# NASCAP SIMULATION OF FREJA SATELLITE CHARGING

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## ABSTRACT

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 some of the discrepancy is resolved by revisiting uncertainties in the Freja study, and the remaining discrepancy can be resolved by revisiting long standing assumptions about the cold plasma background

## 1. INTRODUCTION

For over three decades, the Air Force and NASA have supported models related to the interaction of spacecraft with the plasma environment, but they have also maintained continuity in the development of a series of codes, NASCAP-GEO, POLAR, NASCAP-LEO, and most recently Nascap2k which combines many features of the previous codes using all new coding and architecture. These codes share a basic quasi-steady state approach to charging and use many of the same algorithms so we might expect Nascap2k to behave similarly to POLAR, and should be able to understand the differences. 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. Both codes have analytic surface current models that effectively reduce computation time compared to trajectory tracking as well as multiple options for trajectory tracking to determine surface currents and space charge. Which option is best for a particular problem is not always clear, but validation studies have shown that when both approaches are numerically reasonable, the results are similar. Simulations of very low plasma density as in Geosynchronous Orbit (GEO) or in the high altitude aurora, can lead to an extremely large simulation space, often exceeding the capability of POLAR, and leading to long simulations in the case of Nascap2k when trajectory tracking is used. With the use of grid-less and analytic methods however, Nascap2k can be very efficient, running relevant models on common PC in minutes. POLAR also had a similar heuristic numerical plus analytic approach.

The Freja Satellite [3] was launched in October 1992 into a 1763 km by 590 km, 63◦ inclination orbit, with the mission of investigating auroral plasma physics. Freja was designed with a mostly conductive surface of high secondary electron, SE, emission material, mainly Indium Tin Oxide (ITO). The Freja instrumentation was also suitable to observe charging due to energetic electrons with record levels in excess of – 1000 Volts [4] observed. In addition to Freja, charging has been observed on many polar orbiting satellite such as the Defence Meteorological Satellite Program, DMSP satellite (see the paper by Davis et.al. in this proceedings)

In [4,5,6] Wahlund, Eriksson and others, identified numerous charging events and used the POLAR code [6] to simulate the observed charging. They found that while POLAR could reproduce charging up to 100 Volts for some events, higher levels of charging could not be simulated. The ESTEC [6] study suggested: (a) re-examine the plasma environment, (b) re-examine the materials, (c) account for magnetic field limitation on secondary escape, (d) use NASCAP, (e) Use a larger grid.

In this study, we: Use Nascap2k, re-examine the environmental data, re-examine the material properties, explore using a larger grid to track ions and account for the weak space charged effects, and revisit assumptions about the cold plasma background.

## 2. THE FREJA ENVIRONMENT

Eriksson [6] reported simulation of 5 events charging to levels: -25, -40, -1000, -160, and -40 Volts. We focus here on the event (6b) which observed charging in excess of a kilo-Volt (negative) and the poorest performance by POLAR (-11V). Their figure 5.6.2 displays the environment at the time of the event. The common signature of charging is a distinct peak or edge in the ion energy spectrogram below which few ions are seen indicating electrostatic acceleration to the charged spacecraft. The Freja ion data is provided by an ion mass spectrometer and shows similar if not identical energy peaks for O+ and He+, but it is notable that the H+ peak is seen at perhaps 50 eV lower energy. The electron spectra are provided by the MATE (MAgnetic imaging Two-dimensional Electron spectrometer) and TESP (2D electron spectrometer, 0.01-20 keV)) instruments. The MATE suffered difficulties in deployment and provided only an integral measurement for the highest energy channels (5-100 keV) during this observation. Additional information, e.g. ion pitch angle distribution is provided in [6]

In addition to the fluxes of high energy electrons, the cold plasma ion background has long been recognized as a controlling factor in charging. For measurement of the cold plasma, Freja had Langmuir probes, but as one might expect these did not function well during the charging events. A wave receiver experiment however was able to observe the plasma frequency during the charging events. For a discussion of the anti-correlation between background density and charging, see Erickson et.al. [3]. For the event (6b) here, the background density was fairly steady at 100-200 cm-3, before and after the event, however the study [6] used a value of 30 cm-3 at the time of peak charging and for the POLAR simulation, with a cold plasma temperature of 0.3 eV.

POLAR and Nacap2k use a parametric representation of the energetic electron environment proposed by Fontheim [8] consisting of a Power Law, Maxwellian, and Gaussian components, amounting to a 9 parameter fit. The differential energy spectrum of particles as observed by a charged spacecraft is modified by the spacecraft potential. During negative charging, electrons are repelled and deflected and thus seen to the lowest energy, but the distribution is modified by the deflection and must be corrected before it can be characterized and fitted to the Nascap2k distribution [9]. The formula for mapping between the measurement, *m*, on the charged spacecraft and the distant plasma, ∞, 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 signed potential, E*m* is the measured energy, and F is flux.

