MODELING THE ELECTRIC CHARGING OF THE TARANIS SATELLITE IN THE IONOSPHERIC PLASMA

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ABSTRACT

Spacecraft charging in the Low Earth Orbits (LEO) is generally regarded as insignificant because the cold and dense ionospheric plasma prevents strong potential differences to develop. Nevertheless, even insignificant electrical charging of the satellite structures can perturb the local plasma and thus impact the onboard measurements of thermal plasma and electric field. In order to assess the effect of the TARANIS (CNES) micro-satellite charging on the onboard electric field measurements, numerical simulations were performed using modified Spacecraft Plasma Interaction Software (SPIS) code.

SPIS allows simulations to be performed using different numerical methods, but none of these methods is perfectly adapted to simulate full satellite structure in ionospheric plasma within an acceptable calculation time and low statistical noise.

In this paper, we propose a new numerical method based on a coupling between the Poisson- Boltzmann approximation and the PIC simulation. This approach has the advantages of the analytic methods in terms of noise and computational time, but does not suffer from lack of physical meaning.

1. INTRODUCTION

The TARANIS (Tool for the Analysis of RAdiation from lightNIng and Sprites) micro-satellite developed by CNES (Centre National dEtudes Spatiales) will carry several scientific instruments to measure the local thermal plasma and electric field parameters. Among them the IME-BF instrument developed in LATMOS that measures the electric field from DC (Direct Current) to 1 MHz and has a sensitivity of about 0.5 mVm^{-1} in DC and $\sim \mu$ V m^{-1} in AC (Alternative Current) frequency range. The electric field in the ionosphere is rather weak. Its amplitude varies between few tens to few hundreds mV m^{-1}. Thus, for the correct interpretation of the onboard electric field measurements, it is very important to estimate the influence of the satellite structures and their electric charging on the local plasma. In order to asses these effects, we perform numerical simulations using SPIS code.

SPIS code allows to use different numerical schemes, but none of these schemes is really adapted to simulate the complex structures (like a satellite) in the ionospheric plasma. The problem rises from the fact that the characteristic length (Debye or Larmor length) of the ionospheric plasma at the altitude of about 700 km is small, i.e. of order of $\sim$cm, which is $\sim 10^2$ times less than the characteristic size of the satellite and $\sim 10^3$ times less than the characteristic size of the simulation volume. In consequence, the SPIS code with PIC (Particle-In-Cell) schema has to have 10^9 mesh cells and about 10^{12} macro-particles in order to correctly simulate the satellite environment and ensure the low statistical noise. This approach is very costly, while requires too long computation. On the other hand, quick and stable analytic methods (like Poisson- Boltzmann approximation) do not work properly in the ionospheric plasma, i.e. in the conditions when the drift plasma velocity (or relative velocity of satellite with respect to plasma) is higher than the ion thermal velocity (or comparable with this).

A coupling between the two models, i.e. PIC and Poisson- Boltzmann schema, proposed in this paper, allows to model correctly the ionospheric plasma, to characterise the negative electric charging of the satellite rear surface and the ion wake behind the satellite. The coupling method consists of two steps. First, we use the ion distribution function calculated in PIC schema and compute its momentum (density, mean velocity, temperature). Second, we simulate the temporal and space evolution of the ion and electrons distribution functions using the Poisson-Boltzmann method. We demonstrate that proposed coupling method has the advantages of the analytic methods in term of noise and computational resources and get the solution that converges to the right solution found by costly PIC code.

The structure of this paper is as follows. We start with a short description of the Taranis satellite structure, used materials, IME-BF instrument and parameters expected to be measured in the ionosphere (Section 2). In Section 3 we present the numerical problem and the coupling method. In Section 4 and 5 we present an example of full satellite simulation in the O+ plasma and compare the PIC solution with the coupling method solution. The main findings and future development are summarized in Conclusion.

