A SUMMARY OF THE ENGINEERING RESULTS FROM THE AEROSPACE CORPORATION EXPERIMENTS ON THE SCATHA SPACECRAFT

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Abstract. The Aerospace Corporation experiments on the SCATHA spacecraft consist of the surface potential monitor, pulse analyzer, RF analyzer, VLF analyzer, sheath electric fields, energetic ions, and the spacecraft contamination and thermal control materials monitoring experiments. High lights of the most important engineering results obtained with these instruments will be described. These include the specification of the environment obtained from the "worst-case" surface-charging event on 22 September 1982, the correlation of the discharges measured by the pulse analyzer with the electron environment, the delineation of the surface charging region, changes in the bulk conductivity of Kapton over the first year of the mission, and evidence that spacecraft charging is responsible for an increase in the rate of molecular contamination on exterior spacecraft surfaces. This increase is significant for surfaces with otherwise low contamination rates.

1. Introduction

The P78-2 satellite, known as the SCATHA (Spacecraft Charging at High Altitude) satellite, was the flight test portion of a joint U. S. Air Force/NASA spacecraft charging program. Descriptions of the program and the spacecraft have been given by *Stevens and Vampola* [1] and *Fennell* [2]. The primary objective of the satellite flight was to obtain the environmental and engineering information needed to support design guidelines, materials selection, ESD mitigation techniques, tests and analytical methods to control the differential charging of satellite surfaces.

The experiment complement consisted of a complete set of plasma, energetic particle, composition, field and wave experiments. In this paper we describe some of the more important engineering results from the instruments that were developed for the mission by The Aerospace Corporation. These include the Engineering Experiments that consisted of Surface Potential Monitors and a Pulse Analyzer, The Spacecraft Sheath Electric Fields Experiment which measured low energy ions and electrons and energetic ions, and the Spacecraft Contamination Experiment that measured mass deposition rates and changes in solar absorptance.

The satellite was launched on 30 January 1979 and inserted into its final orbit on 2 February 1979. The orbit of P78-2 was chosen to cover the geosynchronous-orbit region close to the geographic equator. The apogee and perigee are ~ 43,200 km (R ~ 7.8 Re) and 27,500 km (R ~ 5.3 Re) respectively. The inclination of the orbit is ~ 7.8° with apogee and perigee lying in the earth's equatorial plane. The orbital period is ~ 23.6 hr and thus the mean position of the satellite drifts eastward in longitude at ~ 5.3° per day.

2. Important Engineering Results

The spacecraft was taken out of service in March 1990 after successfully collecting data for over ten times its originally planned lifetime. The number of engineering and scientific publications from The Aerospace Corporation experiments alone exceeds 50.

The following is a list of some of the more important engineering results that will be discussed in this paper:

- Confirmation of the spacecraft charging hypothesis
- Relationship between discharges and the space environment
- Specification of a "worst-case" plasma environment for surface charging
- Specification of the surface-charging region in local-time
- Comparison of factory-test discharge amplitudes with on-orbit discharge amplitudes
- Changes in materials properties caused by the space environment

2.1 Confirmation of Charging Hypothesis

The charging hypothesis links the plasma environment to anomalies on the spacecraft. It goes as follows. An anomaly can be caused by the electromagnetic pulse from an electrostatic discharge that occurs on the surface of a vehicle when the electric field between two dissimilar materials exceeds the critical electric field required for breakdown. This field can be reached when the surface materials charge to different potentials with respect to each other or with respect to the vehicle frame when a hot plasma surrounds the vehicle. SCATHA was the first spacecraft to measure all of the parameters required to verify this hypothesis. Most aspects of the hypothesis were verified shortly after launch when on March 28, 1979 surface charging occurred while the vehicle was eclipsed by the shadow of the Earth [3].

