Simulation of an Auroral Charging Anomaly on the DMSP Satellite

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Abstract

Observation of an operational anomaly on the Defense Meteorological Satellite Program (DMSP) F13 satellite has been reported by Anderson and Koons [1996]. On May 5 1995, the microwave imager experiment experienced a lockup of its microprocessor unit. This was attributed to the charging (and discharging) of thermal insulation blankets by energetic auroral electrons. DMSP is equipped with thermal and energetic charged particle detectors that measured the energetic auroral electron spectra responsible for the charging. A satellite frame potential of about -460 Volts was determined from the ion measurements. They presented calculations to show that the capacitance between the blanket surface and the spacecraft of an ungrounded thermal blanket may be low enough to allow rapid charging, and that surface potentials of approximately -3 kV may have been attained in a period less than about 6 sec.

Their approach however, does not account for the ion current collected by the charged surfaces. In this study, we have used the POLAR code to simulate the charging of DMSP at the time of the reported anomaly. POLAR is a three dimensional Fortran code that solves the Poisson-Vlasov system for self-consistent steady state plasma density and currents around a charged spacecraft. The results indicate the highest potentials are achieved only by those few surfaces that have their ion collection restricted by the particulars of their location.

Introduction

The charging of satellites in polar orbit by auroral electrons has been a topic of interest and debate for some time. The relative high density of the Low Earth Orbit (LEO) plasma suggests that auroral charging should be negligible compared to that observed in Geostationary Orbit (GEO). This anticipation has been supported by early observations of charging on the DMSP spacecraft. Besse [1985] and Gussenhoven et al.[1985] report hundreds of volts of negative charging on both the DMSP F6 and F7 spacecraft. The problems attributed to charging in GEO are most often associated with kilo-Volt levels of charging. Until recently, the best argument against concern for auroral charging has been the lack of reported anomalies. The recent reporting of an anomaly observed on DMSP by Anderson and Koons [1996] suggests that although rare, high level charging can indeed occur in low Earth polar orbit.

The Air Force Research Laboratory (formerly the Geophysics Laboratory) has sponsored the development of a charging analysis code, POLAR (POtential of Large Spacecraft in the Auroral Region), to specifically study auroral charging. POLAR has been used previously to model the charging of DMSP [Cooke et al., 1993]. This study showed good agreement with the observations of Gussenhoven et al. [1985], and indicated that individual elements of the dielectric surfaces were not charging to more than about twice the observed spacecraft frame potential of about -400 Volts maximum. Anderson and Koons [1996] concluded however, that for similar frame charging, individual surfaces could be charging to the kilo-Volt levels needed to explain the observed anomaly.

Observations

All of the DMSP satellites since DMSP F6 (launched December 20, 1982) have carried similar complements of plasma monitors. The charging measurements are made with the SSJ/4 instrument which measures precipitating ions and electrons, and the SSIE instrument, which measures thermal plasma. The SSJ/4 sensor consists of four cylindrical curved plate electrostatic analyzers arranged in two pairs. One pair measures electron fluxes in 20 logarithmically spaced energy channels between $30\,eV$ and $30\,keV$, executing a complete sweep each second. The other measures ions over the same range. The analyzer apertures face local vertical, and thus measure only the precipitating particle populations with an angular acceptance of $10° \; x \; 10°$.

The thermal plasma detector, SSIE, consists of a spherical Langmuir probe to measure thermal electrons and a planar retarding potential analyzer, RPA, to measure thermal ions. The Langmuir probe consists of a $1.75\,inch$ diameter collector surrounded by a concentric wire mesh grid of $2.25\,inch$ diameter. It is mounted at the end of a $2.5\;foot$ rigid boom. Complete descriptions of the SSIE instruments, modes of operations, and data analysis methods are given in *Smiddy et al.*, [1978]. From the SSIE data, the thermal plasma density can be determined.

