HIGH LATITUDE PLASMA ELECTRODYNAMICS AND SPACECRAFT CHARGING IN LOW EARTH ORBIT

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Abstract

Charging events have occurred on the DMSP weather satellite and the Freja research satellite in low Earth orbit (over an altitude range of 800 km to 1800 km) with negative potentials of hundreds of volts to even kilovolts. Currently, estimates for severe charging of spacecraft in auroral environments at altitudes of 300-500 km with inclinations near 51 degrees (i.e. International Space Station and associated vehicles) are based on observations made with the DMSP satellites predicting relative probability of the vehicle encountering auroral precipitation and adoption of the severe charging environments. This paper presents analyses of the assumptions used in previous charging estimates for the International Space Station. Analyses show environments which produce extreme charging events on the DMSP and Freja satellites may be encountered by the Space Station; yet unfavorable conditions for extreme charging are most likely localized in space (high latitude and restricted longitude) and time (winter season near solstice) and operational problems are therefore easily avoided by space weather monitoring and modification of on-orbit activities if required.

1.0 Introduction

Negative potentials with magnitudes of hundreds of volts to a few kilovolts have been reported for the DMSP satellites (altitudes of approximately 830 km and orbital inclinations of 98 degrees) [*Gussenhoven et al.*, 1985; *Anderson and Koons*, 1996] and the Freja satellite (range of altitudes from 1000 km to 1756 km and an inclination of 63 degrees) [*Wahlund et al.*, 1999]. Analysis of charging events in the space environment showed that three conditions are typically required for negative potentials to exceed 100 volts. The spacecraft must be in eclipse, the kilovolt electron integral flux from the space environment must exceed 10^8 cm^{-2}s^{-1}sr^{-1}, and the ambient ion densities must be less than 10^3 to 10^4 cm^{-3} [*Gussenhoven et al.*, 1985; *Yeh et al.*, 1987; *Frooninckx and Sojka*, 1992; *Anderson and Koons*, 1996; *Wahlund et al.*, 1999]. The dominant auroral and ambient thermal electron currents to the spacecraft only can be balanced by the smaller ram ion and negligible (or non-existent) photoelectron currents from the spacecraft if the structure potential is a large negative value under these conditions. Statistical analyses of DMSP [*Frooninckx and Sojka*, 1992; *Anderson*, 1998] and Freja charging events [*Wahlund et al.*, 1999] show that the large negative potential events may occur at any local time, they always occur at high magnetic latitudes (>60°), and are most common in the pre-midnight sector between 18 MLT and 24 MLT. Results from *Anderson* [1999] are given in Figure 1 which include both northern and southern hemisphere events. The low Earth orbit charging events are most common in the winter hemisphere where the spacecraft experience eclipse conditions. These events occur more commonly during solar minimum when the ambient plasma densities are the lowest due to reduced solar photoionization of the neutral atmosphere.

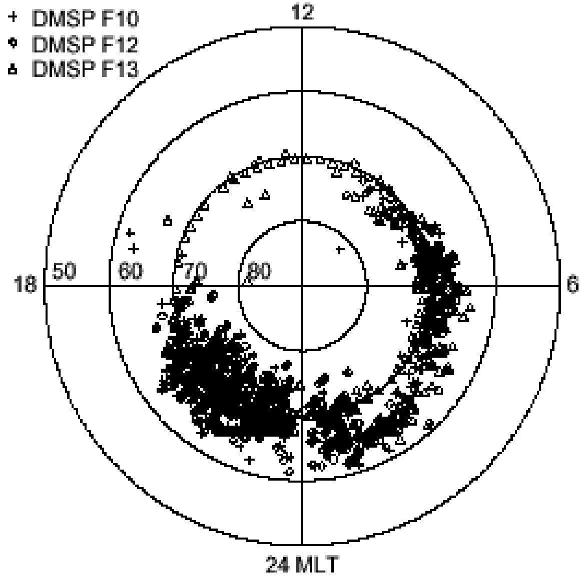

Figure 1. Distribution of DMSP low Earth orbit charging events in geomagnetic latitude and local time. DMSP altitudes are approximately 830 km, well above the 350 km to 450 km altitude range planned for the ISS. The highest magnetic latitudes sampled by the ISS will be approximately 62° in the northern hemisphere and 65° in the southern hemisphere [from *Anderson*, 1998].