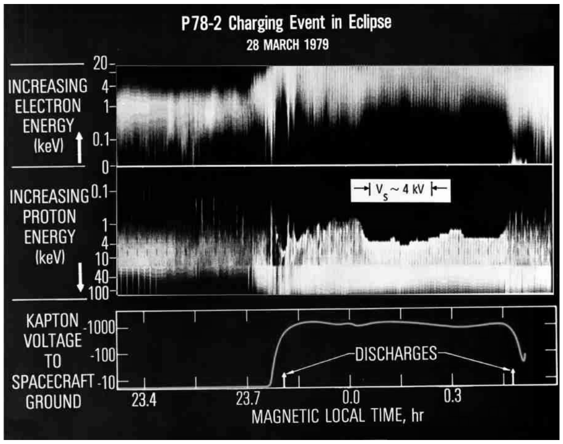

Figure 1. Electron and proton fluxes and Kapton voltage with respect to vehicle structure. In the top two panels a brighter image represents higher particle fluxes.

Figure 1 shows a composite of data from a surface potential monitor and the electron and ion detectors on the sheath electric fields experiment during this event. The top panel shows an electron injection occurring just after 23.7 hr MLT. The Kapton sample charges to about −1 kV with respect to the frame. The mean electron energy increases from 1 keV to greater than 20 keV. About 5 min after the charging began a discharge was detected by the pulse analyzer. Later a second discharge was detected. During the event the proton data indicate that the vehicle structure maintained a potential near –4 kV with respect to the plasma until the spacecraft reentered the sunlight. These data confirm that the spacecraft charging induced by the electrons produced significant differential potentials and electrical discharges. During this time period no anomalies were reported on the vehicle.

On September 22, 1982 a much more severe surface charging event occurred. Three different spacecraft anomalies occurred on the vehicle. The most serious was a two-minute loss of data. The other two were uncommanded mode changes in two of the experiments. These uncommanded mode changes coincided with the injection of hot plasma, large voltages measured by the surface potential monitors, and discharges detected by the pulse analyzer. An example of one type of anomaly is shown in Figure 2.

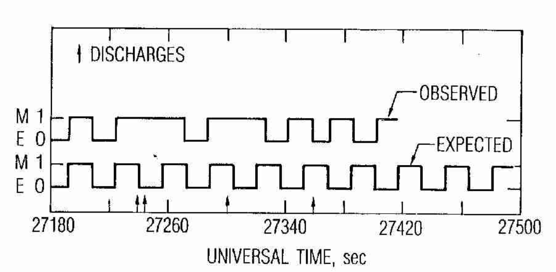

Figure 2. Timing sequence of the antenna switch on the VLF Analyzer during a period of surface charging on September 22, 1982. The arrows show the time discharges occurred.

The VLF experiment collects data from two sensors, an electric antenna and a magnetic antenna. The experiment contains a counter that counts synchronization pulses from the telemetry system. These occur at the rate of one per second. Every 16 sync pulses the antenna is switched. The anomaly was a failure to switch properly after virtually every discharge. The observed and expected switching sequences are shown in Fig. 2. The switching failures coincided with the four discharge pulses during the period shown.

2.2 Relationship between the Space Environment and Discharges

The relationship between the energetic electron environment, surface charging of materials, and electrostatic discharges due to both surface and internal charging was examined by *Koons and Gorney* [4]. They showed that internal discharges occurred primarily near perigee at 5.5 Re while surface discharges occurred about evenly over the radial range covered by SCATHA. Although few surface discharges occurred when the Planetary Magnetic Index, Kp, was less than 4, a modest number of internal discharges occurred under these quiet to normal conditions. Surface discharges had a strong tendency to occur when the flux of electrons with energies of 10’s of keV is high while bulk discharges occur when the flux of electrons with energies of 100’s of keV is high and the flux of 10’s of keV electrons is low.

We have also examined the dependence of internal discharges on SCATHA with the daily average integral flux of >1400 keV electrons measured by Los Alamos National Laboratory detectors in geosynchronous orbit. Although SCATHA has an eccentric orbit and most of the internal discharges were detected below geosynchronous altitude, we found a very definite increase in the frequency with increasing electron flux as shown in Fig. 3. The abrupt increase in frequency occurs at an integral flux of several thousand electrons/cm^2-s-sr.

