PPS Effexts on Satellites
Analyses and Tools in Alcatel Space Industries

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IEPC-01-262

Abstract

Since 1994, ALCATEL SPACE INDUSTRIES (ASPI) has worked on the interactions between the plasma plume and the spacecraft surfaces and greatly deepened its knowledge of these numerous phenomena. Especially, recent achievements within the Research Department allow the modelling of these effects in order to predict the impacts of the electrical propulsion on spacecraft.

ASPI has been building an international network of collaborations involved in electric propulsion and plasma effects research. The fruit of these several years work consists of software development and physical phenomena analyses. These tools are used to predict the numerous identified impacts of the electric propulsion. Indeed in addition to the classical dynamic, thermal and sputtering effects, the software are able to compute the particle concentration of the spacecraft own atmosphere, the induced contamination and its consequences and also the electrical effects and interactions between RF signal and the plasma beam.

Introduction

ALCATEL SPACE INDUSTRIES (ASPI) now implements the plasma propulsion on its ongoing satellites as STENTOR or ASTRA 1K. The electric propulsion subsystem induces various disturbances on the orbiting spacecraft attitude, and on the performances of equipment and materials submitted to thruster plumes. In order to enhance the subsystem performances and to reduce margins to the minimum, mastering of these phenomena requires a continuous improvement.

The effects of the electric propulsion can have several aspects involving numerous domains of physics and mathematical modelling. The purpose of this lecture is to review these different effects from sloshing analyses to the interactions between RF and plasma, also considering plasma plume impingement, sputtering and deposition phenomena, sensitive surfaces degradation, optical disturbances and electrical effects.

For several years ASPI has worked on all these interactions between the electric propulsion and the spacecraft. For all the plasma plume disturbances, ASPI has developed, in collaboration with external societies, some software able to predict the damages caused by the interactions and based on theoretical approach or experimental measurements and validated by in-flight observations.

Sloshing analyses under microgravity

The accurate prediction of the propellant motion during the various thrust phases is of paramount importance for the Attitude and Orbit Control System. Indeed, the propellant mass represents a large part of the total satellite mass. Any motion of the propellant even under micro-gravity can induce perturbations on satellite attitude. The behaviour of the liquid propellant is mainly related to the magnitude of the thrust. For low-g thrusts that is to say electric propulsion thrusts and besides in zero-gravity environment, the liquid free surface in a tank exhibits at equilibrium a sharply curved 3D shape. This shape is due to the liquid propellant surface tension and to the magnitude of the contact angle at the tank wall.

The prediction of the sloshing characteristics under micro-gravity is divided into two parts.

In a first step, the shape of the free surface is determined taking into account in addition to the capillary effects the direction of the plasma thrust. Indeed on the present ASPI telecommunications satellites with electric propulsion on board, Stationary Plasma Thruster is located in such a way that the thrust axis is at a wide angle to the symmetry axis of the tank. The shape of the free surface is hence complex especially in case of low filling ratio for which the free surface can intersect the Propellant Management Device.

Secondly, the sloshing analysis concerns the calculations of the small oscillations of the liquid around its equilibrium position. To predict the dynamic behaviour of the liquid under plasma thrust, a 3D formulation is set on involving a variational fluid boundary element method to model the fluid.[1] This harmonic method directly leads to the determination of the characteristics of an equivalent mechanical model used for the AOCS.

ASPI in collaboration with LEMMA has developed a kit of tools able to compute the equilibrium free surface for any acceleration in terms of magnitude (from 0. to high values) and direction and for a 3D geometrical configuration[1]. These codes will also allow to calculate the sloshing modes occurring during the low-g thrust by solving the hydrodynamics equations taking into account the curvature of the free surface and the surface tension.

Jet/Surfaces Interactions

The effects of the electrical propulsion are numerous. Several software and a lot of risk analyses have been now done in ASPI. And improvements are still in progress or foreseen in a near future to give the best response to the customers requirements. The main interaction plasma plume/surfaces effects are summarised hereafter:

- Mechanical : forces and torque. The magnitudes of these disturbances are much less important than for the chemical propulsion.
- Thermal : thermal fluxes can also affect sensitive areas of the spacecraft.
- Surfaces degradation due to sputtering and deposition : the impact of the high energetic ions of Xenon on the spacecraft surfaces leads to surface material erosion. The yoke and the solar panel are the most involved surfaces subject to these phenomena. The sputtered particles contaminate other surfaces like the OSR (Optical Solar Reflector) and the optical devices.
- Surfaces degradation by deposition of the metal and ceramic particles sputtered from the SPT100 chamber: like classical deposition phenomenon, some metal or ceramic particles can contaminate other spacecraft surfaces.

