PLASMA CURRENT COLLECTION OF HIGH VOLTAGE SOLAR ARRAY: NUMERICAL INVESTIGATION

S. L. G. Hess(1), V. Inguimbert(1), J.-M. Siguier(1), D. Payan(2), A. Gerhard(3), G. D'Accolti(4), E. Gloaguen(2), O. Jorba-Ferro(1), G. Murat(1)

(1)ONERA – The French Aerospace Laboratory , 2 Avenue Edouard Belin, F31400 Toulouse, France, Email:sebastien.hess@onera.fr
(2)CNES, Toulouse, France
(3)Airbus Defence and Space, Germany
(4)ESA-ESTEC, The Netherlands

ABSTRACT

Solar panel are key but sensitive elements of spacecraft that produce the spacecraft energy, but are also interacting with the environment, collecting and re-emitting large currents and playing a primary role in the charge state of the whole spacecraft. The different electrical properties of the different materials and the potential bias between the solar cells leads to large potential differences between different elements that may be only separated by a few tens of microns. This generates a risk of potentially destructive electrostatic discharges that can so far only be assessed by experimentation in vacuum chambers. We developed an analytical model of particle collection by small scale elements that is integrated in the large scale simulations of the spacecraft performed by the SPIS software.

1. INTRODUCTION

Electrostatic discharges (ESD) that arise from the differential charging of the spacecraft surfaces has been a subject of concern since the first times of the space age. Many experiments have been performed in plasma chambers on the ground to validate technologies and qualify the spacecraft elements. This is particularly true for solar panels which are by nature composed of very different materials with different electrical properties and are even more sensitive to ESDs since they are producing the spacecraft energy. Because actual solar panels are large structures (tens of meter wide) composed of small elements (centimetre wide solar cells with exposed edges about 100 micrometres wide, millimetre wide interconnects), the accurate numerical simulation of a solar panel is out of reach, at least for fast runs that would allow testing a variety of configurations. The development of new solar panel technologies thus relies on experiments in plasma chambers that are long, costly and thus limited to a few configurations.

In the recent years, new operational needs arose for solar powered spacecraft: electric propulsion that pushes for the development of high voltage and high power solar panels and the replacement of RTGs powered spacecraft for missions exploring the outer solar system that pushes for the development of solar cells working with low temperatures, low intensities and in high radiation environments. This requires developing new technologies and layouts for the solar panels that will power these spacecraft and to validate them. In this context, the possibility of rapidly testing configurations with a numerical method is clearly lacking.

In the past, some attempts have been made to model analytically the collection of particles by the small conductive elements of the solar panel, in order to allow for large scale but still accurate simulations of the solar panels. [1] developed a "biased pinhole model" to model the current collection by interconnects for Low Earth Orbiting (LEO) spacecraft. Such a model was integrated to the NASCAP-LEO software. It is noticeable that LEO spacecraft are particularly concerned by the current collection by the smallest conductive elements of the solar panels since they are orbiting in low temperature plasma (typically about 0.1 eV). Thus, even low voltage solar panels appear to have high voltages when compared to the particle thermal energy. It follows that the focusing effect of the conductor potential is important and may have a non-negligible effect even at the spacecraft scale.

The model [1] derives for the Orbited Limited Motion (OML) law, in which it is considered that the particle collection (or not) by a surface arise from the conservation of its total energy and of its angular momentum. A maximum impact factor for which particles are collected can be computed this way

$$h_0 = l\left(1 + \frac{q\varphi}{kT}\right)^{\frac{N-1}{2}} \quad (1)$$

where l is the geometrical size of the collecting surface, q and T are the charge and temperature of the collected species, φ the potential of the surface relative to the plasma reference potential and N the dimensionality of the system.

This leads to multiply the element effective collecting surface by a factor $\left(1+\frac{q\varphi}{kT}\right)^{\frac{N-1}{2}}$.

