

# **Nascap-2K Spacecraft Charging Models: Algorithms and Applications**

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## **ABSTRACT**

Nascap-2K is being developed as a replacement for the NASCAP/GEO spacecraft charging code. Currently implemented are an Object Definition Toolkit (OTk), a Boundary Element Method (BEM) charging analysis module, and a user interface for setting up problems and displaying results. Integration of Nascap-2K with the DynaPAC (Dynamic Plasma Analysis Code) code is nearly complete. DynaPAC will be used to study volume potentials, particle trajectories, denser plasmas, thruster plumes, and complex plasma processes. This paper outlines some of the details of the BEM charging analysis, and presents examples of a typical geosynchronous charging calculation, and charging of the STEREO spacecraft in the solar wind.

## **INTRODUCTION**

The NASCAP/GEO code<sup>[1]</sup>, used worldwide for surface charging analysis of geosynchronous spacecraft, was developed during the period 1976-1984. Since that time there have been huge advances in computer capabilities, software tools, software design, mathematical analysis techniques, and user expectations. Plus, we have advanced our knowledge of the space environment, the interactions between space plasma and spacecraft surface materials, and the algorithms to simulate spacecraft charging phenomena. Clearly, a more advanced code is needed for detailed charging analysis.

Nascap-2K is being developed as a successor to NASCAP/GEO. The Air Force Research Laboratory and the NASA Space Environment Effects Program are funding the Nascap-2K effort. Currently implemented are: (1) an Object Definition Toolkit (written in Java); (2) an analysis module (written in C++ and using the Boundary Element Method (BEM)<sup>[2]</sup>) for calculating surface charging in Geosynchronous Earth Orbit, Solar Wind or other tenuous plasma environments; (3) a graphical interface (written in Java) for setting up problems and examining results; and (4) a new GridTool program (Java) for building a DynaPAC grid.

All information is stored in the database of the DynaPAC code<sup>[3]</sup>, or as XML. DynaPAC (written in Fortran and C) is an existing finite element code that solves potentials and tracks particles in the space external to a spacecraft model using a flexible set of plasma treatments. DynaPAC features arbitrarily nested grids to provide good spatial resolution, and strictly continuous electric fields for accurate particle tracking. Nascap-2K's geometric models and BEM charging results are accessible to DynaPAC's modules, so that external potentials and particle trajectories can be calculated. We plan to use the DynaPAC synergy to extend the range of applicability of Nascap-2K to denser plasma environments such as found in low-earth or polar orbits, or resulting from thruster plumes.

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In this paper we describe the Object Definition Toolkit (OTk) and the BEM analysis module, and show as examples charging of a typical geosynchronous spacecraft and of a model of the STEREO spacecraft in the solar wind.

### Object Definition Toolkit

The original NASCAP/GEO code<sup>[1]</sup> included simple object definition routines for defining a spacecraft model (built of cubes, wedges, etc.) within the context of a cubic mesh. While quite impressive in the 1976-80 timeframe, the shortcomings of such a model (*e.g.*, its inability to accurately represent spacecraft dimensions and angles, and the lack of variable resolution) soon became apparent.

Later codes (NASCAP/LEO<sup>[4]</sup>, DynaPAC<sup>[3]</sup>) provided for the importation of geometry definition from third-party finite-element modeling programs, allowing accurate representation of spacecraft geometry. However, these third-party programs tended to be expensive, difficult to learn, and closely tied to analysis programs designed for other purposes. Thus it was decided to build a simple, portable Object Definition Toolkit (OTk) program for spacecraft charging purposes.

OTk is written for the Java 2 Platform using Java3D, and is thus immediately portable to all systems supporting the latest Java technology, including Windows, Linux, and several flavors of UNIX. Its output is written in XML, so as to be both portable and manually editable. It is currently able to import Patran files, and can be extended to import files written in other appropriate formats.

OTk builds spacecraft models from the component types “Box”, “Dish”, “Panel”, “Boom”, “Cylinder”, “Assembly”, and “Primitive”. (See Figure 1.) Each component type has an associated edit dialog to specify its dimensions, gridding, materials, and conductor numbers. Components, along with their associated transformations, are hierarchically combined in assemblies to build a spacecraft model. Currently implemented components are:

1. The **Box** is a general hexahedral object, extending NASCAP/GEO’s RECTAN. Figure 2 shows the edit dialog for a Box. A non-rectangular Box can be made by explicitly specifying the locations of its eight corners.
2. The **Panel** is a Box with one zone in the Z direction, and its edges sewn up.
3. The **Boom** is a Box with one zone in the X direction and one zone in the Y direction. The Boom can be twisted along its length; this property is useful for rotating solar panels.
4. The **Dish** is a simple representation for a parabolic antenna or similar object.
5. The **Cylinder** is the extrusion of a regular polygon.
6. An **Assembly** is a collection of components together with their transformations.
7. A **Primitive** is a geometry which has been imported into OTk, or formed from the mesh of an Assembly.

