Internal Charging Hazards in Near-Earth Space During Solar Cycle 24 Maximum: Van Allen Probes Measurements

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***Abstract*— The Van Allen Probes mission provides an unprecedented opportunity to make detailed measurements of electrons and protons in the inner magnetosphere during the weak solar maximum period of cycle 24. The MagEIS suite of sensors measures energy spectra and fluxes of charged particles in the space environment. The calculations show that these fluxes result in electron deposition rates high enough to cause internal charging. We use omnidirectional fluxes of electrons and protons to calculate the dose under varying materials and thicknesses of shielding. We show examples of charge deposition rates during the times of nominal and high levels of penetrating fluxes in the inner magnetosphere covering the period from the beginning of 2013 through mid-2014. These charge deposition rates are related to charging levels quite possibly encountered by shielded dielectrics with different resistivities. Using a simple model, we find temporal profiles for different materials showing the long-term charge deposition rate and estimated charge density levels reaching high levels. These levels are an indicator of internal charging rates that satellites might possibly experience in the inner magnetosphere. The results are compared with charge densities that can induce internal electrostatic discharge.**

***Index Terms*— Internal electrostatic discharge (IESD), penetrating radiation, spacecraft charging.**

I. Introduction

DIELECTRIC materials used in spacecraft such as circuit boards, cable insulation, and thermal blankets will build up an imbedded charge when exposed to energetic electrons of the space environment. If the electric field resulting from the buried charge exceeds the breakdown levels for the dielectric, an arc can occur. If the arc directly couples to a conductor leading to a sensitive device, it can lead to failure. Such arcs can also cause an internal electrostatic discharge (IESD), which produces an electromagnetic pulse that can indirectly couple to electronics causing upsets and phantom commands.

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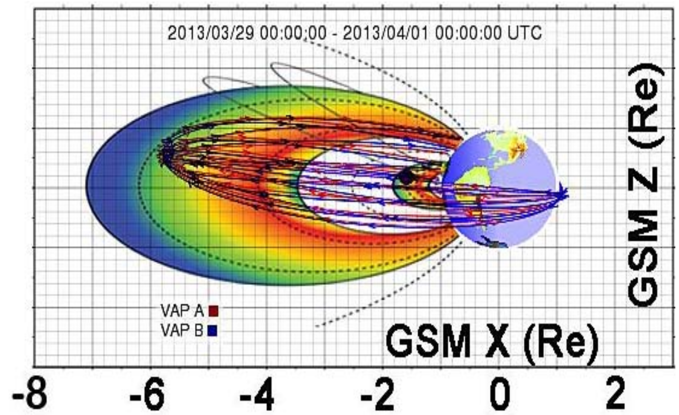

Fig. 1. Van Allen Probes orbit trajectories for five orbit traversals in April 2013 during the study period. An approximate location of the inner and outer radiation belts are shown for context to illustrate the comprehensive coverage of the regions of interest.

For each space vehicle development program, an examination of susceptibility to surface and internal charging needs to be performed as part of its reliability program. Components and subsystems need to be examined for susceptibility to charge buildup and resultant IESD by performing material inventories, resistivity analyses, and shielding assessments. Typically, dielectric materials can be susceptible to deep dielectric charging and IESD when the material is exposed to an average energetic electron flux exceeding 1×10^5–2×10^5 electrons/(cm$^2 \cdot$ s) and achieves an imbedded charge density greater than few 10^{10} electrons/cm^3 [6], [7]. The buildup of charge density in a dielectric is a function of the flux of electrons incident on the dielectric minus the electrons conducted out of the material. If the resistivity of the dielectric material is high, an electric field will build up in the dielectric as the charge density increases. If the rate of leakage of charge from the dielectric to ground is much lower than the rate of charge deposition, the field in the dielectric can buildup until it either reaches a steady-state voltage or until an IESD occurs. Internal charge deposition rates are usually estimated by determining the effect of shielding on a specified electron spectrum. The specified spectra are based on a worst case or an extreme spectrum so as to ensure that remediation will cover nearly all likely spectra that a mission could encounter. For example, some missions specify a 90% or a 95% confidence level spectrum, which indicates that the most