In [6] they chose to map the distant 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, SE, as part of the environment. This can be seen by taking an observed spectrum from the charging event and mapping it to the ambient. Figure 1 shows the TESP spectra from [5] at a time close to the event (unmapped) 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 while none of these mappings are necessarily right, the Power Law fit is contaminated by SE and should be reduced by some amount. Determining and removing the spacecraft generated electron contamination by analysis of original data is not feasible for this effort, so in the following runs we consider 3 levels of reduction in SE

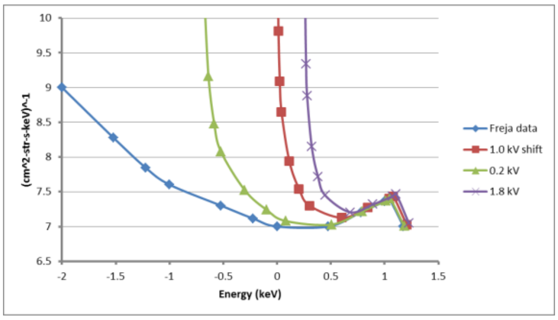


*Figure 1. Freja electron spectrum from the 6b event unscaled and scaled to three levels of charging*

contamination with modifications to the Power Law parameters. These are shown in figure 2. The spectra used in the ESTEC study is labelled Freja6b, a modest repair to the power law and a current catalogue environment in Nascak2k is labelled Nascap6b, and finally a more plausible adjustment is labelled Var-2.

While the Freja wave instrument measured the plasma density, there was no measure of the plasma temperature which is a necessary element of the simulation. 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. In [3] the Freja Langmuir probe measurement at times of non-charging indicated the temperature was between 0.2 and 2 eV.

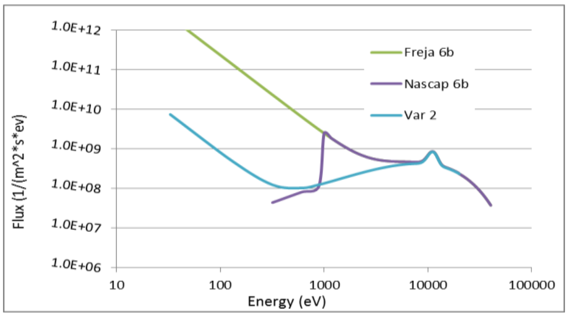


*Figure 2. The three electron spectra used in this study. Freja 6b is the same as in [6], Nascap6b raises the lower power law cut-off, Var 2 lowers the power law flux.*

## 3. MATERIAL PROPERTIES

Secondary Electron Emission, SEE, is the immediate response of a material to energetic electron bombardment, and the primary balancing current in most charging environments. Since we are looking for errors in the modelling of Freja charging, the material SEE is one place to look. We have reviewed the material properties used in the ESTEC study and identified the properties used for the ITO coated surfaces to be 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 again impractical at this level of study to research the differences in material properties and/or SE measurement, so we tested the impact of this difference by using the lower Nascap2k yields here. We find that making this change alone resulted in only 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.

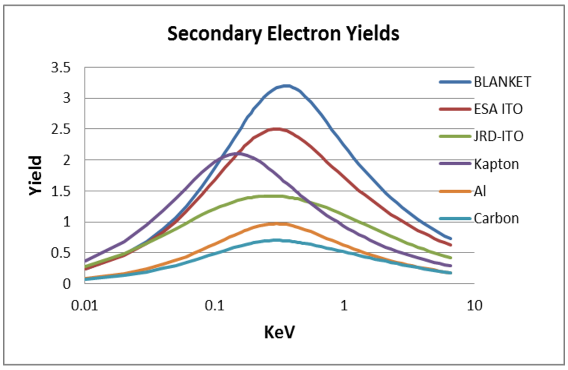


*Figure 3. Secondary electron yield.* IBLANKET *and* ESA-ITO *were used in the POLAR study, but replaced with* JRD-ITO *for the Nascap2k runs.*

## 4. Ion Collection

When the plasma is relatively dense, the Debye length, $\lambda_D = \sqrt{\varepsilon_o kT_c / N_c e^2}$ , where $T_c$ and $N_c$ are the temperature and density of the collected species, can be small compared to the object size and the disturbed sheath through which ions are collected is also comparable to the object. In this case, space charge will affect the orbits and full orbit trajectories can be launched from the simulation boundary or even from the sheath edge since it can also be treated as a boundary. The trajectories determine both space charge and surface currents. Only Nascap2k has the option to track from the simulation boundary, but both Nascap2k and POLAR can track particles from a sheath edge. When the plasma density is low ($\lambda_D \geq$ size) as in GEO, the sheath is very large, the grid needed to contain the sheath becomes enormous, and trajectory tracking becomes tedious and computationally expensive. In this regime however, probe theory provides an approximate analytic formula for surface currents, and the space charge can be neglected for many purposes. The OML formula [11] is,

