MODELING OF THE PHOTOELECTRON SHEATH AROUND AN ACTIVE MAGNETOSPHERIC SPACECRAFT WITH PICUP3D

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Abstract

Emission of photoelectrons by the sunlit surfaces of a spacecraft can affect the plasma environment via the resulting spacecraft potential but also via the induced space charge. The photoelectron cloud structure around Cluster has been investigated with the PicUp3D plasma simulation software taking into account the plume of the onboard ion emitter. Preliminary results are presented related to the shielding of the ion emitter plume by the photoelectron and on the propagation of the photoelectrons around the spacecraft and along the wire booms. Conclusions are drawn related to the possible influence of these effects on electrostatic sensors mounted at the end of long (>40 meters) wire boom antennas.

Introduction

A number of scientific spacecraft have embarked scientific payload dedicated to the investigation of the solar wind interaction with the magnetosphere and other magnetospheric phenomena and massively rely on plasma and field measurements in three dimensions of space. In many occasions, electric field measurements are performed via pairs of electric sensors mounted at the extremity of long wire booms. Occasionally, a spurious electric field has been observed in the spin plane. Four main processes have been suspected to be the cause of such spurious electric fields:

- a wake effect which creates asymmetric environment around the probes [1];
- the effect of active ion emitters plume space charge when operating;
- the effect of the photoelectron space charge [1];
- the effect of asymmetric currents of photo-electrons to the probes [1];

The recent Cluster experiment which is constituted by a fleet of four magnetospheric spacecraft equipped with slightly redundant instruments to measure the electric field allowed to investigate in depth the occurrence of spurious electric field and their possible cause. The modelling of the first effect is currently being studied by the IRF group in Uppsala (Eriksson, private communication) while efforts to model the last three effects have been made at ESA-TOS/EES using the PicUp3D simulation code [2] and the preliminary results are reported in this paper.

<u>**Spacecraft and environment characteristics**</u>

Each spacecraft of the Cluster mission is approximately a cylinder with height 1.2 m and diameter 3 m. The booms in the spine plane are about 42 meters long with electrostatic sensors at the extremities opposite to the spacecraft. The wire booms thickness is of the order of 1 mm. An ion emitter called ASPOC is mounted on near the edge of the top side of the spacecraft. It is used to reduce the floating potential of the satellite, which can otherwise reach up to 40 V in the magnetospheric lobes.

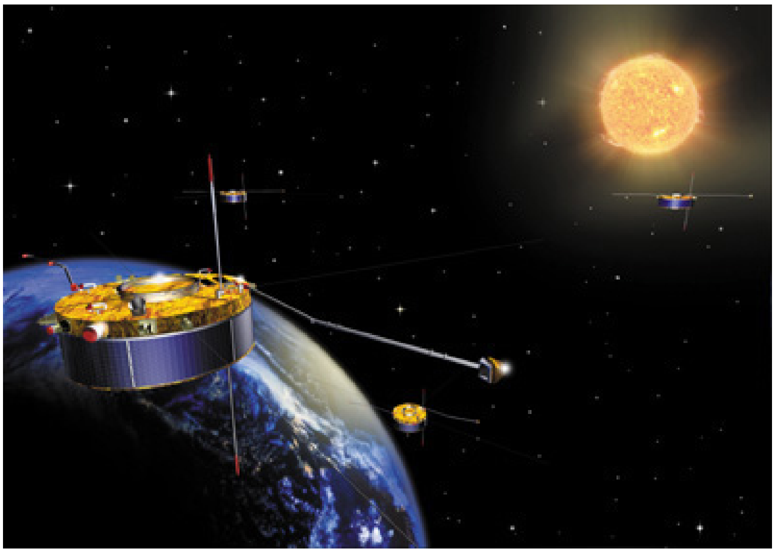

Figure 1. Artist's view of the Cluster satellite

Electrostatic and plasma environment

The Cluster satellite crosses different plasma regions along its orbit with very diverse plasma conditions. It was reported that the spurious electric field was mainly observed in the magnetospheric lobes were the plasma temperature is about 100 eV and the density as low as 0.1 particle cm^{-3} which implies a Debye length is about 235 m. With such plasma conditions and due to the photo-electron emission, the spacecraft potential is typically of about 40 Volts when the ion emitter is off and about 7 Volts positive when the ion emitter is on. The photo-electron emission current density at saturation has been measured and is of about 50 $\mu A\ m^{-2}$.

