SPARCS: AN ADVANCED SOFTWARE FOR SPACECRAFT CHARGING ANALYSES

S. Clerc
Alcatel Space
100 Bd du Midi
FR-06156 Cannes La Bocca Cedex
Phone: +33 4 92 92 64 83
Fax: +33 4 92 92 69 70
E-mail: sebastien.clerc@space.alcatel.fr

S. Brosse
Alcatel Space

M. Chane-Yook
INRIA, Sophia-Antipolis, France

Abstract

We report on the development of SPARCS (SPAcecRaft Charging Software), a simulation tool for spacecraft charging analyses. The code computes electron and ion currents from the magnetosphere on the surfaces of the satellite with a back-trajectories algorithm. Secondary emission and photo-emission currents are computed using standard models. Special care is given to the computation of recollected secondary electrons. The current balance is used to update the absolute and differential potentials.

The code also computes the potential around the spacecraft, which is in turn used to compute electrons and ions collection. In a geostationary environment, space charge can be neglected. The resulting Poisson equation is solved with a Finite Element method on an unstructured mesh, coupled with Infinite Elements to enforce the correct decay of the potential at infinity. Large time steps can be used thanks to a quasi-implicit method.

We describe our validation strategy and give some preliminary results of this work program.

Finally, optimization of the linear system solver with the HYPRE library and parallelization keep the run time low, making SPARCS a fast and accurate tool for spacecraft charging analyses.

Introduction

At Alcatel, numerical modeling plays a crucial role in the management of electrostatic risks arising from spatial charged particles. However, the old version of the reference code NASCAP/GEO currently in use has several limitations. We have therefore decided to develop a new computer code, SPARCS, to perform charging simulations with up-to-date numerical modeling. This effort started in 1998 with a Ph. D. work [1,2] and resulted this year in the first release of a 3D code for spacecraft charging computations in geostationary environment. The aim of this paper is to describe this code in terms of physical and numerical models and capabilities. We also provide some information on our validation strategy and on the parallelization of the code.

Physical Model

The current version of the code is specifically designed for low-density, collisionless, hot plasma found in geostationnary environment during substorms. In this situation, it is legitimate to neglect space charge effects. We thus solve the stationary Vlasov-Poisson equations for the plasma and electrical potential:

$$\begin{cases} mv \cdot \nabla_x f_\alpha + q \nabla_x \varphi \cdot \nabla_v f_\alpha = 0, \\ \Delta \varphi = 0, \end{cases}$$

with suitable boundary conditions.

Classical models are used for secondary electron emission, back-scattering, ion- and photon- induced emission, as well as conductivity of the materials (cf. [3]). Another important aspect of the model is the computation of recollected secondary electrons: this point will be described in more details below.

The differential charge of the dielectric materials and the absolute charge evolves according to the value of the local or global current balance respectively. The code can compute accurate transients or steady-state solutions through time-marching.

Numerical Model

A computational volume is defined around the spacecraft and discretized with elementary thetrahedra. The use of an unstructured mesh has several advantages over that of a structured mesh:

- ✓ Easy modeling of complex shapes (e.g. antennas, scientific instruments)
- ✓ Automatic meshing
- ✓ Easy local refinement.

The Laplace equation is solved on this domain by a P1 finite element method, coupled with an Infinite Element method on the outer artificial boundary to enforce the proper decay of the potential at infinity. The resulting linear system is solved by a conjugate gradient method.

The surface of the spacecraft is discretized in elementary triangles. On each of these triangles the distribution of incident ions and electrons is computed. The half-space of incoming velocity vectors is discretized on a regular grid. For each incident velocity of the grid, the particle is back-tracked to its starting point on the boundary of the computational domain (see Figure 1). By Liouville's principle, the value of the distribution function is constant along this trajectory, and this value is known on all boundary conditions for incoming particles. The case of secondary electrons emitted from satellite surfaces is treated likewise (see below).

