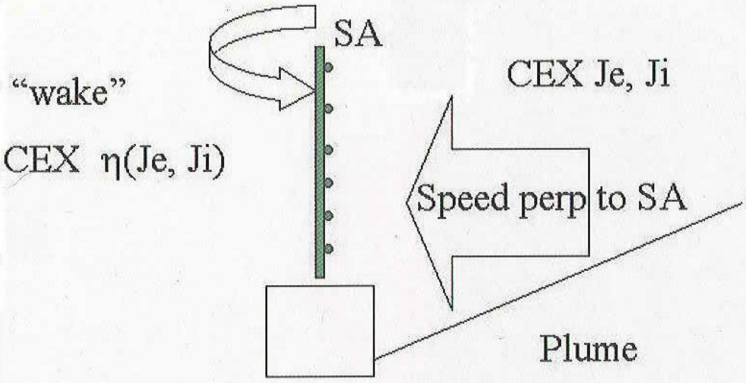

Figure 1: Sketch of the charge exchange plasma back-flow toward the solar array and of the 'wake' formation.

Charge exchange plasma is created in the main plume of the electric thruster engine and part of it is accelerated back to the spacecraft and the solar panel constituting the so-called back-flow. The solar panel is shielding part of this back-flow and as a consequence particle current densities perpendicular to the panel are reduced in the downstream region compared to the upstream one. Eventually, electrodes of the solar array tend to collect the highest electron current when it is facing the back-flow hereby driving the spacecraft potential negative. Quantitative estimates are attempted in the rest of the paper.

2.2 Solar panel 'wake' in the back-flow

Simulation of the thruster plume and CEX plasma expansion around a simplified spacecraft with dimensions relevant to SMART-1 has been performed using the SPIS software [Roussel et al. 2005, Forest et al. 2005, Hilgers et al., 2005]. For these simulations, a PIC description is used for the ions while electrons are assumed to be in a Boltzmann equilibrium. The simulations where performed using an unstructured mesh of about 30,000 tetrahedrons and 200,000 macro particles. The spacecraft hub and the rear of the solar panels were left at negative potential of –20 V while the front of the solar array was left floating. The case when the solar array is facing the back-flow is shown on Figure 2. The opposite case is shown in Figure 3.

It can be seen that depending on the orientation of the solar panel, the solar array with the interconnectors are immersed either in the back-flow with a density typically of 10^7 cm^{-3} or in the wake of the back flow with a density of the order of 10^3 cm^{-3}.

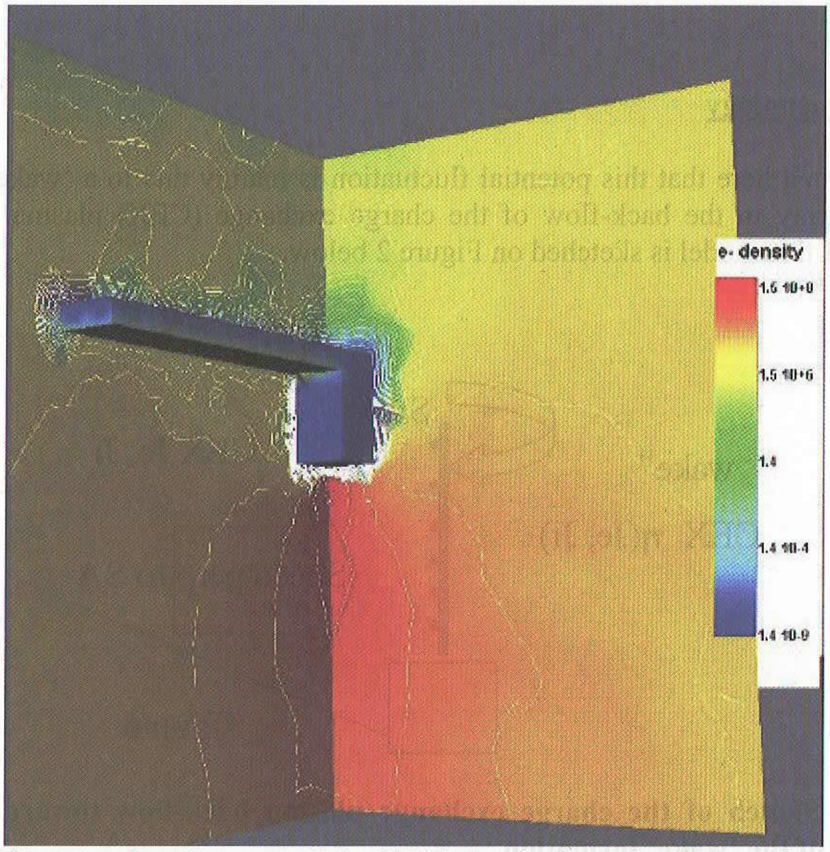

Figure 2: Electron density map of the SPIS simulation of a plasma flow around a simplified model of SMART-1 spacecraft with solar array facing the back-flow.

