Rpro m: /1w / 18 / 2002ed

AIAA 2002-0626

# SPACECRAFT CHARGING CALCULATIONS: NASCAP-2K AND SEE SPACECRAFT CHARGING HANDBOOK

V. A. Davis[*†], L. F. Neergaard[‡], M. J. Mandell[§†], I. Katz[§**], B. M. Gardner[*†], J. M. Hilton[†], J. Minor[††]

## ABSTRACT

For fifteen years NASA and Air Force Charging Analyzer Program for GEOsynchronous orbits (NASCAP/GEO) has been the workhorse of spacecraft charging calculations. Two new tools, the Space Environment and Effects (SEE) Spacecraft Charging Handbook (recently released), and *Nascap-2K* (under development), use improved numeric techniques and modern user interfaces to tackle the same problem. The SEE Spacecraft Charging Handbook provides first-order, lower-resolution solutions while *Nascap-2K* provides higher resolution results appropriate for detailed analysis. This paper illustrates how the improvements in the numeric techniques affect the results.

## INTRODUCTION

Recent spacecraft failures[1,2,3] have brought into focus the need for spacecraft designers, spacecraft charging researchers, and spacecraft managers in government and industry to have increased understanding of spacecraft charging and improved modeling capabilities. Both government and commercial satellite designers need information on how to build satellites using advanced technologies that can survive the natural environment. Two new tools, SEE Spacecraft Charging Handbook[4,5](recently released) and *Nascap-2K*[6] (under development), take advantage of improvements in computer technology, advances in understanding of the phenomenon, and enhanced charging algorithms to address this need.

For the past twenty years, NASCAP/GEO[7] has been the standard tool for the computation of spacecraft surface charging. NASCAP/GEO was developed during the period 1976 to 1984, and since that time there have been significant advances in computing capabilities, software tools, software design, mathematical analysis techniques, and user expectations. The large number of spacecraft in low-Earth orbit requires three-dimensional computer codes that can compute spacecraft-plasma interactions in plasmas in which the Debye length is shorter than the spacecraft dimension. Over the past twenty years, the fully three-dimensional computer codes NASCAP/LEO,[8,9] POLAR,[9,10] and DynaPAC[11,12,13] have been developed to meet this need. While each code works well for the range of problems for which it was designed, by today's standards, these codes (particularly NASCAP/GEO) are complicated to use and require expertise to use properly. In addition, NASCAP/GEO and POLAR are limited with respect to geometry. The SEE Handbook and *Nascap-2K* build on our experience with these codes and were designed to address these limitations.

The SEE Handbook computes spacecraft surface charging for geosynchronous and auroral zone spacecraft. Presently, *Nascap-2K* computes spacecraft charging in tenuous plasmas, e.g., GEO and interplanetary and planetary environments. The numeric modules of DynaPAC are presently being incorporated into *Nascap-2K*. Present plans call for the addition of the appropriate features of the other three-dimensional codes. When complete, *Nascap-2K* will be used to study volume potentials, particle trajectories, denser plasma, and more complex plasma processes within a

[*] Member, AIAA
[†] Science Applications International Corporation, San Diego, CA
[‡] Sverdrup Technology, Marshall Space Flight Center, Huntsville, AL
[§] Senior Member, AIAA
[**] Jet Propulsion Laboratory, Pasadena, CA
[††] Space Environment Effects Program, Marshall Space Flight Center, Huntsville, AL

single framework. The user interface is being designed so that the non-expert user can do common problems and the expert can tackle questions that have not been previously contemplated.

Previous papers have described the new computer codes, their algorithms, and the new numeric techniques used. This paper focuses on a comparison of results for an actual case that illustrates the benefits and limitations of the new approaches.

## SPACECRAFT SURFACE CHARGING

Spacecraft surface charging is the accumulation of charge on spacecraft surfaces. The surfaces of geosynchronous spacecraft can accumulate charge due to incidence of energetic (10 to 50 keV) substorm electrons. As illustrated in Figure 1, several different currents contribute to the charging[14,15,16,17] Kilovolt electrons generate secondary electrons and can be backscattered (reflected) from surfaces. Kilovolt ions can also generate secondary electrons. The current density of low-energy electrons generated by solar ultraviolet emission exceeds that of the natural charging currents. The rest of the spacecraft influences the potential of each surface. In order to compute surface potentials, spacecraft geometry, surface materials, and environment must all be considered. Each insulating spacecraft surface interacts separately with the plasma and is capacitively and resistively coupled to the frame and other surfaces. NASCAP/GEO, the SEE Handbook, and *Nascap-2K* all use this information to compute the time history of the surface potentials and fluxes.

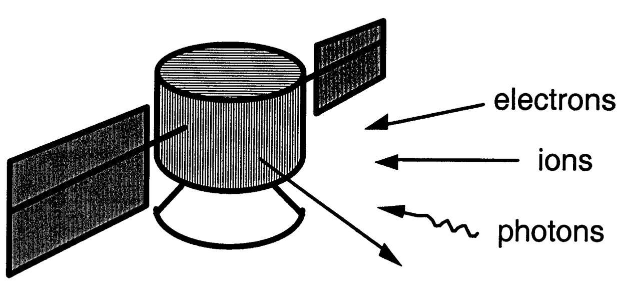


Figure 1. High negative potentials can result from the accumulation of charge on spacecraft surfaces.

Figure 2 shows a circuit diagram for a spacecraft with one insulating surface and exposed conducting surfaces. The widely differing capacitances of the surface to infinity, $C_A$, and the capacitance of the surface to spacecraft ground, $C_{AS}$, make this a complex numeric problem.

$$C_{AS} = \kappa\varepsilon_0 \frac{S}{d} \approx \frac{S}{2} \times 10^{-7} \text{ Farad}$$

$$C_A \approx C_S \approx 4\pi\varepsilon_0 r \approx r \times 10^{-10} \text{ Farad}$$

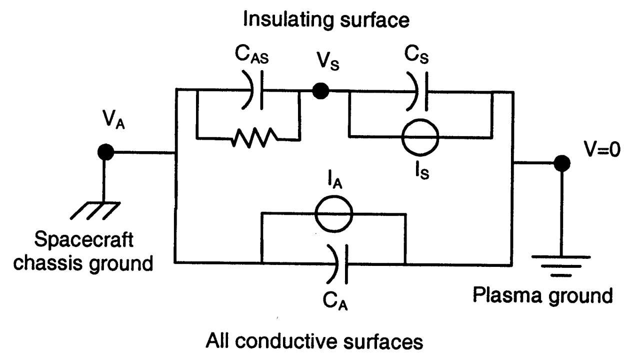


Figure 2. Circuit model of a spacecraft with one insulating surface.

