Transient Pulse Monitor Data from the P78-2 (SCATHA) Spacecraft

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The Transient Pulse Monitor (TPM) onboard the P78-2 (SCATHA) satellite has recorded data that reveal that spacecraft transient pulses may be produced by real-time command execution, automatic subsystem operations, and artificial charging events induced by SC4 ion- and electron-beam emission experiments. Additional transient pulses whose origins are not believed to be associated with these sources, called candidate natural discharge pulses, have been recorded coincidentally with and in the absence of measured spacecraft surface charging. This observation implies that transient pulses may be produced by the breakdown of both surface and embedded charge accumulations. The satellite local time distribution of candidate natural discharge pulses is consistent with a similar plot of unexplained events on other high-altitude satellites, suggesting that such anomalous events may have been produced by surface or embedded charge breakdowns.

Introduction

IN the summer of 1973, a less sophisticated version of the TPM was launched aboard a synchronous equatorial orbit satellite.[1] The electrical transient sensors for this instrument consisted of two 150 cm^2 stainless steel plates that were flush mounted amidst the optical solar reflectors (OSRs) on the outside surface of the spacecraft. These sensors served both as electric dipole antennae for transient pulse detection and as current sensors to provide a rough measure of the ambient charged particle flux. Though this instrument did not provide quantitative data of peak amplitude and pulse integral, it did provide a definite indication of each discharge event in the vicinity of the transient sensors.

Data from this experiment indicated that there was an increase in the detected discharge rate during geomagnetically disturbed periods and also that many orbital engineering anomalies observed on this spacecraft were coincident with electrical discharge events. These results correlated well with data obtained from analysis of anomalous events observed on other high-altitude spacecraft showing an increase in the anomaly rate occurring during geomagnetically disturbed periods.

Both the transient pulse and engineering anomaly events were most frequently observed between spacecraft local time hours 0000 and 0200.[2] Spacecraft local time is a measure of the angle, in the orbit plane, between the Earth-vehicle and Earth-sun lines. There are 24 "hours" of local time that are divided equally in angle about the spacecraft's orbit. A synchronous satellite will spend an equal amount of time in each spacecraft local time hour segment. Spacecraft local midnight (0000 hours) is defined as being when the angle between the Earth-vehicle and Earth-sun lines is 180 deg. Conversely, spacecraft local noon (1200 hours) occurs when this angle is 0 deg. Spacecraft local dawn and spacecraft local dusk will then fall midway between the midnight and noon and the noon and midnight angles, respectively.

In order to investigate the causes of the anomalies onboard the aforementioned and other high-altitude satellites, the joint NASA/AF Spacecraft Charging at High Altitudes (SCATHA) program was initiated. The SCATHA/P78-2 spacecraft was to be used as an experiment platform to qualitatively describe the high-altitude space environment, satellite surface potentials, and transient pulse environment of the spacecraft. In addition to the TPM, the SC1-8B pulse analyzer was designed to detect and characterize the electrical transients occurring onboard the P78-2 spacecraft. The SC1-8B experiment includes two pulse detection sensors located inside the P78-2 Faraday cage and two outside the Faraday cage. This experiment is capable of providing pulse amplitude data vs time, enabling the waveform of a transient pulse to be analyzed. Amplitude measurements are commandable to ranges from 3 to 1.84 mV up to 3.64 to 1910 V. Measurements are taken in the time domain from 7 nsec to 3.7 msec.

Another experiment, the SC1-1, -2, and -3 satellite surface potential monitors (SSPM), was designed to monitor charging and discharging of various selected spacecraft materials. SSPM data are used in conjunction with transient pulse data to describe the pulse environment associated with and independent of measured surface charging events.

A complete description of these and all other P78-2/SCATHA payloads can be found in Ref. 3.