Negative impacts of spacecraft charging on the International Space Station (ISS) are mitigated by the use of the plasma contactor device which provides an active method of discharging excess negative charge to space. A variety of different plasma environments have been adopted for analysis of the effect of charging on the spacecraft in the instance of failure or absence of a plasma contactor. For example, *Carruth et al.* [2001] recently evaluated the effects of charging on the ISS in the advent of a contactor failure. They considered only the thermal ionospheric plasma environments with a 10^6 cm^{-3} ambient ion density, a relatively more benign case than those responsible for the extreme charging events on the DMSP and Freja spacecraft at greater altitudes. In contrast, early studies of *Purvis et al.* [1994] adopted the DMSP severe charging environments as a “worst-case” to estimate the magnitude of ISS structure potentials during auroral encounters if a plasma contactor is not used to control the potential. While ambient ionosphere parameters are a good choice for long-term impact on a spacecraft, the choice of “worst-case” environments for use in charging calculations requires special consideration. Expensive solutions to charging problems that do not exist are the result of overestimating the severity of the environment. Underestimates of the worst conditions that may be encountered in an orbit are particularly dangerous and can lead to operations under hazardous conditions or even system failures.

Frooninckx and Sojka [1992] predicted that the severe charging environments encountered by DMSP and Freja at high altitudes may be present at altitudes as low as 300 km, consistent with the *Purvis et al.* choice as a worst-case design environment for charging studies. This paper determines if objects in ISS type orbits (51.6° inclination and altitudes of 350 km to 450 km) can encounter a space environment which causes negative spacecraft structure potentials in excess of 100 volts, like that experienced by the DMSP and Freja satellites.

2.0 Auroral Electron Flux

There are two primary mechanisms that will decrease the electron flux measured at a low altitude on a magnetic field line from the incident value measured on the same field line at a greater altitude. Scattering and absorption by the atmosphere alters the energy spectrum and reduces the total flux of the precipitating electrons. Mirroring of particles above the lower altitude will alter the initial pitch angle distribution and remove some fraction of the flux observed at the greater altitude.

Theoretical calculations of variations in the auroral electron energy flux due to interactions with the atmosphere over a range of altitudes are shown in Figure 2 [from *Min et al.*, 1993]. Changes to the incident energy spectrum at 800 km in Figure 2(a) are insignificant for energies greater than a few keV at 400 km altitude typical for the ISS. Collision cross sections for electron interactions with the atmosphere are strongly energy dependent and typically peak at energies of 1 to 100 eV (cf. *Rees*, 1989). The reduced atmospheric density and small interaction cross sections at keV (and particularly 10’s of keV) energies result in mean free paths greater than 100 km for altitudes above approximately 250 km. In Figure 2(b) the flux of 2 keV monoenergetic electrons is computed for a range of altitudes. Only at altitudes less than approximately 200 km does a flux decrease, due to atmospheric interactions, become significant. Electron interactions with the atmosphere at energies important to charging will not significantly reduce the electron flux from the values observed by DMSP or Freja at altitudes greater than 800 km over the operational altitude range of the Station.

