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► **To cite this version:**

N de Mejanès, R Pascaud, V Mazières, L Garrigues, O Pascal, et al.. Simulation of the interaction between Hall thruster and communication system integrated on a small spacecraft. 37th International Electric Propulsion Conference (IEPC 2022), Jun 2022, Boston, United States. hal-03855635

**HAL Id: hal-03855635**

**<https://hal.science/hal-03855635v1>**

Submitted on 16 Nov 2022

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# Simulation of the interaction between Hall thruster and communication system integrated on a small spacecraft

IEPC-2022-334

*Presented at the 37th International Electric Propulsion Conference  
Massachusetts Institute of Technology, Cambridge, MA, USA  
June 19-23, 2022*

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**Electromagnetic compatibility is the ability of a system to function regardless of its electromagnetic environment. For small platforms such as CubeSats, the communication system is located close to the electric propulsion system and therefore close to the plasma plume exhausted. However, plasma is a complex medium from an electromagnetic point of view that may disturb the proper functioning of the communication system. In this work we propose a numerical method to estimate the perturbation caused by the plume of an electric thruster on the microwave antennas of a CubeSat platform. A plume simulation model has been coupled to an electromagnetic simulation software to represent the microwave propagation through a plume. This method can be applied to any type of thruster, antenna, or platform. As an example, far field radiation pattern and radioelectric characteristic of a 436 MHz dipole are presented when located near a Hall thruster's plume on a 6U type platform.**

## I. Introduction

The miniaturization of satellites reduces the cost of putting them into orbit. As access to space becomes more affordable, private projects increase and more and more CubeSats are being launched. However, we have little experience of the technologies that enable miniaturization, particularly for the propulsion system and its integration. The use of electric propulsion has made it possible to significantly reduce the size and weight of the thrusters [1]. However, the integration of these systems raises new issues, particularly with regard to electromagnetic compatibility [2]. Indeed, the plume can be source of electromagnetic interference with other subsystems such as the communication one and its microwave antennas. These issues have been studied in the past on large platforms. Two effects due to the presence of the plume have been identified: the emission of RF noise in the microwave antennas bandwidth and the modification of the propagation channel [3, 4]. As a result of these studies, it was suggested that this problem should be addressed by an integration response, i.e., moving the thruster as far away as possible from the microwave antennas to avoid any problem. However, as illustrated in Fig. ref, this solution is no longer possible on small platforms due to the proximity of all the subsystems. The antennas can no longer be isolated from the thruster and its plume. In this work, we propose a numerical method to represent the propagation of signals emitted by microwave antennas located near the plume of a Hall thruster, which is a good candidate in a miniaturization context.

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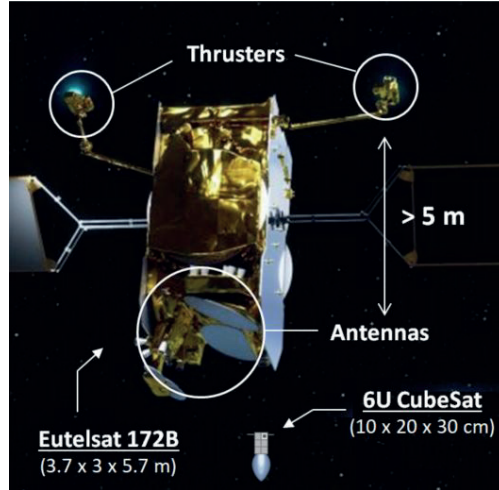


Fig. 1 Representation of a large satellite (Eutelsat 172B from Airbus Defense and Space ©) next to a 6U CubeSat.

## II. Numerical method

An overview of the proposed method is shown in Fig. 2. The plume, which is an inhomogeneous and dispersive medium, is represented by a set of materials of different relative permittivity. The local permittivity is calculated using the Drude model which relates the local electron density within the plume to an equivalent relative permittivity. The numerical analysis of the integrated microwave antennas, with and without the plume, is finally performed with an electromagnetic solver. In the following subsections, we detail each of these steps.

