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Spacecraft Charging: Observations and Relationship to Satellite Anomalies

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14. ABSTRACT

Many studies have shown that satellite charging can cause anomalies on spacecraft. The SCATHA (Spacecraft Charging AT High Altitude) satellite was flown to determine the conditions and document the existence of satellite charging. It was instrumented to measure charging and to detect electrostatic discharges that occurred. Discharges were observed and could be characterized as either surface or internal charging related. More recently, observations were made of charging on a high-inclination Earth-orbiting (HEO) satellite. Both the HEO and SCATHA charging data show occurrence patterns that are consistent with the expected motions of substorm-injected plasma electrons. The SCATHA data was taken in the near-geosynchronous orbit and the HEO data was taken over a wide range of altitudes in a 63° inclination orbit. The SCATHA data showed that the internal discharge rates were related to the intensities of energetic electrons (Ee >100 keV) and that, statistically, their occurrence peaked near local noon. These results can be understood in terms of the flux levels of electrons that can penetrate shielding. The HEO energetic particle data have been combined with CRRES, GOES, and GPS data to estimate some worst-case levels of internal charging fluxes.

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1. Introduction

Satellite charging is a simple concept, and its analog is easily experienced by anyone who shuffles his or her feet across a rug on a dry day. The charge transferred by friction causes the person to become charged relative to their surroundings. The result can be a surprising or painful electric discharge from the person to a nearby object. The same kind of discharge, called an electrostatic discharge or ESD, can occur on a satellite when its surfaces or interior elements build up extreme levels of excess charge relative to the space plasma or to neighboring satellite components. The electromagnetic energy from ESD can be coupled into electronics causing upsets and damage

The problems caused by charging on satellites have been compared to other environmental effects in a recent Aerospace Corporation study.[1] Some of the main results of this study are summarized in Table 1, which indicates that satellite charging is responsible for more than half (161 out of 198) of the documented environment-related anomalies. The study results also showed (Table 2 of Ref. 1) that ESD caused about 50% of the lost or terminated missions associated with environmental effects. Thus, the issue of satellite charging is very serious from the perspective of the threat it poses for satellites in the inner magnetosphere.

Table 1. Distribution of Records by Anomaly Diagnosis

Diagnosis	Number of Records
ESD—Internal Charging	74
ESD—Surface Charging	59
ESD—Uncategorized	28
Single-Event Effects	85
Damage	16
Micrometeoroid/Debris Impact	10
Miscellaneous	26

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2. Satellite Surface Charging

In the early 1970's, it became clear that many of the anomalies on geosynchronous satellites occurred in the near midnight to dawn region of the magnetosphere,[2] as shown in Figure 1. This was reminiscent of the path that the hot substorm-injected electrons from the magnetotail take as they drift around the magnetosphere. Thus, it was thought that the anomalies might be substorm related and could be caused by satellite charging.

As we know, tens of keV electrons do not penetrate the satellite surface materials but reside near the surface. The incident plasma and the solar UV also interact with materials to generate secondary electrons. The satellite's surface materials will take on a charge such that the net current between the surfaces and the plasma is zero under quiescent conditions. The result is that the surface voltages would not be zero. The sunlit areas are usually slightly positive and the shadowed areas are usually negative relative to the plasma at "infinity. If the surface was a conductor, the potential of the surface would be uniform and either positive or negative relative to the plasma.

Electrons are the dominant source of initial plasma current to a satellite because of their higher speed. The photo- and secondary-electron currents from a surface are often higher than the plasma-electron current to it during average conditions. In a "hot" plasma (average electron energy ≥1 keV), a satellite's shadowed regions will generally charge negative to significant potentials, sometimes several kilovolts. If the "hot" plasma is also relatively dense, then even the sunlit regions of a satellite can charge to significant levels.

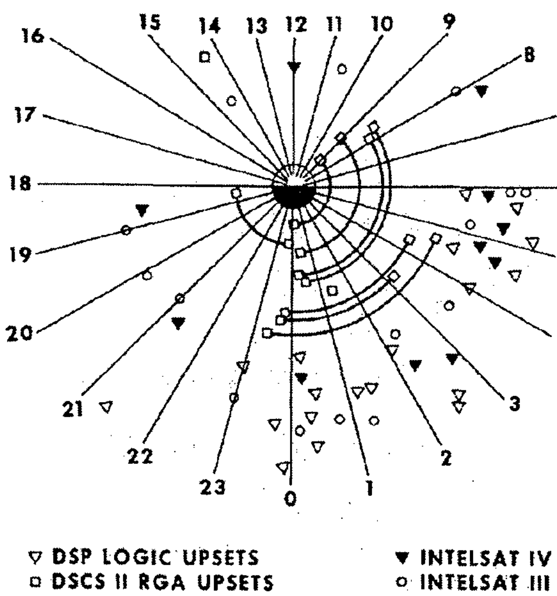

Figure 1. Local time dependence of anomalies observed on geosynchronous satellites.

