ELECTROSTATIC CHARGING SIMULATION OF SPACECRAFT USING A STATIONARY PLASMA THRUSTER IN GEOSTATIONARY PLASMIC ENVIRONMENT.

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Abstract

In order to understand electrostatic interaction between spacecraft and plasma, we studied a numerical model. This model gives us the charging of a satellite in geostationary orbits. The spacecraft flies in a plasma coming from two sources, the magnetospheric plasma and the plasma coming from a stationary plasma thruster (SPT). The physical properties of both plasmas are highly different. Magnetospheric plasma is hot and rarefied wheras the SPT plasma is cold and dense. Consequently, the time and space scaling for both plasmas are opposed. This fact complicates the modelisation of their concurrently charging. This paper introduces methods for solving separately the problem corresponding to the different plasmas and some ideas to couple them.
To solve the magnetospheric plasma we use a particle method. Because of the great Debye length, we can neglect the space charge and calculate incident courant on the spacecraft by backward following of particle trajectories.
To solve the expansion of the SPT plasma thruster, we use different models for both ions and electrons present in the plasma. For ions, we have made the cold approximation. Electrons are assumes to be maxwellians. Also because of a short Debye length, we impose the neutrality in the plasma.
Both of the methods are coupled by the Poisson equation with multiple zones for each plasma. For the boundary condition on the satellite, we have to integrate incident courant.

Introduction

In geostationary orbit, spacecraft are in a hot and rarefied plasma. Some disturbances have been noticed in the past, see investigation from *NASA* ([1]) et ([2]) due to charging effect from plasma. Due to high particle energy and high velocity of electron in geostationary plasma, spacecraft tends to charge itself globally negatively. With the use of a SPT thruster, which exhausts a neutral plasma with energetic ions, we are in concerned to understand how reacts the spacecraft in order to prevent troubleshooting like discharge [3].

Geostationary plasma parameters

In geostationary orbit the plasma is not dense (about one particle per cubic centimeter) but hot (about $10keV$). We give here a table with typical characteristics of geostationary plasma. The density n, the temperature kT for electrons and ions, the Debye length λ_d which is a typical length for electrostatic interaction inside the plasma, the mean free path for collisions between couple of particles (λ_{ee}, λ_{ei}, λ_{ii}) which is a typical length to assume influence of coulombic collisions. Larmor radius is the typical length for magnetic field effect in the plasma.

$n(m^{-3})$	1×10^6
$kT(eV)$	1.2×10^4
$\lambda_d(m)$	8.14×10^2
$\lambda_{ee}(m)$	4.21×10^{17}
$\lambda_{ei}(m)$	5.95×10^{17}
$\lambda_{ie}(m)$	1.39×10^{16}
$\lambda ii(m)$	4.21×10^{17}
$\rho_{Le}(m)$	3.36×10^2
$\rho_{Li}(m)$	1.44×10^4

We take a typical length for the spacecraft of $10m$ to compare with all the plasma physical lengths. Therefore, we can neglect collisions, influence of magnetic field. (we can also neglect magnetic induction, because of small speeds of particles) We can neglect space charge effect. For modelization, we assume the plasma is maxwellian far from the spacecraft.

SPT plasma parameters

In general, plasma coming from electric propulsion are cold (some eV) but dense. (about million particles per cubic centimeter). Here, we restrict our studies to SPT-100 thrusters, and again, we give a table with typical characteristic of its plasma. Because of the presence of neutrals inside the plasma of the thruster, we add in the table more mean free path collision, the coulombic collision between two charged particles, hard sphere collision with almost one neutral and charge exchange collision between a ion and a neutral. The results are given for different distances from the exit.

