FEATURES OF CHARGING OF COMPOSITE CONFIGURATION SPACECRAFT CHARGING IN HIGH ORBITS

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Abstract

Typical feature of spacecraft charging in geosynchronous and high-elliptical orbits in hot magnetosphere plasma is formation of electrostatic potential distribution on the spacecraft surface (differential charging) and complexity of the charging dynamics. For mathematical simulation of spacecraft charging in high orbits, the modified version of the COULOMB program tool was developed in D.V.Skobeltsyn Institute of Nuclear Physics of Moscow State University.

The program tool enables to study dynamics of the spacecraft charging processes in high orbits in various conditions of the spacecraft environment for the spacecraft models with large number of discretization elements.

In the report, the results of modeling of the composite configuration spacecraft charging taking into account the peculiarities of their design and charging conditions are presented.

Introduction

Typical feature of spacecraft charging in geosynchronous and high-elliptical orbits is differential charging of the spacecraft surface dielectric materials. Differential charging is determined by various of electric current on different elements of the spacecraft which has composite geometrical shape. The very important role in formation of the differential current picture of the spacecraft surface elements enlightened by the Sun is played by process of external photoelectric effect, as the initial photoelectric current is superior to all remaining component of the full current.

The modern model of the spacecrafts charging in high-altitude orbits should be are capable to reveal and to research the mentioned above typical features of the charging process, and to describe dynamics of potential and current distribution on the spacecraft surface correctly in various time scales, and to take into account composite structure of the electrical field near to inhomogeneous and geometrically composite spacecraft configuration elements.

Therefore, we have improved physical and mathematical model and the COULOMB program complex for description of spacecraft charging processes in geosynchronous and high-elliptical orbits, which were developed in D.V.Skobeltsyn Institute of Nuclear Physics of Moscow State University (SINP MSU) at the end of 80^{th} – beginning of the 90^{th} years[1, 2, 3, 4] and were based on big computers of the 3^{rd} generation. Considerable progress in computer performance, development of interactive capabilities of PCs have allowed to achieve the qualitatively new level of physical and mathematical models and software for computer simulation of the spacecraft charging in high orbits.

In the paper, basic principles of physical and mathematical model of the spacecraft charging in high orbits are presented, computation results obtained for the model of typical composite shape spacecraft of the are submitted, and the analysis of main features of charging in various conditions of the spacecraft operation is done.

Physical and Mathematical Model of the Spacecraft Charging in High Orbits

The physical and mathematical model of the spacecraft charging in high orbits includes the description of the spacecraft geometrical model, electrophysical characteristics of construction materials of the spacecraft, properties and parameters of hot magnetosphere plasma.

Description of the Spacecraft Model

The model of spacecraft is constructed in terms of a set of basic geometric primitives, integrated in a hierarchic tree structure. Following simple geometrical surfaces and their fragments are used as basic primitives: plane, diaphragm, cylinder, sphere, cone, torus. For each elementary surface, type of material (dielectric or metal) and its electrophysical characteristics taken from appropriate base of the spacecraft construction materials (thickness, conductivity, properties of secondary emission arising at impact of hot space plasma components and of the Sun ultra-violet radiation) are set.

The base three-dimensional surface $F(x, y, z) = 0$ in local coordinate system is described parametrically using the two dimensional system of parametric coordinates: $x=x(t, v)$, $y=y(t, v)$, $z=z(t, v)$. Each surface is triangulated separately into elementary triangles by even grid in the a parametric coordinate system (t, v). The elements are grouped in units and are placed in global coordinate system with the help of translation and rotation of local coordinate system. Finally, the surface of the spacecraft model is described as a grid of large number of elementary triangles. Number of triangles in the each geometrical surface, the triangles sizes, and the total number of elementary triangles can vary in the wide range determined by the spacecraft design features and the computing problem peculiarities.

The system of computer visualization of the 3D spacecraft models and graphical presentation of the computation data on values describing the spacecraft charging (distribution of potential, electric charge, electric field intensity etc.) is closely connected to the program of the spacecraft model construction. As universal graphic interface, the free and commercial VRML browsers (FREEWRL, OpenVRML, Cortona, Cosmo Player etc) are used in the program complex.