Experiment Description

The TPM, as configured for the P78-2 spacecraft, consists of an electronic processor and four electrical transient sensors. As shown in Fig. 1, two of the TPM sensors are passive current probes and two are long-wire antennae. One current probe, referred to as the solar array sensor, is located on one of the two wires that connect the upper solar array to the power conditioning unit (PCU). The other current probe, called the ground sensor, is located on one of seven ground wires between the PCU and the vehicle frame. Both current sensors have sensitivities of 1 mV/mA. The long-wire antennae each consist of unshielded insulated wires tied to the outside of the foil wrap of the main vehicle wiring harness located within the vehicle centertube. Unlike the current probes, these antenna are outside the better-shielded "Faraday cage" volume of the spacecraft. The two antennae wires run parallel to each other and extend halfway around the inside of the vehicle centertube. These antennae differ only in the magnitudes of their termination impedances. As

Presented as Paper 82-0265 at the AIAA 20th Aerospace Sciences Meeting, Orlando, Fla., Jan. 11-14, 1982; submitted Jan. 22, 1982; revision received May 6, 1983.

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shown in Fig. 1, the low-impedance antenna is connected directly to the vehicle frame at the far end and is terminated in 50 Ω within the TPM processor housing. The high-impedance antenna is connected to the vehicle frame through a 100 K Ω resistor at the far end. At the TPM end of the high-impedance antenna, there is a 10 K Ω resistor in series with the 50 Ω TPM input impedance.

Figure 1 also shows the 20 dB attenuators that were installed in the low-impedance antenna and solar array sensor input channels to reduce the TPM sensitivity to internal low-level background noise observed during P78-2 system tests.

The TPM electronic processor continuously monitors electrical signals from each of the four sensors simultaneously and provides the following information for each sensor once per second: Positive peak amplitude, negative peak amplitude, total pulse count, positive integral, and negative integral.

The TPM has four commandable gain settings that affect the sensitivities of the pulse count thresholds and pulse integral channels.

A clock signal is supplied by the vehicle telemetry system to the TPM once per second. Upon receipt of this signal, data acquired during the previous 1-s period are transferred to the outputs of the TPM. Therefore, data supplied by the TPM during any 1-s period represent information gathered during the previous 1-s period.

The two peak-amplitude channels associated with each sensor indicate the maximum positive and negative excursions of the input signals during each timing window.

The dynamic range of the peak-amplitude channels is 2 mV to 24 V for the low-impedance antenna, 20 mV to 240 V for the high-impedance antenna, 4 mA to 48 A for the solar array sensor, and 140 mA to 1700 A for the single-point ground sensor. These ranges include the effects of 20-dB attenuators in the inputs to the low-impedance and ground sensors. They also include the effect of monitoring only one of seven identical power leads by the ground sensor and only one of two identical input leads by the solar array sensor.

The pulse count channel associated with each sensor indicates the total number of times that the magnitude of the input signal exceeds a set threshold during each 1-s telemetry window. However, if the input signal exceeds the set threshold more than once during any 1-ms period, it is counted only once. The pulse counters acquire data throughout each 1-s telemetry frame with a dynamic range of from 0 to 100 pulses per second.

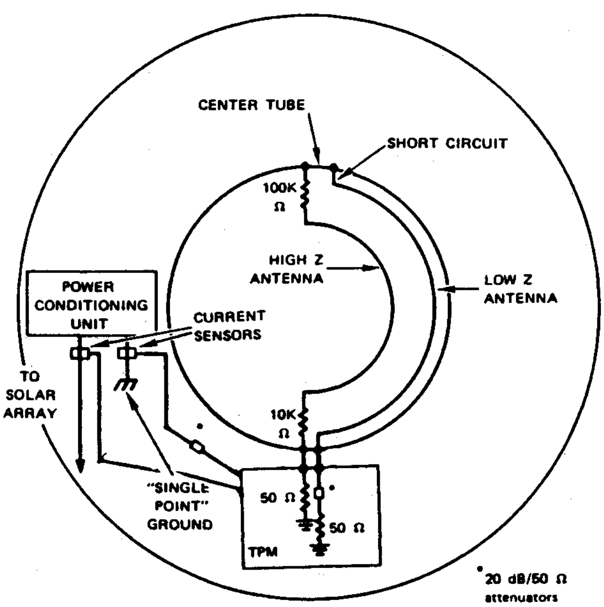

Fig. 1 TPM sensor locations on P78-2.

