High Voltage Frame and Differential Charging Observed on a Geosynchronous Spacecraft

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Abstract. We have studied the frequency and levels of frame and differential charging on a geosynchronous satellite since August of 1995. High voltage differential charging was measured with Surface Potential Monitors (SPM) for two typical spacecraft surfaces (Kapton and Astroquartz). Frame charging was determined using an ion electrostatic analyzer. In addition, the integrated electron population between 20 and 50 keV was also measured. The statistical study includes frame and differential charging over a three-year period. We also address the ability to reduce the charging levels using an autonomous Charge Control System (CCS). The CCS releases a Xenon plasma to help provide current balance when high fluxes of electrons impinge on the spacecraft. A case study of a charging event will focus on identifying the population responsible for charging, current balance issues and differences in charging levels as observed by the SPM and the ion analyzer.

1. Introduction

Spacecraft charging at the surface of a material is due to the need to provide current balance at that surface. In the natural near-Earth space environment, high level charging is always negative due to the higher mobility of energetic electrons, especially during periods of magnetic substorms. The current balance equation is to first order:

$$-I_{CE} + I_I + I_{SE} + I_{BE} + I_{PE} = 0 \quad (1)$$

where:

I_{CE} = current to the spacecraft from the charging electrons

I_I = current to the spacecraft from available ambient ions

I_{SE} = current due to secondary electrons away from the surface due to primary particles hitting the surface

I_{BE} = current due to electrons backscattered away from the surface, and

I_{PE} = current due to photoelectrons away from the surface due to solar UV hitting the surface

In principle I_{CE} contains contributions from incident electrons of all energies. However, *Mullen et al.* [1986] examined data from the SCATHA mission and concluded that, for most geosynchronous altitude spacecraft, incident electrons with energies below a characteristic value of $E_o \approx$ 20-30 keV are self-balancing. These low energy electrons produce sufficient secondary electrons to exactly balance the incident population with $E < E_o$. If current balance isn't maintained at the surface, charging voltage increases until a potential sheath around the vehicle is large enough to accelerate a sufficient number of ions to the surface and/or repel sufficient electrons from the surface to provide current balance.

Active negation of dangerous levels of charge buildup requires a net electron emission or a net positive ion influx. For materials electrically tied to vehicle ground, electron emission and ion capture are both effective. However, if a group of surfaces is electrically isolated from vehicle ground, then, unless an electron emitter is available on each surface, free ions must be made available at or near all the surfaces in order to discharge them. Historically, plasma emission has been shown to be the surest, safest way to discharge space vehicles. An active plasma source allows the vehicle ground to be brought and "clamped" near zero by letting the environment draw out electrons and the vehicle draw back positive ions to effectively balance I_{CE}, providing that the capacity of the plasma emitter is sufficiently large. The presence of both electrons and ions allows the neutralization system to avoid high voltages, over-emission of electrons and other problems associated with electron guns.

When surface charging is a problem, it is mainly due to large differential charging between adjoining spacecraft surfaces (differential charging) and not between vehicle to ambient plasma charging (frame charging). For ungrounded dielectric surfaces, sufficient ions have to be produced to provide current balance at the floating surface. When the source of ions cannot provide enough ions for current balance, the isolated surface tends to remain at some charged level, although lower than it would have if no additional ions were made available. Discharging the frame with electrons alone can produce higher differential charging since vehicle ground returns to ambient plasma ground, but floating dielectrics, in general, do not.

On the dark side of the spacecraft, the outward-facing dielectric material surfaces can become highly charged due to the lack of photoelectrons, while the sunlit side surfaces can be almost entirely charge free. This creates highly asymmetric charging sheaths and total frame charging levels up to about -1 kV. Eclipse frame charging, when the entire vehicle is in total darkness, results in about a factor of ten higher charging potential than sunlit charging. For the materials used to determine differential charging on DSCS, any sunlight on the materials brought the samples back to near vehicle ground.