Description of the Hot Space Olasma in High Orbits

The hot plasma power electron and ion energy spectra in the region of geosynchronous orbit occupy energy range from 0.05 up to 100 keV. It is shown in[5, 6] that the distribution function of the hot magnetosphere plasma particles is correctly approximated by superposition of two Maxwell distributions with energies $kT_1 \cong$ 0.2-0.4 keV and $kT_2 \cong$ 5-10 keV

$$f_j(v_j) = n_{1j}\left(\frac{m_j}{2\pi kT_{1j}}\right)^{3/2} \exp\left(-\frac{m_j v_j^2}{2kT_{1j}}\right) + n_{2j}\left(\frac{m_j}{2\pi kT_{2j}}\right)^{3/2} \exp\left(-\frac{m_j v_j^2}{2kT_{2j}}\right),$$

where n_j - density *j*-th type of particles (electrons, protons or other heavier ions) for components with temperatures T_1 and T_2 accordingly; m_j, v_j - mass and velocity of particles, k - Boltzmann constant.

Program of Solution of the Spacecraft Charging Problem in High Orbits

The spacecraft charging process in high orbits is described by the following set of equations.

1. The potential $\mathrm{U}(\mathrm{r})$ in a point r at time t in rare plasma satisfies the Laplace equation: $\Delta \mathrm{U}(\mathbf{r},t) = -4\pi\rho(\mathbf{r},t)$.

2. The distribution function of primary and secondary particles on velocities $\mathbf{v}$, $\mathrm{f}_\alpha(\mathbf{v},\mathbf{r},t)$, obey to the collisionless Vlasov equation:

$$\mathbf{v}\frac{\partial \mathrm{f}_\alpha}{\partial \mathbf{r}} + \frac{q_\alpha}{m_\alpha}\frac{\partial \mathrm{U}}{\partial \mathbf{r}}\frac{\partial \mathrm{f}_\alpha}{\partial \mathbf{v}} = 0,$$

where index α corresponds to particles with mass m_α, charge q_α and velocity $\mathbf{v}$.

3. The description of processes of interaction of charged particles and solar radiation with the spacecraft surface is described by the set of coupling equations:

$$\mathrm{f}_\alpha(\mathbf{v},\mathbf{r},t) = \int \mathrm{d}\mathbf{x}(\mathbf{vn})\sum_{\alpha'} \mathrm{F}^{\alpha\to\alpha'}(\mathbf{v},\mathbf{v}',\mathbf{n})\mathrm{f}_{\alpha'}(\mathbf{v},\mathbf{r},t),$$

where the factors $\mathrm{F}^{\alpha\to\alpha'}(\mathbf{v},\mathbf{v}',\mathbf{n})$ are the probability characteristics of various processes (e.g. secondary emission process).

4. Local current density on the spacecraft surface taking into account the internal conduction currents:

$$\mathrm{j}(\mathbf{r},t,\mathrm{U}) = \sum_\alpha \int \mathrm{d}\mathbf{v} q_\alpha(\mathbf{vn})\mathrm{f}_\alpha(\mathbf{v},\mathbf{r},t) + \mathrm{j}_{cond}(\mathbf{r},t,\mathrm{U}),$$

where $\mathrm{j}_{cond}(\mathbf{r},t,\mathrm{U})$ – of conduction current density.

5. Full current on the spacecraft:

$$Q(t)=\int_S dS \int_{-\infty}^{t} J(\mathbf{r},t')dt'$$

6. For thin dielectric coatings on the conductive spacecraft ground, the spacecraft boundary conditions for the Laplace equation differentiated in time in approximation of double electrical layer is following:

$$-\frac{\left(\frac{dU}{dn}\right)}{dt}+\frac{\varepsilon(\mathbf{r})}{d(\mathbf{r})}\left(\frac{d\,U(\mathbf{r},t)}{dt}-\frac{d\,U_c(t)}{dt}\right)=4\pi j(\mathbf{r},t),$$

Here:

ε - dielectric permittivity of the material;

d - thickness of the material;

$U_c(t)$ - the potential of the metal ground under the dielectric.

