

# Dynamic Interplay Between Spacecraft Charging, Space Environment Interactions and Evolving Materials

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**Abstract**—While the effects on spacecraft charging from varying environmental conditions and from the selection of different construction materials have been studied extensively, modification of materials properties by exposure to the space plasma environment can also have profound effects on spacecraft charging. Given the increasingly demanding nature of space missions, there is a clear need to extend our understanding of the dynamic nature of material properties that affect spacecraft charging and to expand our knowledgebase of materials' responses to specific environmental conditions so that we can more reliably predict the long term response of spacecraft to their environment. This paper focuses on the effects of environment-induced material modifications of physical properties relevant to spacecraft charging simulations. It also reviews several specific examples in which environment-induced material modifications have significant impact on predicted spacecraft charging.

**Index Terms**—spacecraft charging, space environment, materials testing, conductivity, electrostatic discharge, simulations

## I. INTRODUCTION

Nothing endures but change.  
--Heraclitus of Ephesus (c. 495 BC)

The charge on spacecraft is constantly changing as a result of the dynamic nature of the space environment, the spacecraft orbit, the interactions between environment and spacecraft, and even the evolution of spacecraft materials. While the effects on spacecraft charging from varying environmental conditions [1,2] and due to the materials properties of variously-constructed spacecraft [3,4] have been studied extensively, the modification of material properties by the space plasma environment can also have profound effects on spacecraft charging [5]. Given the increasingly demanding nature of space missions, there is clearly a need to extend our understanding of the dynamic nature of material properties that affect spacecraft charging and to expand our knowledgebase of materials' responses to specific environmental conditions so that we can more reliably predict the long term response of spacecraft to their environment.

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Indeed, Ferguson recently identified “dynamic spacecraft charging models” and “non-static spacecraft materials properties” as two of his four “New Frontiers in Spacecraft Charging”, topics critical to the advancement of the field over the next decade [6]

This paper focuses on methods to assess the effects of environment-induced material modifications on the physical properties which are used as input parameters for spacecraft charging simulations. It also reviews several specific studies in which environment-induced material modifications have had significant impact on predicted spacecraft charging. We present an overview of testing and modeling related to several specific missions that quantify the changes in charging, discharging and emission as material properties are modified by variations in temperature, charge accumulation and electrostatic fields, radiation dose and damage, surface modifications including roughening and contamination, and the duration, rate and history of imposed environmental test conditions. Such changes have been shown to affect measurements of the following material properties: electron-, ion- and photon-induced electron emission yields, spectra, and yield decay curves; dark current and radiation induced conductivity (RIC); electrostatic discharge; electron-induced surface charging and charge decay curves, cathodoluminescence; and ultraviolet/visible/near-infrared reflectivity, transmissivity, absorptivity, and emissivity. We end with a discussion of how a broader materials knowledgebase and a conscious awareness of the dynamic nature of materials can be used in concert with the available modeling tools and materials physics theories to predict and mitigate potential dynamic spacecraft charging problems.

## II. A SIMPLIFIED APPROACH TO SPACECRAFT CHARGING MODELING

Consider a greatly simplified approach to evaluating the environment-induced charging of a hypothetical spacecraft, as illustrated in Figure 1. In the simplest modeling scenarios, the space environment, satellite position and orientation, and materials properties are all assumed to be static. To develop an accurate static model of how the spacecraft charges in response to the space environment—with codes such as Nascap-2k [7], SEE Spacecraft Charging Handbook [8], SPIS [9] or MUSCAT [10] and NUMIT [11-13] or DICTAT [14]—we require three primary elements:

- (i) a description of the static space environment that will influence the spacecraft charging, that is the electron, ion and photon fluxes impinging on the spacecraft as functions of incident particle species, number flux and energy [1];

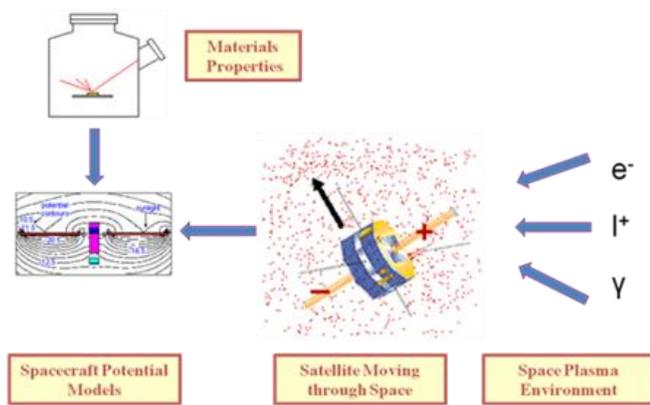


Fig. 1. Simplified schematic diagram of spacecraft charging model components.

(ii) an engineering model of the spacecraft geometry and component material composition [3]; and

(iii) a compilation of the static properties of the component materials that quantify the materials' response to incident fluxes and environmental conditions [15-20].

Assume we begin with a reasonable working knowledge of the static environment and the spacecraft geometry and composition (This is not always a valid or easily quantified assumption!). However, charging results from a complex dynamic interplay between the space environment, spacecraft motion, and materials properties. So what is required to develop "dynamic spacecraft charging models?" Often a range or statistical distribution of temporally varying environmental fluxes—for example, solar cycle variation or solar flares and coronal mass ejections—are considered [21]. Variations in the flux due to the spacecraft position or orientation—for example due to moving in and out of eclipse or the magnetosphere as a result of spacecraft orbits or rotations—are also often considered [22-25]. This requires an accurate description of the juxtaposition of the spacecraft to its environment, on a time scale faster than the response time of the satellite to changes in its environment. Such calculations can predict dramatic changes in both absolute and differential charging of the spacecraft, as well as concomitant changes in electrostatic discharge [2,5,21,26].

### III. "NEW FRONTIERS" FROM A MATERIALS PERSPECTIVE

The objective of this paper is to extend the consideration of "dynamic spacecraft charging models" to include "non-static spacecraft materials properties." We begin by asking, "What specifically do we need to know about the materials properties?" To describe net charge accumulation requires knowledge of the electron yields for incident electron, ion and photon fluxes; that is, how many electrons are emitted or trapped per incident electron, ion or photon. To describe the subsequent rearrangement and dissipation of accumulated charge, we need to know the electron (or other charge carrier) transport properties including the dark current conductivity, RIC, relative dielectric permittivity, and electrostatic discharge threshold electric fields. For charging models these materials properties are most often considered as functions of incident and exit particle species, flux and energy [5,15,17,18,27]. Common modeling assumes that basic materials properties are static, most often using tabulated or

terrestrial measured materials properties for Beginning-of-Life materials.