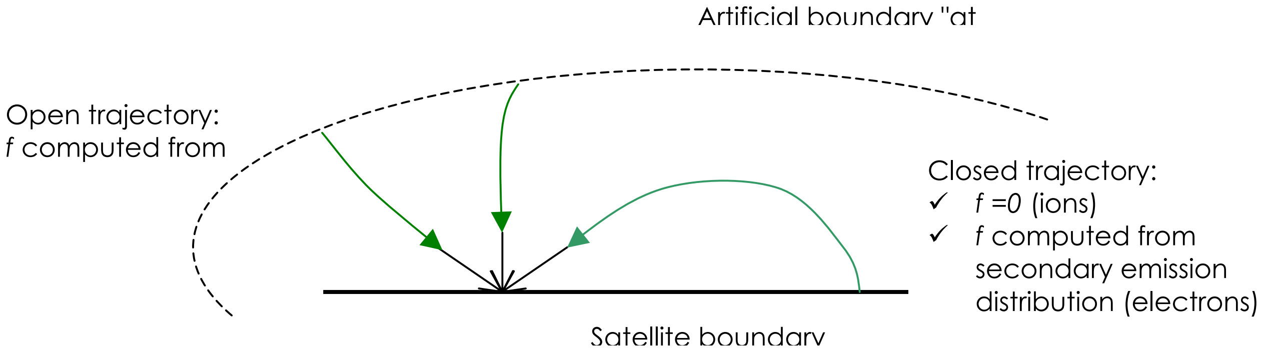

Figure 1. Computation of particle distribution by the back-trajectory algorithm.

Once the incident current of electrons and ions is known, secondary emission and bulk conduction current can be computed. To determine the value of photo-emission current, lighting of each surface (including cast shadows) is computed.

Current balance equations are then used to update the value of absolute and differential potentials. The evolution equation for the absolute potential reads

$$\varepsilon_0 C_{abs} \partial_t \varphi_{abs} = \int_{\Gamma} J ,$$

where C_{abs} is the absolute capacity and the right hand side is the integral of the total current on the spacecraft metallic structure. In order to stabilize the computation with relatively large time-steps, we use a quasi-implicit time-stepping procedure:

$$\varepsilon_0 C_{abs} \frac{\varphi^{n+1}_{abs} - \varphi^{n}_{abs}}{\delta t} \approx \int_{\Gamma} J^n + \tilde{J}' \cdot \left(\varphi^{n+1}_{abs} - \varphi^{n}_{abs} \right),$$

where $\tilde{J}'$ is an approximation of the differential of the total current. A suitable choice for the latter is the differential of the total current on a sphere, which can be computed analytically.

Finally, the value of the potential around the spacecraft is computed and a next time-step can be processed.

Recollection of Secondary Electrons

In geostationary environment, secondary (and photoelectric) emission is limited by the formation of local potential barriers. These barriers are created either by the space charge of the electron cloud or by the configuration of the electric field due to differential charging. Since space charge is not computed in SPARCS, only the second effect is currently modeled.

Also note that potential barrier is not the only phenomenon which leads to electron recollection: two surfaces facing each other will recollect all re-emitted electrons regardless of their energy (screening effect).

The recollection current is computed on satellite surfaces in much the same way as the incident current (see Figure 1). The velocity discretization takes into account the smaller value of the temperature of these electrons. In the absence of specific information on the distribution of secondary an photo-electrons, a Maxwellian distribution with temperature 2 eV is assumed. However, this is not a limitation of the code, and we plan to use better descriptions in the future.

Secondary electrons hitting satellite surfaces will in turn yield new secondarys, in an electron multiplying process. Ideally, this current should be computed and iterations performed until self-consistency is reached. For the sake of simplicity, we chose to neglect this effect.

Validation Strategy

Our validation strategy is composed of three steps:

- ✓ Analytic test cases (sphere)
- ✓ Cross-comparison with other codes
- ✓ Validation with experimental data (on ground and flight)

We have first validated the implementation of the physical models by computing the charging of a sphere and comparing with semi-analytic MATLAB results. Models for each of the secondary emission processes were validated independently. SPARCS calculations were shown to be accurate. As an example, we give the results of the charging of a sphere with magnetospheric currents, back-scattering of electrons, ion-induced secondary current and photo-emission.

Table 1. Example of analytic results on a conducting sphere

	Analytic results	SPARCS results
Potential (V)	-7098.2	-7014.6
Primary electrons (A/m^2)	2.65 10^{-6}	2.67 10^{-6}
Backscattered electrons (A/m^2)	5.836 10^{-7}	5.85 10^{-7}
Ration J_e^{back}/J_e	0.22	0.219
Protons (A/m^2)	1.196 10^{-7}	1.19 10^{-7}
Secondary electrons due to protons	1.448 10^{-6}	1.47 10^{-6}
Ration J_e^{ions}/J_e	12.11	12.38
Photo-emission (A/m^2)	5 10^{-7}	5 10^{-7}

In a second phase, we perform cross-comparisons with NASCAP/GEO [3] on a typical telecom spacecraft. This work is still under progress. We present below some preliminary results of the study. In Figure 2 we show the evolution of the absolute potential during an eclipse and in Figure 3 the differential potential after 10s. More results will be published elsewhere.