For numerical solution of the electrostatic problem in 3D space instead of the differential problem, the method of integral equations is used in which the unknown value of the surface charge density is connected with the given value of the potential on the spacecraft surface:

$$U(\mathbf{r})=\int_S \frac{\sigma(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}dS'+\int_S \frac{\mu(\mathbf{r}')((\mathbf{r}-\mathbf{r}')\mathbf{n})}{|\mathbf{r}-\mathbf{r}'|^3}dS' \quad ,$$

where $\mu(\mathbf{r})$ - density of electrical dipole moment of the double electric layer in the surface point $\mathbf{r}$.

For numerical solution of this integral equation, the method of boundary elements in which the considered values are decomposed in basic functions is used. As the result, the system of linear equations for the charge densities σ_i on discrete parametric elements of the spacecraft model is following:

$$\sum_j \mathbf{A}_{ij}\sigma_j=U_i^* \quad ,$$

where $\mathbf{A}_{ij}$ - matrix of Coulomb interaction of elements, U_i^* - "effective" surface potential of element describing contribution of space charge, and of electrical dipole moment to the potential.

Taking into account features of the considered problem, the inverse matrix of the Coulomb interaction is computed on preliminary step to rise efficiency of computation, and the charge density is evaluated on each time step not with the help of the equation set solution, but by multiplying of the matrix by vector, that considerably increases the computation rate.

$$\sum_j \mathbf{A}_{ij}^{-1}U_i=\sigma_j$$

Thus, the development of the spacecraft charging process in time is described by the system of coupled differential equations for potentials of elementary triangles of the spacecraft surface[7] :

$$\frac{\partial}{\partial t} U_k(t) = \mathbf{G}_{kl} j_{toatl,l}(t)$$

where $\mathbf{G}_{kl}$ - matrix, the elements which are calculated for the spacecraft surface configuration and for given properties of the dielectric coating materials.

Due to composite relation between the current density and the value of the potential, the solution of the set of equations above can be obtained only by numerical integration.

On each integration step the following calculations are carried out:

– in terms of values of potentials on elementary surfaces determined earlier (initial values or ones found on the previous integration step), the values of the electric field intensity on the spacecraft surface elements are calculated;

– in terms of the values of potentials and electric field intensities, the local primary currents for given elementary surfaces are calculated;

– in terms of the computed values of local primary currents and supplementary data on the secondary emission properties of materials of the surface, local secondary currents and photoelectric currents are evaluated taking into account the suppression of the secondary electron and photoelectron output by external electrical field;

– the currents between elementary surfaces and their fragments and spacecraft design elements are calculated in terms of the supplementary parameters on electrical conductivity of materials.

Thus, the iterative loop of the solution of the set of equations above is executed till condition of the current balance on each surface element is achieved, that allows to obtain the equilibrium distribution of the potential on the spacecraft surface.

It is necessary to underline, that rates of potential variations on various spacecraft surface elements and design of can be, generally speaking, significantly different, and may differ on the orders of magnitude. Therefore, Gear method with automatic selection of the integration order and integration step[8] specially developed for solution of “rigid” systems of differential equations was used for computer simulation of development of the spacecraft charging processes in time. The increase of modern PC performance has enabled to use this method for the spacecraft models with number of elements up to ~2000. The test calculations displayed high stability and accuracy of the methods used even at destabilizing influence of the spacecraft model discretization.

The technique developed is applied to the analysis of the spacecraft charging processes in high orbits under different conditions.

Computation Results

The technique above enables to find potentials of separate spacecraft surface elements as function of time, and to determine typical charging times required to achieve the steady state values. It enables also to calculate distribution of the electrical field on the spacecraft surface and in the spacecraft environment, to build 2D maps of the potential distribution in given cross-sections of space.

