SPACECRAFT CHARGING INTERACTIVE HANDBOOK

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ABSTRACT

Under contract to the Spacecraft Environment Effects Program office at NASA/MSFC, we have developed an interactive handbook as a reference and analysis tool for spacecraft charging studies. The Handbook includes tools for defining geosynchronous environments and material properties, and for simulating charging of both single materials and complex structures, as well as internal (deep dielectric) charging. This paper focuses on our recent implementation of models for charging in the auroral region.. The only previous computer model for auroral charging is the POLAR code, written in 1984. This year we have added the capability to perform engineering-level auroral charging assessments to the Spacecraft Charging Interactive Handbook.

NOMENCLATURE

d	= surface thickness, m		V_i	= potential of surface i, V
j	= current density, A/m^2		V_A	= potential of surface, V
r	= spacecraft radius, m		V_S	= potential of chassis (spacecraft ground), V
E	= energy of incident particle, eV		Y	= secondary yield
E_0	= energy of incident electron, eV		Z	= effective atomic number
E_{max}	= energy of maximum yield, eV		a	= angle of incidence, degrees
I	= current, A		ε	= energy of incident electrons, eV
S	= surface area, m^2		ε_o	= permeability constant, F m^{-1}
V	= potential of a surface, V			

INTRODUCTION

Spacecraft charging assessments are needed for designing geosynchronous, mid-altitude, and polar, low-earth orbit spacecraft. Under contract to the Spacecraft Environment Effects Program office at NASA/MSFC, we have developed a web-based, multimedia, interactive Spacecraft Charging Handbook with integrated, updated spacecraft charging models. This product guides the non-expert through the appropriate analysis using the power of sophisticated charging calculational tools. It is easy-to-use and accessible over the Internet. Over a three-year period, six assessment modeling tools were developed and incorporated. They are: Geosynchronous Environment, Auroral Environment, Material Properties, Internal Spacecraft Charging, and Spacecraft Surface Charging in Auroral and Geosynchronous environments. The Handbook is written using HTML, JavaScript, and Java and runs within a web browser, either Netscape Navigator 4.07 or higher, or Internet Explorer 4 or higher. This choice ensures that the application can run on computers running either the Windows or Macintosh operating systems, either standalone or over the World Wide Web. The Spacecraft Charging Handbook is available free of charge from NASA at http://see.msfc.nasa.gov .

The most recent version of the Handbook, Version 3.0 has the capability to perform spacecraft surface charging calculations for the auroral environment. Auroral charging differs from geosynchronous

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charging in that the charging electron currents tend to be much higher, the low energy ionosphere tends to stop the charging, the vehicle is in a charging environment for only seconds, and wake effects are important. The high-energy auroral environment is described by a Fontheim distribution[1] which has three components: a Maxwellian, a Gaussian, and a power law. Unlike the geosynchronous environment, the auroral environment has the ionosphere low-energy (under 1 eV) plasma component. The low energy ions balance the high-energy electron current. The low energy ion currents are calculated using orbit limited collection in a drifting Maxwellian. This approximation is most valid for the low plasma density ionospheric condition where auroral charging has been observed. Higher accuracy requires self consistent three dimensional simulations, such as Polar or the in progress NASCAP-2K. The details of the SEE Handbook auroral charging algorithms are described later in this paper.

