Surface Charging in the Auroral Zone on the DMSP Spacecraft in LEO

Phillip C. Anderson

Space and Environment Technology Center, The Aerospace Corporation, El Segundo, California

Abstract. A recent anomaly on the DMSP F13 spacecraft was attributed to an electrical malfunction caused by an electrostatic discharge on the vehicle associated with surface charging. It occurred during an intense energetic electron precipitation event (an auroral arc) within a region of very low plasma density in the auroral zone. A study of 1.5 year's worth of DMSP data from three satellites acquired during the recent minimum in the solar cycle has shown that such charging was a common occurrence with 704 charging events found. This is the result of significantly reduced background plasma densities associated with the solar minimum; smaller than ever previously experienced by the DMSP spacecraft. At times, the spacecraft charged for periods of 10s of seconds as they skimmed along an auroral arc instead of cutting across it. We show examples of the observed plasma density and the precipitating electron and ion spectra associated with the charging, and the MLT distribution and the seasonal distribution of the events. The preponderance of events occurred in the premidnight and morning sectors with two types of electron spectra being observed: a sharply peaked distribution indicative of field-aligned acceleration in the premidnight sector and a very hard distribution in the morning sector.

1. Introduction

Spacecraft charging has been the cause of a number of significant anomalies on high altitude spacecraft. Concern about these occurrences has led to a number of investigations entirely devoted to the study of spacecraft charging in high-earth orbit. However, little effort has been devoted to the study of high-level charging in low-earth orbit due to the rarity of its occurrence. *Anderson and Koons* [1996] reported the occurrence of an anomaly associated with low-altitude, high-level surface charging on the Defense Meteorological Satellite Program (DMSP) F13 spacecraft. To our knowledge, this was the first published report of the observation of an anomaly associated with spacecraft charging in low-earth orbit. On May 5, 1995, the microwave imager instrument aboard the DMSP F13 spacecraft experienced a lock-up of its microprocessor unit. The anomaly was attributed to an electrical malfunction caused by an electrostatic discharge on the vehicle. It occurred during an intense energetic electron precipitation event (an auroral arc) within a region of very low plasma density in the auroral zone. Plasma measurements indicate that the spacecraft frame charged to a voltage near -459 V within a few seconds. Calculations of the capacitance of the ungrounded thermal blankets covering the top of the spacecraft were consistent with a surface charging time of a few seconds to several kilovolts. Subsequent electrostatic discharge led to the lock-up.

For satellites in low earth orbit, such as the DMSP spacecraft (~840 km), the plasma density is usually high and the main contributors to the currents to the spacecraft are the thermal electrons and ions that constitute the ionosphere. When the plasma density is very low, however, the contribution to the currents to the spacecraft from other sources such as precipitating electrons in the auroral zone can become very important. In fact, the spacecraft can charge to high negative voltages during times when the plasma density is very low and the flux of energetic electrons is very high. *Gussenhoven et al.* [1985] showed that the DMSP F6 and F7 spacecraft could charge to voltages < -100 V when the following conditions were met: 1) the spacecraft was in darkness, 2) The plasma density was less than 10^4 cm^{-3}, and 3) there was a high integral number flux (> 10^8 electrons cm^{-2} s^{-1} sr^{-1}) of high energy (> 14 keV) electrons.

We present the initial results of a study of 704 charging events that occurred during a 1.5 year period around the recent minimum in the solar cycle. We show examples of the observed plasma density and the precipitating electron and ion spectra associated with the charging, and the magnetic local time (MLT) and seasonal distributions of the events.

2. Spacecraft and Instrumentation

The DMSP spacecraft are a series of low-altitude, polar-orbiting satellites whose primary mission is to observe the tropospheric weather. Their secondary mission is to observe the space environment using a set of three instruments: the special sensor for ions, electrons, and scintillation (SSIES), the precipitating energetic particle spectrometer (SSJ/4), and the vector magnetometer (SSM). The instruments of interest here are the SSIES and the SSJ/4. The SSIES measures the *in situ* ion and electron temperatures and the plasma density, fluctuation, composition, and bulk flow velocity. The SSJ/4 measures precipitating energetic electrons and ions in the energy range from 30 eV to 31 keV with downward flight paths within a few degrees of local vertical.