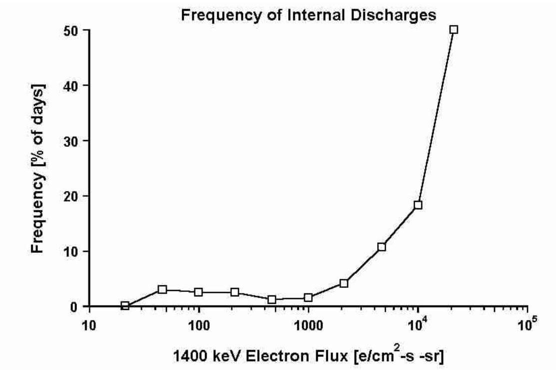

Figure 3. Percent of days with internal discharges on SCATHA as a function of the daily-averaged integral flux of >1400 keV electrons at geosynchronous orbit.

2.3 Specification of a "Worst-Case" Plasma Environment for Surface Charging

"Worst-case" environments are required for the proper testing and selection of materials for spacecraft surfaces. Although there is no definition of what characterizes a worst-case environment for surface charging, we argue that the events of September 22, 1982 make it the best candidate currently available. On that day 29 intense electrostatic discharges were detected by the pulse analyzer on SCATHA.

Table 1. Summary of days on which five or more electrostatic discharges were detected by the Pulse Analyzer. The table is ordered by the decreasing number of discharges.

Date	Discharges	Type	Max. Intensity
22 Sep 82	29	Surface	7.40
25 Sep 84	20	Internal	1.00
28 Sep 83	16	Surface	1.90
24 Sep 84	15	Internal	0.50
13 Sep 87	7	Surface	7.40
26 May 79	6	Surface	0.13
7 Sep 82	5	Surface	7.40
19 Jul 84	5	Internal	0.50
14 Sep 87	5	Surface	7.40
17 Sep 87	5	Surface	1.00

Table 1 shows that the worst case occurred on September 22, 1982. That date had by far the most discharges at 29 and 17 of those exceeded the maximum voltage measured at 7.4 V into a 50 Ohm load. The events of that day were reported by *Koons et. al.* [5]. *Roeder* [6] has derived the differential electron flux from 87 eV to 288 keV for this event. This serves as the worst-case plasma environment for surface discharges observed to date. The spectrum in Fig. 4 shows an excess of electrons above 10 keV and a deficit below 10 keV as compared with the average of the values observed during two one-week periods in 1979 that were chosen as a representative level of geomagnetic activity.

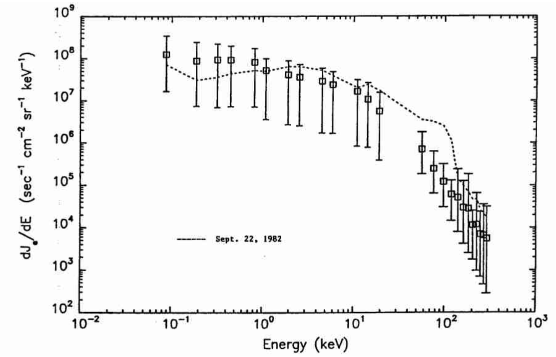

Figure 4. Worst-case electron energy flux for surface electrostatic discharges.

2.4 Specification of the Surface-Charging Region in Local-Time

Sufficient data were collected by the surface potential monitors and pulse analyzer on SCATHA to determine the extent of the surface charging region in local time. For this purpose surface charging was taken to occur when the voltage of any sample as greater than 100 volts negative with respect to the structure. In all cases where the plasma caused surface charging, the samples charged more negatively than the structure. *Mizera* [7] showed that such negative charging occurred more that 10% of the time between 20 hr and 09 hr LT during magnetically disturbed conditions. He also provided a map of the charging region in radius and local time.

When the surface did not meet this definition of being charged, discharges detected by the pulse analyzer were identified as internal discharges. Fig. 5 shows the local time distribution of surface discharges in the top panel and internal discharges in the bottom panel.

