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Charging Results from the Satellite Surface Potential Monitor

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Electrical charging of common spacecraft materials flown on a high-altitude satellite are measured by the Satellite Surface Potential Monitor experiment and the data obtained are used as a framework for future modeling of spacecraft charging. Results from two magnetically disturbed times were chosen; one when the USAF P78-2 satellite was in eclipse on March 28, 1979 and the other which occurred in sunlight on April 24, 1979. On both days, the spacecraft charged negatively in the Earth's shadow to greater than −5 kV. From the results of these data, the location of various insulating materials, as well as their physical properties, must be considered if the details of spacecraft charging are to be understood.

Introduction

THE effects of spacecraft charging on various satellite systems have received a great deal of attention over the past few years. The first observations of charging to thousands of negative volts were made on the ATS-5 (Advanced Technology Satellite).[1] Other studies have shown that over 10% of the time in the Earth's shadow, these high-altitude satellites charge to negative voltages between 1000 and 4000 V.[2] The study of charging of a spacecraft, complicated by the configuration of different insulating and conducting materials immersed in a hot plasma, appeals to both scientists and engineers alike.[3,4] The Spacecraft Charging at High Altitude (SCATHA) program included the flight of a high-altitude spacecraft that was dedicated entirely to the direct measurement of charging events (both natural and artificial) by means of environmental and engineering experiments.

One of the engineering experiments, crucial to the mission, was the Satellite Surface Potential Monitor experiment (SSPM). Three separate instruments (SSPM-1, -2, and -3) provided direct surface potential and bulk current measurements of typical spacecraft insulating materials on a continuous basis at near-geosynchronous altitudes.

Table 1 lists the location and type of sample material flown on the SSPM payload. Since February 1979, the charging characteristics of the sample materials have been monitored almost continuously. This includes two natural charging events which took place on March 28 and April 24, 1979. The purpose of choosing these particular event times for analysis over others is primarily to demonstrate certain features in the data of particular interest in modeling spacecraft charging. In addition, our results have been used to conduct laboratory tests to examine material characteristics in a controlled environment. Some of these tests are described in Ref. 5.

Measurement Technique

A detailed description of the SSPM instrument can be found in Ref. 6. However, a brief summary is included here to allow a better understanding of the experimental results.

Each of the 12 voltage measurements are made by means of an electric field sensor located inside each SSPM box. Figure 1 shows four samples of the SSPM-1 experiment with the electrostatic sensor located under the center of each sample. In order to measure the electric field produced by surface potentials, the grounded backing was removed over the sensor

Table 1 SSPM material samples

No.	Description	Location
SSPM-1		
1	Aluminized Kapton	Perpendicular to satellite rotation axis
2	Optical solar reflector[a]	
3	Optical solar reflector	
4	Gold-plated magnesium	
SSPM-2		
1	Aluminized Kapton[b]	180 deg from the SSPM-1
2	Aluminized Kapton	
3	Reference band	
4	Reference band[c]	
SSPM-3		
1	Aluminized Kapton	Parallel to satellite rotation axis; perpendicular to the satellite-sun line
2	Silvered Teflon	
3	Quartz fabric[d]	
4	Gold flashed-aluminized Kapton[e]	

[a] Indium oxide coated and grounded. [b] Large sample with hole. [c] High gain. [d] Silvered Teflon backing. [e] Grounded.

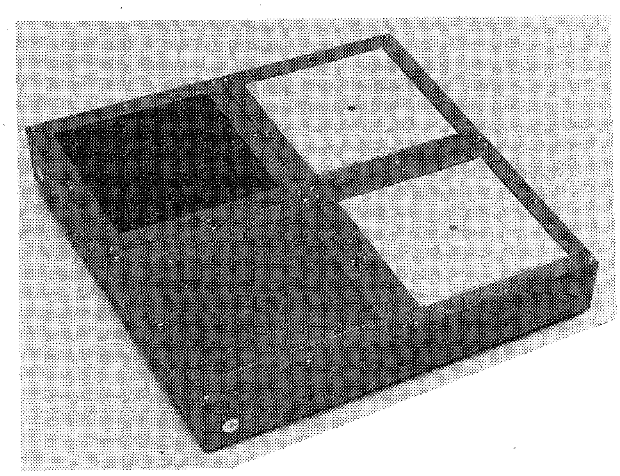

Fig. 1 Photograph of the SSPM-1 experiment showing in the upper left-hand corner, aluminized Kapton and rotating clockwise grounded OSR mirrors, un-grounded OSR mirrors and gold-plated magnesium.

