I Introduction

The use of an electric propulsion system is an attractive solution to the fuel mass saving, payload extension and lifetime increasing problems for the future telecommunication satellites. In order to assess the inocuity of this type of propulsion, it is necessary to evaluate the influence of the plasma jet on the satellite regarding surfaces.

Some effects of the interactions between the plasmic jet and the external parts of the satellite are similar to those arising from the chemical propulsion thrusters, especially perturbation forces and torques, and thermal fluxes.

But the presence of charged particles with very high velocities due to gaz ionisation (plasma) results also in new types of interactions: surface degradation (material erosion and sputtered particles re-deposition) and electrical effects (modification of surface potential).

The knowledge of all these interactions can be obtained by means of ground experiments. But the slightness of the effects to be measured (erosion and deposition rates) and the perturbations induced by the interactions of plasma with the test chamber walls make this kind of experiments very complex.

The development of a software dedicated to the numerical simulation of these new interactions is then really necessary to permit a complete analysis of electrical propulsion effects on spacecraft equipments and therefore allow a secured and optimised integration.
To reach this purpose, ISP (Interaction Software for Propulsion) has been developed in large collaboration between AEROSPATIALE and MAI (Moscow Aviation Institute, Russia). ISP takes therefore a real and great advantage of the twenty years old experience of MAI engineers in electrical propulsion thrusters development (especially SPT70 and SPT100) and in the practical use of this technology on their own satellites.

II Plasma jet model

The working principle of an electrical thruster consists in the ionisation of a gas (Xenon for SPT) used as propellant. This ionisation induces an emission of a plasma plume which contains a high number of charged particles (or not) diffusing at different velocities. Plasma modelisation is linked to its spatial description in terms of density and energy or velocity. All others quantities used in erosion and deposition mathematical models result from those values of spatial distribution.

In ISP for the SPT modelisation, only the interactions of Xe+ and Xe++ with satellite surfaces are taken into account. Plasma plume is represented by a multifraction model based on the following: the Xe ions amount is divided into 2 groups depending on their charge (Xe+ and Xe++), in each group, the particles are separated into monovelocity (monoenergy) classes, called fraction. The dispersion of each fraction is examined separately.

The assumptions are the followings:

- the particles motion is non-collisionnal along the rays going out from SPT outlet cross section center
- no particles exchanging between fraction
- the particles velocities along the rays are constant

The model of the point source with varying intensity on jet divergence angle is taken as model to describe the spatial distribution of particles concentration for each fraction.

\[ n_f(d,\varphi) = n_{f0}(\varphi) \left( \frac{d_0}{d} \right) \]

where:

- \( n_f(d,\varphi) \) particles concentration for the \( f \)-fraction on the \( \varphi \)-ray at a distance \( d \) from thruster outlet
- \( d \) distance between considered point and SPT outlet cross section center
- \( d_0 \) thruster outlet diameter
- \( n_{f0}(\varphi) \) particles concentration for the \( f \)-fraction at distance \( d_0 \) along the \( \varphi \)-ray
The point source model parameter $n_{p}(\varphi)$ can be obtained by several possible determination methods:

- experimental measurements realised by on-ground tests of SPT thrusters

- numerical modelisation of the electric thruster processing and plume expansion (Figure 1). Numerical resolution of Boltzman and Poisson equations as in the JET software developed by RIAME (Russia).

This multifraction model which takes into account a wide energetical range of ions, presence of double charged ions and complicated jet structure, secures high accuracy for surface erosion and disturbance forces calculations.

![Figure 1: Results on JET Software plasma thruster SPT70](image)

III Satellite geometrical description

A very friendly interface allows the user to modelise easily the satellite surfaces with the help of more that 20 types of primitives. Those primitives are represented as first and second order surfaces fragments such as rectangle, triangle, disk, sphere, cone, paraboloid and so on.... All primitives parameters are set in a very simple way through different graphical windows. Moreover, for spacecraft geometrical model, building primitives are positionned quickly through translations and rotations relatively to different systems of coordinates. The primitives can be combined into group, having hierarchical structure of practically unlimited complication.

Electrical propulsion effects are strongly dependent on the impinged surface material properties. For any primitive, the material type has to be precised. An inherited mechanism can propagate properties from parent elements to children elements (i.e. from primary objects to subelements).
ISP is written in an object oriented language. So that it builds an object oriented data base (DB) which permits to store practically all user's informations beginning with initial data and ending with the numerical results. The DB control system allows quick access to any necessary information, guarantees uncontradictoriness and can also operate with object versions.

![Geometrical modelisation of a telecommunication satellite](image)

Figure 2: Geometrical modelisation of a telecommunication satellite

IV Plume impingements analysis

Due to the density level in plasma jet, the flow regime is a free molecular one. The problem of force and heat interaction is therefore solved by classical methods used in aerodynamics of rarefied gases.

The problem of surface materials sputtering is studied separately, assuming a mutual non-affection of these processes. Such an approach is justified by the absence of sufficient experimental informations at present time, as well as a lack of comprehensive description of those processes.