2. Instrumentation

The Charge Control System (CCS) payload [*Mullen et al.*, 1997] was launched aboard a geosynchronous altitude Defense Satellite Communication System (DSCS) spacecraft in August 1995. The goal of the CCS program was to flight prove and flight qualify a unit that could actively protect high orbiting spacecraft against surface charging effects. CCS was designed using information learned from the Spacecraft Charging At High Altitudes (SCATHA) and Combined Release and Radiation Effects Satellite (CRRES) missions. The system was designed to detect hazardous conditions and turn on within 1 minute. CCS was checked out within a few days after launch, but the plasma source was not put into a "limited operation mode" for proof-of-concept until early January 1996. In January 1997, the system completed its 1-year prototype flight qualification testing and has now been in operation for nearly 3 years.

The CCS system consists of: a.) a Xe plasma generator; b.) an ion electrostatic analyzer (ESA) to measure ions in 31 differential channels between 17 eV and 12.3 keV for determining frame charging levels; c.) an electron ESA adapted to measure integral electron counts between 20 keV and 50 keV for determining the intensity of the frame charging electron population; d.) 2 surface potential monitors (SPMs), one with a Kapton blanket material and one with an Astroquartz material, for determining differential charging between the materials and vehicle ground; e.) a gas storage and control assembly with associated tank, valves and plumbing to provide the gas for the plasma generator; f.) a power electronics unit to control the gas assembly and plasma generator; and g.) a microprocessor controller to detect the onset of adverse charging conditions and autonomously discharge the vehicle prior to excessive charge build-up. The general specifications are:

No. of boxes	:	7
Total weight	:	40 lbs
Total power	:	source off - 6 watts
		source on - 18 watts
		heater on - 39 watts
Telemetry	:	72 bits/sec
Op time	:	1000 hours

2.1 Plasma Source

The plasma source was originally developed under an USAF contract with Hughes Research Laboratories, Malibu, CA [*Robson and Williamson*, 1988]. It consists of a plasma generator, power electronics and a gas storage and control assembly. The plasma generator itself consists of a hollow cathode, keeper and anode electrodes, a magnetic structure and a ground shield. Xenon gas which flows through the cathode assemble is ionized by electrons produced from a low work function surface within the cathode. The extremely fast turn-on time is achieved by gas burst ignition. A high voltage arc is applied to the cathode insert until it reaches thermionic emission level at which time it produces the electrons needed to ionize the Xenon gas. Approximately 38000 standard cubic centimeters (scc) of gas was flown on DSCS. Each turn on requires approximately 15 scc of Xe to initialize it and a flow rate of 0.5 scc/min during operation. On DSCS, the plasma source operation was restricted to 1 hour per day, due to an agreement with the DSCS program office. Thus, each turn-on used about 45 scc of gas. Enough gas was flown for over 800 turn-ons of 1 hour duration. The bottle flown was less than half pressurized, according to the specified limit for adequate safety margin. The plasma source was designed for a flow of approximately 2 mA of plasma at a voltage less than 20 V. In space and during test, the plasma emission current could be measured over the range 0-10 mA. The efficiency of positive ion production in the unit was only a few percent of the neutral gas. A higher efficiency would be more desirable, if it could be provided given all the other constraints placed on the source.

2.2 Electrostatic Analyzer (ESA)

The CCS ESA is a modified SSJ/4 detector [*Hardy et al.*, 1984] which measures fluxes of ions and electrons with energies between 0.03 and 30 keV on DMSP spacecraft. The CCS electron ESA energy range was 20 to 50 keV, and the data channels were integrated to produce a single output value, the summed electron flux between 20 and 50 keV. The CCS ion ESA measured fluxes in 31 channels, logarithmically spaced from 0.017 to 12.3 keV.

