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14. ABSTRACT Interactions between hazardous space plasmas and spacecraft surfaces often result in spacecraft charging. Spacecraft charging may disturb the scientific measurements onboard, affect 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: 1) passive emthods using sharp spikes and high secondary emission coefficient surface materials and 2) 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, mitigation of deep dielectric charging is briefly discussed.
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A Critical Overview on Spacecraft Charging Mitigation 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, affect 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: 1) passive methods using sharp spikes and high secondary emission coefficient surface materials and 2) 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, mitigation of deep dielectric charging is briefly discussed.

Index Terms—Dielectric charging, differential charging, discharging, electron beam, ion beam, mitigation, plasma emission, spacecraft charging, space plasma.

I. INTRODUCTION

ELECTROSTATIC charging [1]–[5] of spacecraft surfaces has long been recognized 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 [6], [7]. 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 milliseconds to come to an equilibrium. The time is longer for differential charging.

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

$$\sum_k J_k(\phi) = 0. \quad (1)$$

In sunlight, photoemission is important [8]. The photoelectron flux normally exceeds the ambient flux except during stormy periods. Thus, charging in sunlight is usually at positive

potentials. Since photoelectrons have only a few electronvolts in average energy, they cannot leave if the surface potential is high. Thus, sunlight charging usually reaches a few volts positive [9]. Therefore, it is not of concern except in situations where differential charging [10] is very significant.

Besides the ambient electrons, ambient ions, and photoelectrons, there are secondary electrons [11]–[13] and backscattered electrons [14], [15], 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 [7], often with high-magnetic activity. High-level charging, up to multiple kilovolts negative, has been observed on many occasions [7].

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° latitudes) where high-energy electrons may come down from high altitudes. In general, charged beam emission [16]–[21] 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 mitigate spacecraft charging, various methods have been, proposed, discussed, or tested in the past decade. They have advantages and disadvantages.

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

II. MITIGATION METHODS

The concept of mitigation of spacecraft charging is defined as a method or design which makes spacecraft charging less severe. It would be ideal to mitigate spacecraft charging by means of prevention, i.e., to prevent the build up of high spacecraft surface potentials relative to the ambient plasma and to each other. In practice, prevention is difficult because the properties of different surfaces are different and the space weather varies sometimes by orders of magnitude. If charging has occurred,

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TABLE I
CRITICAL OVERVIEW OF MITIGATION METHODS

METHOD	TYPE	PHYSICS	COMMENT
Sharp Spike	Passive	Field Emission	Requires High E Field. Ion Sputtering of the Sharp Points. Mitigates Charging of Conducting Ground Surface but Not Dielectrics. Differential Charging Ensues.
Conducting Grids	Passive	Prevention of High E Field	Periodic Surface Potential.
Semi-Conducting Paint	Passive	Increase of Conductivity on Dielectric Surfaces	Mitigates Dielectric Surface Charging. Paint Conductivity May Change Gradually.
High Secondary Electron Yield Material	Passive	Secondary Electron Emission	Mitigates for Primary Electrons at Energies Between the $[\delta(E)=1]$ Crossing Points Only.
Hot Filament	Active	Thermal Electron Emission	Space Charge Current Limitation. Mitigates Conducting Ground Charging Only. Differential Charging Ensues.
Electron Beam	Active	Emission of Electrons	Mitigates Conducting Ground Charging Only. Differential Charging Ensues.
Ion Beam	Active	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	Active	Emission of Electrons and Ions	More Effective Than Electron or Ion Emission Alone.
Evaporation	Active	Evaporation of Polar Molecules which Attach Electrons.	Mitigates Conducting and Dielectric Surface Charging. Not Intended for Deep Charging. May Cause Contamination.
Metal Based Dielectrics	Passive	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.

mitigation for lowering the charging level can be carried out by transporting electrons or ions from the surface concerned to the ambient plasma or to other surfaces.