	$0.31m$	$2m$	$4m$
$n_e(m^{-3})$	1.5×10^{16}	5.1×10^{14}	2×10^{14}
$n_i(X_e^+)$	1.5×10^{16}	5.1×10^{14}	2×10^{14}
$n_i(Xe^{++})$	1.5×10^{15}	4.1×10^{13}	2×10^{13}
n_n	2.9×10^{15}	6.9×10^{13}	1.7×10^{13}
$kT_e(eV)$	2	2	2
kT_i	2	2	2
kT_n	8.6×10^{-2}	8.6×10^{-2}	8.6×10^{-2}
$\lambda_d(m)$	8.6×10^{-5}	4.7×10^{-4}	7.4×10^{-4}
ρ_{Le}	4.8×10^{-2}	4.8×10^{-1}	4.8
ρ_{Li}	2.8×10^2	2.8×10^3	2.8×10^4
λ_{ee}^c	5.9×10^{-2}	1.5	3.7
λ_{ei}^c	3.3	8.6×10^1	2.1×10^2
λ_{ie}^c	8.3×10^{-2}	2.1	5.3
λ_{ii}^c	2.9×10^1	7.4×10^2	1.8×10^3
λ_{nn}^{hs}	8.2×10^3	3.4×10^5	1.4×10^6
λ_{in}^{hs}	1.6×10^3	4.6×10^4	1.2×10^5
λ_{ni}^{hs}	1.3×10^2	3.8×10^3	9.6×10^3
λ_{ne}^{dip}	1.7×10^2	4.9×10^3	1.3×10^4
λ_{in}^{CEX}	1.6×10^2	4.9×10^3	1.2×10^4

According to the measures from Manzella [7], we assume that the plasma is isothermal. The ion speed of ejection(2.2×10^4 m/s corresponding to a discharge voltage of 300V) is used to compute mean free path for ions. Also with this speed we can neglect thermal agitation of ions, and consider them as monocinetic. With the data given above, we can consider the plasma plume as unmagnetized. The mean free path for electrons is small, so a fluid model can be a good approximation, All the collisions that affect neutral can be neglected because they don't influence spacecraft charging. For ions collision, all can be neglected except charge exchange collisions. The collisions with electron can be neglected because they do not affect ion mobility. For CEX collisions, we

Interaction with surfaces

The spacecraft is modelized as a metallic box covered (partially or not) with thin layer of dielectric. Due to plasma, some particles impinge surfaces. Some of particles are reemited (backscatterings or secondary reemissions), others are conducted towards metal through dielectric. Also, due to sun exposure, some electrons are emitted by photoemmision. The surfacic charge of the spacecraft is affected, and therefore its potentials.

Governing equation

We introduce here the equations of transport for each plasma and the governing equation for the electrostatic field coupling.

Field coupling equations All magnetic effects are neglected and the dielectrics layers are assume very thin. The charges do not stay in surfaces, and the maxwell equation simplify to :

$$
\begin{gathered}
-\epsilon_0 \Delta \Phi = \rho \text{ in } \Omega^c \\
\frac{\partial}{\partial t}\left(\epsilon_k \frac{\partial \Phi}{\partial n} - \epsilon_0 \frac{\partial \Phi}{\partial n}\right) + \sigma_k \frac{\partial \Phi}{\partial n} - J_{ext}.n = 0 \text{ on } \Gamma_d \\
\int_{\Gamma_c} \frac{\partial}{\partial t}\left(-\epsilon_0 \frac{\partial \Phi}{\partial n}\right) - J_{ext}.n d\gamma + \int_{\Gamma_d} \frac{\partial}{\partial t}\left(-\epsilon_k \frac{\partial \Phi}{\partial n}\right) - \sigma_k \frac{\partial \Phi}{\partial n} d\gamma = 0 \\
\Phi = \Phi_c \text{ on } \partial \Gamma_c \\
\Phi \rightarrow 0 \text{ toward infinity .}
\end{gathered}
$$

Where
Ω represent the spacecraft.
Ω^c the exterior of the spacecraft.
Γ_c the metallic boundary
Γ_d the dielectric boundary
J_{ext} is the total current received.
Φ the external potential.
Φ_c the constant potential of metallic boundary.
ρ the space charge density.
n the exterior normal.

