REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-01-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden to Department of Defense, Washington Headquarters Services Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
08-04-2005	REPRINT	

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Nascap-2k Spacecraft Charging Code Overview	
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 61102F
6. AUTHORS M.J Mandell*, V.A. Davis*, D.L. Cooke, and A.T. Wheelock	5d. PROJECT NUMBER 5021
	5e. TASK NUMBER RS
	5f. WORK UNIT NUMBER A1

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Air Force Research Laboratory /VSBXT 29 Randolph Road Hanscom AFB, MA 01731-3010	AFRL-VS-HA-TR-2007-1094
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/VSBXT
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for Public Relëase; distribution unlimited.

13. SUPPLEMENTARY NOTES

Reprinted from Proceedings, 9th Spacecraft Charging Technology Conference, Tsukuba, Japan, 4-8 April 2005. .

* Science Applications International Corp., San Diego, CA 92121

14. ABSTRACT

Nascap-2k is a modern spacecraft charging code, replacing the older codes NASCAP/GEO, NASCAP/LEO, POLAR, and DynaPAC. The code builds on the physical principles, mathematical algorithms, and user experience developed over three decades of spacecraft charging research. Capabilities include surface charging in geosynchronous and interplanetary orbits, sheath and wake structure and current collection in low-Earth orbits, and auroral charging. External potential structure and particle trajectories are computed using a finite element method on a nested grid structure and may be visualized within the *Nascap-2k* interface. Space charge can be treated either analytically, self-consistently with particle trajectories, or by importing plume densities from an external code such as *EPIC* (Electric Propulsion Interactions Code). Particle-in-cell capabilities are available to study dynamic plasma effects. Auxiliary programs to *Nascap-2k* include *Object Toolkit* (for developing spacecraft surface models) and *GridTool* (for constructing nested grid structures around spacecraft models). The capabilities of the code are illustrated by way of three examples: charging of a geostationary satellite, self-consistent potentials for a negative probe in a LEO spacecraft wake, and potentials associated with thruster plumes.

15. SUBJECT TERMS

Spacecraft charging   Plasma simulation,   Nascap-2k

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Adrian Wheelock
UNCL	UNCL	UNCL			19B. TELEPHONE NUMBER *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

NASCAP-2K SPACECRAFT CHARGING CODE OVERVIEW

M. J. Mandell, (858) 826-1622, Myron.J.Mandell@saic.com
V.A. Davis, (858) 826-1608, Victoria.A.Davis@saic.com
Science Applications International Corporation
10260 Campus Point Dr., M.S. A1, San Diego, CA, 92121 (FAX: 858-826-6584)

D. L. Cooke, A.T. Wheelock
Air Force Research Laboratory, Space Vehicles Directorate
Hanscom Air Force Base, MA 01731 (FAX: 781-377-2491)

Abstract

Nascap-2k is a modern spacecraft charging code, replacing the older codes NASCAP/GEO, NASCAP/LEO, POLAR, and DynaPAC. The code builds on the physical principles, mathematical algorithms, and user experience developed over three decades of spacecraft charging research.

Capabilities include surface charging in geosynchronous and interplanetary orbits, sheath and wake structure and current collection in low-Earth orbits, and auroral charging. External potential structure and particle trajectories are computed using a finite element method on a nested grid structure and may be visualized within the *Nascap-2k* interface. Space charge can be treated either analytically, self-consistently with particle trajectories, or by importing plume densities from an external code such as *EPIC* (Electric Propulsion Interactions Code). Particle-in-cell (PIC) capabilities are available to study dynamic plasma effects.

Auxiliary programs to *Nascap-2k* include *Object Toolkit* (for developing spacecraft surface models) and *GridTool* (for constructing nested grid structures around spacecraft models).

The capabilities of the code are illustrated by way of three examples: charging of a geostationary satellite, self-consistent potentials for a negative probe in a LEO spacecraft wake, and potentials associated with thruster plumes.

Introduction

Designers of spacecraft for government, commercial, and research purposes require advanced modeling capabilities to guide the design of satellites that can survive and operate properly in the natural environment. Computer modeling of flight experiments (including SCATHA, the SPEAR[1,2] series and CHAWS[3]) demonstrated excellent ability to predict both steady-state and dynamic interactions between high-voltage spacecraft and the ambient plasma. This ability was extended to inherently dynamic problems involving three-dimensional space charge sheath formation, current flow in the quasi-neutral presheath, breakdown phenomena, plasma kinetics, ionization processes, and the effect of unsteady processes on spacecraft charging.

NASCAP/GEO[4,5,6] (NASA Charging Analyzer Program for GEosynchronous Orbit) was the standard tool for the computation of spacecraft charging in tenuous plasmas for more than two decades. Since then, the fully three-dimensional computer codes NASCAP/LEO[7,8] (NASA Charging Analyzer Program for Low-Earth Orbit), POLAR[9] (Potentials Of Large objects in the Auroral Region), and *DynaPAC*[10] (Dynamic Plasma Analysis Code) were developed to address various other spacecraft-plasma interactions issues. *Nascap-2k*[11] builds on the capabilities of these older codes, giving the spacecraft designer much-improved modeling capabilities by taking advantage of a greater understanding of the pertinent phenomena, employing more advanced algorithms, and implementing a state-of-the-art user interface, including three-dimensional post-processing graphics. *Nascap-2k* is being developed as part of a program sponsored jointly by the Air Force Research Laboratory at Hanscom AFB and by NASA's Space Environments and Effects (SEE) Program at Marshall Space Flight Center. The current release is Version 3.0.

Nascap-2k is an interactive toolkit for studying plasma interactions with realistic spacecraft in three dimensions. As it incorporates physics developed for all the previous codes, it can solve problems appropriate to both tenuous (*e.g.*, GEO orbit or interplanetary missions) and dense (*e.g.*, LEO orbit) plasma environments. *Nascap-2k* is targeted to spacecraft design engineers, spacecraft charging researchers, and aerospace engineering students. The graphical user interface is designed to help less experienced users easily solve moderately complex plasma interactions problems. Figure 1 shows several views of the *Nascap-2k* interface, including the main problem setup page, the *GridTool* interface, and views of particle trajectories and space and surface potentials.

The core capabilities of *Nascap-2k* include:

1. Define spacecraft surfaces and geometry and the structure of the computational space surrounding the spacecraft;
2. Solve for time-dependent potentials on spacecraft surfaces;
3. Solve the electrostatic potential about the object, with flexible boundary conditions on the object and with space-charge computed either fully by particles, fully analytically, or in a hybrid manner;
4. Generate, track, and otherwise process electrons and ions, represented as macroparticles in the computational space; and
5. View surface potentials, space potentials, particle trajectories, and time-dependent potentials and currents.

To accomplish these capabilities, *Nascap-2k* consists of:

1. The *Nascap-2k* graphical user interface (Figure 1), a user-friendly environment for definition of problem parameters, strategizing and running calculations, and visualizing results;
2. *Object ToolKit* (OTk), an interactive program for the definition of spacecraft surfaces;
3. *GridTool*, an interactive program to create arbitrarily subdivided grids in the space surrounding a spacecraft model;
4. The modules that comprised the *DynaPAC* code as the major computational engine. These have been converted to DLLs (dynamic link libraries) to run seamlessly within *Nascap-2k*;
5. A new analysis module implementing the Boundary Element Method[12] (BEM) for calculating surface charging in Geosynchronous Earth Orbit (GEO), in the Solar Wind, or in other tenuous plasma environments.

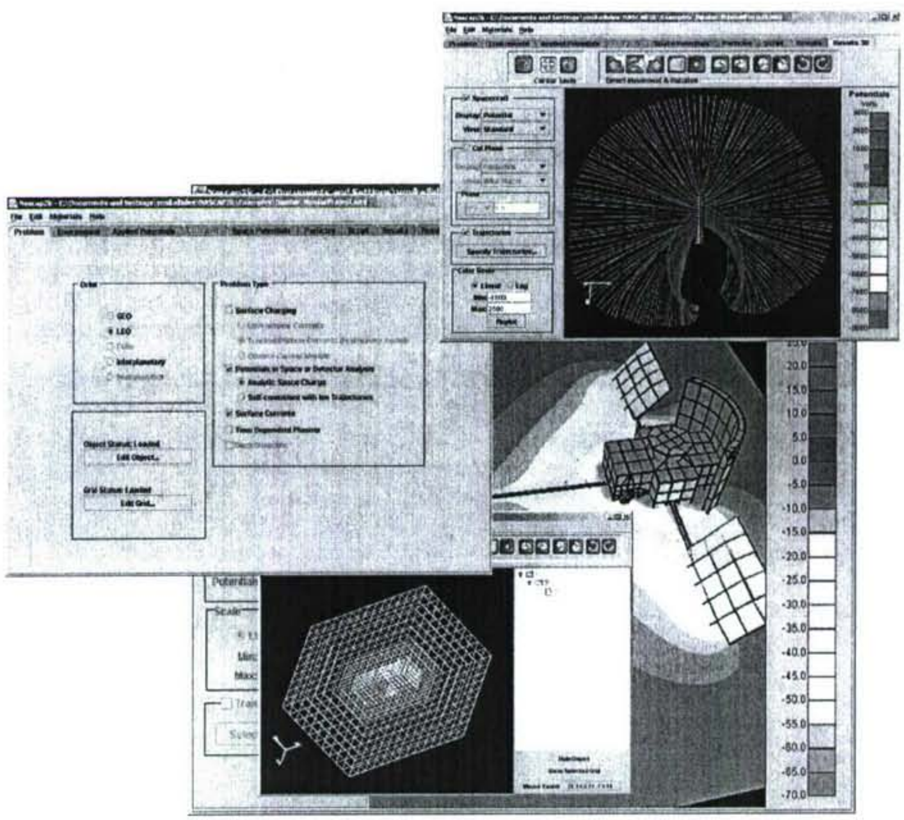

Figure 1. Views of the *Nascap-2k* tabbed user interface, including main problem setup (center left), particle trajectories (upper right), surface and space potentials (center right), and *GridTool* interface (bottom center).

Nascap-2k uses a high-order finite element representation for the electrostatic potential that assures that electric fields are strictly continuous throughout space. The electrostatic potential solver (originally developed for *DynaPAC* [13]) uses a conjugate gradient technique to solve for the potentials and fields on the spacecraft surface and through the surrounding space. Several analytic and numerical space charge density models are available, including Laplacian, Linear, Non-linear, Frozen Ions, Full Trajectory Ions, Hybrid PIC (appropriate to the several microsecond timescale response to a negative pulse), and Full PIC.

Particle tracking is used to study sheath currents, to study detector response, to generate steady-state charge densities, or to generate space charge evolution for dynamic calculations. *Nascap-2k* generates macroparticles (each of which represents a collection of particles) either at a "sheath boundary", the problem boundary, or throughout all space. Alternatively, particles can be initialized with a user-generated file. Particles are tracked for a specified amount of time, with the timestep automatically subdivided at each step of each particle to maintain accuracy. The current to each surface of the spacecraft is recorded for further processing.