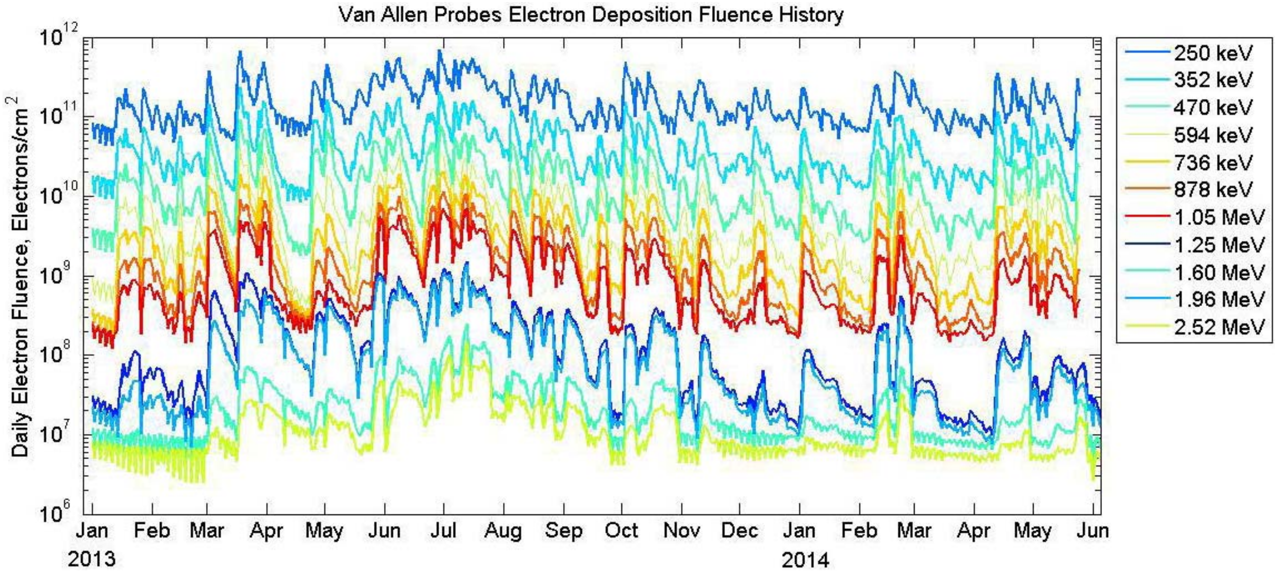

Fig. 2. Daily averaged fluences calculated from the MagEIS electron fluxes from January 1, 2013 to June 8, 2014.

extreme spectrum would not exceed the specified spectrum more than 10% or 5% of the time, respectively. However, such spectra are available for only a few orbits at this time [5], [8], [9]. In orbits where such spectra are not available, the orbit averaged spectrum multiplied by a selected factor is used instead. We have observed that factors ranging from 10 to 25 have been used, often without an underlying justification given. In other cases, the limited data from an orbit have been used to scale a spectrum to match the extreme values observed as an estimate to those observed as an estimate to the extreme spectrum. In addition, the specified spectrum is often used to assess the charge deposition over some fixed time period (e.g., 24 h) based on the assumption that the peak spectrum would not last longer nor would the dielectrics stay charged for long periods. This methodology assumes that the dielectrics inherent resistivity and capacity provides a similar time for bleeding off the charge. However, laboratory testing has shown that the resistivities of many dielectrics in hard vacuum are orders of magnitude higher than those determined by the standard ASTM D149 tests (see [3] and references therein). Even the safe shielding specification in [6] made the assumption that the charge accumulation would be on time scales of ~10–24 h and did not consider that the real charge loss time constants could greatly exceed such periods.

In the following, we show the orbit-averaged charge deposition rates calculated from Van Allen Probes particle flux observations in highly elliptical orbits for different threshold energies over the recent solar maximum. We use the particle flux histories to simulate the charge deposition on different spacecraft materials with different resistivities. These values can be used to estimate internal charging rates for such orbits. We also show the distribution of charging rates so that one can select the confidence limits appropriate to a particular reliability level. In addition, we show the possible level of charge density build up if dielectric resistivities take on values comparable of those carefully measured in hard vacuums.

