DMSP Spacecraft Charging in Auroral Environments

Andrew Colson

Marshall Space Flight Center

December 5, 2011

Reviewed by NASA Mentor
Dr. Joseph Minow
EV44 – Natural Environments Branch

Signature Here

DMSP Spacecraft Charging in Auroral Environments

Andrew D. Colson [1]
Florida Institute of Technology, Melbourne, FL 32901

The Defense Meteorological Satellite Program (DMSP) spacecraft are a series of low-earth orbit (LEO) satellites whose mission is to observe the space environment using the precipitating energetic particle spectrometer (SSJ/4-5). DMSP satellites fly in a geosynchronous orbit at ~840 km altitude which passes through Earth's ionosphere. The ionosphere is a region of partially ionized gas (plasma) formed by the photoionization of neutral atoms and molecules in the upper atmosphere of Earth. For satellites in LEO, such as DMSP, the plasma density is usually high and the main contributors to the currents to the spacecraft are the precipitating auroral electrons and ions from the magnetosphere as well as the cold plasma that constitutes the ionosphere. It is important to understand how the ionosphere and auroral electrons can accumulate surface charges on satellites because spacecraft charging has been the cause of a number of significant anomalies for on-board instrumentation on high altitude spacecraft. These range from limiting the sensitivity of measurements to instrument malfunction depending on the magnitude of the potential difference over the spacecraft surface. Interactive Data Language (IDL) software was developed to process SSJ/4-5 electron and ion data and to create a spectrogram of the particles' number and energy fluxes. The purpose of this study is to identify DMSP spacecraft charging events and to present a preliminary statistical analysis.

Nomenclature

DMSP	=	Defense Meteorological Satellite Program
LEO	=	Low Earth Orbit
SSJ/4-5	=	Precipitating Energetic Particle Spectrometer
IDL	=	Interactive Data Language
JAXA	=	Japan Aerospace Exploration Agency
ADEOS	=	Advance Earth Orbiting Satellite
DoD	=	Department of Defense
SSIES	=	Special Set of for Ions, Electrons, and Scintillation
SSM	=	Special Sensor Magnetometer
ESM	=	Equipment Support Module
NOAA	=	National Oceanic and Atmospheric Association
NGDC	=	National Geophysical Data Center

I. Introduction

Before the space age began, it was realized that space was not empty. Comet tails, meteors, and other extraterrestrial phenomena demonstrated the presence of a space environment. Much as an aircraft operates in and interacts with the atmosphere, a spacecraft operates in and interacts with this space environment. The space environment, however, can limit the operation of the spacecraft and in extreme conditions lead to its loss. Concern over these adverse environmental effects has created a new technical discipline and research area: spacecraft charging in auroral environments.

Spacecraft charging has been the cause of a number of significant anomalies and problems for on-board instrumentation on high altitude spacecraft. These range from limiting the sensitivity of measurements to instrument malfunction depending on the magnitude of the potential difference over the spacecraft surface. One prime example is the loss of the Japan's Aerospace Exploration Agency (JAXA) Advanced Earth Observing Satellite 2 (ADEOS-II). On October 23, 2003, the solar electrical power system failed and the satellite switched to "light load" operation due to an unknown error. At 2355 UTC, communications between the satellite and the ground stations terminated

[1]NASA Intern, EV-44 Natural Environments Branch, Marshall Space Flight Center, Huntsville, AL, 35812.

and further attempts to procure telemetry data failed. After a thorough investigation, JAXA determined that the total loss of ADEOS-II was due to a bus voltage of fifty volts, contributed by the interaction between the plasma environment and the multi-layer insulation.

Concern about these occurrences has led to a number of investigations entirely devoted to the study of spacecraft in high-earth orbit. However, little effort has been devoted to the study of high-level charging in LEO due to the rarity of its occurrence. Due to this fact, the results in this paper represent an on-going statistical analysis of DMSP spacecraft charging events.

II. DMSP Background

DMSP is a long-term satellite program designed to monitor the meteorological, oceanographic, and solar-geophysical environment of the Earth in support of Department of Defense (DoD) operations. The spacecraft are a series of low-altitude, polar-orbiting satellites, which fly in a sun-synchronous, ~99 degree inclination orbit at ~840 km altitude with orbital periods of ~101 minutes. Their mission is to observe the space environment using a set of three instruments: the special set for ions, electrons, and scintillation (SSIES), the SSJ/4-5, and the special sensor magnetometer (SSM). Each satellite is designated with the letter F, followed by its respective spacecraft number. F16, F17, and F18 are the only currently operational DMSP satellites. F19 and F20 will be the last of the DMSP satellites and are scheduled for launch in 2011 and 2013, respectively. This study is primarily focused on SSJ/4-5 data from F16, F17, and F18.