The **Results 3D** tab of the *Nascap-2k* user interface is used to generate graphical output illustrating such quantities as object surface potentials, space potentials, particle positions, or particle trajectories. Using Java3D capabilities, these figures can be rotated, panned, zoomed, or measured. Contour levels and other plotting attributes are modified through the user interface. The **Results** tab is used to view time histories and obtain numerical values for potentials and surface currents.

The modular structure of *Nascap-2k* is illustrated in Figure 2. Surface charging is done in the new BEM module. Space potentials and particle trajectories are calculated with DLLs built from the *DynaPAC* modules[10,14] The suite of codes is written in Java (user interface), C++ and Fortran (science), and C (utility routines) and is maintained on the Win32 platform.

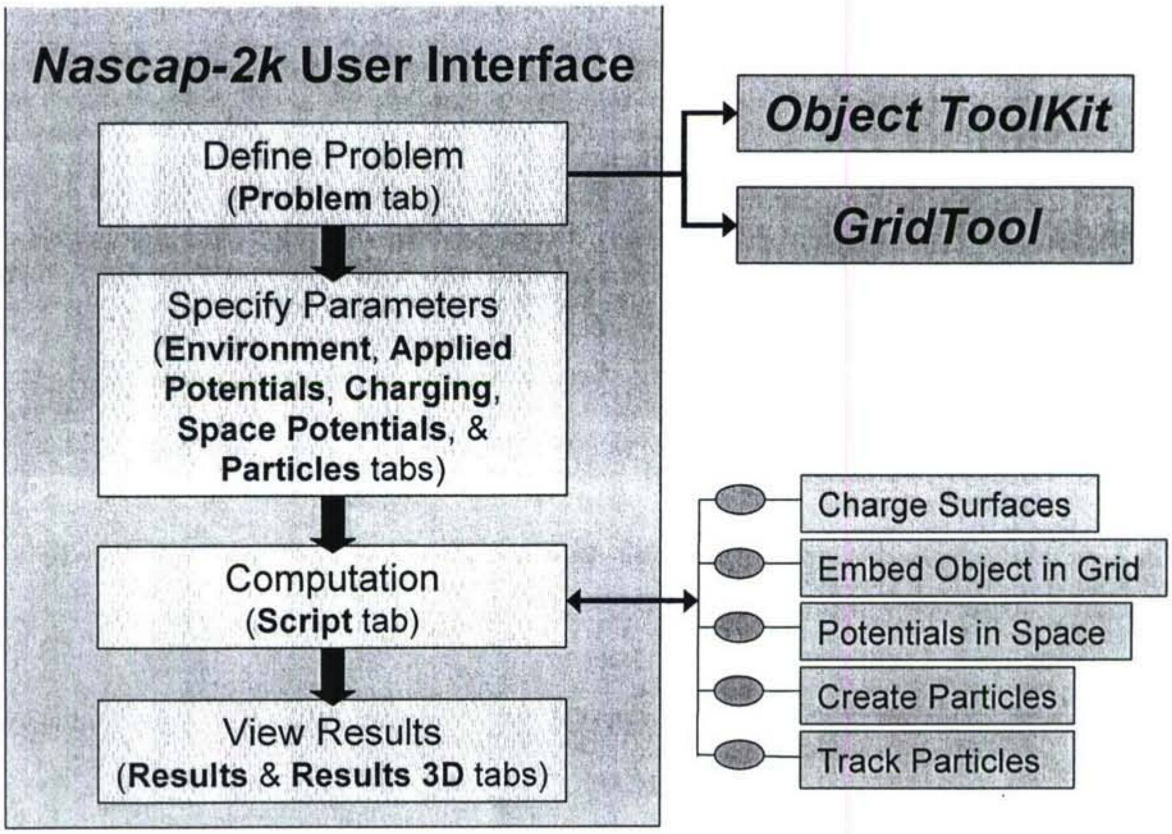

Figure 2. *Nascap-2k* Module Diagram.

Spacecraft Models and Object Toolkit

A Nascap-2k application usually begins by building a geometrical spacecraft model with *Object Toolkit*. Objects are built using the five native components shown in Figure 3, together with components imported from standard finite element preprocessing software and components previously defined and saved using *Object Toolkit*. Direct mesh editing capabilities are available to create subdivision and to build components with complex shapes. Figures 4 through 6 show some examples of spacecraft defined using *Object Toolkit*.

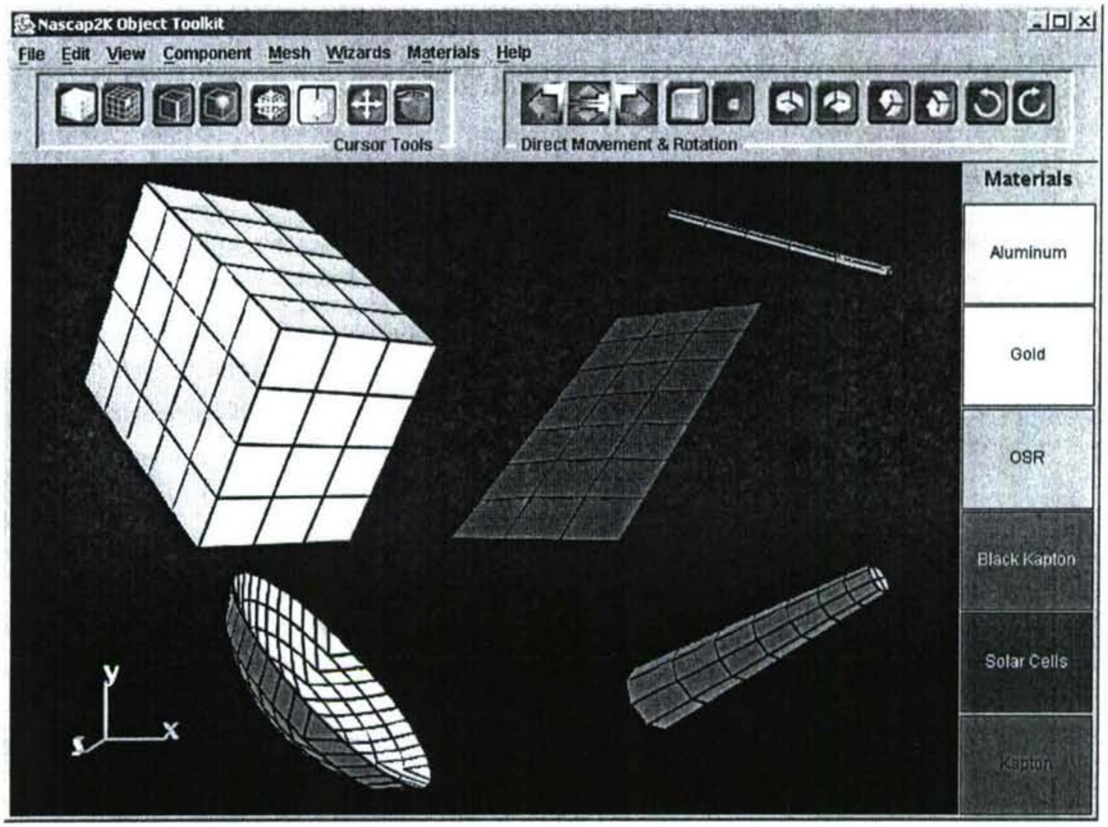

Figure 3. Native components (clockwise from upper left: Box, Boom, Panel, Cylinder, Dish) available within *Object Toolkit* for defining spacecraft models.

Each elemental surface of a spacecraft model has attributes of "Conductor Number" and "Material Name." The conductor number attribute is used to represent electrical circuitry coupling the spacecraft surfaces, such as biasing of surfaces or capacitive/resistive coupling. With each material name is associated a list of properties including thickness, bulk and surface conductivity, and photoemission and secondary electron emission coefficients. Material properties can be edited in both *Object Toolkit* and the main *Nascap-2k* interface. In addition, advanced features such as grounding tabs can be placed on the spacecraft model.

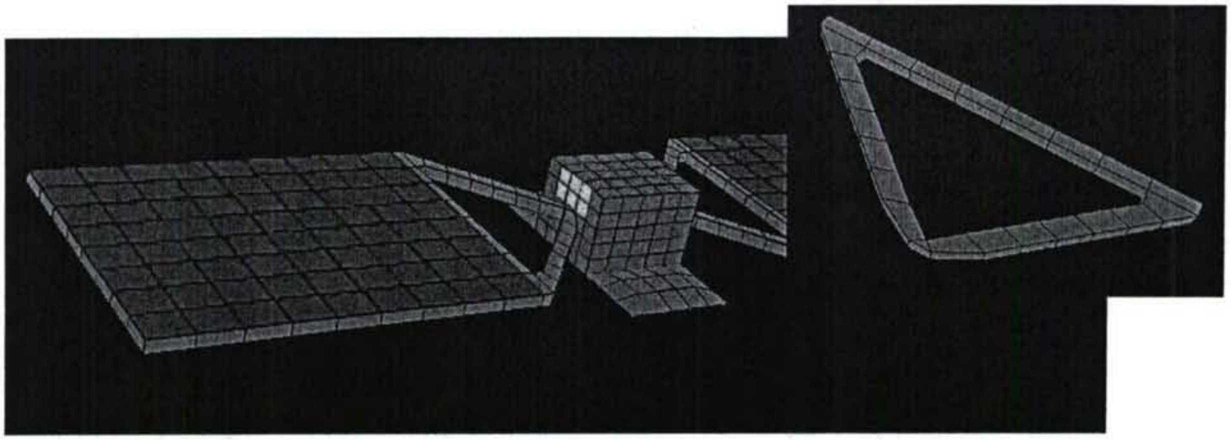

Figure 4. Simple spacecraft model, featuring a solar array yoke (upper right) built in *Object Toolkit* from three booms.

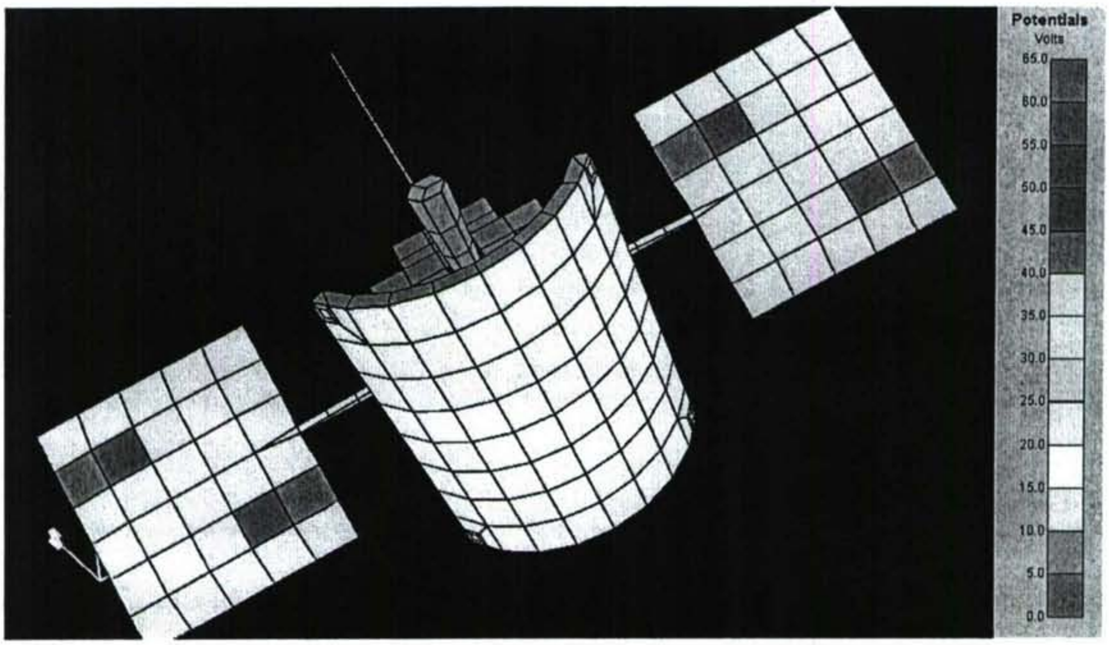

Figure 5. *Nascap-2k* model of the MESSENGER spacecraft, showing biased solar array surfaces.