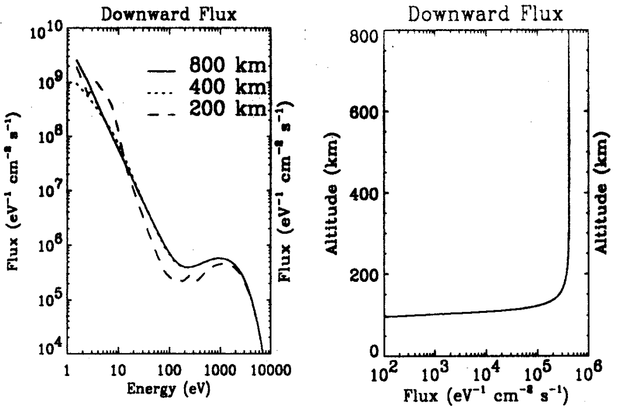

Figure 2. Auroral electron interaction with the atmosphere. Electrons are incident at 800 km with (a) changes in energy spectra shown for two altitudes, and (b) variations in 2 keV electron flux altitude [adapted from *Min et al.*, 1993].

Mirroring of some fraction of the electron population at altitudes greater than the ISS orbit, but below the DMSP or Freja altitudes, is not likely to be a significant process for reducing electron flux below the critical levels identified with the high-level charging events. For example, consider the 10^8 $cm^{-2}s^{-1}sr^{-1}$ flux threshold *Gussenhoven et al.* [1984] identified in the DMSP charging events with the SSJ/4 detectors. DMSP satellites are three-axis stabilized and the SSJ/4 detectors sample the local zenith with acceptance half angles of approximately 3° by 4°. Application of the first adiabatic invariant for particles with 4° pitch angles in a dipole field shows that DMSP observations of electron flux above the critical value for high-level charging at approximately 800 km altitude represents particles that mirror above 350 km (impacting the entire range of ISS altitudes) for all geomagnetic latitudes above approximately 58°. This value is conservative since pitch angle distributions for auroral electrons typically peak along the field line. DMSP observations of precipitating auroral electron flux on field lines with significant dip angles represent a lower bound to the actual flux at altitudes >800 km because the SSJ/4 detector will measure electrons with pitch angles greater than the field aligned component of the pitch angle distribution. Flux measurements in excess of the critical value in this case are still indicative of the presence of flux at ISS altitudes with intensities consistent with the DMSP charging events. In addition, DMSP observations of precipitating electrons show significant periods where the aurora moves equatorward of 60° magnetic latitude (or even to geomagnetic latitudes of 50° to 55°) for intervals of a day or longer [*Madden and Gussenhoven*, 1990]. Field aligned electron fluxes are present in these conditions over a range of latitudes sampled by the ISS.

Auroral electrons of a few to 10's of keV, that are indicated as the primary source of severe charging on the DMSP and Freja spacecrafts, will essentially be unaffected by the atmosphere at ISS altitudes. These same particles will mirror at or below the minimum ISS altitudes. Observations from DMSP or other spacecraft of energetic electron flux which have sufficient energy to result in high-level charging events at altitudes >800 km are directly applicable to the 350 km to 450 km altitudes at which the ISS operates.

3.0 Ionosphere Density

Frooninckx and Sojka [1992] used a Time-Dependent Ionospheric Model (TDIM) to demonstrate that reduced plasma densities, associated with DMSP charging events at 800 km in the winter hemisphere, result from plasma transport effects producing "polar holes" and ion "troughs" due to recombination of the plasma. High latitude holes form where plasma convection paths do not intersect the terminator allowing recombination of ions and electrons to reduce the density without the benefit of periodic replacement due to photoionization of the neutral atmosphere. The ion trough forms in the premidnight sector where the convection electric field produced by the solar wind interaction with the magnetosphere is oppositely directed from the terrestrial corotation electric field. Plasma stagnation where the ion drift velocity is low provides ample time for recombination to reduce the magnitude of the ion density.

