Charging of a conductive spacecraft in the auroral zone

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We present event studies and results of a statistical investigation on charging events seen by the Freja satellite in the auroral zone at 1500-1700 km altitude. Charging up to kilovolts is sometimes observed, though lower values are more normal. Comparing to DMSP at 840 km, Freja experiences fewer charging events, but some of them are found in sunlit conditions, which has not been seen on DMSP. No charging event occured for a density above 2000 cm^{-3}, though correlation between density and charging otherwise was weak. All charging events show enhanced electron fluxes around or above 10 keV, incuding enhanced tails up to 100 keV, while electrons around 1 keV instead counteracts charging, as is expected from high secondary yields in this energy range. Simulations using POLAR reproduced moderate charging events, but not the events with kilovolt charging.

1. Introduction

A primary driver of spacecraft charging studies is the impact of charging on onboard systems. In the most recent review of spacecraft charging, Garrett and Whittlesey [1] suggest that from this point of view, research on internal charging may now be more central than the better understood surface charging processes, for which theoretical and numerical models as well as established design guidelines exists. However, there are several reasons for the continued study of surface charging. On the experimental side, we may note that on-orbit investigations have concentrated either on the geostationary orbit (GEO), with the dedicated SCATHA mission as the prime example, or on low Earth orbit (LEO), with several studies on DMSP, the space shuttle, the ISS etc (see ref. [1] for further references) . In these regions, the relevant plasma scale lengths, the Debye length and the particle gyroradii, are either all large or all small compared to the spacecraft dimensions, allowing some simpifications in the theoretical modelling. From a modelling point of view, the most challenging environment is the intermediate region between the GEO and LEO, where the scale lengths and spacecraft sizes are comparable. The number of experimental results in this regime are small.

While safety of spacecraft systems certainly is the economically most improtant driver for spacecraft charging studies, it is not the only one. Modern space plasma physics instrumentation allows detailed studies of the space plasma and its physical processes, to accuracies of fractions of eV in particle energies and fractions of mV/m in electric fields – provided the electrostatic environment is sufficiently clean, or at least well known. In fact, many of the present-day limitations of in-situ space plasma instrumentation is more due to perturbations of the spacecraft electrostatic environment than to instrument technology as such. For example, to measure naturally occuring fields with an accuracy of a fraction of a mV/m, we need to understand the formation of potentials as small as one volt or even less, as shown in another study in this volume [2]. Similarly, surface charging can be a problem for sensitive scientific instrumentation even at low levels.

2. The Freja spacecraft charging study

Freja was launched in October 1992 into an orbit with perigee 1763 km and perigee 590 km for investigations of auroral plasma physics [3] until the end of its useful operations in June 1995. Freja is well suited for spacecraft charging studies. First, its comprehensive instrumentation allowed observation of effects and causes of surface charging. Second, the auroral region, which is the prime target for Freja measurements, is a known region for spacecraft charging events. Third, its orbit in the intermediate altitude region below the well studied LEO and GEO altitude ranges is underrepresented in spacecraft charging studies.

A study of the Freja charging events was therefore included in ESA's "Study of Plasma and Energetic Electron Environment and Effects" (SPEE) initiative. The study was performed as three work packages, each documented in a separate report: a detailed investigation of a few events [4], a statistical study [5] and a modelling effort using the POLAR code [6]. All of the SPEE study is also summarized in a final report [7]. These reports can all be downloaded from the SPEE homepage, `http://www.ava.fmi.fi/spee`. In the present paper, we summarize the three parts of the Freja charging study, with the perspective gained by the five years passed since its completion.