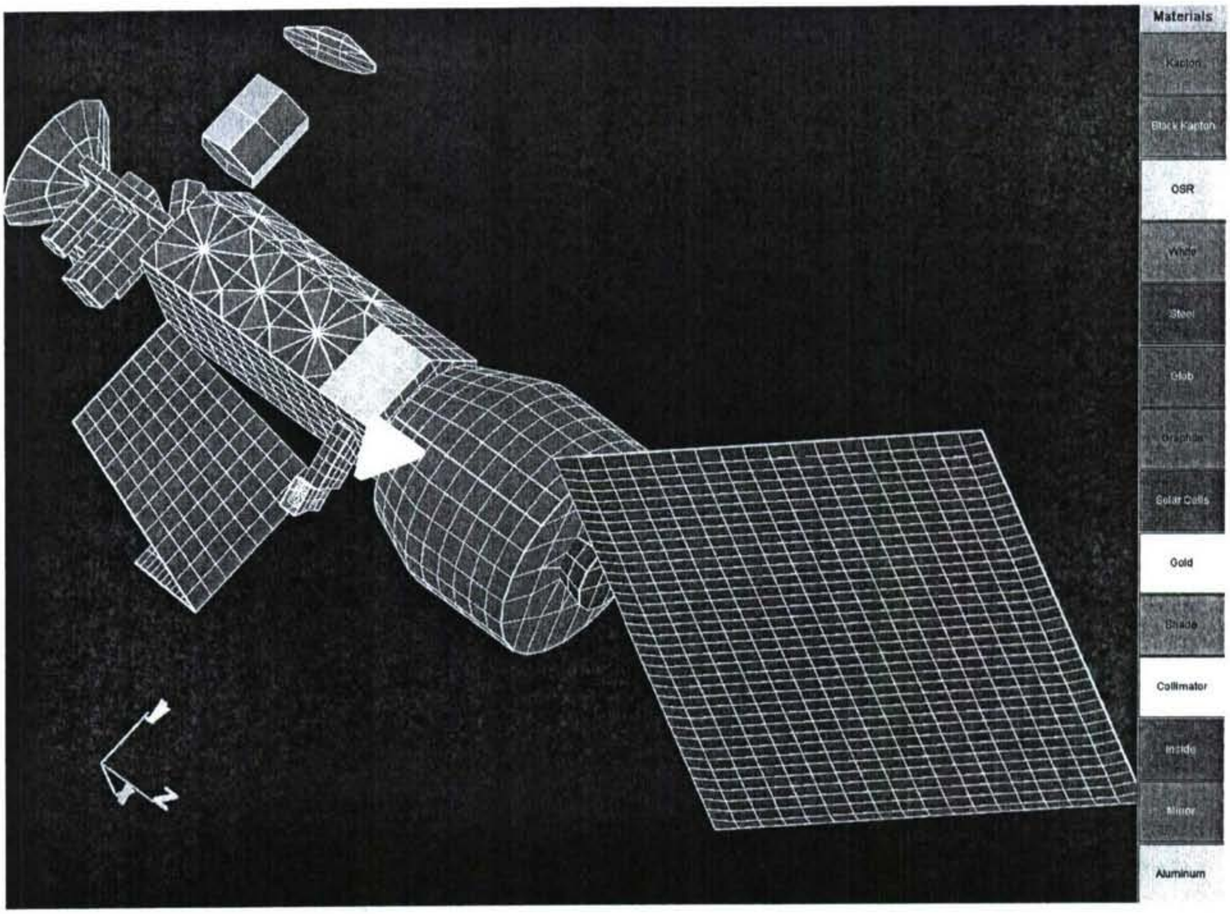

Figure 6. DMSP spacecraft model constructed in *Object Toolkit*.

Nascap-2k Papers and Examples at SCTC Conferences

Descriptions of *Nascap-2k* and its predecessor codes, and simulations and analyses based on those codes, have been presented at every Spacecraft Charging Technology Conference dating back to the first conference in Colorado Springs, October 1976. Table 1 shows a list of the papers, together with the examples contained in each, for the three most recent conferences.

Table 1. *Nascap-2k* papers presented at recentSpacecraft Charging Technology Conferences.

9th Spacecraft Charging Technology Conference (Tsukuba, Japan, April 2005)
• *Nascap-2k* Spacecraft Charging Code Overview (This Paper) o Geosynchronous Charging o Current Collection in Wake o Potentials in Ion Engine Plume
• *Nascap-2k* Simulations of a VLF Plasma Antenna o PIC Capabilities
• Reverse trajectory approach to computing ionospheric currents to the Special Sensor Ultraviolet Limb Imager on DMSP o Determine current to sensor
8th SCTC (Huntsville, Alabama, October 2003)
• Validation of *Nascap-2k* Spacecraft-Environment Interactions Calculations o Current collection by sphere o Geosynchronous charging (comparison with other codes) o Bipolar sheath collection (comparison with older results) o Auroral charging (comparison with older results)
• *Nascap-2k* – An Overview o GEO, interplanetary, and auroral charging o LEO charging showing $\mathbf{v}\times\mathbf{B}$
• *Nascap-2k* as a PIC Code o Dynamic antenna sheath calculations
7th SCTC (Noordwijk, The Netherlands, April 2001)
• MESSENGER Spacecraft Charging Analysis o Charging in Hermean and near-Hermean environment
• Comparison of the NASCAP/GEO, SEE Interactive Charging Handbook, and *Nascap-2k* Spacecraft Charging Codes o Geosynchronous orbit charging
• *Nascap-2k* Spacecraft Charging Models: Algorithms and Applications o Implementation Details o Geosynchronous orbit charging o Solar Wind charging

Example 1: Geosynchronous Orbit Charging

The earliest and most common application for this family of codes is to study charging of spacecraft in geostationary orbit. *Nascap-2k* is designed to make this type of analysis particularly easy.

A simple *Object Toolkit*-built model of a geosynchronous spacecraft is shown in Figure 7. Apart from the solar arrays, the spacecraft is covered with low-secondary-emission insulators, except for some patches of high-secondary-emission OSRs on the side of the box.

On the initial **Problem** tab of *Nascap-2k* (Figure 8) we load the object and select a surface charging problem in a geostationary environment. Since *Nascap-2k* can calculate surface potentials and electric fields using the Boundary Element Method (BEM), there is no need to define a spatial grid, and consequently all options requiring a grid are disabled. With a grid, we would be able to calculate and display space potentials and particle trajectories.

Next we define the environment on the **Environment** tab, as shown in Figure 9. Any single or double maxwellian environment can be defined, and some predefined environments are provided. In this case, we use the built-in "NASA Worst Case"[15] environment. The magnetic field and the sun direction and intensity (1.0 for sunlit and 0.0 for eclipse) are also set here. Note that the tab as shown is customized for geosynchronous substorm parameters; if a low-Earth-orbit or auroral environment is selected the tab looks quite different.

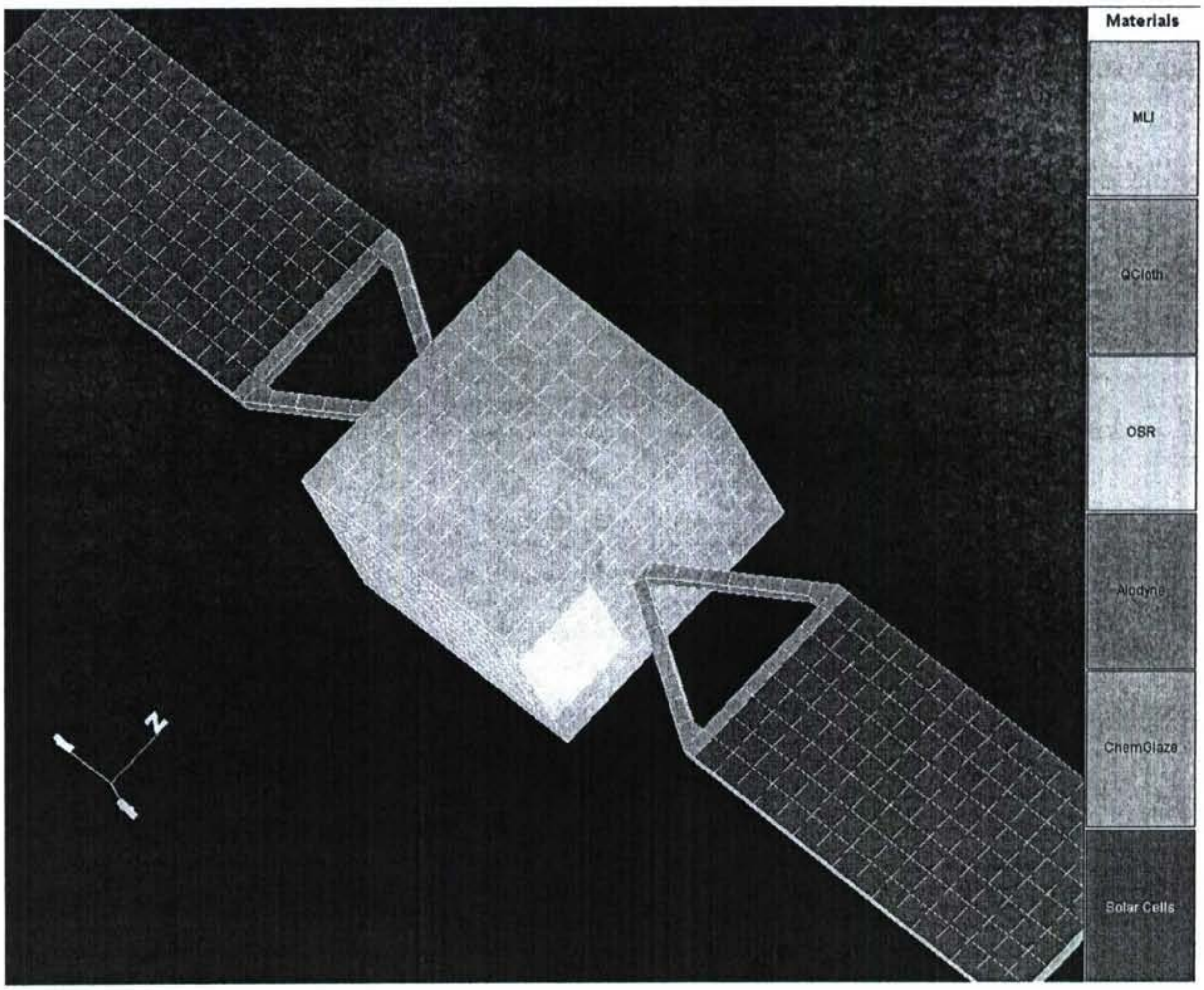

Figure 7. Simple geosynchronous spacecraft used for example.