Because the secondary and photoelectron currents are different for every material, satellites generally have a range of surface potentials. The differences in potential between adjacent materials, such as thermal blankets and metallic structure, can lead to local electrical stress. This can result in vacuum arcs. It is also possible for a surface material to discharge into space (a so-called "blow-off" discharge) or to structure ground. The resulting ESD currents can electromagnetically couple into electronic circuits and subsystems, causing mischief or damage.

2.1 Surface Charging Environment.

The plasma electrons are the primary source of current that causes high levels of charging. They usually have energies of a few hundred to a several thousand eV, but generally less than 50 keV. Above 25 to 30 keV, the electrons start to penetrate thin materials, such as monolayer thermal blankets or paints, and generate internal charging of thick materials or the underlying structure. In the regions where the magnetospheric plasma is very dense, it is usually "cold" and doesn't cause significant charging. The equatorial ionosphere and the plasmasphere are such regions. If the plasma is very dilute (density $< 0.05\ cm^{-3}$), photoemission dominates, and a satellite may have a positive potential. This occurs, for example, in the near-Earth tail lobes.

During substorms, a hot plasma is injected from the magnetotail into the nightside, high-altitude, equatorial regions. These freshly injected electrons cause dramatic changes in the satellite charging levels. They gradient-curvature drift towards dawn. This leads one to predict that the greatest negative charging levels will be observed beyond the plasmasphere in the midnight through dawn regions of the magnetosphere.

2.1.1 Equatorial Satellite Surface Charging.

Figure 1 shows the local time distribution of early geosynchronous satellite anomalies.[2] (The radial position is arbitrary.) Most of the anomalies occurred in the 2300 to 0600 LT region. Such plots convinced the scientific and engineering communities that satellite charging was a problem that needed to be understood, and that mitigation strategies needed to be found. Such observations have since been linked to substorm plasma injections specifically and magnetic activity in general.

An example of a substorm injection of hot plasma and the subsequent charging of the SCATHA satellite[4] is shown in Figures 2 and 3. Figure 2 shows spectrograms of the plasma data from SCATHA. The substorm plasma injection occurred near 0040 UT. The satellite structure potential is identified by the fact that "cold" ions (bottom) were accelerated into the instrument, creating a bright, low-energy feature in the spectrogram. These ion "acceleration" features show that the satellite was charged negatively. The electron fluxes (top) were reduced, and the spectrum shifted by the effective "retarding" potential of the satellite.

These data were used to generate a temporal profile of satellite potential relative to the plasma, as shown in Figure 3 (top). Figure 3 (bottom) shows the potential of a Kapton thermal blanket sample. The Kapton sample started to charge with the substorm onset, and its potential relative to the satellite frame continued to increase while the frame potential stayed low, initially. As SCATHA entered the Earth's penumbra near 0046 UT, its frame charged to high levels (Ref. Figs. 2 and 3). Upon entering the umbra, the differential potential between the Kapton and the satellite frame decreased rapidly.

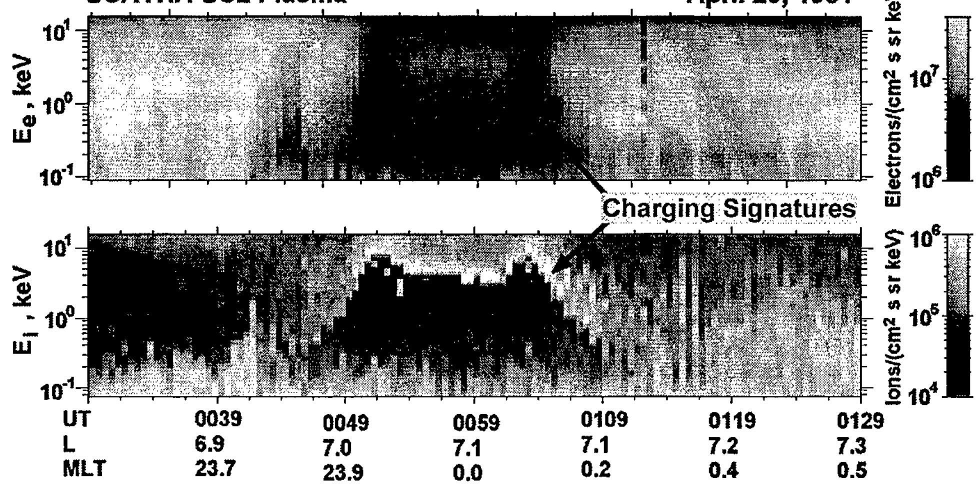

Figure 2. SCATHA plasma spectrogram showing evidence of satellite charging in both electrons (top panel) and ions (bottom panel).