The first reports of DMSP charging by Besse [1985] and Gussenhoven et al.[1985] documented 9 events in 1983 where DMSP charged over -100 volts. The maximum charging level was -680 Volts. Their study indicated the requirements for charging were: [a] the spacecraft be in darkness, [b] the plasma density be below $10^4\,cm^{-3}$, and [c] the integral number flux of electrons over 14 keV exceed $10^8 cm^{-2}\, s^{-1}\, sr^{-1}$.

More recently, Frooninckx and Sojka [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 V were identified. They observed that over a solar cycle, the most variable factor determining charging was not the energetic electron 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, due to a lower ionospheric plasma density at solar minimum.

Anderson and Koons [1996] report what is 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 as determined by the onboard instruments, the microwave imager instrument, SSM/I, experienced a lockup of its microprocessor. Their analysis showed that all of the conditions proposed by Gussenhoven et. al. [1985] were satisfied. For many seconds preceding and including the anomaly, the number flux in just the 31.3 KeV channel of the SSJ/4 exceeded $10^8 cm^{-2}\, s^{-1}\, sr^{-1}$, and peaked at about 10^9. Prior to the charging, the ambient density plasma density was just below $10^3 cm^{-3}$ as determined by the SSIES. At the time of the charging event, the ambient density was not measurable. This was presumably due to two reasons. One, the lower limit of the SSIES is about $10^2 cm^{-3}$. The other is that the charging can contaminate the measurement. The peak frame potential during the episode was -460 Volts.

Anomaly Analysis

The presumed cause of the anomaly was a discharge on some surface where the electro-magnetic pulse can couple directly into the SSM/I or spacecraft cabling coupled to the instrument. The observed spacecraft frame potential was well below the level associated with the discharging of dielectric materials. [Frederickson, 1996]. Anderson and Koons [1996] suggest that a level of about -3 kVolts is needed. Since there are no instruments on the DMSP designed to measure the charging of an isolated dielectric surface, their approach was to evaluate a number of candidate sites using a simplified charging analysis. This analysis is summarized here. From the data, they determined that the integrated precipitating electron flux density was about $5\, x\, 10^{-6} A/cm^2$. This current will be reduced by secondary electron emission and ion current. Since this charging event was limited in duration to about 5 or 6 seconds, any candidate material must have sufficiently low capacitance to the spacecraft frame to attain -3 kV in that time. With this criterion, it was possible to perform a limit analysis on the exposed spacecraft materials using an approximate secondary yield and ignoring the ion current using the equation,

$$\frac{C}{A} = \frac{t\, I\, (1 - \bar{\delta})}{V} \qquad (1)$$

where C is capacitance, A is area, t is time, I is current density, V is voltage, and $\bar{\delta}$ is averaged secondary yield. For Teflon, they used a secondary yield of $\bar{\delta} = 0.2$. For 5 seconds and 3 kVolts, the required capacitance is $8x10^{-9} F/cm^2$.

They determined that the most likely rapid charging material was the MLI thermal blankets with a Teflon outer layer. Teflon is well known as an easily charged material due to its low secondary electron yield. In addition, the internal aluminized layers were not electrically connected to each other or the spacecraft ground, thus producing the required low capacitance. This material is used extensively on DMSP F13 and on the SSM/I.

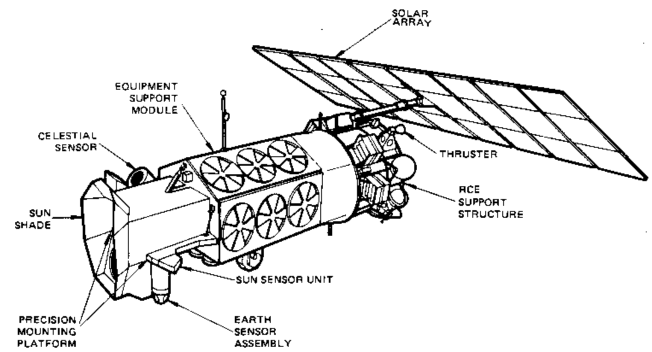

Figure 1. Illustration of DMSP (from Anderson and Koons [1996])

The POLAR Code

POLAR [Lilley et al, 1985] is a self-consistent three dimensional Poisson-Vlasov code that provides steady state solutions by iterating between potential (Poisson) and density (Vlasov) solutions on a cubical mesh. A versatile set of building elements can be combined to form complex objects with a variety of surface materials and electrical connections. A surface charging module can be added to the iteration to provide the spacecraft charging response to both natural and active charge drivers. The Poisson solver uses a finite element conjugate gradient method, with a unique 'charge stabilization' technique of filtering charge densities to suppress grid noise and produce stable solutions. This allows POLAR to compute plasma sheaths for very large grid increment to Debye length ratios.