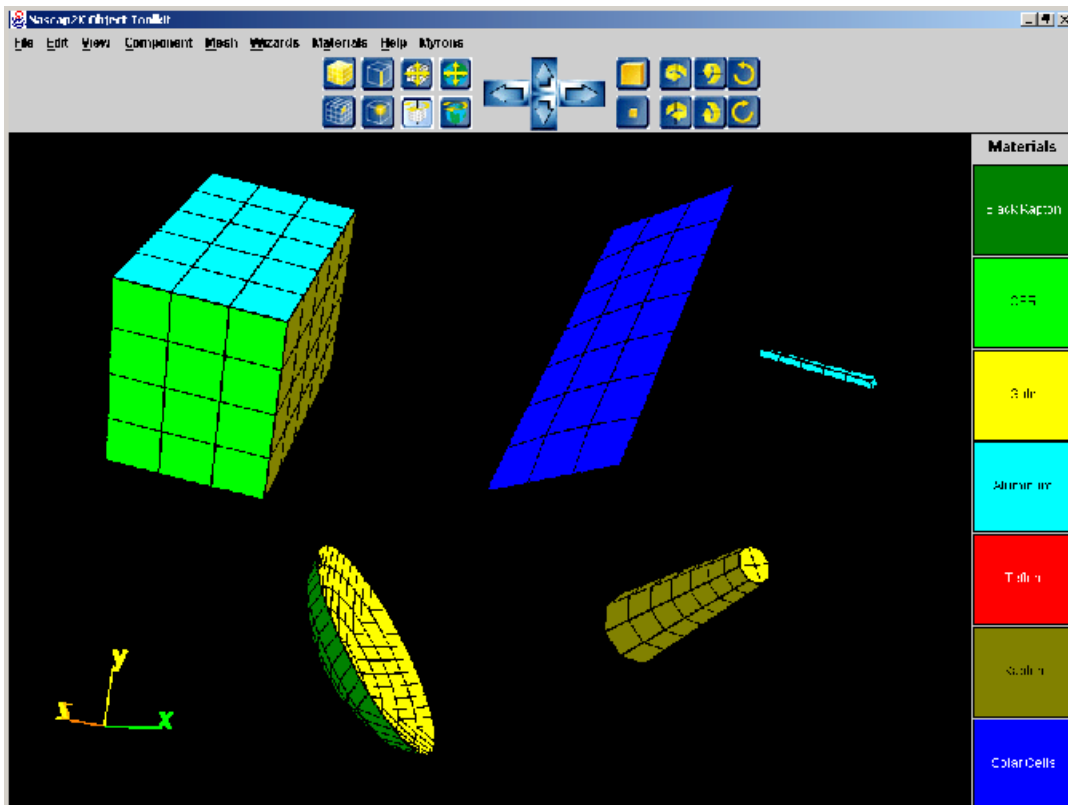


Figure 1. Nascap2K Object Toolkit, showing basic components: (clockwise from top left) Box, Panel, Boom, Cylinder, Dish.