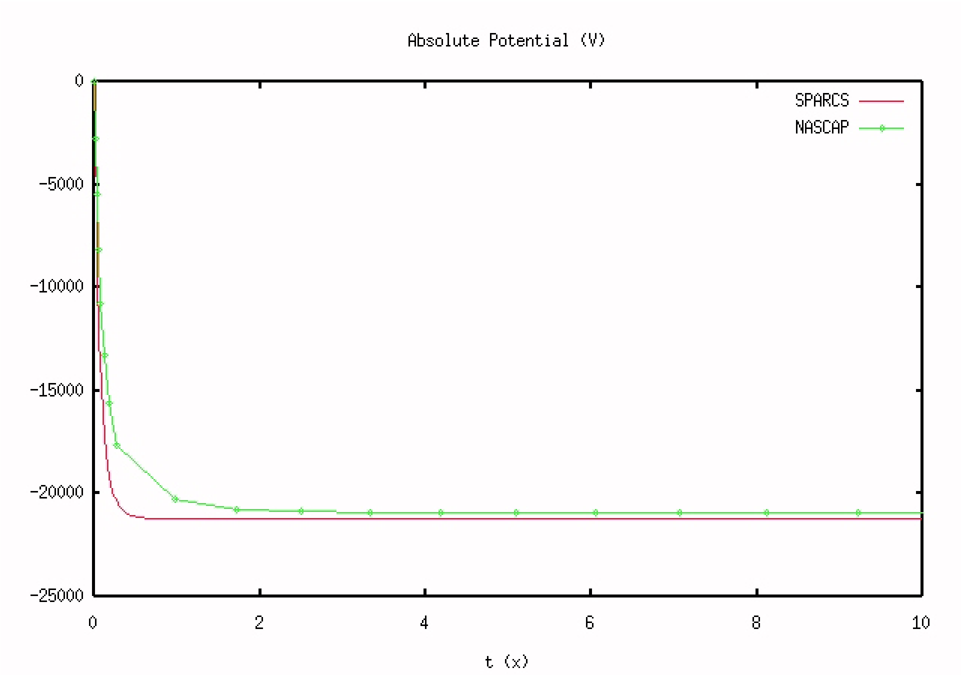

Figure 2. Charging of telecom spacecraft in eclipse.