As an example, the results of computer simulation of the real spacecraft charging in geosynchronous orbit are presented in figs. 1-5. Special method of color code was developed for visualization of the potential distribution on the spacecraft surface. In the method, the spacecraft VRML-model elements of which are painted in colors (or using greyscale for black and white figures) corresponding to the potential values (see the scale in fig. 1). 2D maps of the potential distribution in the spacecraft environment at various moments of time *t* are shown in figs.1-4 (top) with potential values on lines. Corresponding screenshots of the painted spacecraft VRML-model is shown in the bottom of the figures. Arrows show direction of the Sun light. Computation parameters values corresponding to the charging conditions in geosynchronous orbit are following: hot plasma density 1.0 cm^{-3}, hot plasma temperature 10 keV, photoemission current $1.0 \cdot 10^{-8}$ $A \cdot cm^{-2}$.

Fig.1 shows the initial stage of the charging process when the potential is practically constant on the spacecraft (integral charging). Moving from fig. 1 to figs. 2, 3 and 4 (steady state), one can see the arising and development of the potential distribution distortion (differential charging) due to photoemission on the lightened side of the spacecraft. Distortion of the electric field in the vicinity of the spacecraft and variations of the electrostatic potentials of different spacecraft elements achieve maximal values in the steady state. At the same time, the potential of the metal spacecraft ground increases (in absolute value), and the potential difference between the metal ground and the dielectric surface elements increases too. It is important that the equipotential lines in fig.4 show typical electric field configuration ("saddle point") suppressing the secondary electron and photoelectron output from the spacecraft surface.

In fig. 5, potentials on the lighted spacecraft elements and on the dark ones, and the metal ground potential as function of time are shown. One can see that steady state is reached at $\sim 1.0.10^4$ s in the charging conditions above. Note that the charging time in the given environment conditions depends on the electric properties of the spacecraft surface materials. The connection between the material parameters and the charging time value is rather difficult, e.g. decrease of conductivity of the surface materials in the range $10^{-15} – 10^{-19}$ $(Ohm.cm)^{-1}$ leads to increase of the charging time by a factor of ~5.

The computation results presented in figs. 1-5 demonstrate features which are typical for spacecraft charging process in hot magnetosphere plasma. We see that the problem is non-local: electric field on an element of the spacecraft surface influences the process of charging not only on this element but on the other elements of the spacecraft. As an example of the effect, we see that distribution of potential along the solar battery plane (fig. 4) is noticeable.

The modeling technique and the developed visualization tools enable to show the development of the "saddle point" configuration of the electric field (figs. 3, 4), and the effect of shielding of spacecraft design elements by the other ones. Influence of these features on the spacecraft charging depends significantly on the spacecraft design.

Note that the spacecraft charging time is rather high, and the steady state may be unreachable in the real space flight conditions (e.g. when the time of the spacecraft pass through the hot plasma region is short). The modeling technique enables to make prediction of the spacecraft charging in this case too, as far as in the case of rotating spacecrafts.