The Spacecraft-Plasma Interaction Software (SPIS) also integrates the possibility of taking into account the particle collection by small conductors. It allows the user to define the collection law, but uses a 2D OML law by default. Previous work however showed that unrealistic collection laws – such as laws implying that interconnects collect all the particles that reach the solar panel when having an attractive potential - give results closer to reality that the default OML law. Moreover, the model suffer several limitations: It only split the flux of particles impinging the solar panel into particles collected by either the interconnect or the cover glass but does not modify the impinging particle flux as a function of the interconnect potential; It only affects the collection of particles, and does not affect the particle emission rate, although strongly polarized interconnects may directly recollects the secondary and photo-electrons that are emitted by the cover glasses; It also lack the possibility of computing the interaction for each individual interconnect, rendering impossible to separate between a typical or a worst case situation.

We develop an analytical model of the current collection by small conductive elements on solar panel that allows computing a physically accurate collecting law from the geometrical configuration of the conductive element on the panel. This law is fast enough to compute to be implemented in the SPIS software, allowing accurate simulations of the panel and spacecraft charging at global scale.

2. MODELING CURRENT COLLECTION NBY INTERCONNECTS

Most of the existing current collection laws for small conductors derives from the OML collection law with a supplementary geometrical factor that is determined either by numerical modelling or by measurements. In order to have a more complete model of current collection, the computation of this geometrical model must become part of the model.

Typical OML calculations are made for conductors with a cylindrical or spherical symmetry in a plasma with no other nearby surfaces interfering with the particle motion. In this case, the collection efficiency is the same for all particles regardless of their direction of arrival. This is not representative of a conductor at the surface of a dielectric plane or located in small gaps between dielectric elements. In these cases, all particle trajectories are not allowed as they might cross the dielectric surface. Thus, there is an angular acceptance range for the impinging particles that in to be taken into account in addition to the energetic term in the OML calculation.

First step for the modelling is to consider that at first order the potential structure around an interconnect with a size *l* is the same than that around a cylinder of the same diameter. The potential of this cylinder is a weighted average of the interconnect and cover glass potentials, with the weights corresponding to the inverse of the shortest distances of the interconnect and cover glass to the top point of the cylinder. Then we assume that the maximum impact factor for collection by the interconnect is the same than for the cylinder case for all particles with allowed trajectories. These allowed trajectories remain to be defined.

A similar approach was followed by [2] who computed the plasma collection on the cell edges by deriving an analytical law for the particle collection dependence on energy and convolving it with an angular dependence that was calculated using the Gilbert numerical code. Both [2] and the present models allow for a current collection larger than the usual OML collection. In our case, this is due to the fact that the primary collecting area – i.e. that considered before the field of view computation – is the surface of the equivalent cylinder that is π/2 times larger than the surface of a plane interconnect.

The angular acceptance is derived from the computation of the hyperbolic particle trajectories in the interconnect vicinity. For each particle, the distance between the interconnect centre and its impact point depends on the impact parameter, its incidence angle and its deviation due to the potential. Thus for a given impact factor in the range 0 to h0, we can compute incidence angle of the particle reaching the edge of the interconnect as a function of the interconnect potential. Solutions exist within a range of values for the impact parameter that correspond to incidence angles from 0 to π/2. We name h_1 and h_2 the extremal values of the impact parameters corresponding to incidence angles of 0 and π/2, respectively (Fig. 1).

For impact parameters smaller that the smallest of h_1 and h_2, all particles are recollected whatever their incidence angles. For impact parameters larger the largest of h_1 and h_2, no particles can be collected. The actual computation of these limiting impact parameters shows that they are sigmoid functions of $q\varphi/kT$ with an inflexion point close to $\frac{q\varphi}{kT}=1$. For a zero potential, $h_1 = l = h_0$ and $h_2 = 0$; For an infinite attracting potential, $h_1 = h_0/2$ and $h_2 = h_0$. For an interconnect in a gap, both value are modified by taking into account that the trajectory of the particles must not encounter the cover glass first.

In our model, we approximate the expression of the angular acceptance by separating the evolution of the small and large incidence angle limits. The angular limitation due to the evolution of h_1 is done assuming that $h_2=h_0$ and angular limitation due to the evolution of h_2 is done assuming that $h_1=h_0$. The angular acceptance for an interconnect on a flat dielectric surface is then approximated as:

$$\Delta i = \Delta i_1 + \Delta i_2 - \pi/2 \quad (2)$$

with

$$\Delta i_n = \begin{cases} \frac{\pi}{2} & ; 0 < h < h_n \\ \cos^{-1}\left(\frac{h_n - h}{h_n - h_0}\right) & ; h_n < h < h_0 \end{cases} \quad (3)$$

This expression was chosen as it is easily integrable over h and because it gives exact results in the asymptotical cases.