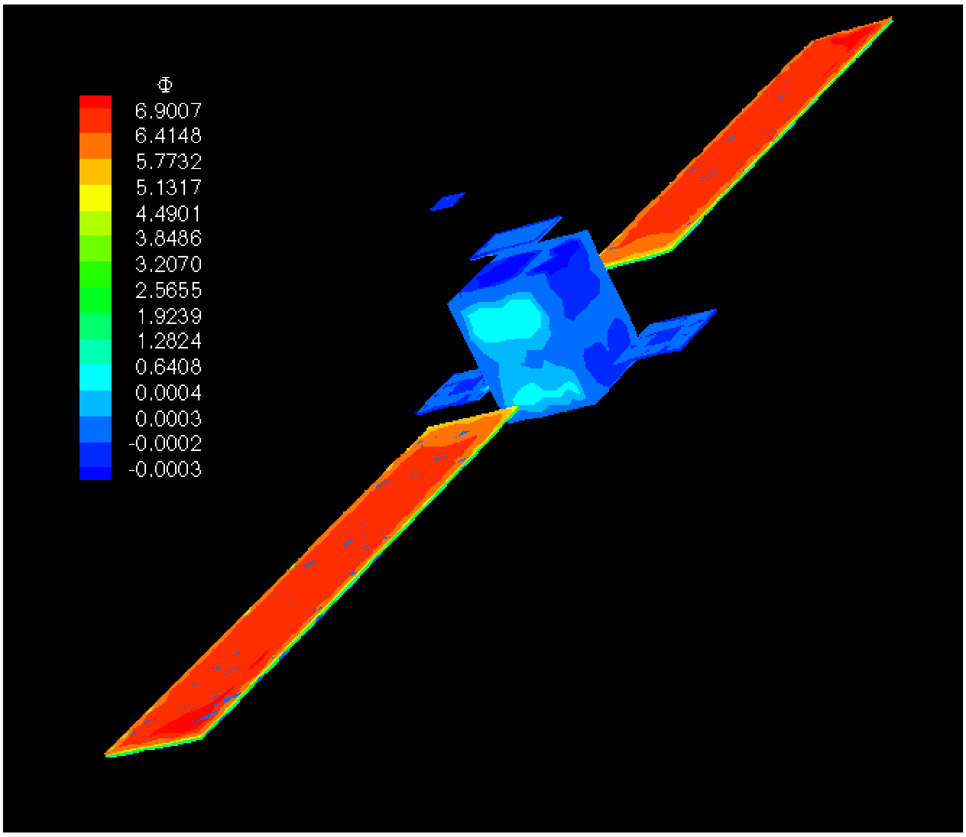

Figure 3. Differential potential on satellite surfaces after 10s.

The third phase will consist of comparisons with experimental ground and flight data. The tentative qualification program is the following:

- ✓ Charging of a material coupon in the SIRENE (large spectrum electron gun) facility at ONERA. The aim is the validation of secondary emission and conductivity models.

- ✓ Potential barrier build-up experiment. The future experimental set-up aims at validating models of secondary of photo- emission current limitation by potential barrier build-up mechanism. This project should be launched in year 2004.

- ✓ We are also thinking about investigating the charging of a complete satellite mock-up in a plasma chamber. This study should benefit from the output of the potential barrier build-up experiment, and would thus start in 2005 approximately.

- ✓ Finally, we are considering an in-flight experiment on a telecom satellite. Another benefit of this work would be to assess the representativity of experimental ground facilities.

Parallelization

It is well known that plasma simulation is very costly in terms of computational time, mainly because problems are set in a high dimensional space ($\mathbf{R}^7$ for time-dependent problems). Even with the important simplification of neglecting space-charge effects, it was found desirable to speed up computations by using parallelization techniques.

In view of this point, we have used two different parallelization paradigms. First, we have used the OpenMP library to distribute the computation of particle trajectories between processors. On the other hand, the HYPRE library [4] was used for the solution of the linear system arising from the Finite Element discretization of the Poisson problem. A state-of-the art Agglomeration Multigrid preconditioner was used to improve the convergence of the conjugate gradient iterative method. The parallelization relies on the MPI library and thus works on computers with distributed memory (e.g. PC clusters). While this dual, shared memory/distributed memory approach yields optimal performance for each task, it is quite cumbersome in terms of portability. This is why we will probably have to rethink the parallelization strategy in the future.

In the meantime, it is often sufficient to parallelize only the particle trajectories to ensure a significant speed up. On a HP GS320 computer, using 4 processors, we have observed a parallel efficiency ranging from 74 to 99 % depending on the cases.

Conclusion

The SPARCS project aims at providing an advanced spacecraft charging software for electrostatic discharge protection analyses. Thanks to innovative numerical treatment and parallelization, we are able to make accurate simulations within a reasonable run-time. In the future, we will concentrate on validation efforts and extensions to other plasma environments (LEO and artificial thruster plasma).

References

1. O. Chanrion, Simulation de l'influence de la propulsion plasmique sur la charge électrostatique d'un satellite en milieu magnétosphérique, Ph. D. thesis, École Nationale des Ponts et Chaussées, 2001.

2. O. Chanrion, Electrostatic charging simulation of spacecraft using a stationary plasma thruster in geostationary plasmic environment, 7th Spacecraft Charging Technology Conference, Noordwijk, The Netherlands, 2001

3. Stannard P.R., Katz I., Gedeon L., Roche J. C., Rubin A.G. and Tautz M.F., Validation of the NASCAP model using spaceflight data, 20th Aerospace Sciences Meeting, Orlando, Florirda, 1982.

4. Falgout, R. D., and Yang, U. M., "hypre: a Library of High Performance Preconditioners," in Computational Science - ICCS 2002 Part III, P.M.A. Sloot, C.J.K. Tan. J.J. Dongarra, and A.G. Hoekstra, Eds., Lecture Notes in Computer Science, vol. 2331, pages 632-641, 2002, Springer-Verlag.