NUMERICAL SIMULATION OF THE ELECTRICAL CHARGING OF THE ROSETTA ORBITER

Jean-François ROUSSEL
ONERA/DESP, 2 Av. Edouard Belin, 31055 Toulouse Cedex, France; roussel@onecert.fr

Jean-Jacques BERTHELIER
CETP, 4 Av. de Neptune, 94100 St Maur des Fossés, France, berthelier@cetp.ipsl.fr

***Abstract** : In the low density plasma of Wirtanen comet environment, the ROSETTA orbiter may float at a positive potential. That may prevent the collection and analysis of the very cold ions by the inboard plasma diagnostics. In order to evaluate those possible problems, we have undertaken an investigation to determine the orbiter floating potential based on a numerical modeling of its interaction with the ambient plasma. This model uses a full particle method for both ions and electrons. It was run for 2 sets of conditions corresponding to the comet at respectively 3 and 1 AU from the Sun and, in each case, for 2 distances of the orbiter from the nucleus, namely 1 R_n (nucleus radius), or approximately 1 km, and 100 R_n. When far from the nucleus, the orbiter was shown to float at positive potentials of about 2 to 4 volts. When close to the nucleus the floating potential is of the order of the thermal energy of the plasma particles. The numerical model and the computed structure of the plasma sheath around the orbiter are presented in this paper.*

1. Introduction

The ESA ROSETTA mission aims at a rendez-vous with comet Wirtanen at a large distance from the Sun of about 3.5 AU followed by an operational phase of 18 months during which the ROSETTA orbiter will accompany the nucleus along its journey towards perihelion. Several instruments will measure the ionised cometary atmosphere in order to determine its chemical and isotopic composition, its temperature and flow properties. Performing accurate measurements of thermal plasma requires that the disturbances arising from the spacecraft floating potential are controlled or, at least, shown not to be detrimental to the quality of measurements. This is particularly true for a cometary mission since estimates of the typical energy of thermal particles ranges from 10 meV to about 100 meV.

In order to evaluate the possible problems raised by this extreme situation, we have undertaken an investigation to determine the orbiter floating potential based on a numerical modeling of its interaction with the ambient plasma. This model uses a full particle method for both ions and electrons. It was run for 2 sets of conditions corresponding to the comet at respectively 3 and 1 AU from the Sun and, in each case, for 2 distances of the orbiter from the nucleus, namely 1 R_n (nucleus radius), or approximately 1 km, and 100 R_n. Corresponding cometary plasma conditions were taken from available models [Mendis et al., 1985; J.P. Lebreton, private communication, 1995] with plasma density varying from 10 cm^{-3} at 3 AU, 100 R_n to 10^5 cm^{-3} at 1 AU, 1 R_n and being equal to 10^3 cm^{-3} for the two other cases.

A first analytical assessment of the floating potential to be expected is presented in a first section. The full numerical results are then presented in the next section.

2. Anticipated conditions for plasma environment and spacecraft

The nominal position of the ROSETTA orbiter will be between the comet and the sun, with the instruments facing the comet. Two other positions, on the terminator plane and in the night side of the comet, were also studied, and are depicted on figure 1. They will however not be discussed here due to the lack of place.

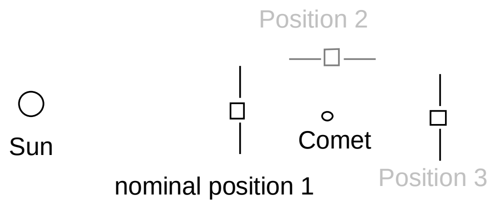


Figure 1: relative positions of sun, comet and spacecraft

The flows onto the spacecraft are thus the supersonic ion flux flow the comet, the subsonic isotropic electron flux, and the UV flux from the sun, as depicted on figure 2.