The two pulse-integral channels associated with each sensor indicate the two positive and negative integral of the input signals during each timing window. However, the portions of the input signal that do not exceed the pulse counter amplitude threshold are not included in the integral measurement.

The P78-2 TPM provides 20 continuous analog outputs (5 for each sensor) as described above.

TPM Transient Pulse Data

The transient pulse monitor has operated nominally throughout its lifetime, providing a quantitative description of the P78-2 transient pulse environment. Data have been collected nearly continuously, with only two interruptions from initial turn-on on February 8, 1979. Both interruptions,

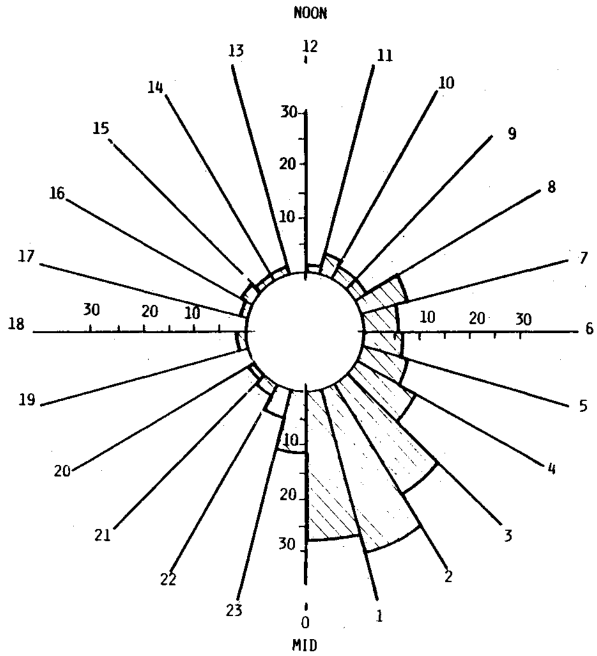

Fig. 2 TPM pulse events vs local time.

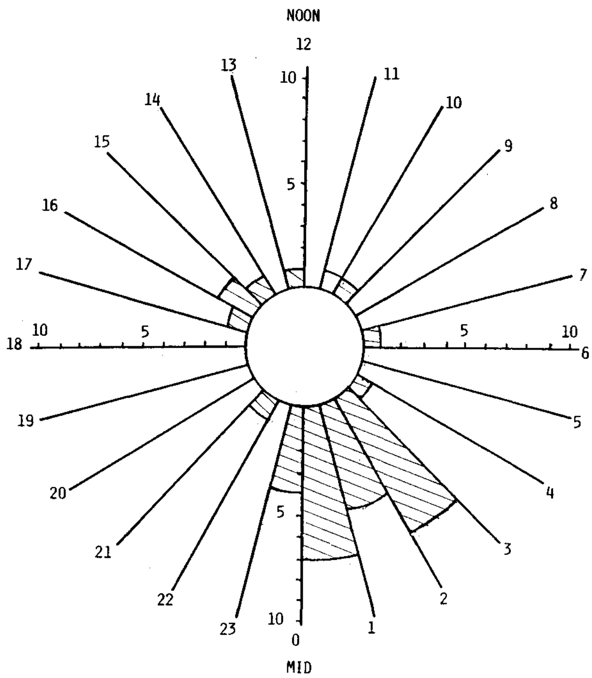

Fig. 3 SC1-8B pulse events vs local time.

of less than 6 h each, occurred in 1979. Of the total collected data, 177 days spanning the period from turn-on through October 1979, plus selected periods of 1980 and 1981, have been examined for transient pulse data.

The TPM data reveal that on this particular spacecraft, most transient pulses are the result of normal vehicle and payload operations. The transient pulse-producing operations have been found to include.:

1) Execution of realtime commands, such as transmitter and payload power on and off and experiment calibrations.

2) Automatic power conditioning unit operations during umbral and penumbral passages.

3) Automatic operational mode switching of the SC1-8A experiment.