Emission of electron or ion beams can control the spacecraft potential, if the beam current exceeds the ambient current [16]–[21]. The potential can be clamped at a finite, positive, or negative, value which can be fairly constant temporarily, if the environment does not vary too much. The idea of clamping the potential at a fixed finite value is not quite the same as the concept of mitigation defined earlier, especially if the finite value is far from zero. In this paper, I will focus on mitigation methods only.

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 I.

To transport electrons or ions from spacecraft to the ambient plasma, the well-known approaches are ejection of 1) electrons, 2) ions, and 3) electrons and ions. In approach 1), a device draws electrons from the spacecraft ground and ejects them into space [22]. This method is effective for reducing the negative charge of the spacecraft ground but is ineffective for mitigating the dielec-

tric 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 approach 2), positive ions return to 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 [23]. 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, approach 2) is effective for reducing differential charging. A disadvantage is that prolonged use may end up electroplating the entire spacecraft. Approach 3) is a combination of approaches 1) and 2) and is recommended. These methods are presented in Table I.

III. SHARP SPIKE METHOD

Sharp spikes protruding from charged surfaces generate very high electric fields E . The E field at the spike tip is proportional to r^{-2} , where r is the radius of curvature of the tip. At suffi-

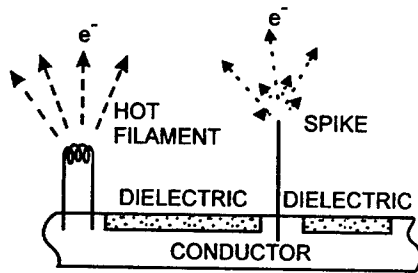


Fig. 1. Electron emissions from a sharp spike and a hot filament.

ciently high fields, field emission of electrons occurs reducing the negative potential of the conducting surfaces connected to the spike (Fig. 1). The current density J of field emission is given by the Fowler–Nordheim equation[24]

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

where A and 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 only draws electrons from the conducting ground only. Thus, differential charging may ensue, as discussed in Section II. 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 electrostatic field of the tip.

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 sputtering the tip inside, because the ion collisional cross section in the coating is larger than 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 [25].

IV. HOT-FILAMENT EMISSION METHOD

In this method, electrons are emitted from hot filaments. The filament materials used are of high melting points. The current density J emitted is given by Richardson's thermionic emission [26]

$$J = AT^2 \exp\left(-\frac{W}{kT}\right) \quad (3)$$

where A is a constant, W is the work function, and kT is 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, electrons are emitted from hot filaments which are not melting. (The use of melting filaments would fall into a different category, 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 Section II). Furthermore, the current emitted may be limited by space charge saturation very near the filament, because the energy of thermal electrons is low.

V. CONDUCTION GRID METHOD

One often heard method is to cover a nonconducting 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.

VI. PARTIALLY CONDUCTING PAINT/SURFACE METHOD

The use of partially conducting paint eliminates the periodic potential problem of Section V and is often effective and convenient. Examples of partially conducting paints are zinc ortho-titanate, alodyne, and indium oxide [27]. Frederickson *et al.* [28] has discussed the properties of a number of spacecraft polymer materials.

The following 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 interstitial 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.