SEE Spacecraft Charging Handbook

Under contract to the Spacecraft Environment Effects Program office at NASA/Marshall, Maxwell Technologies has developed a CD-ROM/web based multimedia interactive Spacecraft Charging Handbook with integrated, updated spacecraft charging models. This product guides the nonexpert through the appropriate analysis using the power of sophisticated charging analysis tools. Figure 1 shows the home page of the Handbook. 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.
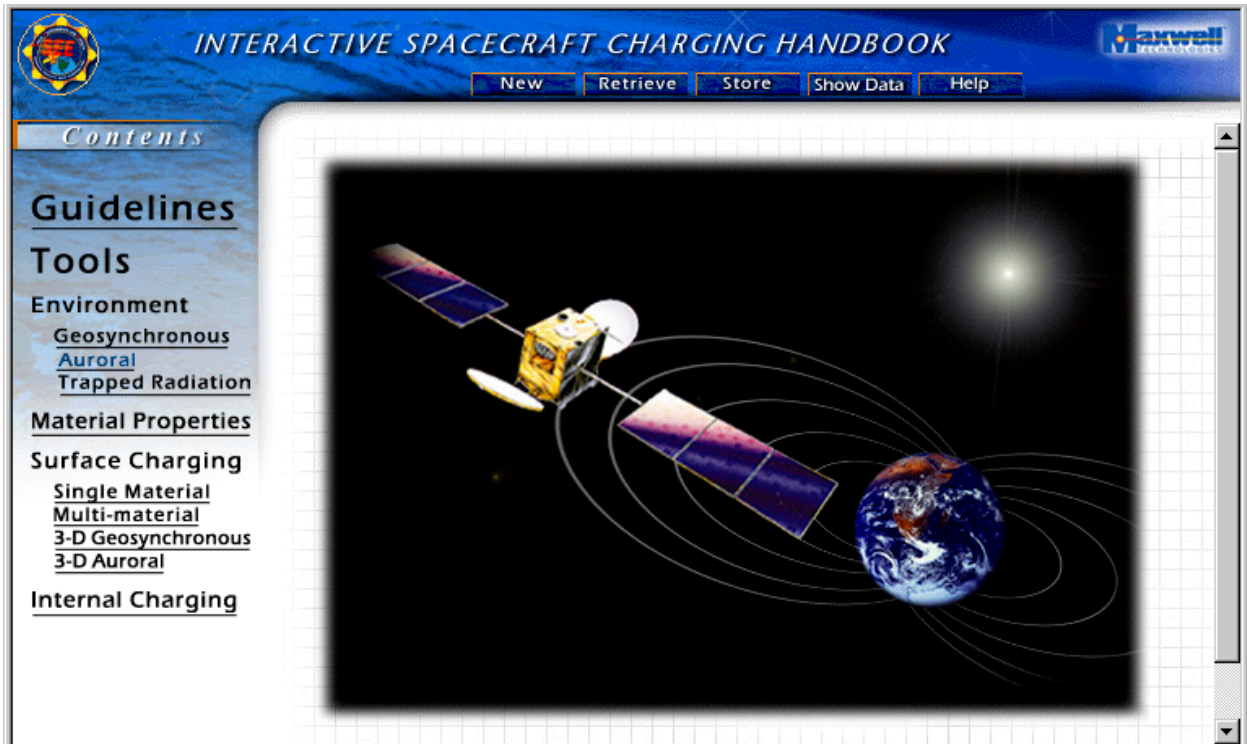

Figure 1.SEE Spacecraft Charging Handbook V3.0 HomePage

The application is navigated using the table of contents on the left side of the page. There are two main sections of the Handbook: Guidelines and Tools. The Guidelines is 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 relevant material for spacecraft surface materials. It also permits the user

to adjust properties (such as the secondary and backscattered yields) until they 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. With the exception of the auroral charging models, described below, the other models are described in Reference 2.

The Design Guidelines consist of four sections: Spacecraft Charging Overview, Interactions Modeling Techniques, Spacecraft Design Guidelines, and Control and Monitoring Techniques. The Guidelines are accessed by clicking on the word "Guidelines" in the table of contents to the left of the page. Within the Guidelines, the chapters are navigated using the bar at the bottom of the page. The document can be printed using the browser's print function. Figure 2 shows the beginning of the introductory chapter of the Guidelines.