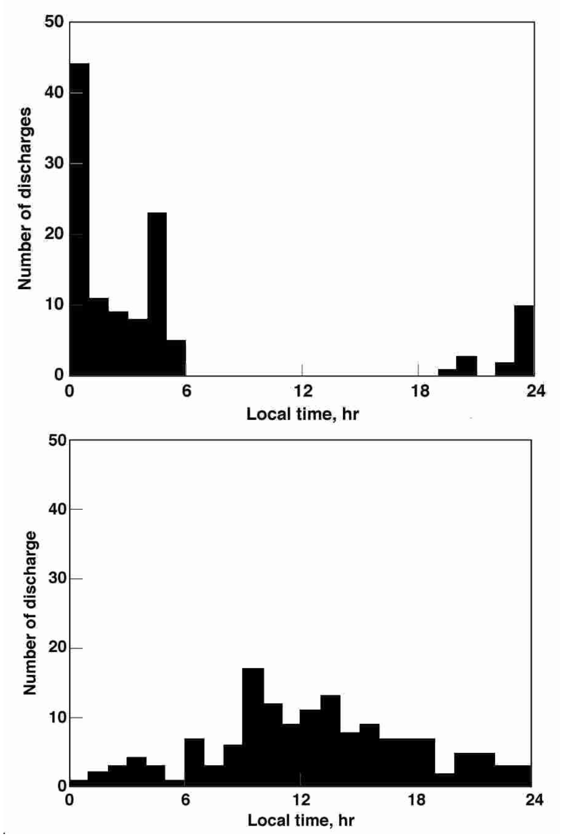

Figure 5. Local time distribution of surface discharges in the top panel and internal discharges in the bottom panel.

The location of the surface charging region was used to develop a launch window for the Centaur vehicle because it was determined that it may be susceptible to large surface discharges. The local-time distributions shown in Fig. 5 have been used for qualitative anomaly analyses for a number of geosynchronous spacecraft. They were also used to show that upsets on the MILSTAR spacecraft were due to Single Event Effects rather that to ESD from spacecraft charging.

2.5 Comparison of Factory-Test Discharge Amplitudes with On-Orbit Discharge Amplitudes

MIL-STD-1541A [8] requires and the *NASA Design Guidelines* [9] recommends that an arc discharge test be conducted for spacecraft that will encounter a surface charging environment. Frequently this test is not performed because people have consider it to be a potentially destructive test.

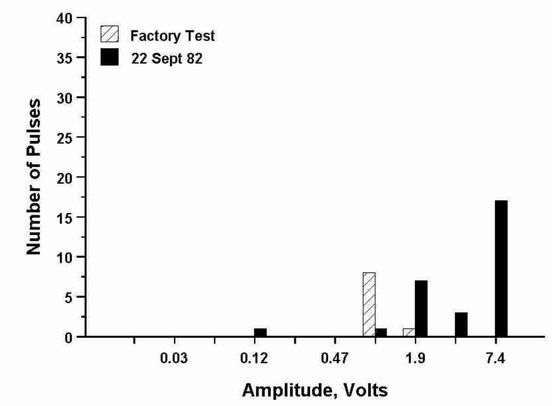

Figure 6. The amplitude of the pulses detected on September 22, 1982 is compared with the amplitude of the pulses measured during the factory arc discharge tests.

System-level arc-discharge tests were conducted on the SCATHA spacecraft in the factory [5, 10]. Figure 6 compares the amplitude distribution of the pulses detected by SCATHA on September 22, 1982 with the amplitude distribution measured on the same sensors during the factory test discharges.

The data in Fig. 6 show that almost all of the pulses detected on-orbit on September 22, 1982 exceeded the amplitude of the factory test pulses. The largest pulses were almost an order of magnitude larger than the pulses from the factory tests. We have concluded that the factory test pulses, performed in accordance with MIL-STD-1541, were not large enough to represent a worst-case on-orbit environment.

2.6 Changes in Materials Properties Caused by the Space Environment

The samples on the surface potential monitors displayed a variety of different effects brought about by their long-duration exposure to the space environment. The following is a brief description of some of the changes observed.

Kapton. After Kapton was exposed to sunlight, its electrical conductivity increased to such an extent that the voltage to which it charged decreased by orders of magnitude after one year in space [7, 10]. A gold sample was used as the reference. The data are shown in the top panel of Fig. 7. The ratio is the maximum voltage of the Kapton sample to the maximum voltage of the gold sample. During the charging periods that occurred early in the mission the Kapton samples reached values of –1400 V. 14 months later they charged to only a few volts.