VII. HIGH SECONDARY ELECTRON YIELD METHOD

The secondary electron emission coefficient $\delta(E)$ is a surface material property [11]–[13]. It is a probability that is defined as the ratio of the number of outgoing secondary electrons per unit incoming (primary) electron with energy E . Depending on the surface material and roughness, $\delta(E)$ may exceed unity for a range of energy, typically between 50 and 1600 eV. In spacecraft charging, it is customary to distinguish backscattered electrons from secondary electrons, the former being the outgoing electrons with energy ranging up to nearly that of the primary electron while the latter have energies up to a few electronvolts only. The coefficient $\eta(E)$ [14], [15] of backscattered electrons is usually much less than unity and stays almost constant for all E . In spacecraft charging, the role of $\eta(E)$ is generally insignificant compared with $\delta(E)$ because of the small values of $\eta(E)$. The secondary electron yield $\delta(E)$ increases with the primary electron energy E at low energies until it reaches a maximum $\delta_{\max}(E)$, beyond which $\delta(E)$ decreases with the energy E at high energies. Physically, the excited electrons generated by high energy (and, therefore, penetrating) electrons are so deep inside the solid that they can not find their way out. This is why $\delta(E)$ decreases with E at high energies. In short, we emphasize that there exists an intermediate energy range in which $\delta(E)$ may exceed unity, depending on the surface material and smoothness.

The use of coatings of high secondary electron emission coefficient ($\delta_{\max} \gg 1$) 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

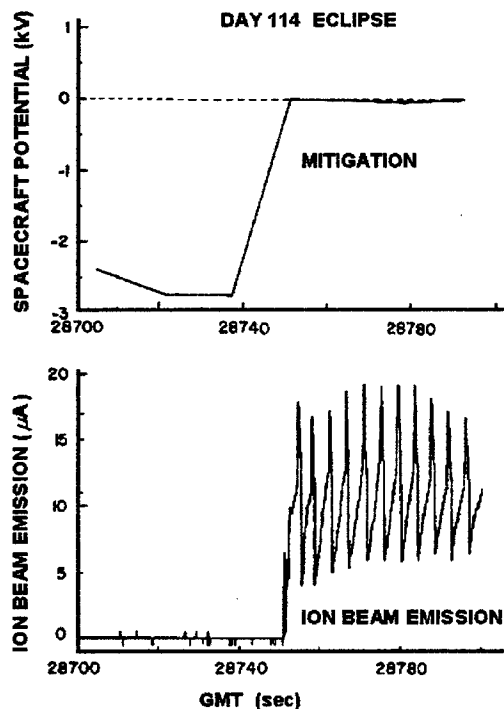


Fig. 2. Mitigation of negative surface potential by means of ion emission from SCATHA [23].

((E) < 1) and, therefore, offers no protection against charging. A case in point is the copperberyllium surface of the SC10 boom [29], [30] on SCATHA. The material has a $\delta_{\max} \approx 4$. When the space plasma became stormy ($kT \gg \text{keV s}$), on Day 114 of the SCATHA mission, the boom suddenly jumped (in a triple-root fashion) from nearly 0 V to a high potential of the order of kilovolt negative [29], [30].

VIII. ELECTRON AND ION EMISSION METHOD

We have stressed (see Section II) 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 a highly negatively charged spacecraft can reduce the potential effectively (Fig. 2). This method has been observed on SCATHA [23], [31] and simulated on computers [32], [33].

An explanation [23] of this apparent paradox is that the low-energy ions cannot go very far and have to return to the spacecraft (Fig. 3). As a corollary, this method is not expected to complete the mitigation of charging. The mitigation process would stop when the spacecraft potential energy $e\phi_s$ reaches the initial energy $e\phi_i$ of the ions emitted from the spacecraft. In other words, the mitigation method using emission of positive ions from negatively charged spacecraft works only if

$$\phi_s > \phi_i. \quad (4)$$

For example, positive ions at -1 keV initial energy are emitted from a spacecraft charged to -2 kV. The ions cannot escape from and, therefore, must return to, the spacecraft. As they return, they not only home in the "hot" spots but also generate secondary electrons. The secondary electrons generated are repelled, carrying away negative charge. However, when the