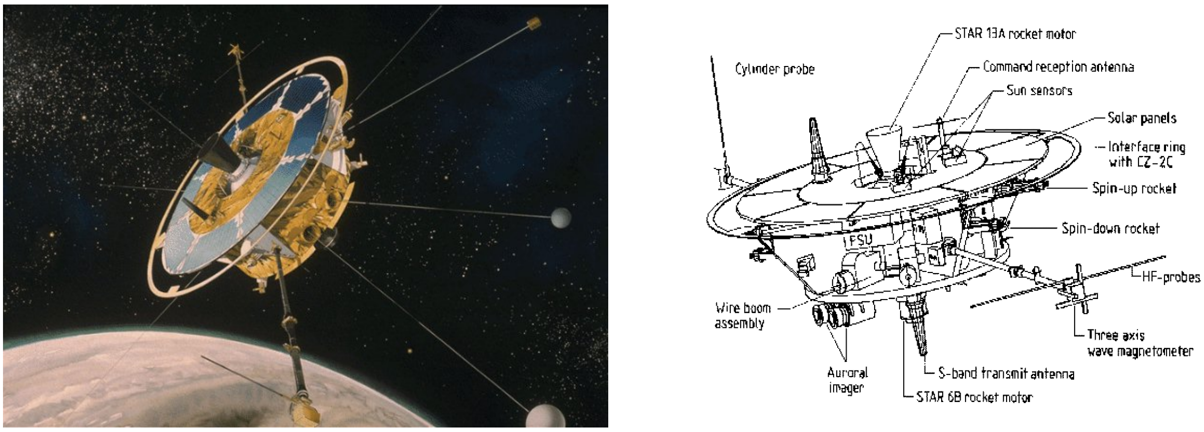

Fig. 1. The Freja satellite in space, and a sketch showing the different instruments and system sub-units.

3. Spacecraft and instrumentation

The Freja inclination of 63° is unusually small for a spacecraft dedicated to the aurora, but due to the offset of the Earth's magnetic from the geographic pole, invariant latitudes above 70° were regularly achieved, with occasional excursions up to 77° (Figure 2). The orbit therefore proved very useful for auroral studies, as it skimmed the auroral oval in the West-East direction for extended time intervals, rather than getting the brief North-South crossings achieved by the polar orbits conventional for satellites investigating auroral physics.

Three Freja instruments were the main source of data. Key to the study is the ion and electron data from the F3 instrument [8], comprising the TICS ion mass analyzer and the MATE electron detector, and the TESP electron spectrometer of the F7 instrument [9]. These allow observation of the charging level from the rise in energy of the ram ion flow as well as diagnostics of the electrons at tens of keV responsible for the charging. However, it turned out that for searching for charging events, the current to the Langmuir probes of the F4 instrument [10] was most convenient, as charging to a spacecraft potential below -10 V would drastically reduce the current to the probes, normally biased at +10 V relative to the spacecraft. The same instrument also included a high frequency receiver [11], which can be used for obtaining a density measure independent of the Langmuir probes by identification of the plasma frequency, from the upper cutoff of the whistler mode or from Langmuir wave emissions.

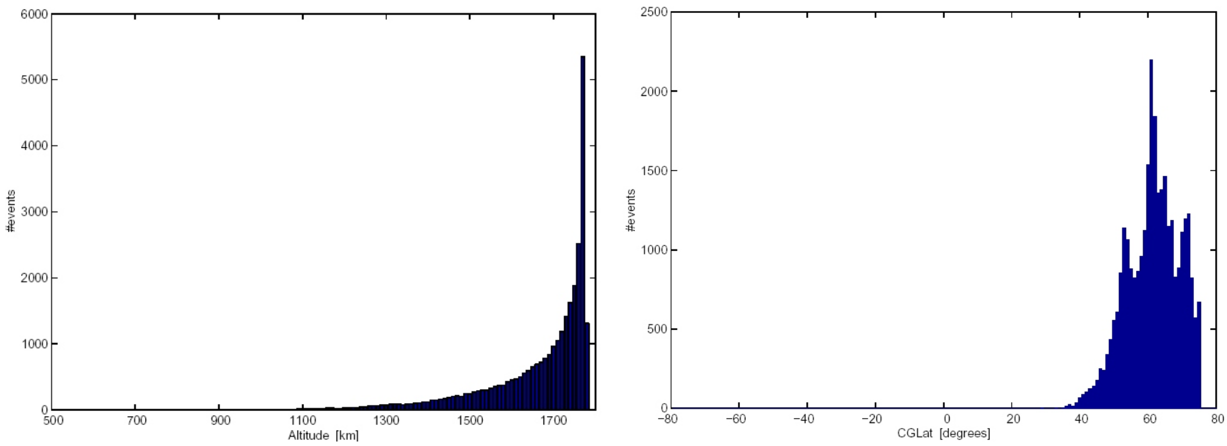

Fig. 2. The Freja coverage coverage of altitudes (left) and corrected geomagnetic latitudes (right) during its almost three years of operational lifetime. The histograms were made by dividing each ground station pass (15 – 30 minutes) into four intervals, using the postitions at their centres.