Teflon. The bottom panel of Fig. 7 shows the voltage levels of the Teflon sample as a function of time after launch [10]. The data were taken near local noon where there is no surface charging from the plasma environment. This must represent the buildup on internal charges in the sample. The Teflon sample was on the top of the vehicle and was exposed to only grazing incidence sunlight.

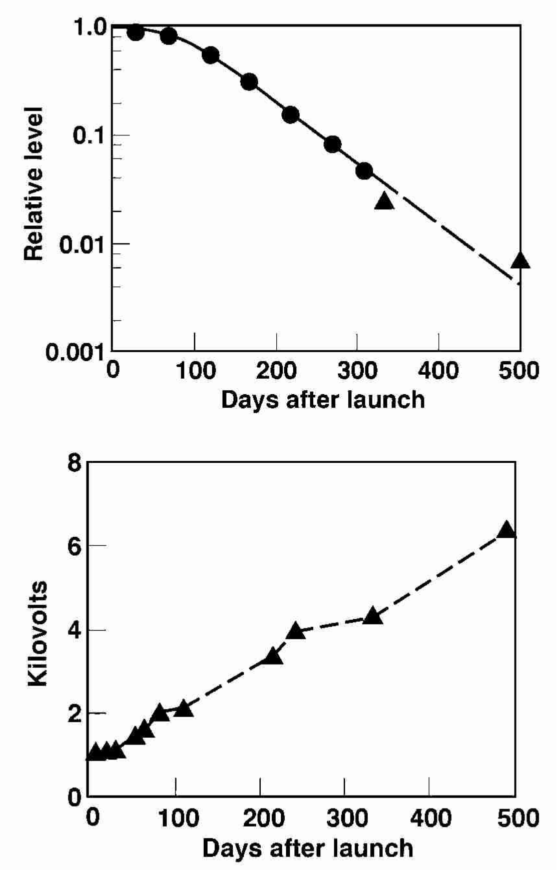

Figure 7 Relative voltage level of Kapton sample to gold sample (top panel). Voltage level of Teflon sample (bottom panel).

Quartz Fabric. The quartz-fabric cloth sample was designed to remain at low potentials during charging events because of its high secondary-electron yields and its large surface-to-volume ratio. Preflight laboratory simulations confirmed this behavior. However, in space the quartz-fabric charged to even higher levels than did Kapton. Measurements later performed in the laboratory at Aerospace confirmed the high voltage levels observed on-orbit when realistically low electron flux levels were used [11].

2.7 Contamination Effects of Charging

The idea that spacecraft charging could also affect spacecraft self-contamination rates was advanced early on [12]. Unlike most spacecraft charging effects, it is the absolute difference between the potential of the exposed surfaces of the spacecraft and the plasma potential, rather than differential potentials on the spacecraft, which drives this process. Because of the low plasma density associated with high earth orbits (HEO), there even a moderately charged vehicle becomes surrounded by a very large plasma sheath (in comparison to the scale of the vehicle). Outgassed molecules venting from the vehicle leave with thermal velocities and remain within the sheath long enough that a small fraction will become ionized by collision with solar photons or plasma electrons. These molecules are then attracted to the negatively charged vehicle, and return to locations that have little or no relationship to the locations of their earlier departures. Thus, unlike so-called line-of-sight (LOS) contamination transport of uncharged molecules, these ions cannot be prevented from reaching contamination-sensitive surfaces with baffles and shields.

A principal goal of the Spacecraft Contamination Experiment was to determine if this process was efficient enough to be significant. Two methods were available to make this assessment. First, it is argued that contamination detected by sensors with clear fields of view (FOV) of space must be evidence of non-LOS processes at work. The only other processes than electrostatic return (ESR) of possible significance at HEO is self scattering within the "plume" from spacecraft vents. This process is very inefficient in plumes with typical densities. Second, two experiment detectors were fitted with a commandable electrostatic grid through which incoming ions had to pass in order to be detected. Biasing the grid positively with respect to the spacecraft frame reflected ions with insufficient kinetic energy to pass through potential barrier the grid created. Thus, if the deposition rate on the detector could be shown to reduce when the grid was positively biased, reduction in electrostaticaly re-attracted ionized molecules reaching the detector must be the reason.