Two main consequences are identified :

- Power loss of the solar panels due to the erosion
- Modifications of the thermo-optical coefficients of the surface materials

In collaboration with a Russian team of the Moscow Aviation Institute (MAI), ASPI has developed several software to compute the plasma plume interactions and its consequences.

ISP

ISP software (Interaction Spacecraft Propulsion) is dedicated to the plasma effects prediction. ISP is used to estimate the mechanical and thermal effects as well as the erosion and deposition phenomena. In ISP software[2,3,4], plasma plume is represented with a multi-fraction model. The expansion jet is modelled with the theory of the point source, which means that varying intensity on jet divergence angle is taken as model to describe the spatial distribution of particles concentration for each fraction. All other quantities used in erosion and deposition mathematical models result from those values of spatial distribution. (figure 1)

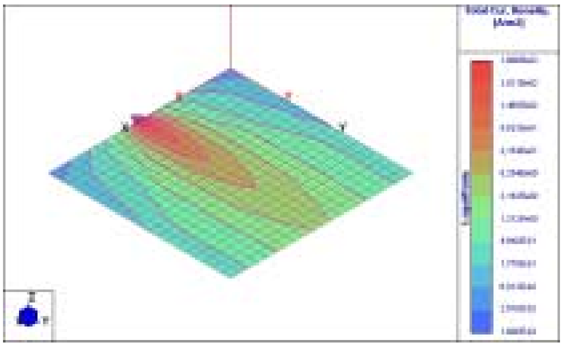
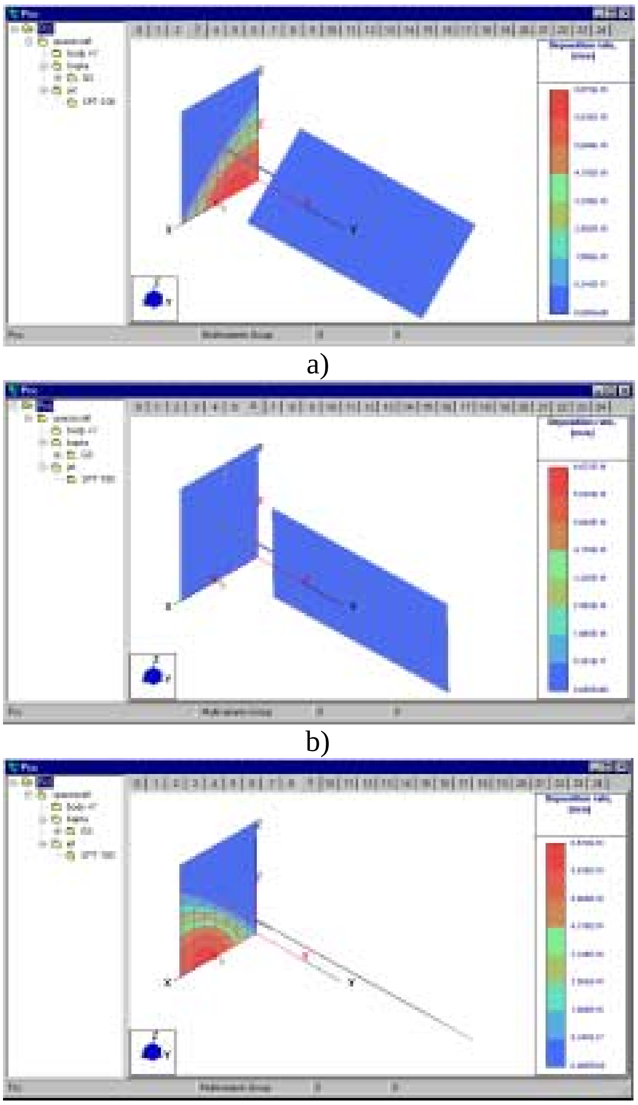


Figure 1: Spatial distribution of the current density

The degradation effects are calculated with ISP through sputtering coefficients. These coefficients mainly depend on the impinged material, the incident angle and the ions energy. To improve the ISP material data base, ASPI has realised a first test campaign in the MAI ground experimental facilities.[5] A second test campaign, in collaboration with ASTRIUM, CNES and ONERA is now in progress in order to extend the data base with new materials sputtering coefficients.