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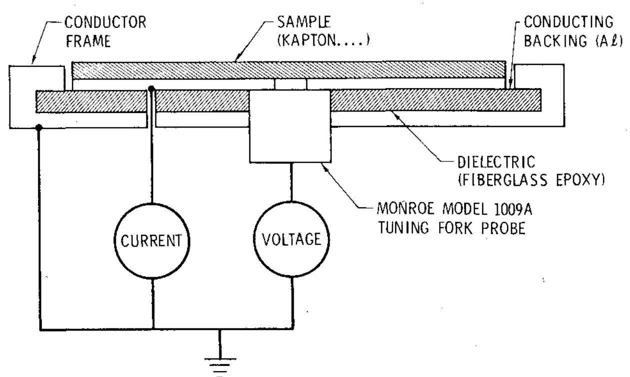

Fig. 2 Schematic of the SSPM measurement with a cross section of the sample mounting.

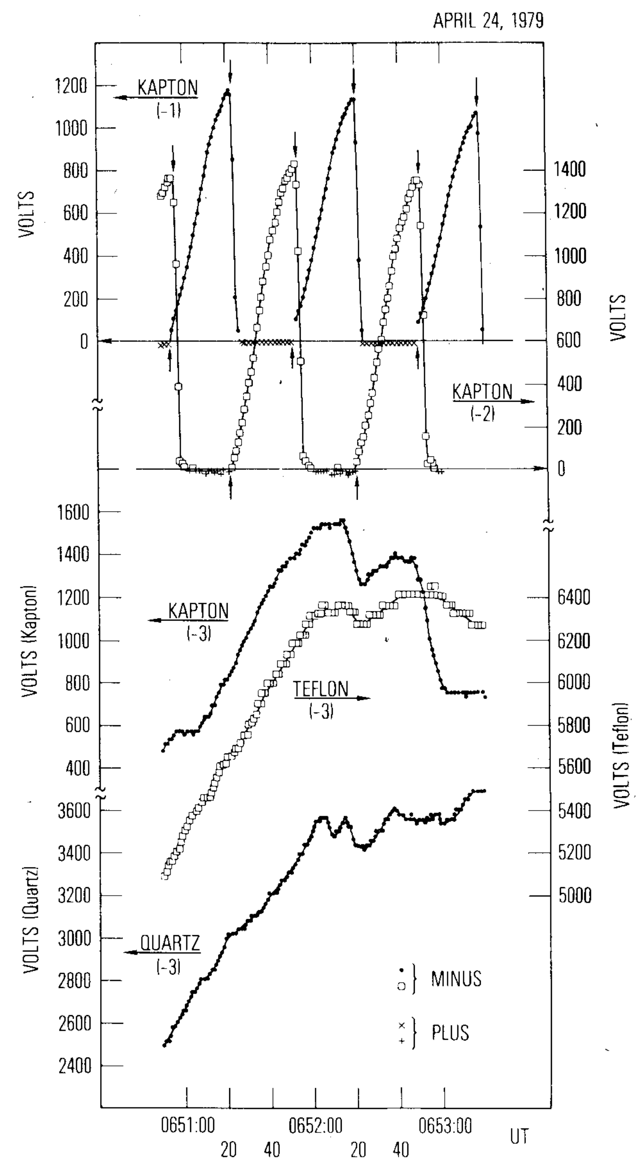

Fig. 3 The first charging results[7] obtained when the satellite was in sunlight on April 24, 1979.

from each dielectric. Each sample was calibrated by means of applying a known potential on a plate in contact with the front surface and with electron beams with energies from 2.5 up to 20 keV.