Figures 10 and 11 show, respectively, the **Charging** and **Script** tabs that customize how the calculation is performed. In this case, the timestepping parameters were edited to produce more, shorter time steps than the default, and the automatically generated script was used without modification. Exposing the script provides a great deal of flexibility in running problems with *Nascap-2k*. Customized scripts can be built and edited both within the **Script** tab and externally using a text editor or specialized XML editor.

The calculation is initiated by clicking the "Run Script" button. Monitors, such as the "BEM Monitor" shown in Figure 12, appear to indicate the progress of the calculation. In this case, the minimum and maximum potentials, simulation time, and elapsed time are periodically updated. Most of the two minutes of elapsed time shown on the monitor is attributable to the calculation of the BEM matrix elements, which are stored on disk so they need not be recalculated for additional simulations.

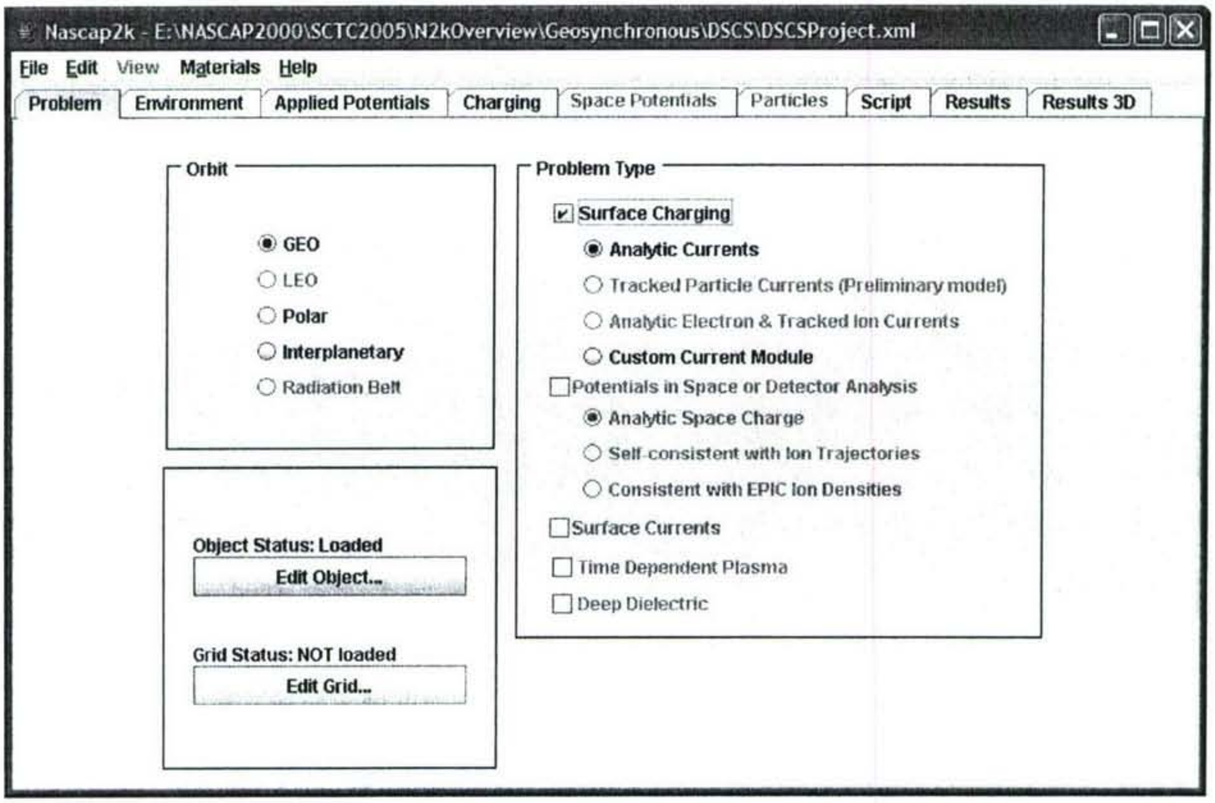

Figure 8. Opening **Problem** tab of *Nascap-2k* interface set for geosynchronous charging example.

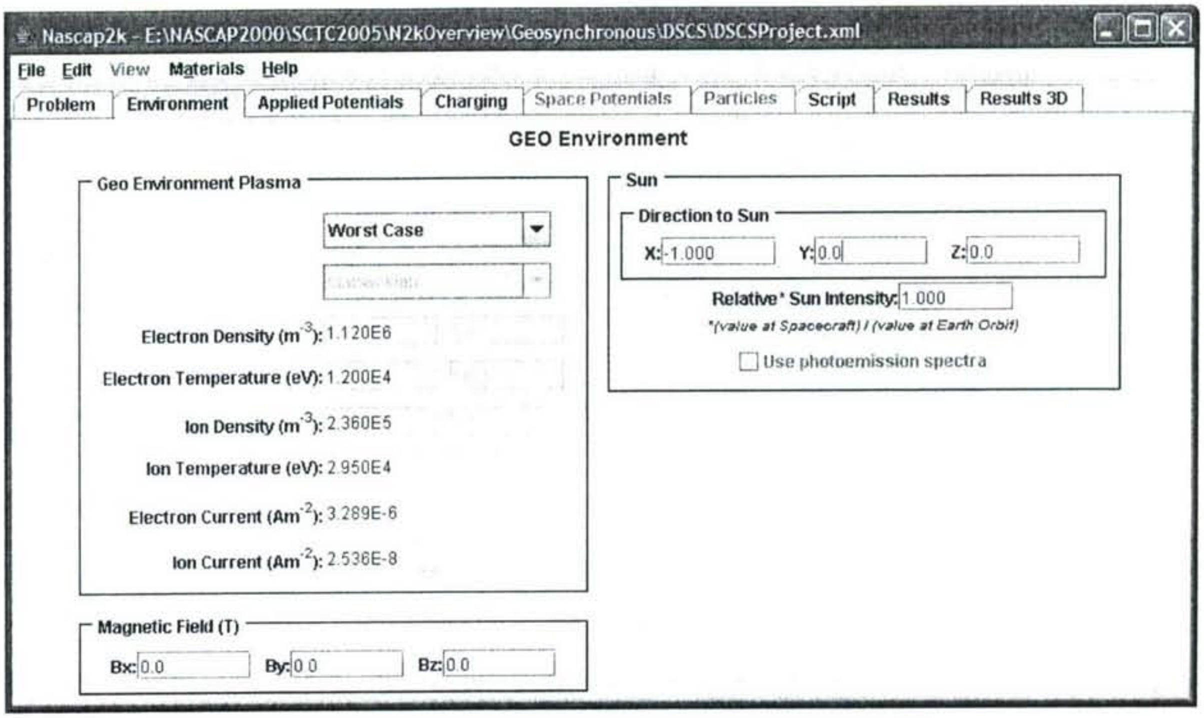

Figure 9. Nascap-2k **Environment** tab, customized for GEO environment definition.

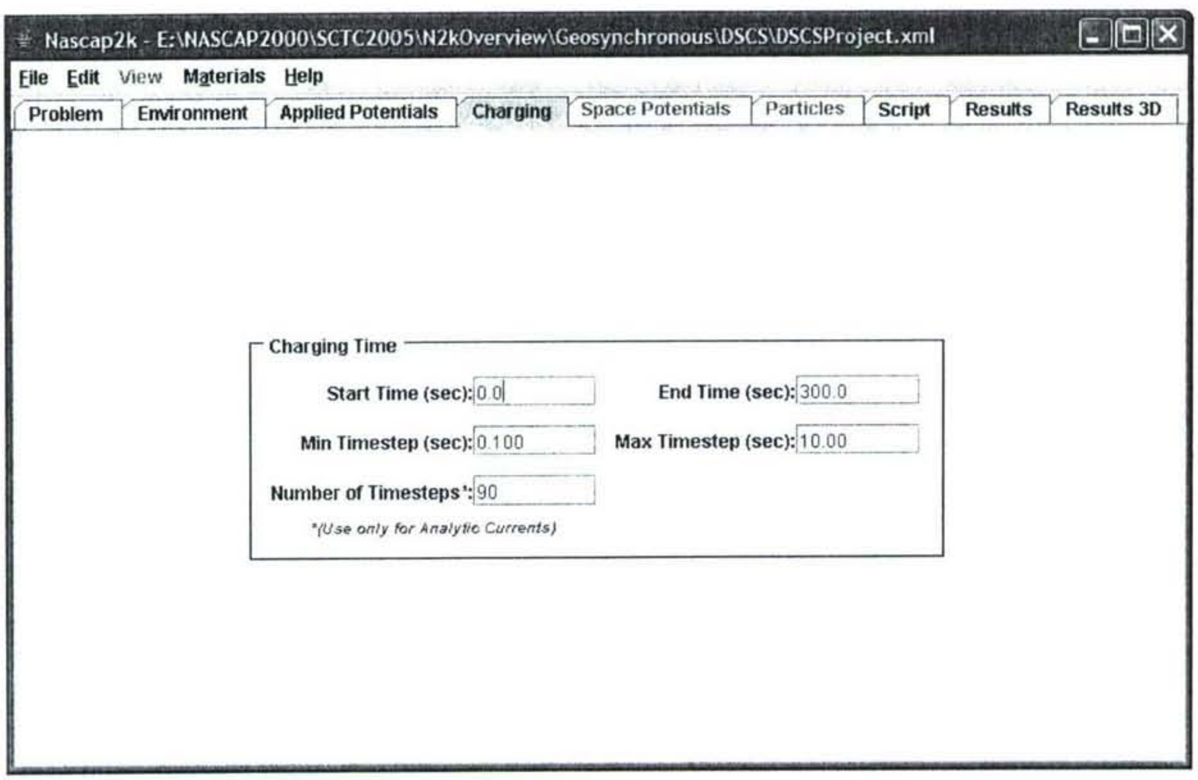

Figure 10. *Nascap-2k* **Charging** tab, used to set timestep parameters for charging calculations.