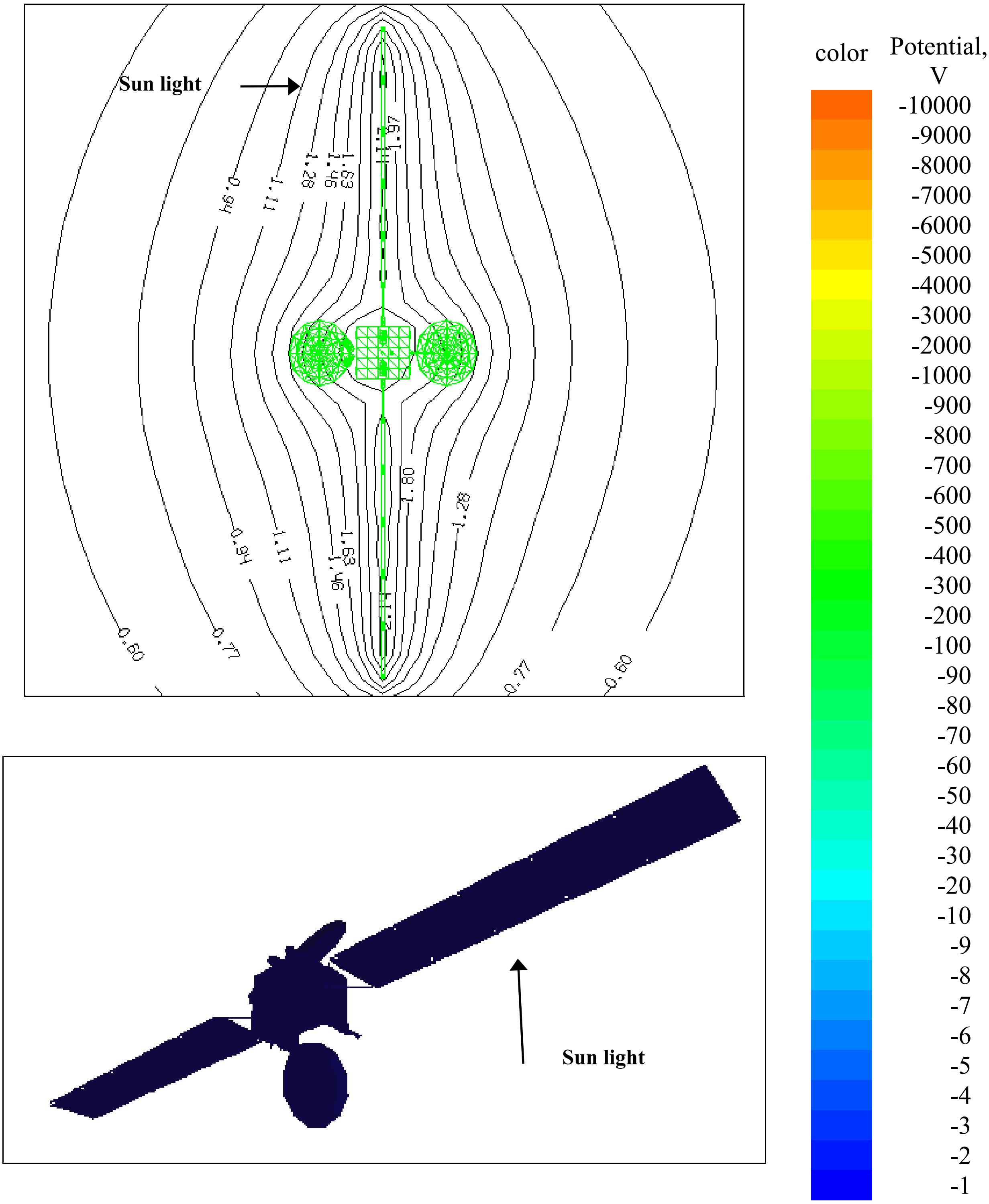

Figure 1. Spacecraft charging at t=1.3.10^{-3} s. Color code scale is on the right