For interconnects in a gap a third source of angular acceptance limitation must be taken into account which comes from the shadowing of the interconnect by the gap edges. A third limit impact parameter is defined, h_3, which corresponds to the minimum impact parameter for which a particle arriving at grazing incidence reach the interconnect without crossing the dielectric surface.

$$\Delta i = \Delta i_1 + \Delta i_2 + \Delta i_3 - \pi \quad (4)$$

with

$$\Delta i_3 = \begin{cases} \frac{\pi}{2} & ; h_3 < h < h_0 \\ \frac{\pi}{2} - \tan^{-1}\left(\frac{h_3 - h}{h_0}\right) & ; 0 < h < h_3 \end{cases} \quad (5)$$

and $h_3/h_0=\delta h/l$, with δh the depth of the gap. Because the interconnects are not symmetrical both halves of the interconnects are treated independently.

A similar calculation can be performed for estimating the recollection of photo- and secondary electrons, using only the h_2 and h_3 limiting parameters computed for particles emitted from the cover glass rather than for particles with grazing incidence (*Figure 1*).

Finally, for high potentials, the OML factor gets close or bigger than the size of the solar cell, hereafter noted s, and the current gets limited by the finite size of the solar cells. This is taken into account by using a new expression for h_0:

$$h_0 = \frac{2l}{\pi}\left(1 + \frac{q\varphi}{kT}\right)^{\frac{1}{2}} \tan^{-1}\left(\frac{\pi s}{2l\left(1+\frac{q\varphi}{kT}\right)^{\frac{1}{2}}}\right) \quad (6)$$

For 3D modelling, both dimensions of the interconnect are treated separately and the effective collection lengths determined for each dimension are multiplied to get the effective collection surface.

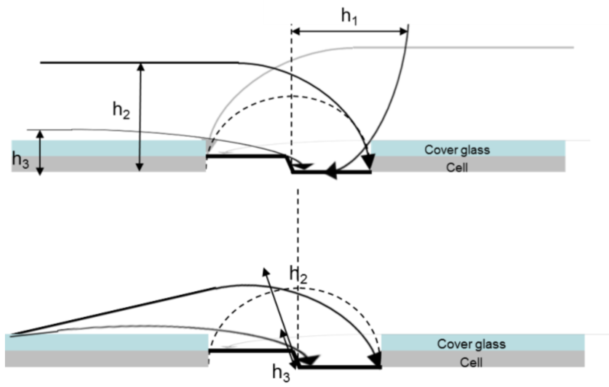

Figure 1: Geometrical description of the collection model. For each halves of the interconnect, the largest impact factors (for normal and grazing incidence) for which particles are collected by the interconnect are computed (h1 and h2 factors). The smallest impact factor for which particles arriving at grazing incidence are collected by the interconnect rather than by the cover glass is also computed (h3). The cases for ambient plasma (top) or secondary electrons (bottom) are computed in similar ways.

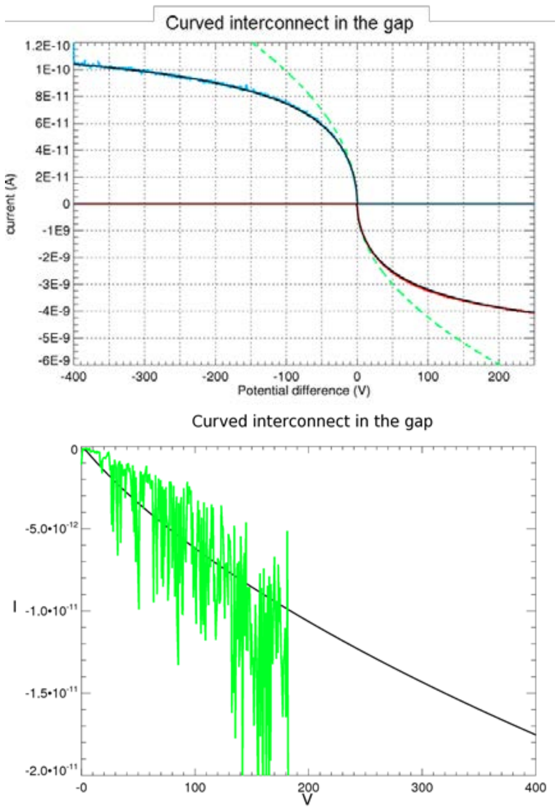

Figure 2: Proton (top-blue curve), electron (top-red curve) and secondary electron (bottom-green curve) currents collected by the curved interconnect down the gap in the SPIS simulation compared to the currents predicted by the model (black curves) and to the 2D-OML model (top-green dashed curve).