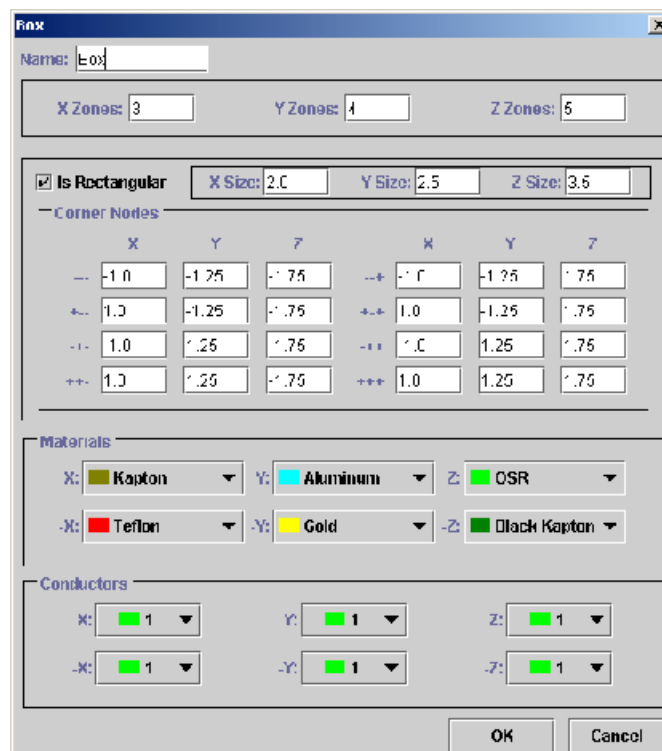
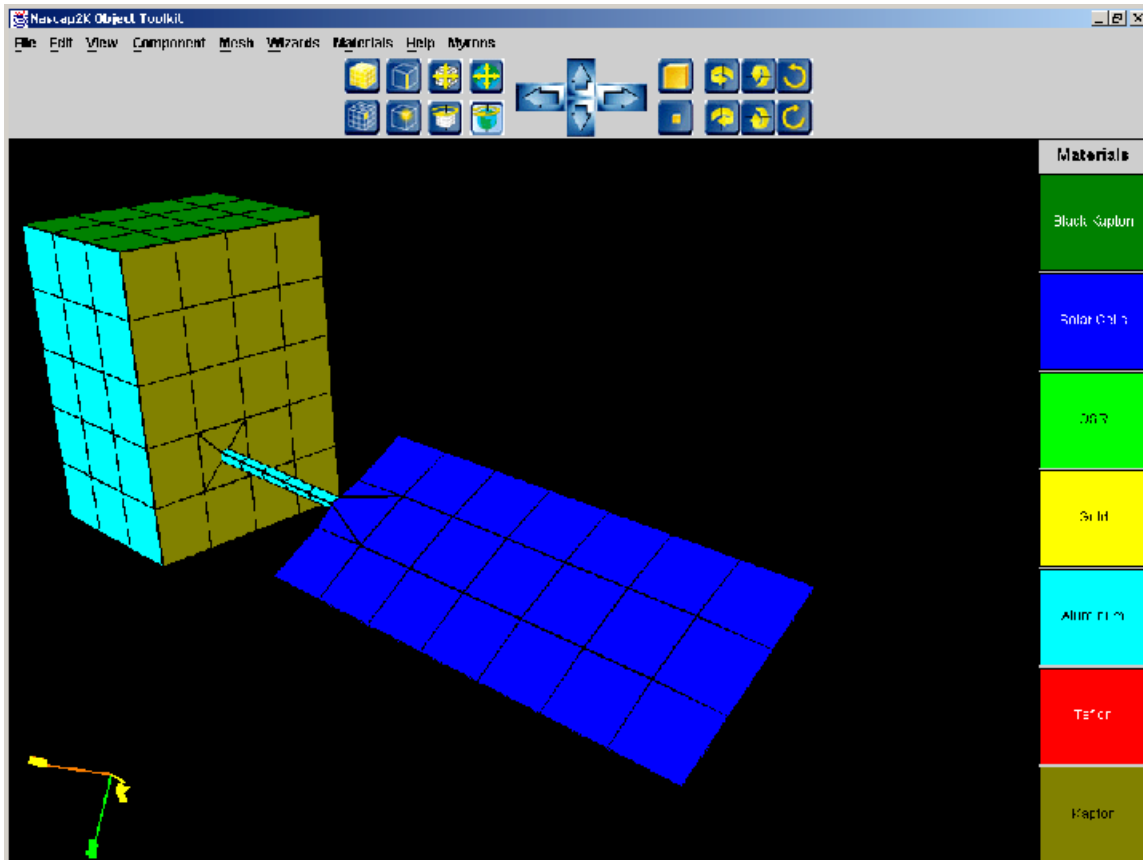


Figure 2. Edit dialog for a Box component. Other types of components have similar edit dialogs.



**Figure 3. Compatible attachment of a solar array to a spacecraft body accomplished using OTk wizards.**

Wizards enable the attachment of components while maintaining “compatible” meshing. In addition, nodes and elements can be edited manually to accomplish complex or non-standard attachments or geometries. Figure 3 shows a solar array attached to the spacecraft body by a Boom. Wizards did both these two attachments, and the compatible zoning was generated automatically. The orientation of the solar array resulted from the twist previously applied to the boom.

Output of the Object Toolkit is an XML file containing the nodes and elements of the top-level assembly, all the information needed to rebuild the model from its original components, and the properties of all the materials used in the model. (Nascap-2K uses the same material treatments as NASCAP/GEO<sup>[1]</sup>.) This file can be edited with a text editor or XML editor, so that minor changes can be made without invoking OTk.