Sensors of two types mounted on the SCATHA bellyband had nearly clear FOVs: a temperature controlled quartz crystal microbalance (TQCM) [13], and three calorimeters [13] fitted with space-stable samples. The bellyband TQCM did acquire a significant mass density over a period of years [14]. The calorimeters with polished Al, Au, and fused silica second-surface mirrors all had slowly increasing temperatures resulting from a growing film of contamination on them that increase the fraction of sunlight they absorbed [15]. Figure 8 shows this temperature growth expressed in terms of solar absorptance calculated from the measured temperatures, the pre-launch measurement of their infrared hemispherical emittances, and the pre-launch measurement of the calorimeter heat leaks.

These increases, though measurable, are much smaller than those normally seen on space-stable materials that have a significant FOV of spacecraft surfaces or vents.

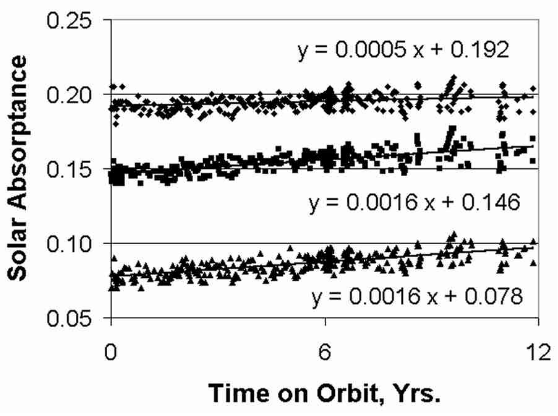

Figure 8. Solar absorptance increases due to ESR contamination: (top) polished Au, (middle) polished Al, (bottom) OSR.

The TQCMs were the sensors with electrical grids (comprising a retarding potential analyzer with an annular charged particle detector) in front of their detectors (quartz crystals). The commandable grid could be set to a maximum of +500 V. One TQCM was on the bellyband adjacent to the calorimeters. Unfortunately, it took hours to accumulate enough contamination to be measurable and large spacecraft charging events were generally an hour or less in duration. Therefore the grid was commanded to different potentials for periods of several days and the average deposition rate over the period was (negatively) correlated with the potentials. Experiments of this design were conducted during part of two winters and summers [16, 17]. Figure 9 indicates the statistical degree of confidence that each experiment and combinations of experiments correlated positive grid bias with reduced contamination rate.

One should be clear on the limitations of this experiment. First, "large" charging events can greatly exceed 500 V, and under those circumstances, most returning ions will have kinetic energies larger than 500 eV and therefore will pass through the retarding grid. Although this is not true of the ions formed near the vehicle, it is true of those formed in most of the sheath around the spacecraft. Second, the experimental design assumes that on average all periods had about the same frequency and levels of conditions that produce spacecraft charging.

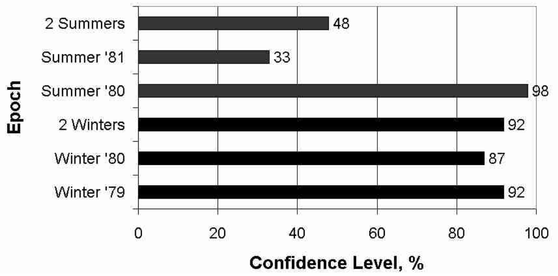

Figure 9. Statistical confidence that ESR contamination was measured during four epochs.

It is not understood why the correlation of deposition rate with grid voltage is stronger in the winter than in the summer. However, analysis of the data indicates that on average up to 30% of the molecules depositing on the TQCM were ions arriving with less than 500 eV kinetic energy.

Acknowledgments. We wish to thank T. Cayton for providing the energetic electron data from the Los Alamos National Laboratories detectors for the time period of the SCATHA mission. This work was supported by the Space and Missile Systems Center, Air Force Materiel Command under contract F04701-93-C-0094.

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