Figure 2 shows a schematic of the measuring technique and a cross section of the dielectric sample mounting. By removing approximately ¼ in. of the metalized backing, the

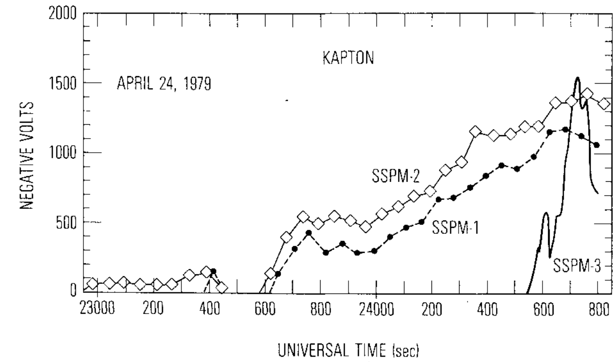

Fig. 4 Voltage profiles of the three SSPM Kapton samples in sunlight. The SSPM-1 and -2 curves are the maximum voltages reached in a 30-s time period when the samples are in satellite shadow. In satellite shadow, the SSPM-3 Kapton voltages are 1-s measurements.

charging time constant for the center was significantly shorter than that of the rest of the sample. This was a fortuitous circumstance that allowed the measurement of charging when the sample rotated into the satellite shadow approximately every 30 s. This effect will be discussed later.

In addition to the surface potential measured by the SSPM instruments, the current which passes through each dielectric sample is measured once per second by an electrometer in contact with the back surface conducting film (Fig. 2).

Aluminized Kapton was selected as the primary dielectric material and is mounted on each of the three SSPM experiments. A list of all the SSPM samples is found in Table 1. For purposes of configuration and scaling information, the SSPM-2 contains one large Kapton sample whose area is approximately five times those of the other two Kapton samples. In addition, one Kapton sample is mounted on the top of the spacecraft and remains in the shadow of the vehicle while the other two samples rotate in and out of sunlight approximately every 30 s.

A direct front surface measurement was attempted with a 0.125-in. hole punched through the SSPM-2 Kapton directly over the #1 electrostatic sensor. This configuration allows fringing fields from the front surface to terminate at the sensor. Since the charging time constant for the front surface is longer than the center of the sample, verification of the front vs back measurements can be achieved only when the sample is allowed to charge for the order of minutes. This can occur only during Earth and lunar eclipse periods.

Voltage measurements of a conducting plate were made by the SSPM-1 on a sample consisting of gold-plated magnesium. In addition, the SSPM-2 measured voltages directly from a gold-plated aluminum reference band which encircled the bottom portion of the spacecraft. Its primary purpose was to provide an absolute reference point used by the other potential measurements. Whenever the satellite is in sunlight, at least one-half of the reference band is exposed to solar uv, which produces photoemitted electron current sufficient to counteract any significant charging currents. All SSPM voltages are referenced to the satellite ground. Only rarely can the plasma charge the vehicle frame to voltages above a few tens of volts in sunlight. When the satellite enters eclipse and significant charging occurs, shifts in the charged particle spectra (both ions and electrons) are used to infer absolute changes in the spacecraft ground system relative to the plasma frame of reference.

Observations

Previously, initial charging results from a brief acquisition on April 24, 1979 were presented by Mizera et al.[7] That event was characterized by an intense plasma injection encountered by the P78-2 satellite just prior to entering the Earth's eclipse near local midnight.

Figure 3 shows the charging of five SSPM samples over a 3-min interval. The top two Kapton voltages are from the SSPM-1 and SSPM-2 samples which rotate into and out of the satellite shadow. The down-pointing arrows indicate the entry into sun, while the up-pointing arrows mark the entry into shadow. Both Kapton sample measurements indicate charging greater than -1000 V. The samples located on the top of the satellite labeled -3 are not affected directly by solar uv and begin to charge to ~ -1500 V, -6400 V, and -3700 V for Kapton, Teflon, and quartz fabric, respectively, with a time delay of a few minutes. These initial results were in disagreement with previous laboratory results and are discussed in another paper.[5] This delay is illustrated better in Fig. 4 where the beginning of the charging near 23,000 s UT is shown. (Note that 0651:00 = 24,660 s.)