The problem becomes much more complex when we consider the dynamic evolution of these materials' properties as they are modified through interaction with the environment [28-33]. Such changes in materials' properties can result from variations as a function of depth within the sample,  $z$  [34]; time (often referred to as aging),  $t$  [35-37]; temperature profile,  $T(z,t)$  [37-40]; dose (or energy deposited in the material per unit mass) profile,  $D(z,t)$  [26,41]; dose rate,  $\partial D(z,t)/\partial t$  or variation with depth,  $\partial D(z,t)/\partial z$  [42-45]; total accumulated charge as a function of depth or time,  $\Delta Q(z,t)$  (or equivalently, voltage,  $\Delta V(z,t)$ ) [46-49]; charging rate (or net current),  $\partial Q(z,t)/\partial t$  or charge gradient,  $\partial Q(z,t)/\partial z$  [34,37]; and conductivity profiles as functions of depth and time,  $\sigma(z,t)$  [50].

### IV. EXAMPLES OF DYNAMIC MATERIALS PROPERTIES

Consider five cases of dynamic changes in materials:

1. contamination and oxidation,
2. surface modification,
3. temperature effects, and its coupling with time and aging,
4. radiation effects, and how time comes in to play and,
5. combined radiation and temperature effects.

Recent Utah State University studies related to several specific missions, described below, have highlighted the operational effects of such environment-induced changes on material properties and ultimately on spacecraft charging.

#### A. Case 1: Evolution of Contamination and Oxidation

Perhaps the most obvious of dynamical materials changes occurs when optical reflectivity, absorptivity, and emissivity are appreciably altered by the deposition of contamination or oxidation layers [51,52]. Figure 2(a) is an example of organic contamination layers deposited from outgassing during 69 months low-Earth orbit (LEO) space environment exposure on LDEF [53]. Figure 2(b) illustrates discoloration and flaking due to oxidation (primarily from atomic oxygen) of a Ag sample during 18 months LEO exposure outside the International Space Station on MISSE 6 [46]. Similar exposure of another sample (Fig. 2(c)) completely removed a vapor deposited aluminum coating [24].

Change in reflectivity or absorptivity can have a direct effect on charging [5,33,48,49,52,54,55], as photoemission changes with reflection. Simply put, if incident photons are reflected they do not deposit energy and will not generate photoelectrons; thus photoelectron charging reduces to zero as a surface approaches a perfect reflector. Figure 2(d) plots the equilibrium charging potential for a flat, two-dimensional satellite panel of Au in full sunlight as the fraction of absorbed photon energy decreases from 100% to 0.1% [5]. Calculations were made using the SEE Environmental Handbook for three geosynchronous environment models [8]. As the absorptivity of highly reflective surfaces decreases to levels below 1.5% to 0.2%, so-called threshold charging (a dramatic swing to tens of kilovolts 180 negative charging from a small positive voltage [2], [5], [26]) is observed [5].

Next, consider the effects of contamination and oxidation on electron emission, and ask the question, "How much contamination is sufficient to make a significant change in

spacecraft charging?" During a visit to NASA Glenn Research Center, Carolyn Purvis made a very astute comment in a conversation about potential electron emission investigations of key spacecraft materials and contamination species [56]. She noted (only half jokingly) that "all spacecraft surfaces can eventually be treated as carbon", implying that all exterior surfaces are inevitably covered with organic or C contamination; Fig. 2(a) shows such an example.

This led to studies of electron emission from aluminum/aluminum-oxide [57] and gold surfaces [25], as they were contaminated with thin layers of carbon. Figure 3(a) shows the modification of the secondary electron yield curves with increasing contamination layers (see Fig. 2), going from the Au (red curve) to C on Au (blue curve). This is an extreme case, since Au has a very high yield for a metal ( $\sim 1.8$  total yield) and C has a very low yield ( $< 1$  total yield). These evolving yield curves were then used to predict the equilibrium charging of a planar satellite surface in eclipse for three different common environments, as a function of the contamination deposition time (roughly proportional to contamination thickness); calculations were made using the SEE Environmental Handbook [8]. Threshold charging is predicted as the C contamination thickness reached only 5 to 8 nm, highlighting the potential influence of even modest contamination levels (see Fig. 3 [5, 29]).

### B. Case 2: Surface Modification

Surface modification through roughening is closely related to contamination and oxidation. The micrometeoroid impact evident in Fig. 2(c) [46,58] is an extreme example of physical modification of surfaces. Less dramatic roughening can result from chemical pitting (see Fig. 2(b)) or abrasion. Studies of the changes in optical reflectivity of polished metal surfaces as a function of surface damage through mechanical abrasion show this can result in increased absorptivity and, as described for Case 1, concomitant changes in charging [5,49,52,59]. Similarly, enhanced surface roughness can change electron emission yields, resulting in charging similar to Case I [60].

### C. Cases 1 and 2: Reflectivity as a Feedback Mechanism

The effects of reflectivity changes addressed in Cases 1 and 2 can illustrate how modifications in one physical property can act as a feedback mechanism to enhance the charging caused by other physical properties. For example, changes in reflectivity can lead to changes in charging, which can in turn affect the rate at which contamination accumulates; this can ultimately affect changes in the reflectivity. Such feedback processes [46] are illustrated by MISSE 6 space environment-induced materials degradation experiments [61]. Sets of four samples (gold, aluminum, Black Kapton<sup>TM</sup> or carbon-loaded polyimide, and Thick Film Black<sup>TM</sup> or carbon-loaded polyester) were maintained at fixed potentials (one held at the ground, one at -5 V, one at -15 V and one at +5 V) over the 18 month exposure to the space environment to try and understand charge-enhanced contamination. Here charging (or applied potential) affected the rate at which charged species were attracted to and adhered to the surface, thereby affecting the sample contamination rate and reflectivity.