The potentials as a function of time are computed using implicit time integration of the charging equations.

$$C_A \dot{V}_A + C_{AS} (\dot{V}_A - \dot{V}_S) = I_A$$
$$-C_{AS} (\dot{V}_A - \dot{V}_S) + C_S \dot{V}_S = I_S$$

The multisurface problem is solved by linearizing the currents and inverting the matrix.

$$\mathbf{C} \dot{V} = I(V)$$

## BOUNDARY ELEMENT METHOD (BEM)

Emission of low energy electrons (photoelectrons and secondary electrons) from surfaces plays a crucial role in charging.[18] For surfaces having a positive (electron-attracting) electric field, these currents are cut off, changing the sign of the surfaces' net current. Effectively, surfaces for which low energy electron emission is the dominant current satisfy a boundary condition of small, positive electric field.

NASCAP/GEO uses a finite element[19] formulation of Laplace's equation to determine potentials in the space surrounding the object and thus the surface electric fields.[20] 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.

Conversely, the SEE Spacecraft Charging Handbook and *Nascap-2K* calculate potentials and electric fields using the Boundary Element Method[21] (BEM). The BEM provides direct relationships between charges, potentials, and surface electric fields. The benefit of the BEM is that the full charging equations are cast into one matrix equation that anticipates changes in electric fields, rather than having to alternate calculations of charging and space potentials. The gradient of the BEM integral directly relates electric fields to surface charges, and its time derivative globally relates potential changes to currents. The cost of the BEM is that these matrices are non-sparse and their matrix elements involve complex integrals. However, modern computers and numerical methods are up to the task.

## SEE SPACECRAFT CHARGING HANDBOOK

Under contract to the Spacecraft Environment Effects Program office at NASA/Marshall, SAIC (then Maxwell Technologies) developed a CD-ROM/web based multimedia interactive Spacecraft Charging Handbook with integrated, updated spacecraft charging models. The target audience for this tool is spacecraft designers, spacecraft charging researchers, spacecraft managers at NASA and industry, and aerospace engineering students. This product guides the non-expert through the appropriate analysis. The Handbook is written with HTML, JavaScript, and Java and runs within a level 4 browser, either Internet Explorer or Netscape Navigator. This choice insures that the application can run on both Windows (95 or NT 4.0) and Macintosh OS 7.5 computers, either standalone or over the World Wide Web.

There are two main sections of the Handbook: Guidelines and Tools. The Guidelines are contained within a text document that provides guidance to the spacecraft design engineer. The Interactive Tools allow users to investigate the charging of their spacecraft. The three environment tools, Geosynchronous, Auroral, and Trapped Radiation, allow users to specify and compare charged particle fluxes of different environments. The Material Properties tool allows users to specify the emission characteristics of spacecraft surface materials and to adjust properties to agree with measured data. The four surface charging tools, Single Material, Multi-material, 3-D Geosynchronous, and 3-D Auroral, are used to examine surface charging of a spacecraft. The Internal Charging tool is used to investigate the electric field due to deposition of high-energy (MeV) electrons within circuit boards, cable insulation, and other dielectrics. The computer code and its models are further described in References 4 and 5.

## SINGLE MATERIAL SURFACE CHARGING TOOL

Figure 3 shows the Single Material Surface Charging tool. The calculation in the figure is for the material "Black Kapton," specified using the Material Properties tool in the environment "Worst Case," specified using the Geosynchronous Environment tool. In eclipse, an isolated sphere of this conducting material reaches a floating potential of -23.0 kV in less than 1 second. The components of the current are displayed along with the net current at 0 V and at the floating potential. When an insulating material is selected, this tool computes the surface potential and current density for a surface of this material on a conducting sphere fixed at the specified backplane potential.

## THREE-DIMENSIONAL GEOSYNCHRONOUS CHARGING TOOL

The Three-dimensional Geosynchronous Charging tool (as shown in Figure 4) computes both overall and differential charging including barrier effects. With this tool, users: (1) specify materials and dimensions on the body, solar arrays, antenna, and omnidirectional antenna of their spacecraft, (2) view a three-dimensional rendering of their model, and (3) calculate and view the potentials on their spacecraft.

Using buttons on the Three-Dimensional Charging screen, the user brings up separate screens to define the dimensions and materials of the spacecraft body, solar arrays, antennas, and an optional omnidirectional antenna. In order to keep the user input simple and the potential calculation fast enough to be computed interactively, a generic spacecraft design is provided. The user specifies which components are to be included, their size, and their surface materials. After each component is modified, a perspective view of the resulting spacecraft shape and surface materials is displayed.

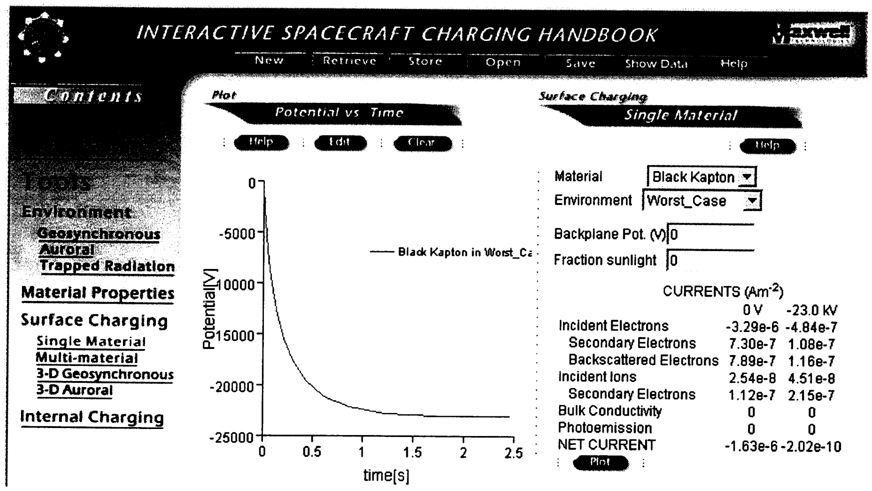


Figure 3. Single Material Charging page of SEE Spacecraft Charging Handbook.