One very important characteristic of the Kapton samples emerges: while the SSPM-1 and -2 voltages have an overall similarity, the large-area SSPM-2 sample charges to a higher level on the average. The points in Fig. 4 for SSPM-1 and -2 are the maximum potential attained in one satellite rotation.

Approximately 1000 s after the SSPM-1 and -2 Kapton samples begin to charge, the SSPM-3 Kapton records a significant potential buildup. Since the SSPM-3 sample is in the spacecraft shadow, solar uv does not discharge the material directly and the 1-s time sampling of the charging profile should represent as accurately as possible the interaction of the charged particle environment with dielectrics in the shadow for extended periods of time. The effect on the other samples was seen in Fig. 3.

Data from the March 28, 1979 event were unique in that the P78-2 satellite was in the Earth's shadow over 1000 s before the plasma was energetic (hot) enough to charge the spacecraft materials. Figure 5 shows the SSPM-1 and -2 Kapton potentials vs the logarithm of the time for a 1000-s interval following initial onset of charging at $\approx 59,778$ s UT. The data are displayed on a logarithmic time scale for the first 1000 s to illustrate the time dependence of the charging. After the initial 100 s, 30-s averages are plotted up to $\sim 60,800$ s UT. Higher time resolution data are again shown as the satellite exits the total eclipse indicated by the arrow in Fig. 5 as umbra exit near 62,080 s UT.

The SSPM-2 (front) triangles represent 30-s averages of the electrostatic measurement behind the 0.125-in. hole from $\approx 59,800$ s UT and then 1-s measurements (dots) beyond 62,080 s UT. Changes in this potential are much more washed out due to the longer time constant as previously discussed. As the data shows in Fig. 4, the SSPM-2 Kapton sample begins to charge sooner and higher than the SSPM-1 sample. (Note the SSPM-2 is multiplied by 2.)

Figure 5 shows a number of interesting effects which require some detailed explanation. First, on a log-log scale the charging of the Kapton samples is quasilinear. Second, the fringing fields of the front surface measurement (bottom curve) show that a significantly longer time is required to charge the entire sample than the center of each sample. Third, when the satellite nears the entry into sunlight (arrow), the discharging response is comparable between the front and back surface measurements and the time required to discharge is on the order of seconds. Finally, both SSPM-1 and -2 Kapton samples show similar responses for this entire charging event as was seen in the previous example in Fig. 4.

These observations explain some of the differences between Kapton voltages seen in Fig. 3. That is, in the time interval each of the SSPM-1 and -2 samples spend in the satellite shadow (~ 30 s), only a fraction of the equilibrium potential is reached. The most striking anomaly seen in the data in Figs. 3 and 4 was that the SSPM-3 Kapton had a charging and discharging profile quite different from the SSPM-1 and -2 Kapton samples. A number of reasons for this difference can be put forth such as scattered uv on the SSPM-3 Kapton, material property changes in the Kapton when exposed to uv cycling, charged particle anisotropies, etc. However, these different behaviors become more obvious because the two belly band Kapton samples have drastically different charging values than the SSPM-3 Kapton sample. That is, the SSPM-3 Kapton charges to very low values (< -10 V) for the March 28 event, while the SSPM-1 and SSPM-2 approach -2000 V while in eclipse.

Figure 6 shows the beginning of the March 28, 1979 event for the other SSPM sample voltages. The top two curves are for the Teflon and quartz fabric samples on the SSPM-3