If we introduce, now a conductivity operator ($\mathcal{K}$), a capacity operator ($\mathcal{C}$) and a current operator $\mathcal{J}$, we can write these equations as :

$$
\begin{gathered}
-\epsilon_0 \Delta \Phi = \rho \text{ in } \Omega^c \\
\frac{\partial}{\partial t} \mathcal{C} \Phi + \mathcal{K} \Phi = \mathcal{J} \text{ on } \Gamma \\
\Phi = \Phi_c \text{ on } \partial \Omega_0 \\
\Phi \rightarrow 0 \text{ toward infinity .}
\end{gathered}
$$

In order to solve numerically these equations, we will introduce a variational formulation :

In C $= \{\Phi \in H^1(\Omega); \Phi \sim \frac{1}{r^2} \text{ in } \Omega_c; \Phi = \text{ Cste } = \Phi_c \text{ in } \Gamma_c\}$:

$$
\begin{gathered}
\frac{\partial}{\partial t}\left(\int_{\Omega^c} \epsilon_0 \nabla \Phi(x,t).\nabla \Psi(x) dx + \int_{\Gamma_d} \frac{\epsilon_k}{e_k}(\Phi(x,t) - \Phi_c(x,t))(\Psi - \Psi_c) d\gamma\right) = \\
- \int_{\Gamma_c} J_{ext}.n \Psi_c d\gamma - \int_{\Gamma_d} J_{ext}.n \Psi d\gamma - \int_{\Gamma_d} \frac{\sigma_k}{e_k}(\Phi(x,t) - \Phi_c(t))(\Psi - \Psi_c) d\gamma + \frac{\partial}{\partial t}\left(\int_{\Omega^c} \rho dx\right)
\end{gathered} \tag{1}
$$

Magnetospheric plasma As we neglect magnetic field and collision, the governing equation for the geostationary plasma is the Vlasov-Poisson system. For particles α which are ions or electrons we have :

$$
\frac{\partial f_\alpha}{\partial t} + v.\nabla_x f_\alpha - Z_\alpha \frac{e \nabla_x \Phi}{m_\alpha}.\nabla_v f_\alpha = 0
$$

with condition at infinity :

$$
\lim_{\|x\| \rightarrow +\infty} f_\alpha = n_0 \left(\frac{m_\alpha}{2\pi k T}\right)^{\frac{3}{2}} exp\left(-\frac{\frac{1}{2} m_\alpha v^2}{kT}\right)
$$

In order to rescale those equations, we introduce characteristic values. The magnetospheric electrons control the potential of the satellite. So the characteristic potential is $\Phi_{mag} = \frac{m_e.(V_e^{mag})^2}{e}$ where V_e^{mag} is the thermal speed of electrons, $\sqrt{\frac{kT}{m_e}}$. D is the characteristic length of spacecraft. $f_{mag} = \frac{n_{mag}}{(V_e^{mag})^3}$ the characteristic distribution function. The time rescaling is given by the boundary condition for potential. The time increment of surfacic charge on the satellite must be on the order of $\frac{\partial \Phi}{\partial n}$. That gives $T_{mag} = \frac{\lambda\, d_{mag}^2}{D.V_{mag}}$.

After rescaling, the Vlasov equations become :

$$\begin{array}{c} \frac{1}{\eta^2}\frac{\partial \tilde{f}_i}{\partial \tilde{t}} + \tilde{v}.\nabla_{\tilde{x}}\tilde{f}_i - \mu \nabla_{\tilde{x}}\tilde{\Phi}.\nabla_{\tilde{v}} f_i = 0 \\ \frac{1}{\eta^2}\frac{\partial \tilde{f}_e}{\partial t} + \tilde{v}.\nabla_{\tilde{x}}\tilde{f}_e + \nabla_{\tilde{x}}\tilde{\Phi}.\nabla_{\tilde{v}} f_e = 0 \\ -\Delta_{\tilde{x}}\tilde{\Phi} = \frac{1}{\eta^2}\left(\tilde{n_i} - \tilde{n_e}\right) \end{array}$$

Where $\eta = \frac{\lambda\, d}{D}$ and $\mu = \frac{m_e}{m_i}$. Because η is huge, we can neglect space charge inside the magnetospheric plasma, and solve the Vlasov equation as a stationary equation.