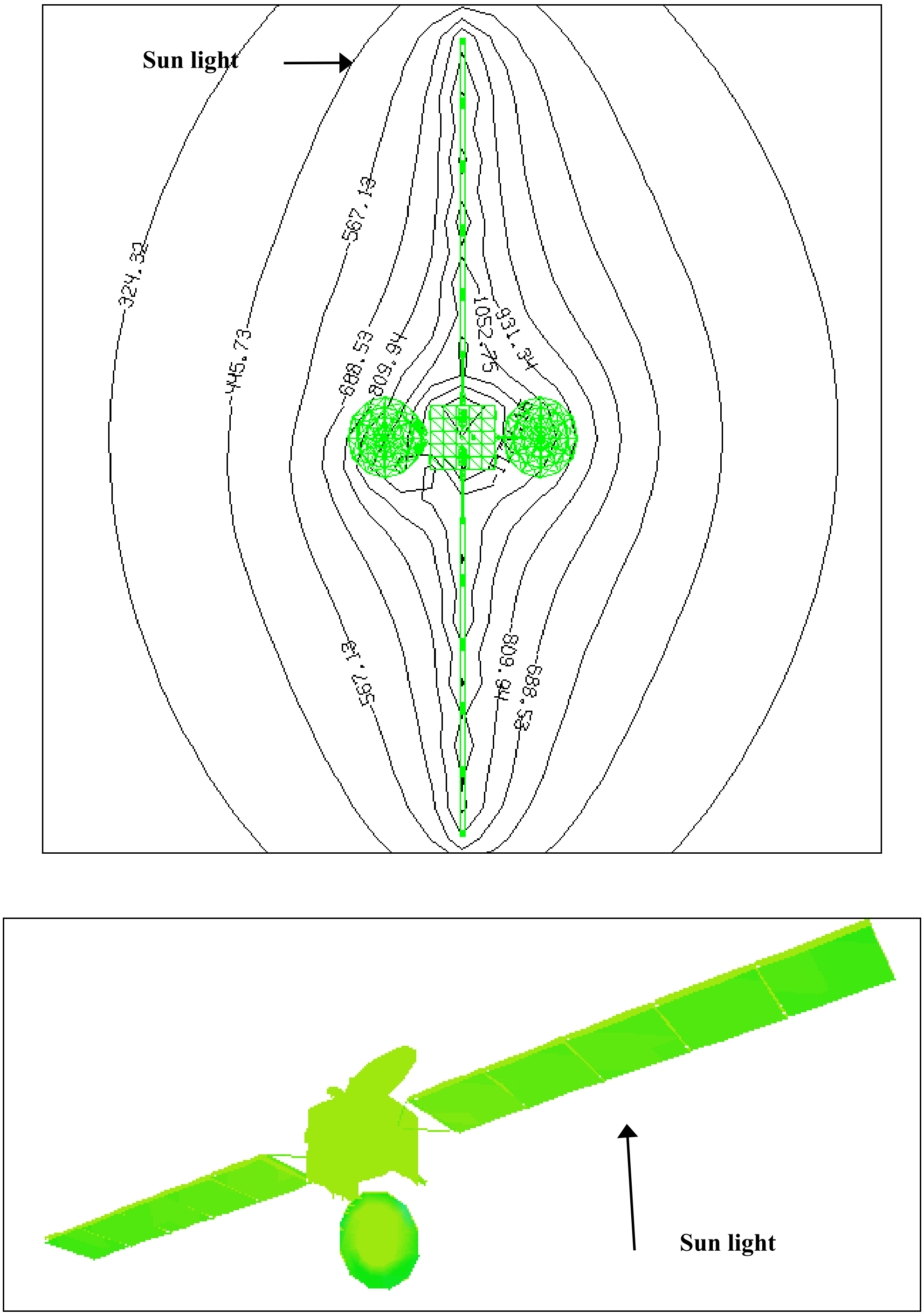

Figure 2. Spacecraft charging at t=3.0.10^2 s.