ISP was widely used for the analyses of STENTOR and ASTRA 1K satellites. This intensive use showed the necessity to improve the software in two main axes : modelling of the cinematic solar panel and exploitation of the results. Since several months, ASPI has got a new version of the ISP software[6] with a new friendly Graphical User Interface developed in collaboration with MAI. New options permits an easy building of the spacecraft geometrical configuration and the definition of the solar array kinematics (figure 2). The whole erosion or deposition for the lifetime of the satellite and also the average of the values can be now computed.


a)

b)

c)

Figure 2: Modelling of the cinematic behaviour of the solar panel

a) 3hours, b) 6 hours c) 9 hours

All along the satellite lifetime, the spacecraft is submitted to a set of complex phenomena. Out-gassing and erosion of the surface of the satellite release particles which stay n the surroundings of the spacecraft. In addition the chemical or electric thrusters produce themselves a lot of charged or not charged particles. All these particles create the so-called SpaceCraft Self Atmosphere (SCSA). New modules recently implemented in ISP permits to compute the concentration and the pressure of the particles all around the satellite (figure 3). The calculation of the contamination of the spacecraft surfaces is now possible taking into account the direct and reflected flow of particles and the back-flow resulting from the different particles interactions.

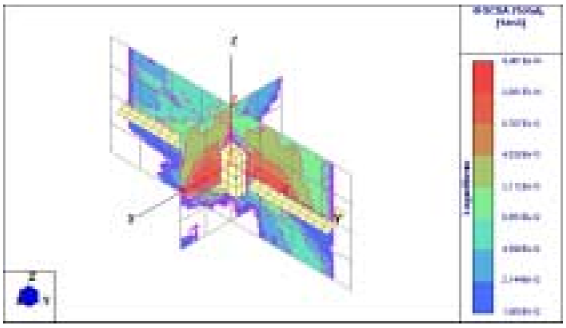


Figure 3: Total particles concentration

SPS

This software[6] predicts the flow of the sputtered particles coming from the erosion of the discharged chamber and thruster magnetic pole pieces. This flow depends on discharge chamber wall geometry and ions flow distribution along the wall. The results are then used as an input data for the ISP software which estimates the contamination on the surfaces of the satellite. The current density is computed with the assumption that all the ions are emitted from the same point called the Kim's point[7]. Walls and magnetic poles erosion is calculated using ion source parameters and materials coefficients of sputtering. Flows of sputtered particles are then computed. The process of cleaning by jet ions is also taken into account in the channel.

This model permits to forecast the isolator erosion and sputtered particles flows for different values of discharge current and for different materials for discharge chamber walls and poles.

SPS software has got a friendly graphical user interface and permits to visualise the phenomenon of isolator erosion versus time (figure 4).

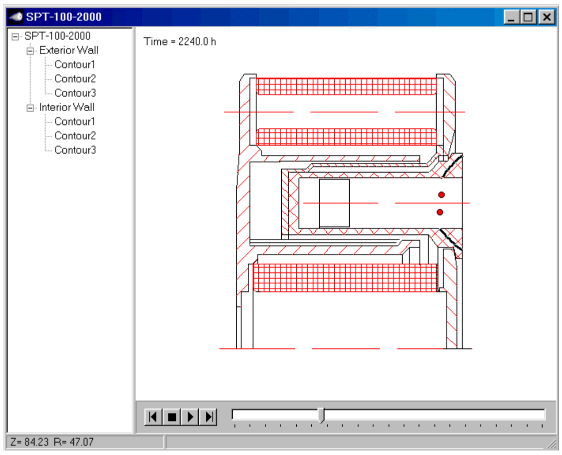


Figure 4: Erosion profile at 2240h

Optic-M

The final aim of the contamination determination is to predict the change of surfaces properties. Some satellite devices such as mirrors, optical sensors or star-trackers are particularly sensitive to this contamination. Other elements, maybe less sensitive, may have some required working specifications at their end of life. That's why, when the contamination rate is known on the surfaces, it is necessary to predict the material properties modifications in order to estimate the encountered risk and its consequences on the devices performances.

