A Critical Overview on Spacecraft Charging Control Methods

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Abstract. Interactions between hazardous space plasmas and spacecraft surfaces often result in spacecraft charging. Spacecraft charging may disturb the scientific measurements onboard, affects communications, control, and operations of spacecraft, and may be harmful to the health of the electronics on the spacecraft. Several mitigation methods have been proposed or tested in recent years. This paper presents a critical overview on all of the mitigation methods known to date: (a) passive methods using sharp spikes and high secondary emission coefficient surface materials, and (b) active methods using controlled emissions of electrons, ions, plasmas, neutral gas, and polar molecules. Paradoxically, emission of low energy positive ions from a highly negatively charged spacecraft can reduce the charging level, because the ions tend to return and may generate secondary electrons which then escape. We discuss the advantages and disadvantages of each of the methods and illustrate the ideas by means of examples of results obtained on SCATHA and DSCS satellites. Finally, mititgation of deep dielectric charging is briefly discussed.

1. Introduction

Electrostatic charging of spacecraft surfaces has long been recognizied as an important consideration for spacecraft design, space experiments, electronics in space, and even spacecraft survivability. The underlying cause of surface charging is mainly due to the difference between the ambient electron and ion fluxes. Electrons are faster than ions because of their mass difference, and therefore the ambient electron flux is often much greater than the ambient ion flux. As a result, the surface intercepts more electrons than ions. High level negative charging is of most concern.

For typical surface areas, charging takes a few millisecond to come to an equilibrium. At equilibrium, Kirchhoff's circuital law applies because the surface is a node in a circuit. Kirchhoff's law states that at equilibrium, the total current coming in at every node equals the total current going out. The current balance equation determines the surface potential ϕ:

$$\sum_k J_k(\phi) = 0$$

In sunlight, photoemission is important. The photoelectron flux normally exceeds the ambient flux unless during stormy periods. Thus charging in sunlight is usually at positive potentials. Since photo-electrons have only a few eV in average energy, they cannot leave if the surface potential is high. Thus, sunlight charging is often up to a few Volts positive only and is therefore not of concern.

Besides the ambient electrons, ambient ions, and photoelectrons, there are secondary electrons and backscattered electrons, both outgoing. The secondary electron flux may exceed the primary one, depending on the primary electron energy and the material properties. The backscattered electrons are less abundant and therefore less important.

Many communication satellites are at geosynchronous altitudes, where spacecraft charging is important. Sometimes, the ambient plasma environment is energetic, often with high magnetic activity. High level charging, up to multiple kV negative, has been observed in many occasions.

In the ionosphere, spacecraft charging is usually much less important because the high density, low energy, ambient charges of the opposite sign would readily neutralize any charged surfaces. The only exception is the auroral region (about 60-70 deg latitudes) where high energy electrons may come down from high altitudes.

Charged beam emission from a spacecraft can affect the spacecraft potential. The beam current should be included in the current balance equation. If the net beam current exceeds the sum of the other fluxes, it controls the spacecraft potential.

Spacecraft charging may be hazardous to the health of the electronics instruments onboard, affect scientific measurements, cause contamination such as ion deposition on mirrors and spacecraft surfaces, generate stray signals in circuits and telemetry, generate erroneous commands in navigation systems, and, in extreme cases, affect spacecraft survivability. To mitigation spacecraft charging, various methods have been, proposed, discussed, or tested in the past decade. They have advantages and disadvantages.

In this paper, we discuss and critize the various mitigation methods. In the last part of the paper, we discuss briefly mitigation of deep dielectric charging, a recent development.

2. Mitigation Methods

In general, there are two types of spacecraft charging mitigation methods, viz., (1) active and (2) passive. The active type is controlled by commands; the passive type is automatic without control. The main methods are listed in Table 1.

There is also another way to arrange the mitigation methods into two general types, viz., (a) electron ejection and (b) ion reception.