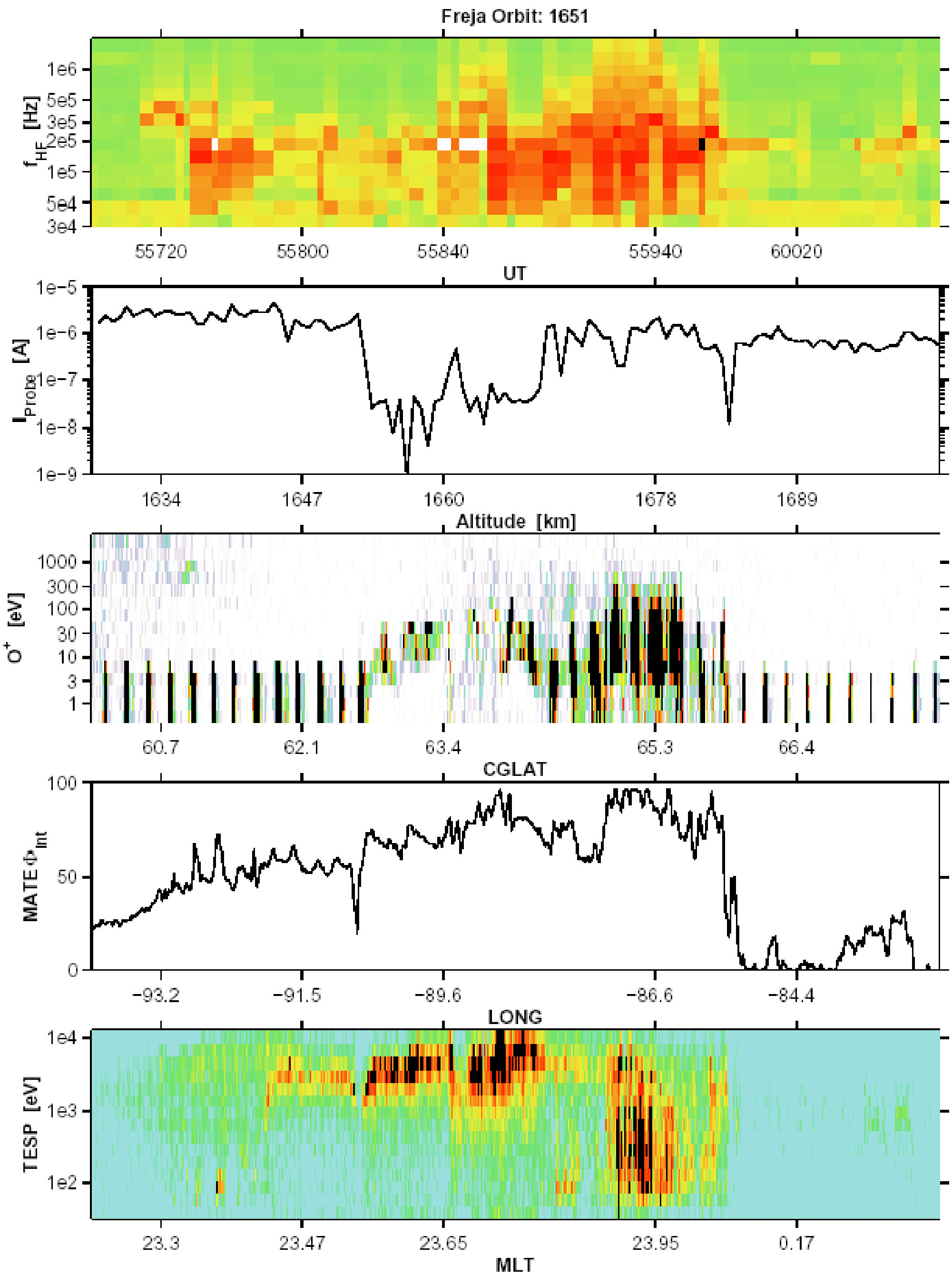

Fig. 3. An example event in the auroral zone. Panels from top to bottom: (i) Wave activity from 30 kHz to 2 MHz. (ii) Current to a Langmuir probe, biased to +10 V. (iii) Ion spectrogram up to 3 keV. (iv) Integrated flux of electrons 5 keV – 100 keV (uncalibrated). (v) Electron spectrogram up to 10 keV. Similar plots for all Freja charging events are available at `http://www.ava.fmi.fi/spee/freja.html`.

4. Example event

Out of the ten Freja charging events studied in detail [4], we here present one. While not showing any high charging levels, only around -20 V, the event in Figure 3 is instructive as presenting a clear signature of some features highlighted in the Freja study. The top panel shows wave spectra, in which peaks at the plasma frequency can at times be observed, for example at 05:57:20 (around 300 kHz, corresponding to a plasma density around 1000 cm^{-3}) and at the end of the plotted time (200 kHz, 500 cm^{-3}). The next panel shows the magnitude of the current to a Langmuir probe biased at +10 V, which can often be used as a proxy for the plasma density. The difference in probe current between the start and end of the plotted interval is consistent with the densities we derived above from the plasma frequency emissions. However, the drop in probe current occurring around 05:58:30 does not seem to have any obvious counterpart in the wave data, keeping in mind that that $n_e \propto f_p^2$).