<u>**Simulation parameters and constraints**</u>

The code used in this study is PicUp3D [2]. It is a simulation software designed to model spacecraft plasma interactions. It is developed with an open source approach, written in Java programming language and is freely available on the web. The algorithms are based on a 3D Particle-In-Cell (PIC) kinetic description of ions and electrons to simulate plasma dynamics.

The size of the simulation box is driven by the need to include the spacecraft and the antenna and its sheath (typically a few Debye length), which is expected to be even more extended along the ion beam. Therefore, a very large computation box is required. For this study simulation box with a size L_{box} varying between 120 m and 450 m has been used. Since PicUp3D algorithms are based on a rectangular mesh the use of such box sizes together with the memory limitation implies a rather low spatial resolution. Typical values of the spatial resolution were of the order of 1 meter allowing the number of computation node to be between 80x80x80 and 150x150x150. Therefore the spacecraft geometry could not be very accurately described, and especially the booms, nor the electric field very close to the surfaces.

Furthermore, a very accurate potential description was required (± 0.1 V) to match the observed level of the spurious electric field. Therefore, a high number of macro particles was used (typically 5.10^6) to achieve a good statistical description and averaging over many plasma periods was necessary.

A small time step, dt, had to be used to accurately compute the particles trajectory ($dt < 0.1 * 1/\omega_{pe}$, where ω_{pe} is the plasma frequency) and the time of computation to reach the equilibrium was very long ($\sim 100 * 1/\omega_{pe}$).

All these constraints lead to highly demanding simulations in term of computing resources. They also have an impact on the accuracy of the results and doubts could be raised on the relevancy of the results in the most extreme situations. Therefore, the approach used in this study was to perform a series of simulations corresponding to increasing complexity in term of the constraints put on the simulation. Typically, one performed a series of three simulations with increasing Debye length. Only the last one corresponds to the relevant environment where the spurious electric field is observed, however, the reality of the phenomena can be checked with the two first simulations for which the confidence of the results is higher. The simulation parameters are shown in Table 1 below.

Simulation parameters

Table 1. Simulation parameters for 3 cases corresponding to increasing Debye length.

Simulation	n_0 (cm^{-3})	T_0 (eV)	λ_D (m)
Case 1	1	1	7.43
Case 2	1	10	23.5
Case 3	0.1	100	235.

Where n_0 is the plasma density, T_0 the temperature and λ_D the Debye length. The ion emitter was simulated only through its ion space charge that was assumed constant and only depending on the ion emitter current, I_{ASPOC}. For all simulations the following parameters to describe the ion emitter plume and the photo-electron current were used.

T_{pe} = 2.5 eV (photo-electron temperature)
J_{pe} = 50 μA/m^2 (photo-electron current density at saturation)
I_{ASPOC} = 10 μA (Ion emitter current)
E_{ASPOC} = 10 keV (Energy of emitted ions)

Furthermore, the simulations were performed in all cases once with the wire booms and another time without the wire booms.

Simulation results

Ion beam shielding

Figure. 2 shows a meridian cut of the potential in the simulation cases 2 and 3 without wire booms. The effect of the ion beam space charge is clearly seen along the Z axis (perpendicular to the sun and to the spine plane). However, it can be seen that it is very efficiently shielded by the ambient plasma electrons and the photoelectrons in direction perpendicular to the Z axis.

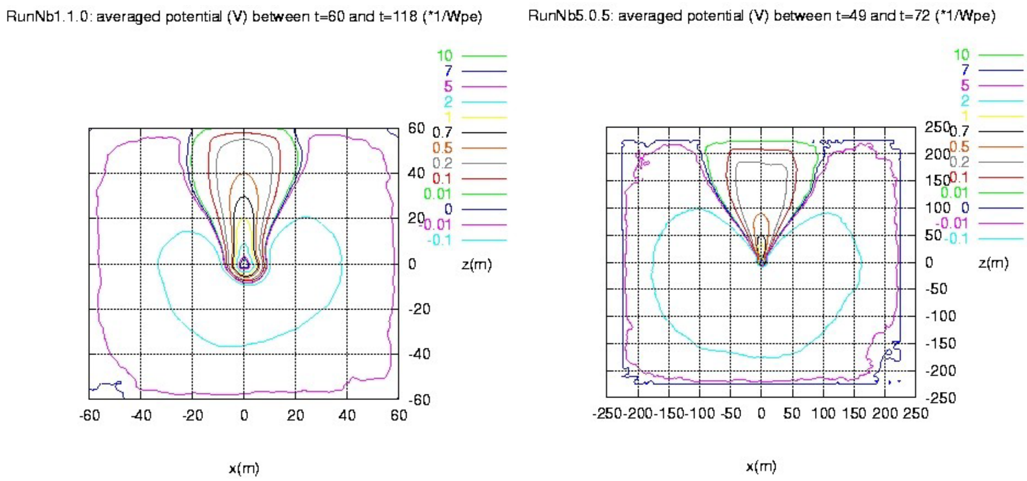

Figure 2. Case 2 (left) and case 3 (right) potential maps. The sunlight comes from the left