### **Boundary Element Analysis Module**

NASCAP/GEO uses the finite element method (FEM)<sup>[5]</sup> to calculate electrostatic potentials in the space around the spacecraft. This calculation dominates the computation time of the code, while giving poor estimates of the surface electric fields, and providing no way of anticipating what field changes would result from changes in surface potential. Nascap-2K, by contrast, calculates potentials and electric fields using the Boundary Element Method (BEM)<sup>[2]</sup>. The BEM provides direct relationships between charges, potentials, and surface electric fields. The benefit of the BEM is that we are able to cast the full charging equations into one matrix equation that anticipates changes in electric fields, rather than alternate

calculations of charging and space potentials. The cost of the BEM is that these matrices are non-sparse and their matrix elements involve complex integrals. We find, however, that modern computers and numerical methods are up to the task.

In the BEM, potential and electric field at any point are constructed as integrals over (assumed constant) sheets of charge on surface elements:

$$V = \frac{q}{4\pi\epsilon_0 r} \longrightarrow (4\pi\epsilon_0)V_i = \sum_j \int d^2r_j \frac{\sigma_j}{r_{ij}}$$

$$E = \frac{q}{4\pi\epsilon_0 r^2} \longrightarrow (4\pi\epsilon_0)\mathbf{E}_i = \sum_j \int d^2r_j \frac{\sigma_j}{r_{ij}^3}(\mathbf{r}_i - \mathbf{r}_j)$$

By doing the integrals we generate matrices relating the potential and electric field at the center of each surface to the charges on all the surfaces:  $V_i = [\mathbf{C}^{-1}]_{ij}\sigma_j$  and  $\mathbf{E}_i \cdot \mathbf{n}_i = \mathbf{F}_{ij}\sigma_j$ .

We can then relate the fields to the potentials:  $\mathbf{E}_i \cdot \mathbf{n}_i = \mathbf{F}_{ik}\mathbf{C}_{kj}V_j$ .

The charges on insulating cells are given by  $q_i = A_i(E \cdot n)_i + C_{ic}(V_i - V_c)$

and the charges on conductors by  $Q_c = \sum_{bare} A_i(E \cdot n)_i - \sum_{insulators} C_{ic}(V_i - V_c)$ .

Since the  $dq_i/dt$  and  $dQ_c/dt$  are given by the plasma and conductivity currents, differentiating these two equations, and providing the plasma currents and their dependence on potential and electric field, gives a single matrix equation for the charging problem:

$$I_i(V_i, (E \cdot n)_i) - \sigma_i(V_i - V_c) = A_i F_{ik} C_{kj} \dot{V}_j + C_{ic}(\dot{V}_i - \dot{V}_c)$$

for insulators, and

$$I_c(V_c, (E \cdot n)_c) + \sum_{insulators} \sigma_i(V_i - V_c) = \sum_{bare} A_i F_{ik} C_{kj} \dot{V}_j - \sum_{insulators} C_{ic}(\dot{V}_i - \dot{V}_c)$$

for conductors, where we have included bulk conductivity explicitly, and neglected surface conductivity.

To solve the above equations implicitly requires linearizing the currents as a function of the potentials. Previously, this was not possible in the case where the current was a function of the electric field,  $\mathbf{E} \cdot \mathbf{n}$ . With the BEM, however, we have

$$I'_{ij} \equiv \partial I_i / \partial V_j = \partial I_i / \partial E_i \times \partial E_i / \partial V_j$$

and since

$$\mathbf{E}_i \cdot \mathbf{n}_i = \mathbf{F}_{ik} \mathbf{C}_{kj} V_j$$

we can take advantage of the result

$$I'_{ij} \equiv \partial I_i / \partial V_j = (\partial I_i / \partial E_i) F_{ik} C_{kj}$$

The BEM Analysis Module imports the object definition information into itself and the DynaPAC database, and formulates the matrices of the charging problem. It also accepts environment definitions and timestepping prescriptions, and performs shadowing calculations. After performing the specified

charging simulation, it makes the results available to other DynaPAC modules for further analysis, and to the Nascap-2K user interface for analysis and display.

### Example: Geosynchronous Charging

Figure 4 shows a model of a “typical” geosynchronous spacecraft in the object definition tab of the Nascap-2K GUI. Note that the other tabs allow us to set simulation parameters, run the simulation, and view the results. For this example, we have used all default parameters (NASA “Worst Case” environment<sup>[6]</sup>, 20 timesteps beginning with 0.1 seconds and extending to a total of five minutes) except for setting the sun direction to match the model.

