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Nascap Simulation of Freja Satellite Charging

David L. Cooke, Christopher J. Roth, Victoria A. Davis, Myron J. Mandell

***Abstract*— Spacecraft charging in the aurora presents an extreme challenge to the understanding and precision modeling of charging due in part to the rapidly changing non-equilibrium environment, and the important but complicated role of ion collection. This study uses Nascap2k to address a previously reported failure of the POLAR code to simulate the charging of the Freja satellite. We find that much of the discrepancy is resolved by revisiting uncertainties in the Freja particle measurements and how those are represented in POLAR and Nascap2k.**

Keywords—component; Freja, charging, Nascap, auroral charging,

I. INTRODUCTION

Over the decades, the Air Force and NASA have supported numerous studies and models, but have also maintained continuity in the development of a series of codes, NASCAP-GEO, POLAR, NASCAP-LEO, DynaPAC, and Nascap2k which combines the features of the previous codes using all new coding and architecture. There are no reused lines of code., but care has been taken to ensure that previously validated capabilities are maintained. These codes share a basic approach to charging; start with a specification of sources of current to an individual surface including its material response, represent a satellite as a resistive capacitive network, implicitly time step a surface potential solution, compute a plasma response if necessary, re-compute currents and repeat. A major distinction between POLAR [1] and Nascap2k [2] is that POLAR uses a single step size grid to compute density & surface electric fields since a Poisson solution is generally necessary. Nascap2k can use either a grid (multi-scale nested) for complicated plasma problems, or a grid-less boundary element method when sheath and wake effects are minimal.

The Freja Satellite [3]. was launched Freja was launched in October 1992 into an 1763 km by 590 km, 63° inclination orbit, with the mission of investigating auroral plasma physics. In addition to significant contributions to the auroral science, Freja was instrumented to make observations of significant charging due to energetic auroral electrons. Moderate negative potentials were regularly observed with record levels in excess of – 1000 Volts.

In [4,5,6] Wahlund, Eriksson and others, supported by ESTEC, identified numerous charging events and used the POLAR code [6] to simulate the observed charging. They found that while POLAR could reproduce charging to less than -100 Volts in magnitude, larger values could only be obtained by switching the ion collection model from an analytic Orbit Motion Limited approximation, OML, to trajectory tracing from a sheath edge that was constrained by the maximum grid size which drastically and artificially reduced the ion collection and led to charging levels far in excess of that observed.

The ESTEC [6] study suggested potential resolutions: (a) Reexamine the surrounding plasma since the electron detectors do not cover all pitch angles and field-aligned electron fluxes can be underestimated, (b) Reexamine the materials, (c) Account for magnetic field limitation on secondary escape [7], (d) Use NASCAP, (e) Use a larger grid.

In this study, we: (a) Use Nascap2k, (b) Reexamine the environmental data and the fitting. (c) Reexamine the material properties. We also explored using a larger grid to track ions and account for the weak space charged effects. Magnetic and space charge effects restricting secondary electron escape are also considered for future work.

Charging in any environment can be understood as a surface potential response to unbalanced charged particle fluxes towards a new potential that reduces the imbalance. A logical hierarchy of charging to negative potential begins with considering energetic electrons as the driver, and the surface emitted secondary and backscatter electrons as the immediate response. Ion collection is of course an equally important component of the net flux, but since the ion response requires separate computation, this is generally considered a separate step. For the ion, or attracted particle flux and density, Nascap2k has much improved PIC algorithms over POLAR that include a sheath algorithm like POLAR, and a more fundamental variable time-step PIC spanning the range from steady state to the electron plasma frequency. Similar to the ESTEC study using POLAR, we found that ion tracking alone could not account for the charging. Thus, following the charging logic, we returned to environment and material specifications. Those results are reported here, and the important step of accurate ion flux determination is deferred to future work.

II. THE ENVIRONMENT

Eriksson [6] reported simulation of 5 events. We focus here on event 6b which observed the greatest charging (-1000V) and the poorest performance by POLAR (-11V). We refer the reader to figure 5.6.2 of [4] for the complete environment measurement at the time of the event. POLAR and Nacap2k use a parametric representation of the energetic environment proposed by Fontheim [8] consisting of a Power Law, Maxwellian, and Gaussian components. The differential energy spectrum of particles as observed by a charged spacecraft is modified. Ions are accelerated giving rise to the well-known signature of a flux uplifted in energy with no flux

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below the S/C potential. Electron fluxes are repelled and thus seen to the lowest energy, but the distribution is modified and must be corrected before it can be characterized and fitted to the Nascap2k distribution [9]. The formula for mapping the observations to the ambient is given by,

$$F_\infty\left(E_m \pm \phi\right) = F_m(E_m)\left(1 \pm \phi/E_m\right) \qquad (1)$$

where the ‘‘+’’ sign is for ions and the - sign is for electrons, *Φ* is the potential, Em is the measured energy, and F is flux.