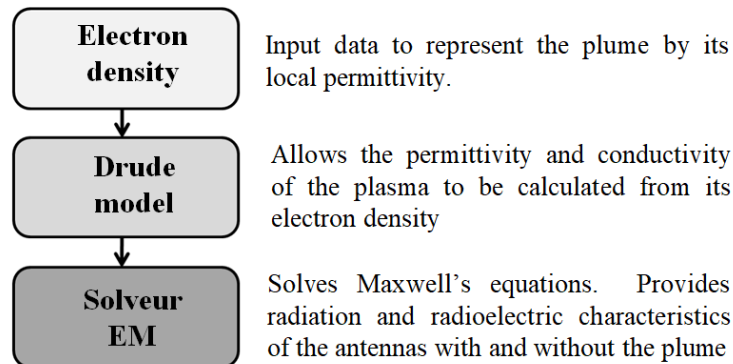


Fig. 2 Numerical method overview.

### A. Electron density

Electron density within the plume in the input data required in order to treat this problem. This distribution depends on the thruster type and its operating condition. There are many different technologies, and they do not exhaust the same plume in terms of composition, density, temperature, or shape. In addition, some of these thrusters operate in a pulsed regime leading to a pulsed behaviour of the plume and a more complex study of the interaction with a microwave signal. Even for so-called stationary thrusters, there are instabilities that lead to oscillations in the plasma electron density [5]. Although a spatio-temporal description would be required to describe the effect of the plasma on the propagation of microwave signals, in this paper, as a first approximation, the plume will be considered stationary. The study of the stationary plume will highlight the degradation of the communication link, but it is important to stress that temporal modulations of the plasma could further degrade the microwave communication link.

In this work, as an example, we propose to study the plume of a low power Hall thruster, which is a good candidate

in a miniaturization context. Here, the JET2D simulation code was used [6]. JET2D is based on a plasma jet model of a Hall thruster. It is a hybrid model where the ions are processed in a particular way by the Monte Carlo particle in cell (PIC) model and the electrons are processed in a fluid way by the local electron density linked to the local potential by Boltzmann's law. The electric field is recalculated at each time step by assuming quasi neutrality. The potential is then deduced from Boltzmann's law. JET2D was originally developed and experimentally validated for standard SPT100 type Hall thrusters used on satellites larger than those of our interest. Thanks to the JET2D input parameters like gas flow rate, specific impulse, discharge current, ion current to total current ratio, and ejection angle we can still approach the conditions of a representative plume of a micropropulsion Hall thruster. Therefore, the input parameters of JET2D, as the angular distribution, have been optimized so that the simulated current density is the closest to the measured current density of 100 W class Hall thruster [7]. Specific impulse  $I_{sp}$ , gas flow rate  $\dot{m}_{Xe}$ , and discharge current  $I_d$  have been fixed as in Ref.[7], namely  $I_{sp} = 1740$  s,  $\dot{m}_{Xe} = 0.50$  mg/s, and  $I_d = 0.44$  A. Fig. 3 shows the distribution in a half plane of the electron density obtained from JET2D for the parameters described previously. The origin  $x = 0$  cm and  $y = 0$  cm represents the center of the half Hall thruster. The electron density is maximum at the thruster exit and decreases along the  $x$  and  $y$  directions. On the simulation domain, the electron density varies between  $n_e = 6.86 \times 10^{10} \text{ cm}^{-3}$  close to the thruster exit and  $n_e = 5.30 \times 10^5 \text{ cm}^{-3}$  far from it. The electron density gradient is strong especially in the  $y$  direction, indeed for  $y = 0$  cm and  $y = 20$  cm in the plane of the thruster exit, the electron density is respectively equal to  $n_e = 6.86 \times 10^{10} \text{ cm}^{-3}$  and  $n_e = 2.6 \times 10^7 \text{ cm}^{-3}$ , i.e., a decrease higher than three orders of magnitude.