Similarly, changes in emissivity can lead to changes in the equilibrium temperature of a surface; temperature changes can affect adhesion rate of contaminants or rates of charge

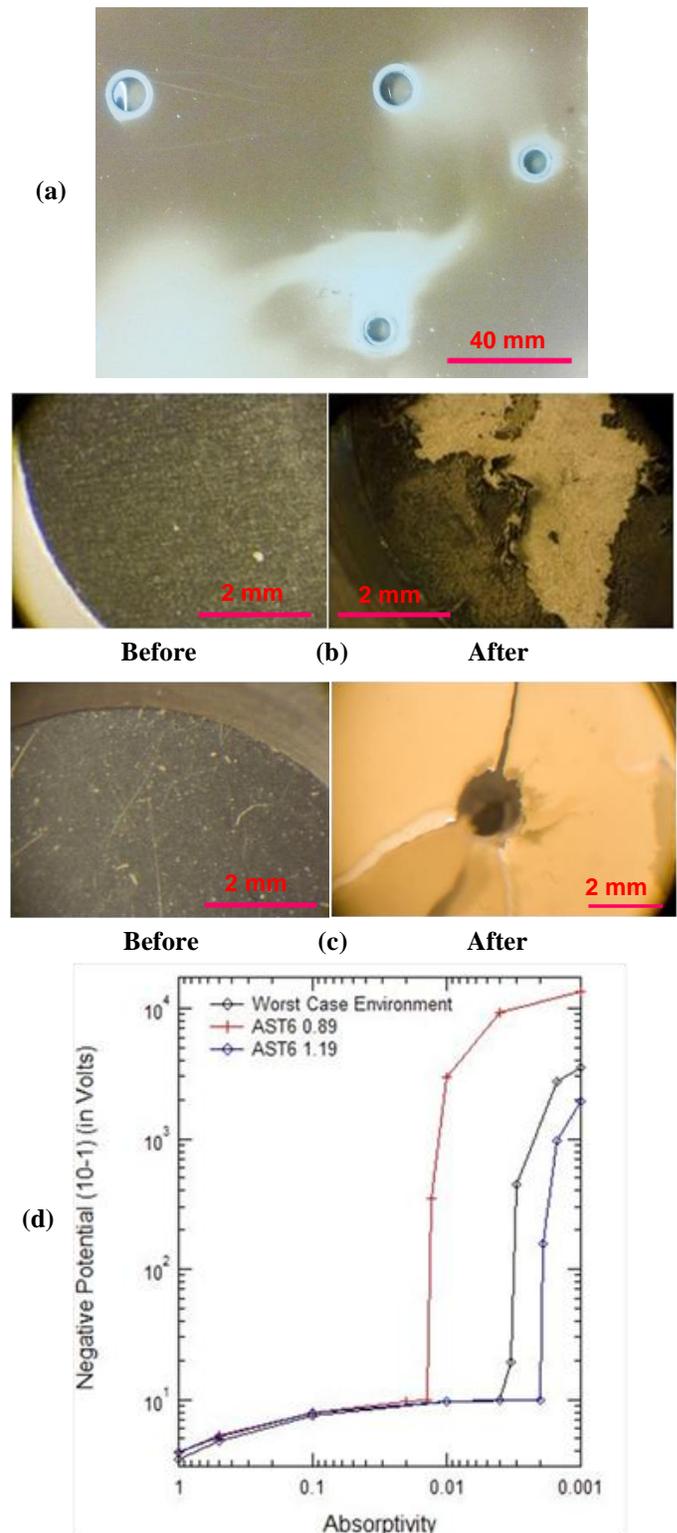


Fig. 2. (a) Organic contamination on white-painted LDEF panel H6. Note shadowing effects in lower left and the masking by washers around the holes. (b) High purity Ag sample before (left) and after (right) space environment exposure [42]. (c) Vapor deposited aluminum on Mylar<sup>TM</sup> (PET) sample subjected to space environment exposure [42]. (d) Equilibrium charging potential for a flat, two-dimensional satellite panel of Au as the fraction of absorbed photon energy decreases from 100% to 0.1%. Curves are for the 4 September, 1997 (squares), worst case (circles), and ATS-6 (triangles) geosynchronous environments in full sunlight. [5].

accumulation and dissipation (see Section IV.F). These, in turn, provide feedback for changes in surface reflectivity and emissivity.

Figure 4 shows another way that surface modifications can lead to changes in reflectivity. A fiberglass and carbon fiber spacecraft structural baffle with a  $\sim 0.1 \mu\text{m}$  thick Au/Cr coating was exposed to a  $\sim 0.05 \text{ nA/cm}^2$ , 22 keV electron beam, leading to severe surface charging and localized electrostatic breakdown. These arcs ablated coating material, leading to a  $\sim 2\%$  decrease in the Au coverage after only 60 min exposure. Reduction in the Au coating coverage decreased the reflectivity and increased the emissivity; these changes could cause changes in the baffle temperature and accompanying changes in the substrate conductivity and charge dissipation rate, electron emission and charge accumulation rate, and electrostatic field strength and capacitance of the sample; all of these can effect the arcing rate and the rate of further coating ablation.

#### D. Case 3: Temperature Effects

There is a very strong temperature dependence, particularly for insulators, in their charge transport properties [5,28,31,32] like conductivity [36,38,40,42-44,50], dielectric constant [22], and electrostatic field strength [35] which affect charge accumulation and dissipation [62]. While this can be significant for any satellite, it is particularly important for satellites experiencing extremes in heat and cold. These include low temperature IR and microwave observatories (e.g., JWST, WISE, WMAP, Spitzer, Herschel, IRAS, MSX, ISO, COBE, Planck) [63] and outer planetary missions (e.g., Galileo, Juno, JEO/JGO, Cassini, Pioneer, Voyager) [70-72]. By contrast, inner planetary and solar missions (e.g., Ulysses, Magellan, Mariner, and Solar Probe Mission) experience very high-temperature extremes [22], [23], [64], [65].

With its cryogenic operating temperatures, the James Webb Space Telescope (JWST) IR observatory [63] is an example in which charging concerns due to low temperatures are of particular importance. JWST observatory design, driven by its science objectives, placed stringent requirements on materials associated with the risks of spacecraft charging. For example, IR observations require most of the satellite to operate at  $\sim 35 \text{ K}$ , which means that almost all the insulators involved become excellent charge integrators due to extremely low conductivities. The long mission lifetime means that these insulators can integrate charge for very long times. JWST has a more open architecture, due to thermal requirements and weight limitations; this increases exposure of some optical elements and blanketing materials to particle fluxes and light. While the observatory location, in orbit around L2, is a more benign environment than some (e.g., polar or Jovian), there can be large variation in fluxes due to large variations in solar activity and trapped radiation as the observatory moves in and out of the Earth's magnetotail. The fixed orientation of the observatory with respect to the Sun means that one side of the sunshield experiences constant solar illumination at near room temperature, while the other cryogenic side with optics and sensors, is in constant eclipse with no photoemission. JWST has large, complex, and sensitive hardware, optics and electronics, particularly susceptible to surface and deep dielectric charging, electrostatic discharge, and electron and photon emission. Cathodoluminescence of materials was also