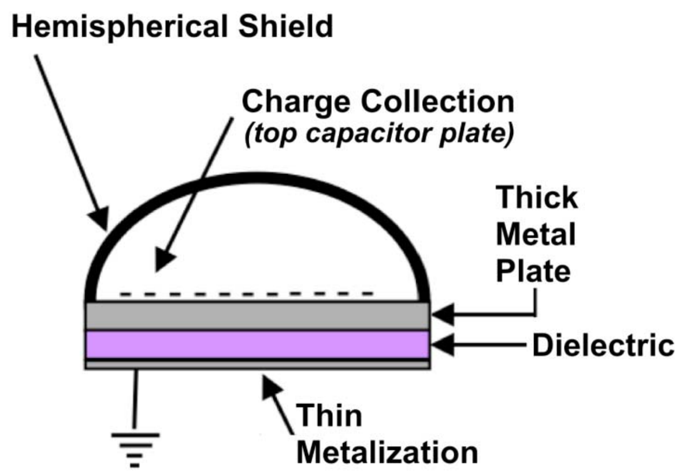

Fig. 3. Diagram of a capacitive model used to estimate charge decay rates as a function of dielectric resistivity. One side of the capacitor receives the charge onto a thick conductor from the environment. The other side is grounded through thin metallization on the dielectric. Adapted from [4].

II. Data Used

In this paper, we used the daily averaged electron fluence taken from the MagEIS electron spectrometers over an energy range from 40 keV to 3 MeV in the highly elliptical orbit of the Van Allen Probes. The two Van Allen Probes are in highly elliptical orbits of 605 km $\times$ 30 140 km and 625 km $\times$ 30 544 km with a 10° inclination on either side of the equator. The orbit period is 9 hours. The slightly different apogees allow simultaneous measurements to be taken over the full range of observatory separation distances several times over the course of the mission. The vehicles are spin stabilized with the spacecraft spin axis 15°–27° off the sun angle. More details of the satellite orbits are in [10]. Fig. 1 shows an example of the satellite trajectories over five orbits at the beginning