The DMSP spacecraft consist of a honeycomb aluminum five-sided equipment support module (ESM) with the solar array at one end and a precision mounting platform at the other. The ESM is covered with thermal blankets and pinwheel thermal louvers are used on all but the side facing the Earth. The thermal blankets covering the top surfaces of the spacecraft consist of 22 layers of dielectric material; each layer is aluminized on both sides while the outer Teflon layer is only aluminized on the side facing the spacecraft. Since the intermediate layers of the thermal blankets are not grounded to the spacecraft frame, the aluminized coatings serve as the plates of a set of 22 parallel-plate capacitors in series. The top plate consists of electrons buried on the top few microns of the Teflon and the bottom plate is the layer of aluminum which is in contact with the spacecraft frame. The total calculated capacitance of the blankets is $7.3 \times 10^{-9}\ Fm^{-2}$.

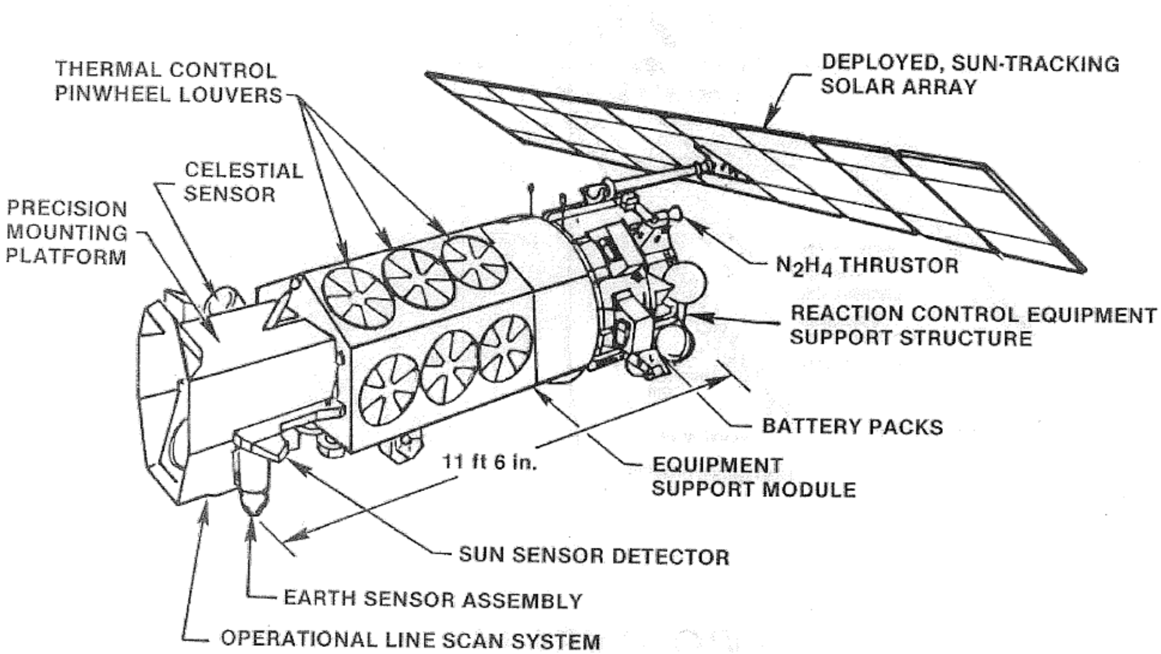

Figure 1. DMSP Diagram.

The SSJ/4-5 instrument measures the flux of precipitating electrons and ions having energies between 30 eV and 30 keV. A detector consists of four curved plate electrostatic analyzers arranged in two pairs; one pair measures electrons while the second measures ions. The detectors' apertures always face radially outward from the Earth, so only precipitating particles rather than the ambient or backscattered particles are measured at high magnetic latitudes. One electron analyzer covers the energy range from 30 to 1 keV via 10 channels with a geomagnetic factor of $2.2 \times 10^{-4}\ cm^2 sr$ and a *ΔE/E* of 9.8%. The other electron analyzer covers the energy range from 1 to 30 keV via 10 channels with a geomagnetic factor of $8.7 \times 10^{-4}\ cm^2 sr$ and a *ΔE/E* of 9.3%. The corresponding analyzers for ions have geometric facts of $3.2 \times 10^{-2}\ cm^2 sr$ and $8.6 \times 10^{-4}\ cm^2 sr$, respectively, and a *ΔE/E* of 9.8% and 9.3%, respectively.