SPT plasma As physical characteristics of plasma inside the beam from SPT are different, the model and scaling parameter are very can be different. Again, magnetic effects will be neglectable. The electrons in the plasma from SPT are supposed to be isothermal. Because of their low temperature, we concentrate on current coming from ions. Because of their small mass, if we look for a fluid description and if we neglect inertial term in the momentum equation, we obtain that the pressure equilibrate the electrostatic pressure. So, the electron verify the Boltzmann relation, with density $n_e = n_{ref} \exp \frac{e(\Phi - \Phi_{ref})}{kT_e}$. Φ_{ref} and n_{ref} are respectively potential and density at a point of the thruster exit. The collisions for ions are ineffective but they have great mass, high speed of ejection from the thruster and low temperature. We use a cold approximation and a fluid model with no pressure. The governing equations are for the ions :

$$\partial_t n_i + \nabla_x.(n_i u_i) = 0$$
$$\partial_t(n_i u_i) + \nabla_x.(n_i u_i \otimes u_i) = -\frac{q}{m_i} n_i \nabla_x \Phi$$

Again, in order to rescale those equations, we introduce the characteristic potential $\Phi_{SPT} = \frac{kT_{SPT}}{e}$ where kT_{SPT} is the electrons temperature. The characteristic speed of ions $V_{SPT} = \sqrt{\frac{2eU}{m_{Xe+}}}$, where U is the discharge voltage of the thruster, the characteristic density n_{ref}. The time rescaling is given like for magnetosphere, so $T_{SPT} = \frac{\lambda\, d_{mag}^2 n_{mag}}{n_{ref} V_{SPT} D}$. After rescaling we have :

$$\gamma \partial_{\tilde{t}} \tilde{n_i} + \nabla_{\tilde{x}}.(\tilde{n_i}\tilde{u_i}) = 0$$
$$\gamma \partial_t(\tilde{n_i}\tilde{u_i}) + \nabla_{\tilde{x}}.(\tilde{n_i}\tilde{u_i} \otimes \tilde{u_i}) = -\frac{kT_{SPT}}{2U}\tilde{n_i}\nabla_{\tilde{x}}\tilde{\Phi}$$
$$\tilde{n_e} = \exp \tilde{\Phi} - \tilde{\Phi}_{ref}$$
$$-\Delta_{\tilde{x}}\tilde{\Phi} = \frac{1}{\eta^2}\left(\tilde{n_i} - \tilde{n_e}\right)$$

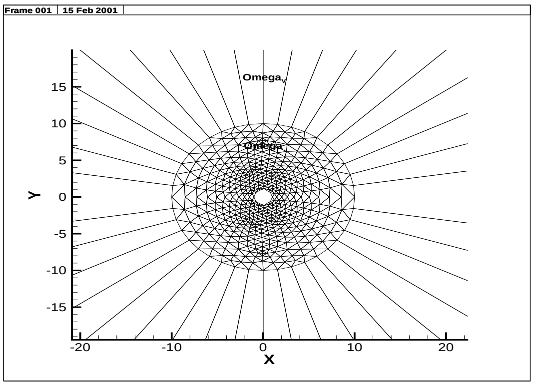
Where $\gamma = \frac{n_{SPT} D^2}{n_{mag} \lambda d_{mag}^2}$ and $\eta = \frac{\lambda d_{SPT}}{D}$.

Since η is small in the center of the thruster jet, the neutrality can be impose. Then, we have $n_i = n_e = n_{ref} \exp \frac{e(\Phi - \Phi_{ref})}{kT_e}$ and we can calculate the potential. Therefore, external potential are screen in the center of the jet, which is physically relevant. We have $T_{SPT} << T_{mag}$, so we can consider, when the thruster is ON, that the process of charging from magnetosphere unchanged. But because the thruster does not fill all space around the spacecraft, some region near the boundary of the plume have higher Debye length. The neutrality could not be impose any more. In these regions, the Poisson equation must be solve with space charge in order to take in account the sheath between magnetosphere and plume border.

Numerical point of view

Since the current received by the spacecraft controls its charge, the most important calculation is the incident current. We will present how to calculate them from both plasma, and an approach for coupling models. The aim is to have a software able to charge negatively a spacecraft with geostationary plasma and to simulate what happen when the thruster is switch ON. All computations exposed here are done in 2D-axysymetrical geometry.