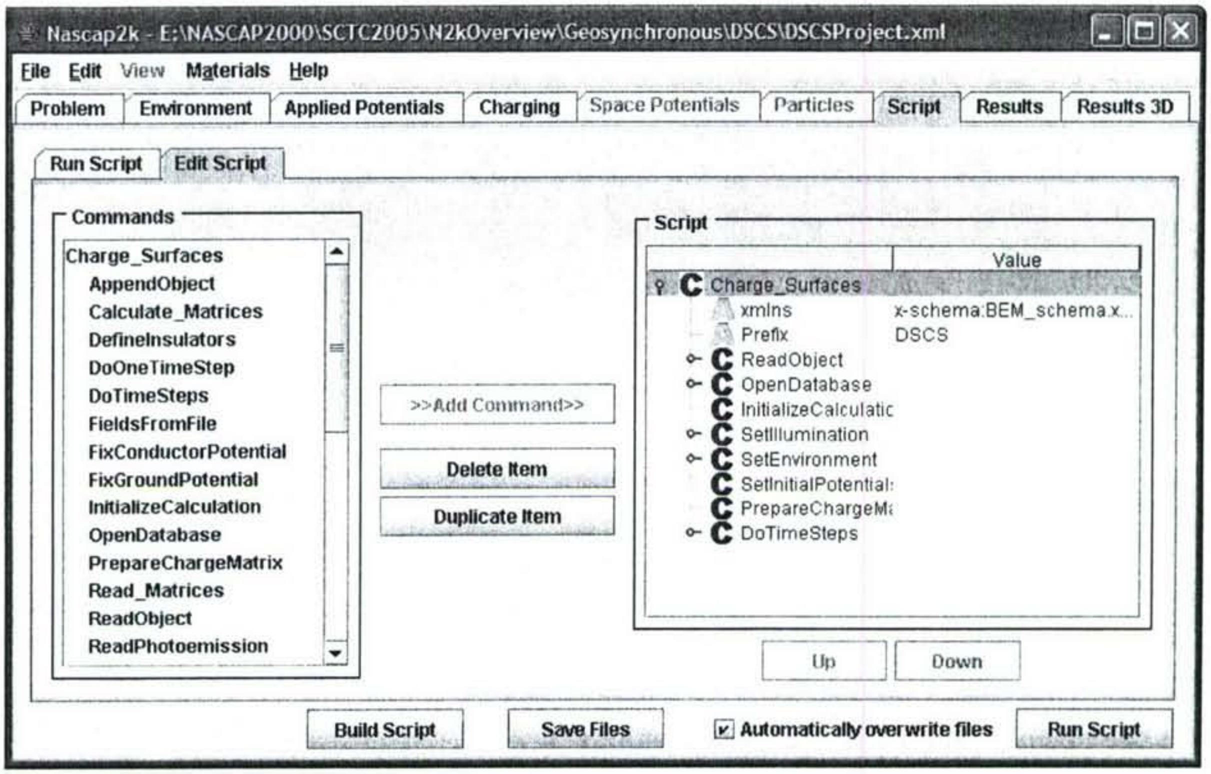

Figure 11. *Nascap-2k* **Script** tab, set for a simple geosynchronous environment charging calculation. While this script was generated automatically, more complex and customized scripts can be built and edited either within this tab or externally using a text or XML editor.

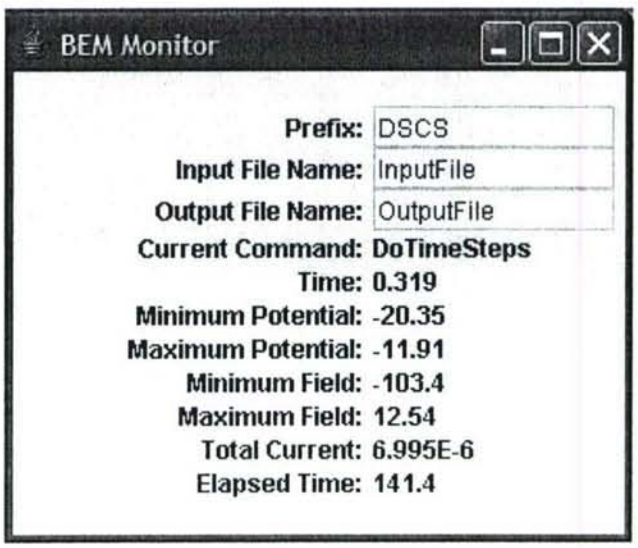

Figure 12. "BEM Monitor" indicates the progress of a calculation using the BEM module, such as a surface charging calculation.

Calculation results are post-processed and displayed on the **Results3D** tab (Figure 13) and on the **Results** tab (Figure 14). Figure 13 shows that, after five minutes of charging, most of the dark surface material charges to about 10 kV negative, with the emissive OSR surfaces about 8 kV negative. The least negative surfaces, at about 7 kV negative, are at the center of the sunlit side of the central box and toward the outboard end of the solar arrays. As shown in Figure 13, we can select individual surfaces to obtain detailed information about them. In a gridded calculation, this tab can define and display contour planes of external potential and particle trajectories superposed on the surface plot.

The **Results** tab (Figure 14) is used to display detailed numerical and time-dependent information. The left part of the tab allows specification of groups of surface cells, individual surfaces, or conductor entities, and selection of potentials, electric fields, or currents. Shown in Figure 14 are the conductor potential (most negative curve) and the minimum, maximum, and average potentials of the solar cells. The plotted information may be displayed as text on the **Text** subtab and pasted into a spreadsheet for further processing. Figure 15 shows the same data plotted in Microsoft Excel, along with the potential of the dark insulator that covers most of the satellite surface.

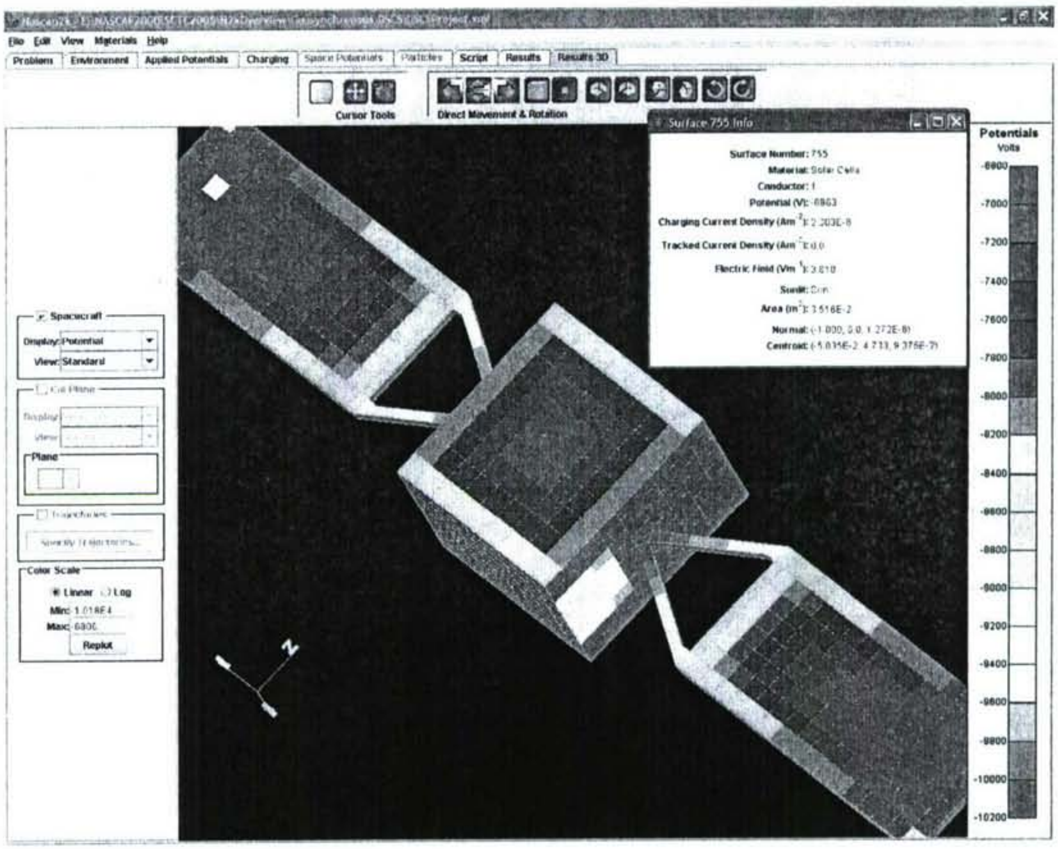

Figure 13. Results3D tab showing surface potentials at end of calculation, and detailed information for a selected surface cell.

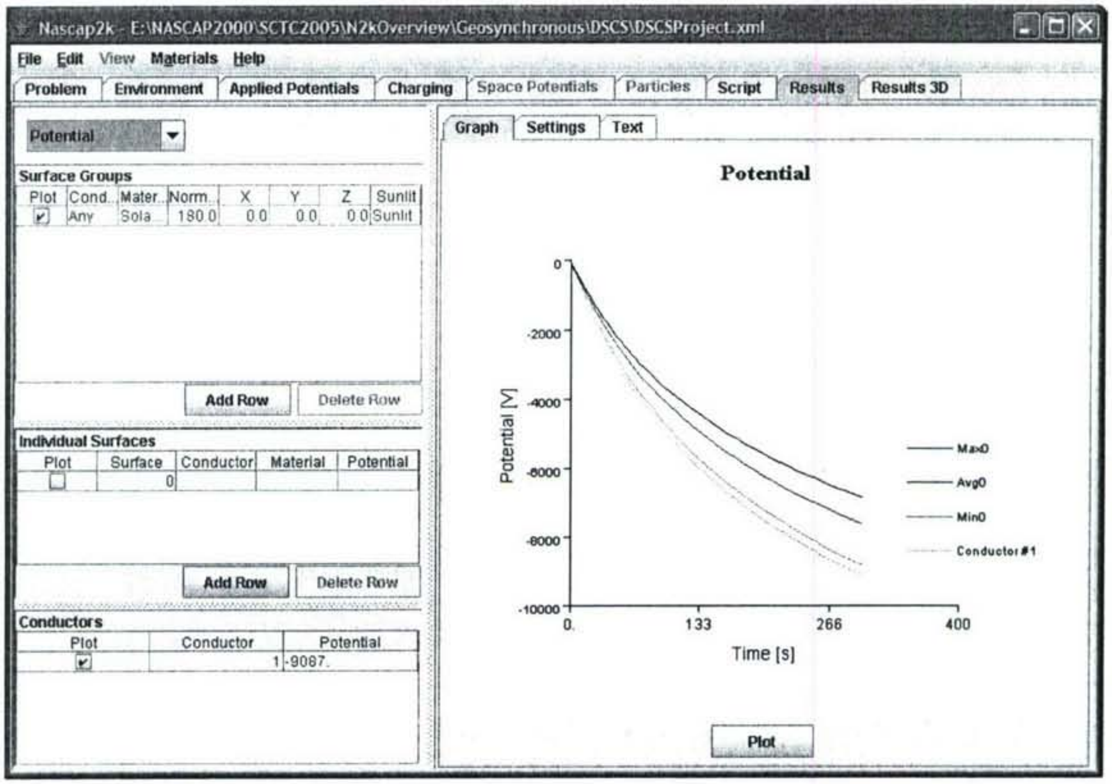

Figure 14. Results tab, showing time development of ground potential and range of potentials on solar array surfaces.