Charging events are identified using the ion portion of the SSJ/4 detector. The sensor aperture is grounded to the spacecraft frame so that when the frame charges to some large voltage, the ambient thermal ions (which have energies less than 1 eV) are accelerated to the spacecraft frame voltage as they pass through the plasma sheath in front of the aperture. Therefore a large flux is observed in the ion channel with energy range spanning the frame voltage, generally a much larger flux than from ambient precipitating ions and thus easily identifiable.

The DMSP spacecraft consist of a honeycomb aluminum, five-sided equipment support module (ESM) with the solar array at one end and a precision mounting platform at the other. The ESM is covered with thermal blankets and pinwheel thermal louvers are used on all but the side facing the earth. The thermal blankets covering the top surfaces of the spacecraft consist of 22 layers of dielectric material; each layer is aluminized on both sides while the outer Teflon layer is only aluminized on the side facing the spacecraft. Since the intermediate layers of the thermal blankets are not grounded to the spacecraft frame, the aluminized coatings serve as the plates of a set of 22 parallel-plate capacitors in series. The 'top' plate consists of electrons (i.e., auroral electrons) buried in the top few microns of the Teflon and the bottom plate is the layer of aluminum which is in contact with the spacecraft frame. The total calculated capacitance of the blankets is 7.3×10^{-9} F m^{-2}.

The three satellites used in this study, F10, F12, and F13, all fly in sun-synchronous, 99°-inclination orbits at ~840 km altitude with ascending nodes at about 2230, 2130, and 1800 solar local time respectively, and orbital periods of 101 min.

3. Statistical Distribution of Charging Events

One of the *Gussenhoven et al* [1985] requirements for high-level charging on the DMSP spacecraft, based on a sample of 11 events, was that the background thermal plasma density be less than 10^4 cm^{-3}. During the recent minimum in the solar cycle, the plasma density was at the lowest level ever experienced by the DMSP spacecraft; the density over the dark polar regions was nearly always below 10^4 cm^{-3}. This led to a significant increase in the number of charging events on the DMSP spacecraft. We searched 1.5 years of data during the recent solar minimum and found 704 charging events on 639 polar passes during which the DMSP spacecraft frame charged to over 100 volts negative. Most of the charging periods were for a few seconds but there were some in which the spacecraft charged for over 60 seconds.

Figure 1 shows the distribution of charging events for the period of the study, separated by hemisphere and MLT. There is a strong seasonal effect, driven by the requirement that the spacecraft be in darkness (because of the production of photoelectrons). The few events that occurred in sunlight were associated with very intense electron precipitation. There is a large preponderance of events in the southern hemisphere (80%) and there are considerable differences in the distribution of events from satellite to satellite, These are largely driven by the orbit parameters and their relationship to the magnetic pole (F13 is in a dawn-to-dusk orbit and F10 and F12 are both in premidnight-to-postnoon orbits). The distributions of F10 and F12 charging events are considerably different even though their orbits are very similar, only differing by an hour in ascending node local time. The F10 orbit takes it on the dawn side of the magnetic pole much more often than F12's orbit thus producing a significantly larger number of morning side events.

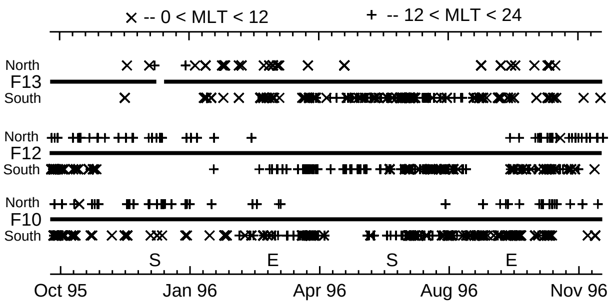

Figure 1. Distribution of events over the time period of the study, separated by hemisphere (above and below the solid line) and MLT (+ and ×). The solstices and equinoxes are indicated by the S's and E's at the bottom of the plot.

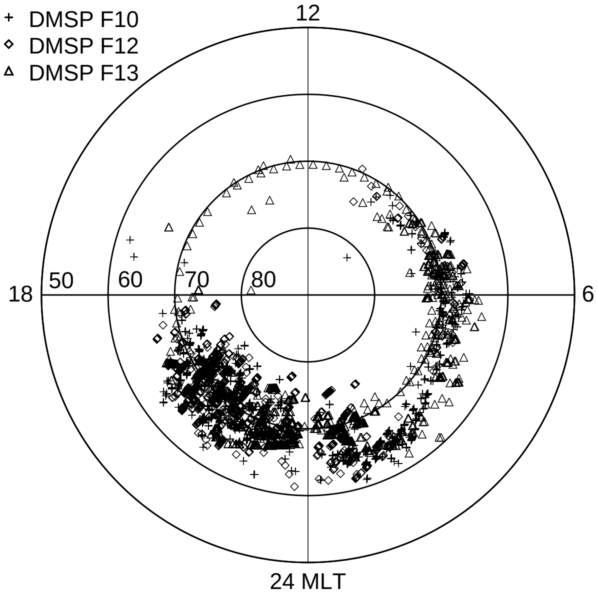

Figure 2. MLT and MLAT distribution of 2824 1-second SSJ/4 sweeps associated with the 704 charging events.