III. The Space Plasma Environment

In LEO, the solar ultraviolet ionizes the ambient oxygen and nitrogen atoms, producing plasma. Since the LEO plasma is produced when the solar ultraviolet ionizes ambient neutrals, the plasma density is seen to vary both with local time and with solar cycle. Normally, the colder plasma found at lower altitudes is incapable of inducing significant charging. However, because energetic particles may move along the magnetic field lines, spacecraft in low-altitude polar orbits, such as DMSP, may encounter the more energetic plasma that is seen to originate at higher altitudes. In situ observations confirm that auroral electrons can be accelerated to several kilovolts, producing a plasma environment capable of more severe charging. This energetic plasma is confined to an annular region near the poles, in the region where the magnetic field lines enter the lower altitudes. Since a spacecraft will only pass through this region periodically during the course of its orbit, charging in the auroral regions is typically of very short of duration. Sever charging is more likely when the ambient plasma density is lower because the presences of the low-energy ambient plasma acts as a source of neutralizing current.

IV. Charging Background

The potential of a body in space determined by a balance between various charging currents. The most important are transfer of charge from plasma particles and secondary electron emission. The currents are affected by the body's charge and motion and by local magnetic and electric fields. Dielectric surfaces may have surface potential gradients which can affect the current balance through the creation of potential barriers.

An orbiting spacecraft, such as DMSP, is immersed in plasma that consists of free electrons and ions. These particles impinge on the spacecraft surface and therefore constitute negative and positive currents to the spacecraft. Other current sources include precipitating energetic electrons and ions, photoelectrons kicked off the spacecraft by ultraviolet photons from the Sun, and secondary electrons produced by energetic particle impact with the spacecraft surface. In LEO, the plasma density is usually high and the main contributors to these currents are the thermal electrons and ions that constitute the ionosphere. Because the electron thermal velocity is much larger than the thermal velocity of ions, the electron flux to the spacecraft is much larger than the ion flux, and the spacecraft charges to some negative potential. However, when the plasma density is very low, the contribution to the currents to the spacecraft from other sources can become very important. In fact, the spacecraft can charge to high negative voltages during times when the plasma density is very low and the flux of energetic particles is very high. A negatively charged spacecraft has an increased drag in the Earth's ionosphere because of its larger cross section for momentum transfer to positive ions.

Charging events are identified using the ion portion of the SSJ/4-5 detector. The sensor aperture is grounded to the spacecraft frames so that when the frame charges to some large voltage, the ambient thermal ions (which have energies less than 1 eV) are accelerated to the spacecraft frame voltage as they pass through the plasma sheath in front of the aperture. Therefore, a large flux is observed in the ion channel with energy range spanning the frame voltage, generally a much larger flux than from the ambient precipitating ions and thus easily identifiable. This "ion line" charging signature is widely used to document spacecraft charging using data from electrostatic analyzers on satellites in both low Earth orbit auroral environments and geostationary orbit.

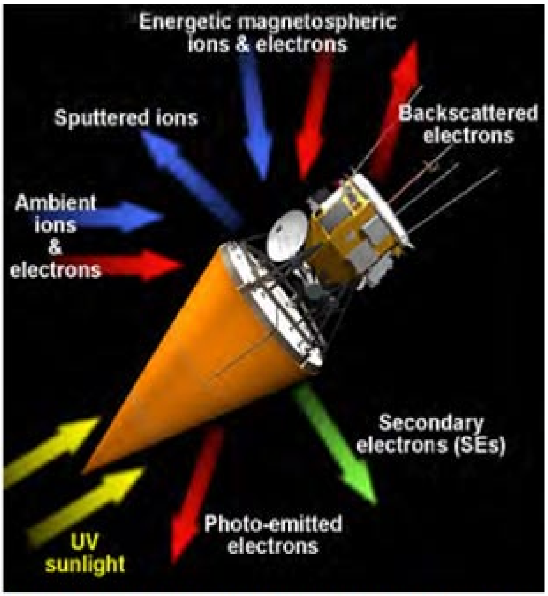

Figure 2. Illustration of the current balance equation.

In summary, spacecraft charging refers to the effects of physical processes that produce an electrical potential or voltage difference between the spacecraft conducting structure and the surrounding space environment, as in absolute charging. Additionally, spacecraft charging is seen as the effects of processes that produce voltage differences between electrically isolated parts of the spacecraft, as in differential charging. The accumulation of charge on spacecraft and its components is described and quantified using the current balance equation.

$$J_e + J_{ion} + J_{pe} + J_{sec} + J_{back} + J_{art} = C\frac{dV}{dt} = 0 \quad (1)$$

Equation (1) shows that the spacecraft charges to the voltage at which all of the currents balance to zero at equilibrium, where J_e and J_{ion} represent the currents from external plasma electrons and ions, J_{pe} is the net photoelectron current, J_{sec} is the net current due to secondary electrons, J_{back} is the backscattered current from electrons, and J_{art} is a possible artificial current due to current sources on the spacecraft. The spacecraft capacitance C is important to the rate of change of the spacecraft voltage V as a function of time t before the currents balance at equilibrium.