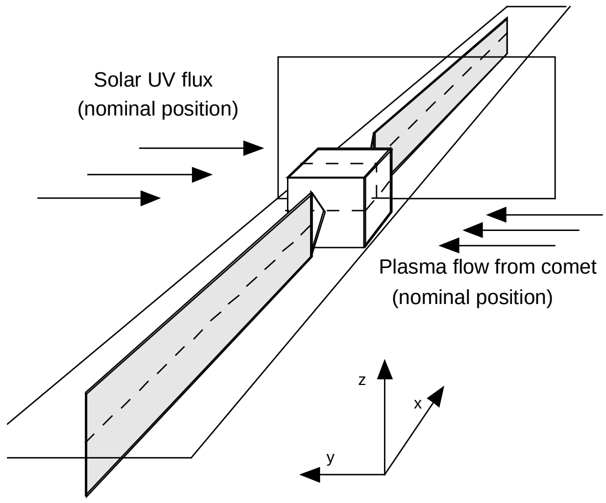


Figure 2: local conditions around spacecraft.

Horizontal and vertical symmetry planes (*xy* and *yz* respectively) used in the numerical simulation are also represented. The spacecraft body is approximately 2x2x2 meters and its solar arrays 2x15 meters.

The anticipated plasma conditions are the following:

- ions: drift velocity 300 to 1000 m/s, temperature 30 to 200 K, hence a supersonic flow of typical Mach number ~ 2 to 5 for H_2O^+ ions. Values used for numerical simulation are: 100 K, drifting velocity 500 m/s, hence drifting average kinetic energy 0.023 eV.
- electrons: 50 to 100 K, subsonic flow, hence assumed isotropic. Value used for numerical simulation: 50 K, or 0.004 eV.

The plasma conditions in the four cases considered are summarised in the next table (two different distances to sun and to comet). When the orbiter is far from the comet (100 R_n), the photo-electron current is significantly larger than the electron thermal current, which is likely to result into positive potentials to compensate for photo-emission.

Distance to sun (AU)	Distance to comet (*R* units)	Plasma density (cm^{-3})	Debye Length (cm)	Electron thermal current density (nA/cm^2)	Photo electron current density (nA/cm2)
1	1	10^5	0.15	18	5
1	100	10^3	1.5	0.18	5
3	1	10^3	1.5	0.18	0.6
3	100	10	15	0.0018	0.6

Table 1: Plasma conditions depending on the distances to sun and to comet.

3. Simplified analytical assessment of the floating potential

Before beginning costly numerical simulation, first analytical assessments of the floating potentials on the orbiter were performed. Realistic quantitative values were only expected as a result of the forthcoming numerical simulations, and these analytical computations were thus rather straightforward, aiming only at an order of magnitude.

The current and energy distribution of photo-electrons were taken from experimental measurements of the net emitted photo-current from a spacecraft at potential $\Phi_{s/c}$ (Volts) [Pedersen 1995]:

$$J_{ph} = J_1 \exp(-\Phi_{s/c}/2.5) + J_2 \exp(-\Phi_{s/c}/7.5)$$

with J_1 = 5 nA/cm^2 [Hilgers et al. 1992] and J_2 = 0.3 nA/cm^2 at 1 AU from sun.

The collected thermal electron current was taken from Boltzmann current in case of negative S/C potential

$$I_e = S\, j_e \exp\left(\frac{e\,\Phi_p}{k\,T_e}\right)$$

with the thermal current

$$j_e = -e\,n_e\sqrt{\frac{kT_e}{2\pi m_e}}$$

In case of positive S/C potential, depending on the Debye length, either the thin sheath hypothesis currents (thermal current collection at the sheath edge in case of small λ_D) or the Orbital Motion Limited (OML) currents collection (large λ_D) were used:

$$I_e = j_e S\left(1+\frac{e\phi}{kT_e}\right)$$

for OML collection by a sphere, or

$$I_e = j_e S\frac{2}{\sqrt{\pi}}\left(\sqrt{\frac{e\phi}{kT_e}}+\frac{\sqrt{\pi}}{2}e^{\frac{e\phi}{kT_e}}\left(1-\mathrm{erf}\left(\sqrt{\frac{e\phi}{kT_e}}\right)\right)\right)$$

for OML collection by a cylinder.