The contamination influence onto spacecraft optics is very complicated due to two main very complex facts

- process of the contamination
- description of an optical device

Experimentally, the real configuration can not be easily reproduced in a vacuum chamber. And the surface performance under real conditions are also difficult to measured.

To predict the modification of the properties of the surfaces, ASPI developed, in collaboration with the MAI , the OPTICS-M software[6]. This software, based on a semi-empirical model describe coating properties changes as a dependence on contaminant composition and thickness.

Electrical effects

The primary plasma ejected by the thruster and the secondary plasma (backflow due to charge exchange collisions) interact with the spacecraft and may produce electrostatic and electric perturbations like spacecraft charging, solar panel power loss and shorting current.

Spacecraft charging is considered as a phenomenon associated with the interactions between plasma and spacecraft surfaces. Charging effects can produce potential differences and high electrical field between spacecraft surfaces or between spacecraft surfaces and spacecraft ground. Over breakdown threshold, an electrostatic discharge (ESD) can occur. The transient phenomenon generated by this discharge may couple with spacecraft electronics and cause upsets ranging from logic switching to complete system failure (EMC). Discharges can also lead to degradation of exterior surface coatings and induce contamination of surfaces.

The charge and discharge phenomena due to the natural plasma in geo-stationary environment have been studied over a long period of time. Methods and design rules have been set out to prevent from spacecraft charging and ESD occurrences in this environment.[9] But, the charged particles flow ejected by the electrical thruster creates an artificial plasma which modifies the natural electrical environment of the spacecraft. The software ESCAPE[8] (Electro Static Charging in Artificial Plasma Environment) developed in collaboration with the RIAME (Research Institute of Applied Mechanics and Electrodynamics in Moscow) simulates the electrostatic charging of a spacecraft with electrical propulsion on board in geo-stationary environment. This software calculates the modification of spacecraft surfaces charges and potentials due to the plasma of the electrical propulsion. Its main inputs, in addition to the geometrical description of spacecraft, the physical properties of surface materials and the parameters describing the geo-stationary environment, are the location of the thruster, the direction of the plume and the angle, velocity and current density distribution of the particles (ions and electrons). The outputs are the time dependence of potentials and electrical fields for surfaces cells, the time dependence of the current density of each type of particle (current balance) on surface cells, the 3-D visualisation with color indication of the potentials and electric fields on surfaces (figure 5) and visualisation of ions and electrons trajectories coming form the electric thruster (figure 6).

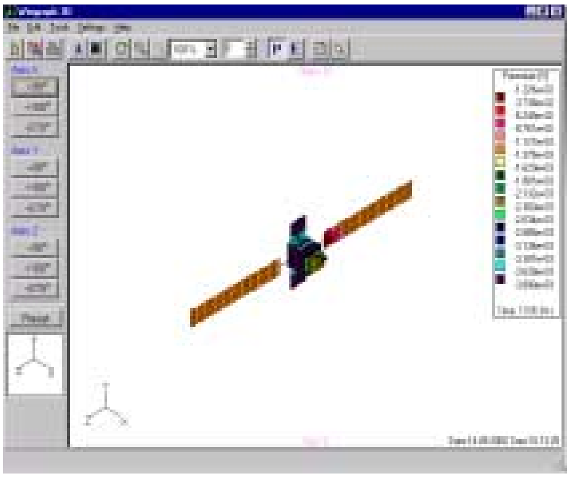


Figure 5: 3D visualisation of surface potentials

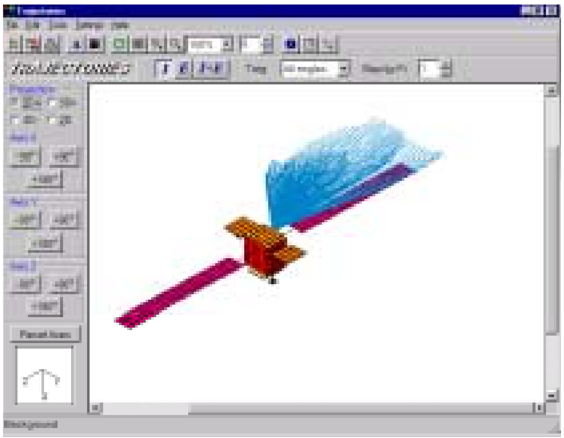


Figure 6 : Particles trajectories from SPT thruster

The study of the capabilities of this new software is now in progress at ASPI.