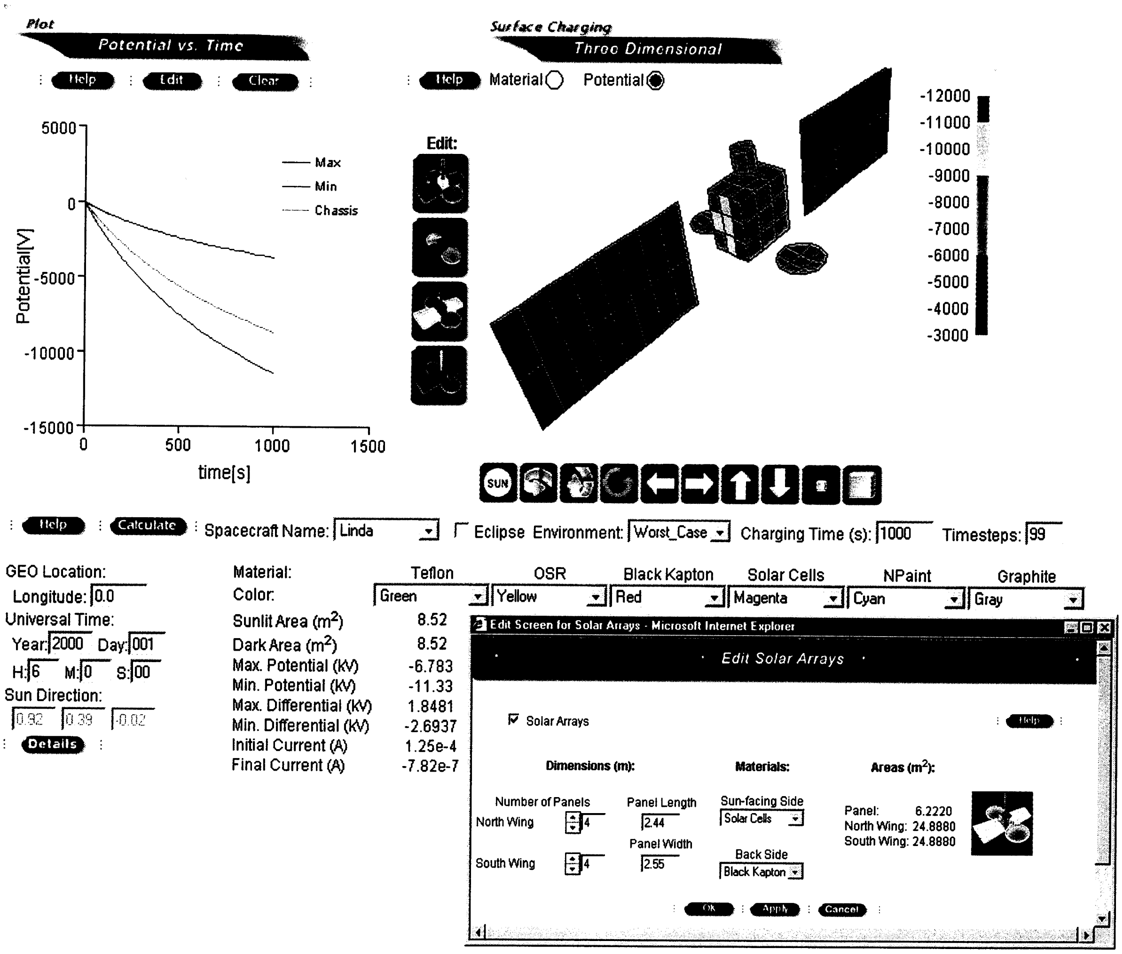


Figure 4. Three-dimensional spacecraft surface charging tool includes barrier effects in its calculations. The screen to specify the solar arrays is shown.

Once the spacecraft geometry, a sun direction (longitude and universal time), an environment, a charging time, and number of timesteps are specified, the user requests a calculation. The tool calculates the surface potentials as a function of time. At completion of the calculation, the perspective view of the spacecraft is color coded by surface potential. This allows the user to locate the high and low potentials on the spacecraft. The results are also displayed in tabular form.

## NASCAP-2K

### Code Structure

The Air Force Research Laboratory and the NASA Space Environment Effects Program are funding SAIC to develop *Nascap-2K* as a successor to NASCAP/GEO, NASCAP/LEO, and POLAR. The goal is to build a three-dimensional spacecraft charging code for all environments: tenuous plasma environments such as in geosynchronous earth orbit and in the solar wind (replacing NASCAP/GEO), short debye length plasma environments with high voltage spacecraft (replacing NASCAP/LEO), and auroral precipitation (replacing POLAR). The tool is targeted to spacecraft design engineers, spacecraft charging researchers, and aerospace engineering students. The suite of codes is written in Java (user interface), C++ and Fortran (science), and C (utility routines) and runs on the Win32 platform. We anticipate that the code will eventually be ported to LINUX and UNIX. *Nascap-2K* uses the DynaPAC database. All DynaPAC modules are being incorporated into *Nascap-2K*. DynaPAC (written in Fortran and C) is an existing finite element code developed with funding from the Air Force Research Laboratory 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* consists of a graphical user interface for setting up problems and examining results, a new GridTool program for building a DynaPAC grid, the Object Definition Toolkit, an analysis module (using the Boundary Element Method) for calculating surface charging in Geosynchronous Earth Orbit, Solar Wind or other tenuous plasma environments; and DynaPAC modules to compute potentials in space and particle trajectories and currents. When the DynaPAC modules are fully integrated, *Nascap-2K* will be used to investigate denser plasma environments as found in low-earth or polar orbits or resulting from thruster plumes. All information is stored in the database of the DynaPAC code or as XML.

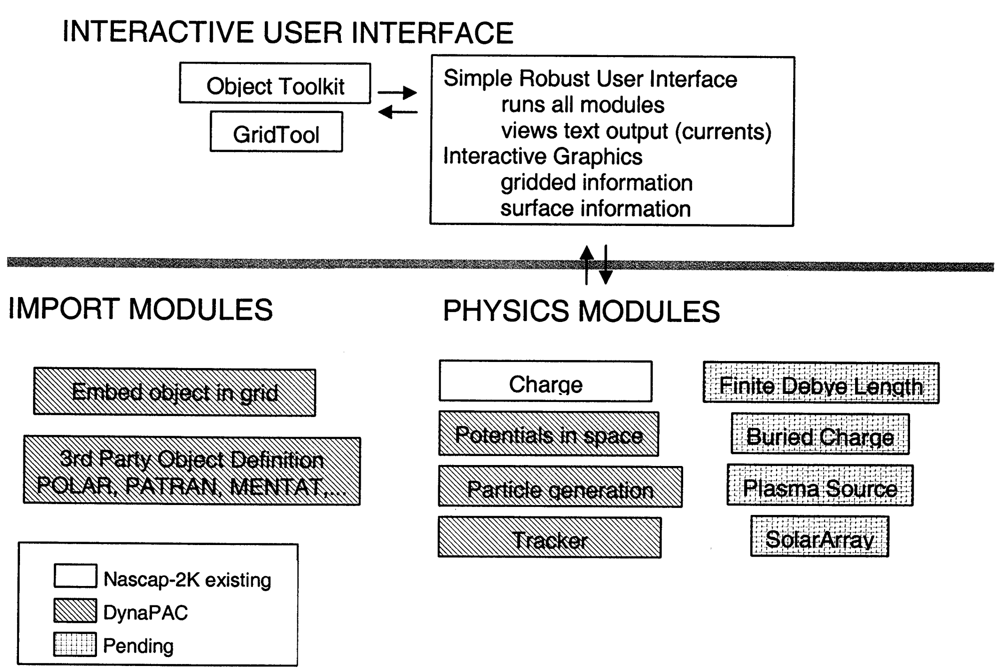


Figure 5. *Nascap-2K* structure.