In [6] we find they chose to map the POLAR spectrum to the spacecraft and do the fitting there (see figure 27 of [6]). While this is valid, we suggest that it allowed misidentification of spacecraft generated secondary electrons. This can be seen by taking an observed spectrum from the charging event and mapping it to the ambient. Figure 1 shows TESP spectra from [5] at a time close to the event along with this spectrum mapped to the ambient for three different assumed potentials, but presumably -1 kV is the closest estimate at that time. We suggest that none of these mappings are realistic, and that the Power Law fit is contaminated and should be reduced by some amount. Since one of the key elements of charging is Secondary Electron Emission, SEE, which generally peaks at or below 1 keV, it seems likely that this is a major contributor to the lack of charging modeled by the codes.

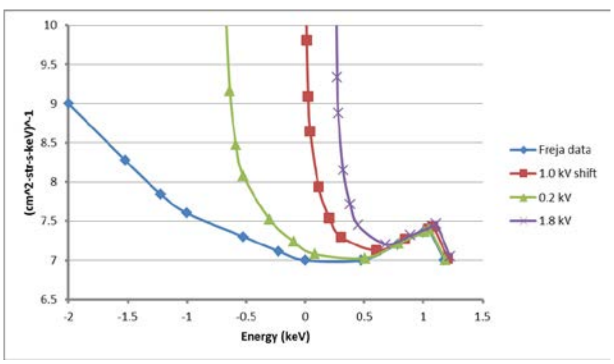

Figure 1. Freja electron spectrum from the 6b event unscaled and scaled to three levels of charging

Determining and removing the spacecraft generated electron contamination is not feasible at this stage of study, so in the following runs we consider 3 levels of reduction in SE contamination with modified Power Law parameters. These are shown in figure 2. The spectra used in the ESTEC study is labeled Freja, a modest repair to the power law and a current catalog environment in Nascak2k is labeled Nascap6b, and finally a more radical, but plausible adjustment is labeled Var-2. All three of these environments are tested in the runs.

III. Material Properties

SEE is of course a property of the material. We have reviewed the material properties used in the ESTEC study and identified the properties used for the ITO coated surfaces to be

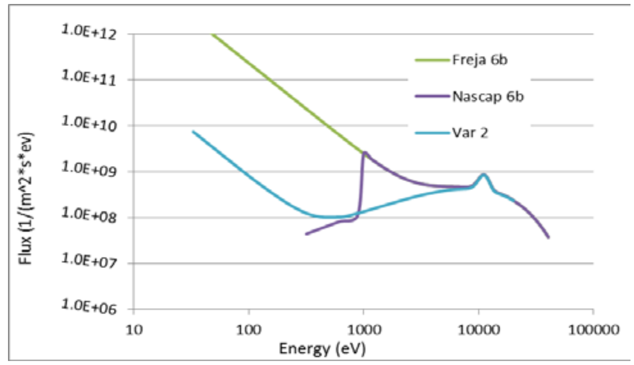

Figure 2. The three electron spectra used in this study. Freja 6b is the same as in [6], Nascap6b raises the lower power law cutoff, Var 2 lowers the power law flux.

significantly different to that reported by [10], with the ESTEC SEE yields being noticeably higher. The SEE yields for these and a few other materials are shown in figure 3. Both studies report testing of Sheldahl blanket material, but it is impractical at this level of study to research the possible differences in material, so we tested the impact of this difference using Nascap2k here. We find that making this change alone resulted in a moderate increase in charging, but not sufficient alone to achieve the observed high levels of charging. In the runs reported here, we used the lower yield data.

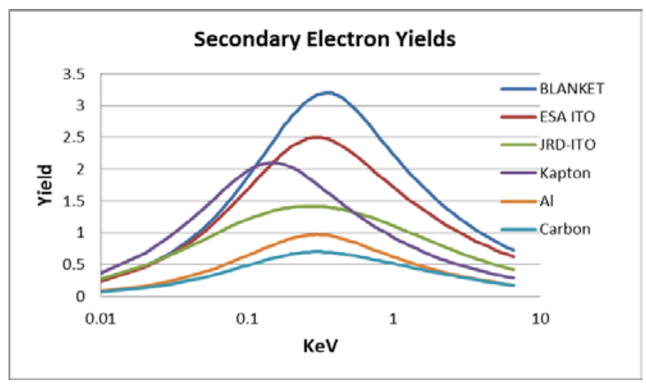

Figure 3. Secondary electron yield. IBLANKET *and* ESA-ITO *were used in the POLAR study, but replaced with* JRD-ITO *for the Nascap2k runs.*