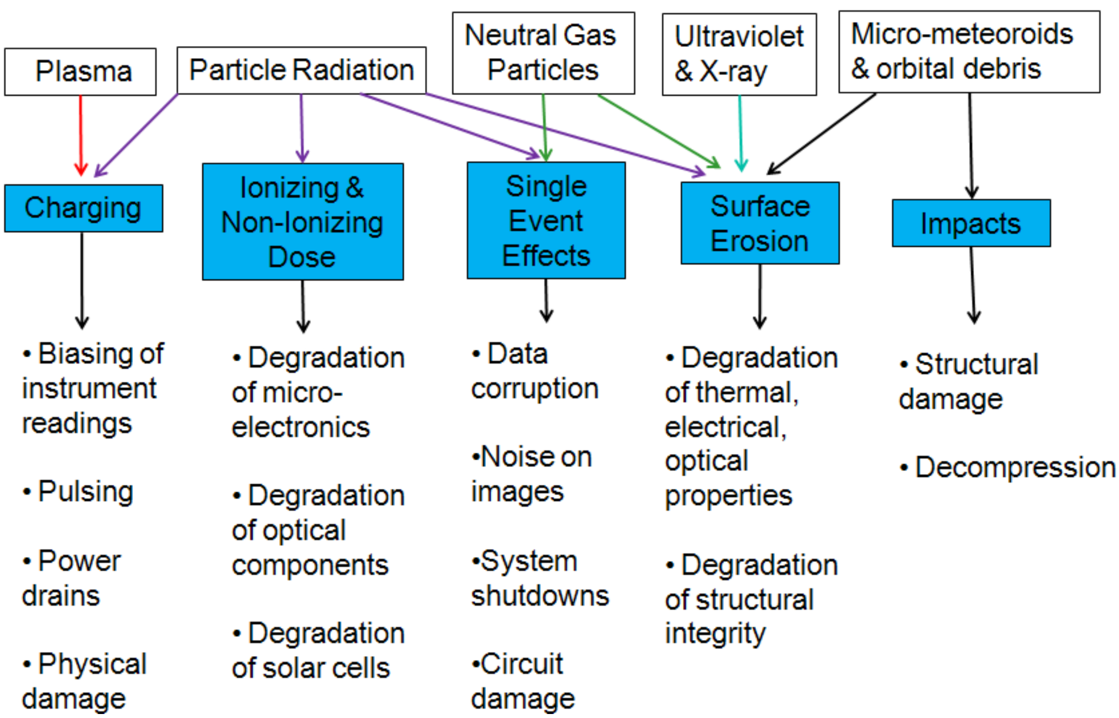

Figure 3. Effects of spacecraft charging and space environments. *As previously mentioned, spacecraft charging can ultimately lead to the loss of a satellite such as ADEOS-II. This figure outlines the variety of effects observed by spacecraft due to the space environment including the effects of spacecraft charging [adapted from J. Barth/GSFC].*

V. Early Studies of DMSP Charging

Even before the loss of ADEOS-II, spacecraft charging has been an area of research interest. The first report of DMSP charging by Gussenhoven[1] et al. (1985) documented 9 events in 1983 where DMSP charged to negative potentials over 100 Volts. The maximum charging level was -680 Volts. The study indicated the requirements for charging were: a) the current density be greater than ~$10^{-1} nA\ cm^{-2}$, and b) the integral number flux of electrons over 14 keV exceed $10^{8} cm^{-2} s^{-1} sr^{-1}$. These requirements have been adopted by other studies, including the results published in this paper, for identifying charging events.

More recently, Frooninckx[2] and Sojka[2] (1992) surveyed data from the DMSP satellites F6, F7, F8, and F9 over a multi year period. One hundred eighty-four charging events from -46 to -1430 Volts were identified. They observed that over a solar cycle, the most variable factor determining charging was not the energetic fluxes shown to generate charging, but rather, a solar cycle dependent variation in plasma density. Solar minimum conditions generated charging more frequently and with greater magnitude, die to a lower ionospheric plasma density at solar minimum.

Anderson[3] and Koons[3] (1996) reported what is the apparently the first observed anomaly associated with charging in the aurora. On May 5, 1995, the DMSP F13 satellite encountered a charging environment. Seconds after the spacecraft frame began charging,, the SSM instrument experienced a lockup of its processor. Their analysis showed peak frame potential during the episode was ~ -460 Volt and that all of the conditions proposed by Gussenhoven were satisfied.

VI. Results and Analysis

To identify charging events, IDL code was adopted from the National Oceanic and Atmospheric Association (NOAA) and modified to process SSJ data and to plot the current density, a spectrograph of the particles' number and energy fluxes, as well as the spacecraft's latitude and longitude. SSJ data was downloaded from the National Geophysical Data Center (NGDC) [4]. Figure 4 shows the resulting graphs for DMSP F16 SSJ data from May 4th, 2010.