Transient pulses are also produced during SC4 ion- and electron-beam emission experiments. SC4 operations entail emitting into the plasma around the vehicle 1.0 or 2.0 kV ions at currents of 0.3 to 2.0 mA and 0.05 to 1.5 kV electrons at currents from 0.0001 to 13mA. Transients associated with SC4 operations are believed to have been produced by power fluctuations during the experiment and discharging of artificially charged vehicle surfaces. These surfaces had been charged by the experimentally controlled space plasma around the vehicle.

Pulses not associated with the abovementioned effects are classified as candidate natural discharge pulses, for brevity now referred to as the TPM transient pulses. Although these pulses are not believed to be operation related, neither have they been positively correlated with an identifiable discharge on the spacecraft. A total of 198 candidate natural discharge pulses have been identified in the TPM data and are used as the basis of this study.

All TPM transient pulses have been recorded by the low-impedance antenna on the TPM and 182 of the 198 pulses were also recorded by the high-impedance antenna. Forty-two of the TPM pulses have had coincident solar array probe amplitude measurements. Only eight of the pulses have had an additional amplitude measurement on the single-point ground probe. Recorded peak amplitude values typically have been less than 1V on the low-impedence antenna and less than 6 V on the high-impedance antenna. These values generally are less than those associated with transmitter and experiment command operations and with SC4 experiments. Excursions in amplitude were seen on April 23, 1981 (SCATHA day 3113) when the low-impedance antenna measured a pulse with a peak signal of 20 V and the high-impedance antenna measured the same pulse at a peak signal of approximately 100 V. These extreme values are significantly larger than the operation-related pulses.

Due to the higher threshold setting of the SC1-88 pulse analyzer (generally 50-100 mV in contrast to a 2 mV TPM threshold), pulse events recorded by this experiment have not occurred as frequently as those recorded by the TPM (33 vs 198).[4] The majority of pulse events detected by the TPM, therefore, were not detected by the SC1-8B, but, despite the higher SC1-8B threshold, nearly half of the SC1-8B pulse events were not detected by the TPM. This illustrates the importance of sensor sensitivity and location and the complexity of electromagnetic coupling paths in determining the overall system response to spacecraft charging effects.

Local Time Distribution of Transient Pulse

TPM pulse events have shown a strong dependence on satellite local time. Figure 2 illustrates this correlation. The plot shows the premidnight-to-dawn sector of the orbit to have the highest occurrence of pulse events. Nearly 70% of all TPM pulses occurred in this region. Figure 2 is consistent with the local time distributions of transient pulses recorded by the SC1-8B experiment onboard P78-2, and unexplained anomalies observed on other high-altitude satellites. These distributions are shown in Figs. 3 and 4, respectively. The radial location of each point in Fig. 4 is irrelevant. The

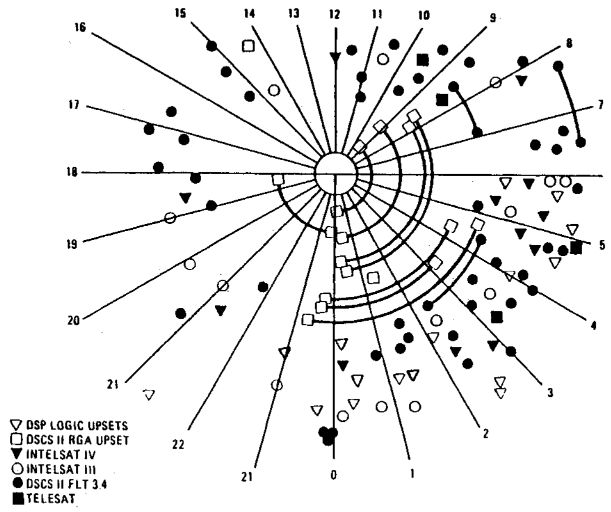

Fig. 4 High-altitude spacecraft anomalies vs local time.[2]

agreement between Figs. 2 and 3, and Fig. 4 indicates that transients seen by the two P78-2 pulse detection experiments are pulses likely to have been caused by discharge mechanisms similar to those that caused anomalies on other spacecraft.