2. TARANIS

2.1. Mission

Recent observations of enigmatic electrical discharges producing light emissions in the medium and upper atmosphere known as TLEs (Transient Luminous Event) [1][2] and of gamma emissions from atmospheric origins called TGFs (Terrestrial Gamma-ray Flashes) [3] demonstrate that there is impulsive coupling of the Earth's atmosphere with the ionosphere and the magnetosphere above active storm cells. With regards to space plasma and the chemistry and dynamics of the medium atmosphere, this direct coupling and the considerable energy involved leads to the intervention of processes that had not been envisaged until now. It can be triggered by cosmic radiation, solar winds and the meteorological and volcanic processes that affect the lower layers in the atmosphere.

Since the discovery of these phenomena is very recent, current knowledge is limited to light emissions observed in the spectrum visible from the ground or using optical detectors embedded on satellites and directed towards the horizon. The aim of the TARANIS (Tool for the Analysis of RAdiation from lightNIng and Sprites) mission is to detect and study this phenomena placing a micro satellite in a quasi-polar orbit above these events at around 700 km of altitude. The chosen orbit will allow a slow drift from the local observation time.

2.2. Satellite

TARANIS satellite is composed by a cuboid platform, along with all the on-board instruments and solar cells. TARANIS structure and main elements which could have an electromagnetic impact, as well as its composition, has been resumed in table 1.

Figure 1 schematize TARANIS geometry and materials. It will have a velocity of 7.5 km/s towards the $+Z$ axe, while the $+X$ axe is always directed to the center of the earth, the solar cells are deployed $40°$ in relation to the Z axe towards the X axe. In this position, the left boom would be partly in shadow, so important potential differences between the two IME-BF instrument could be developed.

The Kapton configuration is today unknown, nevertheless it could have an important impact, so we will carry on several model for different configurations of Kapton, going to 0% to 50% of the TARANIS and IMM surface.

TARANIS will carry two deployable booms of about 4 m length for the IME-BF instruments, so the satellite will

[1] As CuBe and MoS2 properties unknown

Table 1: TARANIS main structural elements and associated materials

Element	Material
Taranis covering	Black MLI
Solar cells	Indium tin oxide (ITO)
Boom IMM	White conductor paint (PCBZ)
Boom IME	Aluminum [1]
IME sphere	DAG 213 (Graphite)
Optics	Optic Solar Reflector
Radiators	Indium tin oxide (ITO)
Deflector (External)	White conductor paint (PCBZ)
Deflector (Internal)	Conducting carbon fibre (CFRP)
Dielectric plates	Kapton
Titanium plates	Titanium

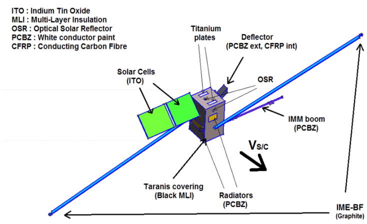

Figure 1: Geometry and Materials used on SPIS simulations

have a width of about 9 m, therefore a simulation domain will be a 6 m radius sphere with TARANIS in the center. The IME-BF instrument from the LATMOS laboratory will have a sensibility of about 0.5 mV, therefore is expected that simulations will have at least below this level of noise.

2.3. Environment

TARANIS will have an almost circular heliosynchronous orbit at 700 km, the environment used in this paper can be considered an average environment for this orbit: A plasma density of 10^{10} m^{-3} and a temperature of 0.2 eV. Two different populations of ions are considered: 85% of atomic oxygen (O+) and 15% of hydrogen (H+).

3. NUMERICAL PROBLEM

Considering an N population plasma environment inside a computational domain Ω, and applying Poisson equation:

$$-\Delta\phi(\mathbf{x},t) = -\frac{1}{\epsilon_0}\sum_{\alpha=1}^{N}\rho_\alpha(\mathbf{x},t) \quad \forall \mathbf{x}\in\Omega \text{ and } \forall t\in\mathbb{R}^+ \tag{1}$$

Therefore the ϕ_{SC} potential boundary condition can be calculated taking into account the different current density $\mathbf{J}$ from all N populations collected or emitted by the spacecraft surface S:

$$\frac{d\phi_{\text{sc}}}{dt} = \frac{1}{C_{\text{sat}}}\sum_{\alpha=1}^{N}\oint_S \mathbf{J}_\alpha \mathbf{dS} = \frac{1}{C_{\text{sat}}}\sum_{\alpha=1}^{N}\Phi_\alpha \tag{2}$$

