Extreme Spacecraft Charging in Polar Low Earth Orbit

Andrew D. Colson  
Space Telescope Science Institute, Baltimore, MD

Joseph I. Minow  
NASA, Marshall Space Flight Center, Huntsville, AL

L. Neergaard Parker  
Jacobs Engineering, ESSA Group, MSFC, Huntsville, AL

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 (~105 kilo-electrons) 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 space system designer and to spacecraft operators. The goal of the presentation is to bridge the gap between science and design approaches to unknown how space weather impacts both spacecraft design and operations for vehicles on orbital trajectories that traverse auroral charging environments.

Charging Simulations

Surface Charging Physics

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

\[
\frac{dQ}{dt} = \dot{q} - (\Sigma_i + I_{s})
\]

where \(Q\) is the total charge and \(q\) the surface charge 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

\[
\begin{align*}
I_{\text{incident}} &= \frac{e \cdot \dot{Q}}{A} \\
I_{\text{secondary}} &= \frac{e \cdot \dot{Q}}{C} \\
I_{\text{conduction}} &= \frac{e \cdot \dot{Q}}{\sigma} \\
I_{\text{photoelectrons}} &= \frac{e \cdot \dot{Q}}{\tau}
\end{align*}
\]

where \(\dot{Q}\) is the current into the spacecraft, \(\dot{q}\) the charge input due to the environment, \(\Sigma_i\) the incident charge, \(I_{s}\) the surface charge, \(\sigma\) the conductivity, and \(\tau\) the lifetime of the photoelectrons.

Identification of Auroral Charging

Auroral charging is readily identified from the “ion line” signature that appears in ion electrositric analyzer records. Here, the ion line in the DMSP F9 satellite SSU/4 instrument ion record is the result of ambient low energy ions accelerated by the spacecraft potential from an initial energy \(E_i\) to a final energy \(E_f\) at \(V\) where \(q\) is the charge of the ion and \(\Phi\) the spacecraft surface potential in volts.

Charging Analysis Tool

Quantitative information for the charging events is obtained using a software package that processes SSU 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]
Future work is planned to extend the study to a wider range of charging environments. The examples shown here are the result of an initial effort to characterize extreme auroral charging events. These events are encountered infrequently, but the duration of charging at these potential levels is limited to periods of a few seconds to perhaps ten to fifteen seconds, and mean potentials over the period of a charging event never exceed a few hundred volts except for the 16 June 1999 event with a maximum potential of ~2 kV and mean of ~500 kV. The frame potential exceeds 900 V for 24 seconds in this case, and the rise time of the frame potential is rapid for the four examples, typically requiring less than ten seconds to reach the initial maximum potential value. Therefore, the examples shown here are the result of an initial effort to characterize extreme auroral charging events. These events are encountered infrequently, but the duration of charging at these potential levels is limited to periods of a few seconds to perhaps ten to fifteen seconds, and mean potentials over the period of a charging event never exceed a few hundred volts except for the 16 June 1999 event with a maximum potential of ~2 kV and mean of ~500 kV. The frame potential exceeds 900 V for 24 seconds in this case, and the rise time of the frame potential is rapid for the four examples, typically requiring less than ten seconds to reach the initial maximum potential value. Therefore, the examples shown here are the result of an initial effort to characterize extreme auroral charging events.

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 of charging events, 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 Frooninckx and Sojka [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 Frooninckx and Sojka [1992] events, and finally five additional extreme charging events that range from ~0.5 kV 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 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 1999 event with a maximum potential of ~2 kV and mean of ~500 kV. The frame potential exceeds 900 V for 24 seconds in this case, and the 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.

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References