Correlating TPM pulse events with differential surface potentials recorded by the P78-2 satellite surface potential monitor (SSPM) experiment (SC-1, -2, -3) can help define the transient pulse-producing mechanisms. Pulses coincident with SSPM charging events (Kapton sample potential greater than 100 V) are most likely to have been produced by a breakdown of charge on the surface of P78-2.‡ Conversely, pulses not coincident with SSPM charging events are more likely either to have been produced through some other mechanism, such as embedded charge breakdowns (due to high-energy electrons penetrating and internally charging spacecraft materials) or to have occurred at a surface location having a different physical configuration and hence, different charging characteristics than those of the SSPM samples.

For days on which SSPM data were available, approximately 80% of the TPM pulses were coincident with SSPM charging events. This indicates that surface charging was likely to have been a contributor to transient pulse production. Figure 5 presents the pulses as functions of local time and L-shell.§ The enclosed areas correspond to the regions of space in which there has been a high probability of SSPM charging during disturbed geomagnetosphere conditions, and to the region in which highest SSPM charging is likely to occur.[5] Nearly 65% f the TPM pulses coincident with SSPM charging events occurred within these regions.

Figure 6 shows the local time distribution of transient pulses not correlated with SSPM charging events. The uniform distribution of this plot points to a transient pulse-producing mechanism that does not have the local time, and therefore magnetospheric dependence, that surface charging and correlated TPM transient pulses were seen to have. A charging mechanism such as high-energy charges penetrating and being stored within dielectrics would have a uniform discharge pattern throughout the orbit due to the uniform nature of the high-energy space environment. This distribution also points out the embedded charging may also have been a cause of some previous spacecraft anomalies. The single-known natural anomaly on P78-2¶ occurred at a time when there was no SSPM charging present.

‡Positive identification of an SSPM discharge has not been made.

§L-shell refers to the radial location within the Earth's dipole magnetic field such that $L = [(\text{Earth radii})/\cos^2(\text{magnetic latitude})]$.

¶SC11 bandpass filter switch on June 14, 1980 (SCATHA day 2166).

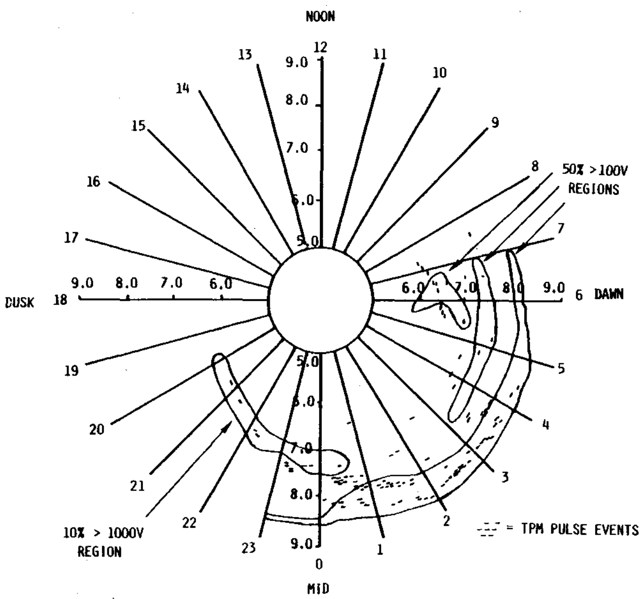

Fig. 5 TPM pulse events in presence of SSPM charging vs *L*-shell and local time, noting extreme SSPM charging regions.

