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, ESSSA 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 (~10's kilovolt) 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 ~2 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 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 charging environments.

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

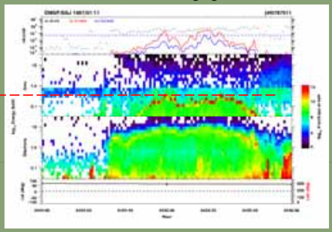
$$\frac{dQ}{dt} = \frac{d\sigma}{dt}A = C\frac{dV}{dt} = \sum_k I_k \approx 0 \text{ (at equilibrium)}$$

where Q is the total charge and σ 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 I(V) of importance to surface charging are

$\frac{dQ}{dt} = \sum_k I_k = +I_i(V)$	incident ions
$-I_e(V)$	incident electrons
$+I_{bs,e}(V)$	backscattered electrons
$+I_c(V)$	conduction currents
$+I_{se}(V)$	secondary electrons due to I_e
$+I_{si}(V)$	secondary electrons due to I_i
$+I_{ph,e}(V)$	photoelectrons
$+I_b(V)$	active current sources (beams, thrusters)

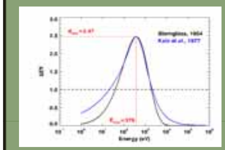
Identification of Auroral Charging

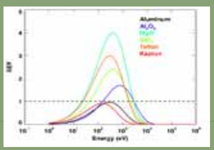
~ -300 Volts



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_0 ~ 0 eV to a final energy $E = E_0 + q\phi$ eV where q is the charge of the ion and ϕ the spacecraft surface potential in volts.

Secondary Electron Yield



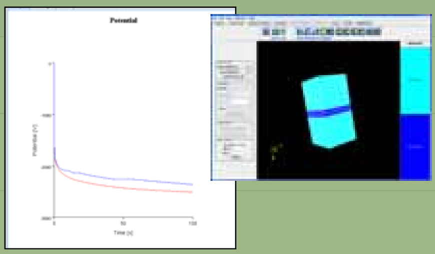


$$\delta_e(E,\theta) = \delta_{e,\max}\frac{E}{E_{\max}}\exp(2-2\sqrt{E/E_{\max}})\exp[2(1-\cos\theta)]$$ ***Sternglass*, 1954**

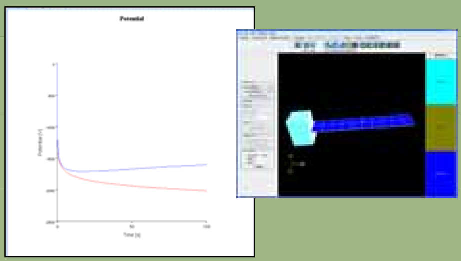
$$\delta_e(E,\theta) = \frac{1.114\delta_{e,\max}}{\cos\theta}\left[\frac{E}{E_{\max}}\right]^{0.35}\left\{1-\exp\left[-2.28\cos\theta\left[\frac{E_{\max}}{E}\right]^{1.35}\right]\right\}$$ ***Katz et al.*, 1977**; ***Whipple*, 1981**

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 spacecraft surfaces positive if the electron energies are on the order of a few kilovolts, energies where the secondary electron yields exceed unity. Electron energies on the order of ten kilovolts are required for surface charging to large negative potentials.

Charging Simulations



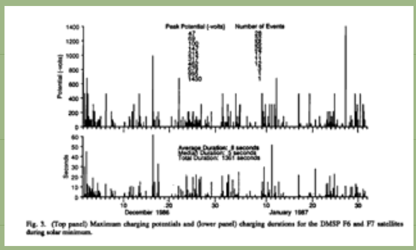
(a) 1 m x 1 m x 2 m in darkness
solar cells on aluminum



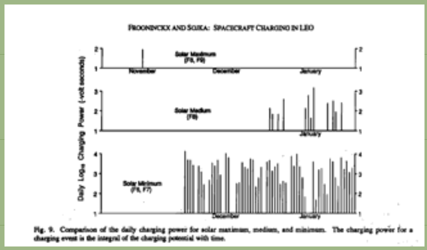
(b) Bus: 3m x 2 m x 2 m aluminum; Solar array: 2m x 10 m solar cells on Kapton; in darkness

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.