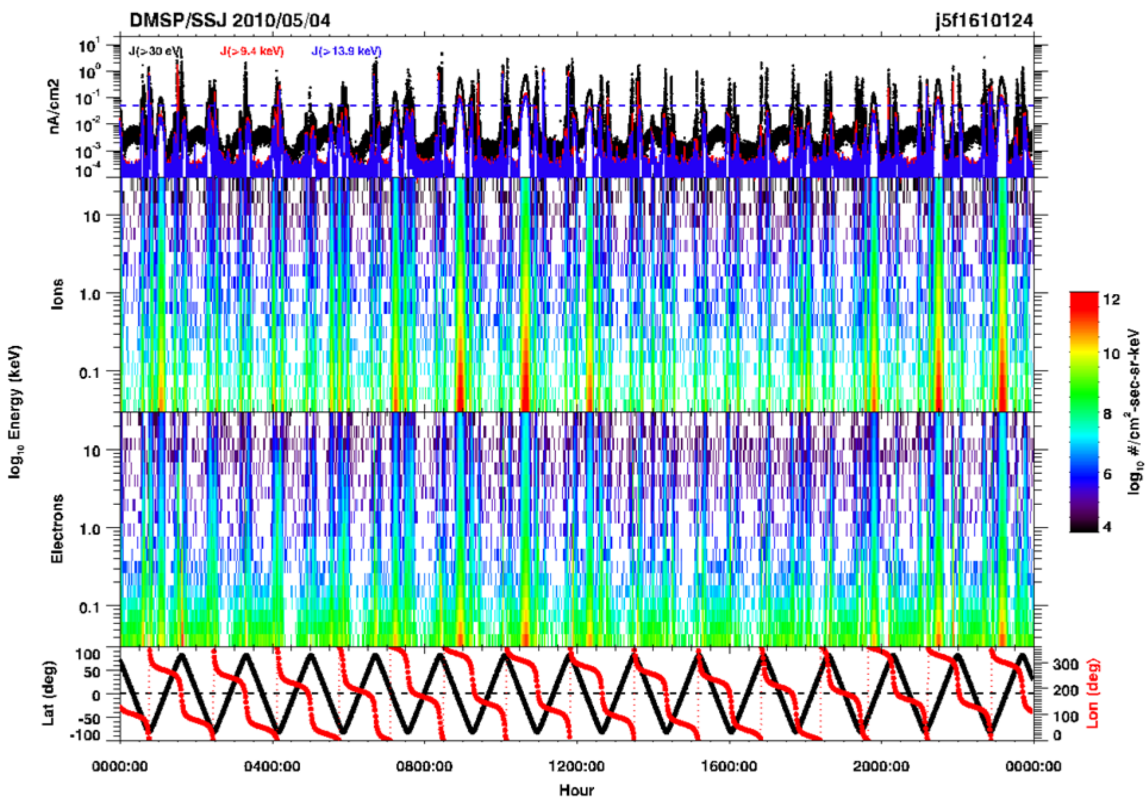

Figure 4. The current density, electron and ion fluxes, and coordinates of DMSP.

As illustrated in Fig 4, the top panel displays the current density for electrons with energies greater than 9.4 *keV*, 13.9 *keV*, and 30 *V* in red, blue, and black line colors, respectively. The >30 eV current density provides an estimate of the total electron flux measured by the SSJ instrument while the >9.4 keV and >13.9 keV current densities characterize electron flux at energies responsible for auroral charging. The blue dashed line represents the threshold level at which electrons greater than 13.9 *keV* must surpass to be considered a charging event. The second and third panels are spectrographs of the ion and electron fluxes. Finally, the bottom panel plots the latitude and longitude of DMSP. Each pixel in the ion and electron spectrographs represents one second of time. Therefore, there are 86,400 pixels to represent 86,400 days in the full 24 hour spectrograph. Gray colored pixels are time periods when the SSJ detector did not record data, which are not to be confused with time periods where the flux values are zero, or white colored pixels.

Charging events were identified as such by searching for the "ion line" signature during periods when the electron environment followed the criteria used in previous DMSP studies by Gussenhoven. If potential events did not satisfy all criteria, they were not documented in this report. One option in the spectrograph program is for the user to select a specific time period to analyze data. In this study, time periods were analyzed in two hour increments. This method ensured that no potential charging events were overlooked. Figure 5 clearly shows a DMSP F16 charging event from May 4th, 2010.