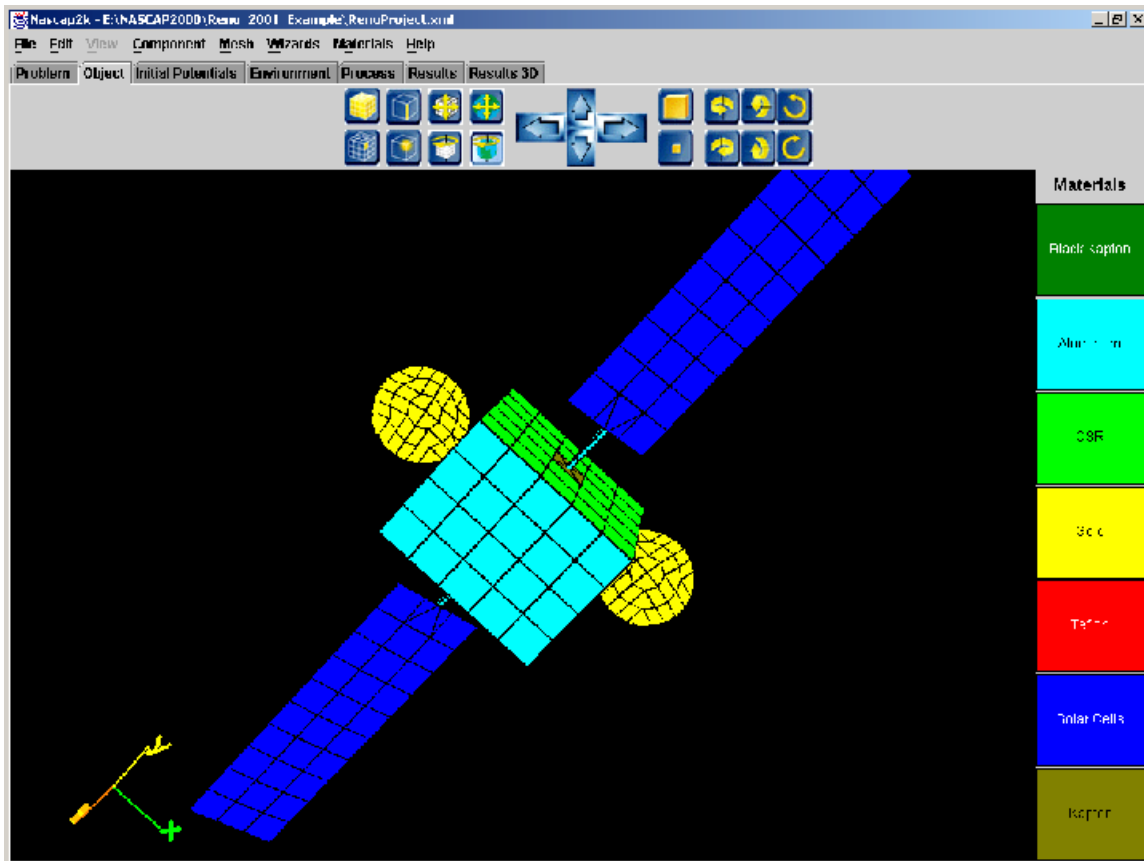


Figure 4. “Typical” geosynchronous spacecraft in the Nascap-2K GUI.

A surface potential plot of the result is shown in figure 5. The entire solar array surface is at negative potential due to barrier effects, with the inboard cells more negative than the outboard cells. Non-sunlit insulators on the side of the spacecraft and on the back of the dishes are at large negative potentials.

The “Results” tab allows us to plot potential, current, or electric field of sets of cells as a function of time (similar to NASCAP/GEO’s TermTalk). Figure 6a shows the minimum, maximum, and average potential of all the cells, showing that 2 kV of differential potential has developed over the five minute period. Figure 6b shows the same plot for the solar cells only, showing a range of –50 to –400 volts. The plotted data is also available in text format, suitable for pasting into a spreadsheet for further plotting or analysis.