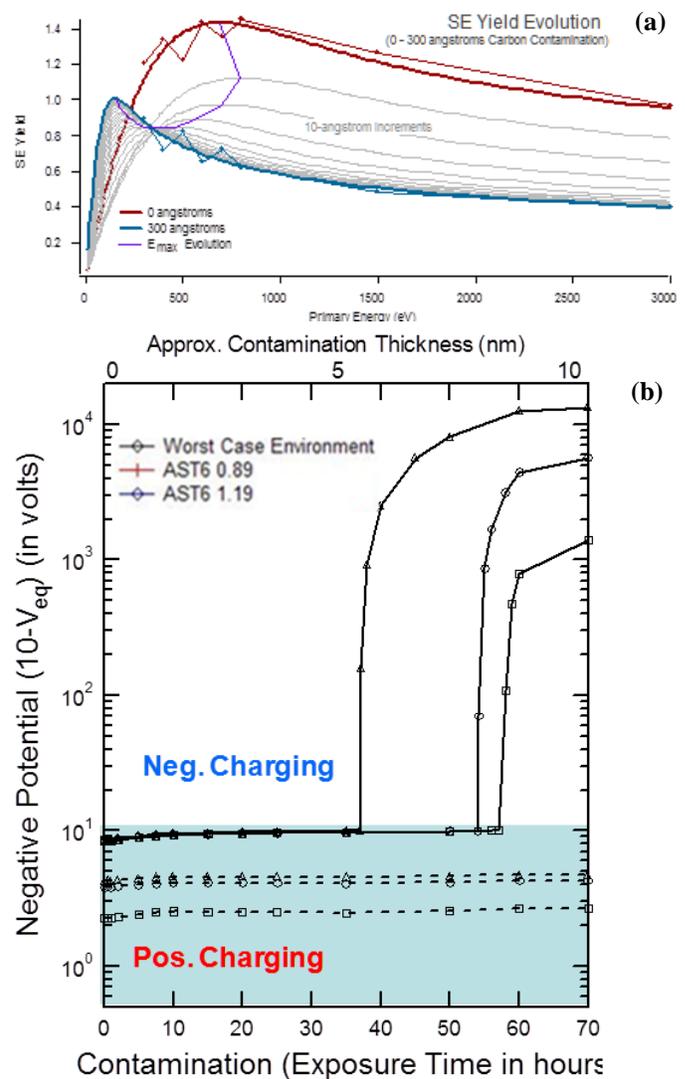


Fig. 3. (a) Evolution of secondary electron yield of Au surface with increasing carbon layer thickness [21]. (b) Equilibrium charging potential for a single material using the time evolution of the secondary electron emission parameters for contaminated gold. Curves are for the 4 September, 1997 (squares), worst case (circles), and ATS-6 (triangles) geosynchronous environments in full sunlight (dashed curves) and eclipse (solid curves) [5].

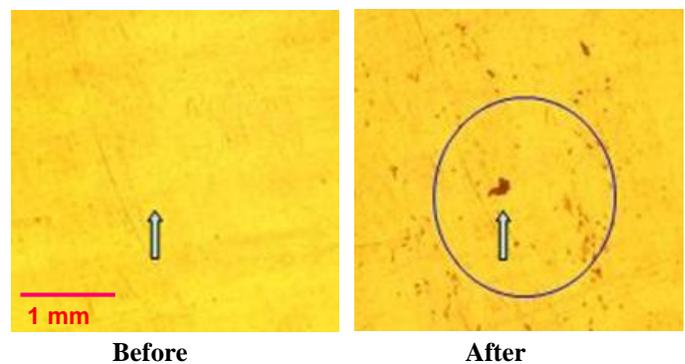


Fig. 4. Damage of  $0.11 \mu\text{m}$  thick Au/Cr coating on fiberglass and carbon fiber composite substrate due to electron beam induced arcing. Arrows indicate location of the largest  $\sim 100 \mu\text{m}$  diameter damage site in the photographs before (left) and after (right) electron exposure. Numerous other smaller damage sites are also visible

an important consideration for JWST, to assure that background light at the instrument detectors is minimized [37,73,74]. A significant and prolonged effort was required [35,37,40-45,47,67] to understand and mitigate the multiple factors presenting charging risks, including the charging characteristics of particular materials at cryogenic temperatures and how exposure to the various charging environments affects these materials. Findings from these investigations were incorporated into the design to retire all charging concerns.

#### E. Case 4: Radiation Effects

Energy deposition from incident electromagnetic or charged particle radiation can modify materials and lead to evolving charging behavior [27,33]. The energy and species of the incident radiation affect the penetration depth and thus the range of damage in the material [66,67]. Extreme radiation total doses, at  $\geq 10^8$  rad or higher for common materials, can cause mechanical or optical damage [27]. Charging behavior can change due to direct modification from radiation damage, or indirectly through changes in electron transport or reflectivity, emissivity and electrostatic discharge. These high total doses can be attained in  $\geq 1$  month in very high radiation environments such as auroral fields in terrestrial (*e.g.*, RBSP mission [24,68,69]) or Jovian environments (*e.g.*, JUNO or JGO/JEO missions [70-72,75]) or in near solar environments (*e.g.*, Solar Probe Plus mission [22,23,64,65] geosynchronous orbit (GEO), LEO and solar wind environments typically require years to produce these total dose levels [1,53,61].

As an example, note the yellowing of a thin surface layer of the polyethylene terephthalate (PET) in Fig. 2(c) which resulted from  $\sim 10^8$  rad of UV irradiation over  $\sim 10$  months exposure on the International Space Station [46,51,61]; contrast this with the whiter material exposed by the micrometeoroid impact and subjected to much less UV radiation. Similar discoloration and a  $\sim 150\%$  increase in absorptivity occurred for polyvinyl fluoride samples with 1 year GEO exposure [24].

At a somewhat lower dosage,  $\geq 10^7$  rad for common materials, changes are often observed in the electron transport and emission properties [76]. This level of total dose can be realized from electron fluxes in GEO and interplanetary orbits over time spans on the order of a year [1], and in the more severe environments noted above over shorter times. These are caused, particularly in polymers, by bond breaking and trap creation [32-37,39,40]. An example of a change in electron yields is provided by yield decay curves of Kapton<sup>TM</sup>, where the change in electron yield is measured as internal charge in the material is gradually accumulated [77]. After modest total dose, the total electron yield asymptotically approaches unity as the charge builds up enough to re-attract a number of emitted secondary electron equal to the number of incident electrons. After exposure to  $\sim 10^7$  rads total dose, the total yield asymptotically approaches a value about 10% higher than unity, as a result of deeply embedded charges trapped in additional defects created by the radiation damage. It is interesting to note that the initial behavior, and unity asymptote, can be recovered by annealing the sample for several hours at  $\sim 320$  K. It is also important to recognize the differences that result from irreparable damage from higher energy (*i.e.*, chemical or deep trap) defects like bond breaking

in contrast to those from lower energy (*i.e.*, physical or shallow trap) defects that cause damage repairable with thermal annealing, like dislocations or bond bending [35].