Field coupling computations. For calculation we resolve the variationnal formulation (1). For the time dependence, we use a Newton algorithm in order to calculate increment of surfacic charge coming from external current and conductivity. The expression of the variationnal formulation links them to jump of potential gradient on boundary of metallic box and dielectrics. Outside the spacecraft a triangular P1-finite element method is used in a sphere of about 10 m. Outside this sphere, we consider that there is no space charge. But, in order to reach the boundary limit for potential $\Phi \to 0$ at infinity, we couple with infinite element.



Due to the thickness of dielectric, the array resulting of this Galerkin resolution must be preconditioned. While the thruster is OFF, the space charge is neglected, but when it is ON, we have to fix potential inside the SPT-thrust, and to take care about space charge coming from the boundary of the thrust.

Magnetospheric currents calculation. For calculation of incident current from geostationary plasma, we use a particles method. Because we don't need to calculate space charge density and because we can consider the stationary Vlasov equation, we use a method inspired by Riame (Research Institute of Applied Mechanics and Electrodynamics in Moscow [8]). Solving for the Vlasov equation, we know that for particles reaching surface from infinity, the distribution function is known as a maxellian scaled with potential. Starting from each surface cell on the spacecraft, we follow backwards trajectories. If a trajectorie reach boundary of our sphere, we assume this particle come from infinity, and then, we increment current value on the surface. If the trajectories come from other part of the spacecraft or from the thruster plume, we have no current. This method is more efficient than injection of particle from the boundary that implies a huge number of trajectories.

SPT plume calculation. First of all, by assuming external electric field do not penetrate the center of the plasma plume, we have made a calculation of the center of the plume. This center is define by small Debye length. We use a direct particular method (PIC) assuming monocinetic speed for ions wich are injected from the thruster exit. We interpolate primary ions density on each node. We create secondary ions coming from CEX collisions, using creation rate :

$$q_i = n_i n_n V_i \sigma_{CEX}(V_i)$$

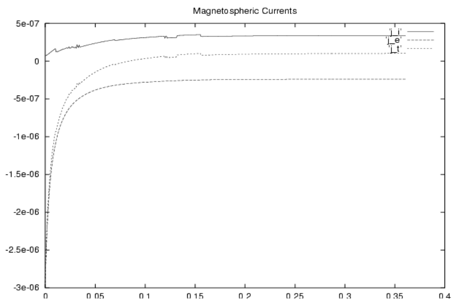
with :
$-n_i$ the primary ions density.
$-n_n$ the neutral ions density (taken as 5% of the primary ion density)
$-V_i$ primary ions speed
$-\sigma_{CEX}(V_i) = (k1 \ln(g) + k2)^2 \times 10^{-20} m^2$
with $k1 = -0.8821$ and $k2 = 15.1262$ ([5]).

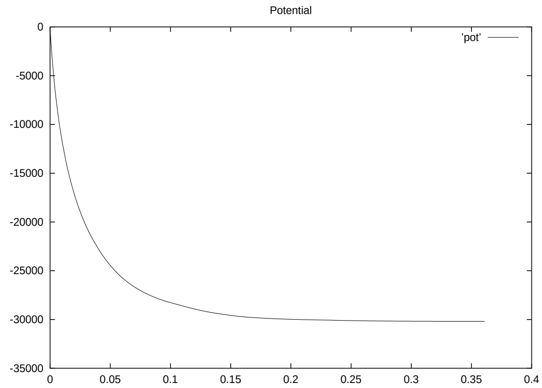
And we also follow these secondary ions using a particular method and interpolate their density. Therefore, assuming neutrality of the plasma, and Boltzmann equilibrium for electrons, we calculate potential value on each node. We iterate until equilibrium is reached. The main aim is to fill the zone corresponding of the center of the plume and to follow ions coming out from the boundary layer of the plume. If trajectories hit surfaces of the spacecraft we increment received current. The boundary layer between the plume and vaccum is defined by a criteria on the Debye length where a shealth should be created. Everything in the model is done in order to solve the Poisson equation with the space charge influence in this shealth. But, at the moment, the iterated algorithm still unstable. So, the result presented here are computed by assuming an infinity thin shealth at the boundary. The shealth is obtained by superposition of external potential calculated separatly and the internal potential calculated inside the plume.