The computed floating potentials are given in next table for the four situations (same 2 distances to sun, 2 distances to comet). The values displayed are typical ones since, depending on the hypotheses on the electron collection, an uncertainty of a factor of 2 was observed.

Distance to sun (AU)	Distance to comet (*R* units)	Plasma Density (cm^{-3})	Debye Length (cm)	Estimated floating potential (V)	Typical sheath extension (cm)
1	1	10^5	0.15	**-0.007**	0.15
1	100	10^3	1.5	**5**	100
3	1	10^3	1.5	**1.5**	50
3	100	10	15	**5**	1000

Table 2: Analytical assessment of the floating potential, depending on the distances to sun and to comet.

As expected from the thermal electron current and photo-current of table 1, the floating potentials are positive when the orbiter is far from the comet (100 R_n).

The third case (3 Au from sun, 1 R_n from comet) is in fact very close to the limit between positive and negative floating potentials. The thermal electron current and photo-current displayed on table 1 are rather close: 0.18 and 0.6 nA/cm^2 respectively, but with an area of collection for thermal current larger by almost a factor of 2. The collected and emitted currents at plasma potential are thus very similar for thermal and photo electrons. A small change in potential should thus be sufficient to establish a balance. However, the present crude modelling of electron collection through a sharp edge hypothesis (thermal current collection at sheath edge) resulted in a large potential (1.5 V ~ 300 T_e). Taking into account the pre-sheath, which extends at a large distance, and allows to concentrate electrons, would certainly achieve current balance for a much smaller potential.

4. Numerical simulations

Since positive potentials are bound to build up on ROSETTA orbiter, the electron dynamics was to be really modelled. They could not be simply described by a Boltzmann distribution. The ions have a drifting hypersonic flow, and are also far from thermal equilibrium. The dynamics of ions and electrons were thus to be modelled simultaneously. This is known to be a situation very costly in computation time due to the large ratio of electron and ion velocities.

We were thus led to use a *numerical times* method [Roussel 2001, Jolivet and Roussel 2001]. Similarly to *real time* methods, in such a method ions and electrons are moved over a fraction of a cell, and Poisson equation is then solved with the new densities, before particles are moved again. But ions and electrons are not moved by the same physical amount of time: ions are moved by an unphysical amount of *numerical* time 10 or even 100 times larger than electrons. But provided steady state solutions are searched for, it does not matter how much time ions are moved. They simple give constant density when steady state is reached.

That method first gives a good stability since the plasma reaction to potential fluctuations is modelled at each step, contrarily to steady state methods where particles are moved across the whole computation box before Poisson equtaion is solved. Secondly, it is fast since the larger time increment for ions allows to have them moved over distances comparable to electrons during each iteration.

The justification of the method is that the solutions found are solutions of steady state Vlasov and Poisson coupled equations, provided convergence is achieved, whatever way is was achieved. Such was the case for those ROSETTA simulation. It does not prove yet that the reality is steady state, and real physical solutions may be time dependant, or turbulent if the computed steady state solutions are indeed unstable.

The numerical modelling results are summarised in the table 3. As expected, the potentials are very positive when the orbiter is far from the comet. As discussed at the end of the previous section, the case 3 AU, 1 R_n, gives a potential very close to zero since the global photo-current and thermal current almost balance one another at plasma potential.

Distance to sun (AU)	Distance to comet (R units)	Plasma Density (cm^{-3})	Computed floating potential (V)
1	1	10^5	**-0.023**
1	100	10^3	**1.8**
3	1	10^3	**0.0015**
3	100	10	**4.3**

Table 3: Numerical computation of the floating potential, depending on the distances to sun and to comet.

Several plots of potentials and densities are also given in the next figures. The sheath extension is of course very variable, depending on Debye length. It is in particular very large in the last case: approximately 5 to 10 metres, i. e. 30 to 60 Debye lengths, due to the 4.3 V potential much larger than T_e (~ 1000 T_e).