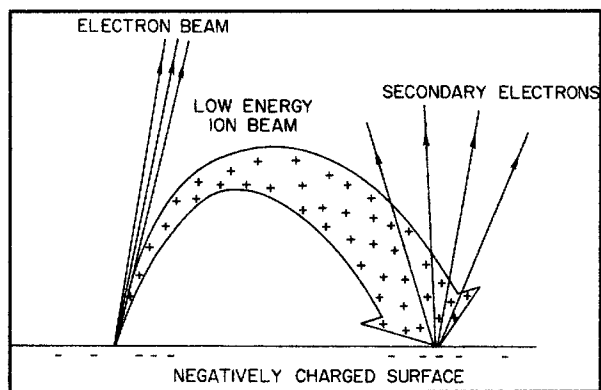


Fig. 3. Emission of electrons and ions from a negatively charged surface. The ions return; the electrons leave.

spacecraft potential is reduced to about -1 kV, no further reduction of spacecraft potential 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.

IX. DSCS CHARGE CONTROL EXPERIMENT

Emission of a mixture of low-energy ions and electrons, i.e., plasma, is a reasonable method for active mitigation of spacecraft charging. It combines the advantages of both the electron and the ion emission methods. The charge control experiment on the DSCS satellite demonstrated this method. The results [34] showed that it worked. We present some case studies.

The DSCS satellite [34] is at geosynchronous altitudes.

Two dielectric samples, viz., kapton and quartz, are on the ram side of the spacecraft. A field-mill device behind each sample measures the potential difference between the sample and the spacecraft ground. When the spacecraft is in sunlight, the spacecraft ground is often charged positively to a few volts only. When the kapton reaches a certain level, -1.5 kV for example, an ionized xenon gas (plasma) of energy below 10 eV can be released automatically or by command.

In Figs. 4 and 5, the top panel indicates the plasma release rate (arbitrary units) from DSCS, and the lower panel gives the kapton (red) and quartz (green) potentials relative to the ground. The zero level of the sample voltage is offset and changes with temperature and radiation exposure over time [34]. Fig. 4 shows the data obtained on Day 67, 1999, the charging level of the kapton sample reaches about -2 kV relative to the spacecraft ground and that of the quartz sample reaches about -1.4 kV. A plasma release starts at about 10 000 UT (s). Note how quickly the potential responses. It promptly decreases to almost the pre-charging level. The release lasts until about 13 000 s.

On Day 116, 1998, a similar plasma release demonstrates mitigation again (Fig. 5). After the release has stopped, another charging event begins at about 10 000 s. This event demonstrates that active potential control methods, such as low-energy plasma releases, have to be on during the charging period. As soon as the plasma release stops, charging can resume again.

In Fig. 6, there is no plasma release on Day 106, 1996. The kapton relative potential climbs to -3.5 kV, which is well be-

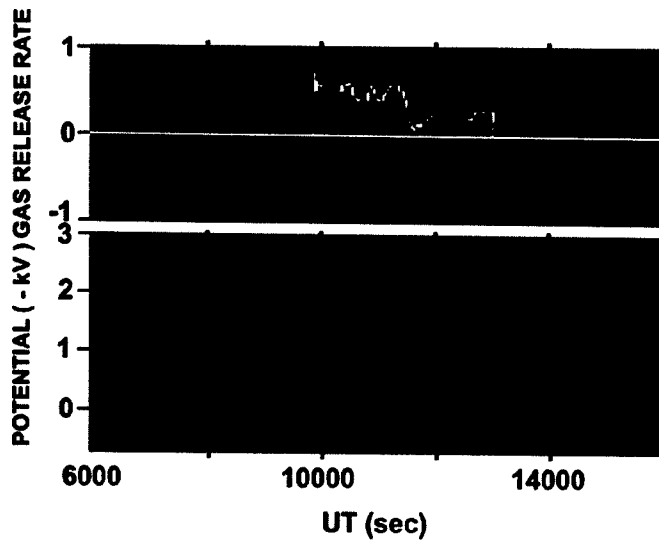


Fig. 4. Mitigation experiment on DSCS, day 67, 1999. The top panel indicates the plasma release rate (arbitrary units) from DSCS, and the lower panel gives the kapton (red) and quartz (green) potentials relative to the ground.