The centre panel shows ion energy spectrograms. At the beginning and the end of the plot, the ion signature to be seen is the oxygen ram flow due to the satellite motion. This signature appear once every 6 s, when the satellite spin brings the ion detector in the ram flow direction. Between 05:58:10 and 05:59:10, the low energy cutoff of this ram flow is elevated, to around 10 eV for a large part of the time, possibly reaching 30 eV briefly. Interpreting this elevation as spacecraft charging to negative values of the same magnitude, it also becomes clear why the Langmuir probe current could drop without any signature of density depletion in the wave data. The probe is positively biased with respect to the satellite, but when the spacecraft goes sufficiently negative, the probe will also be at negative potential with respect to the plasma. In this situation, the probe current drops, irrespective of the density and consistent with the observed probe current.

The cause of the charging can be identified in the two lowermost plots. The electron spectra up to 20 keV in the bottom panel shows enhanced flux of the typical narrowband auroral electrons of what is known as ”inverted-V” type during the charging event. For electrons between 5 keV and 100 keV, we only have the total flux in this case, shown as a line plot. These electrons are seen all the time from 05:57:40, but it is only when their flux increases around 05:58:10 that charging sets in, causing the probe current to drop and the ion energy to be elevated.

There is little evidence for any density drop from the wave data during this time. In fact, the probe current values during all the plotted interval is consistent with the density staying at the 500 – 1000 cm^{-3} levels observed at the start and end of the plotted interval (see discussion on wave activity above). The lower values during the the charging event (05:58:10 – 05:59:10) are as expected when the probe goes negative with respect to the plasma, hence sampling ions rather than electrons, due to the charging of the spacecraft. This event thus examplifies the weak correlation between plasma density and charging events found in the Freja data, to which we return in the discussion on statistical results below (Section 5).

The time interval 05:59:10 – 06:00:00 is also of interest. During this period, the electron data show equal or higher fluxes above 5 keV than during the charging event, but also high flux levels at and below 1 keV. Some elevation of the ions may possibly be seen, though more important ion features are higher energy spread and wider pitch angle distribution due to ion heating in the plasma. The Langmuir probe current shows no drop. High fluxes of electrons around and below 1 keV should cause increased secondary electron fluxes, counteracting spacecraft negative charging, and this seems indeed to be the case here.

5. Statistics

An important part of the Freja spacecraft charging study was scanning of the whole useful database for establishing the full statistics, reported by Wahlund et al. (1999b). The data base consist of the time period when the three critical instruments (Section 3) all have good data, which for our purposes means October 1992 to April 1994. To find charging events, we first scanned the Langmuir probe current for all events (some 500) where this dropped below 20 nA. The ion spectra for these candidates were then visually inspected for distributions lifted in energy by at least 5 eV, which we classified