A possible solution to those positive potentials was then studied. In the basic configuration studied until now, the S/C was assumed to be equipotential due to its ITO coating. Since photo-electrons are emitted on sunlit surfaces while positive potentials are a nuisance on the instrument side, most of the time in the shade, disconnecting both sides could yet bring a great improvement. Since we did not know what electrical configuration was possible in practice, we simply assumed that the whole S/C body and the back side of the solar array could be grounded, while the sunlit coverglass could be disconnected (left floating).

The resulting floating potentials are given in table 4, where only the problematic cases at 100 R_n where modelled. Although the situation is improved, the problem is only solved for a sun-comet distance of 1 AU. For a distance of 3 AU, the potential is only lowered form 4.3 to 1.3 Volts, which is insufficient. That positive potential of ground is due to the photo-emission of the sunlit face of S/C body. A real solution of the problem can only be found through a real uncoupling of all sunlit surface from ground. Its feasibility depends yet on technical considerations beyond the scope of that study.

<table>
<tr><th rowspan="2">Distance to sun (AU)</th><th rowspan="2">Distance to comet (R units)</th><th colspan="2">Computed floating potential (V)</th></tr>
<tr><th>ground</th><th>coverglasses</th></tr>
<tr><td rowspan="2">1</td><td rowspan="2">100</td><td colspan="2">1.8</td></tr>
<tr><td>0.0005</td><td>3.7</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">100</td><td colspan="2">4.3</td></tr>
<tr><td>1.3</td><td>7.4</td></tr>
</table>

Table 4: Consequences on floating potentials of disconnecting the coverglasses from ground.