At even lower doses (or, more correctly, at lower dose rates of  $\geq 10^0$  rad/s), the contributions to conductivity of insulators and semiconductors due to energy deposition from incident radiation—referred to as the radiation induced conductivity (RIC)—become a significant contribution to the overall conductivity of spacecraft materials [28,30,31,42-45,71]. Such dose rates are routinely encountered in GEO and interplanetary orbits, as well as the more severe environments noted above [1]. RIC exhibits pronounced temperature effects [42-44]. Further, at higher doses, RIC can be affected by changes in temperature resulting from the changes in the optical properties of materials modified by the radiation; again, we can have complex feedback mechanisms at work.

#### F. Case 5: Temperature and Dose Effects

As a final example, we consider a combination of temperature and dose effects. The 2005 concept of the Solar Probe Mission (in its original configuration) started at the Earth, flew by Jupiter for a gravitational assist, and then flew to within about 4 solar radii of the Sun [64]. During the mission it was to have experienced a wide temperature range, from  $< 100$  K near Jupiter to  $> 1800$  K near the Sun, and more than five orders of magnitude variation in the solar wind dose rate.

A charging study of the mission was conducted, which focused on the changes in the materials properties over the wide ranges of environmental conditions [22,23]. It modelled the differential charging on the satellite as a function of distance from the Sun, including the orbital dependences of the temperature and dose rate and the resulting changes in properties of the heat shield materials. The most striking change is the more than 12 orders of magnitude roughly exponential increase in conductivity predicted over the temperature range. There are also significant, though less dramatic changes predicted for RIC, dielectric permittivity and electrostatic breakdown field strength. In general, it was found that dose rate decreased as  $\sim r^{-2}$ ,  $T$  decreased as  $\sim e^{-r}$ ,  $\sigma_{DC}$  decreased as  $\sim e^{-1/T}$ ,  $\sigma_{RIC}$  decreased as  $\sim e^{-1/T}$  and permittivity decreased as  $\sim r^{-2}$  (here  $r$  is the orbital radius and  $T$  is satellite temperature).

One might expect charging to be most severe closest to the Sun, where the radiation and charged particle dose rates are highest and charge could build up fastest. Or, one might expect differential charging to be worst furthest from the Sun, where conductivity was lowest at the cold temperatures and low dose rates, thereby limiting charge transport and mitigation of charging through enhanced charge rearrangement over the satellite. However, interplay between these effects led to the prediction of a maximum in differential charging at intermediate distances over the Probe's orbital range at an orbital distance of  $\sim 0.3$  and  $2.0$  AU. A fascinating trade-off was predicted as absolute and differential surface charging increased from increased dose rate at closer orbits, while charge dissipation from T-dependant conductivity increased faster at closer orbits. In the end a peak in the charging was predicted, as the exponential temperature dependence won out over the power law dependence of the dose rate.

## V. CONCLUSION

It is clear from the discussions above that an understanding of the “non-static spacecraft materials properties” that affect spacecraft charging is essential to develop “dynamic spacecraft charging models” to reliably predict the long term time-dependant response of spacecraft to their environment. We have shown numerous examples where accurate dynamic charging models require accurate dynamic materials properties. Environmentally-induced changes in materials properties, like changes in the environment itself, can cause significant changes in the charging behaviour of real satellites that must be considered. It is not sufficient to just use static (Beginning-of-Life and/or End-of-Life) materials properties in charging studies.

The numerous materials properties that must be considered and their dependence on myriad environmental conditions—including variations in temperature, charge accumulation and electrostatic fields, radiation dose and damage, surface modifications, and the duration, rate and history of imposed environmental conditions—presents a daunting task. Further, under certain conditions, environment/material modifications lead to feedback mechanisms which can make charging behaviour even more pronounced and difficult to predict. It is also important to recognize that not all environmentally-induced materials changes conspire to make charging issues worse, but in fact can often act to mitigate charging effects.

However, it is imperative to realize that using foresight, even a rudimentary understanding of the changes in materials properties with changing environmental conditions can provide ways to address these problems. Simply a conscious awareness of the dynamic nature of materials properties can be used in concert with the available modeling tools to foresee and mitigate many potential spacecraft charging problems. For dynamic materials issues in spacecraft charging, as with most materials physics problems, synthesis of the results of different studies and techniques [74,78] and the development of overarching theoretical models [28,29,31-33,35,36,43,44, 47,79] allow extension of measurements over limited ranges of environmental parameters to broader ranges encountered in space.