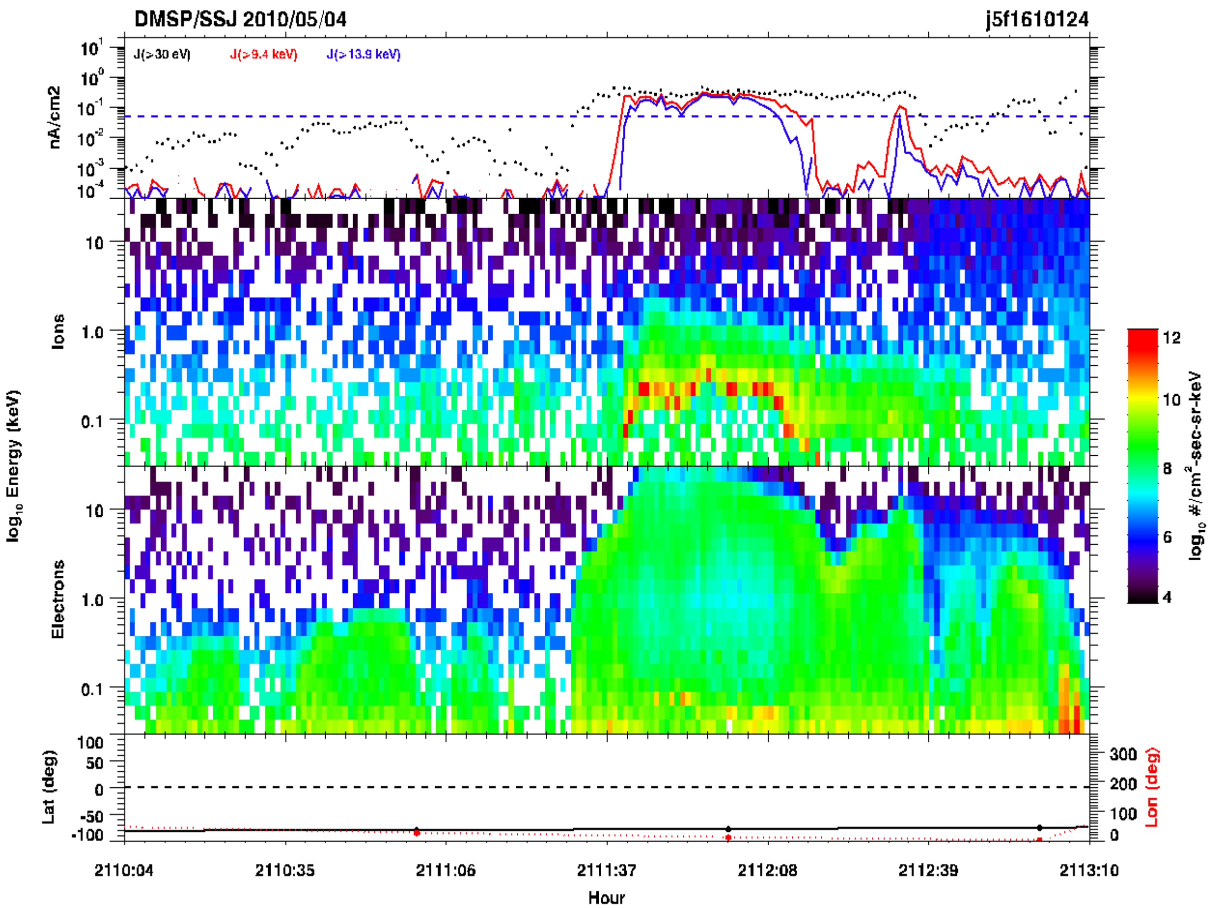

Figure 5. A clear charging event on DMSP F16 from 2010/05/04. *The maximum negative potential is approximately -320 volts derived from the maximum 0.320 keV ion energy in the "ion line" signature between 2111:37 UT and 2112:23 UT.*

The charging event in Fig 5. clearly has the shape of an arc or hook. Furthermore, the current density exceeds the Gussenhoven threshold level for the entire duration of the charging event. In addition to meeting the current density criteria, the integral number flux of electrons over 14 keV exceeds $10^8 cm^{-2} s^{-1} sr^{-1}$, as seen in Fig. 6. In summary, this particular charging event is 31 seconds long and the spacecraft voltage ranges from -68.7 to -320 Volts based on the variation on ion energy from 68.7 to 320 eV in the "ion line" signature in the ion record.