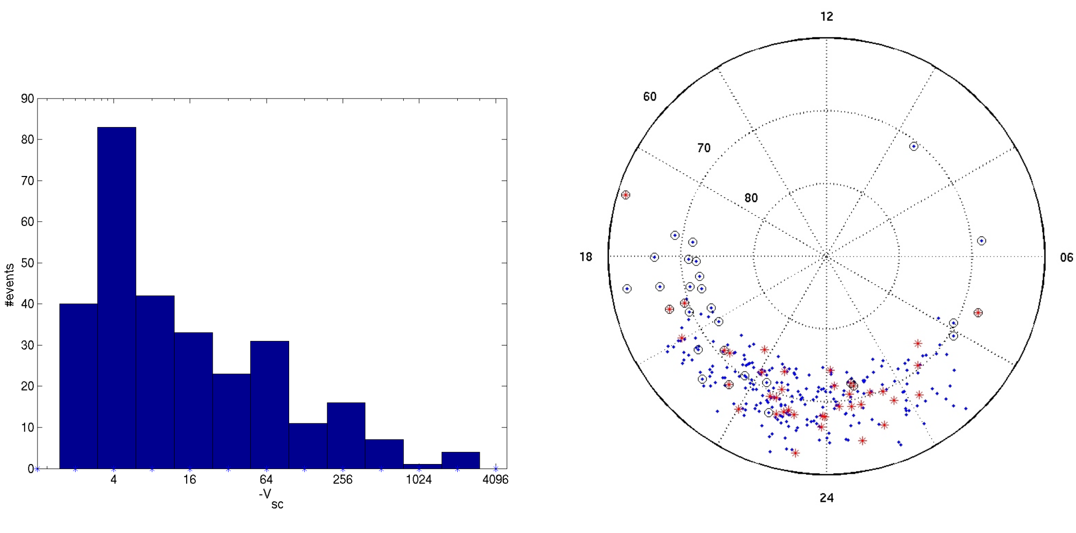

Fig. 4. *Left:* Histogram showing the charging voltage in the Freja charging events, binned in logarithmically spaced intervals. *Right:* Polar plot illustrating their distribution in geomagnetic coordinates. Red stars mark events charged below -100 V, and rings denote events in sunlight.

as charging events. There were 291 such events, though with a more strict limit on the charging potential, this number diminishes rapidly. This is illustrated in the left plot in Figure 4, showing the distribution of events on charging levels. The number of events reaching more negative potential than -100 V is 39 in the just below 1.5 years covered in this study.

This may be compared to a study of 12 years of DMSP data [12], which identified 1253 events below -100 V (see [13] for an update to that study). Before comparing these numbers, we should note that the distribution of DMSP charging events was far from even in time, with lower occurrance frequency during solar maximum than at solar minimum. The plots produced in reference [12] suggest that some 80 charging events were identified in DMSP data during the period covered by the Freja database. However, we should also note that many of the Freja events occur very close to each other, but are classified as distinct events due to changing environmental parameters. Thus, the 291 events are from only 161 different Freja orbits, with 121 events being separated by 5 minutes or less. In addition, Freja spends a longer time in the auroral zone on every orbit, due to the dominantly West-East direction of motion in the auroral zone caused by its low inclination. It therefore seems quite clear that DMSP at 840 km is more prone to auroral charging than Freja at roughly double that altitude.

The right plot in Figure 4 shows the distribution of Freja charging events in corrected geomagnetic coordinates. Blue dots and red stars mark events where the s/c goes less or more negative than -100 V, respectively, and we find essentially the same pattern for both. Comparing to the DMSP statistics [12], we find an almost identical distribution on the nightside, shifted slightly duskward from magnetic midnight as expected for active aurora.

What stands out as a difference from DMSP are the 30 events occurring in sunlight (marked with black circles), of which 7 reached potentials more negative than -100 V. From DMSP, no charging event was found in sunlight [14, 12]. However, it is worth noting that while Freja herself is sunlit at these events, the ionpsphere below her is in darkness. This is consistent with auroral acceleration occurring mainly over the dark ionosphere [15]. As for DMSP, charging events on Freja occur almost exclusively in winter time. Our data set is only from the northern hemisphere, and no event was found between April 10 and September 19. We will discuss the Freja charging events in sunlight further in Section 6.

Figure 5 shows averages of all available electron spectra from the TESP (10 eV – 30 keV) and MATE (5 keV – 100 keV) detectors, sorted for three different charging levels. The limited and different angular coverage of both the instruments means that the data do not perfectly match in the region where they overlap, and also that a significant part of the total