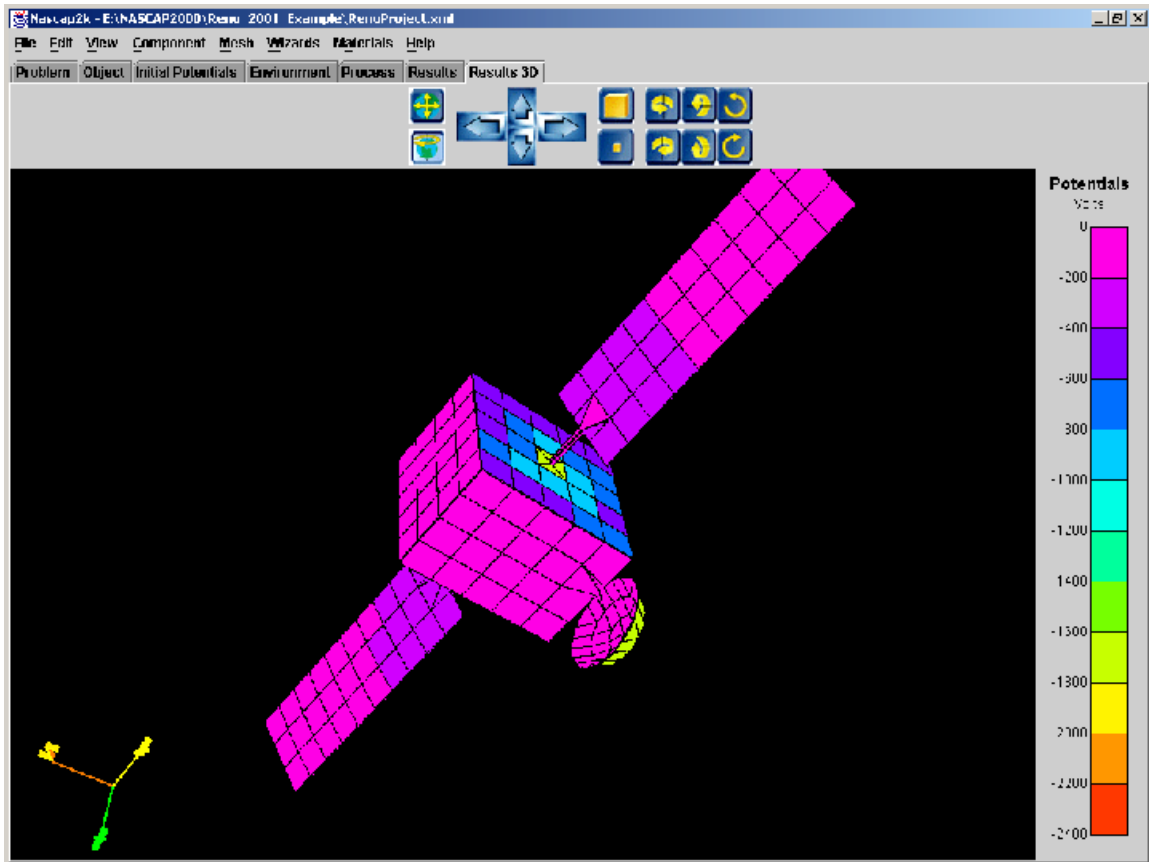


Figure 5. Surface potential plot for “typical” geosynchronous spacecraft.

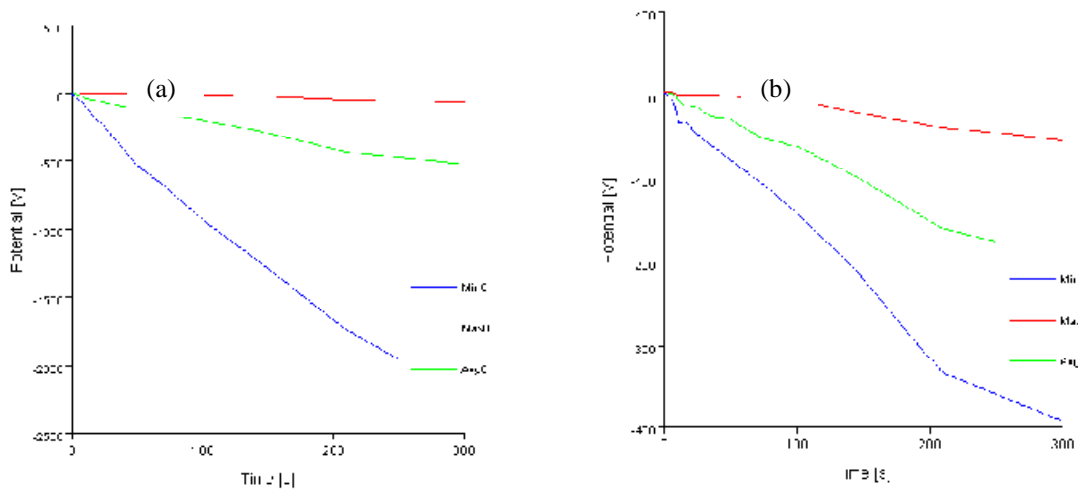


Figure 6. Surface potential plot for “typical” geosynchronous spacecraft: (a) all surfaces; (b) solar cells only.

### Example: Solar Wind Charging

The interplanetary or solar wind plasma environment, like the charging environment in geosynchronous orbit, consists of a tenuous plasma with a long Debye length. Thus, the computational techniques appropriate for geosynchronous charging calculations are also appropriate to charging in the solar wind, requiring only some modification in the treatment of the plasma currents. The STEREO project proposes to launch two spacecraft into solar orbit at 1 AU, one leading Earth and the other lagging. We are assisting the project by performing charging calculations of solar wind charging using Nascap-2K.