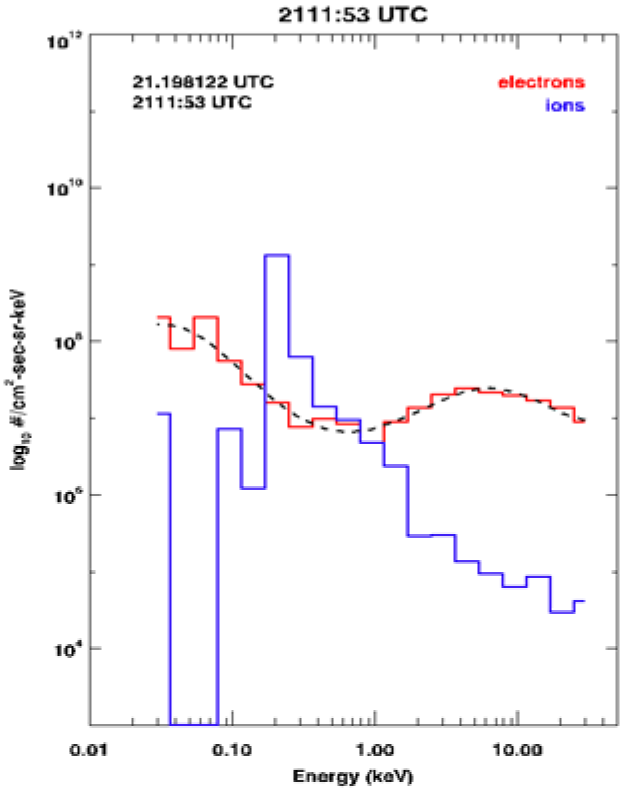

Figure 6. Spectra of the energy flux for the 2010/05/04 charging event.

Using this methodology and criteria for identifying charging events, this study presents the charging events from June, 2011 across DMSP F16, F17, and F18. The month of June was selected for this study because of its high geomagnetic activity as recorded by the hemispheric power index. Table 1 summarizes identified charging events from June of 2011 and a full list of the events is included in Appendix A.

June 2011	F16	F17	F18
Number of Events	17	6	7
Longest Duration (seconds)	58	36	71
Average Duration (seconds)	20.9	14.8	16.9
Minimum Voltage (Volts)	-46.7	-66.9	-68.7
Maximum Voltage (Volts)	-1030.7	-1435.9	-700.1

Table 1. Identified DMSP F16, F17, and F18 charging events during June 2011.

VII. Conclusion

IDL software was successfully developed to process DMSP SSJ data and to plot the current density, integral number fluxes, and spacecraft coordinates. The IDL software helped identify 30 charging events from June 2011 in SSJ records from the across DMSP F16, F17, and F18 satellites. Identification of the minimum -40 V to -60 V charging levels during this period were limited by the energy resolution in the SSJ low energy channels while charging events in the kilovolt range are well resolved by the SSJ instrument. Most notably, a charging event from June 16, 2011 on F17 charged to a voltage of -1435.9 V, which surpasses the highest recorded voltage in all previous DMSP studies. All of the reported charging events are in agreement with the criteria used in previous DMSP charging studies.

Statistical studies of DMSP charging events have been reported in the past including the Frooninckx and Sojka[2] (1992) study which used selected data from time periods in 1986 through 1990 and a more complete study covering 12 years from 1989 through 2001 by Anderson[5] (2001). The additional charging events identified during the June 2011 period including negative charging events at kilovolt levels—and particularly the extreme -1435.9 volt charging event—demonstrates that additional extreme charging events are present in the more recent DMSP data sets. An update to the statistical analyses using the full set of DMSP data available from 1982 through 2011 would be a valuable contribution to understanding the auroral charging process in support of design and operations of NASA satellites in polar orbits.

Acknowledgements

A. D. Colson thanks NASA Undergraduate Student Research Program (USRP) for this opportunity and financial support. Also, a special thanks to the mentor Dr. Joseph Minow for his time, dedication, and enthusiasm to participate in this NASA experience.

References

[1]Gussenhoven, M. S., Hardy, D. A., Rich, F., Burke, W. J., and Yeh, H.-C., "High-Level Charging in Low-Altitude Polar Auroral Environment," *Journal of Geophysical Research*, Vol. 90, No. A11, November 1, 1985, pp. 11009-11,023.

[2]Frooninckx, T. B., and Sojka, J. J., "Solar Cycle Dependence of Spacecraft Charging in Low Earth Orbit," *Journal of Geophysical Research*, Vol. 97, No. A3, March 1, 1992, pp. 2985-2996.

[3]Anderson, P. C., Koons, H. C., "Spacecraft Anomaly on a Low-Altitude Satellite in an Aurora," *Journal of Spacecraft and Rockets*," Vol. 5, No. 5, September-October 1996, pp. 734- 738.

[4]USDOC/NOAA/NEDIS/National Geophysical Data Center (NDGC), URL: http://www.ngdc.noaa.gov/ [cited 03 October 2011].

[5]Anderson, P.C., "A Survey of Surface Charging Events on the DMSP Spacecraft in LEO", in *Proceedings of 7th Spacecraft Charging Technology Conference*, ESA, SP476, 2001, pp.331-336.