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## REFERENCES

- [1] D. Hastings, and H. Garrett, *Spacecraft-environment Interactions*, Cambridge University Press, 1996.
- [2] R.C. Olsen, “A Threshold Effect for Spacecraft Charging,” *J. Geophys. Res.*, Vol. 88, 1983, pp. 493-499.
- [3] NASA Technical Handbook, “*Mitigating In-Space Charging Effects—A Guideline*,” NASA-STD-4002A, 2011.
- [4] K. Toyoda, “Effect of material properties on spacecraft charging simulation,” *Proc. 13<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Pasadena, CA, June 25-29, 2014).
- [5] J.R. Dennison, R.C. Hoffmann, and J. Abbott, “Triggering Threshold Spacecraft Charging with Changes in Electron Emission from Materials,” Paper AIAA-2007-1098, *Proc. 45<sup>th</sup> Am. Inst. of Aeronautics and Astronautics Meeting on Aerospace Sci.*, Reno, NV, Jan., 2007.
- [6] D. Ferguson, “New Frontiers in Spacecraft Charging,” *IEEE Trans. Plasma Sci.*, vol. 40, no. 2, pp. 1-5, 2012.
- [7] M. J. Mandell, V.A. Davis, and D.L. Cooke, “Nascap-2k Spacecraft Charging Code Overview,” *IEEE Trans. Plasma Sci.*, Vol. 34, 2006, pp. 2084–2093.
- [8] I. Katz, V.A. Davis, M.J. Mandell, B.M. Gardner, J.M. Hilton, J. Minor, A.R. Frederickson, D.L. Cooke, “Interactive spacecraft charging handbook with integrated updated spacecraft charging models,” AIAA paper AIA 2000-0247, 2000.
- [9] J.-F. Roussel, F. Rogier, G. Dufour, J.-C. Mateo-Velez, J. Forest, A. Hilgers, D. Rodgers, L. Girard, and D. Payan, “SPIS open source code: Methods, capabilities, achievements and prospects,” *IEEE Trans. Plasma Sci.*, vol. 36, no. 5, pp. 2360–2368, Oct. 2008
- [10] T. Muranaka, et al., “Development of Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT),” *IEEE Trans. Plasma Sci.*, Vol. 36, No. 5, 2336-2349, 2008.
- [11] A. R. Frederickson, “Radiation Induced Electrical Current and Voltage in Dielectric Structures,” AFRLTR-74-05823, Air Force Research Laboratory, Hanscom AFB, MA, 1974.
- [12] I. Jun, H. B. Garrett, W. Kim, and J. I. Minow, “Review of an Internal Charging Code, NUMIT,” *IEEE Transactions on Plasma Science*, vol. 36, pp. 2467-2472, 2008. [3]
- [13] Brian Beecken, and Bryan Wallin, “Modeling of Deep-dielectric Spacecraft Charging in Realistic Environments with NUMIT2,” 3<sup>rd</sup> AIAA Atmospheric Space Environments Conference, AIAA paper 2011-3975, 2011.
- [14] J. Sorensen, D. J. Rodgers, K. A. Ryden, P. M. Latham, G. L. Wrenn, L. Levey, and G. Panabiere, “ESA’s Tools for Internal Charging,” *IEEE Transactions on Nuclear Science*, vol. 47, no. 3, pp. 491–497, June 2000.
- [15] L. Levy, D. Sarraill, and J.M. Siguier, “Conductivity and secondary electron emission properties of dielectrics as required by Nascap,” 3<sup>rd</sup> *Euro. Symp. on Spacecraft Materials in Space Envir.* 1993, pp. 113-123.
- [16] W.Y. Chang, J.R. Dennison, N. Nickles and R.E. Davies, “Utah State University Ground-based Test Facility for Study of Electronic Properties of Spacecraft Materials,” *Proc. 6<sup>th</sup> Spacecraft Charging Techn. Conf.*, (AFRL Sci. Center, Hanscom Air Force Base, MA, 2000).
- [17] J.R. Dennison, J. Abbott, R. Hoffmann, A. Sim, C.D. Thomson, and J. Corbridge, “Electronic Properties of Materials with Application to Spacecraft Charging,” *Charge Collector Database [online database]*, NASA Space Environments and Effects Program, NASA Marshall Space Flight Center, October, 2005. URL: [http://see.msfc.nasa.gov/ee/db\\_chargecollector.htm](http://see.msfc.nasa.gov/ee/db_chargecollector.htm). [cited January 10, 2007].
- [18] J.R. Dennison, A.R. Frederickson, N. Green, Nelson, C.E. Benson, J. Brunson, and P. Swaminathan, “Materials Database of Resistivities of Spacecraft Materials,” *Charge Collector Database [online database]*, NASA Space Environments and Effects Program, NASA Marshall Space Flight Center, October, 2005. URL: [http://see.msfc.nasa.gov/ee/db\\_chargecollector.htm](http://see.msfc.nasa.gov/ee/db_chargecollector.htm). [cited January 10, 2007].
- [19] S. Clerc and J.R. Dennison, “Importance of Accurate Computation of Secondary Electron Emission for Modeling Spacecraft Charging,” *Proc. 9<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Epochal Tsukuba, Tsukuba, April, 2005).
- [20] I. Katz, M. Mandell, G. Jongeward, and M.S. Gussenhoven, “The importance of accurate secondary electron yields in modeling spacecraft charging,” *J. Geophys. Res.*, Vol. 91, No. A12, 1986, pp. 13,739-13,744.
- [21] S.T. Lai, “Spacecraft Charging Thresholds in Single and Double Maxwellian Space Environments,” *IEEE Trans. Nucl. Sci.*, Vol.19, 1991, pp. 1629-1634.
- [22] M.M. Donegan, J.L. Sample, J.R. Dennison and R.C. Hoffmann, “Coating-Induced Charging of the Solar Probe Spacecraft: A Materials and Modeling Study of Environmental Extremes,” *J. Spacecraft and Rockets*, 47(1), 134-146, (2010).
- [23] M.M. Donegan, V.A. Davis and M.J. Mandell, “Surface Charging Predictions for Solar Probe Plus,” *Proc. 13<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Pasadena, CA, June, 2014).
- [24] T. Guild, J. Fennell, J. Roeder, M. Chen, and J. Clemmons, “New plasma observations in highly elliptic orbits,” *Proc.11<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Albuquerque, NM, Sept., 2010).
- [25] W.Y. Chang, J.R. Dennison, J. Kite and R.E. Davies, “Effects of Evolving Surface Contamination on Spacecraft Charging,” Paper AIAA-2000-0868, *Proc. 38<sup>th</sup> Am. Inst. Aeronautics and Astronautics Meet. on Aerospace Sci.*, (Reno, NV, Jan. 2000).