The solar wind plasma is highly variable, with a plasma density of 0.1 to 10 cm<sup>-3</sup>. The electrons are approximately isotropic, with a temperature of 1 to 10 eV. The ions (mostly protons) travel outward from the sun with a velocity of about 4×10<sup>5</sup> ms<sup>-1</sup>, or, equivalently, and energy of nearly 1 keV. Taking a density of 1 cm<sup>-3</sup> and a temperature of 3 eV gives a Debye length of 13 m, electron thermal current of 4.6×10<sup>-8</sup> Am<sup>-2</sup>, and beaming ion current of 2.5×10<sup>-8</sup> Am<sup>-2</sup>. Because the ions are not isotropic and at very high mach number, we added the option to treat the ions as monoenergetic, beaming from the sun direction, and being shadowed in the same manner as sunlight.

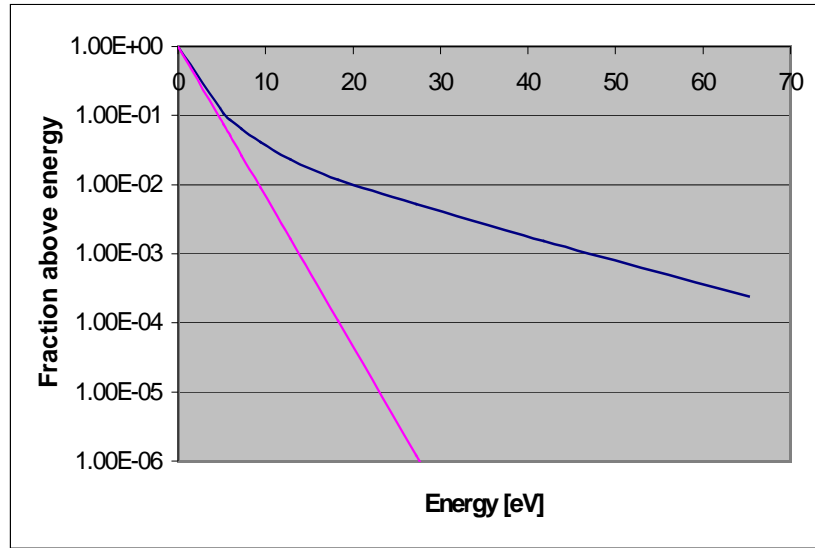
Because the electron current is less than one percent of the photoemission current, spacecraft in this environment charge to positive potentials ranging from five volts up to several tens of volts. To calculate this charging requires knowledge of the spectrum of emitted photoelectrons ranging up to several tens of volts. The photoelectron spectrum for each material is an additional input file to the code. Needless to say, there is a great deal of uncertainty in what this spectrum should be, as well as in the value of the raw (total) photoemission current. Figure 7 shows a photoelectron spectrum<sup>[7]</sup> based on data from the WIND spacecraft. It is apparent that the approximation of a 2 eV maxwellian considerably underestimates the effective photoemission for a surface more than a few volts positive. The actual photoelectron spectrum causes spacecraft to charge to positive potentials of tens of volts under conditions of low solar wind density.

Figure 8 shows a Nascap-2K model of the STEREO spacecraft. The model is completely conducting, except for the solar cell covers. The resistivity of the coverslips decreases with increasing temperature. We have taken the nominal value to be 1×10<sup>13</sup> Ω-m. As the resistivity drops below this value, the solar cell applied potentials begin to show through the coverslips. (Photoelectron-mediated surface conductivity may modify this effect.) To include this effect in the model, we put half the solar cell area at ground, and the other half at the nominal solar array potential of 60 volts.

Table 1 shows charging results for three levels of solar wind density, plus a fourth result for decreased coverslip resistivity. In general, the spacecraft charges immediately to a mean level, then differentially charges over a period ranging from several seconds (at high density) to several minutes (at low density). The coverslips charge positively until the enhanced electron current balances the attenuated photoemission. The conducting grounded surfaces are less than 20% illuminated, so the ground potential is well below the coverslip potential, though still positive.

Conductivity to the underlying solar cells is important in the third and fourth cases in the table. When the density is very low, the plasma currents drop to the point of being comparable to the conduction through the coverslips, so that the underlying potentials show through. Conversely, increasing the conductivity of the coverslips brings the conductivity current up to the level of the plasma currents. In the fourth case of the table, electrons collected through the coverslips by the 60-volt biased solar cells caused a 0.2 volt drop in ground potential.