Appendix A. June 2011 DMSP F16, F17, and F18 Charging Events

F16

UT Date	Time (hh:mm:ss)	Duration (seconds)	Voltage (negative)
6/1/2011	00:25:15 - 00:25:53	38	68.7 to1030.7
6/2/2011	x	x	x
6/3/2011	x	x	x
6/4/2011	x	x	x
6/5/2011	18:19:47 - 18:19:59	12	48 to 166.4
6/6/2011	23:08:56 - 23:09:00	4	58.7 to 161.9
6/7/2011	x	x	x
6/8/2011	x	x	x
6/9/2011	x	x	x
6/10/2011	10:33:42 - 10:33:59	17	48 to 56.6
6/11/2011	03:25:17 - 03:25:19	2	46.7 to 58.2
6/12/2011	01:24:20 - 01:24:33	13	196.4 to 488.8
6/13/2011	x	x	x
6/14/2011	x	x	x
6/15/2011	x	x	x
6/16/2011	x	x	x
6/17/2011	x	x	x
6/18/2011	x	x	x
6/19/2011	x	x	x
6/20/2011	03:09:57 - 03:10:03	6	66.9 to 81.1
6/21/2011	x	x	x
6/22/2011	x	x	x
6/23/2011	14:33:18 - 14:33:22	5	48 to 78.9
	21:14:28 - 21:15:26	58	46.7 to 161.9
6/24/2011	16:00:35 - 16:00:39	4	248 to 55.1
	19:21:17 - 19:21:33	16	48 to 245
	21:02:08 - 21:02:57	49	48 to 488.8
	22:38:23 - 22:38:28	5	46.7 to 83.4
6/25/2011	02:04:17 - 02:05:45	58	66.9 to 1030.7
	02:07:11 - 02:07:49	38	46.7 to 341.3
6/26/2011	00:08:14 - 00:08:22	8	46.7 to 81.1
	20:35:08 - 20:36:22	74	196.4 to 77
6/27/2011	x	x	x
6/28/2011	x	x	x
6/29/2011	x	x	x
6/30/2011	23:09:17 - 23:09:24	7	46.7 to 166.4

Appendix A (continued). June 2011 DMSP F16, F17, and F18 Charging Events

F17

UT Date	Time (hh:mm:ss)	Duration (seconds)	Voltage (negative)
6/1/2011	x	x	x
6/2/2011	x	x	x
6/3/2011	x	x	x
6/4/2011	x	x	x
6/5/2011	x	x	x
6/6/2011	x	x	x
6/7/2011	x	x	x
6/8/2011	04:29:23 - 04:29:24	2	109.9
6/9/2011	x	x	x
6/10/2011	x	x	x
6/11/2011	x	x	x
6/12/2011	x	x	x
6/13/2011	x	x	x
6/14/2011	23:29:16 - 23:29:33	17	207.5 to 341.3
6/15/2011	x	x	x
6/16/2011	00:56:04 - 00:56:40	36	297.2 to 1435.9
6/17/2011	x	x	x
6/18/2011	x	x	x
6/19/2011	x	x	x
6/20/2011	x	x	x
6/21/2011	x	x	x
6/22/2011	x	x	x
6/23/2011	21:32:07 - 21:32:18	11	66.9 to 502.5
6/24/2011	00:57:59 - 00:58:00	2	98.4 to 245
6/25/2011	x	x	x
6/26/2011	x	x	x
6/27/2011	x	x	x
6/28/2011	x	x	x
6/29/2011	x	x	x
6/30/2011	23:28:52 - 23:29:13	21	289.1 to 681

Appendix A (continued). June 2011 DMSP F16, F17, and F18 Charging Events

F18

UT Date	Time (hh:mm:ss)	Duration (seconds)	Voltage (negative)
6/1/2011	x	x	x
6/2/2011	x	x	x
6/3/2011	x	x	x
6/4/2011	x	x	x
6/5/2011	x	x	x
6/6/2011	02:27:23 - 02:27:34	11	141 to 488.8
6/7/2011	x	x	x
6/8/2011	00:23:27 - 00:23:36	9	141 to 488.8
	00:25:46 - 00:25:51	5	98.4 to 488.8
	14:07:25 - 14:07:27	2	144.9 to 231.8
6/9/2011	x	x	x
6/10/2011	x	x	x
6/11/2011	x	x	x
6/12/2011	x	x	x
6/13/2011	x	x	x
6/14/2011	x	x	x
6/15/2011	x	x	x
6/16/2011	09:01:56 - 09:02:12	16	68.7 to 166.4
6/17/2011	x	x	x
6/18/2011	x	x	x
6/19/2011	x	x	x
6/20/2011	01:21:21 - 01:21:26	5	207.5 to 700
6/21/2011	x	x	x
6/22/2011	x	x	x
6/23/2011	x	x	x
6/24/2011	20:59:08 - 20:59:09	2	273.6 to 502.5
6/25/2011	02:02:08 - 02:02:12	4	137.1 to 171
6/26/2011	20:33:02 - 20:34:13	71	141 to 700
6/27/2011	x	x	x
6/28/2011	x	x	x
6/29/2011	x	x	x
6/30/2011	x	x	x