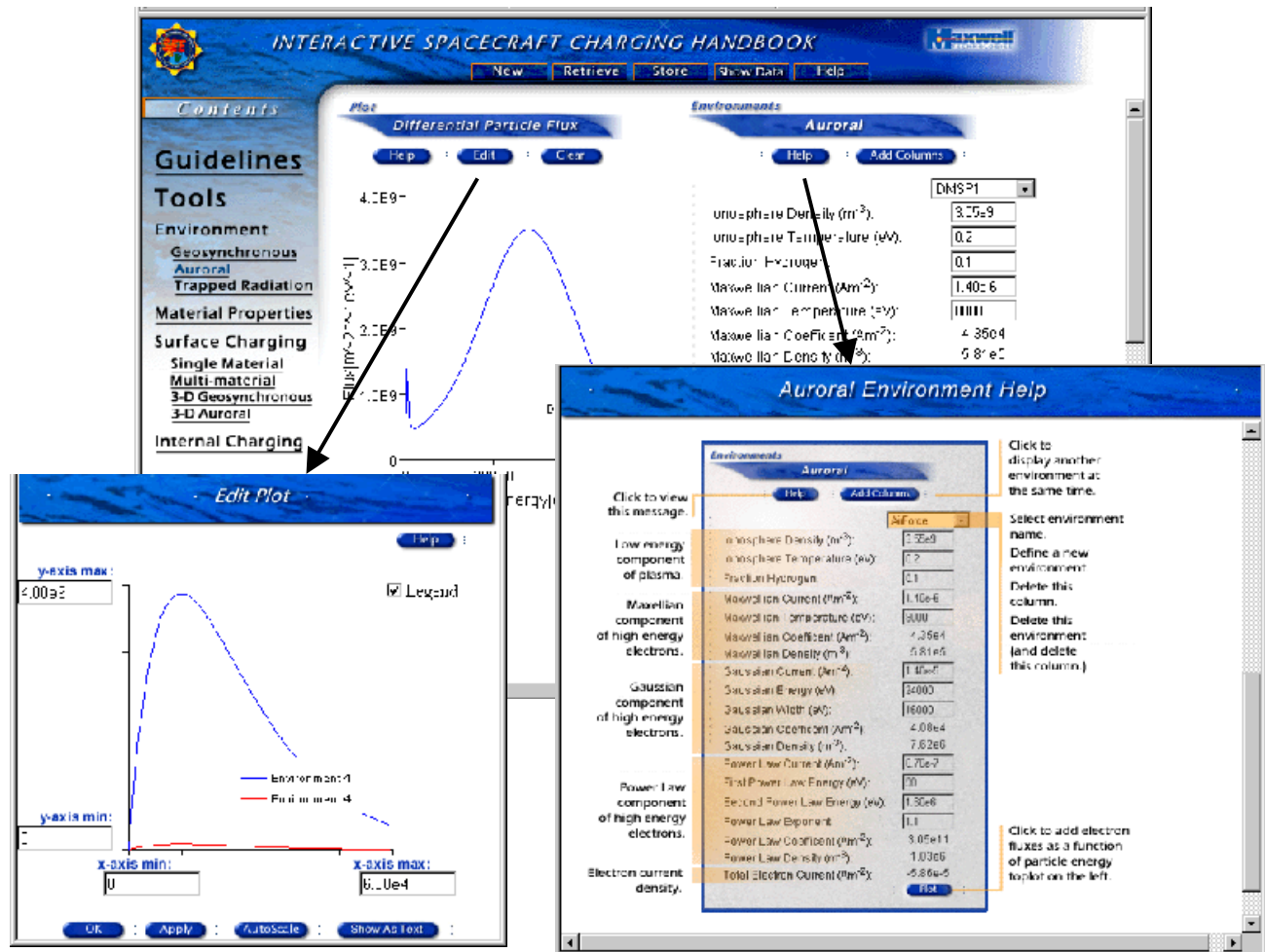Figure 2. Front page of the Guidelines.

Figure 3. The Auroral environment page, showing some features of the Handbook.

Figure 3 illustrates some of the capabilities of the tools. Whenever a tool is open, there is a plot in the upper left corner of the tool area. The edit button brings up a separate window to specify the minimum and maximum axis values. This window also allows the user to specify autoscaling or to bring up a third window in which the plotted data is shown as a table. The data can then be transferred to another plotting package. The clear button clears the plot. Whenever a plot button (bottom right) is clicked, the appropriate data is added to the plot. The Add Column button permits the simultaneous display of different items. The pull-down menu at the top of the column is used to specify the environment, material, or spacecraft being displayed, to create new named items, to delete named items, or to delete the column. The Help button brings up a help screen.

AURORAL ELECTRON ENVIRONMENT

At high latitudes, during periods of auroral activity, low-earth polar orbiting spacecraft can pass through a region of intense (10^{14} m-2 sec–1), energetic (10 to 20 keV) electron fluxes and low (10^{10} m–3) thermal plasma density. The composition and time evolution of this plasma environment are quite complex, more complex even than for a geosynchronous environment. Here it is treated as the

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superposition of a low-energy neutral plasma and high-energy electrons. The low energy plasma is described by a Maxwellian distribution. The ion species are oxygen and hydrogen, where the fraction hydrogen is specified. The high energy electrons are described by a Fontheim distribution[1], which has three components, specified by the net current in each component. The Maxwellian component describes the usual plasma environment, the Gaussian component describes the inverted V event, and the Power Law component describes the secondary and backscattered electrons from interactions between the Gaussian beam and the rest of the plasma. The Power Law component only contributes at energies between the lower and upper cutoffs. The effective density of each component is the expectation value of the distribution function.