3. NUMERICAL VALIDATION

The physical accuracy of the model is verified through numerical computation performed with SPIS. We simulate the collection of plasma particles by an interconnect. The simulation domain is 4x0.2 x4 cm wide. The Z=0 plane is that of the dielectric surface. The gap in which the interconnect lies is in the middle of the X axis, along the Y direction. It is 0.8 mm wide and 0.4 mm deep.

Four different geometries of the interconnect were tested: two perfectly flat interconnects, at the cover glass surface and down the gap and two curved interconnects, at the cover glass surface and down the gap. Fig. 2 shows the simulation results in term of collected currents for the curved interconnect down the gap superimposed to the currents predicted by the 2D-OML model and the present model. The model we developed matches well the current computed from full Particle-in-cell simulations.

4. EXPERIMENTAL VALIDATION

The analytic model we derived has been implemented in SPIS as a new physical module that:

- Splits the incoming currents into a fraction collected by the interconnect and a fraction collected by the cover glass, following the previously determined model.
- Computes the "far field" potential as a surface weighted average of the cover glass and interconnect potentials
- Splits the flux of emitted electrons (photo-electrons and secondaries) into a flux of effectively emitted particles and a flux of directly recollected electrons. For interconnects positive relative to the cover glass, the recollected flux is that of the previously described model, otherwise this recollection is due to the potential barrier caused by the far field and is recollected by the cover glass.
- Monitors the min, mean and max collected currents per interconnect and computes the I(V) curve for each species.
- Provides a simple user interface to define the interconnect and panel geometries.

We use this new physical module to model an experimental set-up corresponding to an experimental campaign performed at ONERA in which a large (1 by 4 metres) solar panel was put in LEO conditions in the JONAS vacuum chamber [3]. An ion source was emitting 1 mA of 20 eV argon ions from one end of the chamber along the panel direction. The ten strings of the panel that are the closest to the ion source are polarized relative to the panel structure from 0V to a potential Vbus. The ten next strings are polarized from Vbus to 0V. The remaining 32 strings are short circuited and grounded to the panel structure. For Vbus ranging from 0V to 350V, the currents collected by each strings and the floating potential of the solar panel were measured.

We reproduce this experiment with SPIS using the plasma parameters of the source and of the JONAS chamber as published in [4]. We run simulations for Vbus=0V, 100V, 200V and 350V. For comparison, we run the older physical module of SPIS describing the current collection by interconnects with its default model (2D-OML model) and with a 3D-OML model. The equivalent interconnect surface for the OML models is such that the effective collection area is the same for the three models at 0V.

Fig. 3 shows the results of the simulations compared to the solar panel floating potential evolution with respect to Vbus. The 3D-OML law reproduces correctly the strong dependence of the solar panel floating potential on Vbus, but fail to give accurate results. The 2D-OML law clearly underestimate the floating potential which is not surprizing since the 2D-OML collection enhancement for a Vbus=350V equals that of the 3D-OML model for Vbus=6V. The present model gives the best fit of the experimental values, with an error of the floating potential smaller than 20%. Such a result is acceptable since the panel current circuit is not exactly reproduced in the simulations.

5. APPLICATION TO TARANIS

The results from the experiments and simulations seems to predict a catastrophic effect of the interconnect polarization for LEO satellite. To further investigate the impact of the interconnect potential on the spacecraft in LEO we simulated the charge state of the TARANIS mission. We use the same model than that used in [5], with a Poisson-Boltzmann approximation for the ions and electrons. We used a dedicated interface in SPIS to reproduce TARANIS solar panel wiring (Fig. 4).