Being C_{sat} the spacecraft capacitance and Φ_α the current flux through the spacecraft. The current density can be described as:

$$\mathbf{J}_\alpha = q_\alpha n_\alpha \int_{\mathbb{R}^3} f_\alpha \mathbf{v}_\alpha d\mathbf{v} = q_\alpha n_\alpha \mathbf{V}_\alpha \tag{3}$$

Being ϕ the bulk potential and ρ_α the charge density of the population α. For computing this set of equations, the density and the current distributions has to be set before.

3.1. Poisson - Boltzmann Approximation

Considering an isotropic plasma in thermal equilibrium the charge density and current density can be described by the Boltzmann relations:

$$\rho_\alpha(\mathbf{x},t) = q_\alpha n_\alpha^0 \exp\left(-\frac{q_\alpha\phi(\mathbf{x},t)}{k_B T_\alpha}\right) \tag{4}$$

$$\mathbf{J}_\alpha(\mathbf{x},t) = q_\alpha n_\alpha^0 \sqrt{\frac{k_B T_\alpha}{2\pi m_\alpha}} \exp\left(-\frac{q_\alpha\phi(\mathbf{x},t)}{k_B T_\alpha}\right) \tag{5}$$

The charge density can be therefore integrated into Eq.1 and the current density into Eq.2.

3.2. PIC method

Considering a system of study of N particles interacting via electric and magnetic fields, each particle p in the space phase $(\mathbf{x}_p,\mathbf{v}_p)\in\mathbb{R}^6$ will be subjected to a Lorentz force:

$$F_p = q_p\left(\mathbf{E}(\mathbf{x}_p,t) + \mathbf{v}_p\times\mathbf{B}(\mathbf{x}_p,t)\right) = m_\alpha\frac{d^2\mathbf{x}}{dt^2} \tag{6}$$

Therefore, the Vlasov equation for a collisionless plasma can be expressed as:

$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\nabla_{\mathbf{x}} f + \frac{q}{m}\left(\mathbf{E}+\mathbf{v}\times\mathbf{B}\right)\cdot\nabla_{\mathbf{v}} f = 0 \tag{7}$$

Being f the distribution function. Vlasov equation can be solved by a method of characteristics using a Lagrange frame, taking in account that the electric and magnetic field vary in time following the Maxwell equations. Thus, for each time step the density and velocity moments will be computed for solving the Maxwell equation in an Eulerian frame.

In order to make simulations efficient or at all possible, so-called superparticles are used. A superparticle is a computational particle that represents many real particles. It is allowed to rescale the number of particles, because the Lorentz force depends only on the charge to mass ratio, so a superparticle will follow the same trajectory as a real particle would, nevertheless a statistical noise is introduced which can be computed as:

$$b \approx \frac{k_B T}{\sqrt{N_m}} \tag{8}$$

Being N_m, the number of particles per mesh.

3.3. Coupled method

The coupled method consist in initialize the algorithm using a PIC distribution for computing the density and velocity moments and consequently integrate them into the set of equations. The density n_α^{pic} is integrated into a Local Maxwell distribution as:

$$\rho_\alpha(\mathbf{x},t) = q_\alpha n_\alpha^{pic}(\mathbf{x}) \exp\left(-\frac{q_\alpha\phi(\mathbf{x},t)}{k_B T_\alpha}\right) \tag{9}$$

Whereas the velocity moment $\mathbf{V}_\alpha^{pic}$ is used for computing the current density:

$$\mathbf{J}_\alpha(\mathbf{x},t) = \rho_\alpha(\mathbf{x},t)\mathbf{V}_\alpha^{pic}(\mathbf{x}) \tag{10}$$

The charge density can be therefore integrated into Eq.1 and the current density into Eq.2.