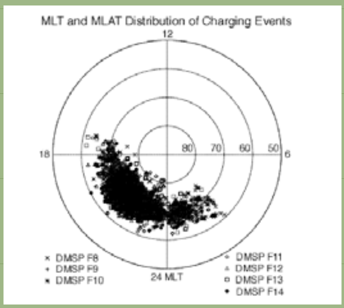
Frequency and Distribution of Auroral Charging



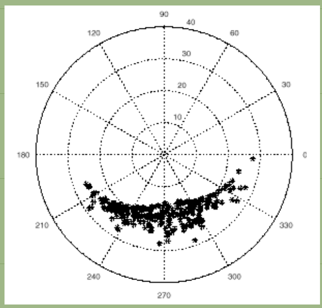
(a) DMSP Charging Frequency December 1986 – January 1987



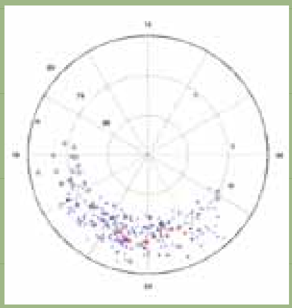
(b) Distribution of DMSP and Freja Charging Events



[Anderson, 2001]



[Wahlund et al. 1999]

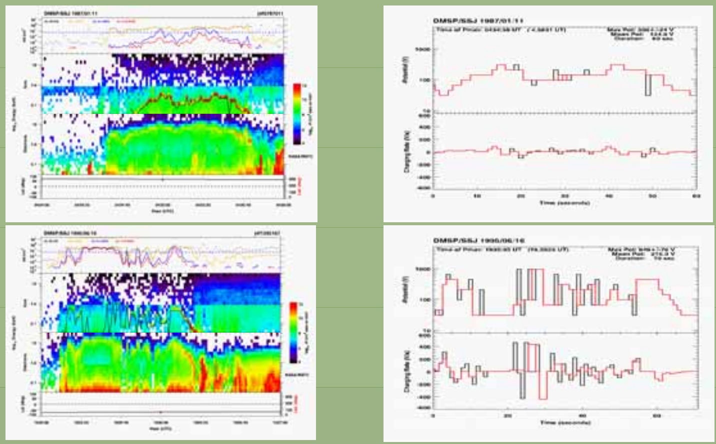


Blue <100 volts Red sunlight
[Ericksson and Wahlund, 2005]

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 [*Frooninckx and Sojka*,1992; *Anderson* 2000,2001; Wahlund et al. 1999; *Ericksson 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

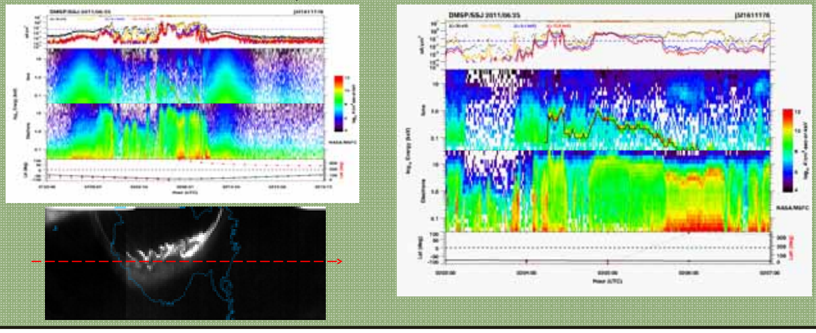
Quantitative information for the charging events is obtained using a software package that processes SSJ records and allows users to extract time series of frame potential and charging rates along with maximum potential and the number of time intervals the potential exceeds a threshold value. The information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