ESCAPE will be used to predict the surface potentials when spacecraft is submitted to both geostationary environment (geomagnetic substorms) and plasma from the electric thruster. This prediction is necessary to verify that the surface potentials meet the specifications (classical tolerable levels according to the NASA guidelines, -1000V and +500V).

Solar panel interactions

When the solar panel is in contact with a dense and cold plasma, it can, because of its active tension, collect a parasitic current from the plasma which passes through the solar cells and creates a power loss. This power loss is mainly function of the plasma characteristics (density and energy), solar array active voltage and spacecraft structure characteristics.

A spacecraft in space environment or in any other plasma acts like a Langmuir Probe. Each surface of the spacecraft will assume the floating potential (V_f), function in this case of the surface material characteristics. More particularly, the passive conductive structure of spacecraft will adjust itself to the floating potential. But, a solar array is an active system. By the working of solar cells, the solar array develops active voltage. If we consider that the solar array is constituted of only one string of the solar array, the voltage is distributed along the string as shown on the figure 7. In a cold and dense plasma the active voltage Vgs is higher than the interval [Vf; Vp]. Vp is the plasma potential. The floating condition for the solar array requires that the zero potential point of the array adjusts itself so that no net current is collected; that is, the collection of ions equals the collection of electrons. In balancing currents, the spacecraft conducting-area must be taken into account. In theses conditions, in a dense and cold plasma some cells will collect a high electrons current whereas the other part of cells will collect ions (figure 7).[11,12]

The electrons collected by the cells generate a parasitic current in these cells. The overall effect on the solar array of parasitic current is to change the effective operating point of the solar array: the current at each solar cell is the sum of normal load current and parasitic current. When the current increases the potential decreases and so degrades useful array power output.[13]

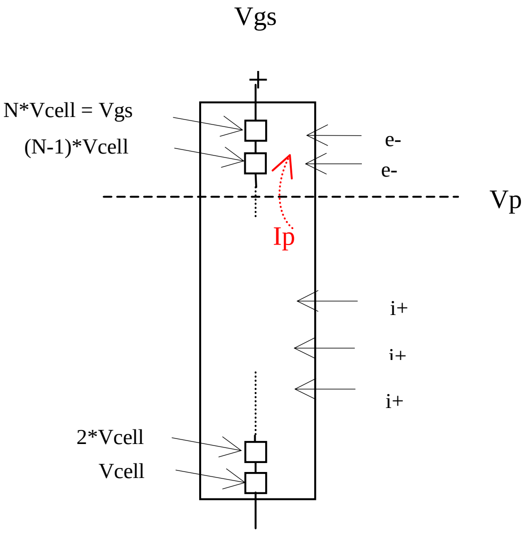


Figure 7: Electrons and ions current on a solar array

In geostationary environment (hot and not very dense plasma) the parasitic current is a very small fraction of the array current and is therefore not observed. But this parasitic current may result from the interaction of spacecraft-generated plasma by electric thruster and high-voltage solar array.[10] The plasma can be either the plasma jet ejected by the thruster. In this case, in the spacecraft configuration, the inboard sections of the solar array will be the most affected. Or it can be the Charge-EXchange plasma (back flow) generated by the electric thruster. This plasma is less dense than the primary plasma jet, but it can be sufficient to generate power loss on some section of solar array. if we consider only the first inboard string of our GS, the order of magnitude of the parasitic current through one string can be estimated to about a few mA, that is relatively negligible towards normal load current (about 1-2 A). But it is necessary to estimate more precisely this current because a lot of parameters impact the results: The model of current collection (secondary emission, photoemission), the geostationary environment, the sheath effect on the connectors. Of course, parasitic current can be calculated if the collected current is know. But this collected current is mainly function of the plasma characteristics along the solar array. These characteristics vary with the distance between the considered solar array element and the electric thruster. Therefore, the most difficult problem is to obtain the distribution of the characteristics of the plasma created by electric thruster along the solar array.

Shorting currents

If an isolated conducting element is in contact with a plasma which characteristics (Vf and Vp for example) change along this conductor, a shorting current can be created in the conductor.

For example, suppose a conducting plate (PC) immersed in a plasma divided in two zones. The characteristics of the plasma (Vf, Vp, Te, Jeo, Jio) are not the same in each zone. As the plate is conductive, the potential of the plate will fit a new floating potential (Vft) to have zero total current. So, one part of the plate will collect electrons from the plasma in this zone whereas the other part will collect ions of the plasma in the zone. Hence, a current is created and circulates on the plate from one part to the other (figure 8).