The positive potential typically vanishes within about 20 meters from the Z axis. Therefore, the possible influence of the ion space charge on the electrostatic probes located 40 meters apart from the spacecraft can be ruled out.

Photoelectron space charge

A set of photo-electron trajectories shown in Figure 3 below in a case without wire booms illustrates how the photo-electron are shielding the ion space charge. Furthermore, a significant amount of photo-electrons propagates relatively easily very far from the spacecraft. The photo-electron density is shown on the right panel of Figure 3. This photo-electron behaviour explains why instead of a positive potential one rather observes a negative potential beyond 20 meters across the ion beam. It results a negative potential barrier as shown in the potential profile along the X axis drawn on Figure 4. The reality of such barriers is discussed elsewhere in this conference [3]. The value of the photo-electron induced potential disturbance is relatively high (slightly less than 0.01 V) but marginal compared to the magnitude required to induce the observed spurious electric field. Furthermore, it must be noted that in absence of wire booms, the PicUp3D simulations predict a rather symmetric photo-electron cloud beyond a few meshes from the spacecraft surfaces. However, this aspect must be taken with caution since it may be an artefact due to the poor resolution near the spacecraft surface.

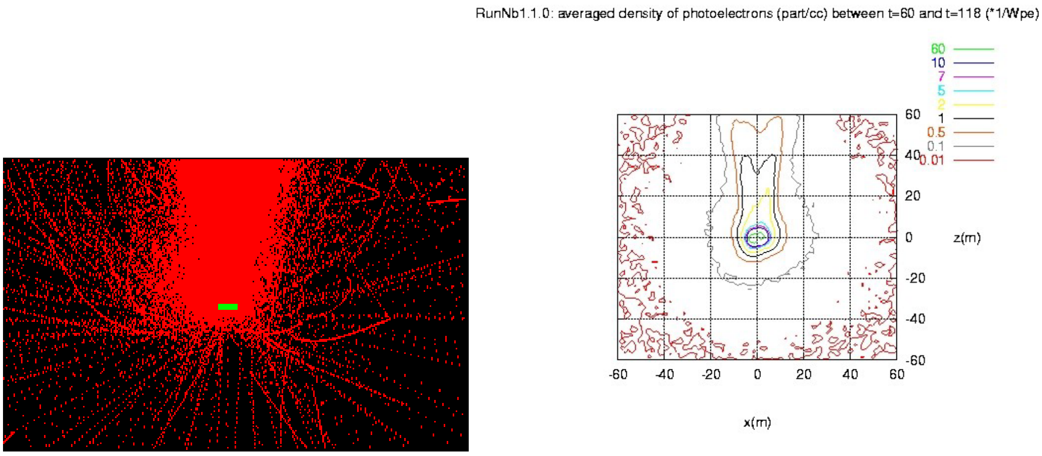

Figure 3. Set of photoelectron trajectories around the spacecraft and the ion emitter plume (left panel) and corresponding density contours in Z*X plane (right panel).The sunlight comes from the negative X values.

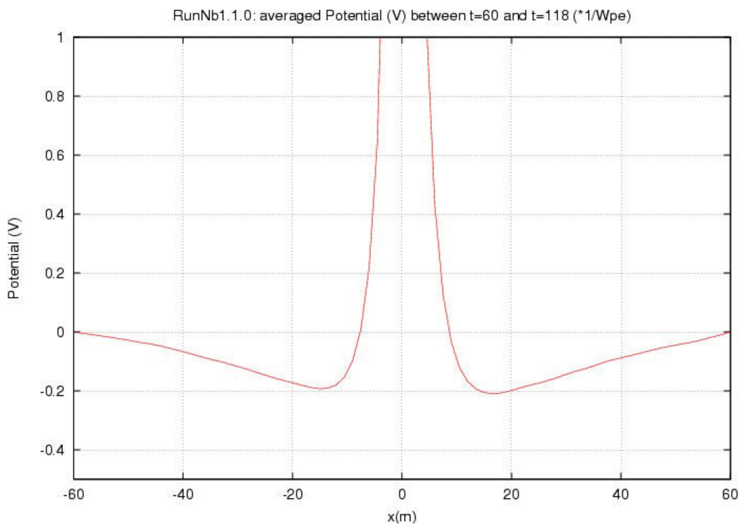

Figure 4. Case 2 potential cut along the sunlight axis. The sunlight comes from the left