2.3 Surface Potential Monitors (SPM)

The SPMs are electric field mills with sample materials used as witness plates from which to measure the potential difference between accumulated charge on the sample materials and vehicle ground. They were flown as originally built by Hughes Research Laboratories [*Robson and Willamson*, 1988] with slight modifications. The two sample materials used on the SPMs for DSCS are: a) GE type 171A488TY1P6 ITO-coated polyimide film (Dupont Kapton H) aluminized on the back surface, and b) GE Astroquartz fiberglass fabric type 171A4676TY8. The polyimide film (here referred to as the Kapton blanket) is approximately 0.05 mm thick and the fiberglass fabric (here referred to as Astroquartz) is approximately 0.3 mm thick. These materials are the same as used on DSCS outer surfaces. The SPM hardware also contained sun sensors mounted coplanar with the samples (since photoelectrons emitted are important to the charging level, it is helpful to know when the material samples are exposed to sunlight). The samples were calibrated to measure from approximately 1 kV positive potential difference to 4 kV negative potential difference.

2.4 Control Electronics

The microprocessor-based controller was built at Assurance Technology Corporation in Carlisle, MA using design parameters supplied by Hughes as part of the original development contract, and operations criteria supplied by AFRL. The plasma source system could be turned on by ESA electron count levels and/or SPM charging levels. The levels for turn on reside in software and can be easily changed in flight. The control electronics provided all the time critical commands to the plasma source electronics and gas valves to initiate the plasma discharge, and to shut the source off at the prescribed time.

2.5 Configuration and operation on-orbit

The individual boxes that make up the CCS were placed at various locations inside and outside the spacecraft to replace ballast weight so as not to affect the total weight (and therefore the expendables lifetime) of the satellite. The ESA, SPMs and plasma generator were positioned with exterior exposure of necessary surfaces. The plasma source was almost 180^o around the vehicle from the ESA and SPMs. This gave the optimum test of how well the discharge system would reduce charge anywhere on the vehicle and not just local to the plasma source.

For the first year "proof-of-concept" operation, the CCS was configured to turn on when the Kapton blanket SPM sample charged to near 1000 volts above the offset value. The controller had to detect 4 consecutive measurements above the 1000 volt charging level before it initiated the turn-on procedure for the plasma source. This was to preclude initiation from data spikes or noise contamination. In mid-1998, the SPM trigger voltage was raised to 2500 volts to conserve the Xe gas supply.

3. Experimental Results

The ion ESA data were used to measure the DSCS spacecraft frame charging, while the SPM data determined the differential charging of surface dielectric materials. Frame charging voltage levels can be measured by examining peaks in the in ion flux energy distributions produced when the ambient plasma is accelerated by the spacecraft potential [*DeForest*, 1972]. Differential charging levels were determined by measuring the voltage levels developed across the two SPMs as a result of incident electron bombardment. Experimental results from the CCS operation show that the ion source activity was very effective in suppressing both frame and differential charging.

3.1 Differential Charging

The useful operation of the CCS SPM detectors was restricted in local time due to the fact that the SPMs never recorded voltages above the nominal level when illuminated by sunlight. As the data from the sun sensors showed, any amount of incident sun light was sufficient to produce enough photoelectrons from the SPM surface to completely discharge the SPM, regardless of the intensity of electron bombardment. The position of the SPMs on the DSCS satellite brings the SPMs out of the view of the sun for several hours around local midnight (the exact length of time depends on the time of year).

CCS was configured to trigger the ion source when 4 consecutive readings from the Kapton SPM exceeded a threshold of –1,000V (from 4 January 1996 to 15 June 1998) or –2,500V (after 16 June 1998). The increase in the threshold voltage was motivated by the desire to conserve gas by reducing the number of turn ons. During the initial period of operation, the –1,000V threshold was exceeded on 20% of the days, while, during the second period, the –2,500 V threshold was exceed on 13% of the days.