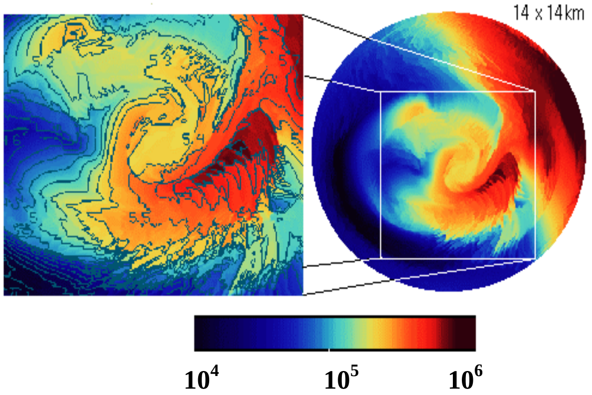

Figure 3. Example of ion density (cm^{-3}) at 290 km for geographic latitudes greater than 50° from UAF EPPIM for winter solstice conditions at 5 UT. Note presence of plasma "tongue" due to convection of plasma into the polar cap. Region of depleted plasma density in night sector is the ion trough. Minimum densities are approximately 10^4 cm^{-3} in this example. The expanded region on the left highlights the high resolution capability of the model [from *Maurits and Watkins*, 1996a].

Examples of the ion trough and variations in high latitude ion density due to convective electric field drifts of the plasma are shown in Figure 3 using results from a three-dimensional and time dependent Eulerian Parallel Polar Ionosphere Model (UAF EPPIM) developed at the University of Alaska [*Maurits and Watkins*, 1996b]. UAF EPPIM provides distributions of plasma density for geographic latitudes greater than 50° in the simulation results shown in figure 3 (although the code itself is implemented on a Cartesian grid that considers lower geographic latitudes). This model has the capability of providing real-time estimates of latitude, longitude, and altitude variations of the ambient plasma density in the vicinity of the pre-midnight sector for midwinter conditions over a geomagnetic latitude range of 50°-65° that are important to ISS. At the University of Alaska the UAF EPPIM code is run in real time and results are available on a public access web site:

http://www.arsc.edu/SpaceWeather

Real-time monitoring of extreme charging environments for high latitude segments of the ISS orbits can be implemented using the UAF EPPIM code. Parameters used to define auroral electron input, convection electric fields, geomagnetic activity, are all updated on a regular basis using solar wind plasma and magnetic field parameters obtained from the Advanced Composition Explorer satellite at L1 coupled with geomagnetic indices and other required environment data available from the National Oceanic and Atmospheric Administration's Space Environment Center.

Frooninckx and Sojka [1992] identified the high latitude polar hole and the ion trough as regions of particular importance to the DMSP charging events because ion density is further reduced from ambient nightside ionospheric values in this regions. Ambient ion densities as low as 10^3 cm^{-3} are predicted by TDIM for 300 km altitudes within the polar hole. The TIDM results are consistent with 10^2 to 10^3 cm^{-3} densities measured in

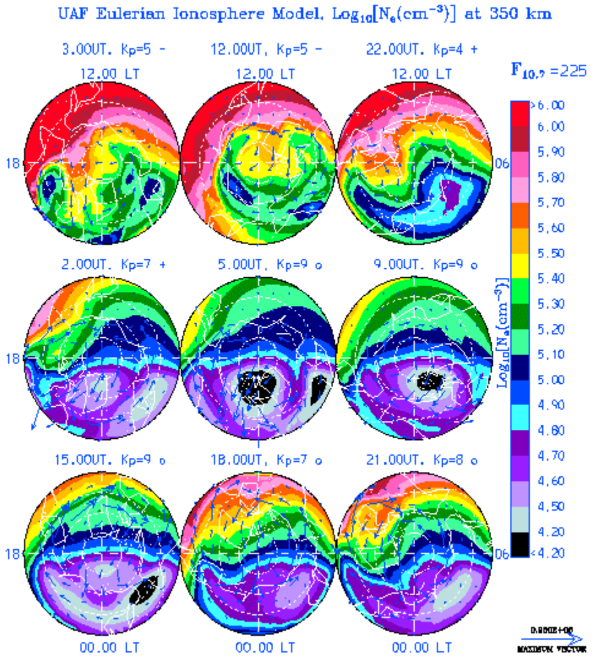

Figure 4. Selected UAF EPPIM electron densities at 350 km from a real time run for equinox conditions. Variations in the plasma convection and electron precipitation are due to diurnal variations of the convection electric fields as well as changes in geomagnetic conditions as indicated by the Kp index. Ion densities (=electron density) in the polar holes and troughs are approximately 10^4 $\mathrm{cm^{-3}}$.