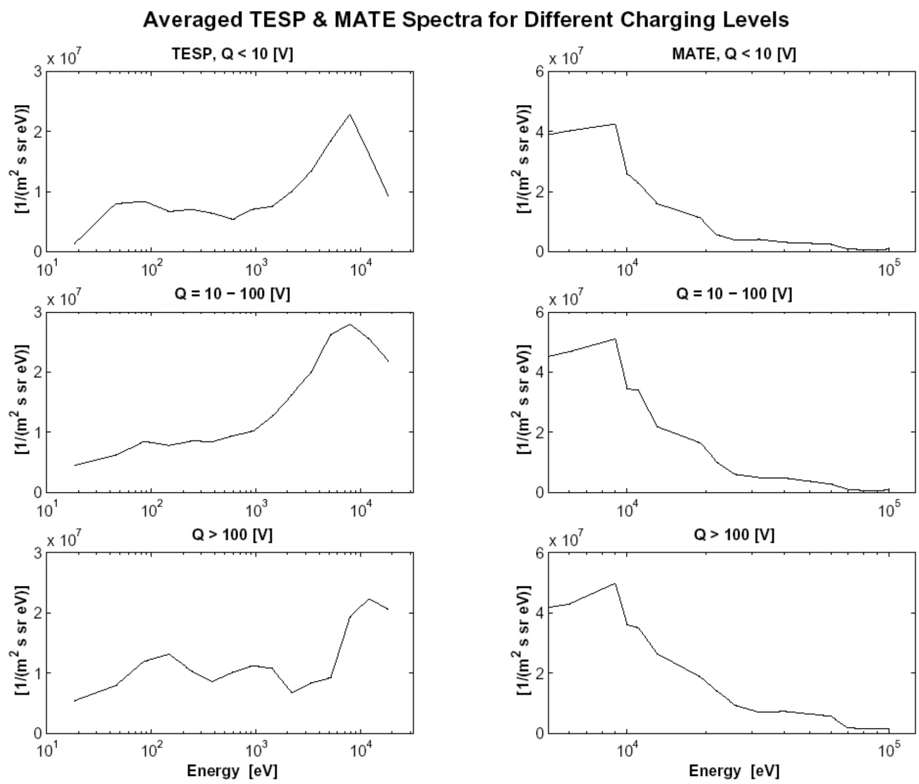

Fig. 5. Averages of all electron spectra obtained during charging events by the two lectron detectors TESP [9] and MATE [8], sorted by the magnitude of the charging level, Q.

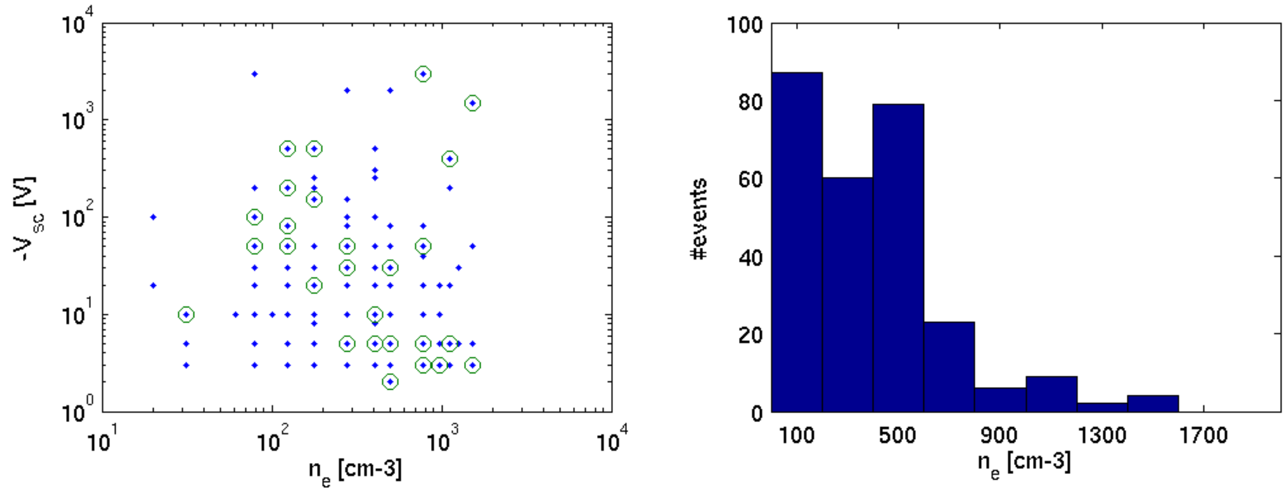

Fig. 6. *Left:* Charging level vs. plasma density. Rings mark charging events in sunlight. *Right:* Distribution of plasma densities in charging events, with bins centred on 100, 300, 500, ... cm^{-3}.

flux may at times be missed. Nevertheless, it is clear that the peak just below 10 keV is typical, and that the higher level charging events stand out by an increase in flux in the 10 – 100 keV tail of the distribution. Note also that fluxes below 1 keV: electrons in this energy range have a high secondary yield, meaning that their presence would inhibit rather than enhance the charging (for basics on spacecraft charging theory, see e.g. [16]). A peak around or above 10 keV, an enhanced high energy tail and low fluxes at lower energy are found also in the DMSP charging events DMSP [14, 12].

An advantage with Freja was that the density could be determined in two independent ways, from the Langmuir probes and from the plasma frequency. We showed in Section 4 how the plasma density showed little sign of depletion during a charging event. The density in all Freja charging events is seen in Figure 6. Another difference to DMSP is that for Freja, the correlation between charging events and unusually low densities were not so clear. This can be understood from the fact that densities at Freja orbit ($\sim$1700 km) are generally much lower than what DMSP encounters at roughly half the altitude. The low plasma density values needed to cause charging of DMSP are not so low at Freja altitude, so further depletion of the plasma is not a necessary condition for Freja charging. However, no charging event took place at densities above 2000 cm^{-3}, and very few above 1000 cm^{-3}. This could be due to higher densities inhibiting charging even in presence tens-of-keV electron fluxes that would otherwise be sufficient for causing spacecraft charging. It is also possible that the reason is more due to auroral physics than to spacecraft charging physics: it could well be that sufficient electron fluxes occur only rarely when the density is higher, as auroral acceleration depends on ionospheric densities [15]. We leave this question open here.