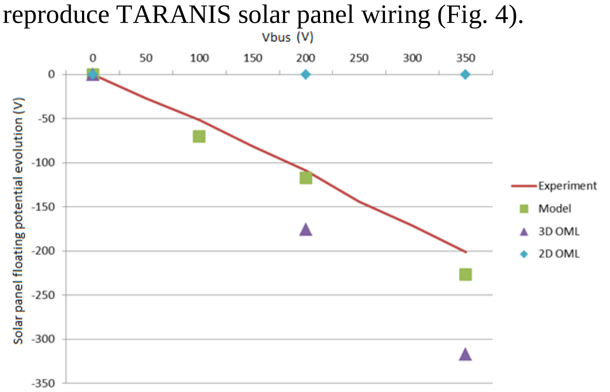

Figure 3: Evolution of the solar panel floating potential with respect to the bus potential in experiments (red line), for the 2D-OML model (blue diamonds), the 3D-OML model (purple triangles) and for the present model (green squares).

TARANIS solar cells have thick (~500µm) cover glasses covered by a grounded ITO layer. The gaps between cells are narrow (~500µm) and grouted. We simulated the charge state of TARANIS in this configuration and without grouting. No noticeable differences in the surface potentials were observed.

The difference between the simulation of the experiments in the plasma chamber and that of TARANIS may be explained in several ways. First TARANIS bus voltage is about 30V, much smaller than the hundreds of Volts in the experiments; Second, the gap is deeper and narrower in the TARANIS case; Third, the solar panel surface does not represent the majority of the TARANIS surface; Finally, the Poisson-Boltzmann approximation used in the TARANIS simulation does not take into account the drift of the ions. Thus, further analysis are required to investigate to influence of the interconnects on the spacecraft potential, but it is already possible to state that this effect is not necessarily large for all configurations.

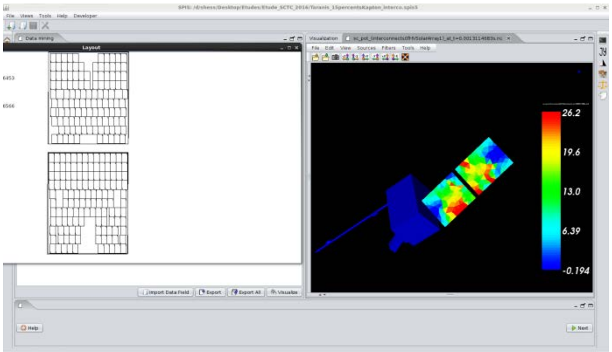

Figure 4: Screenshot of the SPIS layout configuration panel for the TARANIS simulation and the resulting interconnect potential map.

6. CONCLUSION

We present a new analytical model of current collection by the interconnects that has been validated against simulations and then implemented in the SPIS software, allowing simulations of large spacecraft taking into account the effect of the interconnect polarization. This implementation has been validated against experiments in the JONAS plasma chamber at ONERA and applied to the CNES TARANIS mission.

7. ACKNOWLEDGEMENTS

The model of current collection by the interconnects has been partially funded by ESA/ESTEC contract 4000113120. The TARANIS simulation and the experiments in the plasma chamber have been performed under CNES contracts and a PhD grant.

8. REFERENCES

1. Mandell, M.J., and Katz, I. (1983). Potentials in a Plasma over a Biased Pinhole. IEEE Transactions on Nuclear Science 30, pp 4307-4310
2. Mandell, M.J., Davis, V.A., Gardner, B., Jongeward, G., (2003). Electron collection by international space station arrays. Proceedings of the 8th Spacecraft Charging Conference
3. Siguier, J.-M., Inguimbert, V., Murat, G., Hess, S., Payan, D., Gloagen, E. (2016).Plasma Current Collection of High Voltage. Proceedings of the 14th Spacecraft Charging Conference.
4. Matéo-Vélez, J.-C., Roussel, J.F., Sarrail, D., Boulay, F., Inguimbert, V., Payan, D. (2008). Ground Plasma Tank Modeling and Comparison to Measurements. IEEE Transactions on plasma science, vol. 36, no. 5, pp 2369-2377
5. Jorba-Ferro, O., Hess, S., Seran, E, Godefroy, M., Bastien-Thiy, C., Payan, D., (2016). Modeling the Electric Charging of the TARANIS Satellite in the Ionospheric Plasma. Proceedings of the 14th Spacecraft Charging Conference.