A typical charging event, with a source turn on, occurred on day 115 of 1998. The electron counts, SPM voltage and the net source current for that event are shown plotted in Figure 1. As the incident electron flux level increases from the background value, the SPM charging level increases to over 2,000 V (negative), triggering the ion source at 8,155 sec UT. As the plasma source is ignited with a burst of gas, initially producing a net ion current of +150 µA, the SPM charging levels decreases significantly. Once the ion source gas output reaches its steady state value of 0.5 scc/min, the SPM charging and incident electron counts track each other while the net plasma source emission current shows an opposite behavior.

As the charging flux of electrons from the environment increases, there are relatively more net electrons emitted from the plasma source to offset the incoming negative charges, thus reducing the net ion current. Conversely, as the environmental electron flux decreases, the net ion current increases. At the highest ambient electron count levels, the net current flow from the plasma source has been observed to be negative, indicating more electrons were leaving the source than positive ions. Note the negative source current values occurring at the same time as a maximum in the electron flux near 10,850 sec UT.

Immediately after the ion source shuts down at 11,411 sec UT, the charging levels increase to over 2,000 V, even though the measured electron counts are decreasing. Slight increases in the electron counts near 13,000 sec UT are correlated with SPM charging voltages that saturate the CCS measurement capability. The high degree of tracking normally observed between the measured electron counts and the SPM charging indicate that the 20-50 keV electron population is an important contributor to differential charging. However, the huge increase in charging observed near 13,000 sec UT is evidence

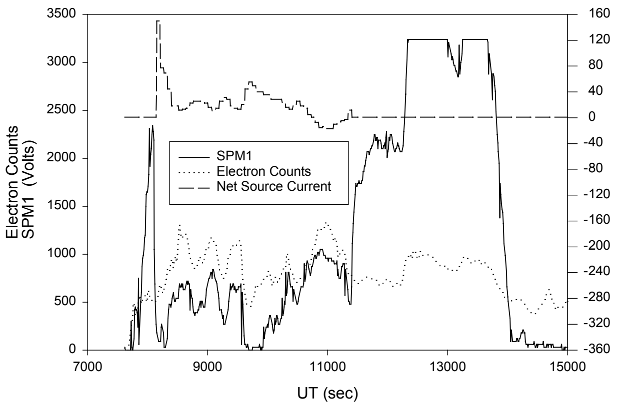

Figure 1. Electron, SPM and Source current data for charging event during day 115 of 1998.

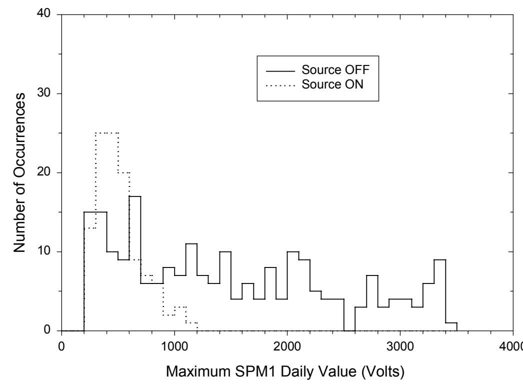

Figure 2. Histograms of maximum daily SPM1 charging levels with the source on and off.

that, under some conditions, lower energy electrons can also contribute to charging.

Overall, the effect of an ion source turn on was to reduce the SPM voltage to a much lower value, if not to zero, in a time shorter then the time resolution of the SPM readouts (10 sec). The reduced or zero SPM voltage would be sustained for the one hour of ion source activity, with only a weak dependence on incident electron flux. The effectiveness of the Xe source in reducing differential charging is illustrated by the data shown in Figure 2. The "Source OFF" histogram displays the distribution of the maximum SPM charging level reached for each of 225 days when the SPM charged to at least 30 V during the portion of the day when the source was not on. The "Source ON" histogram shows the distribution of the maximum charging levels above 30 V reached during the portion of the day when the source was active (110 days). The strong influence of the source on the observed differential charging is evident.