Example 2 keV charging event [*Anderson*, 2012]

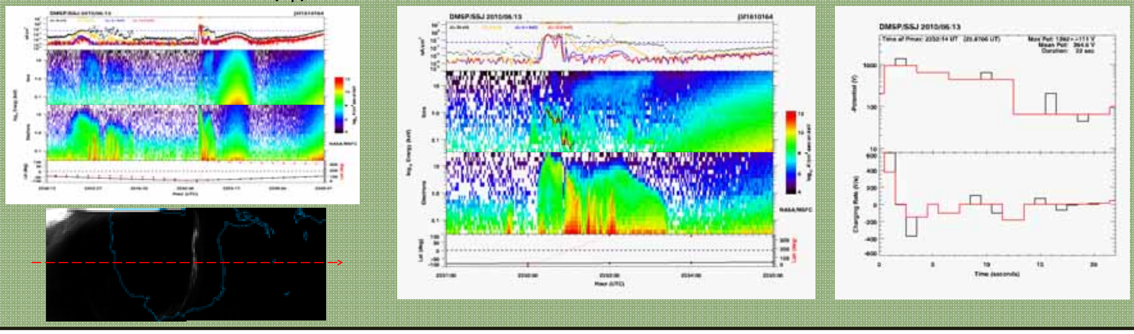
```
#-------------------DMSP Charging Event-----------------
# DMSP_CE_f07_1987-01-11_0434:59__300.txt
# Satellite: f07
# Date: 1987/01/11
# Data file: j4f0787011
#
#    Max V: 300 +/- 24 Volts     Mean V:   134.9 Volts
# Time Max V: 0434:59 UT   ( 4.5831 UT)
# Duration:    60 sec
#
# Time (sec) > V summary:
# >4 kV:          0
# > 3 kV:         0
# > 2 kV:         0
# > 1 kV:         0
# >900 V:         0
# >600 V:         0
# >400 V:         0
# >300 V:         0
# >200 V:        18
# >100 V:        34
# >  40 V:       56
#
# UT Hr  Seconds  Pot (V)  Rate (V/s)
#-----------------------------------------
  4.5789   0.0     65   -24.47
  4.5792   1.0     44   -17.50
  4.5794   2.0     30    -7.01
          ----------------
  4.5825  13.0    139    32.47
  4.5828  14.0    204    80.53
  4.5831  15.0    300    48.09
  4.5833  16.0    300   -48.09
  4.5836  17.0    204   -48.09
  4.5839  18.0    204    48.09
  4.5842  19.0    300     0.16
  4.5844  20.0    204  -102.52
  4.5847  21.0     95   -54.60
  4.5850  22.0     95   -15.03
  4.5853  23.0     65    -0.05
          ----------------
  4.5950  58.0     44    -6.99
  4.5953  59.0     30    -6.99
  4.5956  60.0     30     6.99
#-----------------------------------------
```