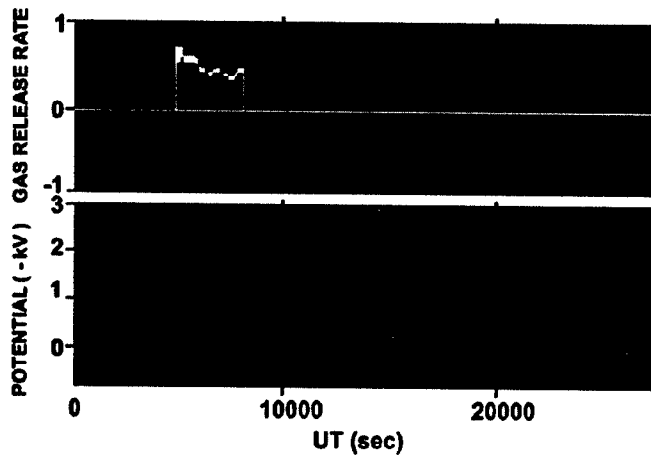


Fig. 5. Mitigation experiment on DSCS on day 116, 1998. (See caption of Fig. 4.)

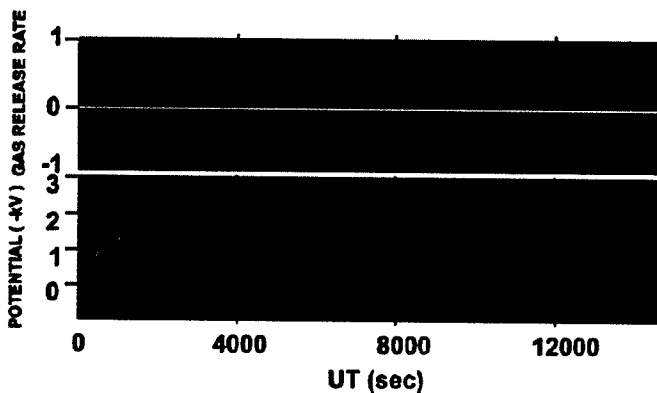
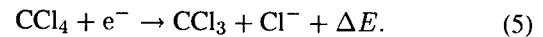


Fig. 6. Mitigation experiment on DSCS, day 106, 1996. (See caption of Fig. 4.)

yond the triggering voltage of -1.5 kV. This demonstrates the effect of the absence of potential control.

X. VAPORIZATION METHODS

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 [35]



Lai and Murad [37]–[39] suggested a new type of charge control methods 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. During evaporation, highly charged droplets may burst into several smaller droplets [36]. The reason for bursting is based on the classical Rayleigh mechanism, viz., the electric field due to the sharp curvature of the evaporating charged droplet eventually exceeds the surface tension. 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.

XI. 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 [40], [41]. 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 [42], [43] 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 [44] on discharges in irradiated metal-based polymer are encouraging. The conductivity change and control in space needs further study.

XII. CONCLUSION

This critical overview on spacecraft charging mitigation methods presents the advantages and disadvantages of each method. Depending on the requirements, the passive methods are sometimes adequate. Active methods are, no doubt, more complicated. It is important to point out that mitigation methods using electron ejections alone (for example, by using sharp spikes or electron beams), may lead to differential charging between various metallic and dielectric surfaces. Using surface materials of high secondary emission coefficients can prevent charging in low temperature space plasmas. When the electron

temperature exceeds the critical temperature of the surface material [7], surface charging occurs. The active method of releasing low energy plasma (electrons and positive ions) [23], or neutral gas which becomes ionized upon release [34], has been demonstrated to work well and is highly recommended. Release of polar molecules [37]–[39] has not been, but should be, demonstrated in space. Mitigation of deep dielectric charging is in its infancy at this time. The method of using metal based dielectrics is promising. Shielding of instruments and development of micro- or nano-electronics are outside the scope of this paper.

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