- [26] S.T. Lai, M.S. Gussenhoven, and H.A. Cohen, "The Concepts of Critical Temperature and Energy Cutoff of Ambient Electrons in High Voltage Charging of Spacecraft," *Proc. 17<sup>th</sup> ESLAB Symposium*, edited by D. Guyenne and J.H. A. Pedersen, European Space Agency, Noordwijk, The Netherlands, pp. 169-175, 1983.
- [27] J.R. Srour and J.M. McGarrity, "Radiation effects on microelectronics in space," *Proc. IEEE*, Vol. 76, No. 11, 1443-1469 1988.
- [28] A.M. Sim and J.R. Dennison, "Comprehensive Theoretical Framework for Modeling Diverse Electron Transport Experiments in Parallel Plate Geometries," Paper Number, AIAA-2013-2827, *5<sup>th</sup> AIAA Atmospheric and Space Environ. Conf.*, (San Diego, CA, June, 2013).
- [29] P. Molinié, "A Review of Mechanisms and Models Accounting for Surface Potential Decay," *IEEE Trans. Plasma Sci.*, 40(2), 167-176, 2012.
- [30] P. Molinié, R. Hanna, T. Paulmier, M. Belhaj, B. Dirassen, D. Payan, and N. Balcon, "Photoconduction and radiation-induced conductivity on insulators: a short review and some experimental results," *Proc. 12<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Kitakyushu, Japan, May, 2012).
- [31] H.J. Wintle, "Conduction Processes in Polymers," in *Engineering Dielectrics – Volume IIA: Electrical Properties of Solid Insulating Materials: Molecular Structure and Electrical Behavior*, R. Bartnikas, Eds. (Am. Soc. Testing and Materials, Philadelphia, PA 19103, 1983).
- [32] K.C. Kao, *Dielectric Phenomena in Solids* (Elsevier Academic, San Diego, 2004), pp. 41-114.
- [33] F.J. Campbell "Radiation Effects of the Electrical Properties of Solid Insulation," in *Engineering Dielectrics – Volume IIA: Electrical Properties of Solid Insulating Materials: Molecular Structure and Electrical Behavior*, American Society for Testing and Materials, R. Bartnikas, Editors, (American Society for Testing and Materials, Philadelphia, PA 19103, 1983).
- [34] J.R. Dennison and L.H. Pearson, "Pulse Electro-Acoustic (PEA) Measurements of Embedded Charge Distributions," *Proc. SPIE Optics and Photonics Conf.*, Vol. 8876, 2013, 887612-1-887612-11.
- [35] A. Anderson, J.R. Dennison, A. M. Sim and C. Sim, "Electrostatic Discharge and Endurance Time Measurements of Spacecraft Materials: A Defect-Driven Dynamic Model," *Proc. 13<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Pasadena, CA, June, 2014).
- [36] J. Dekany, A.M. Sim, J. Brunson, and J.R. Dennison, "Electron Transport Models and Precision Measurements in a Constant Voltage Chamber," *IEEE Trans. Plasma Sci.*, 41(12), 2013, 3565-3576.
- [37] A.E. Jensen, J.R. Dennison, G. Wilson, J. Dekany, C.W. Bowers, R. Meloy and J.B. Heaney, "Properties of Cathodoluminescence for Cryogenic Applications of SiO<sub>2</sub>-based Space Observatory Optics and Coatings," *Proc. SPIE Cryogenic Optical Systems and Instr. Conf.*, Vol. 8863, 2013, pp. 88630A1-88630A10.
- [38] J. Dekany, R.H. Johnson, G. Wilson, A. Evans and J.R. Dennison, "Ultrahigh Vacuum Cryostat System for Extended Low Temperature Space Environment Testing," *IEEE Trans. Plasma Sci.*, 42(1), 2014, 266-271.
- [39] M. Belhaj, N. Guibert, K. Guerch. P. Sarraihl, N. Arcis, "Temperature Effect on the Electron Emission Yield of Bn-SiO<sub>2</sub> Under Electron Irradiation," *Proc. 13<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Pasadena, CA, June, 2014).
- [40] J.R. Dennison, A.M. Sim, J. Brunson, S. Hart, J.C. Gillespie, J. Dekany, C. Sim and D. Arnfield, "Engineering Tool for Temperature, Electric Field and Dose Rate Dependence of High Resistivity Spacecraft Materials," Paper Number AIAA-2009-0562, *Proc. 47<sup>th</sup> Am. Inst. Aeronautics and Astronautics Meet. on Aerospace Sci.*, 2009.
- [41] R.C. Hoffmann and J.R. Dennison, "Methods to Determine Total Electron-Induced Electron Yields Over Broad Range of Conductive and Nonconductive Materials," *IEEE Trans. Plasma Sci.*, 40(2), 298-304 (2012).
- [42] J.R. Dennison, J. Gillespie, J.L. Hodges, R.C. Hoffmann, J. Abbott, A.W. Hunt and R. Spalding, "Radiation Induced Conductivity of Highly-Insulating Spacecraft Materials," in *Application of Accelerators in Research and Industry*, Am. Instit. Phys. Conf. Proc. Series, Vol. 1099, ed. F.D. McDaniel and B. L. Doyle, (Am. Instit. of Phys., Melville, NY, 2009), pp. 203-208.
- [43] J.C. Gillespie, J.R. Dennison and A.M. Sim, "Density of State Models and Temperature Dependence of Radiation Induced Conductivity," *IEEE Trans. Plasma Sci.*, 2015, in press.
- [44] A. Tyutnev, V. Saenko, and E. Pozhidaev, "Experimental and Theoretical Studies of Radiation-Induced Conductivity in Spacecraft Polymers," *Proc. 13<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Pasadena, CA, June, 2014).
- [45] J.A. Roth, R. Hoffmann, and J.R. Dennison, "Effects of Radiation Induced Conductivity on Electrostatic Discharge in Insulating Materials," *Proc. 1<sup>st</sup> AIAA Atmospheric and Space Environments Conf.* (San Antonio, TX, 2009).
- [46] J.R. Dennison, A. Evans, D. Fullmer, and J.L. Hodges, "Charge Enhanced Contamination and Environmental Degradation of MISSE-6 SUSpECS Materials," *IEEE Trans. Plasma Sci.*, 40(2), 254-261 (2012).
- [47] A.E. Jensen and J.R. Dennison, "Defects Density of States Model of Cathodoluminescent Intensity and Spectra of Disordered SiO<sub>2</sub>," *IEEE Tran. Plasma Science*, 43(9), 2015, 2925-2932.
- [48] J.R. Dennison, C.D. Thomson, and A.M. Sim, "The effect of low energy electron and UV/VIS radiation aging on the electron emission properties and breakdown of thin-film dielectrics," *Proc. 8<sup>th</sup> IEEE Dielectrics and Electrical Insulation Soc. (DEIS) Intern. Conf. on Solid Dielectrics (ICSD)*, IEEE, Piscataway, NJ, 2004, 967-971.
- [49] S.T. Lai, K. Cahoy, M. Martinez-Sanchez, "Trapped photoelectrons during spacecraft charging in sunlight," *Proc. 13<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Pasadena, CA, June, 2014).
- [50] J.R. Dennison and J. Brunson, "Temperature and Electric Field Dependence of Conduction in Low-Density Polyethylene," *IEEE Trans. Plasma Sci.*, 36(5), 2246-2252, 2008.
- [51] K. Peterson and J.R. Dennison, "Atomic Oxygen Modification of the Nanodielectric Surface Composition of Carbon-Loaded Polyimide Composites," *Am. Phys. Soc. Four Corner Sect. Meeting*, Univ. Denver, Denver, CO, October, 2013.
- [52] S.T. Lai. "Importance of Surface Conditions for Spacecraft Charging", *J. Spacecraft and Rockets*, Vol. 47, No. 4 (2010), pp. 634-638.
- [53] W. Kinard, R. O'Neal, B. Wilson, J. Jones, A. Levine, and R. Calloway., "Overview of the space environmental effects observed on the retrieved Long Duration Exposure Facility (LDEF)," *Adv Space Res.*, Vol. 14, No. 10, pp. 7-16, 1994.
- [54] S.T. Lai, and M. Tautz, "Aspects of Spacecraft Charging in Sunlight," *IEEE Transaction on Plasma Sci.* Vol. 34, No. 5, 2006, pp. 2053-2061.
- [55] D.C. Ferguson, "Effect of Space Coverglass Degradation on GEO Spacecraft Charging," *Proc. 13<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Pasadena, CA, June, 2014).
- [56] C. Purvis, private communications, 1995.
- [57] R.E. Davies, and J.R. Dennison, "Evolution of secondary electron emission characteristics of spacecraft surfaces," *J. Spacecraft and Rockets*, Vol. 34, No. 4, 1997, pp. 571-574.
- [58] K. Peterson and J.R. Dennison, "Space Impact Ejecta Model of Micrometeoroid Collision on MISSE-6," *Am. Phys. Soc. Four Corner Sect. Meeting*, New Mexico Institute of Mining and Technology, Socorro, NM, Oct., 2012.
- [59] A. Evans and J.R. Dennison, "The Effects of Surface Modification on Spacecraft Charging Parameters," *IEEE Trans. on Plasma Sci.*, 40(2), 291-297 (2012).
- [60] V. Nistor, L.A. Gonzalez, L. Aguilera, I. Montero, L. Galdo, U. Wochner, and D. Raboso, "Multipactor Suppression by Micro-structured Gold/Silver Coatings for Space Applications," *Appl. Surf. Sci.*, 2014.
- [61] K.K.D.E. Groh, B.A. Banks, J.A. Dever, D.A. Jaworske, S.K. Miller, E.A. Sechkar, S.R. Panko, "NASA Glenn Research Center's Materials International Space Station Experiments (MISSE 1-7)," *Earth* (2008), 10(11), 10-11.
- [62] J.L. Hodges, A.M. Sim, J. Dekany, G. Wilson, A. Evans, and J.R. Dennison "In Situ Surface Voltage Measurements of Layered Dielectrics," *IEEE Trans. Plasma Sci.*, 42(1), 2014, 255-265.
- [63] P.A. Lightsey, C. Atkinson, M. Clampin, and L.D. Feinberg, "James Webb Space Telescope: large deployable cryogenic telescope in space", *Opt. Eng.* 51(1), 011003 (2012).
- [64] NASA, "Solar Probe: Report of the Science and Technology Definition Team," NASA/TM-2005-212786, 2005. Available at [http://solarprobe.gsfc.nasa.gov/SolarProbe\\_STDT2005.pdf](http://solarprobe.gsfc.nasa.gov/SolarProbe_STDT2005.pdf).
- [65] A. Hilgers, D. Fontaine, and D. Delcourt, "Investigation of Spacecraft Plasma Interactions on Mercury Mission Orbiter," *Proc. 13<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Pasadena, CA, June, 2014).
- [66] G. Wilson and J.R. Dennison, "Approximation of Range in Materials as a Function of Incident Electron Energy," *IEEE Trans. on Plasma Sci.*, 40(2), 305-310 (2012).
- [67] G. Wilson, J.R. Dennison, A. Evans and J. Dekany "Electron Energy Dependent Charging Effects of Multilayered Dielectric Materials" *IEEE Trans. Plasma Sci.*, 41(12), 2013, 3536-3544.
- [68] K. Kirby, et al., "Radiation Belt Storm Probes—Observatory and Environments," pp. 59-125, in *The Van Allen Probes Mission*, ed. N. Fox, J.L. Burch, (Springer New York, 2014).