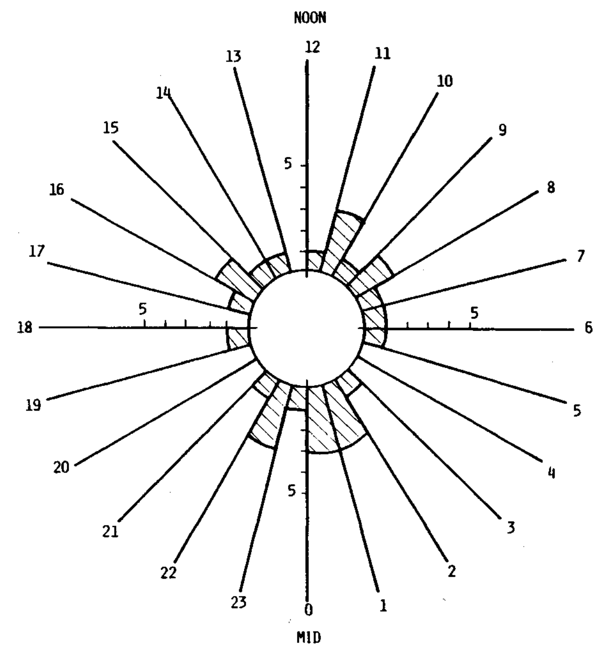

Fig. 6 TPM pulse events in absence of SSM charging vs local time.

Sun Angle Dependence of Transient Pulses

On-orbit operational requirements of the P78-2 spacecraft specified that the angle between the spin axis (pointing toward Earth at 1800 h satellite local time) and the solar vector was to vary between 85 and 95 deg. For spin-stabilized vehicles such as P78-2, the approximately 1 deg per day movement of the Earth around the sun will cause this angle, called the sun angle, also to increase by nearly 1 deg per day. Standard operating procedures were to command a precession maneuver when the sun angle approched the upper limit of 95 deg, in order to obtain a sun angle of 85 deg.

The solid line in Fig. 7 presents the average number and standard deviction (due to counting statistics of sun angle values) of transient pulses seen per day at each sun angle value. These data show that the trend of TPM candidate natural discharge pulses have been toward sun angles in which the aft end of the vehicle is shadowed. Also shown in Fig. 7 are the average number of pulse events per day per sun angle for which SSPM data were available. It is seen that the sum of

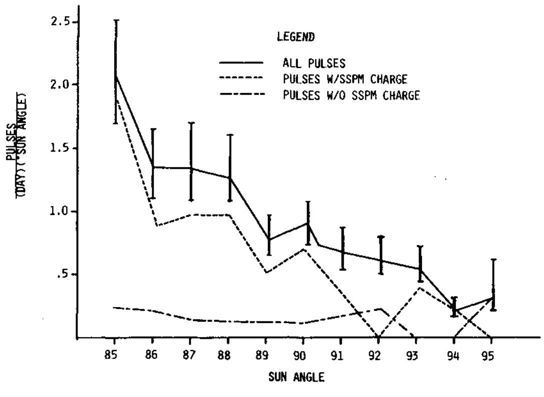

Fig. 7 TPM pulse events vs sun angle.

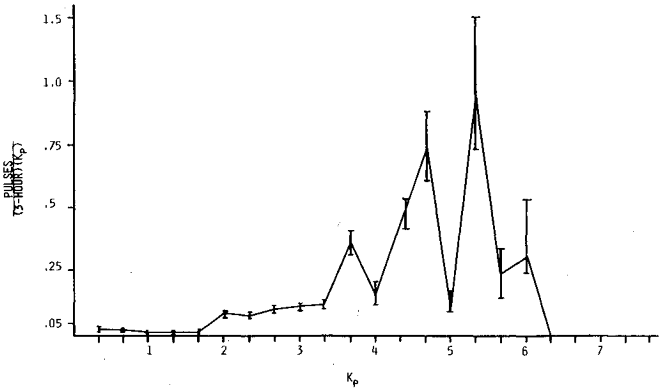

Fig. 8 TPM pulse events vs *Kp*.

these lower two curves does not equal the upper curve. This is due to the unavailability of SSPM data for the entire TPM dataset.

Pulses which correlate to SSPM charging events follow a similar pattern to the upper curve, indicating that surface charging at smaller sun angles has been most conducive to candidate natural pulse events. Those pulse events that do not correlate with surface charging events are nearly evenly distributed throughout all sun angle values. This suggests, in a manner similar to Fig. 5, that a uniform transient pulse-producing mechanism is present in the near-synchronous environment.