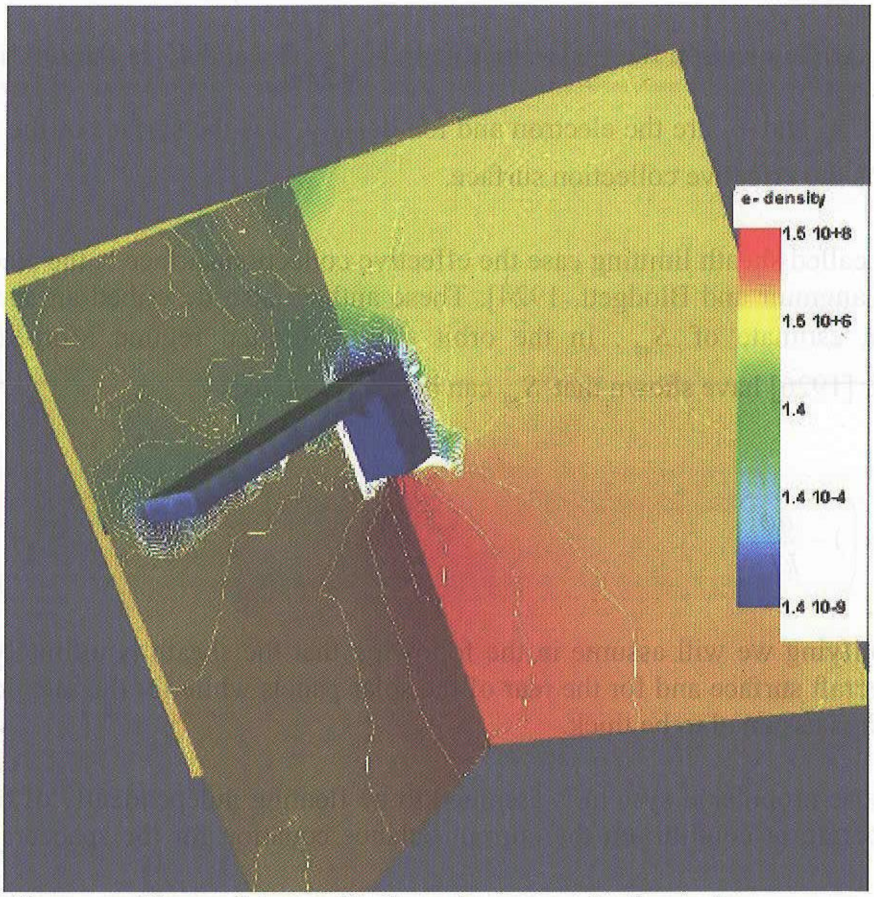

Figure 3: Same as Figure 2 but with the solar array in the wake.

2.3 Floating potential estimates

The floating potential estimate relies on the computation of the current collected by the conductive surface of the spacecraft. Given the very complicated geometry of the distribution of conductive and non-conductive elements on the solar array an accurate modelling of this current via simulation tools like SPIS would be very demanding and maybe impossible. Instead, rough estimates can be derived by using Langmuir probe formulas. The current collected by a surface S in a plasma can be estimated as a first approximation through the formulas of Langmuir and Blodgett [1924] for thin sheath and Mott-Smith and Langmuir [1926] for thick sheath. 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: $V_e = \sqrt{\frac{kT_e}{2\pi m_e}}$ and V_i is the ion back-flow speed 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:

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

For simplifying we will assume in the following that the sheath is infinitely thin for the spacecraft surface and for the rear of the solar panels while for the interconnectors the sheath is assumed to be thick.

The Electric propulsion system is assumed to be floating independently of the rest of the spacecraft. at equilibrium the current balance equation for the spacecraft can be written:

$$\Sigma I = I_{e1} + I_{i1} + I_{e2} + I_{i2} = 0$$

where I_{e1} and I_{i1} are respectively the currents of electrons and of ions collected by the solar array electrodes and I_{e2} and I_{i2} are respectively the currents of electrons and of ions collected by the spacecraft surface at ground potential (including the rear of the solar panels).

In reality the electrodes are at various potentials varying from 0 to +40 V with respect to the spacecraft potential, Φ. A further simplification is to assume all electrodes at the average potential Φ_B=20V with respect to Φ.

It is now straightforward to express the sum of the current ΣI as a function of the total collecting surface of the spacecraft hub, σ_s, and of the rear of the solar panel, σ_p, at ground potential, the total surface of the electrodes, σ_e, the ratio of density near the solar array in the wake and density facing the backflow, η, and to solve it for Φ.

Table 2: Parameters for the simulation of SMART-1 floating potential.

Hub surface R	σ_s	3 m^{-2}
Rear of solar panel surface	σ_p	10 m^{-2}
Total surface of interconnectors	σ_e	0.1 m^{-2}
Mean working voltage	Φ_B	20 V
Ratio wake/front for density near solar array.	η	10^{-4}

The values of the various parameters are indicated in Table 2 below. The solution for Φ as a function of the orientation of the panel is indicated in Table 3.

Table 3: Floating potential estimates with parameters from Table 2.

Floating potential for array facing	-14 V
Floating potential for array in wake	-3 V

3. Conclusion

In this paper a simple model has been proposed to explain the variation of SMART-1 spacecraft potential as a function of the orientation of the solar array with respect to the back-flow of the charge exchange ions generated in the thruster plume. When the solar array is facing the back-flow, the density is of the order of 10^{13} m^{-3} and many electrons are collected by the electrodes hereby driving the spacecraft potential negative. When the solar array is in the 'wake' of the back-flow the density if of the order of 10^{9} m^{-3} and the spacecraft potential floats less negative. Although very preliminary, the quantitative estimates of this model turn to be in reasonably good agreement with the observations.

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