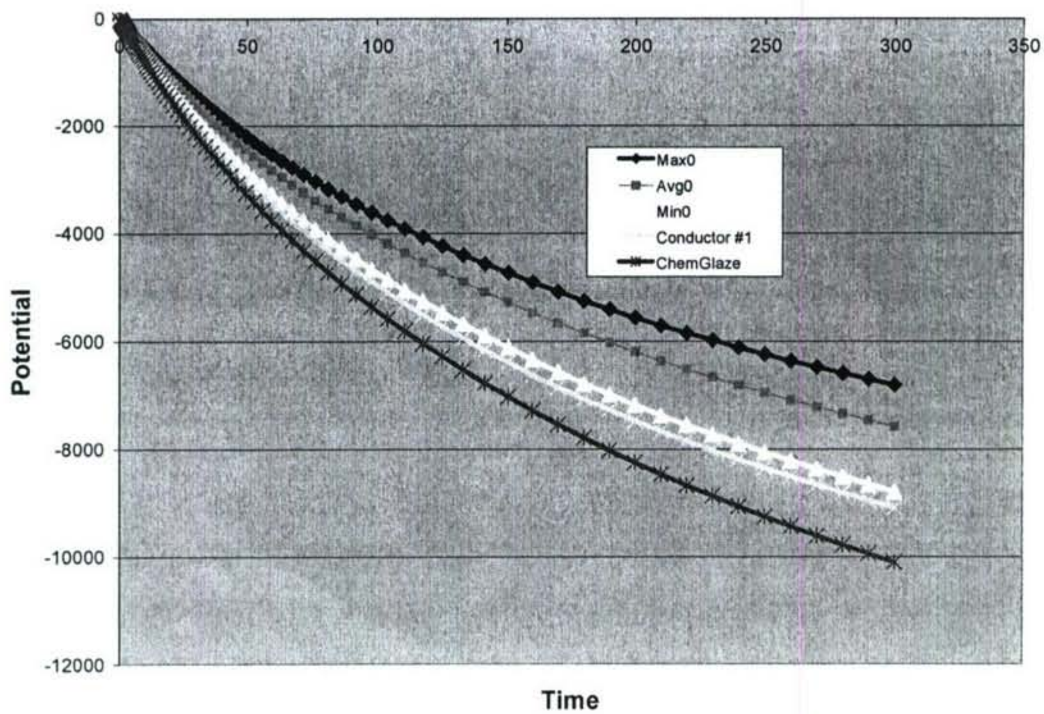

Figure 15. Charging results imported into Microsoft Excel from **Text** subtab.

Example 2: Self-Consistent Potentials in a Wake

To study ion collection by a high voltage object in a spacecraft wake, the CHAWS[16] (Charging Hazards and Wake Studies) experiment was flown about the WSF (Wake Shield Facility) on STS-60 (February 1994) and STS-69 (September 1995). Originally simulated using the *DynaPAC* code, we use this problem as the primary example of a self-consistent (between potentials and trajectories) calculation in *Nascap-2k*.

Figure 16 shows the Object Toolkit model of the WSF with CHAWS. The CHAWS probe is the off-center well-resolved rod seen toward the left of the figure, which shows the wake side of the WSF. Negative biases of up to 2 kV were applied to the probe, which was instrumented to measure both the total current and the distribution of current over the surface.

Since we need to calculate both space potentials and particle trajectories, a grid structure is built in the space surrounding the model. The GridTool representation of the grid structure is shown in Figures 17 and 18. The grid is designed to provide high resolution both in the neighborhood of the probe and in region of plasma flow that is perturbed by the applied potential.

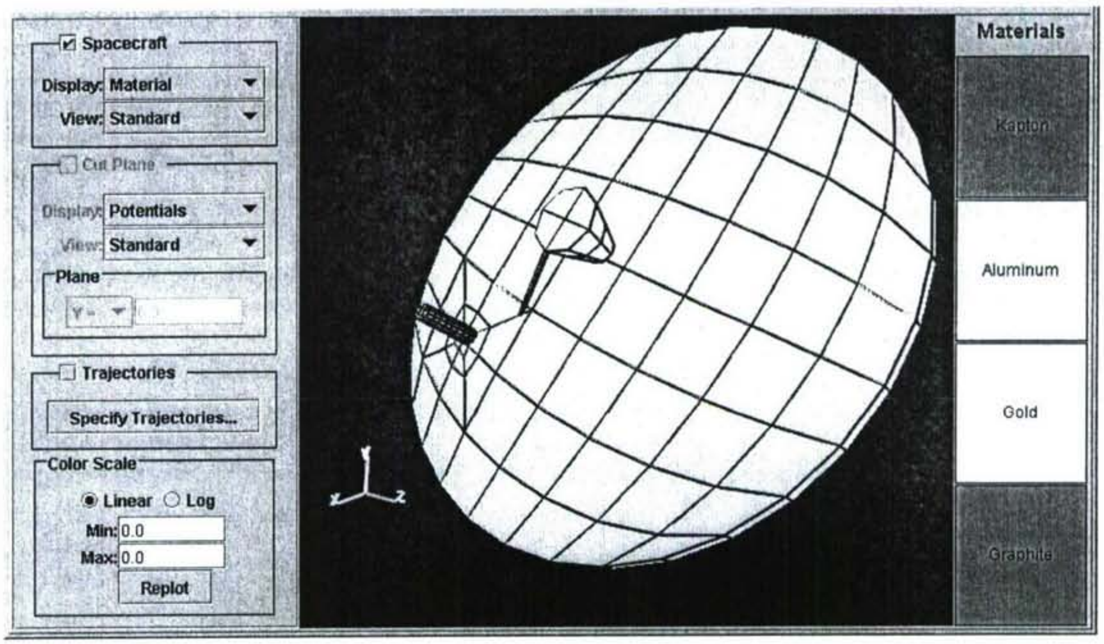

Figure 16. Geometric model of the WSF wake side, showing the CHAWS probe (well-resolved cylinder at left).

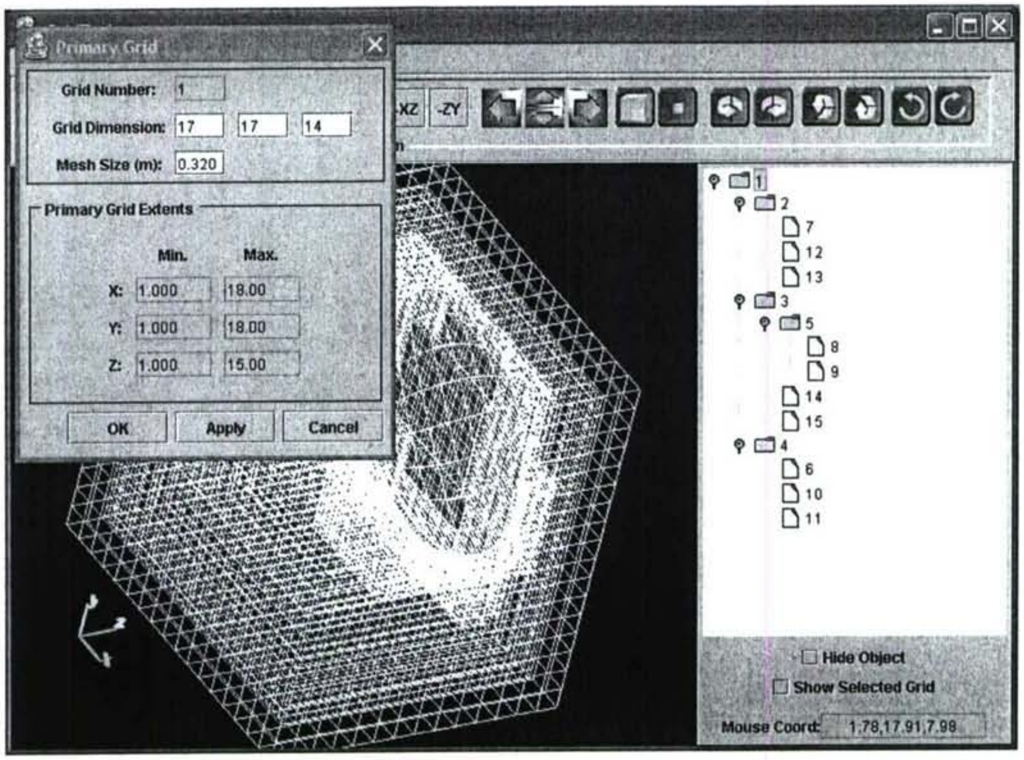

Figure 17. GridTool view of grid structure used for the CHAWS problem. The right pane details the grid and subgrid structure.

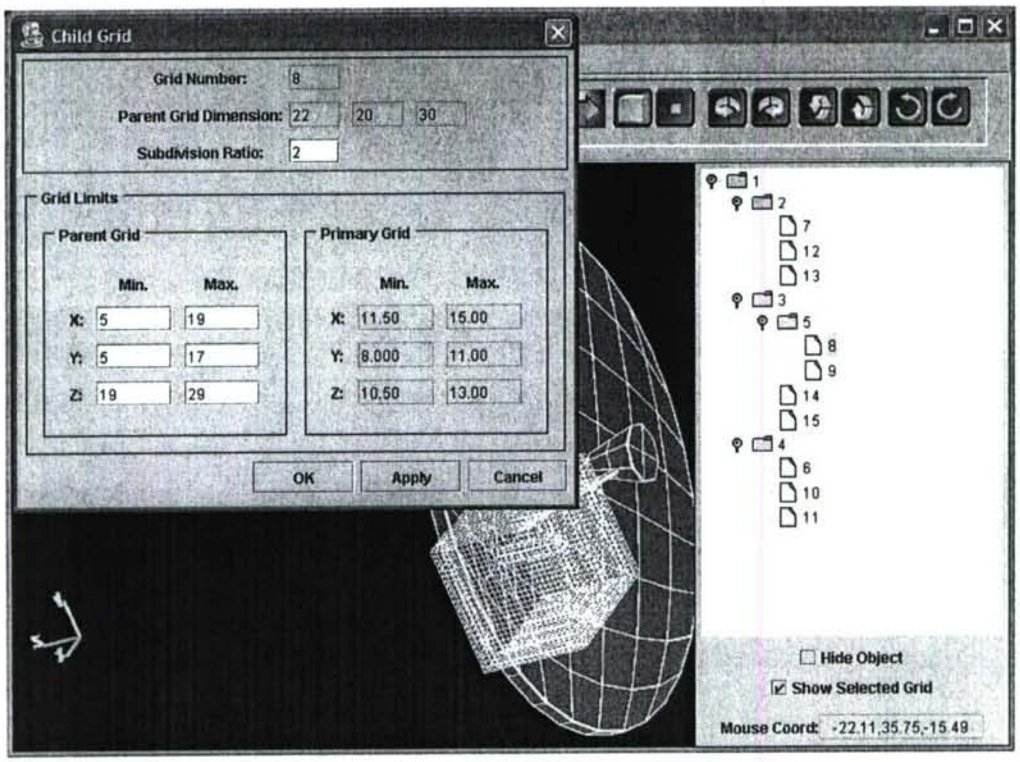

Figure 18. GridTool view of highly resolved grid near CHAWS probe.

Figure 19 shows the environment specification for this problem. For a spacecraft orbiting in a LEO plasma, we must specify not only the plasma density and temperature, but also the spacecraft velocity and the ion species, which together determine the ram ion energy. Figure 20 shows the script for this calculation, which is generated automatically by *Nascap-2k*. The script directs the code to generate and track particles in the existing potentials, and then recalculate the potentials using space charge derived from the ion trajectories. (The electron density is assumed to be barometric.) The sequence repeats to approach a self-consistent solution. The script also refers to input files (which are generated automatically and can also be user-edited) to the *Nascap-2k* modules and to the output files from those modules.