Frooninckx and Sojka [17] found that a parameter regulating the DMSP charging level was the high energy electron flux $\Phi_{\rm he}$ divided by the ambient plasma density n, in the sense that the charging level $-V_{\rm sc}$ correlated better to $\Phi_{\rm he}/n$ than to $\Phi_{\rm he}$ or n on their own. In the Freja case, we found that the correlation of $V_{\rm sc}$ was only slightly better to $\Phi_{\rm he}/n$ than to $\Phi_{\rm he}$ or n: neither showed any reasonable correlation. However, hinted by the apparent alleviation of charging by electrons around 1 keV discussed in Section 4, we also divided by the electron flux at 1 keV, Φ_0, finding a covariation of $-V_{\rm sc}$ and $\Phi_{\rm he}/(n\,\Phi_0)$ [5]. Such a covariation is readily interpreted in terms of high energy electrons causing charging, with cold plasma ions and the secondary electrons caused by 1 keV electrons working to neutralize the charging.

6. Simulations

As seen in Figure 6, the plasma density in the Freja charging events varied between 20 cm^{-3} and 2000 cm^{-3}. We do not know the electron temperature, but may reasonably expect it to stay between 0.2 eV and 2 eV. In these circumstances, the electron Debye length could vary from less than 10 cm to over 2 m. Given a magnetic field of 25 – 30 μT the electron gyroradius should be on the order of 10 cm, and the cold ion gyroradius on the order of 5 m for protons and 20 m for oxygen ions. Freja is 2.2 m in diameter and around 50 cm in height. The gyroradius of the dominating ion species (oxygen) may thus be taken to be infinite, but all other characteristic lengths are comparable to the spacecraft scale. As local charging of remaining exposed dielectrics was suspected to be an ingredient to the charging problem, modelling had to be done with a code well resolving small structures, and capable of handling the complexities of a spacecraft sheath.

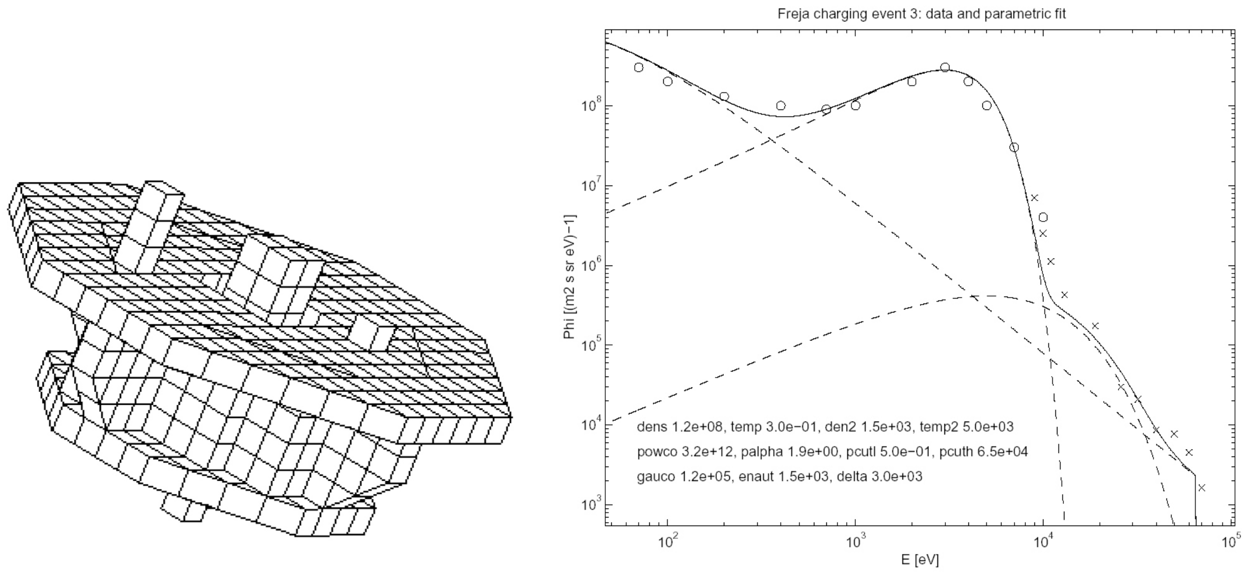

Fig. 7. *Left:* The most complete Freja model used in the POLAR simulations, with 10 cm grid resolution. *Right:* Observed and fitted electron spectra for modelling with POLAR. Circles are data from the TESP detector, crosses from MATE (Section 3). The fitted curve has been mapped through the observed spacecraft potential to correct for effects of the charging event.