In method (a), a device draws electrons from the spacecraft ground and ejects them into space [*Grard*, 1975]. This method is effective for reducing the negative charge of the spacecraft ground but is ineffective for mitigating the dielectric surface potential. As a result, differential charging between the dielectric surfaces and the conducting ground ensues. The resulting differential charging may pose a worse situation than before.

In method (b), positive ions arrive at a spacecraft which is charged negatively. The method is effective in mitigating any negatively charged surface, regardless of dielectric or conductor. The ions neutralize the negative charges. The ions may preferentially land on the 'hot spots', where the negative potential is higher [*Lai*, 1989]. Furthermore, if the ions are energetic enough, they may act as secondary electron generators. The secondary electrons are repelled by the negative surface potentials and therefore leave, carrying away negative charges.

Thus, method (b) is effective for reducing differential charging. A disadvantage is that prolong use may end up electroplating the entire spacecraft. A combination of both types (a&b) is recommended.

We now discuss each of the methods listed in Table 1 as follows.

3. Sharp Spike Method

Sharp spikes protuding from charged surfaces generate very high electric field E. The E field at the spike tip is proportional to r^{-2}, where r is the radius of curvature of the tip. At sufficiently high fields, field emission of electrons occurs reducing the negative potential of the conducting surfaces connected to the spike. The current density J of field emission is given by the *Fowler-Nordheim* [1928] equation:

$$J = AE^2 \exp(-BW^{3/2}/E)$$

where A,B are constants and W the work function.

This is a convenient passive method requiring no command/control. It is a disadvantage that the electron emission draws electrons from the conducting ground only. Thus differential charging may ensue, as discussed in the previous section. There is another disadvantage, viz., ion sputtering of the tips can blunt them, rendering field emission ineffective. This is due to ambient positive ions attracted by the high E field of the tip.

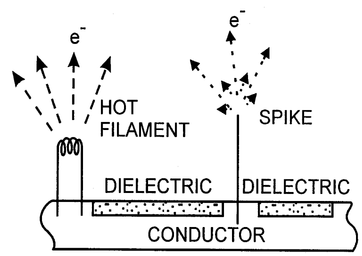

Figure 1 Electron emissions from a sharp spike and a hot filement.

There are ways to mitigate sputtering. One way is to protect a spike tip by means of ceramic coating. Such a coating would prevent ions from spluttering the tip inside, because the ion collisional cross section in the coating is larger that of electrons. Another way is to house the spike inside a silo so that the attracted ambient ions, which are homing in with larger gyroradii than electrons, may hit the silo structure instead of the spike tip [*Adamo and Aguero*, this proceedings].

4. Hot Filament Emission Method.

In this method, electrons are emitted from hot filaments. The filament materials used are of high melting points. The current J density emitted is given by the thermionic emission equation [*Richardson*, 1902]:

$$J = AT^2 \exp(-W/kT)$$

where A is a constant, W the work function, and kT the thermal energy.

Near or above the melting points of the materials, both neutrals and ions are "evaporated", and the ion current density J^+ is given by an equation of the same form as J but the constants are different.

For charging mitigation using hot filaments, electons are emitted from hot filaments which are not melting. (The use of melting filments would fall into a different catagory, viz., ion or plasma emission.) Since electron emission can reduce the charging level of the spacecraft ground but not the dielectric surfaces, differential charging may ensue (see Sec.2). Furthermore, the current emitted may be limited by space charge saturation very near the filement, because the energy of thermal electrons is low.

5. Conducting Grid Method

One often heard method is to cover a non-conducting surface, such as a solar cell, with a mesh of conducting wires. Although the wire mesh provides an uniform potential along the wires throughout the area, periodic potential differences between the wires and the surface area may develop. This method is convenient and passive. It may be adequate for some applications, but not recommended for most cases.