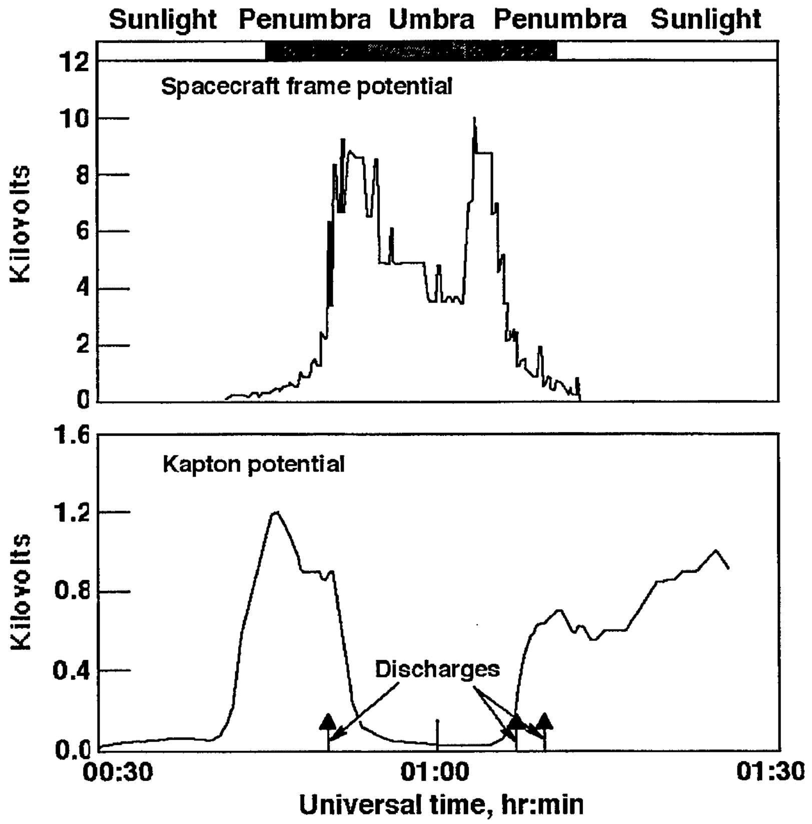

Figure 3. Example of substorm-related charging near midnight. The spacecraft frame potential is shown in the top panel, and potential of a Kapton thermal blanket in the bottom panel. The potentials were negative.

The sequence reversed as SCATHA exited the eclipse. ESDs were detected during the periods of rapid change in potential associated with the eclipse entry and exit. This example contains many of the common features of surface charging observed by SCATHA. These are: (1) each dielectric material and the satellite frame responded differently; (2) ESD tended to occur when the potentials were changing rapidly; and (3) the potentials were never stable during an event.

Data similar to the Figure 3 Kapton potentials were used to produce statistical maps of surface charging for the SCATHA orbit. One such map is shown in Figure 4. It shows that surface charging in the near-geosynchronous orbit region follows the same pattern as that expected for the drift of a few to tens of keV electrons. Figure 4 shows local time features similar to those observed in geosynchronous satellite anomaly maps, like Figure 1.

2.1.2 High-Altitude Off-Equator Satellite Surface Charging

Observers recognized that the auroral displays were associated with disturbances in the high-latitude geomagnetic field. The events associated with the auroral forms and magnetic disturbances were denoted "auroral substorms or magnetic substorms." Over time, it was recognized that the auroral substorm, magnetic substorm, and plasma injections were different aspects of the same process called a magnetospheric substorm.

The correlation between magnetic activity and satellite charging becomes clear when one examines the relationship between satellite anomalies and a magnetic disturbance index like Kp. Figure 5 shows such a comparison for a set of HEO (Highly Elliptical Orbit) satellite anomalies.[5,6] The increase in anomaly occurrence with increasing Kp means that the HEO anomalies were preferentially associated with the high levels of magnetic activity. [The normal Kp distribution peaks near Kp = 2 and falls steeply toward smaller and larger values.]. The local time pattern of the anomalies and

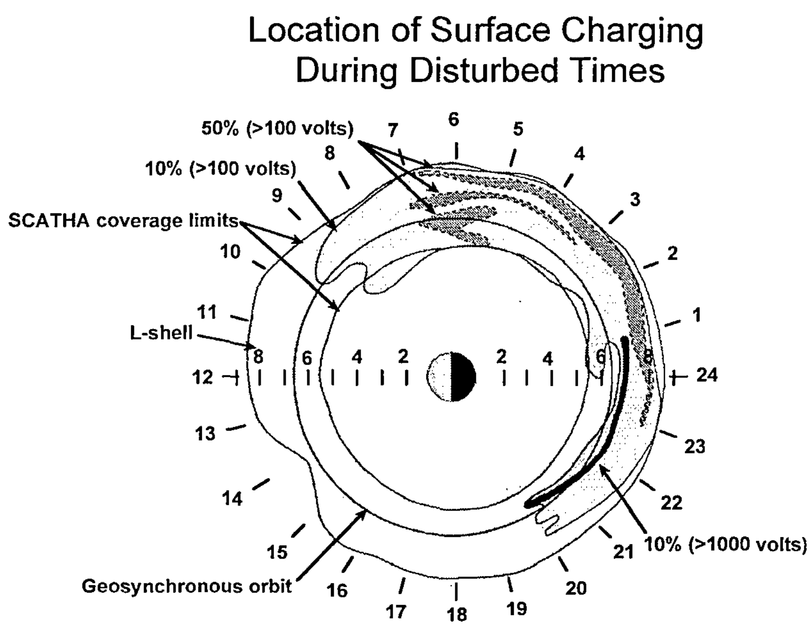

Figure 4. Location of surface charging as determined by SCATHA.