Figure 21 shows a subset of ion trajectories for this problem. Ions are generated at the problem boundary with a thermal spread about the ram direction and are tracked until they strike the object or leave the problem space. Ion space charge is accumulated in the grid at each tracking step, and the current corresponding to ions reaching to CHAWS probe is recorded. It is noteworthy that no ions strike the side of the probe nearest the edge of the WSF, but rather ions either strike the tip of the probe or else miss the tip and are attracted back to the side of the probe facing the center of the WSF.

Finally, Figure 22 displays the self-consistent potentials about the CHAWS probe behind the WSF. Note that the potential field of the probe extends considerably into the ram flow in the vicinity of the near edge of the WSF, and this influence manifests itself in the trajectory deflection for this region seen in Figure 21. The grounded rear surface of the WSF, the WSF instrumentation, and the ion space charge all play a role in limiting the penetration of CHAWS potentials into the wake, so that the potential is shielded much faster than would be the case if the wake were a cylindrical vacuum region.

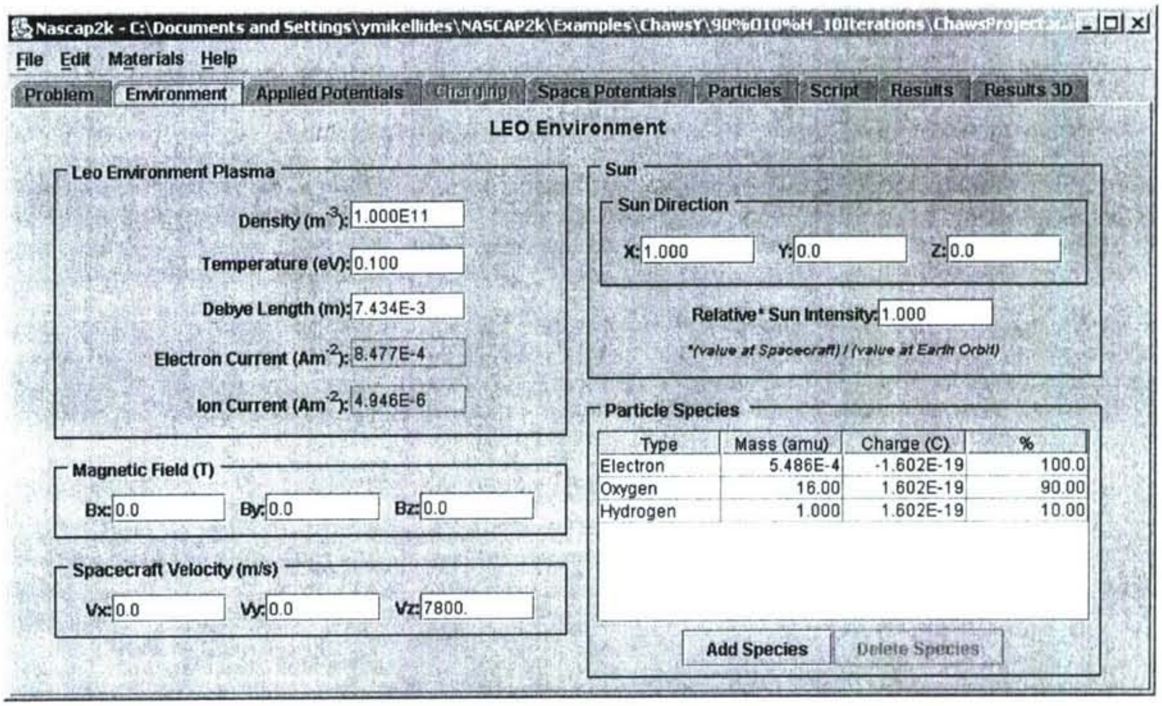

Figure 19. Environment tab, showing specification of plasma, spacecraft velocity, and particle species for the CHAWS problem.

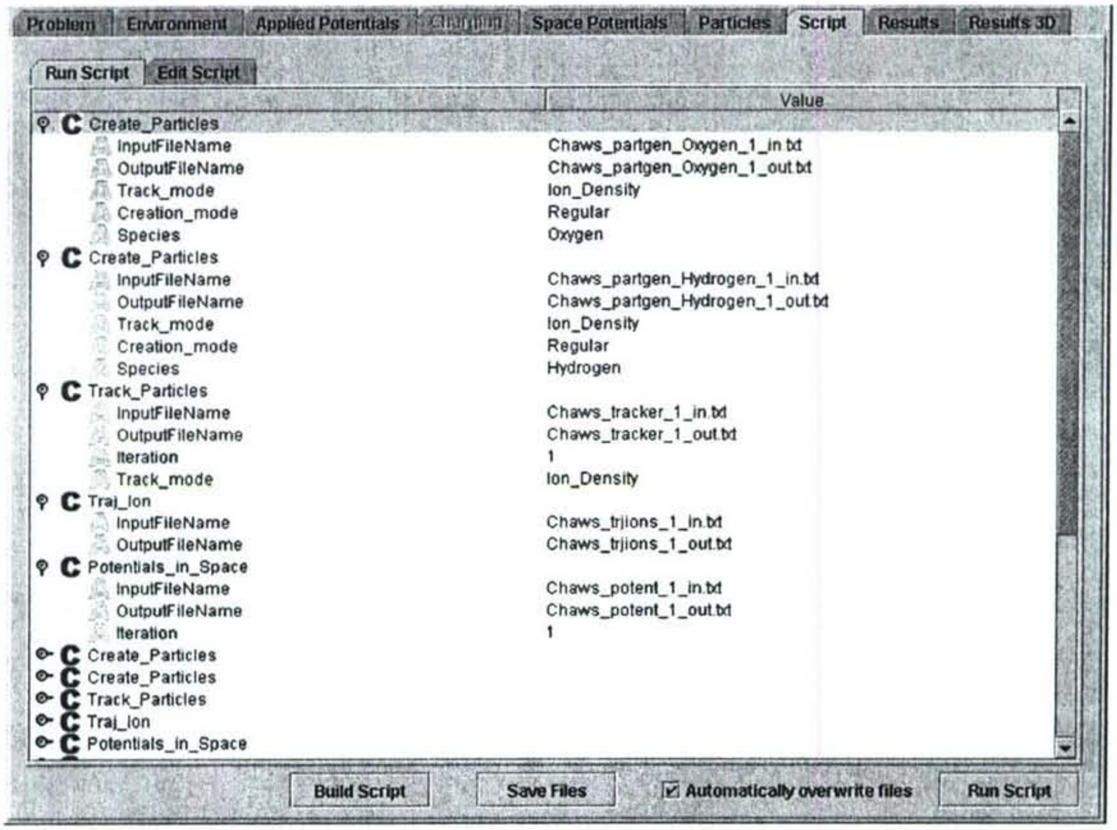

Figure 20. CHAWS problem script to iteratively create and track ions and solve potentials in the space charge of those ions.

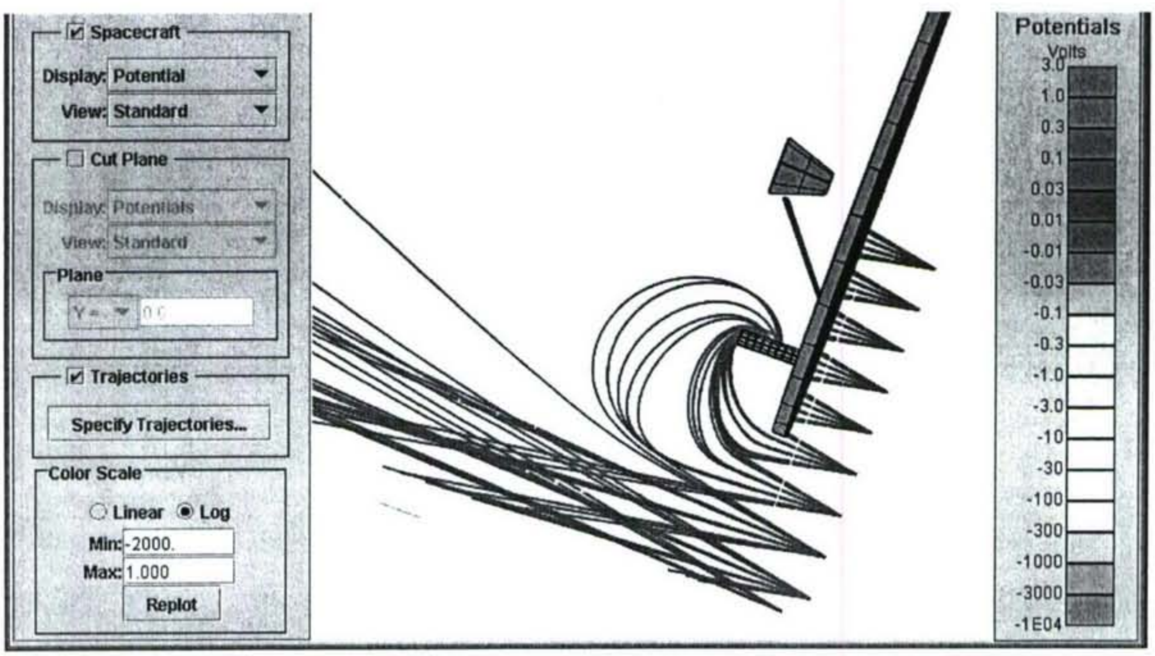

Figure 21. Trajectories of ram particles, including thermal spread, for CHAWS problem.

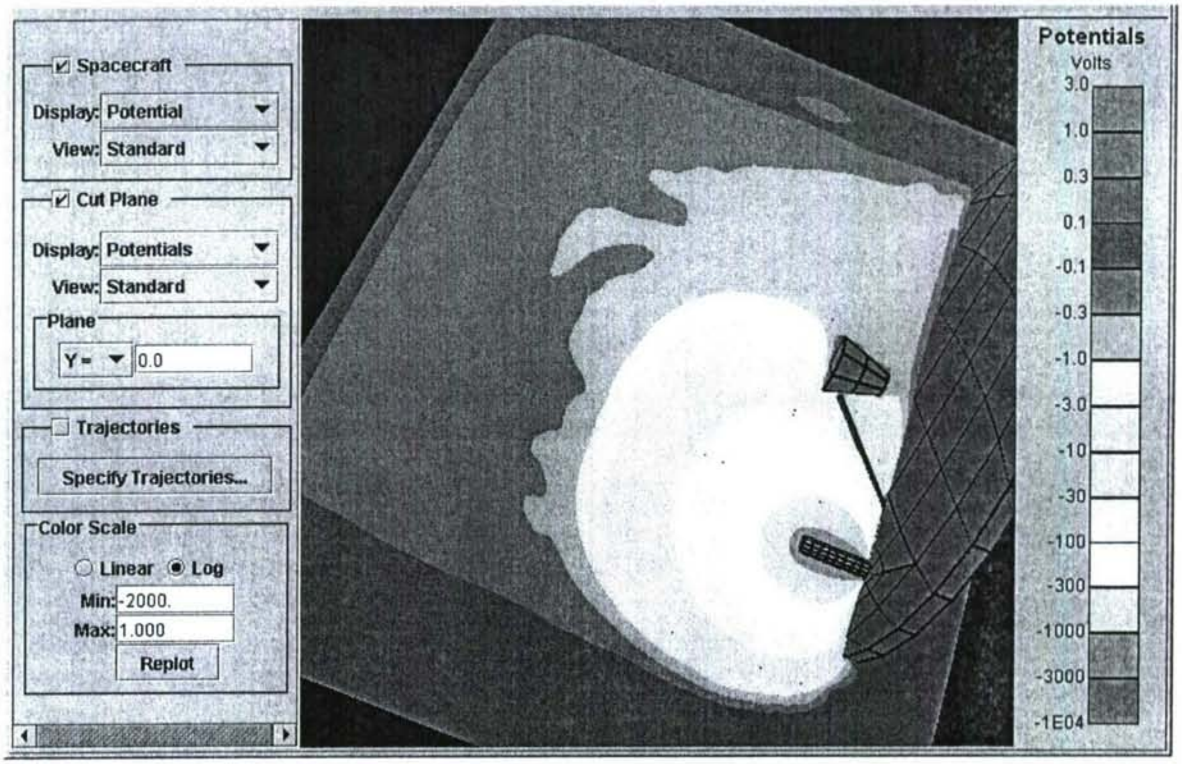

Figure 22. Self-consistent potentials about the CHAWS probe in the wake of the WSF.