6. Partially Conducting Paint/Surface Method

The use of partially conducting paint eliminates the periodic potential problem of Sec.5 and is often effective and convenient. Examples of partially conducting paints are zinc ortho-titanate, alodyne, and indium oxide [*Purvis and Garrett*, 1984]. *Frederickson* et al. [1986] has discussed the properties of a number of spacecraft polymer materials.

Two comments are offered. (1) Under bombardment by electrons, ions, and atoms (especially oxygen atoms), the surface material properties, including conductivity, change gradually in time. More measurements and research are needed in this area. (2) Introducing metal atoms into the intersititial lattice sites of polymers would produce metalized polymers not homogeneous enough for many purposes. The recent techniques of introducing metal atoms at the molecule level deserve good attention, and this topic will be discussed later in the deep dielectric charging section.

7. High Secondary Electron Yield Method

The use of coatings of high secondary electron emission (δ_{max}>>1) would work for a certain primary electron energy range (typically up to about 1 keV) only. Beyond that range, the secondary emission decreases to below unity ($\delta(E) < 1$) and therefore offers no protection against charging. A case in point is the copper-beryllium surface of the SC10 boom [*Lai*, 1991a] on SCATHA. The material has a $\delta_{max} \approx 4$. When the space plasma became stormy (kT >> keVs), on Day 114, the boom suddenly jumped, in a triple-root fashion, from nearly zero V to a high potential of the order of kV negative [*Lai*, 1991b].

8. Electron and Ion Emission Method

We have stressed (Sec.2) that electron emission alone is not effective in reducing the negative potentials of a spacecraft as a whole. Paradoxically, emission of low energy positive ions from highly negatively charged spacecraft can reduce the potential effectively. This method has been observed on SCATHA [*Cohen and Lai*, 1982; *Lai*, 1989] and simulated on a computer [*Wang and Lai*, 1996].

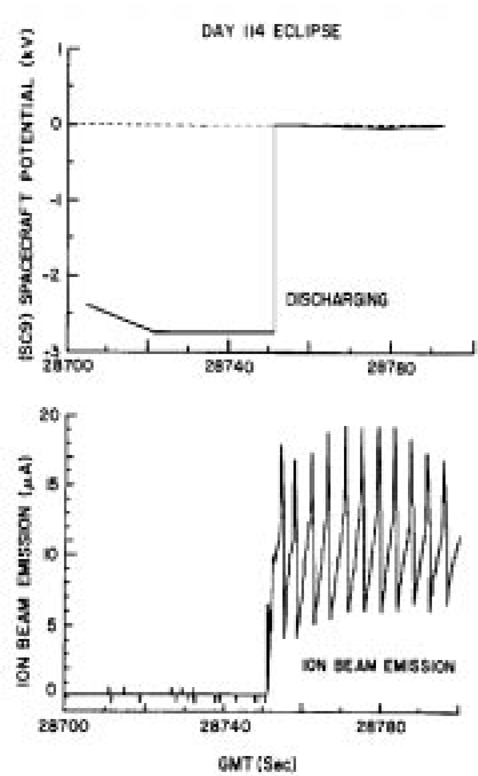

Figure 2. Xe^+ (50 eV) ion emitted from SCATHA charged to nearly -3 kV. The emission mitigated the charging. The potential was measured at 16 sec interval.

An explanation [*Lai*, 1989] of this apparent paradox is that the low energy ions cannot go very far and have to return to the spacecraft. As a corollary, this method is not expected to complete mitigation of charging. The mitigation process would stop when the spacecraft potential ϕ_s reaches the emission energy $e\phi_i$ of the ions.

$$e\phi_s \geq e\phi_i$$

For example, positive ions emitted at 1 keV energy are emitted from a spacecraft of -2 kV. The ions cannot escape from, and therefore must return to, the spacecraft.