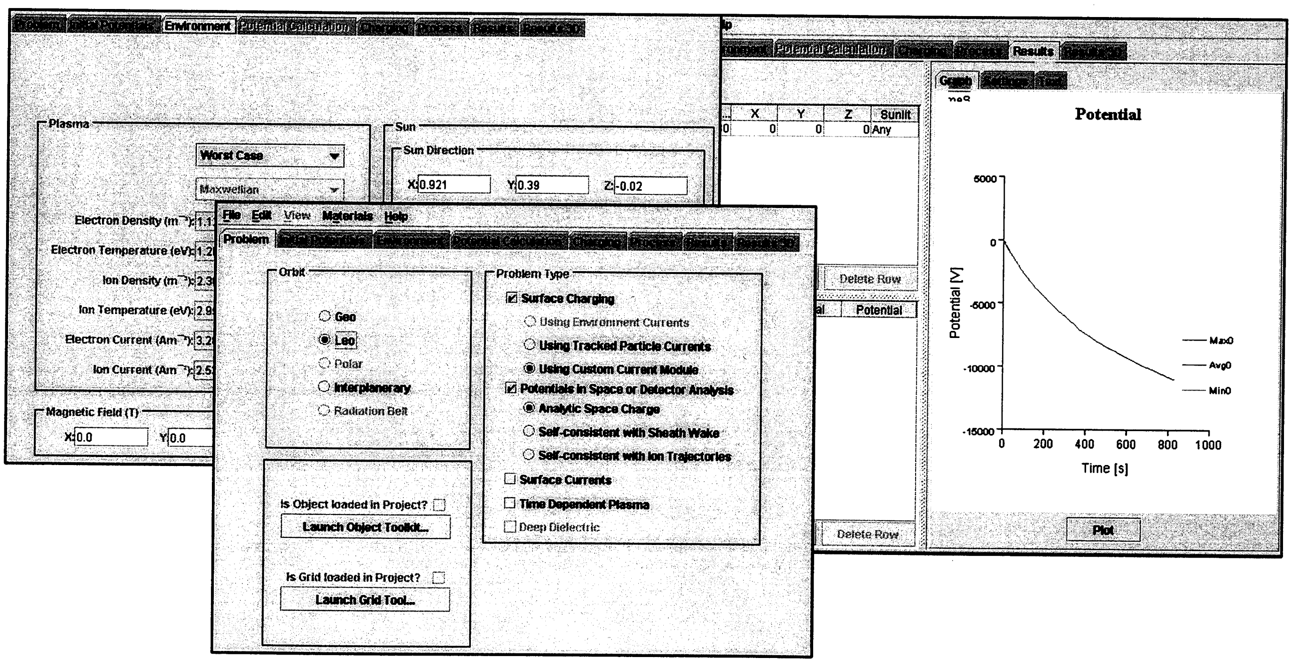


Figure 6. Selected screens from *Nascap-2K* GUI.

## Object Toolkit

As NASCAP/GEO's object definition is limiting and difficult to use, later codes (NASCAP/LEO, DynaPAC) provided for import 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 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". Each component type has an associated edit dialog to specify its dimensions, gridding, materials, and conductor numbers. Components, along with their associated transformations, are assembled in an hierarchy to build a spacecraft model. 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.

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.

## GridTool

GridTool reads an object from either the Object Toolkit XML file or the DynaPAC database and assists the user in building an arbitrarily subdivided grid around it for analysis. A description of the grid is stored in an ASCII file (identical to that used by DynaPAC). GridTool can then build the element matrices needed to embed the object in the grid structure.

## Charging in Tenuous Plasmas

The BEM module for computing spacecraft surface charging in tenuous plasmas has been fully implemented in *Nascap-2K*. It was used in the analysis of the STEREO[6] spacecraft (solar wind), the MESSENGER[22, 23] spacecraft (near Mercury), and some commercial geosynchronous spacecraft. *Nascap-2K* uses the same material properties as NASCAP/GEO.

## COMPARISON

A very simple spacecraft, illustrated in Figure 7, was created so that direct comparisons for all three models could be accomplished. The direction of the solar arrays is appropriate to a spacecraft at 6 am local time. The proportions of the spacecraft were chosen to fit neatly in the NASCAP/GEO grid structure. The proportions of actual spacecraft almost always must be distorted in order to fit within the 17 x 17 x 33 grid. The SEE Handbook and *Nascap-2K* do not have this constraint.

The calculations use the environment recommended by Reference 14 (see Table 1) for initial modeling during the spacecraft design process. The spacecraft charges for 15 minutes, as this is longer than any spacecraft would be exposed to such a severe environment.

The sun is taken to be incident on the spacecraft from the (0.92, 0.39, -0.02) direction. This is appropriate to a spacecraft in geosynchronous orbit at 0 longitude at 6 am GMT on January 1, 2000, consistent with the geometry model.

An important part of defining any spacecraft charging calculation is the determination of the appropriate values to use for the material properties for each surface. NASCAP/GEO, the SEE Spacecraft Charging Handbook, and *Nascap-2K* all use the same 14 material properties and incorporate them into the calculation in the same way. The focus here is in understanding variations between the results given by these codes. Therefore, the specific values are not important as long as they are consistent. *Nascap-2K* provides a set of default values for all the materials except the non-conducting paint on the antenna. The calculations use the values from *Nascap-2K* for all the materials except the non-conducting paint on the Earth facing antenna. For these surfaces, the values for Npaint provided as a default material of NASCAP/GEO are used.