Figure 2 shows the MLT and magnetic latitude (MLAT) distribution of 2824 1-second SSJ/4 sweeps associated with the 704 charging events. Just over half of the events occurred in the premidnight sector between 1800 MLT and 2400 MLT; with most of the rest occurring in the morning between 0000 MLT and 1000 MLT, and a few events in the afternoon sector when the spacecraft was sunlit. The precipitating electrons that are causing the charging display very different distributions in the premidnight and morning sectors.

3. Environmental Data

3.1. Premidnight sector

Figure 3 shows an example of the environmental parameters associated with a typical charging event in the premidnight sector on F13; this is actually the event that caused the anomaly reported by *Anderson and Koons* [1996]. The top panel is the ion (electron) density, the middle panel is the precipitating electron number flux spectrogram, and the bottom panel is the precipitating ion number flux spectrogram with energy plotted from top down. The charging is identified by the large flux in a single ion channel as indicated on the plot. The density remains below the *Gussenhoven et al.* [1985] requirement of 10^4 cm^{-3} during the entire polar pass with excursions below the sensitivity of the instrument associated with 5 separate auroral arcs. (These are called auroral cavities and are common features of auroral

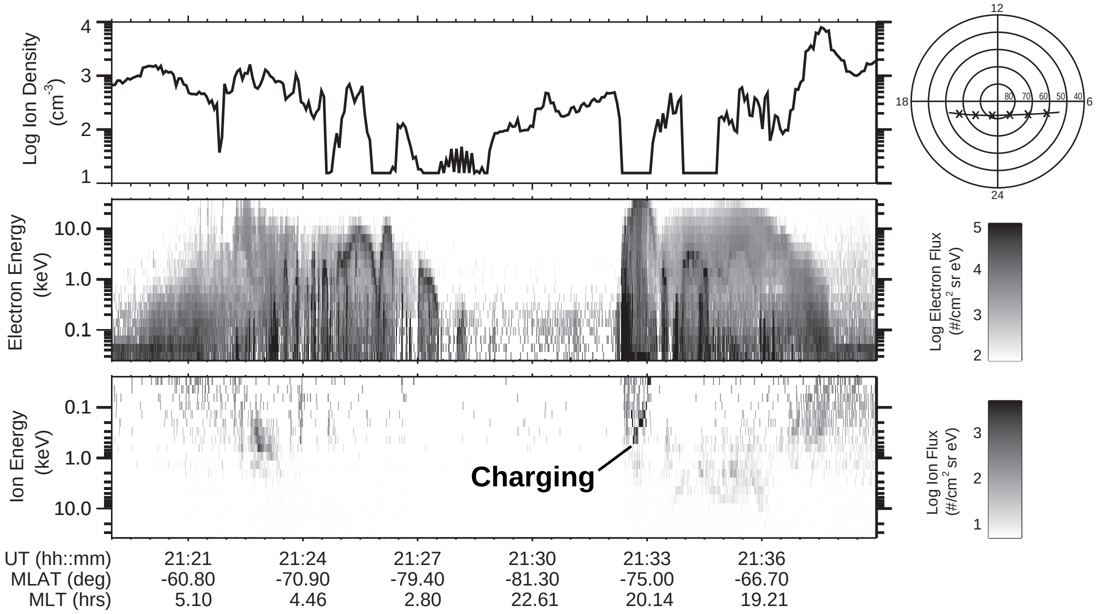

Figure 3. The environmental parameters associated with a charging event in the premidnight sector: the ion (electron) density (top panel), the precipitating electron number flux spectrogram (middle panel), and the precipitating ion number flux spectrogram (bottom panel). The ion spectrogram is plotted with low energy at the top and high energy at the bottom. The polar dial at the top right indicates the spacecraft orbit track in MLT and MLAT.

arcs.) However, the only charging occurred within the arc where the peak energy exceeded 10 keV. This is because of strong secondary electron production for electrons below 10 keV.