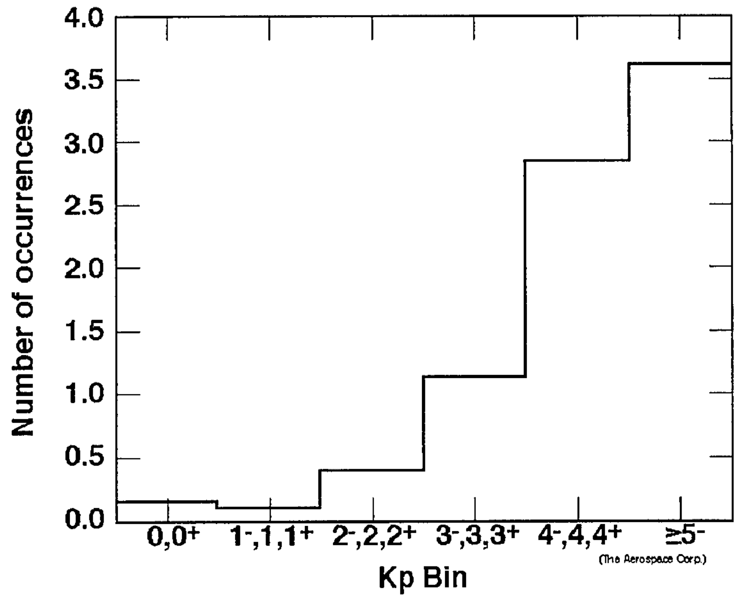

Figure 5. Anomaly occurrence versus Kp.

charging, the Kp dependence of the anomalies, and the direct observation of satellite charging in response to substorms links the satellite charging and anomalies to the substorm process. However, we must make it clear that while surface charging can be tied to substorms, not all substorms will lead to such satellite charging.

The auroral extension of the plasma sheet, from a few hundred km upwards, contains a mixed plasma, combining low-density, high-temperature electrons from the equator with cool, high-density ionospheric electrons. During substorms, density cavities can appear at ionospheric altitudes, and the average electron energies rise. This combination of lower background density and raised electron energies can cause satellites to charge in the low-altitude auroral regions.[3] This has been borne out by the fact that some DMSP satellites have charged to fairly high levels,[7] and one has experienced an anomaly associated with such charging.[3]

The plasma sheet, plasma that maps to the auroral regions, exists all along high-latitude field lines. Any satellite that intercepts these field lines is connected to equatorial charging regions and can experience surface charging. This was borne out by the occurrence of anomalies on HEO satellites.[5] [HEO orbits have high apogees and latitudes (~40,000 km and 63°, respectively).] They cross magnetic-field lines that map to the equator from well inside to well beyond geosynchronous orbit. If one uses a magnetic-field model to project the position of the satellites along the field lines to the magnetic equator for each anomaly observed, one obtains a local time and equatorial distance pattern for the anomalies like that shown in Figure 6. It is immediately obvious that the spatial distribution of these HEO anomalies mirrors the pattern expected for substorm-injected electrons and satellite charging near the magnetic equator. This pattern convinced us that the HEO satellites were suffering surface charging-related anomalies.

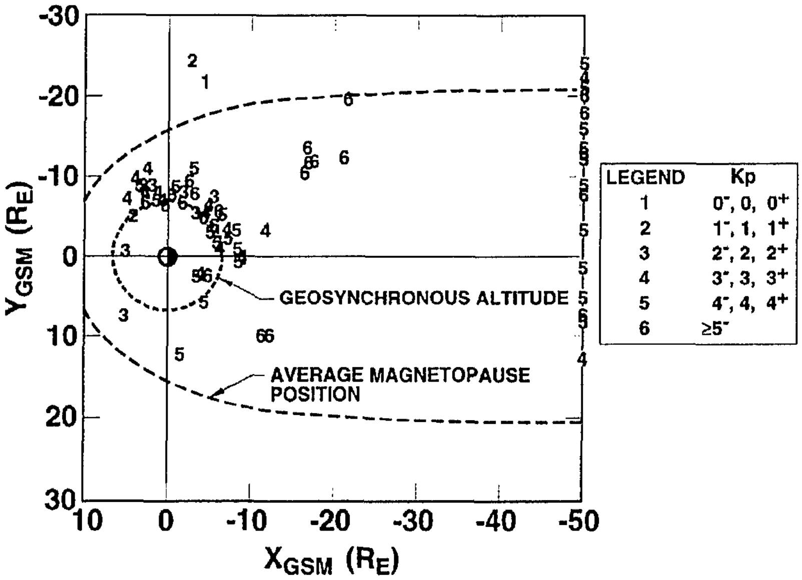

Figure 6. HEO anomalies mapped to magnetic equator. Symbols indicate the associated Kp value.