Table 1. 90% worst-case environment for geo-synchronous orbits used for all charging runs as defined in Reference 14.

| | Temperature (keV) | Density ($cm^{-3}$) |
|---|---|---|
| **Ions** | 29.5 | 0.236 |
| **Electrons** | 12.0 | 1.12 |

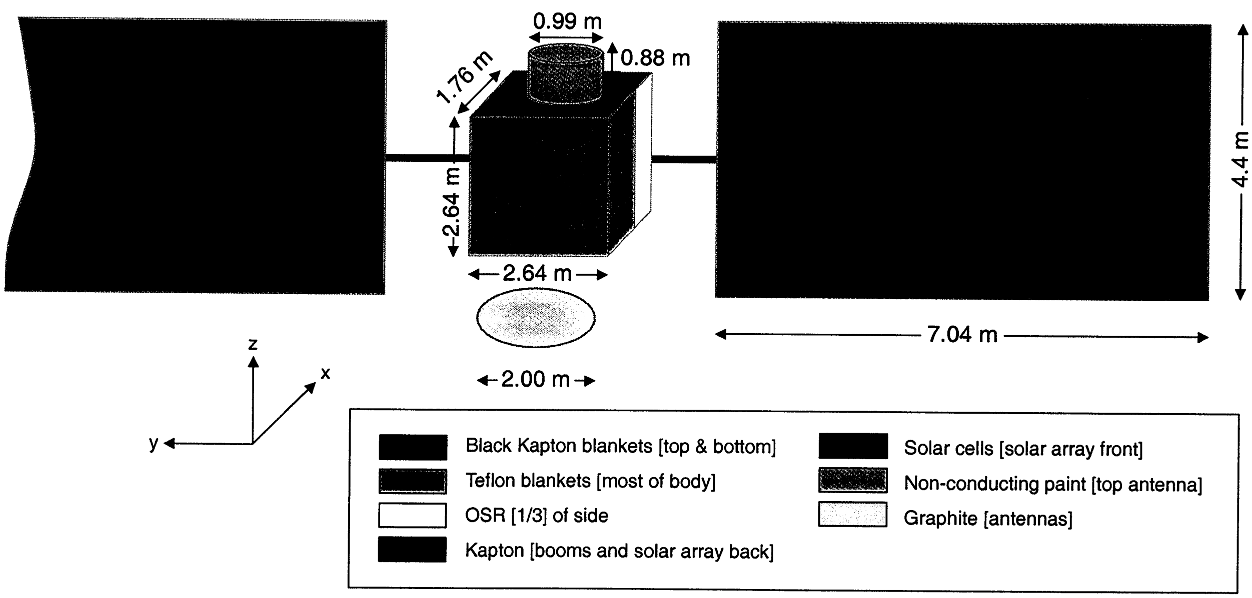


Figure 7. Illustrative spacecraft used for comparison of different modeling software.

The Single Material Charging tool can be used to determine the charging behavior of each of these materials in isolation. The Kapton and Teflon materials do not reach equilibrium in the 5000 seconds allowed for by the tool. The conducting black Kapton reaches equilibrium quickly as the relevant capacitance is with infinity. The solar cells go slightly positive as the high secondary yield dominates the current balance. The other insulating materials are at kilovolts and still not at equilibrium at 5000 seconds. Note that the fidelity of the underlying time dependence is poor.

Table 2. Charging of spacecraft materials.

| Material | Equilibrium potential (kV) | Time to reach equilibrium (sec) |
|---|---|---|
| **Black Kapton** | -23 | 1 |
| **Kapton** | <-14.1 | > 5000 |
| **OSR** | -1.03 | > 5000 |
| **Solar Cells** | 0.002 | 1 |
| **Teflon** | < -12.7 | >5000 |
| **Non-conducting paint** | -745 | 1500 |
| **Graphite** | -22.1 | 1 |

## Geometric Models

NASCAP/GEO calculations are done within a nested grid structure, with the innermost main grid 17 x 17 x 33 units in size. With the exception of booms that can extend beyond the main grid, the complete object must fit within this main grid. The object is made up of cubes, plates, wedges, tetrahedrons, and what is left of a cube after a tetrahedron is cut off of it. Booms (long cylindrical projections of arbitrary radius) can also be used. Booms must extend along the X, Y, or Z direction.

The NASCAP/GEO model is reoriented to fit within the grid. (Note that the sun direction must also be reoriented to match.) The best fidelity model that can be made is that shown in Figure 8. The OSR area is one-half rather than two-thirds of the spacecraft side. A cube represents the omni antenna. Actual spacecraft require even more distortion in order to fit them within the grid.

The SEE Handbook model of the spacecraft can be seen in Figure 9. The location of each of the components is set internal to the code. The user has no control over the distance between the various components or the zoning. This was done in order to insure stability and reasonable calculation speed in the tool, which is intended for general investigations. The orientation of the solar arrays is set by the longitude, date, and time.

*Nascap-2K* has a flexible geometric modeling capability. The user can control the size, shape, and gridding of each component. Figure 10 shows the model in *Nascap-2K*. The omni antenna is represented by an octagonal cylinder and the side antennas are concave dishes.

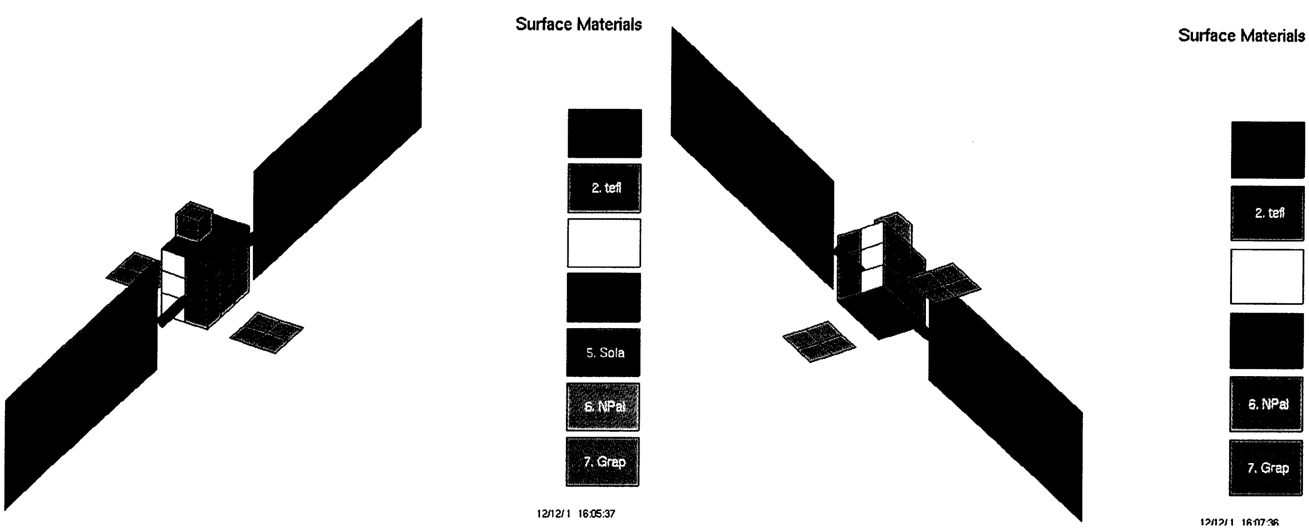


Figure 8. NASCAP/GEO geometric model of spacecraft.