**Figure 7. Photoelectron spectrum based on WIND data (upper curve), compared with the 2 eV maxwellian (lower curve) commonly used for geosynchronous orbit charging.**

**Table 1. Charging results for the STEREO model in the solar wind. In all cases, the electron temperature is taken as 3 eV, and the raw photoemission of the coverslips is  $2 \times 10^{-5} \text{ Am}^{-2}$ .**

Environment	Density	Resistivity	Coverslip/60	Coverslip/0	Ground
High Normal	$10 \text{ cm}^{-3}$	$1 \times 10^{13} \Omega\text{-m}$	8.2 V	8.1 V	3.2 V
Low Normal	$1 \text{ cm}^{-3}$	$1 \times 10^{13} \Omega\text{-m}$	18.4 V	17.5 V	8.3 V
Very Low	$0.1 \text{ cm}^{-3}$	$1 \times 10^{13} \Omega\text{-m}$	39.2 V	33.3 V	19.5 V
Low Normal	$1 \text{ cm}^{-3}$	$1 \times 10^{12} \Omega\text{-m}$	26.3 V	16.5 V	8.1 V

## CONCLUSIONS

Nascap-2K is well on its way toward the goal of replacing the existing spacecraft charging codes. Object Definition Toolkit is used to define analysis models that are both fairly simple to create and provide a good representation of actual spacecraft geometry. The Boundary Element Method has been integrated into a new and superior scheme for performing spacecraft charging analysis. Coupled with the DynaPAC code, Nascap-2K can provide space potentials and particle trajectories with greater accuracy than the older codes were able to provide. Further development within the DynaPAC framework will enlarge the capability and range of applicability of Nascap-2K. Examples of typical geosynchronous charging and of charging in the solar wind illustrate that Nascap-2K is nearing the point of replacing NASCAP/GEO as a charging analysis tool.

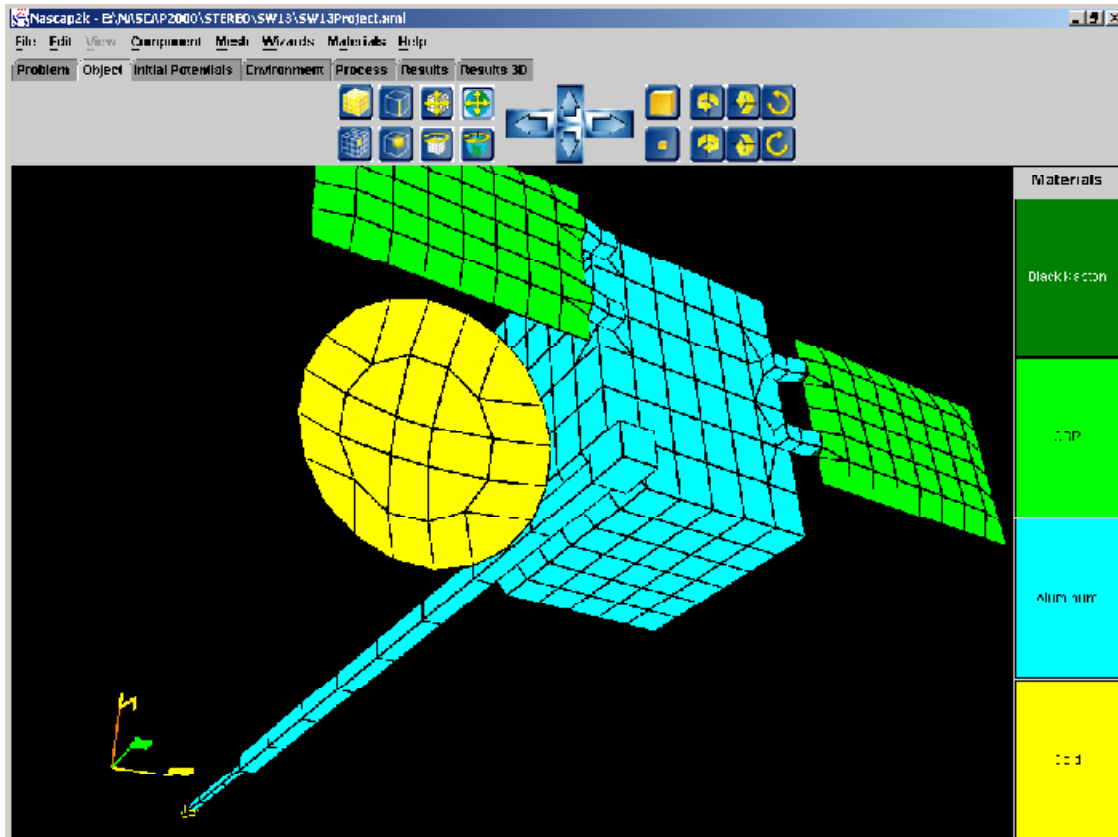


Figure 8. Nascap-2K model of the STEREO spacecraft.

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