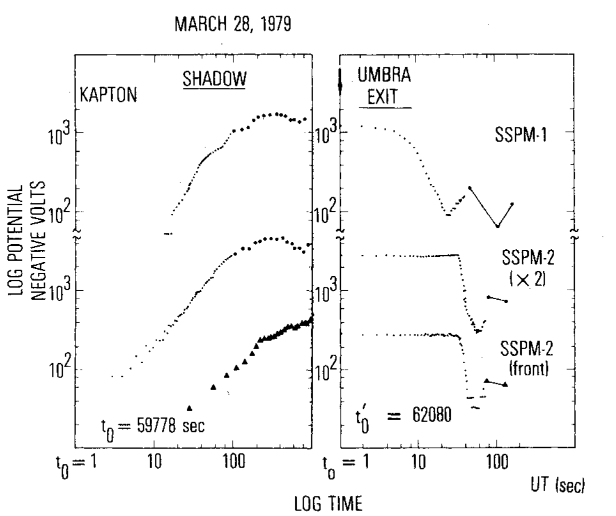

Fig. 5 Voltage profiles of the SSPM-1 and SSPM-2 Kapton samples in eclipse. The heavy points are 30-s averages. In addition to the back surface measurements, fringing fields from the front surface of the large SSPM-2 Kapton sample are plotted as front voltages.

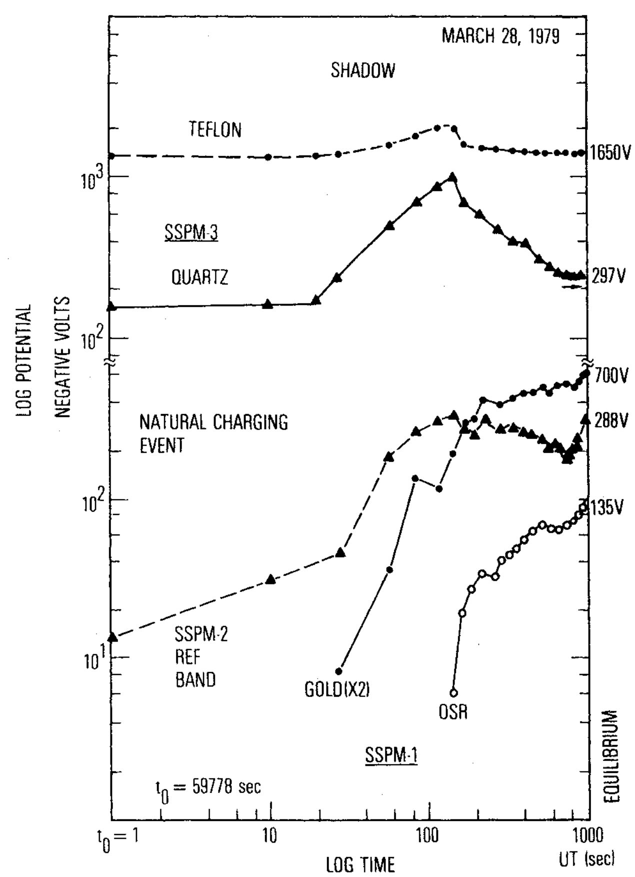

Fig. 6 Voltage profiles of the other SSPM material samples for the same charging event as was shown in Fig. 5. The voltages at the right-hand-side scale are the equilibrium values of each sample.

instrument. Both samples begin to charge approximately 25-39 s following $t_0 = 59,778$ s. The voltage offsets on each sample are true potential offsets and remain relatively constant with time. The Teflon and the quartz charging profiles in Fig. 6 are different from the profiles of the SSPM-1 and -2 samples in Fig. 5. Both Teflon and quartz samples show significant positive currents when their voltages begin to decrease. This coupled with the near zero response of the SSPM-3 Kapton at this time suggests that asymmetrical charging effects may be occurring in the eclipse event of March 28, 1979. That is, the samples on top of the spacecraft are discharging while those on the belly band are charging.

Since no solar uv flux is present to discharge the gold reference band, it also begins to charge up to between -200 and -300 V with respect to the vehicle potential. The only other conducting sample on the SSPM experiment is also gold plated and shows a final voltage approaching -350 V. Finally, the Optical Solar Reflecting (OSR) sample begins to charge some 150 s after the onset and reaches only -135 V.