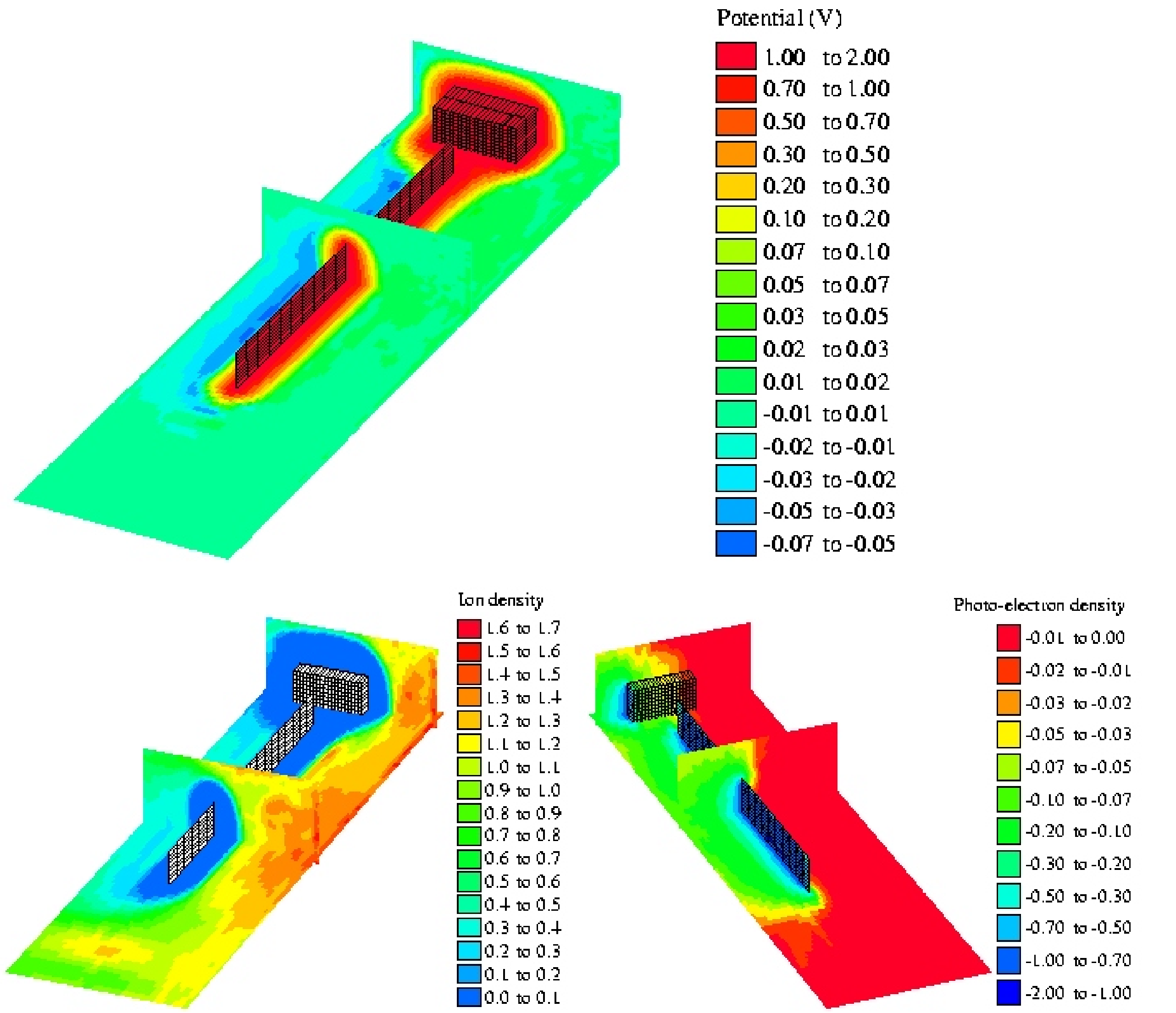
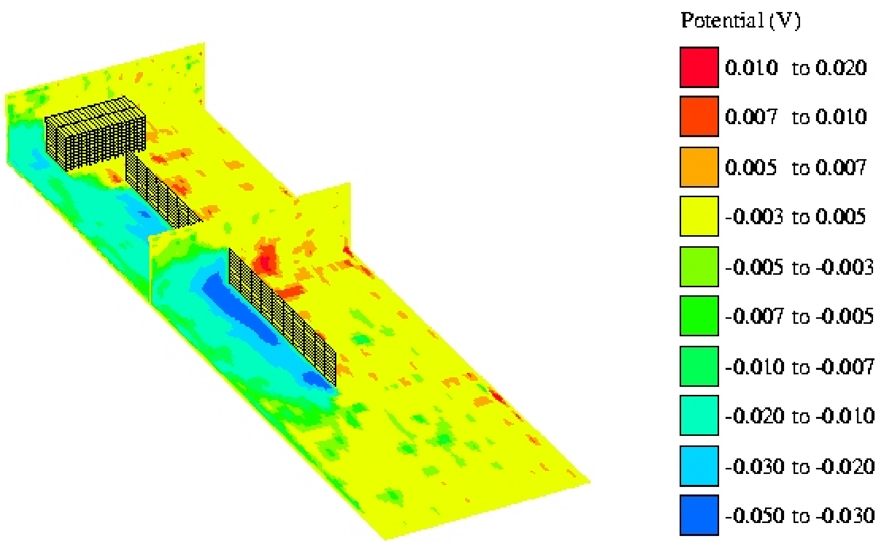


Figure 3: Maps of potential, ion and photo-electrons densities (normalised to ambient density), comet at 1 AU from sun, orbiter at 100 R_n from comet nucleus.