4. MODELING AND RESULTS

In an ionospheric plasma ($T_\alpha \approx 0.2\, eV$) and using a full-PIC schema [2], a mV precision can only by achieved by

[2]Using a PIC distribution for electrons and ions

introducing at least $4\,.10^4$ particles per cell. Additionally, for stability criteria the mesh size has to be $\Delta x < \lambda_D$, being λ_D the Debye length. Taking TARANIS geometry into account [3] this results in about 10^{12} particles, which would require several months of computation in a cluster.

A hybrid schema can be considered, where the electrons are treated as a fluid following the Boltzmann-Poisson distribution. Using this schema, the mesh size can bigger, however the cell size must remain about the same the order of the Debye length and the number of ions per cell must still be of the order of 10^4 particles per cell. This results in about 10^9 for a TARANIS simulation. This approach results in several weeks using a multicore machine.

Finally, we can use the Boltzmann-Poisson approximation for the electrons and treat the ions using the coupled method. This result in a very fast simulation: about several minutes in a multicore machine.

Figure 2 and 3 shows the ionic density of atomic oxygen (O+), respectively, from a hybrid simulation, using 200.000 mesh cells and more than 90 millions particles, and from a coupled method using 23.000 mesh cells. The hybrid simulation has been executed in about 18 hours using a multicore machine whereas only 12 minutes were needed for the coupled method.

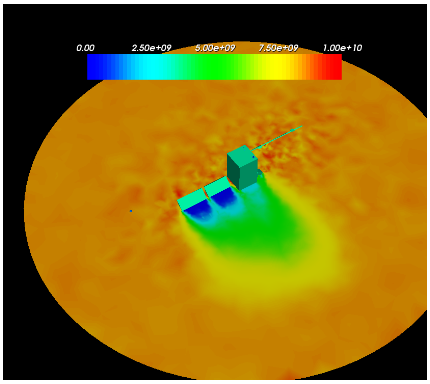

Figure 2: Ionic density of 0+ (m^{-3}) using a PIC distribution for ions

Figures 4 and 5 shows the temporal variation of the surface potential for spacecraft ground, dielectric surfaces and the IME-BF instrument. We can see that using a PIC distribution for ions produces a lot of noise on the IME-BF instrument, therefore we are not able to distinguish the differential potential between the two instruments. With the coupled method, there is no statistical noise, and therefore we are able to measure the influence of having the left boom partly in shadow, as well as the ionic wake.

[3]The computational volume being a 6 m radius sphere.

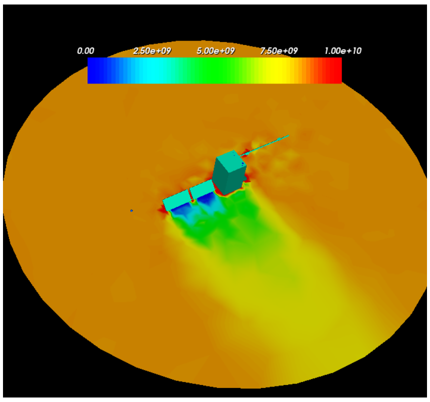

Figure 3: Ionic density of 0+ (m^{-3}) using the coupled method for ions

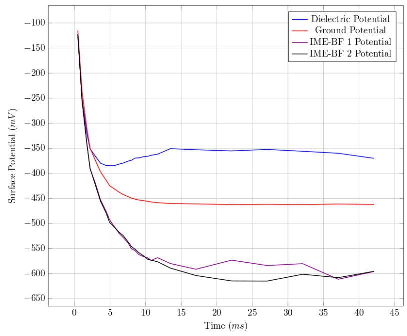

Figure 4: Temporal variation of the surface potentials using a PIC distribution for ions O+

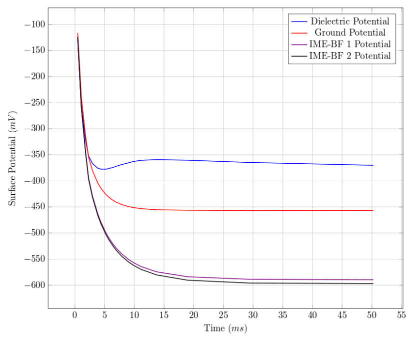

Figure 5: Temporal variation of the surface potentials using the coupled method for ions O+

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