One of the authors flew a plasma analyzer on a HEO satellite.[5,6] Figure 7 shows where the HEO satellite structure experienced charging to less than −100 V. The squares [■] and dots [●] correspond to the lower and upper bounds in **L**, respectively, of charging observed during satellite traversals. The local time pattern of charging is consistent with that observed by SCATHA (Figure 4), except it extends to higher **L**. The lower **L** bound of the charging starts just outside the nominal plasmapause, extending somewhat lower in L than the region covered by SCATHA. The upper **L** range of charging extends well into the auroral field line regions. This would be consistent with our present understanding of which spatial regions are accessible to substorm injected electrons in the nightside inner magnetosphere.

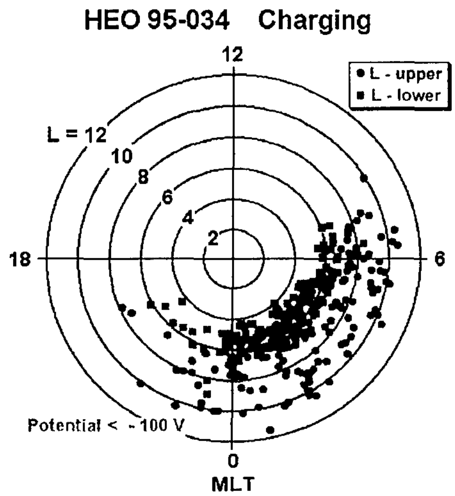

Figure 7. Occurrence of >100 V satellite frame potentials in HEO/Molniya orbit. The symbols mark the upper and lower bounds in L for each charging interval.

2.1.3 Complexities of Surface Charging

Figures 3 and 4 showed both the apparent simplicity and inherent complexity of the surface charging process. The correlation of the satellite frame charging with the increased mean energy of the electrons caused by substorm injections is, at first look, quite simple. However, Figure 3 shows that tracking the satellite frame potential is not the whole answer. The potential of the materials on the satellite do not track the frame potential but respond in their own way. The differential potentials that develop between the satellite's surface materials and the grounded structure are complex, in fact, more complex than even these figures indicate.[8,9] The hazards caused by spacecraft charging result from complex interactions between the space environment and the materials and the ESD and electronics on a spacecraft.

There is some evidence that the shape of the distribution function is important to surface charging. At low energies, the secondary-electron yield from surfaces is high. Thus, if the low-energy flux is large, it may prevent spacecraft from charging. This makes it difficult to predict charging periods and to understand whether satellites with mixed surface materials will charge and to what degree. More importantly, will ESD occur, and will the satellite's electronics respond? Figure 8 provides a good example of what the space weather community is up against in trying to predict satellite charging. It shows, as the solid line, the electron spectrum that was observed during a sunlight charging event. It produced the most and largest discharges on SCATHA for any single day.[10] An "average" electron spectrum, taken on 15 non-charging days, is also shown. The vertical bars represent the range of flux variability during the 15 days. The extreme charging environment differs little from the maximum in normal daily variations. It is only slightly higher in the 10–100 keV range. Yet, the response of SCATHA to this difference was quite extraordinary.

Thus, a link has been forged between observations of surface charging, predictions of how injected electrons drift, observations of ESD noise, and satellite anomalies.

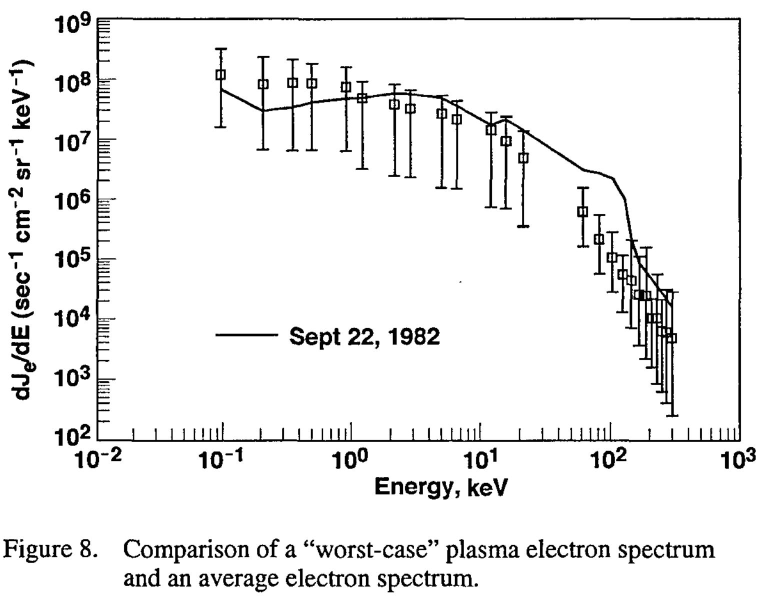

Figure 8. Comparison of a "worst-case" plasma electron spectrum and an average electron spectrum.