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

where J is the flux at the surface, $N$ is the ambient density, $m$ is the ion mass, $\Phi$ is the surface potential, and $T$ is temperature. In the low density reported for Event 6b, 30/cc, this can be a good approximation. When there is a significant flow velocity, the ion flow energy should be included. To include the flow energy, Nascap2K computes the OML current to each surface by considering semi-analytic reverse trajectories from the surface to infinity as in the derivation of equation (2), but also computes the precise turning angles from the surface to the flow direction assuming a 1/r potential. Thus the OML option for Nascap2K does not exactly match POLAR, but both have the same $(1+\phi / E_C)$ characteristic where $E_C$ is a characteristic energy such as T, or ram ion energy. Examination of this characteristic suggests that once charging begins, the ion current will be constant and not respond to the increasing potential until $E_C$ is reached after which the ion current will increase linearly with potential. Thus if $E_C$ is assumed to be too low, charging will be rapidly quenched by an increasing potential and ion current.

Using POLAR, the ESTEC study found that the OML approximation led to low levels of charging in the kilo-Volts cases, and the sheath based trajectory option was constrained in the maximum available grid, leading to higher charging but also numerical instability. This led to their suggestion of using a large grid and/or Nascap2k, and that is where we began. While Nascap2k does not have a grid size limit, we did find that neither the sheath nor boundary based tracking options resolved the non-charging problem. Since the physical nature of the ion collection suggest the OML model is proper, and experience with Nascap2k suggests tracking in a large grid will give much the same result, we concluded the OML model was sufficient to investigate the material, environmental, and other uncertainties.

## 5. Simulation With Nascap2k

Charging in any environment can be understood as a surface potential response to unbalanced charged particle fluxes, charging 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, and closure to a quasi-steady potential by collection of ions. We have followed that same approach in evaluating the simulation of Freja charging. We found where the SEE for ITO could have been too high and used a lower value. We identified how secondary electrons had contaminated the energetic electron fitting and employed corrections. Finally, we identified that the characteristic temperature for OML collection had a strong clamping effect on charging. We now present a matrix of Nascap2k runs to pull these effects together.

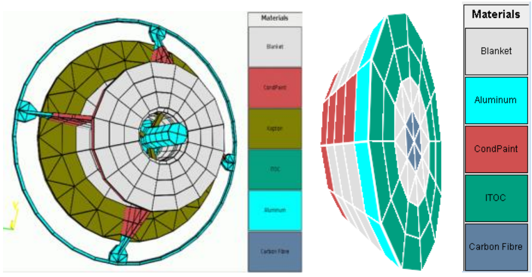


*Figure 4. The High-Res Nascap model of Freja (left) and the Simple Freja Model used in this study*

Two of the 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. The improvements in Nascap2k over POLAR suggested this was a good place to start. These simulations however did not show high levels of charging and pointed to the uncertainties discussed concerning the environment and material properties. The Simple-Freja model was used here to more quickly explore the effects of environment specification and material properties. In these runs, we used the lower ITO yield values of [10] (JRD-ITO in figure 3). We also found that both the density value of 100 $cm^{-3}$ as suggest in [5] and 50 $cm^{-3}$ in [6] did not produce kilo-Volt charging when combined with the low temperature (0.2 eV). So, a series of Nascap2k runs was set up to explore the environmental uncertainties with a matrix of values T1-T3 (0.3, 3.0, 30 ev) and D1-D3 (30,3,0.3/cc), spacecraft velocity (7.5 km/sec), and Oxygen background . We also included in the matrix, the three different electron spectra of figure 3. We show only the most interesting of the results.

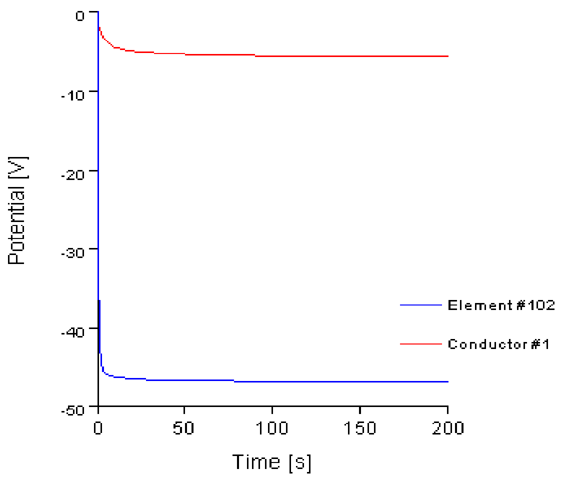


*Figure 5. Nascap2k simulation of Freja using material, environment, and plasma parameters close to that used in the ESTEC study with POLAR.*

In figure 5, we show Nascak2k run with parameters as close as possible to the POLAR runs in [5], and a very similar result can be observed. Figure 6 presents a run with the lower SEE material, the Var 2 electron environment, T1 & D1, and 7/5 km/sec spacecraft velocity. Now we see that the frame charging begins and proceeds to a larger value before becoming clamped by the ion current (not shown) at about -120 Volts. Element #102 is ungrounded carbon fiber.