IV. Ion Collection

As discussed, high fidelity modeling of collection requires significant computation, and is still dependent on the ambient conditions, which present another significant uncertainty since the ambient ion temperature was not measured. The ambient ion density and temperature are necessary parameters for any model of ion collection. POLAR and Nascap2k have default parameters typical of the quiet ionosphere. The ESTEC study matched the cold plasma density to the observations, but left the temperature at the cold default, 0.3 eV. We consider it unlikely that ions that cold could coexist with the very energetic precipitating electrons, and note that heated ion conic distributions are observed immediately after the event [5], thus the ambient ion temperature becomes another

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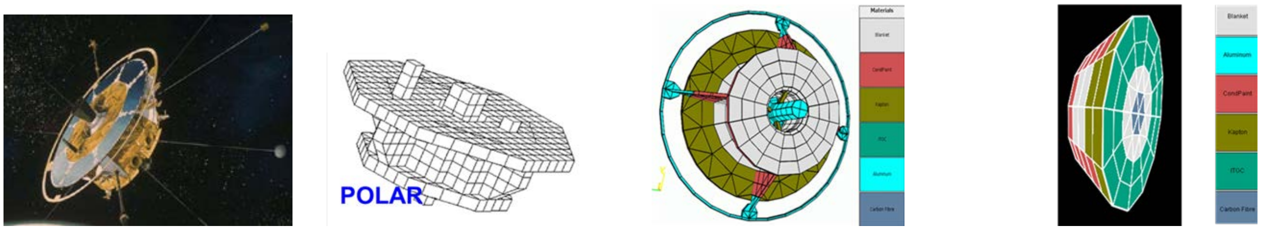

Figure 4: Freja models: POLAR (left), Nascap2k high resolution (center), Nascap2k "Simple-Freja" (right)

uncertainty to test in the simulations. We chose to use the simple Orbit Motion Limited approximation available in both POLAR and Nascap2k to explore this dependency before committing to longer runs. That expression is given by,

$$J_i = Ne\left(\frac{kT_i}{2\pi m_i}\right)^{\frac{1}{2}}\left(1+\frac{e\phi}{kT_i}\right) \qquad (2)$$

Where J is the flux at the surface, *N* is the ambient density, *m* is the ion mass, *Φ* is the surface potential, and *T* is temperature. In the low density reported for Event 6b, 30/cc, this is a good approximation. We can see the ion current will increase linearly with potential scaled by the inverse square root of the ion temperature, so if the assumed temperature is too low, charging will be rapidly quenched by an increasing potential and ion current. Because the OML model is strictly true for only ideal conditions, the sort of precision ion tracking available in Nascap2k is needed, but we feel OML is sufficient here to study the impact of the many uncertainties. The POLAR simulations in the ESTEC study tested both the OML model which led to low but stable charging, and a sheath edge based model which is a poor model for these extreme low densities. The ESTEC simulations using the sheath edge mode exhibited kV level charging, but also numerical instability when the sheaths became unrealistically bounded by the (maximum) grid. This and other experience has been a motivation for the improved Nascap2k PIC models and larger nested grids. Results

V. Simulation with Nascap2k

The various models of Freja used so far are shown in figure 4. The high resolution model of Freja was used for the first ion tracking studies, and to explore the impact of geometric complexity. These numerical experiments were inconclusive due to the difficulties with the environment and material difficulties studies here. We will need to return to the geometric and ion flux considerations. The Simple-Freja model was used here to explore the effects of environment specification and material properties. In these runs, the ITO yield was fixed to the lower values of [10]. To explore the environmental uncertainties a matrix of Nascap runs were conducted with values T1-T3 (0.3, 3.0, 30 ev) and D1-D3 (30,3,0.3/cc). We also considered three different electron spectra to produce the matrix of results presented in figures 5, 6, and 7. Because the results are difficult to describe, we present the results pictorially. Features to judge the results by are the level of charging, with approximately -1 kV being the target, and the rate of charging as only the first 10 to 50 seconds are consistent with the rapidly changing auroral conditions. The three traces shown in all figures are for surface element #53 Kapton, #102 Carbon Fiber (representing the central rocket nozzle and insulated from the frame), and the frame/conductor 1.