2.2 Internal Charging

What is internal charging? It is simply the deposition of charge on the internal elements of a satellite by electrons with sufficient energy to penetrate through the satellite skin. In some cases, the electrons deposit their charge in thick dielectrics near the surface of the satellite, in the interior, or on isolated conducting structures inside the satellite. In any case, if the leakage path to ground is sufficiently resistive, the charge can build up over time until arcing or ESD occurs. The energy in the discharge can be coupled into electronics as a fast signal or can over-voltage devices and damage them. Internal charging can lead to satellite anomalies by this mechanism. Most of the time, the satellites can recover from the anomaly. In rare cases, the anomaly can cause vehicle operations to be suspended or can even be fatal.

As was shown in Table 1, internal charging causes a significant fraction of charging-related anomalies. Once surface charging was established as a serious and real threat to satellites, the question of whether the space radiation was sufficiently intense to actually charge items in the interior of satellites was raised. Initially, the high-energy component of the space environment was examined to assess how the radiation dose it gave to surface materials might affect the performance of the materials from the surface charging perspective. Later, it was realized that, in the heart of the inner magnetosphere, the energetic electrons that can penetrate significant thickness of satellite materials could cause internal charging of satellites.

2.2.1 Internal Charging Observations

Some of the first evidence of internal charging came from the SCATHA satellite.[11] Figure 9 shows the local time distribution of ESD pulses on SCATHA that were determined to be from internal discharges. The noise pulses were not associated with satellite or instrument operations. They occurred when neither the satellite nor any of the monitored surface materials were charged. Note that the occurrence of internal discharges peaked near local noon. This may result from the fact that a near-geosynchronous satellite is on lower **L** values near noon than near midnight because of the asymmetric magnetospheric magnetic field. The penetrating electron fluxes tend to peak at **L** < 6.6. Thus, the interior of a near-geosynchronous satellite would charge more rapidly when it was near local noon.

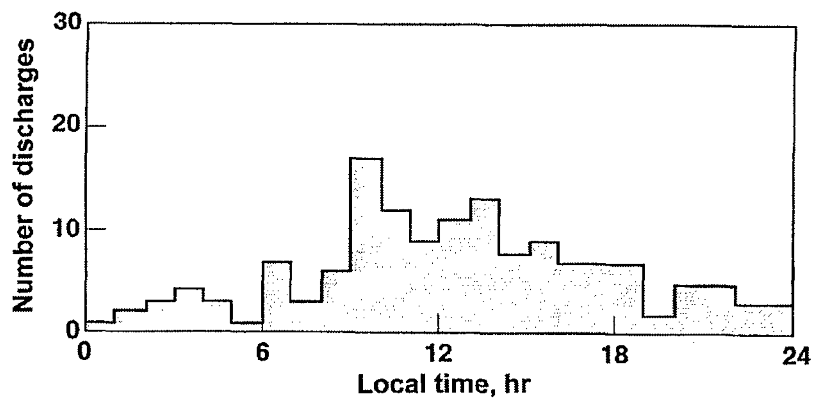

Figure 9. Local time distribution of internal ESD on SCATHA.

Once one accepts that internal charging occurs and can lead to ESD, a reexamination of Figures 1 and 6 leads one to suspect that some of the anomalies plotted there may have been caused by internal charging. For example, in both figures, there are a few anomalies in the noon sector. In addition, there have not been observations of significant surface charging in the noon sector. This is consistent with the fact that the keV plasma electrons are much reduced in flux by the time they drift to noon. It is most likely that there were internal charging effects on satellites from the beginning, but that they were not recognized as such initially.

2.2.2 Causes of Internal Charging—Magnetic Storms

Magnetic storms are often generated by coronal mass ejections (CMEs) from the sun. Earthward-directed CMEs often appear as "magnetic clouds" with high bulk speed and a southward directed magnetic field on their leading edge. This combination efficiently couples the solar-wind energy into the magnetosphere. The geoeffectiveness of a CME or magnetic-cloud-associated magnetic storm can, in some sense, be quantified by the magnitude of the ring current disturbance it causes, as measured by the D_{ST} index. As D_{ST} rapidly drops, the energetic electron fluxes are often reduced significantly in the inner magnetosphere.[17] As D_{ST} recovers, the energetic electron fluxes also recover. If the interplanetary conditions are just right, the energetic electron fluxes will increase by orders of magnitude over their pre-storm values. It is these event-related enhancements in the energetic electrons that can cause internal charging problems for satellites.

2.2.3 Causes of Internal Charging—Energetic Electron Variability

The energetic electron fluxes ($E_e \geq 300$ keV) in the inner magnetosphere are highly variable, and their variability is tied to the variability of the solar wind velocity.[12] More recently, it has been shown that the enhancements in the energetic electrons require not only an enhanced solar-wind velocity but also a southward component of the interplanetary magnetic field at the same time.[12] Figure 10 shows an example of the energetic electron-flux variability at geosynchronous orbit. During the interval shown, there was a nearly periodic arrival of high-speed solar wind streams at Earth. The energetic electron fluxes varied by orders of magnitude. In particular, they exceeded the long-term average levels by more than an order of magnitude for days at a time. Some satellites experienced anomalies during this period that were ascribed to internal charging.