The CCS plasma source is capable of maintaining the spacecraft frame at plasma potential (see Section 2.2), but does not always provide sufficient ions to completely eliminate the SPM charging on the other side of the spacecraft. Thus, the Xe source works as expected, producing a plasma that maintains charge neutrality of the spacecraft ground. However, the total ion capacity of the system needs to be increased if all floating dielectrics are to be reduced to near spacecraft ground levels. This can be done by 1) increasing the efficiency of ion production in the source, 2) having a higher gas flow rate, or 3) putting multiple sources at different locations on the satellite.

3.2 Frame Charging

Although frame charging in sunlight is not, by itself a problem for the spacecraft, it is an accurate proxy for the probability of occurrence of differential charging. Frame charging is caused by an enhanced population of keV electrons, the same population that is responsible for differential charging. Since the local time extent of the observable SPM charging on DSCS is limited, frame charging provides a useful tool to study differential charging probabilities during the time between local midnight and local noon.

At geosynchronous altitude, significant charging levels can only be reached during only about 1/2 a day because of local time variations in particle and plasma populations. No frame charging is observed when the average 20-50 keV electron flux is below approximately 10^5 electrons/cm^2-sec-sr-keV and this restricts charging to four hours before and nine hours after local midnight (see Figure 3).

The DSCS data on frame charging and electron fluxes as a function of local time are in very good agreement with data from the SCATHA mission [*Mullen et al.,* 1986]. There is a slight suppression of observed DSCS frame charging probability relative to the probability measured on SCATHA, for the four hours before local midnight. The reason for this discrepancy is that most CCS ion source turn-ons occur during this time interval and each turn on results in eliminating frame charging for one hour. The net effect of the CCS ion source is to reduce the observed probability of charging for several hours before local midnight.

4. Conclusions

The results of the analysis of the charging events on DSCS show that CCS is effective in significantly reducing or eliminating frame and differential charging. The factor that most limits the CCS effectiveness is the amount of plasma produced by the Xe source. If this amount can be increased, then a CCS-like system could eliminate differential charging in even the most extreme electron environments.

The CCS data also show that electron flux levels can be used as a good detector for the highest differential charging levels and may be a good choice for turning on an operational plasma source. However, for some lower level differential

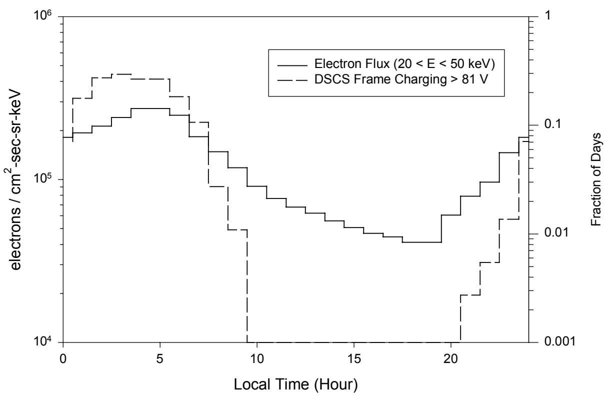

Figure 3. Local time dependence of frame charging and 20-50 keV electron flux as measured by CCS on DSCS.

charging (up to about -1,500 V on the SPM), the electron detector did not always record high count rates. This is not unexpected, since different materials respond to different portions of the electron energy spectrum. Furthermore, charged particle currents can be directional and miss the field of view of the instrument. This is also the main reason an ion ESA should not be used to trigger a source. Ion return currents to a charged vehicle are directional, and thus the lack of an ion charging peak doesn't mean the vehicle isn't charged. The energy range of the electron detector could be changed to better match the satellite material properties, if known, and/or multiple ranges could be used.

One possible plasma source trigger would be a combination of an electron sensor and one or more SPMs. The material on the SPM should be the external satellite dielectric material thought to be the most sensitive to high charging. The number and location of the SPMs needed must be such that one SPM was always out of any sunlight. At this time the CCS is considered to be "flight proven" and ready for use by spacecraft designers as an option for controlling adverse effects of charging.

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