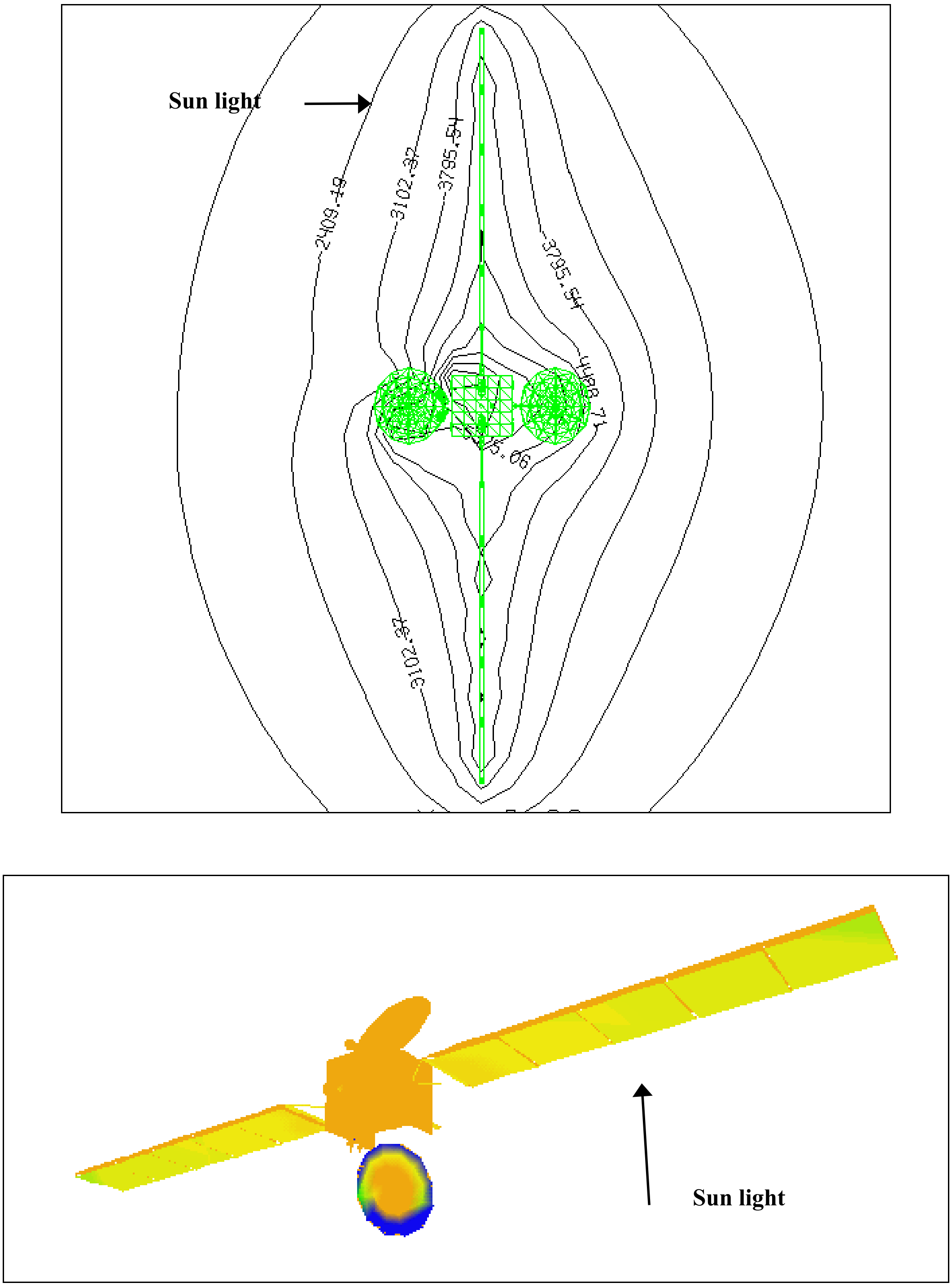

Figure 3. Spacecraft charging at t=2.9.10^3 s

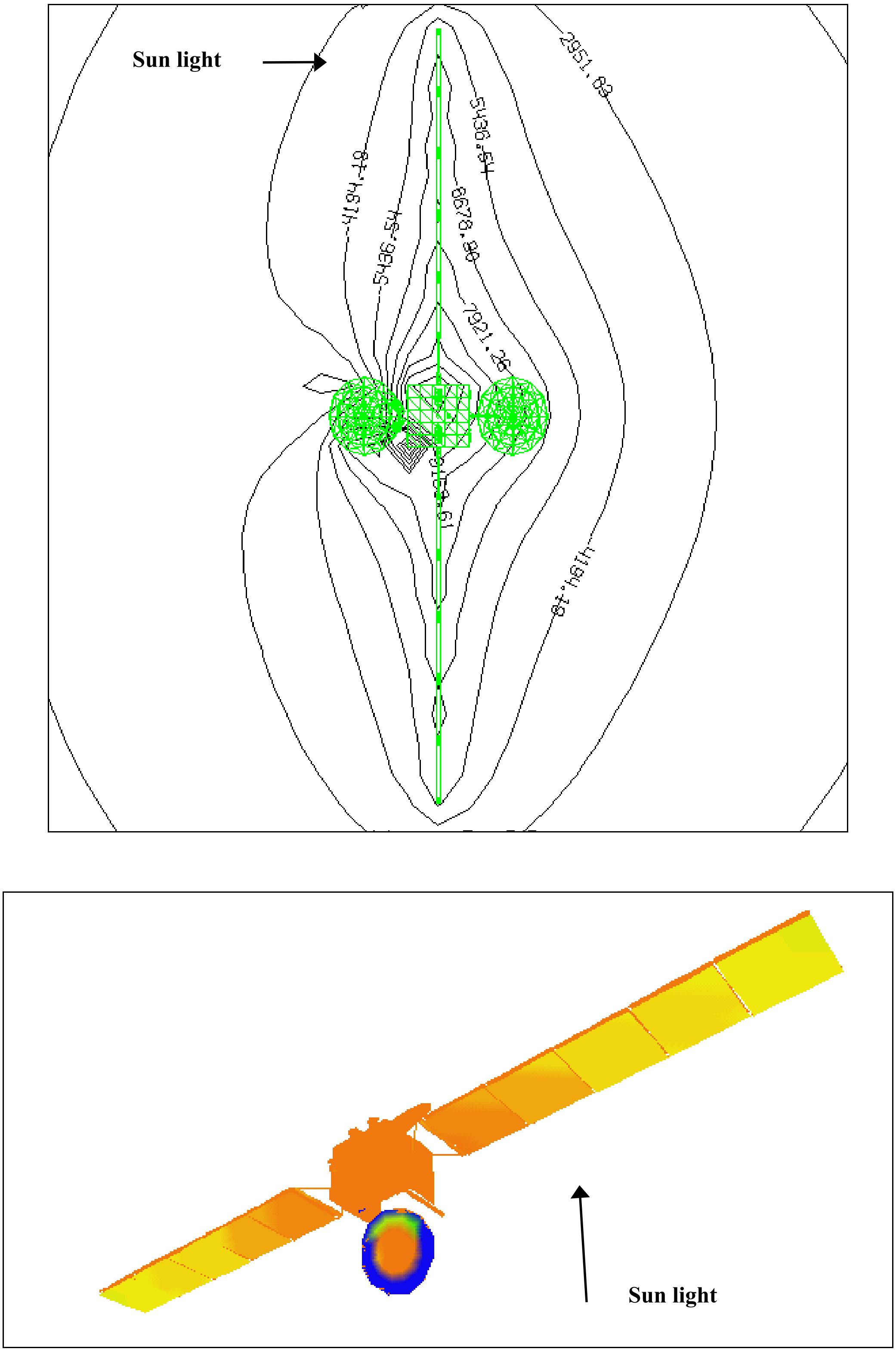

Figure 4. Spacecraft charging at t=2.0.10^4 s (steady state)

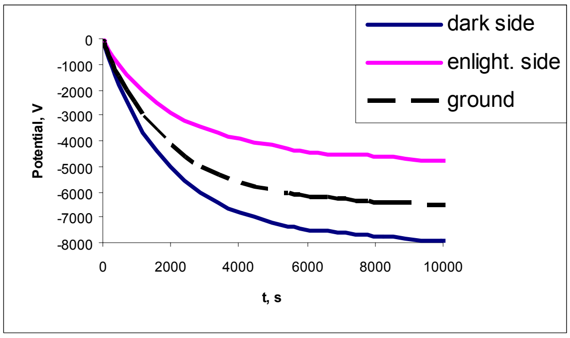

Figure 5. Potential on various spacecraft surface elements as function of charging time

Conclusion

The modified version of the COULOMB tool developed in SINP MSU for modeling of spacecraft charging in high orbits enables to calculate the values of electrostatic potential on the spacecraft surface as the in case of integral charging, and in case of differential charging. Modeling of the dynamics of the spacecraft charging in the given irradiation conditions enables to obtain typical charging time of the spacecraft surface elements. The modern software is applied to the spacecraft model building and to the computer visualization of the modeling results.

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