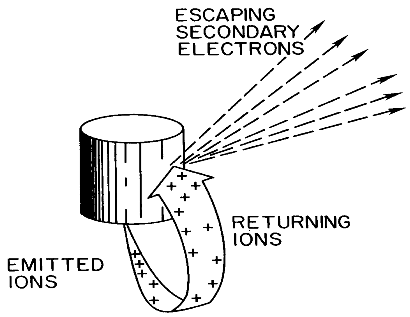

Figure 3. Ion emission from a highly negatively charged spacecraft. The ions are returning. [*Lai,* 1989]

Any secondary electron generated is repelled, carrying away negative charge. However, when the spacecraft potential is reduced to about -1 kV, no further reduction should occur. To prove this theory, we advocate a future experiment using variable ion beam energies to correlate with the limiting levels of charging reduction.

9. The DSCS Charge Control Experiment

Emission of a mixture of low energy ions and electrons, i.e. plasma, would be a reasonable method for active charge mitigation. It would combine the advantages of both the electron and the ion emission methods. The charge control experiment on DSCS is for demonstrating this method. Early results [*Mullen, et al.*, 1997] showed that it worked. The next section will discuss some case studies. The DSCS satellite [*Mullen, et al.*, 1997] is at geosynchronous altitudes. Two dielectric samples, viz., kapton and quartz, are both on the same side of the spacecraft. A field-mill device behind each sample measures the potential difference between the sample and the spacecraft ground. The spacecraft is often in sunlight and therefore the ground is charged slightly positively near 0 V. When the kapton reaches -1.5 kV, a device onboard would automatically trigger the release of an ionized xenon gas (plasma) of energy below 10 eV.

In Figure 4, the top panel indicates the plasma release rate from DSCS, and the lower panel gives the kapton and quartz potentials relative the ground. The blue lines are sunlight indicators on the samples. The step function indicates the "on/off" of the plasma release. Electron (20 to 40 keV) count is also measured but not used. The RHS y-axis labels are in -V. Figure 4 shows that, on Day 43, 1996, the plasma release started at about 11000 sec quickly reduces the potential to the pre-charging level. The release lasted until about 14600 sec.

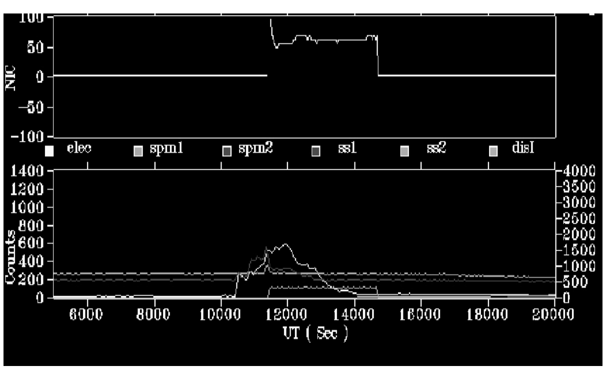

Figure 4. Automatic plasma release (top) on Day 43, DSCS, when the kapton potential reached -1.5 kV (bottom). The plasma reduced the potential immediately.

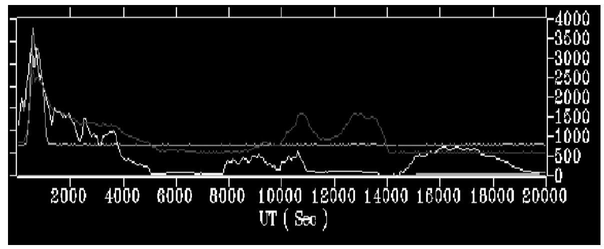

Figure 5. No plasma release on Day 106, DSCS. The kapton potential exceeded -3 kV at about 500 sec UT.

On Day 71, a similar reduction is repeated. However, the potential climbs back up after the plasma release stopped. This demonstrates that active potential control methods, such as low energy plasma releases, have to be on as long as the charging period.

In Figure 5, there is no plasma release on Day 106, 1996. The kapton relative potential climbs to -3.5 kV, which is well beyond the triggering voltage of -1.5 kV. This demonstrates the effect of the absence of potential control.