The electron differential flux (m–2 s–1 eV–1) is specified by

$$
\begin{aligned}
\text{Flux}(E) = {} & n_1 \sqrt{\frac{e}{2\pi\theta_1 m_e}} \left(\frac{E}{\theta_1}\right) \exp\left(-\frac{E}{\theta_1}\right) \\
& + n_2 \sqrt{\frac{e}{2\pi\theta_2 m_e}} \left(\frac{E}{\theta_2}\right) \exp\left(-\frac{E}{\theta_2}\right) \\
& + \mathrm{B}\, E \exp\left(-\left(\frac{E_0 - E}{\Delta}\right)^2\right) \\
& + \mathrm{A}\, E^{-\alpha}
\end{aligned}
$$

Figure 4 shows the electron flux for one of the two default auroral environments. This environment is based on observations made by instruments on a Defense Meteorological Support Program (DMSP) satellite (Reference 3). As with the SEE Handbook's other environments, all of the parameters can be modified by the user. The auroral electron environments can be used for both material and 3-D surface charging calculations.
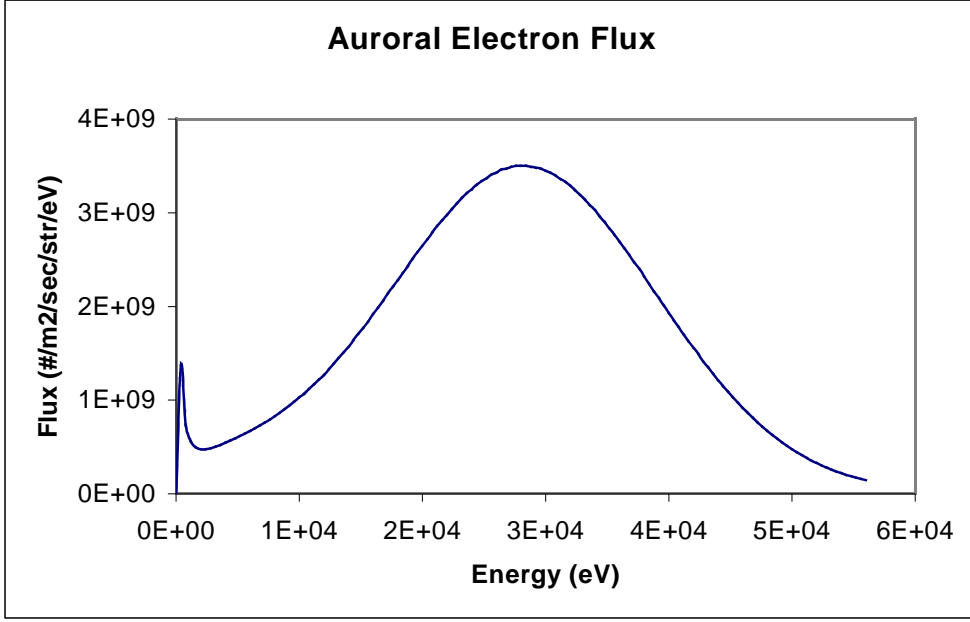
Figure 4. One of the SEE Handbook's two default auroral spectra described by the Fontheim formulation.

COLLECTION OF RAM IONS

The auroral electron flux, described in the previous section, is counteracted by thermal ionospheric ions collected by the moving spacecraft. In the Handbook, we use orbit limited probe theory to calculate the ion current density. The current to each surface at a specified potential and angle to the ram is assumed to have the same current density as surface at the same angle with respect to the ram on sphere with a uniform potential. This is the same approximation used in the geosynchronous charging calculations, but it is a much better approximation in GEO than it is for auroral charging.

We derive the equations for ion collection by a negatively charged conducting sphere of radius a in a flowing plasma with temperature T. We determine the current density as a function of angle. All velocities are in units of the plasma thermal velocity

$$V_T = (kT/M)^{1/2}$$

where k is Boltzmann's constant and M is the ion mass. Energies are measured in units of kT, so that energy conservation for an ion at the surface of an attracting sphere is expressed by

$$\frac{1}{2}v^2 - \Phi = E = \frac{1}{2}v_0^2$$

where v is the velocity of the ion, Φ the potential energy of the ion at the surface of the sphere, E the total energy of the ion, and v_0 the speed of the ion at an infinite distance from the sphere.