Results

Magnetospheric calculation

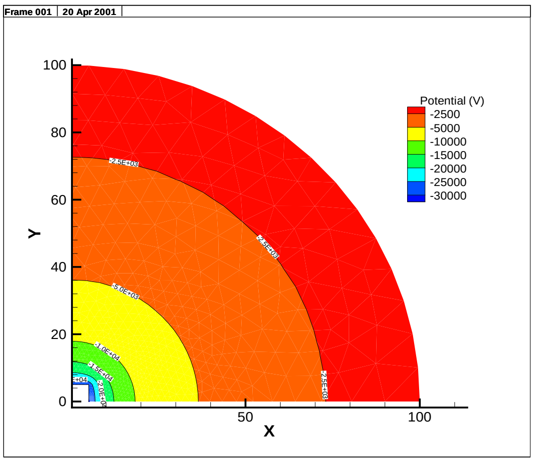
We gives here some results. First we give results from geostationnary current calculation. The first figure gives ions, electrons and total current on a numerical cell. An the second figure gives the potential evolution of this cell.





These calculations have been validated with analytical result from Laframboise [6]. We reach convergence when, globaly the total current is zero.

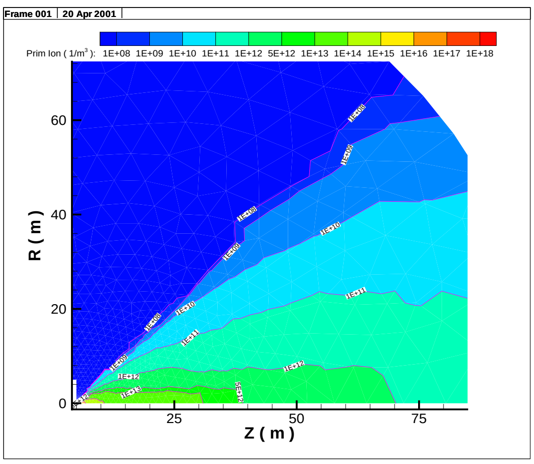
The space potential when equilibrium is reach is presented below :

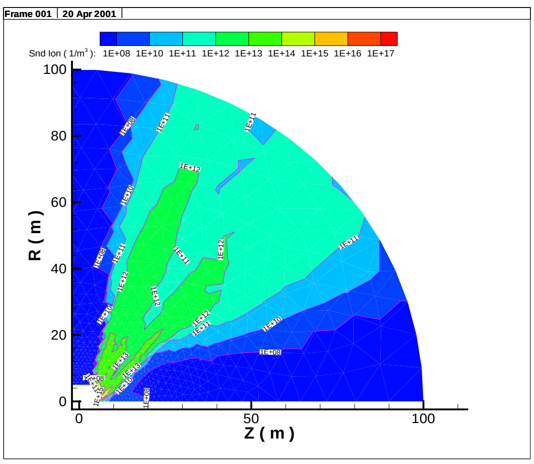


On some cells exposed from the secondary plasma ions, the calculated current coming from slow ions is about $2A/m^2$. With this current the potential go quickly to zero when the thruster is switch ON. But another equilibrium is not reached since we have not included currents from thruster electrons. Also, these results have not yet validated.

SPT plasma plume computation

The figures presented here are ions density inside the SPT plume. For primary ions, and for secondary ions :





Because the neutrality is imposed inside the center of the plume, the isopotential are the same that isodensity. We can notice on the primary ions density, that electric field push slow ions on the boundary of the plume and some of them impinge satellite surfaces. This is on good agreement with Samanta Roy results on backflow contamination. [9]

Conclusion

We have develloped a $2D-$axysymetric model that gives, charging from geostationnary plasma and calculated SPT plasma plume with CEX collision and calculation of secondary slow ions current. The resulting secondary ions current, received by the satellite, give a way of uncharging itself. Everything is prepared, in order to couple both plasma, but at the moment the shealth between SPT plasma and geostationnary plasma is not yet accomplished. The result presented here, are obtained by assuming infinity thin shealth. In the future we have to calculate with more accuracy all shealth, to integrate secondary reemissions, to validate secondary currents coming from CEX collisions and their influence on charging. Also, in order to treat most realistic case, $3D$ computation should be necessary.

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