POLAR calculates particle densities by a method that divides space into (one or more) sheath and non-sheath regions separated by a sheath edge(s), located as an equi-potential near kT. External to the sheath, the plasma distribution is presumed to be Maxwellian with possible flow. External densities are determined by geometric ray tracing with an analytic correction for the plasma expansion electric field in the wake. This approach has been shown to correctly predict wake formation about the Space Shuttle Orbiter [Murphy et al., 1989]. At the sheath edge reasonable assumptions about the external potential structure and the usual constants of motion are used to determine the flux and velocity of ions entering the sheath which are assigned to a super-particle and tracked inward. Internal sheath densities are determined from the time spent in each volume element, and surface currents from their final deposition. When particles are repelled, their density is assumed to be Boltzmann.

Auroral electrons are introduced with three distinct energetic populations [Fontheim, 1982]: Power Law, specified by intensity, exponent, lower and higher cutoffs; Maxwellian, specified by density and temperature; Gaussian, specified by intensity, energy peak, and peak width. Auroral electrons do not contribute significant space charge and are not included in the Poisson solution. A charging step sums all sources of current and updates conductor and surface potentials. The auroral electron flux is assumed to be isotropic, with no surface - surface shadowing, and secondary and backscatter currents are determined from surface potential and material properties [Katz et al., 1986]. The isotropy assumption is a limitation on accuracy, and could be removed, but remains since 4π observations are not usually available, and since a charging code is often used for 'worst case' analysis. Photo electron currents are also included, with shadows calculated from sun direction information.

Satellite Models

A sketch of DMSP from the paper by Anderson and Koons is shown in figure 1. A similar view of the POLAR model is shown in figure 2. Two versions of the model were used in this study. The model shown in figure 2 is configured as DMSP F7, which used Kapton surfaced MLI on the central ESM module (see figure 1). For F13, the ESM was covered with the Teflon MLI previously discussed. For both models, the Precision Mounting Platform (left, light gray) and the RCS support structure (light gray, near the solar array) were covered with the Teflon MLI. For the POLAR F7 model, the MLI blankets were assumed grounded but it is not known if this assumption is correct. With the exception of the Teflon MLI, the other materials were chosen from the default list of POLAR (NASCAP) materials, which in some cases are guesses. The solar cells have been modeled as uniform solar cell cover glass.

POLAR Simulations

The first step in developing the POLAR model was fitting the observed electron spectra. Figure 3 shows the electron spectra observed at the time of the anomaly, and the POLAR fit. As the three spectra are similar, a single POLAR environment was used thru out the calculations. One uncertainty in these observations is the unknown flux above 30 keV. The ion density was assumed to be $3x10^3/cc$. This is larger than the observations, but it still allows for charging of the spacecraft frame. POLAR has significant difficulty with the large sheaths produced by densities much lower than this. The ion temperature was assumed to be $0.02\,eV$.

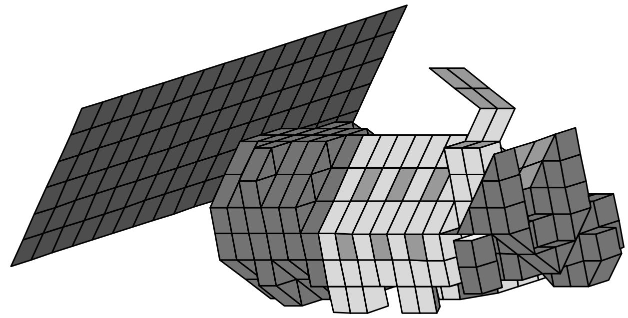

Figure 2. Surface cell material composition of the POLAR F7 model. Light gray surfaces are Teflon MLI. The isolated medium gray surfaces are aluminum.The darker gray is Kapton MLI. The darkest gray is the painted backsurface of the solar array.