The normal current density at a point on the sphere where the unit outward normal is **n** is given by

$$j = j(\mathbf{n}) = \iiint \mathbf{v} \cdot \mathbf{n} \, f_0(\mathbf{v_0}) d^3 \mathbf{v}$$

where f_0 is the plasma velocity space distribution function and the integration variable is the negative of the impact velocity at the surface. In the rest frame of the sphere

$$f_0(\mathbf{v_0}) = (2\pi)^{-3/2} \exp\left(-\frac{1}{2}(\mathbf{v_0} - \mathbf{V_0})^2\right) \text{where } \mathbf{V_0} \text{ is the flow velocity of the plasma.}$$

Now introduce a coordinate system whose z axis lies in the direction of the normal to the sphere at the point where we wish to calculate j. Let the x-z plane be determined by this normal and the plasma

flow velocity and let φ be the azimuthal angle between the x-z plane and the orbital plane of an ion. The angle between the surface normal and the flow velocity is ξ. A particle launched at the sphere surface with polar angle α has polar angle θ_∞ at r = ∞.
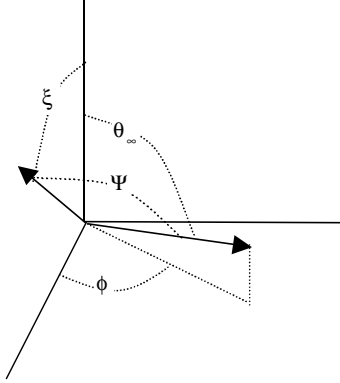

Figure 5. Coordinates used in the drifting Maxwellian ion current calculation

The current j may now be written

$$j = (2\pi)^{-3/2} \int\limits_0^\infty dv_0 \int\limits_0^{\pi/2} d\alpha \int\limits_0^{2\pi} d\varphi \, v_0 \left(v_0^2 + 2\Phi\right)\exp\left(-\frac{1}{2}\left(v_0^2 - 2v_0 V_0 \cos\psi + V_0^2\right)\right)\cos\alpha\sin\alpha$$

where α is the polar angle of the reverse trajectory ion launched from the sphere and ψ is the angle between the flow vector and the incident velocity at infinity associated through the dynamics with the angle α. Referring to the figure, we have

$$\cos\psi = \cos\xi\cos\theta_\infty + \sin\xi\sin\theta_\infty\cos\varphi$$

Integration over the azimuth yields

$$j = (2\pi)^{-3/2}\int\limits_0^\infty v_0(v_0^2 + 2\Phi)\exp(-v_0^2/2)F(v_0)dv_0 \text{ , where}$$

$$F(v_0) = 2\pi \int\limits_0^{\pi/2} \exp\left(-V_0^2/2\right)\exp\left(v_0 V_0 \cos\xi\cos\theta_\infty\right)I_0\left(v_0 V_0 \sin\xi\sin\theta_\infty\right)\cos\alpha\sin\alpha d\alpha$$

and $I_0(x)$ is the modified Bessel function of zero order:

$$I_0(x) = \frac{1}{2\pi}\int\limits_0^{2\pi}\exp(-x\cos\varphi)d\varphi$$

The angles at infinity are functions of the launch angle and the energy. The required relations are determined from the orbit relations in a 1/r potential:

$$\frac{a}{r} = \frac{\Phi}{2(E+\Phi)\sin^2\alpha}\left(1 + \sqrt{1 + \frac{4E(E+\Phi)}{\Phi^2}\sin^2\alpha}\cos(\theta - \theta_0)\right)$$

Measuring orbital angles from the polar axis that is normal to the sphere at the launch point and setting a = r determines the angle θ_0,

$$\cos\theta_0 = \left(2\left(\frac{E}{\Phi}+1\right)\sin^2\alpha - 1\right)\sqrt{1 + \frac{4E(E+\Phi)}{\Phi^2}\sin^2\alpha}^{-1}$$

Setting r = ∞ gives

$$\cos(\theta_\infty - \theta_0) = -\sqrt{1 + \frac{4E(E+\Phi)}{\Phi^2}\sin^2\alpha}^{\,-1}$$