VI. Discussion

We see from the Nascap2k simulations that an ensemble of runs covering a range of environmental and material uncertainty can encompass the observed levels of charging. Purely by inspection on the basis of sufficiently strong and rapid charging, we have selected a "winner" shown in figure 8. It is far from proven, but the results imply that the Var-2 spectrum coupled with highest temperature (30 eV) and lowest density (3/cc) give the best results. Further investigation

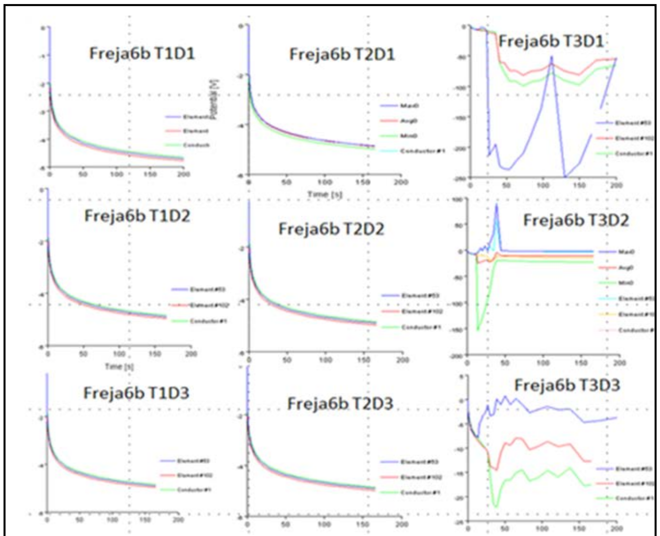

Figure 5. Nascap2k simulation with the originally ESTEC corrected environment.

should be able to narrow the range of uncertainty, but as with many such observations, comprehensive particle measurement are extremely difficult, and model fidelity will always be limited. Additional attention should be given to other satellite observations that might improve understanding of the cold ion population that might exist in strong auroral arcs, if any.

Acknowledgment

We wish to acknowledge most all the authors represented in the references for their support and discussions over the years since the first study of Freja with POLAR.

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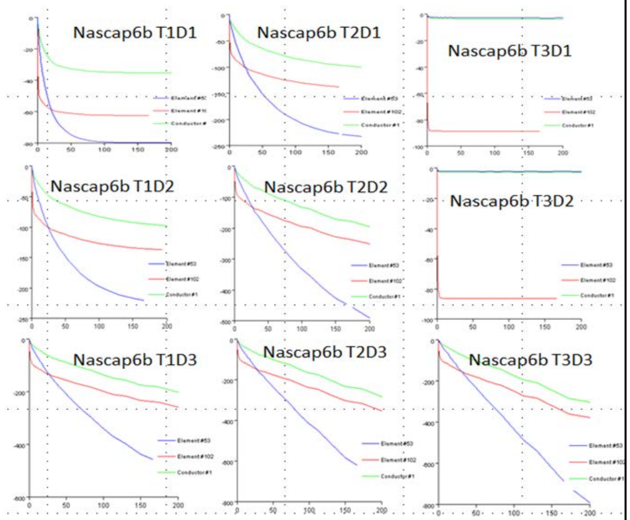

Figure 6. See text

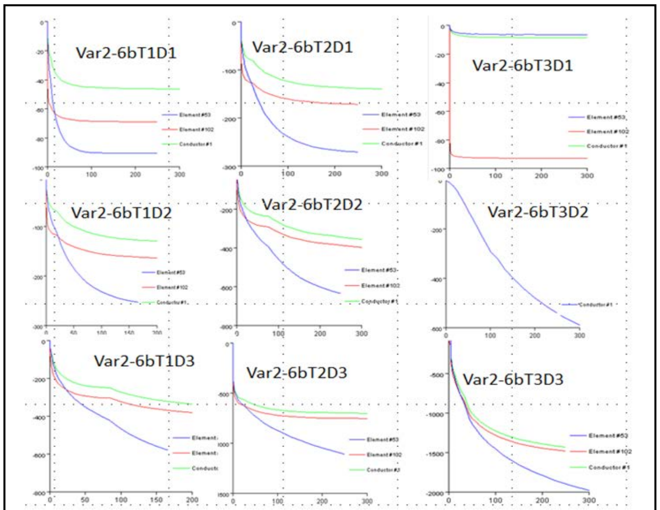

Figure7 . See text

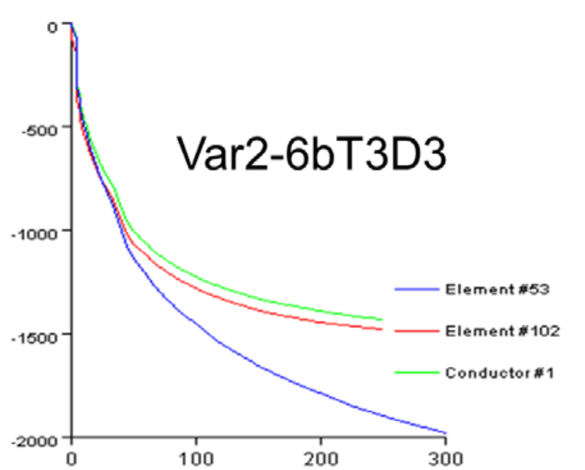

Figure 8. Using the modified electron spectrum, reduced ITO SEE yield, reduced ion density, and elevated ion temperature.

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