Two POLAR Simulations were run using the environment just described. One run corresponds to the DMSP-F7 surface configuration with $1.3x10^{-4}m$ thick Teflon and Kapton as shown in figure 2. The other run corresponds to DMSP-F13 with Teflon surface MLI covering the ESM and most all upward facing surfaces. The DMSP-F13 model used a Teflon thickness of $2.8x10^{-3}m$ and a dielectric constant of 2.0 to give a capacitance per unit area of $6.3x10^{-9}F/m^2$.

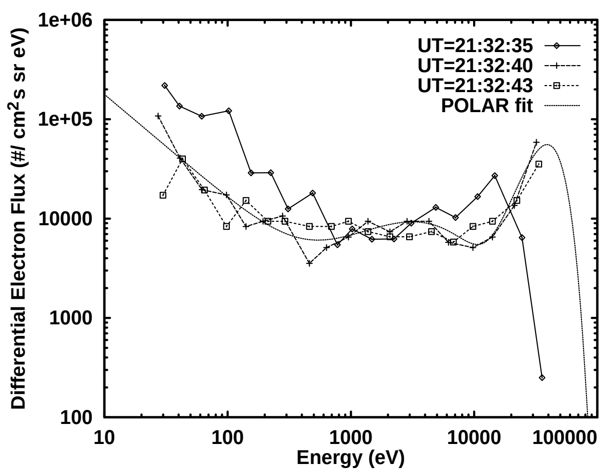

Figure 3. F13 electron spectrum and POLAR fit.

The charging histories for each run are presented in the figures 4 and 5. The histories both show frame potentials in agreement with the observation. In addition, these results confirm the anticipated charging behavior of the Kapton and Teflon surface materials. These are the histories for a few surface elements that were chosen because of their extreme charging. Figures 6 and 7 show graphically the surface potentials from the F13 model, where it can been seen that most

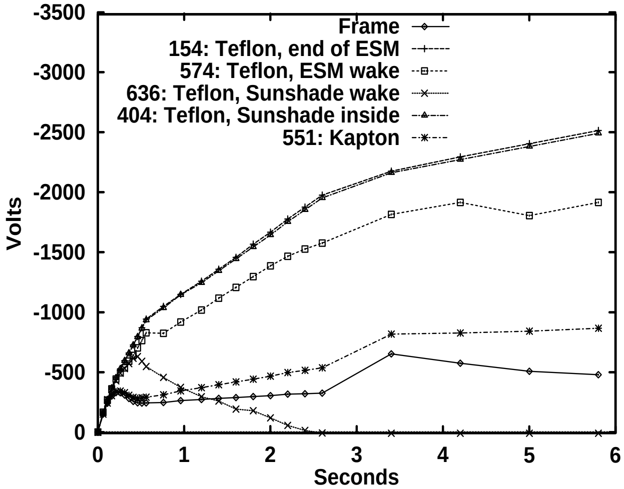

Figure 4. Charging history for the DMSP F13 model.