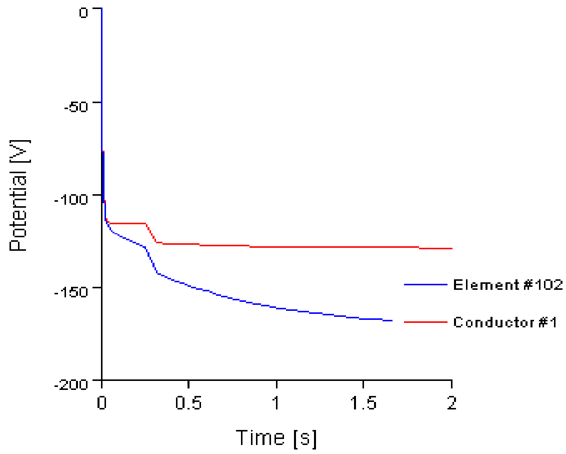


*Figure 6. Nascap2k simulation using the Var 2 environment (see text), lower SEE yields, Ne=30/cc, T=0.3 eV, V=7.5 km/s*

McFadden et.al. [12] using data from the FAST satellite, have found times when in the aurora there are no cold ions, suggesting that below the satellite, ions have been accelerated into beams with energy up to kilo-Volts in some cases. This possibility was not considered in the ESTEC [6] study, or by in the development of POLAR and Nascap2k. We expect that replacing the cold background with energetic streaming ions will have a large impact on ion collection and charging because of the increase in the characteristic energy, $E_C$. To pick a trial value, we take note of the difference between the O+ and H+ energy observed by Freja. If the ion energy was all due to the spacecraft potential, there should be no time for the H+ to lose any energy. If however some of the observed ion energy was imparted by lower regions, H+ would be able to lose some of that on the way to the satellite. So, we make the limiting assumption that there was 50 eV of remote acceleration, H+ lost all of that energy and O+ none. Nascap2k does not (yet) have the functionality of assigning a beam energy to each species of ion, but we can accomplish this for a single species (O+) by adjusting the spacecraft velocity vector to from below and 24 km/sec. The results are presented in figure 7. In addition to the streaming ion velocity, we found it necessary lower the background density further (from 30/cc to 10/cc) to get sufficiently close to the Freja observation.

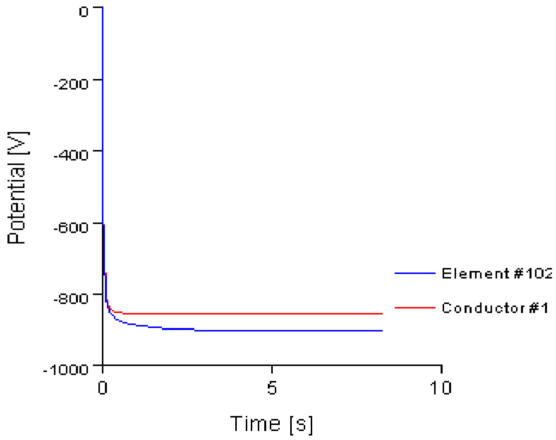


*Figure 7. High level charging using the same materials and environment as figure 6 with the exception of raising the plasma drift velocity to 24 km/sec and lowing Ne=10/cc.*

## 6. Discussion

We suggest the present study demonstrates Nascap2k has the proper physics to simulate auroral charging when the material and environment parameters are properly specified, and the earlier failure of POLAR has been resolved. It should be apparent that the charging problem of satellites in the aurora is subject to many difficult to determine parameters that can frustrate a goal of precise simulation. This effort however, has shown that the envelope of parameter uncertainty can be tightened enough to advance our understanding of the problem. We might also conclude from this study that it may be the unique environment inside auroral density cavities that facilitates extreme LEO charging. This is consistent with a picture of mostly electrostatic acceleration of one sign charge downward (electrons here) and the opposite sign upwards. Additional attention should be given to other satellite observations such as FAST [12] that might improve understanding of the cold ion population that might exist in strong auroral arcs, if any. As suggested in [12] the absence of cold plasma may be a regular feature of auroral cavities and these in turn may be the primary requirement for kilo-Volt charging of satellites. In this case, it will be necessary to determine the ion temperature and/or streaming velocity before better comparisons between simulation and observation can be made.

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