situ by instruments on board the Atmosphere Explorer C (AE-C) satellite in the winter hemisphere for solar minimum conditions at 310±10 km [*Brinton et al*., 1978]. Statistical analysis of AE-C data shows that ion density may vary from values of 10^3 to 10^4 $\mathrm{cm^{-3}}$ in the pre-midnight ion trough region (between 60° and 70° magnetic latitude where the DMSP charging events are most common). Ion densities in the AE-C observations at 310 km are well below the reduced density criteria for low Earth orbit charging and confirm that time-dependent ion models predict realistic depleted densities in the high latitude regions where ISS will encounter auroral precipitation.

A series of electron densities at 350 km (the lowest altitude planned for ISS operations) from a UAF EPPIM run are given in Figure 4 to demonstrate the time dependence of ion density at high latitudes. Ion density is the same as the electron density since the model assumes quasi-neutrality over the entire simulation domain. The sun is at the top of each image where the ion densities are a maximum (local noon). Results are presented for selected times showing the ionospheric response to variations in geomagnetic activity, diurnal variations in the location of the geomagnetic pole relative to the Earth's rotation axis, and variations in electron precipitation. The minimum latitude of the geographic coordinate system is 50°. Near equinox conditions are present with the sunlit atmosphere extending to the geographic pole. The density over most of the night time region for these conditions is generally much greater than 10^4 $\mathrm{cm^{-3}}$, exceeding the density threshold for high level charging. However localized regions within the holes and troughs exhibit depleted densities, at or less, than 10^4 $\mathrm{cm^{-3}}$. Even at equinox there are regions where density depletions may be sufficiently large to provide the conditions necessary for high-level charging in low Earth orbit.

Ionospheric modeling [*Froonickx and Sojka*, 1992; this paper] and direct observations of ion density at 300 km by the AE-C satellite [*Brinton et al.*, 1978] demonstrate that depleted ion densities at altitudes greater than 800 km identified as important to high level low Earth orbit charging can also be found over the range of ISS altitudes. Indeed, typical values of ion density over most of the night time ionosphere for the winter hemisphere are 10^4 to 10^5 $\mathrm{cm^{-3}}$ and depletions within polar holes and troughs can be further reduced to levels well below that required for high level charging.

Rapid expansion of auroral precipitation equatorward into the ion trough during the substorm expansion phase is a good candidate for the kind of event that would explain the large number of charging events in the 18 MLT to 24 MLT sector between 60° and 75° magnetic latitude shown in Figure 1.

The UAF EPPIM code provides a useful method of predicting in advance possible charging conditions along the ISS orbit. Standard ionosphere models used for ISS analysis (IRI90, IRI95) are insufficient for this task because they do not include the important time dependent plasma transport and auroral effects.

4.0 Probabilities of ISS Auroral Encounters

Spacecraft in 50° to 60° inclination orbits are well known to encounter the aurora. For example, auroral observations from Salyut 4, Salyut 6, and Mir (all at 51.6° inclination) as well as passage of the spacecraft through the southern auroral oval are described by *Avakyan et al.* [1991]. The Space Shuttle has been placed in orbits with inclinations as high 57° where auroral observations have been made in both hemisphere. The ISS itself has already encountered the southern auroral oval on a number of occasions with observations of passing through auroral arcs reported by the crew.

Well before launch of the first ISS components, *Purvis et al*. [1994] estimated that ISS will make approximately 80 auroral encounters per year. The statistical analysis assumed the probability of an ISS orbit encountering the aurora is approximated by the fraction of the latitude circle with the same value as the inclination of the spacecraft orbit lies within the auroral oval. No attempt was made to consider diurnal variations of the auroral oval relative to instantaneous locations of the spacecraft since the probability of an orbit passing through its maximum latitude at a given local time was assumed to be equally probable for all local times. Geomagnetic activity was included by increasing the size of the auroral oval as a function of increasing Kp index. The technique is valid since the ISS orbit precession rate is once every 72 days and the spacecraft samples all local times at maximum latitudes during the course of a year.