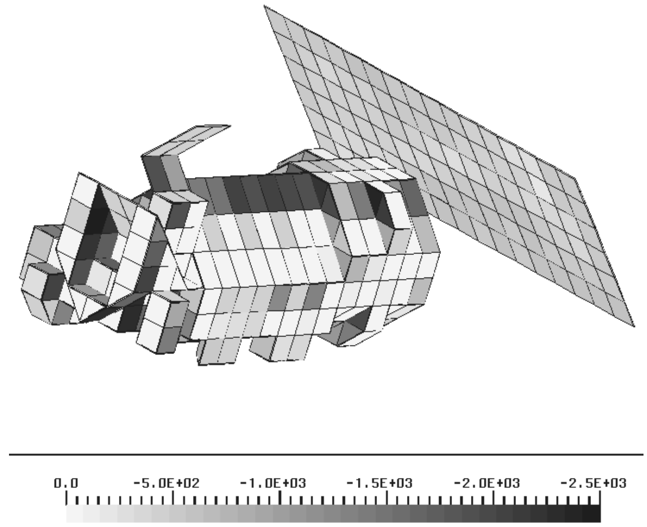

Figure 6. Wake side view of the F13 surface potentials

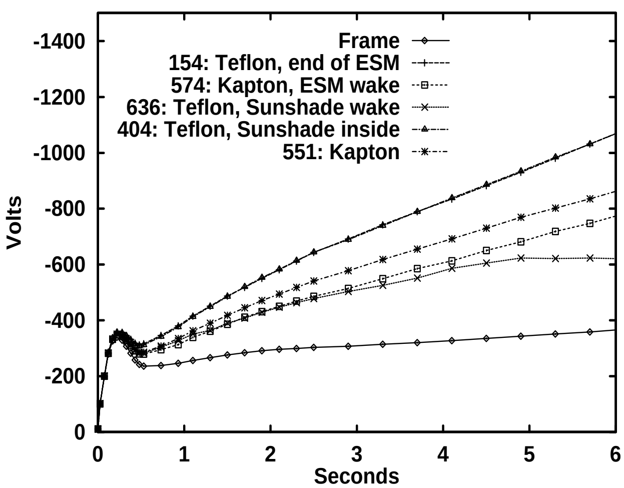

Figure 5. Charging history for the DMSP F7 model.

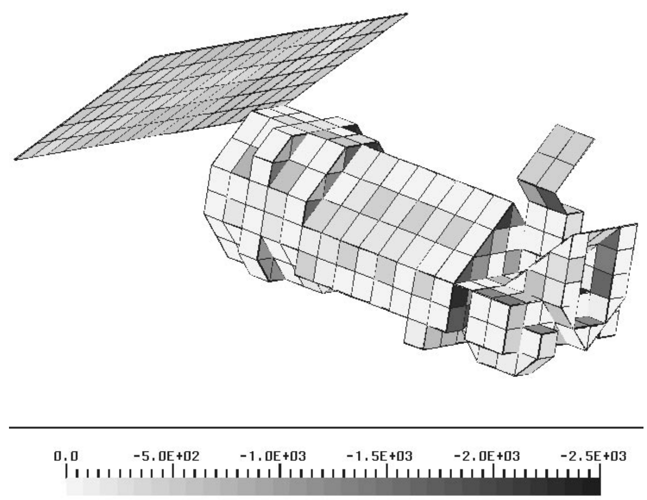

Figure 7. Ram side view of the F13 surface potentials

of the spacecraft surface is charged to levels close to the frame potential. Figures 8 and 9 present the same views for the F13 surface currents. Most surfaces are able to collect an enhanced ion current. The few that do charge are positioned such that they cannot be easily reached by ions and thus charge in the manner assumed by the Anderson and Koons [1996] analysis. The ion flux to a square surface element (roughly $600cm^2$) on the ram side of an uncharged satellite would be about $2.0\,x\,10^{-7}\,Amp$. This would be mostly white in figures 8 and 9. This effect is further illustrated in figure 10, which is a cut through the POLAR calculation showing potential contours in the sheath and a few selected trajectories. For an uncharged spacecraft, the wake surfaces receive an ultra low ion current. At these higher potentials though, we see that the large sheath distributes the ion current almost evenly between ram and wakes.

In the wake however, the longer trajectory lengths lead to a more uneven distribution. It appears that those surfaces that have difficulty attracting ions do so most of the time.