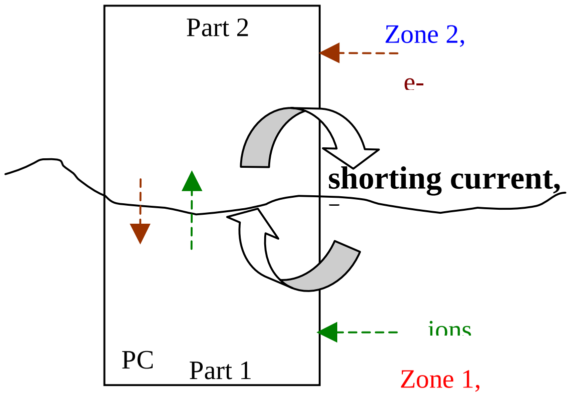


Figure 8 : Shorting current

We can apply this phenomenon to the impact of the plasmic thruster on spacecraft. Indeed, the potential and more generally the characteristics of the plasma jet ejected from the truster change along the jet line. Therefore, if the plasma jet is in contact with conducting elements of SC structure through different zones, a shorting current will be generated in these elements. In the same way the secondary plasma produced by the back flow can generate shorting current in the conductive structure of the spacecraft when they are in contact with it. Another case can occur: one part of spacecraft structure, the Solar Array (SA) for example, is in contact with the plasma jet of the thruster while another part is in contact with secondary plasma. In this case, a shorting current will circulate between the solar array and the spacecraft body. This case could be critical because these currents create a large current loop (with size equals approximately to the size of the Spacecraft plus the solar array). This current loop oscillates in correlation with the pulses of the EP discharge current and therefore creates magnetic oscillations and consequently potential electromagnetic interference. Moreover, these oscillations increase after some hours of the thruster operating. A collaboration with the TsNIIMASH (Moscow) has been built up in order to perform an analytical study on shorting currents generated by the interaction between SPT 100 and spacecraft. In a first phase of the study, an order of magnitude of the shorting currents intensity will be determined to have an estimation of the criticity of this phenomenon. The results will be compared with the specification of common mode emission on structure (Ampere peak versus frequency).

RF/Plasma perturbations

ASPI has to verify the compatibility between electric propulsion and the radio-frequency transmissions of its spacecraft, meaning the interactions between the electric thruster plasma and the RF signal transmitted by antennas or horns only.

The plasma generated by an electric thruster can disturb the electromagnetic waves in the following terms :

- static : wave attenuation (gain loss), phase difference, wave depolarisation
- dynamic : discrete spurious modulation (apparition of other frequencies than the RF nominal one)

The goal is to know the radio frequency signal modification after crossing the plasma jet, in terms of gain, phase and discrete spurious modulation, and then to ensure that these disturbances are compatible with the typical specifications concerning the RF on the payload and on the platform.

The typical RF disturbances allowable are :

- phase error due to plasma : several degrees is the magnitude order of the allowable disturbance
- wave polarisation : no wave depolarisation allowed (no rotation of the polarisation plane)
- attenuation : no attenuation allowed
- discrete spurious modulation : TBD dB wrt the RF main signal

The computations need in input the spatial repartition of the plasma electronic computed by ISP.

Due to the cylindrical symmetry of the plume (without the geomagnetic fields influence) the spatial distribution (in the harmonic domain) of the iso-densities given by ISP is plotted on the figure 9, where the thruster axis is in Z.

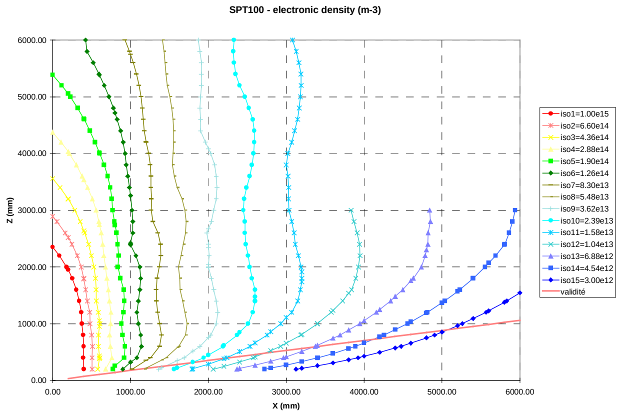


Figure 9 : Iso-densities of a SPT 100

The time-domain model of the density consists in the addition of a constant and a time modulation term. This last term has the form of a travelling wave with a spherical wave front phased at the centre of the thruster exit plane. The form of the thruster supplying current wave causes these fluctuations.