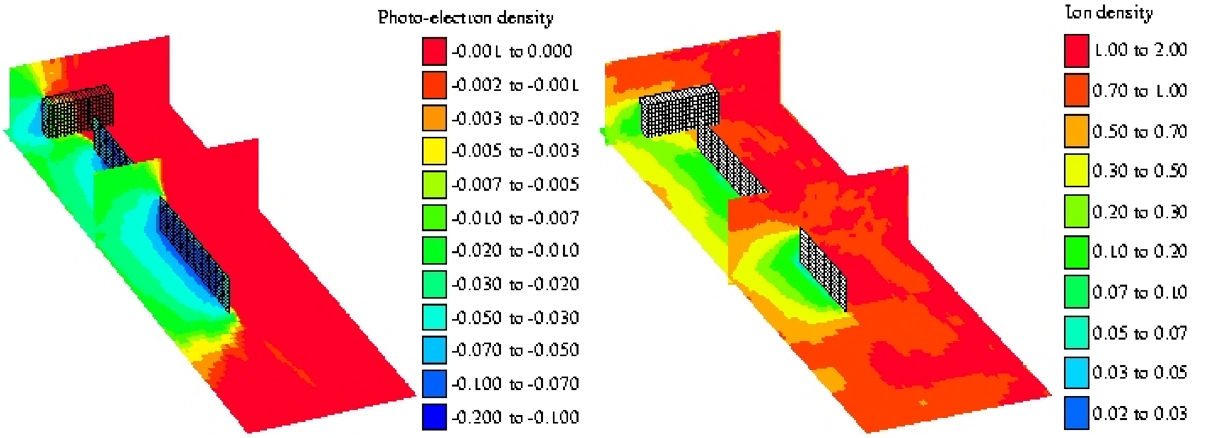


Figure 4: Maps of potential, ion and photo-electrons densities (normalised to ambient density), comet at 3 AU from sun, orbiter at 1 R_n from comet nucleus.