Discussion

The POLAR code simulation has confirmed the basic analysis of Anderson and Koons [1996]. That is, an easily charged surface material with low capacitance to the spacecraft frame surfaces may indeed charge to kiloVolt levels. The simulation provides further insight. We see that the ion current cannot be ignored everywhere. If it were truly negligible, the entire satellite would charge to kiloVolt levels regardless of the capacitance, and this is not observed. So, grounding the blankets everywhere would probably change the charging behavior, but not substantially change the fact that some materials like Teflon are

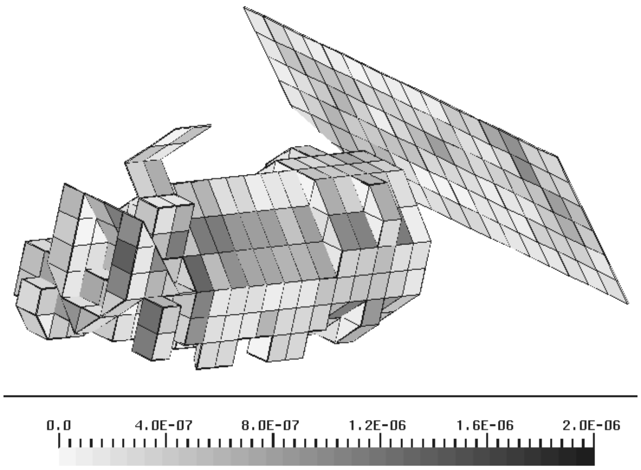

Figure 8. Wake side view of the F13 surface currents

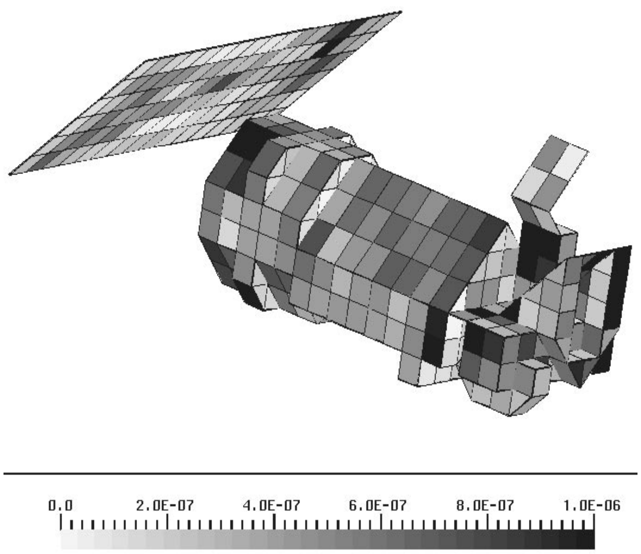

Figure 9. Ram side view of the F13 surface currents

easily charged. If it is necessary to use such materials, this study indicates that it may be possible to use simulation to discover potential problem sites.

This study places additional significance on the observed anomaly. It is tempting to consider it rare compared to the long history of the DMSP series of spacecraft on orbit with no other such problems. It appears however, that this may say as much about choices in spacecraft surface material as the true likelihood of deleterious charging in polar orbit.

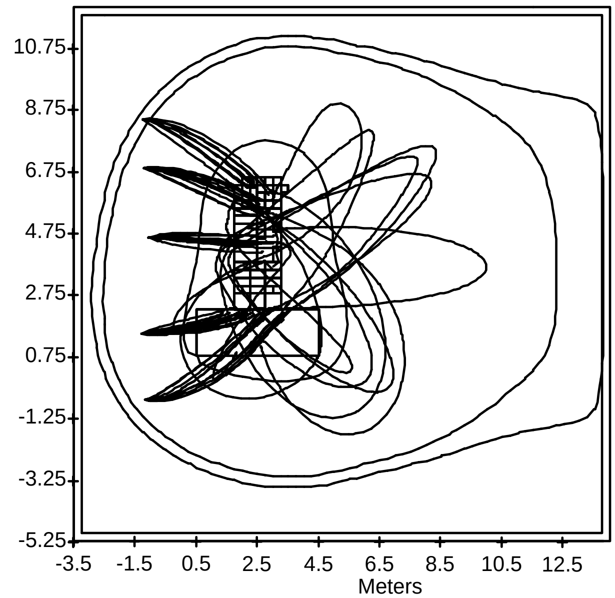

Figure 10. A cut through the POLAR simulation showing potential contours and trajectories.Contour levels: -200 -20 -2 -0.2

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