Since the P78-2 satellite is immersed in a hot charging plasma at this time with no solar uv flux to maintain charge balance, the whole spacecraft structure becomes negative due to the high intensity of energetic electrons. The SSPM voltage monitors measure a sample surface potential relative to spacecraft ground. Therefore, the potential of the various samples shown in Figs. 5 and 6 relative to infinity (or the plasma) would be the sum of the measured potential plus the potential of the spacecraft ground with respect to the plasma environment to first approximation. During this 2300-s interval, the potential inferred from ion energy spectra varied between 0.6 and 6 kV.[8]

Charged Particles

A brief description of the charged particle distributions which produced the material charging is given for the March 28 and April 24 events. For times before $t_0 = 59,778$ s UT on the 28th, the electron population is well represented by a Maxwellian distribution with an average temperature near 1 keV. After the charging begins, the spectrum of electron changes to a non-Maxwellian shape, with the low-energy component depressed and the high-energy tail ($E > 10$ keV) showing enhancements of the order of 5-10. The maximum calculated current impinging on the P78-2 satellite is of the order of 0.1 nA/cm^2 just prior to the onset of charging of materials.[8] These noncharging currents are produced primarily by electrons below 1 keV. During the charging event, the current drops by almost a factor of 10 but is carried primarily by higher-energy electrons.

The more energetic charging event on April 24, 1979 begins with electron flux enhancements primarily in the 10-20-keV region. That is, near 23,600 s UT in Fig. 4, the electron fluxes with energies between 10 and 20 keV increase between a factor of 3-4. Electron fluxes with energies below 10 keV show very small changes at this time. Electron fluxes with energies >20 keV also show little if any changes in intensity. In Fig. 4 near 24,100 s UT, the Kapton SSPM-1 and SSPM-2 begin a steady increase which is accompanied by the largest increases in the electron fluxes with energies between 20 and 50 keV. By 24,600 s UT, electron fluxes in this energy range increased by as much as a factor of 5. Throughout the whole charging time period (23,600-24,800 s UT), the total current (for $0.09 < E_e < 20$ keV) did not change more than a factor of 2.[8]

One final note regarding the material charging in Fig. 5 near 62,075 s UT on March 28 when the P78-2 satellite reenters sunlight. The SSPM-1 is the first Kapton sample to see sufficient uv flux to discharge the surface potential down to a few hundred volts. Prior to this time the SSPM-2 Kapton measurement shows a decrease presumably due to the penumbra. By the time the instrument rotates back to view the sun, the satellite is in full sunlight and the front and back surface potentials drop to low values. The averaged potentials plotted following this time are spacecraft shadowed values which show the charging event is still occurring. In fact, the electron spectrum above a few hundred electron volts remains relatively constant for this whole time period and the energetic component (10-20 keV) is approximately equal to the value at the beginning of the charging event, some 2300 s earlier.

Summary

Two natural charging events, recorded by the SSPM experiment during magnetically disturbed conditions, illustrate some of the complexities involved in modeling spacecraft charging. Specifically, the three Kapton samples present a gross three-dimensional view of charging potentials. In the sunlight, on April 24, 1979, the two belly band Kapton samples (SSPM-1 and SSPM-2) displayed similar charging profiles with the SSPM-2 Kapton showing a slightly higher tendency to charge. Only during the most intense portion of that charging event did the SSPM-3 samples begin to charge. In the eclipse on March 28, 1979, the SSPM-1 and SSPM-2 Kapton again showed similar charging characteristics while the -3 Kapton showed only a hint of charging. The samples adjacent to the -3 Kapton, namely, Teflon and quartz, began to discharge during the times when charging continued for samples located on different parts of the vehicle. These results suggest a combination of the effects of the angular dependence of the charged particles and the physical layout of the satellite must be considered. In addition, when the satellite was in transfer orbit, the top of the spacecraft was exposed for long time periods to sunlight which may have produced some long-term changes in the SSPM-3 material properties.

The two examples presented are the first in situ measurements of spacecraft material charging and represent only a fraction of the on-orbit data collected over the first four months of satellite operations. Therefore, it is important to understand the subtleties of the actual charging characteristics in order to apply the results to spacecraft design. These details are just beginning to emerge as a result of combining data analysis with charging models, simulation studies, and laboratory material studies. The actual impact of spacecraft differential charging on future space programs requires the level of understanding obtainable through the SCATHA program and the P78-2 satellite data. Nevertheless, under present circumstances, thorough understanding of these phenomena will probably never occur.

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