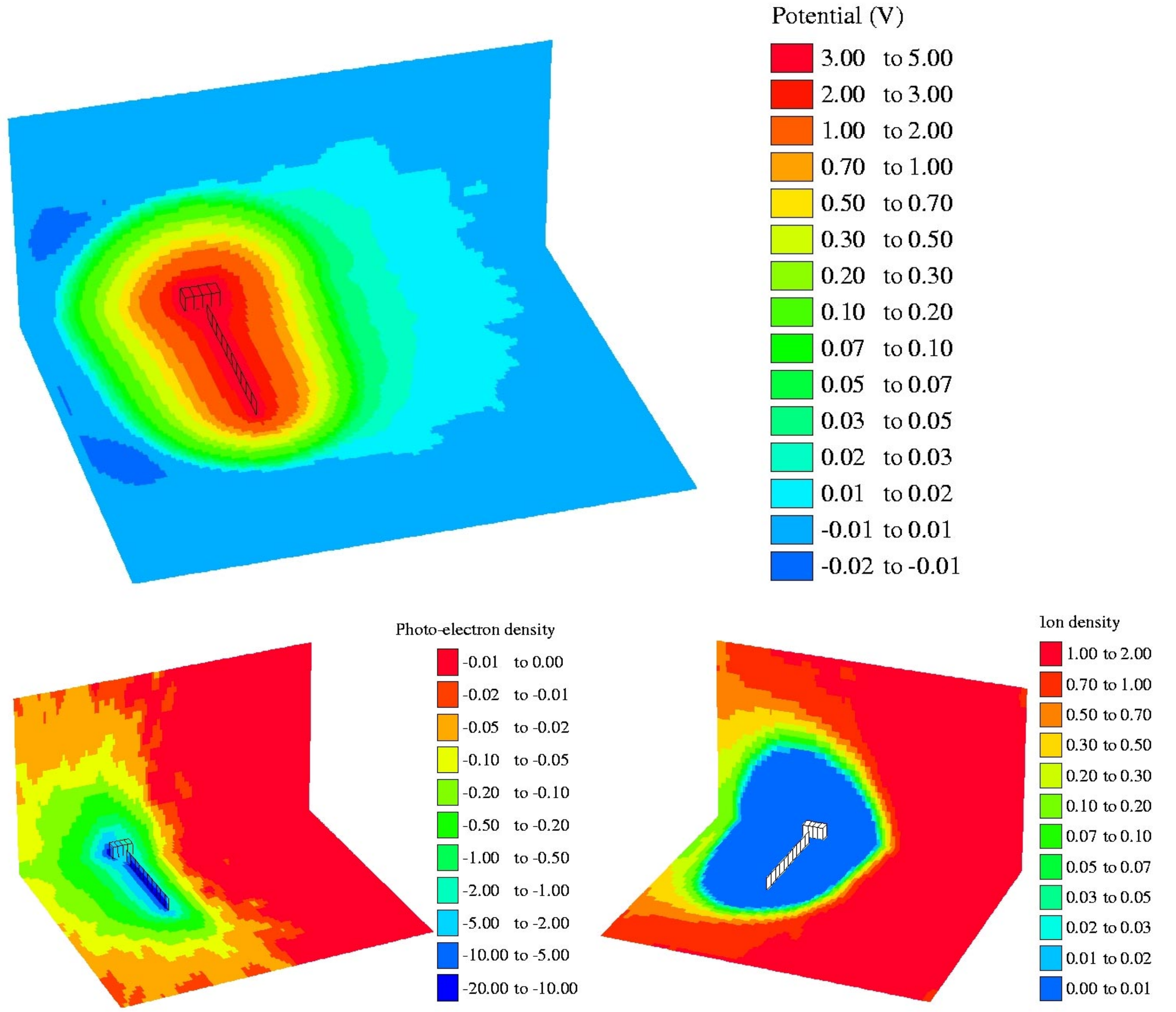


Figure 5: Maps of potential, ion and photo-electrons densities (normalised to ambient density), comet at 3 AU from sun, orbiter at 100 R_n from comet nucleus.

5. Conclusion

It was shown that significant positive potentials can really be reached on ROSETTA orbiter in Wirtanen's comet plasma environment. This is a serious threat to plasma ion measurements. The potentials will yet remain small and negative when close enough to the comet (standard LEO-like situation).

The conductive ITO coating used on all orbiter surfaces can be viewed as the source of that problem. It is used to avoid any ESD risk and to ensure potential homogeneity in the vicinity of scientific instruments. It has yet the counterproductive consequence to increase the S/C ground potential due to the photo-emission on the coverglasses connected to ground.

A solution to that problem could thus be to disconnect the coverglasses, and even any sunlit surface, from the ground. That could be simply done by letting those sunlit insulators float independently (no ITO), or by connecting them together thanks to an ITO coating, but independently from ground. In that second case they could even be related to ground through a power supply, which could allow to fully control ground potential. The technical feasibility of those solution is still to be assessed yet.

Biasing plasma diagnostics negatively with respect to ground could also be imagined as an alternative solution. This is commonly done through an entrance grid biasing. However, in the present case of large sheaths, positive potential barriers build up in front of biased grids as a result of the surrounding positive potentials, and suppress the effect of that attractive potential. As a rule of thumb, it can be considered that the negative bias of a grid of size L will have a significant effect against the surrounding positive potential up to a distance L. Hence if the sheath is much larger than L, a positive potential barrier will still exist at a distance larger than L. The issue of potential barriers is also discussed in the companion paper about the experimental validation of those simulations [Berthelier and Roussel 2001].

Acknowledgements

The authors are very grateful to European Space Agency for its financial support to that study (Alain Hilgers, ESA/TOS/WMA).

References

Berthelier, J.-J., and Roussel, J.-F., Experimental Tests of Numerical Simulation of the Interaction of the ROSETTA Orbiter with the Cometary Plasma, 7th *Spacecraft Charging Technology Conference*, Noordwijk, The Netherlands, April 23-27, 2001.

Hilgers, A., B. Holback, G. Holmgren and R. Boström, Probe measurements of law plasma densities with application to the auroral kilometric radiation source, *J. Geophys. Res., 97*, 8631, 1992.

Jolivet, L., and Roussel, J.-F., Numerical Simulation of Plasma Sheath Phenomenon in Presence of Secondary Electronic Emission, submitted to *IEEE Transactions on Plasma Science*, 2001.

Mendis, D.A., H.L.F. Houpis and M.L. Marconi, The Physics of Comets, *Fundamental of Cosmic Physics*, Vol. 10, pp1-380, 1985.

Pedersen, A., Solar wind and magnetospheric plasma diagnostics by spacecraft electrostatic potential measurements, *Ann. Geophysical 13*, 118, 1995.

Roussel, J.-F., Modelling of Spacecraft Plasma Environment Interactions, 7th *Spacecraft Charging Technology Conference*, Noordwijk, The Netherlands, April 23-27, 2001.