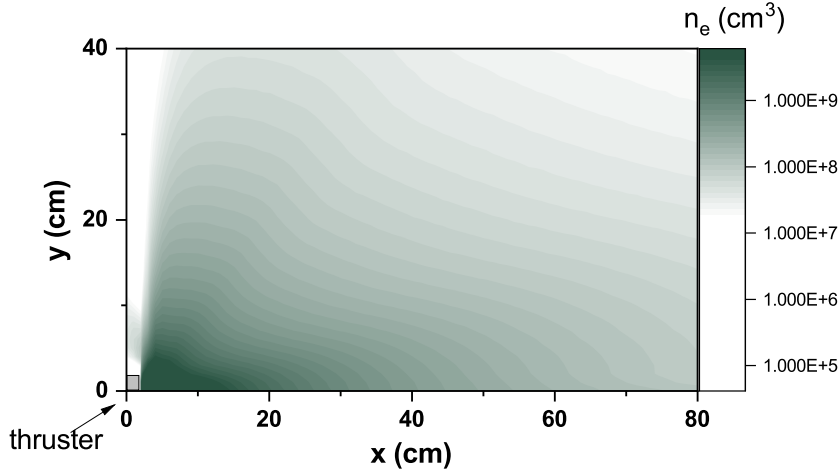


Fig. 3 Half plane distribution of the electron density in the Hall thruster plume simulated with JET2D.

## B. Drude model

From the microwave point of view, the Hall thruster plume simulated with JET2D is represented as an isotropic dispersive medium with a complex equivalent local relative permittivity given by the Drude model [8]

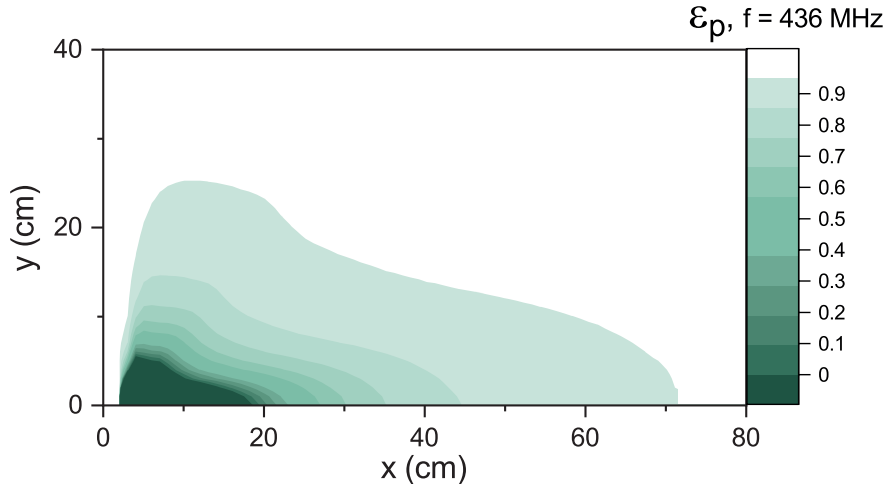
$$\epsilon_p(\vec{r}) = 1 - \frac{\omega_{p,e}^2(\vec{r})}{\omega(\omega - j\nu_{e-n})} \quad (1)$$

with  $\omega$  the angular frequency of the wave that interacts with the plasma,  $\nu_{e-n}$  the electron-neutral collision frequency, and  $\omega_{p,e}(\vec{r}) = \sqrt{\frac{n_e(\vec{r})e^2}{m_e \epsilon_0}}$  the angular plasma frequency where  $n_e(\vec{r})$  is the local electron density,  $e$  the elementary charge,  $m_e$  the electron mass, and  $\epsilon_0$  the vacuum permittivity.

The real part of the relative permittivity represents its dielectric constant and the imaginary part the energy absorption via the electron-neutral collision frequency. For a plume, the collision frequency which is proportional to the neutral density, is very low compared to the frequency of the microwave signal since the neutral pressure is very low in space vacuum condition. For a neutral density on the order of  $10^{12} \text{ cm}^{-3}$  and an electron temperature of 2 eV and the electron-neutral collision frequency is around  $3 \times 10^5 \text{ s}^{-1}$ . So the ratio between the collision frequency and the frequency of a microwave signal is very low and the plasma is therefore weakly collisional. The imaginary part is then

negligible compared to the real part of the permittivity (i.e..

Fig. 4 shows the distribution of the real part of the relative permittivity for a frequency of 436 MHz for the electron density showed in Fig. 3. We can see a zone where the real part of the permittivity is negative. In this area, electromagnetic waves become evanescent and therefore do not propagate. We also notice a gradient in the dielectric constant and so in the index of refraction  $n = \sqrt{\epsilon_p}$  all along the plume.