We used the POLAR (Potential of Large Spacecraft in the Auroral Region) code package, described by Cooke [18, 19], who applied it succesfully to auroral charging events on the DMSP satellites. The modelling effort included establishing a complete materials list for the surface areas on Freja. Some care had been taken in the Freja design process to minimize non-conductive areas on the surface in order to minimize impact on the measurements of unknown perturbation fields due to charge accretion on isolated parts. Consequently, solar panels were coated with indium tin oxide (ITO), a conductive thermal blanket was used, and other exposed parts were painted with a conductive paint. A detailed description of the simulations, including the Freja model for POLAR and the materials list, is available in [6].

Several Freja models were used in the simulations. The most detailed model, capable of including localized exposed insulators like telemetry antenna covers, is shown in Figure 7. As POLAR uses a fixed grid, of equal resolution for spacecraft and space, simpler models were used for trial simulations.

Five of the Freja charging events were modelled. Observed electron spectra was fitted to the model by Fontheim et al. [20] which is used in POLAR for the describtion of auroral electrons. This was possible to do with good accuracy, as can be seen in the example in the right plot of Figure 7. It was necessary to correct the observed spectra for the observed charging: as the detector is on a satellite charged to some potential, the observed electron flux spectrum must be mapped out to its value in the unperturbed plasma by use of the Liouville equation [6].

Charging to moderate levels (~ 50 V) could be succesfully modelled. We could not obtain any significant charging in sunlight if photoemission was included in the simulation. The solar zenith angle was close to 90° in our cases, so the sunlight reaching Freja has travelled a large distance through the atmosphere, attenuating its UV content and hence decreasing the photoemission, which may explain this problem. However, to reproduce the kV potentials seen in some of the events we had to vary the environmental parameters and/or materials constants out of the range considered to be supported by our data.

There are many possible reasons for our inability to model the highest charging levels with POLAR. Material properties is one area of uncertainty, particularly if some materials change in space, though the appearance of charging events within a month after launch would require such change to be quick. Quenching of photoelectrons or secondary electrons due to barrier formation [21] may possibly occur. For the sunlit cases, the large solar zenith angle serves to decrease UV intensity and hence photoemission. In addition, decreased photoemission by reflectance effects is a possibility, as noted elsewhere in this volume [22]. As shown by the explanation of its acronym (see above), POLAR was developed primarily for large spacecraft, i.e. structures significantly larger than the Deye length. Freja is smaller than DMSP and the plasma is less dense. In the simulations, the sheath tended to expand to the edge of the simulation box, which may indicate a problem here. Finally, our information on the surrounding plasma may be in error. In particular, the electron detectors do not cover all pitch angles, so that field aligned electron fluxes can be underestimated.

7. Conclusions

The principal results of the Freja spacecraft charging study can be summarized as follows:

1) Even a spacecraft designed for electrostatic cleanliness and where exposed dielectrics have been minimized may experience significant charging in the auroral region.

2) The particle environment causing charging on Freja is consistent with reports from previous studies: sufficient electron fluxes above or around 10 keV with high energy tails.

3) We could also observe how lower energy electrons (1 keV and below) actually alleviates charging, presumably because of the high secondary electron yield (> 1) of many materials at these energies.

4) Already at the altitude of 1500 – 1700 km typical for Freja, the plasma density is sufficiently low for it to be a less decisive factor for charging than at DMSP in true LEO orbit (840 km). However, no charging event was observed for plasma densities in excess of 2000 cm^{-3}.

5) Several of the Freja charging events occurred in sunlit conditions. The solar zenith angles are low in these events, so the photoelectron emission may still be small.

6) The charging events in sunlight all occured over a dark (non-illuminated) ionosphere. This can be due to the known fact that aurora occurs primarily over the dark ionosphere [15], but may also be influenced by the locally lower plasma density.

7) Cases with moderate charging levels could be modelled by POLAR. However, we did not succeed in simulating the highest charging levels with POLAR.

8) The observed auroral electrons could be well fitted to the models by Fontheim et al. [20] used in POLAR. Correcting for the charging voltage was crucial for good modelling.

9) In addition to the results as presented here and in the reports [4, 5, 6], the study provided the community of a database on spacecraft charging at intermediate altitudes, available at `http://www.ava.fmi.fi/spee`.

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