- [69] J.I. Minow, E.M. Willis, and L.N. Parker, "Characteristics of Extreme Auroral Charging Events," *Proc. 13<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Pasadena, CA, June, 2014).
- [70] H. B. Garrett, W. Kim, I. Jun, and R. W. Evans, "Spacecraft Charging at Europa," *Proc. 13<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Pasadena, CA, June, 2014).
- [71] W. Kim, I. Katz, J.R. Anderson, H.B. Garrett, "Surface Charging Study of the Juno Spacecraft using Nascap-2k," *Proc. 13<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Pasadena, CA, June, 2014).
- [72] F. Cipriani, D. Rodgers, A. Hilgers, "Surface Charging of the Jupiter Icy Moons Explorer (JUICE)," *Proc. 13<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Pasadena, CA, June, 2014).
- [73] J. Dekany, J. Christensen, J.R. Dennison, A.E. Jensen, G. Wilson, T. Schneider, C.W. Bowers and R. Meloy, "Variations in Cathodoluminescent Intensity of Spacecraft Materials Exposed to Energetic Electron Bombardment," *IEEE Trans. Plasma Sci.*, 2015, *in press*.
- [74] J.R. Dennison, A.E. Jensen, J. Dekany, G. Wilson, C.W. Bowers and R. Meloy, "Diverse Electron-induced Optical Emissions from Space Observatory Materials at Low Temperatures," *Proc. SPIE Cryogenic Optical Systems and Instr. Conf.*, Vol. 8863, 2013, pp. 88630B1-88630B15.
- [75] J. Lee, E. Lee, J. Seon, K.-H. Kim, and J. Lee, "Relationship between internal charging and particle fluxes in the outer radiation belt," *Proc. 13<sup>th</sup> Spacecraft Charging Techn. Conf.*, (Pasadena, CA, June, 2014).
- [76] A.R. Frederickson and J.R. Dennison, "Measurement of Conductivity and Charge Storage in Insulators Related to Spacecraft Charging," *IEEE Trans. Nucl. Sci.*, Vol. 50, No. 6, pp. 2284-2291, 2003.
- [77] R. Hoffmann, "Electron-Induced Electron Yields of Uncharged Insulating Materials," M.S. Thesis, Dept. Physics, Utah State Univ., Logan, UT, 2010.
- [78] W.Y. Chang, J.R. Dennison and P. Judd, "Measurements of Electronic Properties of Conducting Spacecraft Materials with Application to the Modeling of Spacecraft Charging," Paper AIAA-2000-0870, *Proc. 38th Am. Inst. Aeronautics and Astronautics Meeting on Aerospace Sci.*, (Reno, NV, 2000).
- [79] S. A. Khatipov, "Radiation-Induced Electron Transport Processes in Polymeric Dielectrics (A Review)," *High Energy Chem.*, Vol. 35, No. 5, pp. 291-307, 2001.



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