The velocity and angle integrals are done numerically. Figures 6 and 7 show how the calculated ion current varies with angle, Mach number, and sphere potential.
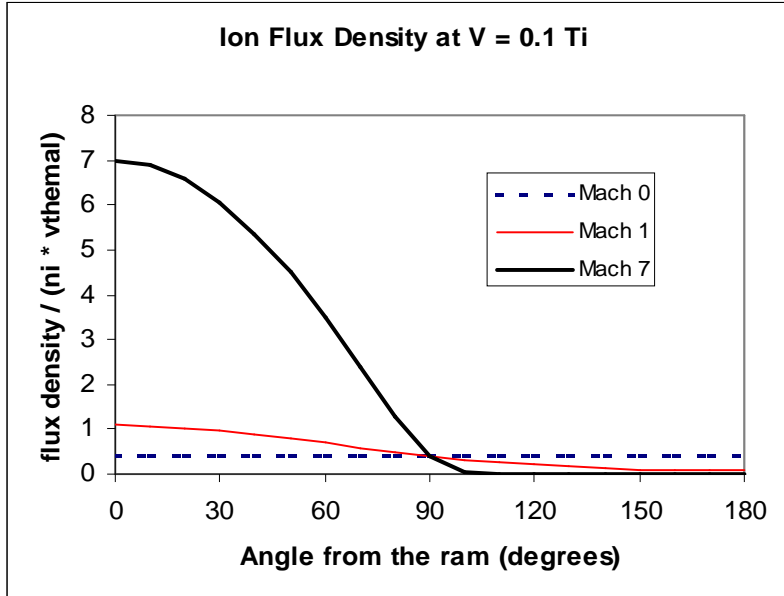
Ion Flux Density at V = 0.1 Ti

Figure 6. Relative ion currents at low sphere potentials.
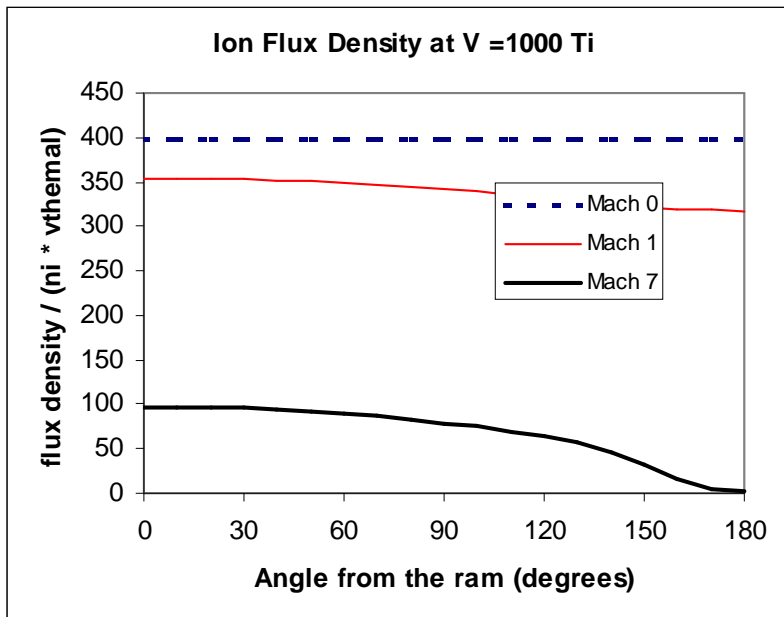
Ion Flux Density at V =1000 Ti

Figure 7. Relative ion currents at about 100V in the ionosphere

AURORAL SURFACE CHARGING TOOLS

Single Material

   The Single Material surface charging tool has been modified to provide rough estimates of how a material patch will charge in an auroral environment. The user selects whether the material is ram facing (0° from the ram) or wake facing (1800° from the ram), and the ram velocity. The electron currents and ion currents are calculated using the formulations discussed above.