Event 1: DMSP F16 25 June 2011 |-ϕ| ~ 950 Volts



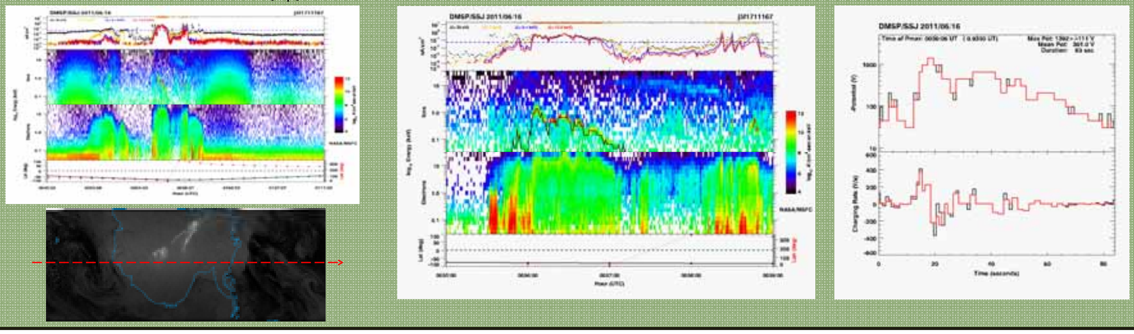
```
#--------------------DMSP Charging Event---------------
# DMSP_CE_f16_2011-06-25_0204:25__949.txt
#Satellite: f16
#   Date: 2011/06/25
#Data file: j5f1611176
#
#   Max V: 949 +/- 76 Volts
#   Mean V: 234.9 Volts
#Time Max V: 0204:25 UT   ( 2.0736 UT)
# Duration:  115 sec
#
# Time (sec) > V summary:
# > 4 kV:      0 sec
# > 3 kV:      0
# > 2 kV:      0
# > 1 kV:      0
# >900 V:      4
# >600 V:      12
# >400 V:      28
# >300 V:      28
# >200 V:      57
# >100 V:      69
# > 40 V:      105
#
```

Event 2: DMSP F16 13 June 2010 |-ϕ| ~ 1400 Volts



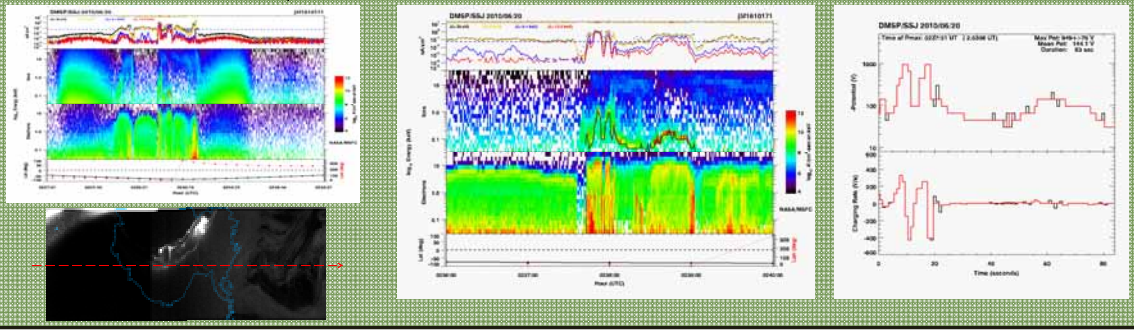
```
#--------------------DMSP Charging Event---------------
# DMSP_CE_f16_2010-06-13_2252:14__1392.txt
#Satellite: f16
#   Date: 2010/06/13
#Data file: j5f1610164
#
#   Max V: 1392 +/- 111 Volts
#   Mean V: 394.6 Volts
#Time Max V: 2252:14 UT   (22.8706 UT)
# Duration:  22 sec
#
# Time (sec) > V summary:
# > 4 kV:      0 sec
# > 3 kV:      0
# > 2 kV:      0
# > 1 kV:      1
# >900 V:      3
# >600 V:      7
# >400 V:      12
# >300 V:      12
# >200 V:      14
# >100 V:      14
# > 40 V:      23
#
```

Event 3: DMSP F17 16 June 2011 |-ϕ| ~ 1400 Volts



```
# --------------------DMSP Charging Event---------------
# DMSP_CE_f17_2011-06-16_0056:06__1392.txt
#Satellite: f17
#   Date: 2011/06/16
#Data file: j5f1711167
#
#   Max V: 1392 +/- 111 Volts
#   Mean V: 301.0 Volts
#Time Max V: 0056:06 UT   ( 0.9350 UT)
# Duration:  83 sec
#
# Time (sec) > V summary:
# > 4 kV:      0 sec
# > 3 kV:      0
# > 2 kV:      0
# > 1 kV:      2
# >900 V:      6
# >600 V:      16
# >400 V:      29
# >300 V:      29
# >200 V:      45
# >100 V:      56
# > 40 V:      78
#
```