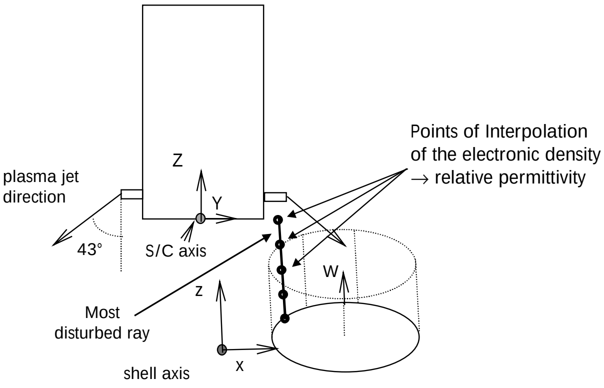


Figure 11: Points of interpolation of the density

Using the distribution determined thanks to ISP, the electronic density is interpolated on equally spaced points of the most disturbed ray of the antenna (figure 11). These interpolated values and the antenna frequency allow to determine the permittivity at these points, and then to compute the phase difference thanks to PlasEM, a software developed by ASPI. This software solves the Maxwell equations of a plane wave going through a plasma slice with variable permittivity. Its inputs are the radio frequency and the relative permittivities on given equally spaced points (on a line only, see figure 12). Its outputs are the attenuation and the phase difference.

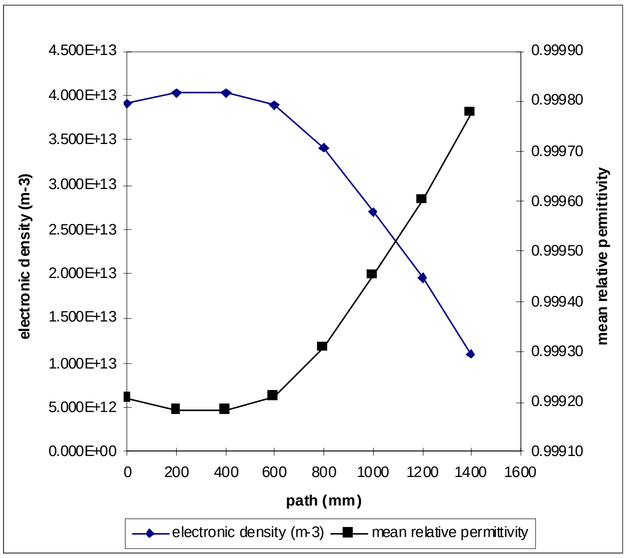


Figure 12: Inputs data of the PlasEM software

A very good correlation has been shown with the test results obtained by J.C.Dickens[14].

By the way, this concerns only 1D evaluations, made with a little-consuming computer code, without taking into account any 3D geometrical effect.

In that case of more general and accurate calculus, Elfi2R, an ASPI made computation code, is able to simulate the Maxwell-exact electromagnetic behaviour of any axi-symmetrical dielectric plume in the field of a given antenna. Elfi2R is based on a boundary integral formulation, with axi-symmetrical finite elements developments. Moreover, for a real full 3D geometry (for instance a twisted plume with a part of the satellite, in the field of view of an antenna), ASPI uses its Echo-light code, a new and very original method based on iterative objects RF interactions, each object treated with its own most appropriate formulation (Elfi2R in case of rotational symmetry, or multi rotational symmetries with different axes – think two different plumes on the

spacecraft, an Optical Physics module for full 3D objects, …).
To be more complete, we have now to compare our numerical results with in-flight ones, namely Stentor results, as soon as available.

Conclusion

Based on the theoretical and numerical advances of the Research Department, ASPI has set out a lot of tools to predict and possibly to avoid the damages on satellites on boarding the electric propulsion. A lot of collaborations with well-known international laboratories having a great experience in electric propulsion have been built. The results of numerical simulations are always, if possible, validated by tests campaign or in-flight results. Any problem occurring in that complex domain can now be handled in order to give the customer a good confidence in ASPI satellite.

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