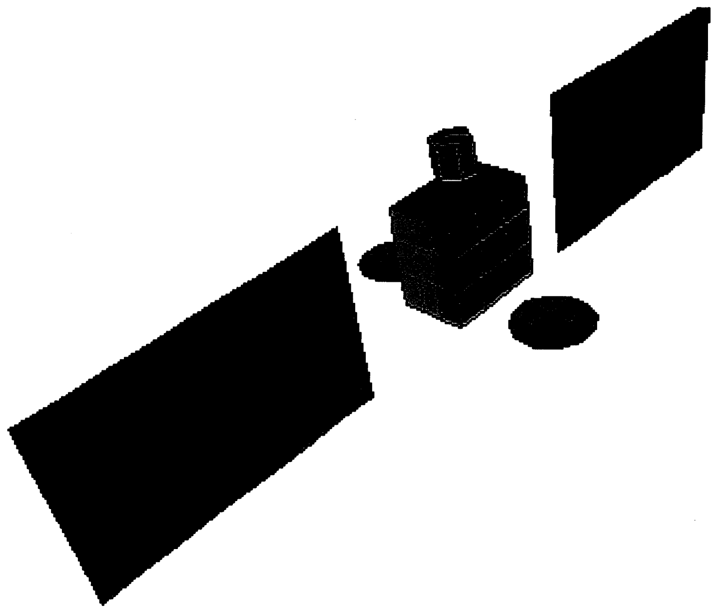

Figure 9. SEE Handbook geometric model of spacecraft.


Figure 10. *Nascap-2K* geometric model of spacecraft.

## Calculation Results

The calculations were set up for 99 timesteps for a time period of 1000 seconds. The timesteps were chosen in the way most natural for each code. The NASCAP/GEO calculation uses geometrically growing timesteps starting with 1 second, with subsequent timesteps of 1.045 times the previous timestep. The SEE Handbook uses geometrically-distributed timesteps that the user cannot control. For *Nascap-2K*, the default of geometrically distributed with a minimum of 0.1 seconds and a maximum of 60 seconds was used.

Table 3 compares the time required for an expert user to build a model and set up a calculation. This does NOT include the time needed to determine the most reasonable parameters for a specific problem. The determination of the appropriate material properties, geometry, environment, and calculation parameters for an actual analysis is typically weeks. It takes about as long to build a *Nascap-2K* model as to build a NASCAP/GEO model. However, the model created has the actual geometry and the resolution required. Sometimes it is necessary to build two NASCAP/GEO models at different resolutions in order to resolve questions.

The results of these sample calculations are summarized in Table 4. The potentials at 1000 seconds are shown in Figure 11 through Figure 13. The three codes give consistent results. The least negative surfaces are the ends of the solar arrays. The shaded Teflon surfaces are the most negative. All the surfaces that are more negative than the chassis are shaded insulators. In the center of the sun-facing side of the spacecraft body, the Teflon is slightly positive with respect to the chassis. This is most pronouced in the highest resolution *Nascap-2K* model. The sunlit insulators on the body are near the chassis potential or positive with respect to the chassis.

Table 3. Comparison of ease of use.

| **Code** | **Time to build model (min)** | **Time to set up calculation (min)** | **Time for charging calculation to complete (min)** |
|---|---|---|---|
| NASCAP/GEO | 30 | 5 | 3 on Sun |
| SEE Charging Handbook | 15 | 2 | 2 on 800 Hz PC |
| Nascap-2K | 30 | 3 | 12 on 800 Hz PC |

Table 4. Results of calculations in kV.

| | **Chassis** | **Kapton** | **OSR** | **Solar Cells** | **Teflon** | **Non-conducting paint** |
|---|---|---|---|---|---|---|
| **Absolute potentials** | | | | | | |
| NASCAP/GEO | –10.0 | -8.2 to -13.1 | -8.23 to -10.7 | –5.2 to -7.68 | –7.5 to -12.7 | -8.3 to -10.3 |
| SEE Spacecraft Charging Handbook | -8.6 | | -7.3 to -9.6 | -3.6 to -5.7 | -6.8 to -11.3 | -7.5 to -8.9 |
| Nascap-2K | -12.0 | -11.5 to -14.4 | -10.0 to -13.7 | -7.2 to -10.8 | -7.9 to -14.0 | -10.0 to -12.2 |
| **Differential potentials** | | | | | | |
| NASCAP/GEO | | 1.8 to -3.1 | 1.77 to -0.7 | 4.8 to 2.3 | 2.5 to -2.7 | 1.7 to -0.3 |
| SEE Spacecraft Charging Handbook | | | 1.3 to -1.0 | 5 to 2.9 | 1.8 to -2.7 | 1.1 to -0.3 |
| Nascap-2K | | 0.5 to -2.4 | 2 to -1.7 | 4.8 to 1.2 | 4.1 to -2 | 2 to -0.2 |

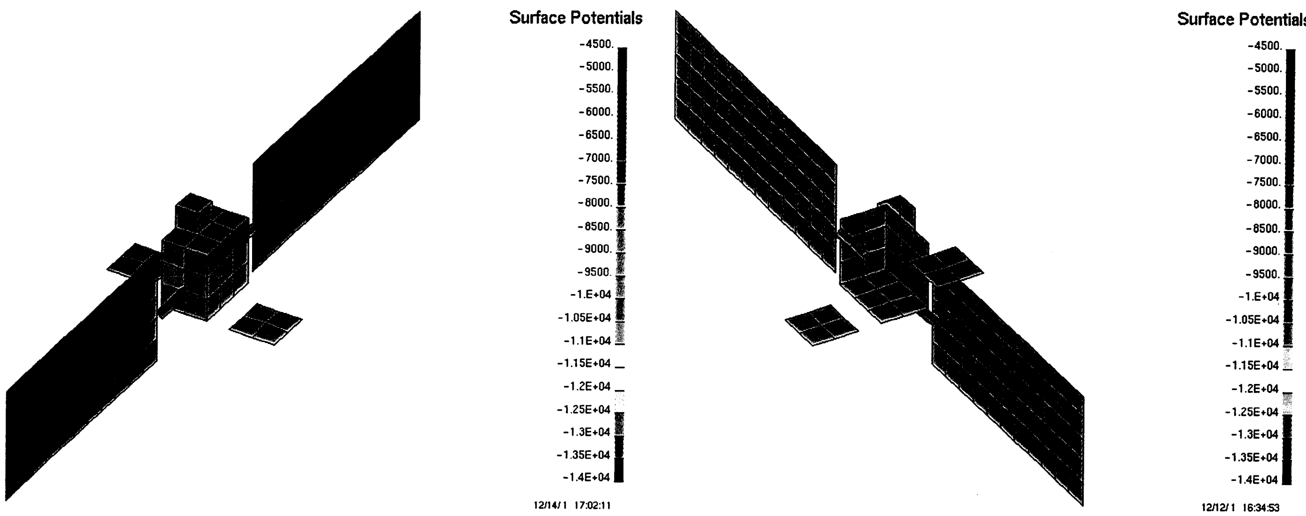


Figure 11. Results of spacecraft charging calculation using NASCAP/GEO.