1. Disturbance forces and torques

The interaction of particles flow of the plume, which are coming to the surface under angle $\theta$ (Figure 3) is accompanied by emergence of a disturbance force $F$.

The force $F$ is analytically defined by a model of exchange processes, with help of accommodation coefficients widely used in these kind of interactions.

As these parameters are depending on a combination of properties of particles and surface, particles energy, incidence angle, it seems evident that the validity of this modelisation should be greatly increased by experimental testing.

![Force and heat flux interaction](image)

Figure 3: Force and heat flux interaction
2. Heat fluxes

As for chemical thruster, the interaction of the particles of a plasma jet with a regarding surface produces the generation of an heat flux that can damage the impinged materials (Figure 4). The modelisation of this interaction is similar to the previous one relative to the mechanical effects, using some adequate accommodation coefficients.

![Figure 4: Example of heat flux on solar array](image)

3. Erosion rate

The impact of high energy plume ions induces regarding surfaces degradation. Indeed, impacts create sputtering of wall material particles. This effect of erosion may become serious due to the long lifetime of telecommunication satellite.

Critical surfaces subjected to this effect are the solar cell coverglass coating and the conductive solar cell interconnector material. Erosion of the solar cell coating can result in a degradation of the solar cells optical performance and erosion of the interconnectors can also degrade solar array performance by increasing the circuit resistance.

In order to describe the ion sputtering in the energy range of interest, several methods are available. For the majority of the materials, the sputtering theories based on collisionnal models of the surface atoms give the best results.

According to this theory, the sputtering coefficient is defined by the following equation:

\[
S = \frac{Nb \text{ of sputtered atoms}}{Nb \text{ of incident ions}}
\]

This coefficient is depending on the incidence angle and the ion energy. It has to be experimentally determined. These data are then specified in tables with fixed ion energy and angle of incidence values. Interpolation formula are then used to modelise all the satellite configurations.
The total sputtering rate (Figure 5) is calculated using the following relationship:

\[ \lambda(d, \varphi) = \frac{m}{\rho_s} \sum f n_f(d, \varphi) \mu_s(\varepsilon, \theta) \]

Figure 5: Example of sputtering rate on solar array

4. Sputtered material redeposition

Sputtered particles coming from exposed surfaces degradation can deposit on other satellite parts. This process may change the contaminated surface functional characteristics, especially for the solar cells. Indeed, the accumulation of any material on solar cell cover glass can affect the thermo-optical coefficients. Thus the solar cell performance can be significantly reduced. At the same time, contaminated surfaces are also affected by the high velocity plume ions so that deposited stuff can sputter recurrently. Then a partial or complete cleaning of the surfaces can occur.

ISP offers the capability to compute this complex phenomenon of sputtering + deposition + cleaning.

The mathematical model used in ISP allows to calculate the different particles flow density coming from every sputtered surfaces and arriving on contaminated surfaces. Those particles densities depend widely on geometrical parameters such as emission angle of sputtered particles \( \theta_{s} \) and viewing angle in the direction \( \theta_{a} \) (Figure 6).
Summing up all the particles densities, coming to point B from all elements of the spacecraft subjected to sputtering and being in the direct visibility range from point B, the total flow density and then the mass deposition rate are computed.

In order to take into account the cleaning of the contaminated surface, ISP calculates an erosion rate of the deposited stuff in the same way as direct sputtering.

5. Electrical effects

This part of the ISP software gives to the user the capability to calculate the changing of the satellite surface electrical potential. In high orbital spacecrafts, these surfaces are charged by the action of high energy particles (electrons) coming from the Earth magnetosphere. For the determination of the surface potential, the following equation of current balance is used:

$$- j_e(e_e) + j_i(e_i) + j_w(e_e) + j_w(e_i) + j_{rh} + j_s = 0$$

where $j_e$ and $j_i$ – the electrons and ions on surface current density;

$j_{we}$ – current density of the secondary electron-electron emission;

$j_{wi}$ – current density of the secondary ion-electron emission;

$j_{rh}$ – density of the photo-emission current;

$j_s$ – density of the current conductivity to the spacecraft body;

$e_e$ and $e_i$ – electrons and ions energy.
The different terms of the equation are expressed analytically with help of appropriate coefficients. Giving the values of these coefficients for each surface material and the parameters of the plasma jet at the spacecraft examined point, it is possible to calculate the surface potential.

**IV Conclusion**

The development of ISP gives now to the spacecraft engineers an enhanced capability to optimise the integration of a plasmic propulsion system on board of the telecommunication satellites.

The multifraction model taking into account a wide energetical range of ions, the presence of double charged ions and a complicated jet structure secure an high accuracy for the surface erosion and disturbance forces applications.

The very friendly user interface offers at the same time an easier and more effective method of description of the geometrical configuration, minimising time and making the software accessible for a wide group of users.

Finally, developed tools for 3D coloured visualisation permit a quick and clear presentation of the numerical results.

Because of capabilities, ISP is an efficient, very clear and easy engineering tool, that can be used by specialists from spacecrafts designers up to students and post-graduates.

The validity of its modelisation should be moreover improved by comparison with the results of the tests activities (in-flight and on-ground) dedicated to electrical propulsion interactions.