Figure 4 shows the 1-second electron and ion spectra around the time of the anomaly; the spectra at the time of the anomaly are indicated by the heavy bordered plots. The spacecraft frame (instrument aperture) voltage is indicated by the high ion flux in a single channel. (The ion fluxes seen at energies below the peak are actually contamination from high energy electrons.) The electron spectra show strong field-aligned acceleration, indicated by the spectral peak at high energies and sharp falloff at higher energies, as in the spectra at 21:32:35 UT where the peak is just above 10 keV. Near the time of the anomaly, the spectral peak was located above 31 keV. (This is a rather intense, although not uncommon event. The spectral peak is usually below 31 keV.) The spacecraft began charging near 21:32:34 UT, was charged to near -439 V at the time of the anomaly at 21:32:40 UT, and remained charged for 15 seconds after the anomaly.

3.2 Morning sector

Figure 5 shows the electron and ion spectrograms associated with a typical charging event on F10 in the morning sector. (F10 did not have a functioning SSIES at the time of this study, so there were no plasma density measurements available.) Unlike the charging events in the premidnight sector, this event is not

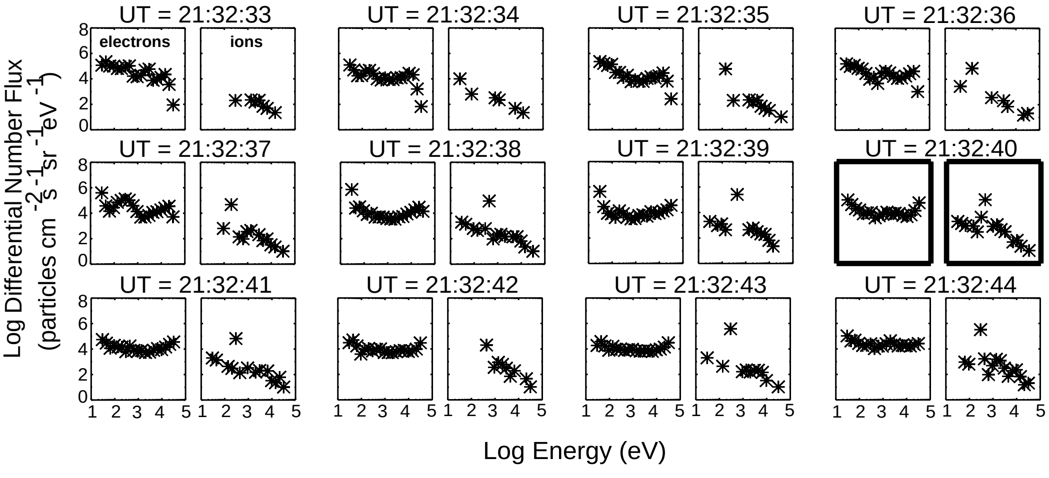

Figure 4. The individual, 1-second electron and ion spectra at the time of the charging event shown in Figure 3. The spectra at the time of the anomaly are indicated by the heavy border around them.