   As shown in Figure 8, "Kapton" (specified using the Material Properties tool) in the environment "DMSP 1" (specified using the Auroral environment tool) in the dark with a backplane bias value of 0 volts will reach a floating potential of –43 V in under 5 seconds on the wake side, and only –7 V on the ram. The components of the current are displayed along with the net current at 0 V and at the floating potential.
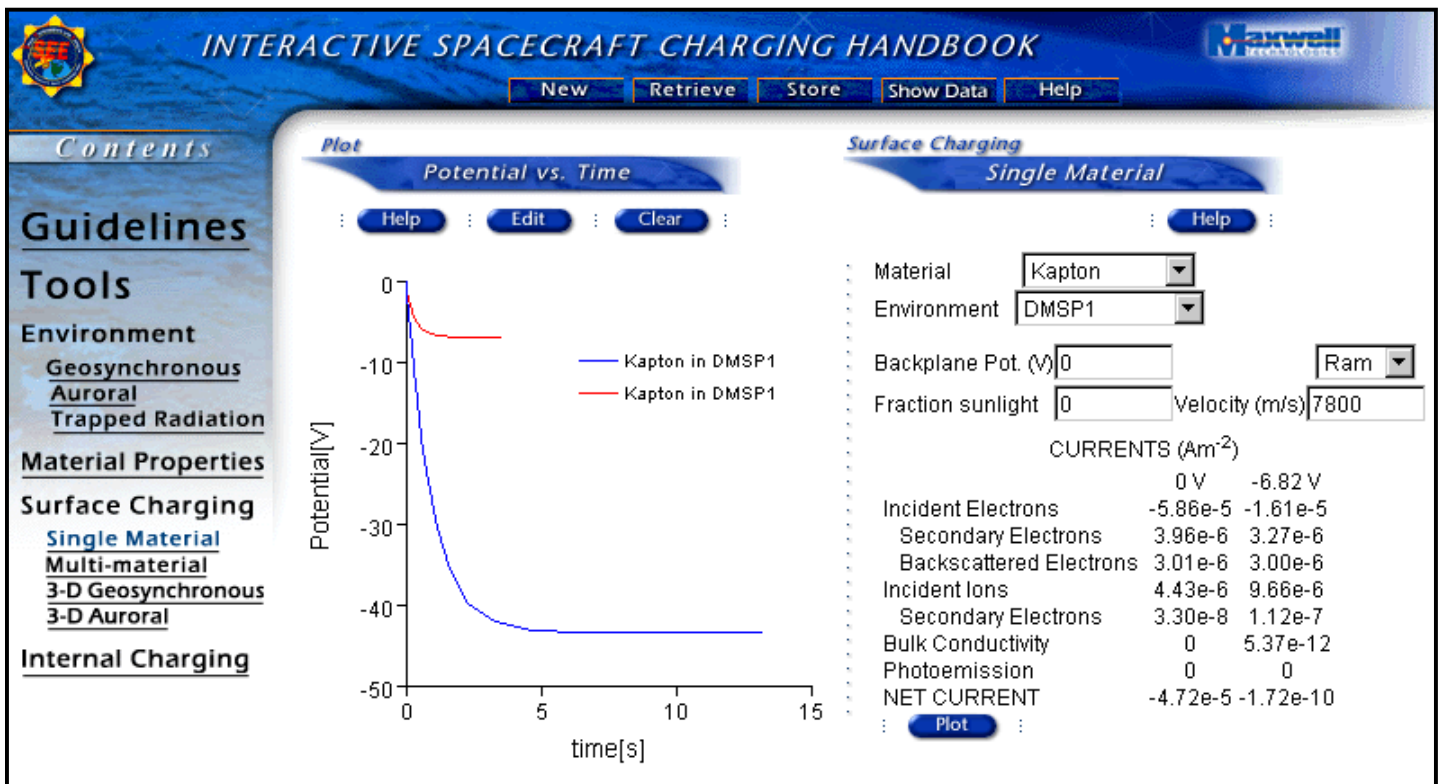