**Fig. 4 Half plane distribution of the relative permittivity for a frequency of 436 MHz.**

### C. EM solver

Finally, in order to study the propagation of the microwave signal emitted or received by onboard microwave antennas through the plume of a thruster integrated on a small satellite, we use a commercial electromagnetic numerical code that solves Maxwell's equations. More specifically, we use Ansys HFSS that is based on the finite element method (FEM) to solve time-harmonic Maxwell's equations. This code provides the far field characteristics of the antenna studied with and without plasma. For this purpose, we first present the method for plume discretization.

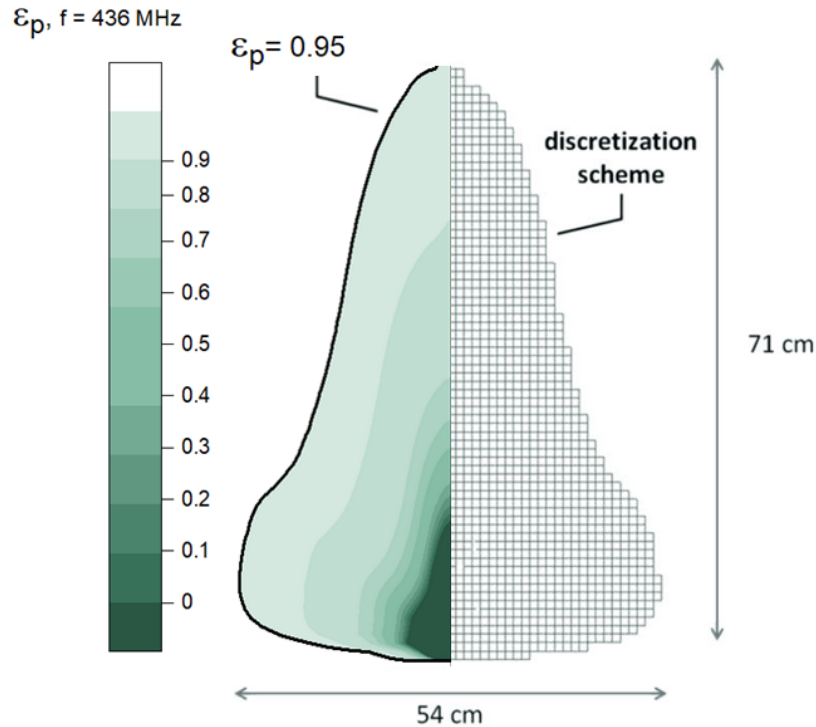
It is well known that the dielectric permittivity of a plume is continuous and inhomogeneous, but it must be discretized in the solver to be simulated. Although the plume is already sampled in the JET2D model, it is necessary to choose a discretization scheme adapted to our electromagnetic interaction problem. Indeed, the discretization needed to represent the plume physics is not the same to represent the plume/microwave interaction.

It was chosen to represent the plume by an assembly of toroids. Indeed, the electron density distribution obtained from JET2D consists of a 2D grid where in each grid cell the local electron density is given. Each grid cell in 2D is equivalent to a 3D toroidal object using axial symmetry along x direction. In each of these objects the local relative permittivity is fixed using the electron density of the cell in question and the Drude model. The axial and radial resolution  $\Delta x$ ,  $\Delta y$  of each square section toroid is a function of the wavelength  $\lambda$  of the signal such that  $\Delta x$ ,  $\Delta y \ll \lambda$  and with the aim of limiting the simulation time. In this study for a frequency equal to 436 MHz,  $\Delta x$  and  $\Delta y$  are both equal to 1 cm so the ratio  $\Delta x$ ,  $y/\lambda = 0.0145$ .

Another parameter to set is the maximum limit of the relative permittivity, that is to say the limit between what we consider to be the plasma plume and vacuum in the simulation. In other words, we need to specify a given threshold from which any element coming from JET2D will be simply represented by vacuum and not as plasma in the electromagnetic solver. The objective is to limit the computational time because the more elements to simulate, the longer it takes. But we still need to represent correctly the problem so that this choice does not influence the final results. In this aim, a convergence study (not shown here) has been performed in order to choose the value of the limit permittivity, which is in our case  $\epsilon_p = 0.95$ .

Fig. 5 shows the simulated and discretized plume when considering these choices, i.e., a limiting permittivity of 0.95 and a spatial resolution of 1 cm. The plume under these conditions is 71 cm long and 54 cm wide. The left side of the Fig 5 shows permittivity with the limit permittivity contour line equal to  $\epsilon_p = 0.95$ . The relative permittivity ranges from -28 in highest density area near the thruster exit plane to a maximum of 0.95. Beyond this, the medium is considered to be vacuum. The right-hand side of the figure shows the discretization scheme used to construct the torroids

in the electromagnetic solver. Here, the plume is the assembly of 1097 torroids of different relative permittivities.