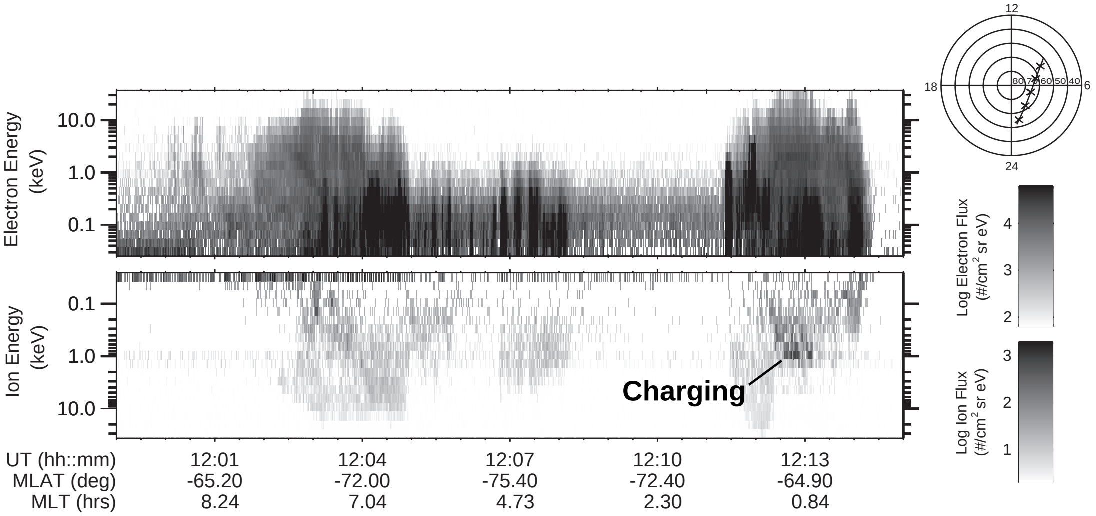

Figure 5. The environmental parameters associated with a charging event in the morning sector; the precipitating electron number flux spectrogram (top panel), and the precipitating ion number flux spectrogram (bottom panel).

associated with an auroral arc but with an intense morningside diffuse aurora.

Figure 6 shows some of the 1-second electron and ion spectra at the time of the charging event shown in Figure 5. The electron spectra lack the strong peak associated with field-aligned acceleration and show a much harder spectra at high energies than typically seen in the premidnight sector.

3.3 Extended charging

Auroral arcs are nominally aligned with constant magnetic latitude; therefore a polar spacecraft will generally cut horizontally across an arc thus minimizing its time within the arc. However, a lower inclination satellite, and even a polar satellite under the right orbital and magnetic field configurations, can skim along nearly constant magnetic latitude within the auroral zone. Such an event is shown in Figure 7: near 03:00 UT the spacecraft charged for well over 60 seconds. The electron density stayed well below the required level for charging during the entire pass and the spacecraft charged a number of times; at 02:56:35 UT the spacecraft charged to near -1000 V. All of the charging events on this pass are associated with the typical premidnight electron spectra with the exception of the one near 02:54 UT which is associated with the typical morningside spectra.

4. Discussion and conclusions

We have found a significant number of high-voltage charging events (704) on the DMSP spacecraft during a 1.5 year period surrounding the recent solar minimum, much greater than previously expected. This was due to the greatly reduced thermal plasma density in the ionosphere associated with the reduced UV output from the sun. Although only one anomaly has been directly associated with such charging, the vast majority of DMSP anomalies have not been investigated in detail for

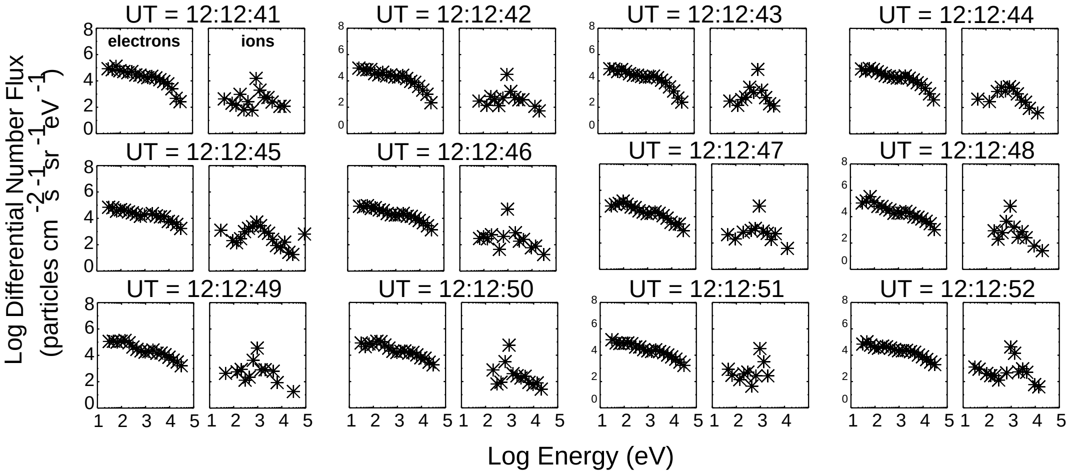

Figure 6. The individual 1-sec electron and ion spectra associated with the charging event of Figure 5.