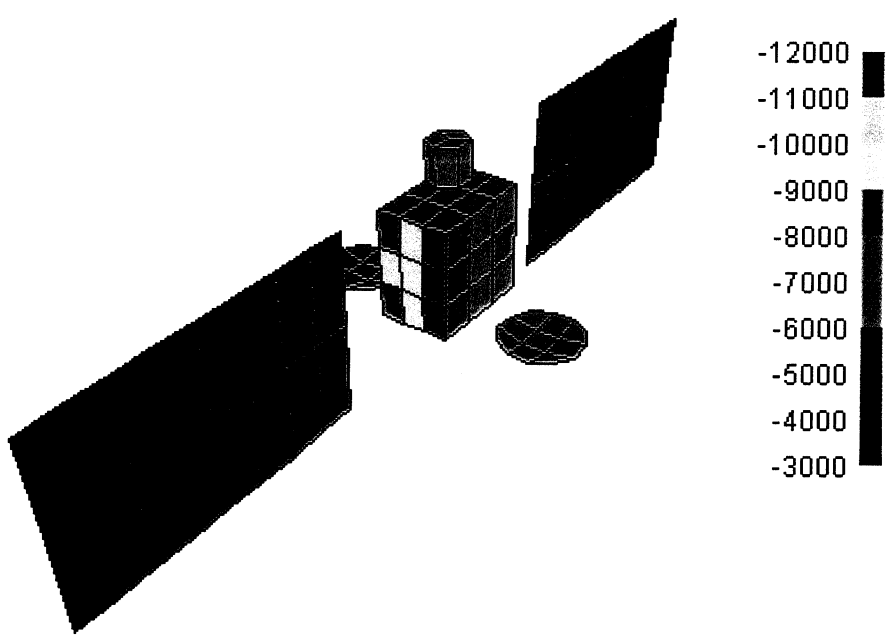


Figure 12. Results of spacecraft charging calculation using SEE Handbook.


Figure 13. Results of spacecraft charging calculation using *Nascap-2K*.

With the exception of the solar arrays, the surface potentials computed by the three codes are within approximately 35% of each other. The differences are primarily driven by the difference in the chassis potential. The differential potentials at the ends of the solar arrays, where the conductivity of the coverglass and barrier formation dominate the relative potentials, the differential potentials predicted by all three codes are within 4%. At the inner edges of the solar arrays, where the solution is complex, the differentials vary by almost a factor of two between the minimum and the maximum.

There are two main contributions to differences between the solutions obtained using these three codes: resolution of the geometry and time fidelity.

In order to obtain a stable solution, the variation of the potential within a single timestep is limited. The algorithms for this limiting are complex and different for each of these codes. The SEE Handbook uses a strong limiting algorithm in order to insure that the results are stable for a wide variety of problems. In NASCAP/GEO the limiting is partially under user control and moderate limiting (the default) was used for this calculation. *Nascap-2K* uses much less stabilization as the user is assumed to understand the code well enough to make the appropriate adjustments in the number and distribution of the timesteps in order to obtain a stable solution. As can be seen in Figure 14, the charging in *Nascap-2K* is faster than either of the other two codes.

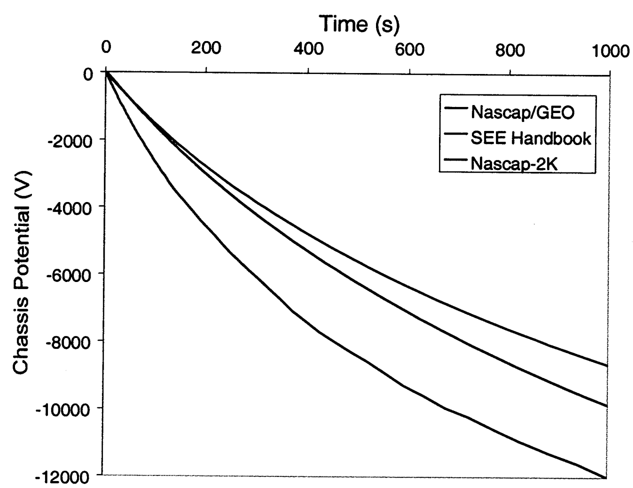


Figure 14. Comparison of time dependence of solutions.

The importance of geometric resolution can be illustrated by a comparison of the equilibrum solution given by the three codes as shown in Table 5. In order to further understand the differences due to geometry, a *Nascap-2K* object very similar to the SEE Handbook object was built and *Nascap-2K* used to compute potentials on it. The maximum negative differential in the NASCAP/GEO and *Nascap-2K* calculations are on the Kapton booms supporting the solar arrays. The SEE Handbook model and the simplified *Nascap-2K* model do not have these booms and the maximum negative differential potential is smaller than in the other cases.

Table 5. Comparison of equilibrum solutions.

| | Chassis (kV) | Max Positive Differential (kV) | Max Negative Differential (kV) |
|---|---|---|---|
| **NASCAP/GEO** | -20.3 | 10.8 | -2.5 |
| **SEE Handbook** | -17.8 | 10.4 | -0.14 |
| **Nascap-2K** | -19.5 | 7.8 | -3.6 |
| **Nascap-2K with Handbook object** | -19.2 | 9.4 | -0.06 |

The chassis potentials computed by all three codes are within 13% of each other. The maximum positive differential potential is on the ends of the solar arrays. After 15 minutes of charging, all three codes give 5 kV differential. At equilibrum, the results are within 30% of each other. Most of this difference appears to be due to the difference in the geometric resolution as the *Nascap-2K* calculation with the simplified model give a differential closer to the SEE Handbook than the full geometry model. In all cases the maximum positive differential is about half of the chassis potential.

## CONCLUSIONS

The SEE Spacecraft Charging Handbook and *Nascap-2K* improve our ability to model spacecraft surface charging. The surface charging calculated by the new codes is similar to the charging calculated by NASCAP/GEO. The SEE Handbook provides the user with insight with only a small investment in building an appropriate model and setting up an appropriate and stable calculation. *Nascap-2K* can be used for detailed calculations that include all the geometric features of interest and the best time fidelity available.