10. Vaporization Method

Polar molecules, such as water, attach electrons readily. This is why touching a door knob after walking over a carpet on a dry winter day may generate an electrostatic spark whereas no spark occurs on a humid day. Some polar molecule species, such as CCl_4 and SF_6, attach electrons more readily than water [*Christophorous*, 1984]. During evaporation, highly charged droplets may disrupt into several smaller droplets [*Roth and Kelley*, 1983].

$$CCl_4 + e \text{ -> } CCl_3 + Cl^- + \Delta E$$

Lai and Murad [1995] suggested a charge control method by spraying polar molecule liquid droplets all over a spacecraft. The polar liquid droplets attach the electrons on the spacecraft surfaces, evaporate, are repelled by the surface potential, take away the excess electrons, and therefore reduce the surface potential. This method has an advantage that it mitigates metals and dielectric surfaces alike, thereby reducing differential charging. Unlike the ion or plasma release methods, prolonged use of this method does not end up electroplating the entire spacecraft. This is because the charged droplets evaporate away. It is not meant for deep dielectric charging. It should not be used if contamination is a concern.

11. Deep Dielectric Charging

Deep dielectric charging can occur when high energy electrons and ions are deposited inside dielectric materials. Charge accumulation in dielectrics can build up high electric fields [*Violet and Frederickson*, 1993; *Wren*n, 1995]. To mitigate deep charging inside dielectrics, metalized dielectrics are useful. Although introducing metal atoms into random interstitial lattice sites of a dielectric material can alter the conductivity, the spatial distribution of the resultant conductivity inside the material would be inhomogeneous. For many purposes in highly delicate electronics, pure homogeneous conditions may be needed. The recent success [*Manners*, 1995; 1998] of introducing metal atoms into the molecular level instead of the lattice level gives a promising method for mitigating deep dielectric charging. By opening the rings of dielectric polymer molecules, metal atoms can be inserted, resulting in pure homogeneous metallized dielectrics. Preliminary laboratory results [*Balmain*, this proceedings] on discharges in irradiated metal based polymer are encouraging. The conductivity change and control in space needs further study.

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Table. Critical Overview on Mitigation Methods

METHOD	PHYSICS	COMMENT
Sharp Spike	Field Emission	Requires High *E* Field. Ion Sputtering of the Sharp Points. Mitigates Charging of Conducting Ground Surface but Not Dielectrics. Differential Charging Ensues.
Hot Filament	Thermal Electron Emission	Space Charge Current Limitation. Mitigates Conducting Ground Charging Only. Differential Charging Ensues.
Conducting Grids	Prevention of High E Field	Periodic Surface Potential.
Semi-Conducting Paint	Increase of Conductivity on Dielectric Surfaces	Mitigates Dielectric Surface Charging. Paint Conductivity May Change Gradually.
High Secondary Electron Yield Material	Secondary Electron Emission	Mitigates for Primary Electrons at Energies Between the [$\delta(E)=1$] Crossing Points Only.
Electron Beam	Emission of Electrons	Mitigates Conducting Ground Charging Only. Differential Charging.
Ion Beam	Return of Low Energy Ions	Neutralizes the "Hot" Spots. Effective for Both Conducting and Dielectric Surfaces. The Ions May Act As Secondary Electron Generators. Cannot Reduce Potential Below the Emitted Ion Energy.
Plasma Emission	Emission of Electrons and Ions	More Effective Than Electron or Ion Emission Alone.
Evaporation	Evaporation of Polar Molecules which Attach Electrons.	Mitigates Conducting and Dielectric Surface Charging. Not Intended for Deep Charging. May Cause Contamination.
Metal Based Dielectrics	Increase of Conductivity in Dielectrics.	Mitigates Deep Dielectric Charging. Metal Based Material Needs to be Homogeneous to be Useful. Conductivity Change and Control Need to be Studied.