Event 4: DMSP F16 20 June 2010 |-ϕ| ~ 950 Volts



```
#--------------------DMSP Charging Event---------------
# DMSP_CE_f16_2010-06-20_0237:51__949.txt
#Satellite: f16
#   Date: 2010/06/20
#Data file: j5f1610171
#
#   Max V: 949 +/- 76 Volts
#   Mean V: 144.1 Volts
#Time Max V: 0237:51 UT   ( 2.6308 UT)
# Duration:  83 sec
#
# Time (sec) > V summary:
# > 4 kV:      0 sec
# > 3 kV:      0
# > 2 kV:      0
# > 1 kV:      0
# >900 V:      4
# >600 V:      5
# >400 V:      8
# >300 V:      8
# >200 V:      11
# >100 V:      23
# > 40 V:      79
#
```

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 *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 ~0.6 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 most extreme levels are 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 kV. 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.

Satellite	Date	Φmax (volts)	<Φ > (volts)	Duration (sec)				Kp	Notes
				>900 V	>400 V	>100V	Event		
F7	16 Dec 1986	-646 ± 52	93.2	0	2	7	37	2.0	Frooninckx and Sojka, 1992 (FS 92 reports -949 V)
F7	27 Jan 1987	-1430	---	---	---	---	---	2.7	Frooninckx and Sojka, 1992 (no data, value from FS 92)
F6	1 Dec 1986	-646 ± 52	131.9	0	2	29	58	1.7	Frooninckx and Sojka, 1992
F12	16 Jun 1995	-2040 ± 163	537.1	14	31	52	64	4.0	Anderson, 2012
F16	1 Jun 2011	-949 ± 76	116.6	1	4	17	54	2.7	Colson, 2011
F16	25 Jun 2011	-949 ± 76	234.9	4	28	69	115	2.0	Colson, 2011
F17	16 Jun 2011	-1392 ± 111	301.0	6	29	56	83	1.0	Colson, 2011
F16	16 Jul 2012	-949 ± 76	240.6	6	38	108	174	2.7	This work
F17	16 Jul 2012	-646 ± 52	239.5	0	28	91	136	2.7	This work
F16	13 Jun 2010	-1392 ± 111	394.6	3	12	14	22	1.7	This work
F16	20 Jun 2010	-949 ± 76	144.1	4	8	23	83	0.3	This work
F16	27 Jun 2010	-646 ± 52	113.2	0	4	13	58	3.0	This work

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

References

Anderson, P.C., Surface charging in the auroral zone on the DMSP spacecraft, 6th SCTC, AFRL-VS-TR-20001578, 2000.

Anderson, P.C., A survey of spacecraft charging events on the DMSP spacecraft in LEO, 7th SCTC, ESA SP-476, 2001.

Anderson, P.C., Characteristics of spacecraft charging in low Earth orbit, JGR, VOL. 117, A07308, doi:10.1029/2011JA016875, 2012.

Colson, A., DMSP spacecraft charging in auroral environments, NASA USRP-Internship Final Report, MSFC, 5 Dec 2011.

Frooninckx, T.B., and J.J. Sojka, Solar cycle dependence of spacecraft charging in low earth orbit, *JGR, 97, 2985 – 2996, 1992.*

Katz et al., A three-dimensional dynamic study of electrostaticc hargingi n materials, NASA CR-135256, S–Cubed Rep. SSS-R-77-3367, NASA, 1977.

Sternglass, E.J., Theory of secondary electron emission, Phys. Rev., 95, 345, 1954.

Wahlund et al., Analysis of Freja Charging Events: Statistical Occurrence of Charging Events, SPEE-WP130-TN (Version 2.0), European Space Agency, 1999.

Whipple, E.C., Potentials of surfaces in space, Rep. Progress Phys., 44, 1197, 1981.