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 are episodically exposed to environments characterized by a high flux of energetic (~1 to 10’s kilovolt) electrons in regions of very low background plasma density which is similar in some ways to the space weather conditions in geostationary orbit responsible for spacecraft charging to kilovolt levels. While it is well established that charging conditions in geostationary orbit are responsible for many anomalies and even spacecraft failures, to date there have been relatively few such reports due to charging in auroral environments. This presentation first reviews the physics of the space environment and its 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 and discuss how space weather impacts both spacecraft design and operations for vehicles on orbital trajectories that traverse auroral charging environments.
Space Weather Impacts on Spacecraft Design and Operations in Auroral Charging Environments

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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 are episodically exposed to environments characterized by a high flux of energetic (\(10^5\) to \(10^6\) keV) electrons in regions of very low background plasma density which is similar in some ways to the space weather conditions in geostationary orbit responsible for spacecraft charging to kilovolt levels. Analysis of DMSP and Freja spacecraft charging in auroral environments [Gussenhoven et al., 1983; Yeh et al., 1987; Frooninckx and Sojka, 1992; Anderson and Konr, 1996; Wahland et al., 1999] has shown that these conditions are required for charging to negative potentials exceeding 100 volts:

- Spacecraft in low altitude, high inclination (including sun-synchronous) orbits

- Integral electron flux \((\geq 10^5\) keV\)) exceeds \(10^7\) e/cm\(^2\)s-keV

- Ambient ion densities less than \(10^7\) ions/cm\(^3\)

These conditions are dominated by electrons at energies where secondary electron yields are too small to reduce the current collection and there is insufficient background plasma to balance the charging current density on the spacecraft surface. Dark conditions eliminate the photoemission currents which also serve to reduce the accumulating electron surface charge density.

The impact of auroral charging on space missions in a number of notable cases demonstrates that following standard spacecraft charging mitigation techniques is warranted when designing systems deployed for operation in auroral charging environments. Space weather is involved in the design process where it is important to know the duration, magnitude, and frequency of the most extreme auroral charging environments that must be considered for robust design.

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:

\[
\frac{dQ}{dt} = \sum I = \sigma \left( \frac{V}{A} \right) t + \sum ebs, si
\]

where \(Q\) is the total charge and \(\sigma\) 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 \(V\) (in importance to surface charging are:

- Incident ions
- Incident electrons
- Backscattered electrons
- Conduction currents
- Secondary electrons due to \(I_i\)
- Photons
- Active current sources (beams, thrusters)

Identification of Auroral Charging

Auroral charging is readily identified from the “ion line” signature that appears in ion electrostatic analyzer records. Here, the ion line in the DMSP F9 satellite SSJ/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 \(E_f\).

Low energy secondary electrons generated by impact of energetic primary electrons and ions are an important process controlling the sign and magnitude of the surface potential in auroral charging environments. Even the most intense auroral electron currents will charge conditions assume that if the collection angles are on the order of a few keVols, energies where the secondary electron yields exceed unity. Electron energies on the order of ten keVols are required for surface charging to large negative potentials.

Magnitude of Extreme Charging Events

Charging events exceeding a few hundred volts are a possible threat to spacecraft. An analysis of DMSP charging events by Frooninckx and Sojka [1992] showed charging events ranging from \(-60\) to \(-1400\) Volts with additional extreme events varying from \(-700\) to \(-900\) Volts with the most numerous and extreme events occurring during the solar minimum winter period of December 1986-January 1987. The events shown here from June 2011 are similar in magnitude to the worst case events reported by Frooninckx and Sojka but all occur during the ascending phase of the current solar cycle.

Extreme Durations for Charging Events

Extended exposure to auroral charging conditions doesn’t necessarily lead to extreme charging. Example (a) is the record duration charging event of nearly three minutes (maximum potential approximate \(-400\) Volts) reported by Anderson [2001]. Events (b) and (c) are two example charging events that exceed the maximum \(-60\) second duration charging events reported by Frooninckx and Sojka. The magnitude of the maximum potential -500 Volts in (b) and -162 Volts in (c).

Rise Time to Maximum Potential

The onset of frame charging is often a very rapid process requiring only a few seconds to reach the maximum potential. The temporal variations in the spacecraft potential through an individual charging event is therefore due to the variations in electron flux sampled by the spacecraft as it transits a region of auroral electron precipitation. Charging event (a) requires nearly 90 seconds to reach the maximum potential of \(-300\) Volts and is an example of a relatively slowly developing frame potential. In contrast, the events in spacecraft F16 transits to -660 Volts in only four seconds. Event (c) is an increase in spacecraft potential to over -1400 Volts in approximately four seconds. This is the largest DMSP charging event reporting in the Frooninckx and Sojka study.

Charging Only Occurs Over Some Fraction of the Auroral Oval Encounter

Fortunately, auroral charging is typically limited to restricted regions within the auroral oval during active substorms. While much of the nightside oval may be generated by precipitation of electrons at kilovolt energies, these electrons are too low in energy to drive strong auroral charging due to the secondary electron yields which exceed unity for most spacecraft materials at this energy. High flux of electrons accelerated to tens of keVols are required for the charging events and these are typically restricted to isolated regions of the auroral oval and only last for relatively short periods of time. High inclination orbits pass through the auroral oval each orbit while spacecraft in lower inclination orbits that normally do not intersect the quiet time auroral oval may only encounter auroral charging during strong substorms that drive the auroral equatorward to unusually low latitudes.

References


Spacecraft Exhibiting Auroral Charging

Frequency and Distribution of Auroral Charging

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All spacecraft in orbits that encounter auroral precipitation are susceptible to auroral charging, this includes all low Earth orbit satellites in sun-synchronous orbits as well as vehicles in high inclination orbits that encounter the auroral oval episodically during strong substorms. The opportunity to document charging is limited by the instrumentation on the spacecraft. (a), (b) Electrostatic analysers and (c) Langmuir probes are the most common instruments used to measure the effects of auroral charging.

Impacts to Low Earth Orbit, Polar Missions Attributed to Energetic Electrons

Charging Simulations

Discussion

Auroral charging is a potential threat to spacecraft traversing regions of auroral electron precipitation. The results presented here are derived from a review of published information on auroral charging and evaluation of additional data from the NOAA DMSP archives not included in the published studies. Additional kilovolt charging events on the same order of magnitude as the worst case events identified by Frömming and Sugita, 1992 were identified from June 2011, a period characterized by an ascending (or solar medium) phase of the current solar cycle. Since extreme events are occurring as we approach the next solar maximum it is possible that charging events may be observed through the next solar maximum, an event that has not been observed previously. These results suggest that more careful examination of the full DMSP data set is warranted to determine the full range of extreme auroral charging environments possible for use in spacecraft design.

Acknowledgements

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