Extreme Spacecraft Charging in Polar Low Earth Orbit

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Introduction

Spacecraft in low altitude, high inclination (including sun-synchronous) orbits are widely used for remote sensing of the Earth’s land surface and oceans, monitoring weather and climate, communications, scientific studies of the upper atmosphere and ionosphere, and a variety of other scientific, commercial, and military applications. These systems episodically charge to frame potentials in the kilovolt range when exposed to space weather environments characterized by a high flux of energetic (>10 keV) electrons in regions of low background plasma density. Auroral charging conditions are similar in some ways to the space weather conditions in geostationary orbit responsible for spacecraft charging to kilovolt levels. We first review the physics of space environment interactions with spacecraft materials that control auroral charging rates and the anticipated maximum potentials that should be observed on spacecraft surfaces during disturbed space weather conditions. We then describe how the theoretical values compare to the observational history of extreme charging in auroral environments. Finally, a set of extreme DMSP charging events are described varying in maximum negative frame potential from ~0.6 kV to ~3 kV, focusing on the characteristics of the charging events that are of importance both to the spacecraft design and to spacecraft operators. The goal of the presentation is to bridge the gap between scientific studies of auroral charging and the need for engineering teams to understand how space weather impacts both spacecraft design and operations for vehicles on orbital trajectories that traverse auroral environments.

Surface Charging Phisics

Surface charging is the result of a current balance on the surface of a spacecraft. Charging is described by the time dependent current balance relation

\[ \frac{dQ}{dt} = \frac{-dA}{dt} \cdot A - \sum_i q_i (V_i) \cdot I_i \]

where \( Q \) is the total charge and \( q \) the surface charging accumulating on the surface area \( A \), \( C \) is the capacitance of the area \( A \), and \( V \) the voltage of the surface. The currents as a function of surface potential \( V \) of importance to surface charging are

\[ I = \sum_{\text{incident ions}} \text{incident ions} - I_{\text{incident electrons}} - I_{\text{backscattered electrons}} + I_{\text{secondary electrons due to I}} + I_{\text{secondary electrons due to L}} - I_{\text{photons}} - I_{\text{active current sources}} \]

Identification of Auroral Charging

Auroral charging is readily identified from the "ion line" signature that appears in ion electrospectroscopic analyzer records. Here, the ion line in the DMSP F9 satellite SSI/4 instrument ion record is the result of ambient low energy ions accelerated by the spacecraft potential from an initial energy \( E_i \approx 0 \) keV to a final energy \( E = 10 \) keV where \( q \) is the charge of the ion and \( q \) the spacecraft surface potential in volts.

Charging Simulations

NascaP-2k surface charging simulations using a realistic harsh auroral charging environment derived from the DMSP F13 satellite for input to the charging code. The simulations show that spacecraft regardless of size are susceptible to auroral charging when their orbits encounter auroral charging environments. Frame charging develops over very short timescales on the order of a few seconds while differential charging is slower requiring minutes to develop significant differential potentials between the ground plane and insulators over the surface. The temporal history of charging will depend on the specific design details of a spacecraft and each satellite is unique.

Frequency and Distribution of Auroral Charging

A wealth of information on solar cycle variations and local time distributions of auroral charging events have been obtained from the DMSP and Freja spacecraft [Frohninckx and Sojka, 1992; Anderson, 2000, 2001; Wahlund et al, 1999; Erickson and Wahlund, 2005]. These studies show that auroral charging is most common during solar minimum and most commonly encountered in the midnight sector of the auroral oval.

Charging Analysis Tool

Quantitative information for the charging events is obtained using a software package that processes SSI records and allows users to extract time series of frame potential and charging rates along with maximum potential and the number of time intervals the potential exceeds a threshold value. The information is written to an external file for later analysis.

Example 2 keV charging event [Anderson, 2012]
Discussion and Summary

The examples shown here are the result of an initial effort to characterize extreme auroral charging events. These events are encountered infrequently by spacecraft in polar low Earth orbit but are the kind of event that drive spacecraft design. We have focused on the extreme potentials, duration the potentials exceed a threshold value, and mean potentials because the information needed by spacecraft designers for evaluating the response of the spacecraft to the charging environment. The events chosen for this study include the three worst case DMSP charging events reported by Frolov and Sofka [1992], the extreme DMSP charging event reported by Anderson [2012], three extreme charging events identified by Colson [2012] that are equal to or exceed the three worst Frolov and Sofka [1992] events, and finally five additional extreme charging events that range from ~0.5 V to 1.5 kV. Based on the selected charging events used for this study, we demonstrate that:

- Temporal variations of the spacecraft potential through a charging event are important since extreme potentials are generally only a subset of the charging event.
- Frame potentials may reach kilovolt levels in auroral charging environments, but the duration of charging at these most extreme levels is limited to periods of a few seconds to perhaps ten to fifteen seconds.
- Mean potentials over the period of a charging event never exceed a few hundred volts except for the 16 June 1995 event with a maximum potential of ~2 kV and mean of ~500 V. The frame potential exceeds 900 V for 14 seconds in this case, and
- Rise time of the spacecraft potential is rapid for the four examples, typically requiring less than ten seconds to reach the initial maximum potential value.

Future work is planned to extend the study to a wider range of charging events to more fully characterize the auroral charging environment.

Acknowledgements

DMSP SU/4 and SU/5 electrostatic analyzer records were obtained from the NOAA National Geophysical Data Center (NGDC), Operational Limit Scan images are from the NOAA Space Physics Interactive Data Resource (SPIDR) application. Magnetic Kp indices were obtained from NOAA NGDC. We thank Dr. William Dooig for providing his SU analysis software which forms the basis of the charging analysis tool.

References