While not discussed here, it should be noted that the SEE Spacecraft Charging Handbook includes buried charge and surface charging due to auroral precipitation.

*Nascap-2K* is already proving valuable with its improved geometric modeling and surface electric field accuracy. When complete, it will be possible to do the highest accuracy three-dimensional spacecraft-plasma interaction calculations with a single, straightforward user interface.

The Spacecraft Charging Handbook is distributed by the Space Environment and Effects Program at the NASA Marshall Space Flight Center. Instructions for obtaining a copy are posted on the following website: http://see.msfc.nasa.gov

For additional information or to become a beta user of *Nascap-2K*, contact Jody Minor, jody.minor@msfc.nasa.gov.

## ACKOWLEGEMENTS

The SEE Spacecraft Charging Handbook was developed with funding from the SEE Program at NASA/Marshall. *Nascap-2K* is jointly funded by the Air Force Research Laboratory and NASA's Spacecraft-Environment Effects Program. The *Nascap-2K* GUI is being developed with funding from the SEE Program. Algorithms to apply the BEM to the spacecraft surface-charging problem were developed under contract to the Air Force Research Laboratory.

## REFERENCES

1. I. Katz, V.A. Davis, D.B. Snyder, Mechanism for Spacecraft Charging Initiated Destruction of Solar Arrays in GEO, AIAA Paper 98-1002, *AIAA Aerospace Sciences Meeting & Exhibit, 36th, Reno, NV*, Jan. 2000

2. Hoeber, C.F., E.A. Robertson, I. Katz, V.A. Davis and D.B. Snyder: Solar Array Augmented Electrostatic Discharge in GEO, AIAA Paper 98-1401 A98-19062), International Communication Satellite Systems Conference and Exhibit, 17th, Yokohama, Japan, Feb. 23-27, 1998.

3. Gordon L. Wrenn, Conclusive evidence for internal dielectric charging anomalies on geosynchronous communications spacecraft, *J. of Spacecraft & Rockets, 32*, p 514, 1995.

4. I. Katz V. A. Davis, M. J. Mandell, B. M. Gardner, J. M. Hilton, J. Minor A. R. Fredrickson, D. L. Cooke, Spacecraft charging interactive handbook with integrated, updated spacecraft charging models, Aerospace Sciences Meeting, AIAA Paper 2000-0247, *AIAA Aerospace Sciences Meeting & Exhibit, 38th, Reno, NV,* Jan. 2000.

5. I. Katz V. A. Davis, M. J. Mandell, D. E. Parks, B. M. Gardner, J. M. Hilton, J. Minor, D. L. Cooke, An auroral charging model in the spacecraft charging interactive handbook, AIAA Paper 2001-0956, *AIAA Aerospace Sciences Meeting & Exhibit, 39th, Reno, NV,* Jan. 2001.

6. M.J. Mandell, I. Katz, J.M. Hilton, J. Minor, D.L. Cooke, Nascap-2K, A Spacecraft Charging Analysis Code for the 21st Century, AIAA Paper 2001-0957, *AIAA Aerospace Sciences Meeting & Exhibit, 39th, Reno, NV,* Jan. 2001.

7. M.J. Mandell, P.R. Stannard, I. Katz, *NASCAP Programmer's Reference Manual,* NASA CR 191044, 1993.

8. M.J. Mandell, and I. Katz, High Voltage Plasma Interactions Calculations Using NASCAP/LEO, AIAA Paper AIAA-90-0725, 1990.

9. I. Katz, G.A. Jongeward, V.A. Davis, M.J. Mandell, R.A. Kuharski, J.R. Lilley, Jr., W.J. Raitt, D.L. Cooke, R.B. Torbert, G. Larson, and D. Rau, Structure of the Bipolar Plasma Sheath Generated by SPEAR I, *J. Geophysical Research, 94,* A2, p. 1450, 1989.

10. J.R. Lilley, Jr., D.L. Cooke, G.A. Jongeward, I. Katz, *POLAR User's Manual*, GL-TR-89-0307, Oct. 1989.

11. M.J. Mandell, T. Luu, J. Lilley, G. Jongeward, and I. Katz, *Analysis of Dynamical Plasma Interactions with High Voltage Spacecraft,* (2 volumes), Rep. PL-TR-92-2258, Phillips Lab., Hanscom Air Force Base, MA, June 1992.

12. V.A. Davis, M.J. Mandell, D.L. Cooke, C.L. Enloe, High-voltage interactions in plasma wakes: Simulation and flight measurements from the Charge Hazards and Wake Studies (CHAWS) experiment, *J. Geophys. Res., 104,* A6, p. 12445, 1999.

13. M.J. Mandell, G.A. Jongeward, D.L. Cooke, W.J. Raitt, SPEAR 3 flight analysis: Grounding by neutral gas release and magnetic field effects on current distribution, *J. Geophys. Res., 101,* A1, p. 439, 1998.

14. C.K. Purvis, H.B. Garrett, A.C. Whittlesey, N.J. Stevens, *Design Guidelines for Assessing and Controlling Spacecraft Charging Effects*, NASA TP 2361, 1984.

15. V.A. Davis, L.W. Duncan, Spacecraft Charging Handbook, PL-TR-92-2232, Nov 1992.

16. H.B. Garrett, The Charging of Spacecraft Surfaces, *Reviews of Geophysics and Space Physics, 19,* 4, p. 577, 1981.

17. E.C. Whipple, Potentials of Surfaces in Space, *Reports on Progress in Physics, 44,* p. 1197, 1981.

18. M.J. Mandell, I. Katz, G.W. Schnulle, P.G. Steen, J.C. Roche, The decrease in effective photocurrents due to saddle points in electrostatic potentials near differentially charged spacecraft, IEEE Trans. *Nucl. Sci., NS-25,* 6, p. 1313, 1978.

19. Cavendish, J. C., *J. Comp. Phys. 19,* 211 (1975).

20. I. Katz, J.J. Cassidy, M.J. Mandell, G.W. Schneulle, P.G. Stene, and J.C. Roche, The capabilities of the NASA Charging Analyzer Program, *Spacecraft Charging Technology--1978,* NASA CP-2071, AFGL TR-79-0082, 1978.

21. S. A. Brebbia, *Boundary Element Methods*, Springer Verlag, New York, 1981.

22. Messenger Home Page," http://sd-www.jhuapl.edu/MESSENGER/index.html.

23. I. Katz, M. Mandell, B. Gardner, R. Mauer, MESSENGER Spacecraft Charging Analysis, Presented at the 7th Spacecraft Charging Conference in Noordvijk, The Netherlands, 2001.