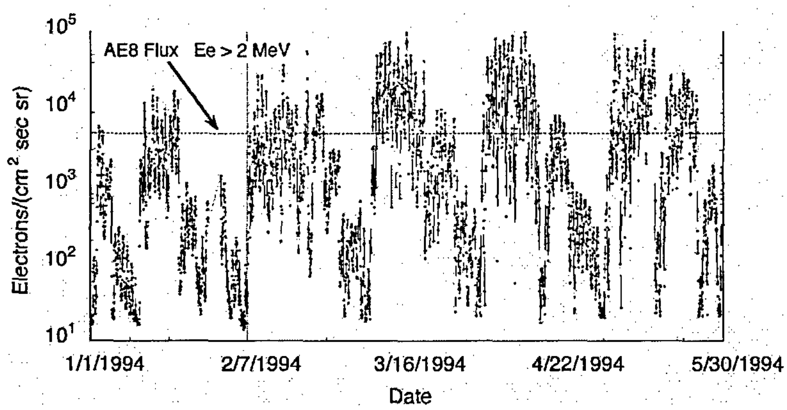

Figure 10. Variation in geosynchronous energetic electron fluxes during a period of successive high-speed solar wind streams in 1994

2.2.4 Relation between Internal Charging ESD and Penetrating Electron Fluxes

Both SCATHA[4] and CRRES[13] carried science and engineering instrumentation that could measure charging-related ESD, as well as the electron fluxes that could cause it. Figure 11 shows one example of the kind of data obtained. It shows the increased frequency of internal discharges detected by SCATHA with increasing average energetic electron flux. SCATHA and CRRES both showed that when average fluxes of 300 keV electrons were greater than 10^5 electrons/(cm^2 s sr), the rate of internal discharges increased dramatically.[11,14] Frederickson et al.[14] indicated that a ten-hour-average penetrating-electron flux greater than 10^5/(cm^2 s) was a possible reference level for the onset of discharges from internal charging. This level has been adopted[14] as the maximum average flux that should be allowed to penetrate into the interior of a satellite.

Whether discharges from internal charging occur or not depends on the amount of shielding a satellite has to protect its sensitive circuitry. The peak levels of electron fluxes depend on the effectiveness of the magnetic storm for enhancing the fluxes. The maximum average electron flux experienced by a satellite also depends on its orbit. A satellite that spends a long time in the heart of the radiation belts, as the GPS satellites do, will experience very high fluxes and require very thick shielding to protect them from internal charging.

2.2.5 Internal Charging Specifications

The major unknown in the problem of internal charging is what the worst electron fluxes may be. For example, what is the result of a "100-year" magnetic storm? It is only in the last decade or so that we have had continuous measurements of the energetic particle fluxes in the inner magnetosphere and then only for L ≥ 4 at the magnetic equator. To date, the energetic particle measurements needed to specify the extreme conditions have not been routinely taken throughout the inner magnetosphere where internal charging is a problem.

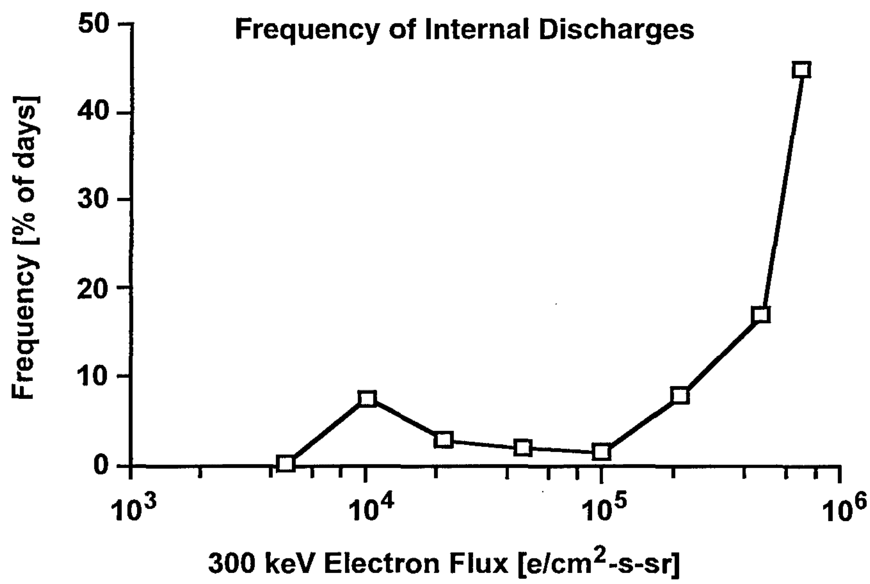

Figure 11. Comparison of SCATHA anomalies with energetic electron fluxes.