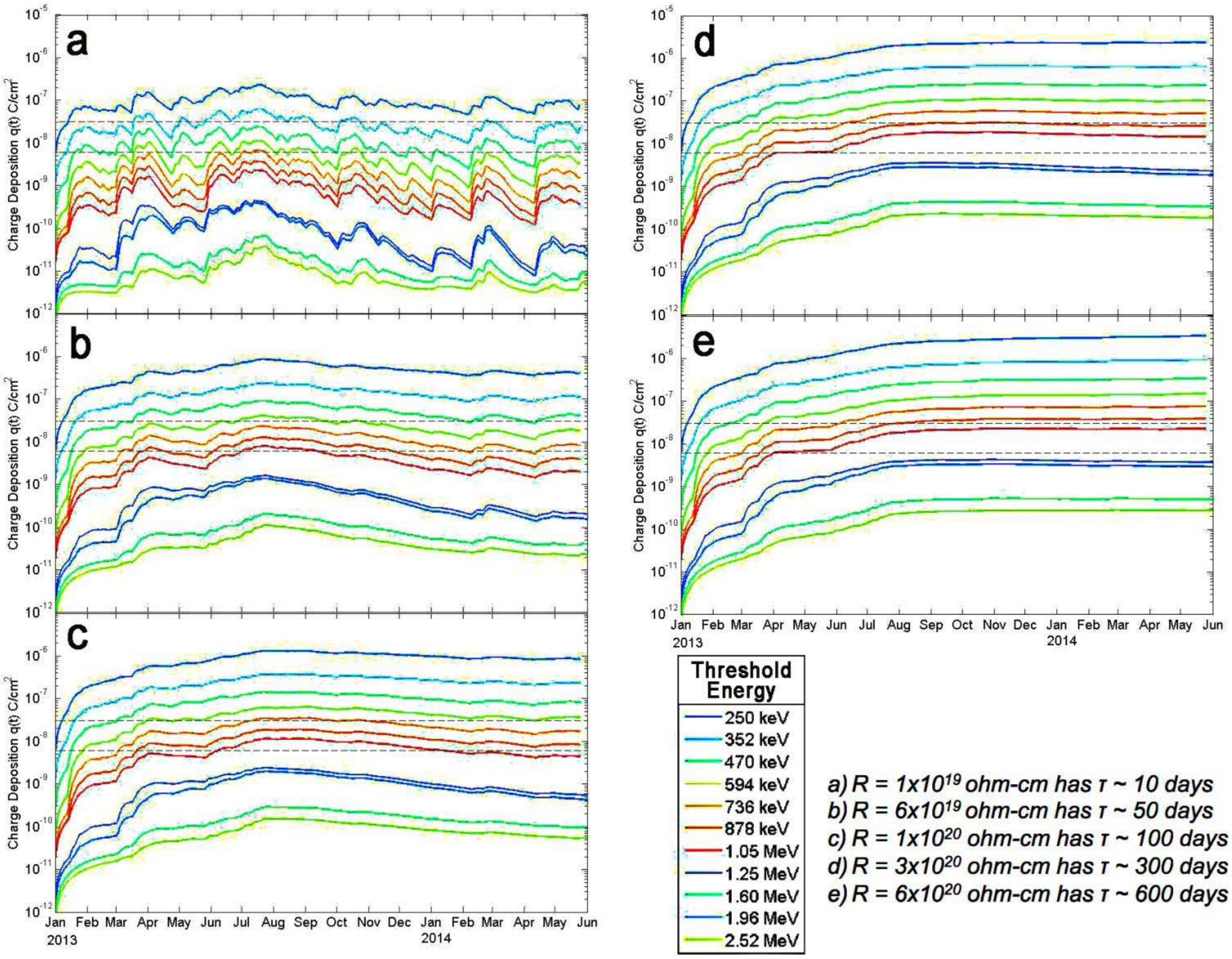

Fig. 4. Charge deposition calculated from daily fluences observed by MagEIS and shown in Fig. 2, in the same fashion as [4]. Panels (a) through (e) show the charge deposition levels for dielectrics with resistivities that correspond to time constants of 10, 50, 100, 300, and 500 days, respectively. Dashed lines show the estimated charge density at which typical dielectrics will discharge as determined by laboratory testing (see text for more details).

of April. The three panels show the orbit paths in the *xy*, *yz*, and *xz* planes in the GSM coordinate system. Because the orbit is elliptical, it traverses a wide range of radial distance from the earth (also known as L-space, where L is nominally a measure of the geocentric distance in earth's radii to the magnetic equator) at both low and high magnetic field intensities. This results in all regions of the inner and outer radiation belts being sampled at a statistically high level. Since the energetic particle flux in the near-earth space environment is mainly found within the radiation belts and the flux intensity can vary by many orders of magnitude on timescales of days, the extensive sampling afforded by the Van Allen Probes orbit ensures accurate characterization of the electron flux histories used to determine charge deposition rates in this paper. Details on the energy ranges, performance, and calibration of the MagEIS spectrometers can be found in [1] and references therein.

III. Observations

A. Electron Charge Deposition Rates

The electron charge deposition rates are obtained by accumulating the omnidirectional electron fluxes over $\sim$24 h (approximately three Van Allen Probe orbits) and converting them to electron fluence per day. Fig. 2 shows electron daily fluence levels in electrons/cm^2 above threshold energies (colored traces) specified by the various MagEIS energy channels. The energy channels correspond to 250, 352, 470, 594, 736, 878, 1050, 1250, 1600, 1960, and 2520 keV. The study period covers 1 January 2013 through 8 June 2014 during the current solar cycle maximum.

Solar cycle 24 is unusual in that marks the lowest level of recorded activity for over 100 years [11]. The low activity of this current cycle was preceded by an extended solar minimum from October 2005 to November 2009, ranked the eighth longest quiet period in the sunspot number record [12]. Despite the overall lull in solar activity during the current solar cycle, Fig. 2 shows a number of low-level enhancements in the radiation belt during small geomagnetic storms from high speed stream interaction regions and small solar transient disturbances.