**Fig. 5 436 MHz plume permittivity contour lines (left) and discretization scheme (right).**

### III. Results

In this section the characteristics of a 436 MHz dipole antenna is studied with the Hall thruster plume and the discretization conditions described before.

Fig. 6 shows the representation of the whole problem in the electromagnetic solver. The antenna is positioned on the center of the top face of a 6U, i.e. a platform with dimensions equal to  $10 \times 20 \times 30 \text{ cm}^3$ . The discretized plume is in the centre of the lower face to represent a thruster at this place. Also the two main cut planes for the radiation pattern of this antenna, namely  $\phi = 0^\circ$  and  $90^\circ$  are also shown in Fig. 6.

Fig. 7 compares the real and imaginary part of the input impedance  $Z$  of the antenna on 406 – 466 MHz band when the thruster is OFF (simulation without the plume) and when the thruster is ON (simulation with the plume). We observe that the presence of the plume has little or no influence. In both cases, for a frequency equal 436 MHz, the real and imaginary part are close to  $Re(Z) = 50 \Omega$  and  $Im(Z) = 0 \Omega$ . Thus, whether the plume is present or not, the antenna still appears to be matched to  $50\Omega$  at 436 MHz.

Fig. 8 shows the simulated gain radiation pattern, i.e., the angular energy distribution of the 436 MHz dipole as a function of angle  $\theta$  in the  $\phi = 0^\circ, 90^\circ$  planes for the ON and OFF conditions for the thruster. In both planes, a decrease in gain equal to 1 dB is observed for angles  $\theta$  close to  $180^\circ$ , i.e., around the plume position. Since there is no loss in the plasma due to the non-collisional assumption, the energy is not absorbed by the plasma. The decrease in gain in this area is due to a change in the directivity pattern of the antenna since the plume, due to its permittivity gradient, behaves as a refracting medium which can change the far field radiation characteristics of the antenna.

### IV. Conclusion

The proposed method provides a simple way to evaluate the interaction between an electric thruster plume and integrated microwave antennas on a CubeSat platform. The only input data required is the distribution of the density

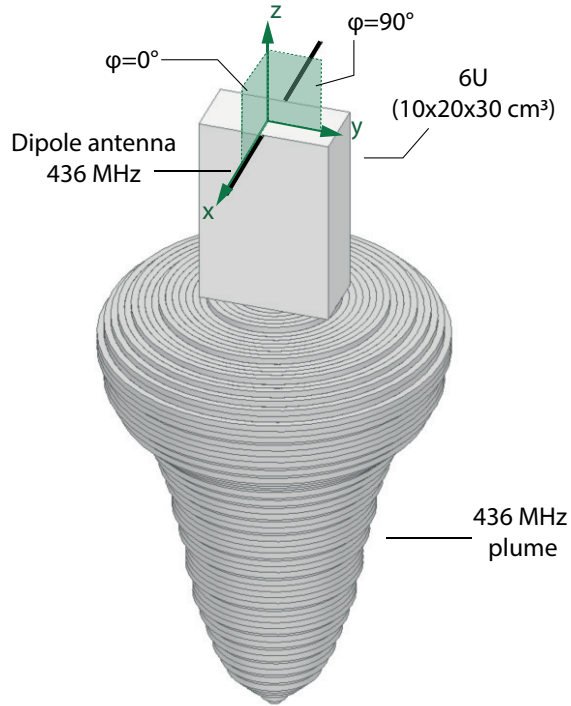


Fig. 6 Ansys HFSS CAD of a UHF dipole (436 MHz) on a 6U CubeSat with the Hall thruster ON.