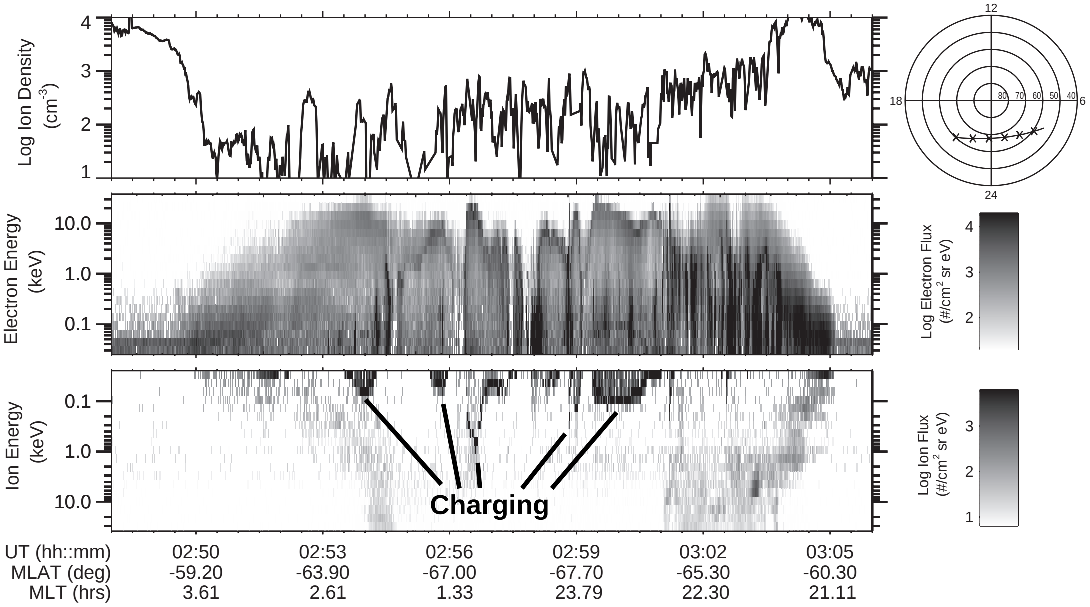

Figure 7. The environmental parameters associated with a charging event that lasted for over 60 seconds.

spacecraft charging. We are gathering a database of anomalies for such an investigation and are continuing this study with the investigation of another 1.5 years of data during solar maximum.

The requirement that the spacecraft be in darkness (the few events occurring when the spacecraft was sunlit had particularly intense electron precipitation associated with them) led to a seasonal dependence with most of the events occurring around winter solstice. There was a strong anisotropy between occurrences in opposite hemispheres; 80% of the events occurred in the southern hemisphere. This is due to the spacecraft orbits and their relationship to the magnetic poles. Even two spacecraft with nearly identical orbits separated by only one hour of local time show considerable difference in the seasonal distribution of charging events.

The majority of events occurred in the premidnight sector, with most of the rest occurring in the morning sector, and a few in the afternoon sector when the spacecraft was sunlit. The precipitating electron spectra associated with events in the premidnight sector show evidence of strong field-aligned acceleration with the differential number flux peaking at energies > 10 keV and falling off rapidly above the peak. In the morning sector, the spectra lack the strong peak and show a much harder distribution at higher energies.

Most of the events showed spacecraft frame charging in the few hundred volt range, with one event in which the frame charged to almost -2000 V. *Anderson et al.* [1996] showed that the ungrounded multi-layer thermal blankets covering most of the surface of the spacecraft could easily charge to several kilovolts in a few seconds and recommended that the top layer of the thermal blankets be grounded. This would lead to an increase by a factor of 20 in the required charging time. However, there were events in which the spacecraft charged to high negative values for several 10s of seconds. Such considerations are very important when designing of low-altitude satellites, despite the typically large plasma densities. Polar satellites orbiting in the altitude regime a few hundred km above the DMSP orbit, where the plasma density is smaller, will experience very similar conditions to those experienced during the DMSP charging events and lower inclination satellites could remain in auroral arcs and charge for considerable periods of time.

Acknowledgments. This work was supported by the Aerospace Sponsored Research Program. The author thanks Dr. Fred Rich for providing the data used in this study.

References

Anderson, P. C. and H. C. Koons, A spacecraft charging anomaly on a DMSP satellite in an aurora, *J. Spacecraft Rockets*, 33, 734,1996.

Gussenhoven, M. S., D. A. Hardy, F. Rich, W. J. Burke, and H. -C. Yeh, High Level Charging in the Low-Altitude Polar Auroral Environment, *J. Geophys. Res.*, *90*,. 11000, 1985.

P. C. Anderson, The Aerospace Corporation, MS: M2/260, P.O. Box 92957, Los Angeles, CA 90009-2957. (e-mail: phillip.c.anderson@aero.org)