B. Estimates of Electron Charge Accumulation in Dielectrics

Following [3], we model the charge deposition behind the sensor shield as falling on a capacitor composed of a thin dielectric bounded by a thick top conductor and thin bottom metallization as shown in Fig. 3 and in Fig. 5 of [4]. The electrons that pass through the hemispherical shielding are assumed to embed themselves in the top conductor at a rate consistent with the electron fluences observed in Fig. 2. As the charge on the top plate builds up, an electric field is generated across the dielectric. The field draws electrons through the dielectric to the grounded metallization. The bulk resistivity of the dielectric limits the flow of electrons. In essence, we have virtual device that can charge quickly in response to high electron fluence resulting in high electric fields across the dielectric. For simplicity (and to generate results consistent with those in [3]), this method of evaluation neglects the electron induced electron yield, which contributes to the development of the surface potential. Photoyield also contributes to the surface potential; however, in this model the dielectric is under shielding, so we can neglect the effect of incident photons. A more realistic model including these effects will be included in a future publication.

Using this simple model configuration, electrons continuously flow to ground at a rate controlled by the electric field and the bulk resistivity of the dielectric. Once electron flow has come to equilibrium (which may take hours or days to reach), the charge flow to ground will have an e-folding time constant related to the bulk resistivity. Again, following [3] and [4], we use the electron fluence history along with a set of assumed levels of resistivity for the dielectric to assess the possible rates of change in the charge density of our internally charging floating conductor. The higher the dielectric resistivity, the slower will be the flow of electrons to ground.

Applying the electron fluence histories given in Fig. 2, we obtain sets of electron charge densities that will wax and wane as the electron fluence increases and decreases. The higher the assumed bulk resistivity for the dielectric is, the more slowly the charge densities will fall as the electron fluence falls as shown in Fig. 4. The plots show that if the dielectric has a very high resistivity, then successive electron fluence increases can cause the charge density stored on the capacitor to continue to rise because the time between fluence increases is short compared with the e-folding time to bleed charge off. Even though the electron fluence can drop to zero between isolated fluence bursts, the stored charge continues to build with each burst. We note that laboratory testing has shown that dielectrics will arc when charge density exceeds 6–20 nC/cm^3 [dashed black lines in Fig. 4(a)–(e)] (see [3] and references therein).

The charge density history for the higher resistivity materials takes on a smooth character with higher average charge density levels. Take for example the charge density profiles in Fig. 4(e). The corresponding resistivity is approximately a representative of Teflon. In fact, Teflon may have an even higher resistivity [4]. As Fig. 4(e) shows for the Van Allen Probes orbits, the charge density of such a high resistivity material is estimated to be relatively constant for energies above a threshold of $\sim$736 keV [Fig. 4(d)] even during the low activity levels of the current solar maximum. Since the Van Allen Probes spend much of their time in the heart of the outer radiation belt, they experience higher electron fluence levels and thus higher charge deposition rates than the HEO orbit and nearly the same fluence levels and charge deposition rates as the MEO orbit shown in [4, Figs. 6 and 7].

IV. Conclusion

The charge deposition history for electrons with energy $\geq$40 keV can be highly variable on time scales of days to weeks in orbits that sample the earth's radiation belts such as the Van Allen Probes. As far as IESD is concerned, knowing the vacuum resistivity of the materials used is more important than worrying about when in the solar cycle they will be on orbit because the high resistivity materials can store charge for many orbital periods. Highly resistive dielectrics, such as Teflon/PTFE, could be near breakdown level nearly all the time if only lightly shielded. This is of particular importance to electrical cables that use such dielectrics (coax and triax) and that are routed outside the heavily shielded spacecraft body to exterior mounted payloads. Moderately shielded highly resistive dielectrics will have electrical stress levels conducive to IESD for months to years following periods where electron fluxes reach extreme levels. Elliptical orbits that traverse the outer radiation belts carry a greater risk of IESD because they experience higher charge deposition rates than other orbits nearly all the time.

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