Example 3: Potentials in Electrostatic Thruster Plumes

A recent enhancement made to *Nascap-2k* is the inclusion of ion densities from plasma sources (such as thruster plumes) in the computation of potentials in space. One reason for needing potentials due to plasma sources is the computation of contaminant trajectories. We plan to extend this capability to study, among other phenomena, the influence of spacecraft surfaces on engine plumes and interactions between plumes.

For this example the ion density due to plasma sources is imported from the *EPIC* (Electric Propulsion Interactions Code) computer code[17] which, like *Nascap-2k*, has been developed by SAIC for NASA's SEE program. The import is done via SOAP (an XML-based interprocess communication scheme formerly known as Simple Object Access Protocol). *Nascap-2k* then solves a nonlinear Poisson equation for space potentials using the surface potentials as boundary conditions. As was done in the CHAWS example presented above, the charge density consists of a known ion density plus a barometric electron density:

$$\frac{\rho}{\varepsilon_0} = \frac{\rho_{ion}}{\varepsilon_0}\left(1-\exp\left(\left(\phi-\phi_b\right)/\theta\right)\right)$$

$$\phi_b = \theta \ln\left(\frac{\rho_{ion}}{en}\right)$$

where θ and n are the plume electron temperature and reference density respectively, ρ is the total charge density to be used in Poisson's equation, and ρ_{ion} is the known ion density, in this case imported from *EPIC*.

We treat a configuration that might characterize a geosynchronous spacecraft during North-South station-keeping. On the same spacecraft used above for the geostationary charging example, we affix two NSTAR[18] thrusters pointing NorthWest and NorthEast. (A thruster as large as NSTAR is unlikely to be used for this purpose, but we selected it because we had a good model for its plume.) Figure 23 shows the spacecraft and plasma densities as displayed in *EPIC*.

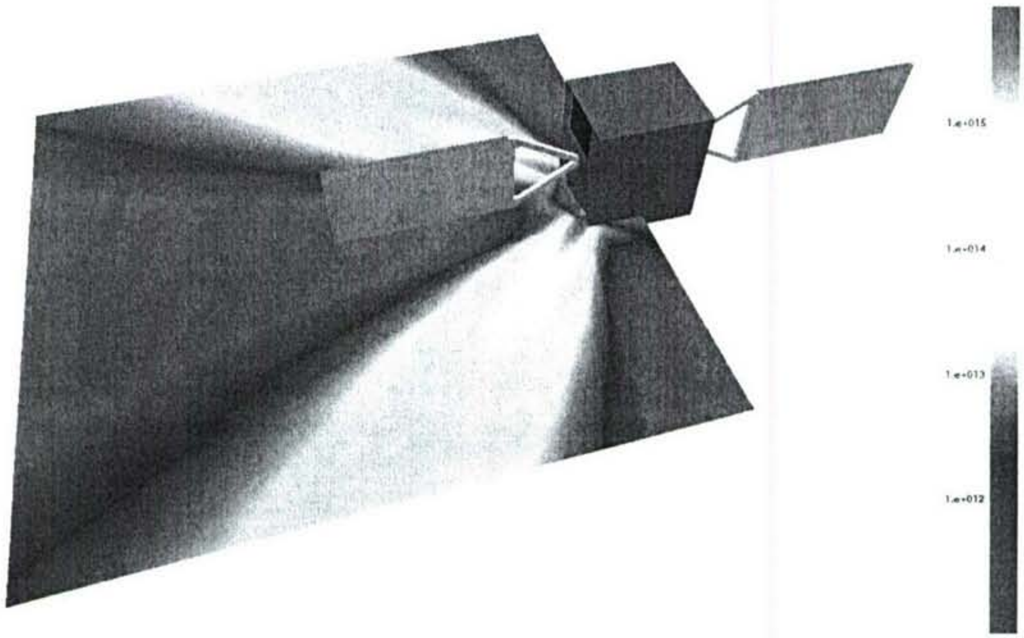

Figure 23. Plasma density displayed in *EPIC* for two NSTAR thrusters, as described in text.

For a reference density we chose a value of 1×10^{12} m^{-3}, which is the density of charge exchange ions just outside the main beam. This density is also used as the minimum ion density, so that regions void of plume ions are set to zero potential. The beam electron temperature was taken as 1 eV. We set the average potential on the solar arrays to be +20 V, and the potential of all other surfaces to be -2 V. Figure 24 shows the resulting potentials in space.

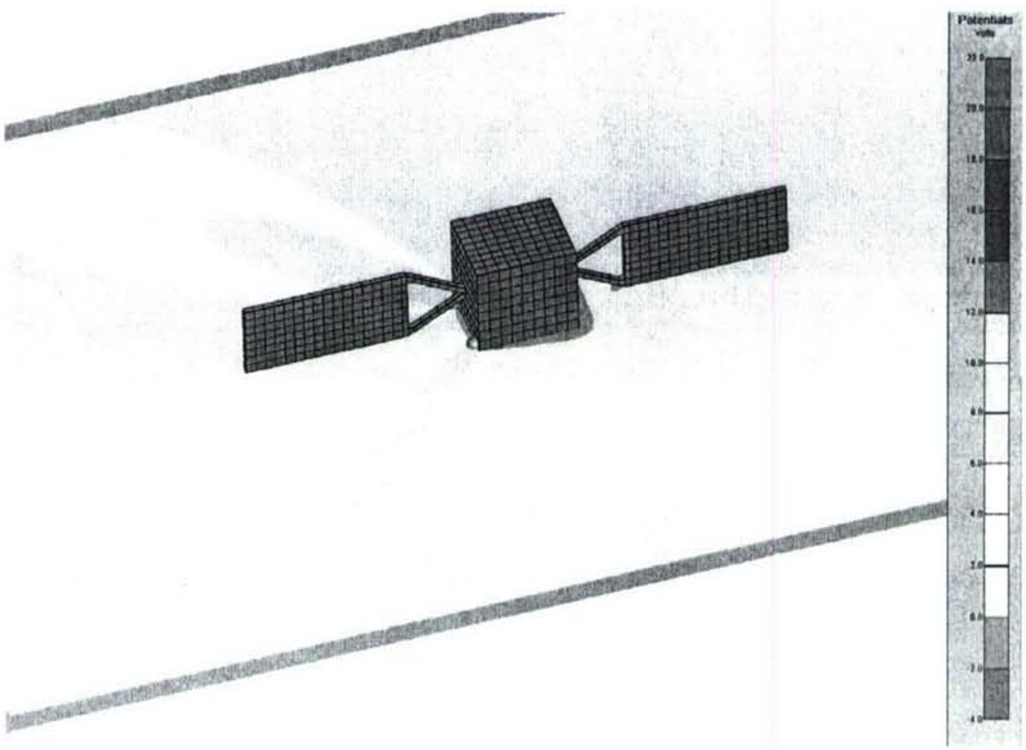

Figure 24. *Nascap-2k* display of space and surface potentials in the presence of the thruster plumes shown in Figure 23. Other parameters as described in the text.

Summary

Nascap-2k is a user-friendly code for the study and analysis of spacecraft-plasma interactions in a variety of important space environments. The code builds on many years of study and experience in building codes and performing analyses. Many examples of *Nascap-2k* calculations have been presented at this series of conferences. Additional examples of calculations by *Nascap-2k* and its predecessor codes may be found in the published literature dating back to the late 1970's. In this paper we show a quick walk-through of a geosynchronous charging calculation, and results for potentials in a spacecraft wake, and for potentials in thruster plumes.

Nascap-2k is distributed by the Space Environments and Effects Program at NASA's Marshall Spaceflight Center, Huntsville, Alabama, http://see.msfc.nasa.gov/.

References

[1] 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.

[2] 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.

[3] V.A. Davis, M.J. Mandell, D.L. Cooke, and 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.

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

[5] P. R. Stannard, I. Katz, L. Gedeon, J.C. Roche, A.G. Rubin, M.F. Tautz, *Validation of the NASCAP Model using Spaceflight Data*, AIAA -82-0269, 1982.

[6] I. Katz, P. R. Stannard, L. Gedeon, J.C. Roche, A.G. Rubin, M.F. Tautz, "NASCAP Simulations of Spacecraft Charging of the SCATHA Satellite," *Spacecraft/Plasma Interactions and Their Influence on Field and Particle Measurements*, ES SP-198, edited by A. Pedersen, D. Guyenne, and J. Hunt, European Space Agency, Noordwijk, The Netherlands, p. 190, 1983.

[7] M.J. Mandell and V.A. Davis, *User's Guide to NASCAP/LEO,* SCUBED report number SSS-R-85-730-R2. 1990.

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

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

[10] 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.

[11] 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.

[12] S. A. Brebbia, *Boundary Element Methods*, Springer Verlag, New York, 1981.

[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," *JGR.* 101, A1, p. 439, 1998.

[14] 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," *JGR.* 101, A1, p. 439, 1998.

[15] 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.

[16] Davis, V. A., M. J. Mandell, D. L. Cooke, L. Enloe, "High-Voltage Interactions in Plasma Wakes: Simulation and Flight Measurements from the Charge Hazards and Wake Studies (CHAWS) Experiment," *Journal of Geophysical Research 104*, 12445-12459, 1999.

[17] Mikellides, I. G., M. J. Mandell, R. A. Kuharski, V. A. Davis, B. M. Gardner, J. Minor, "The Electric Propulsion Interactions Code," 8th Spacecraft Charging Technology Conference, Huntsville, AL, October 2003.

[18] Sengupta, A., *et al.*, "Status of the Extended Life Test of the Deep Space 1 Flight Spare Ion Engine after 30,352 Hours of Operatation," AIAA-2003-4558, July 2003.