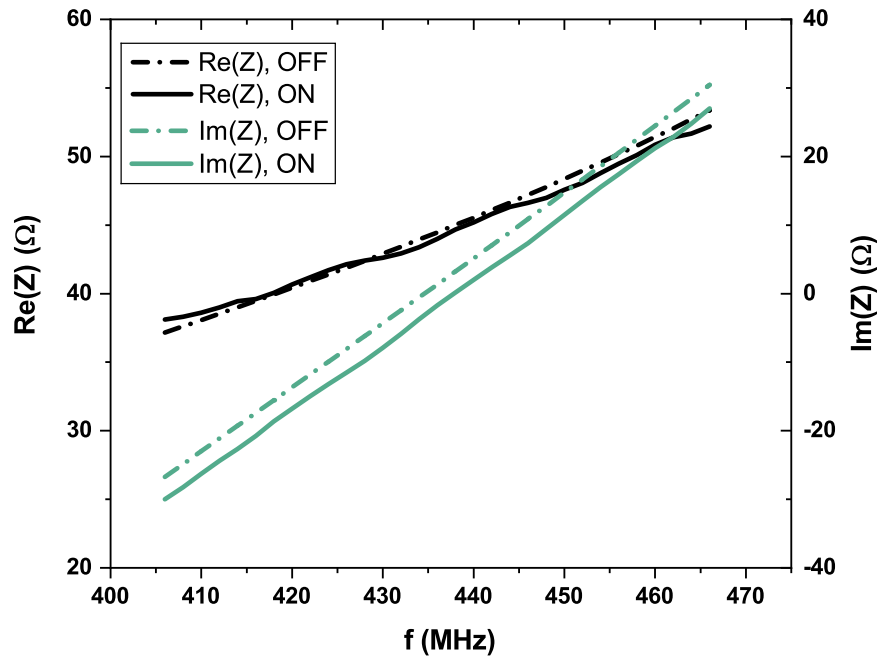
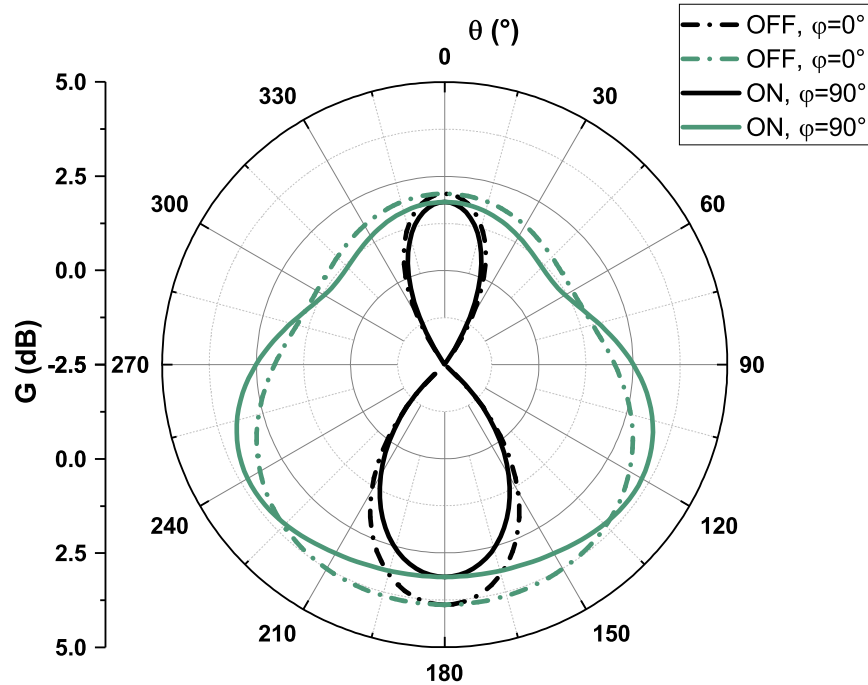


Fig. 7 Real and imaginary part of the impedance ( $Z$ ) as a function of the frequency with (ON) and without (OFF) the plasma.



**Fig. 8** Antenna gain radiation pattern in the two cut planes  $\phi = 0^\circ$  and  $\phi = 90^\circ$  of the dipole antenna with (ON) and without (OFF) the plasma.

distribution within the plume. In this way, a wide variety of cases could be tested: several types of thrusters, operating conditions, antennas, or integration. In order to validate the proposed method, this work will soon be completed by measurements of the far field radiation of a microwave antenna in the presence of plasma in an anechoic chamber.

### Acknowledgments

The authors would like to thank the Centre National d'Etudes Spatiales (CNES), and the Institut Supérieur de l'Aéronautique et de l'Espace (ISAE-SUPAERO) for their financial support.

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