One can inter-compare measurements taken by different satellites to try to infer what the worst-case fluxes could be. Fennell et al.[14] have done this using CRRES, HEO, GPS, and geosynchronous energetic electron data. The storm time data from these spacecraft were examined, and it was found that the great magnetic storm of March 1991 was a good representation of a worst-case storm. They used the data to generate worst-case average spectra for the satellite orbits identified in Figure 13. They selected a 10-h interval as the averaging interval based on the work of Frederickson et al.[13] The orbits were geosynchronous (GEO), HEO, and a lunar transfer-phasing trajectory (MAP). The level of shielding required to protect satellites in such orbits can be derived from the spectra in Figure 12.

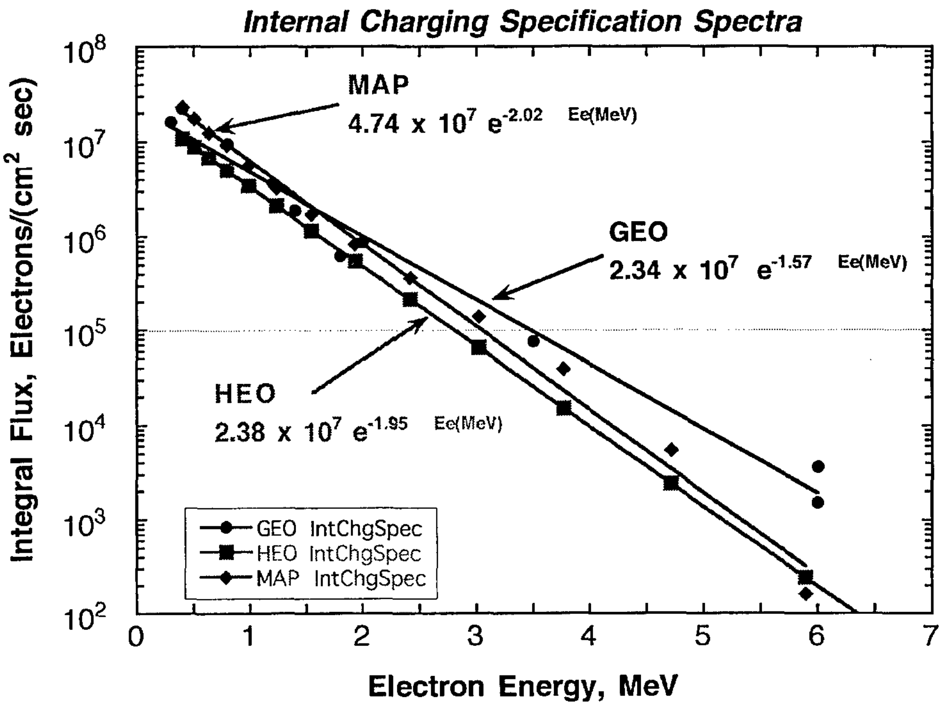

Figure 12. Examples of worst-case 10-hour-average electron spectra for three different orbits.

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3. Discussion

The linkage of substorms with surface charging and magnetic storms with internal charging is clear, as noted above. Where the difficulty lies is in (1) predicting when storms and substorms will occur, (2) predicting the particle environment that will result, and (3) predicting whether the environment will cause a problem for a given satellite.

Predicting substorms seems to be impossible at the present stage of our knowledge. We also cannot predict the changes in the particle distributions that, in turn, cause the surface charging. Finally, we cannot predict whether a specific satellite will suffer problems from a given substorm environment. There are too many imponderables.

The recent work with SOHO has taken us a long way in predicting whether a CME will strike the Earth's magnetosphere. Future advances in tracking CMEs will raise our success rate for predicting the arrival of their effects at Earth. However, we still do not know how to predict which events will be geoeffective. At present, all Earthward-directed halo-CMEs are presumed to have large effects, according to news releases. That is obviously not true. Since magnetic storms also have many associated substorms, they are, in some sense, also a source of surface charging events.

For geosynchronous satellites, one could use near-real-time measurements to make near-continuous estimates of the flux behind different shielding thickness. Then individual satellite operators could track the levels that they feel are important to them based on how their system responds to the environment.

It is clear that we are making steady progress in understanding the relationship between magnetospheric processes and charging-related effects on satellites. We are also making progress toward predicting the occurrence of storms and being able to predict and now-cast whether the storm-related environment changes are approaching problem-causing levels. We have also made progress in learning how the charging can affect real systems. We still have a long way to go in providing useful predictions to the satellite operators at the high level of confidence they require. This is especially true for surface charging where we cannot predict substorm onsets and resultant environmental changes with any degree of accuracy. The substorm-related surface charging problems are big challenges for the whole space weather community and are likely to remain so for the near future.

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Space Materials Laboratory: Evaluation and characterizations of new materials and processing techniques: metals, alloys, ceramics, polymers, thin films, and composites; development of advanced deposition processes; nondestructive evaluation, component failure analysis and reliability; structural mechanics, fracture mechanics, and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures; launch vehicle fluid mechanics, heat transfer and flight dynamics; aerothermodynamics; chemical and electric propulsion; environmental chemistry; combustion processes; space environment effects on materials, hardening and vulnerability assessment; contamination, thermal and structural control; lubrication and surface phenomena.

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