Figure 8. Single Material charging screen showing auroral environment.
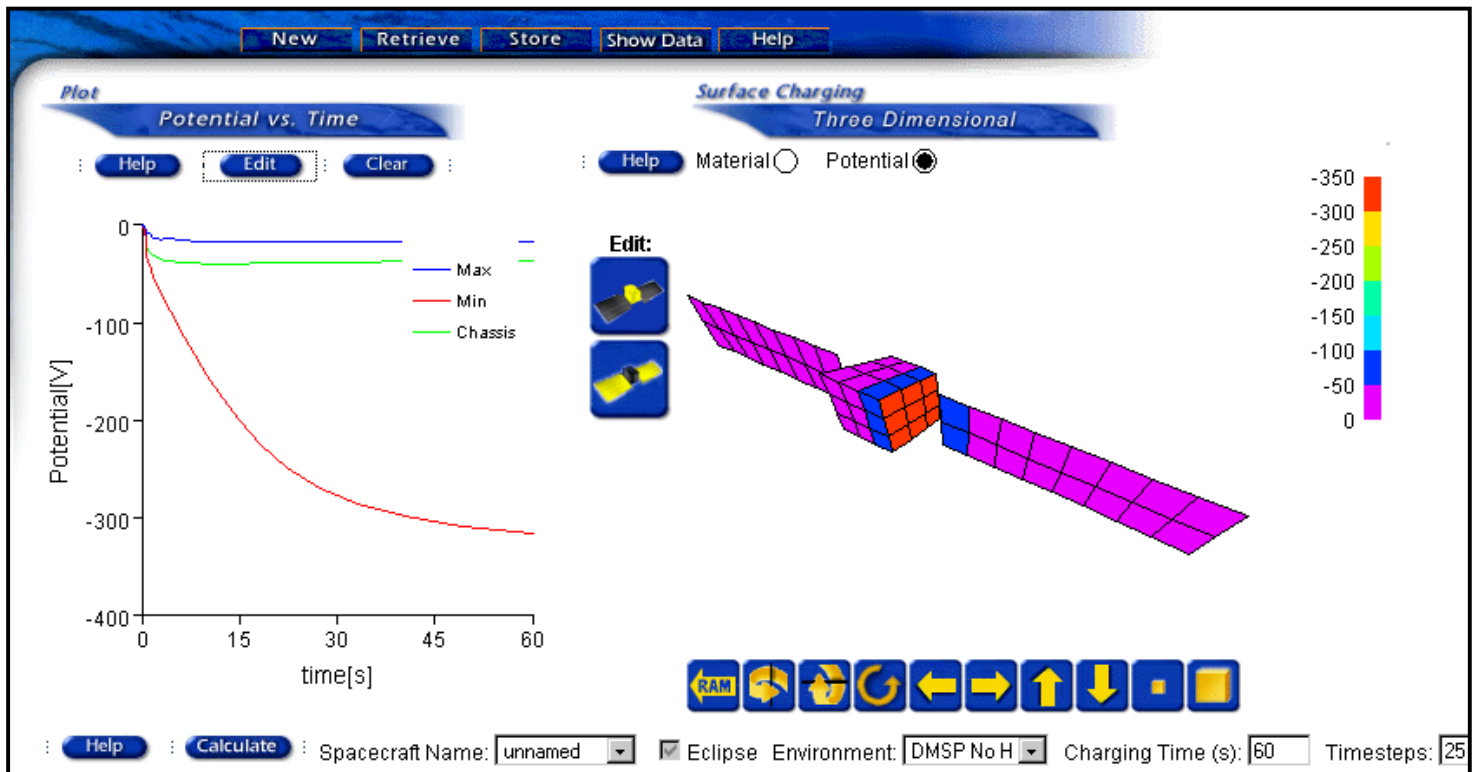
Figure 9. Three-Dimensional Charging Screen for Auroral environment.

Using buttons on the Three-dimensional charging screen, the user brings up separate screens to define the dimensions and materials of the spacecraft body and solar arrays. 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. The "RAM" button shows a view of the spacecraft normal to the orbit plane with the satellite moving from right to left.

The Three-dimensional Auroral charging tool uses the Boundary Element Method[5] (BEM) from the 3-D Geosynchronous Charging tool to compute self-consistent potentials and electric fields. This algorithm is described in reference 8. Algorithms to apply the BEM to the spacecraft surface charging problem were developed under contract to the Air Force Research Laboratory.[6,7]

Once the spacecraft is defined and an orbital velocity and an environment are specified, the user requests a calculation. The tool calculates the surface potentials as a function of time. The surface potentials and electric fields are computed using the boundary element method. At completion of the calculation, the perspective view of the spacecraft is color coded by surface potential, and a tabular presentation of the minimum and maximum potential for each material appears.

ADDITIONAL INFORMATION

The Spacecraft Charging Handbook is distributed by the Space Environment and Effects Program at the NASA Marshall Spaceflight. Instructions for obtaining a copy are posted on the following website:

http://see.msfc.nasa.gov

For additional information, contact Jody Minor, jody.minor@msfc.nasa.gov.

ACKNOWLEDGEMENTS

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