Asymmetric photoelectron cloud and possible influence of the booms

The photoelectron density dominates over the ambient plasma density up to a factor 60 near the sunlit surfaces. However, at the electrostatic probe position, the photoelectron density is negligible with respect to the ambient density and should not in this case directly induce an asymmetry of the measurements.

The simulations performed while taking into account the wire booms provide a completely different picture. The density of photo-electrons and the corresponding potential distribution when booms potential is taken into account are shown in Figure 5. As shown on the density map, the positive boom may guide photo-electrons very efficiently toward the end of it. In absence of any active potential barrier, the density at the electrostatic probe would be dominating over the ambient plasma. Furthermore, the density is this time asymmetric, more photo-electrons propagating in the sunward direction than in the anti-sunward one. However, in reality there are small a few centimeters segments of the boom biased at a negative potential which may repel the photo-electrons. Unfortunately, the resolution accessible on current standard computing machines with PicUp3D does not allow testing properly the efficiency of these guards.

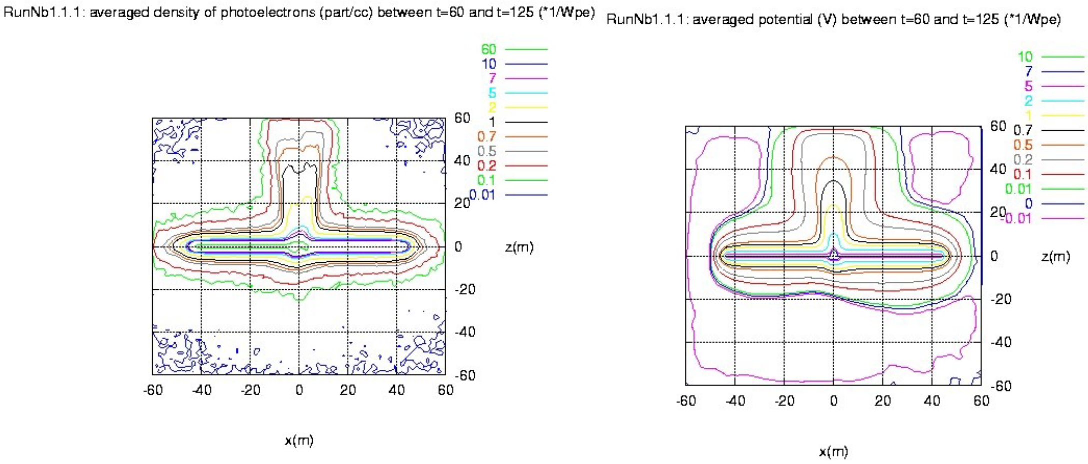

Figure 5. Case 2 photoelectron density map (left) and potential map (right) in a simulation taking the wire booms into account. The sunlight comes from the left

Conclusion

A full 3D modelling of the electrostatic sheath of a magnetospheric spacecraft equipped with an ion emitter has been attempted in plasma regions where the Debye length is very large compared to the spacecraft hub dimension. Although the quantitative output suffers from a strong uncertainty related to the coarse meshing, these preliminary results give evidence of complicated sheath structures influenced by the following factors:

- Ion beam space charge (but not beyond a few meters across the beam).
- Photo-electrons (evidence of negative potential barrier and long ranging influence, i.e., up to 40 meters away from the spacecraft hub).
- Wire booms (guide photo-electrons to very long distance with sun/shade asymmetry).

The photoelectron cloud has been identified as a potential problem that may induce spurious electric field due to an asymmetric guiding along the booms. However, a quantitative prediction of the spurious electric field requires much more detailed geometric description of objects (booms, guards detectors and sources). This would be possible only with the use of meshing techniques, which may cope with ratio of size varying from 1 mm for accurate modeling of the wire booms to hundred meters (boom length), which is the size of the sheath.

Acknowledgments

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