An independent analysis [*B. Cooke*, 1996] used a more sophisticated technique to count individual orbits that intersect the auroral oval in the northern hemisphere as a function of geomagnetic activity (and doubled the result to obtain total encounter rates for both hemispheres). Results from this analysis for a period of eight years from solar minimum to solar max range varying from a minimum of 179 encounters per year to a maximum value of 302 per year. The average for all eight years was 235 auroral encounters per year of which 145 occur in eclipse conditions.

Neither the *Purvis et al.* nor *Cooke* study included analysis to validate the theoretical results. Work is currently underway at MSFC to validate the auroral crossing predictions using the DMSP midnight boundary index [*Madden and Gussenhoven*, 1990]. An anticipated result of this study will be a resolution to the discrepancy between the approximately 80 encounters per year predicted by *Purvis et al.* and over 200 per year in the *Cooke* results.

5.0 Wake Environments

Theoretical studies [*Al'pert*, 1990] and in situ observations [*Murphy et al*., 1986; *Reasoner et al*., 1986; *Murphy and Katz*, 1989; *Murphy et al*., 1989; *Tribble et al*., 1989] indicate that ambient plasma density in the wake of spacecraft may be reduced by factors of 10 to 100. Ion density over much of the night time regions shown in Figures 3 and 4 for example would be below the critical threshold and any auroral electron input would provide the appropriate conditions for high-level charging.

The maximum ambient plasma densities obtained by *Brinton et al.* [1978] at 300 km in the ion trough region where ISS is most likely to encounter depleted density environments was less than 10^4 cm^{-3}. Plasma density in spacecraft wakes under these conditions may be further depressed to values less than 10^3 cm^{-3} or even 10^2 cm^{-3} (well below the threshold identified in the DMSP and Freja studies for the onset of high-level spacecraft charging). Indeed, reductions of plasma densities by factors of 10 or 100 would reduce the minimum ion densities identified in the *Brinton et al*. results to such levels that the entire night-side high-latitude region could exhibit plasma densities consistent with low Earth orbit spacecraft charging. Even in the case of maximum densities, the wake effect would allow significant regions of the high latitude polar ionosphere to allow for charging. Auroral electrons penetrating this region lead to excessive negative current collection if the spacecraft or an object in the wake are in eclipse.

6.0 Summary and Conclusions

Satellites at altitudes as low as the ISS orbit may encounter space environments consistent with high-level spacecraft charging. Precipitating electron fluxes are not significantly altered by the atmosphere at altitudes above 200 km so that observations by DMSP or other spacecraft at altitudes above the ISS orbit may be adopted in ISS charging analyses. Ion density may be sufficiently depleted due to recombination on convective paths that do not encounter solar EUV illumination in the winter hemisphere to meet the density threshold identified as critical for charging of the DMSP and Freja spacecraft. The region where the strongest density depletions and energetic particle precipitation is most likely to be encountered by the ISS is the 18 MLT to 24 MLT sector. Finally, the plasma wake formed by the passage of the spacecraft through the ionosphere further reduces the ion density. Isolated dielectric materials in the wake side of the spacecraft may experience significant enhancements in charging in these conditions.

Impact to the ISS is not expected to be important as long as an operational plasma contactor removes the excess charge. In addition, excess free charge must be able to make it to the structure in order to be removed by the plasma contactor. Dielectrics and electrically isolated conductors may collect large amounts of charge in the auroral environment even with the contactors operating. Failure of the plasma contactor and resulting loss of potential control of the ISS could result in high level charging under hazardous conditions. Conditions favorable for extreme charging are localized in space (high latitude and restricted longitude) and time (winter season near solstice) for the ISS orbit and operational problems are therefore easily avoided by space weather monitoring and modification of on-orbit activities if required.

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