Spin Angle Dependence of Transient Pulses

Analysis of the spin rotation angle at the time of candidate natural discharge events reveals that groups of consecutive pulses that occurred at the same rotation angle were recorded on two occasions. Though SSPM data were not available for both occurences, a high level of surface charging had been recorded during the first event. The frequency of pulse events during these periods indicates that charging and discharging of surfaces may be as rapid as a single spin period, approximately 58 s. The configuration of the P78-2 spacecraft includes several booms, any of which may be shadowed at a given time, and many dielectric surfaces that are not monitored for charging and discharging. This condition precludes using the angle of rotation of these pulse groups as a factor in determining the particular discharge location.

For all other TPM data that can be correlated with SSPM data, there are relatively constant distributions over all angles of rotation for pulse events coincident with and in absence of surface charging.

The first observation of spin-synchronized transient pulses occurred on May 26, 1979 (SCATHA day 146). On this day, the TPM recorded 11 pulses (six were coincident with pulses recorded by the SC1-8B experiment) over a span of 15 rotations. The SSPMs were measuring surface potentials of greater than 1000 V during this timespan. There were no

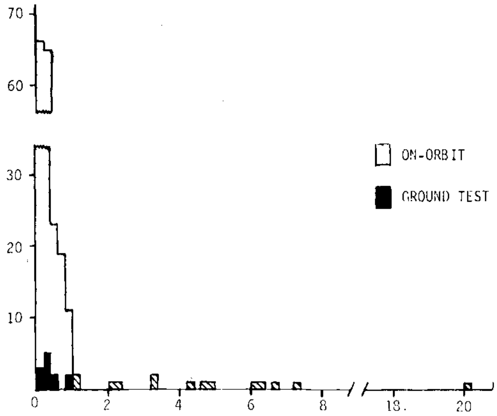

Fig. 9 Low impedance antenna peak amplitude (V) distribution, on-orbit vs ground test.

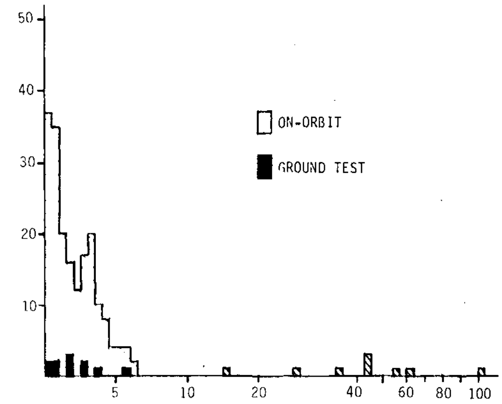

Fig. 10 High impedance antenna peak amplitude (V) distribution, on-orbit vs ground test.

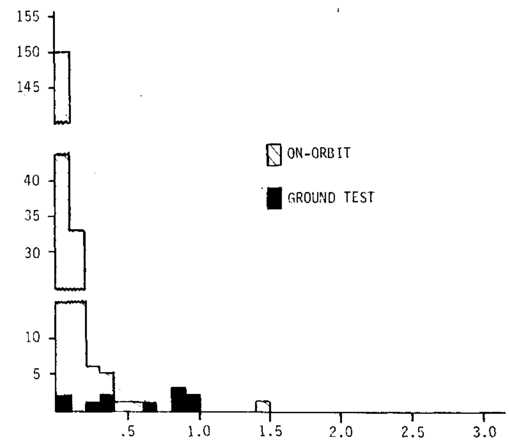

Fig. 11 Solar array probe peak amplitude (A) distribution, on-orbit vs ground test.

fluctuations, however, recorded in either the differential charge level or in spacecraft potential at the times of the transient pulses.

A second group of spin-synchronized transient pulses were observed on October 21, 1979 (SCATHA day 294) and included five pulses recorded over three spin periods. The second and third spin periods each had two transient pulse events less than 2 s apart. No SC1-8B pulses were recorded on this day. The particular spin angles of these pulses were different from those on day 146 (317 ± 6 deg vs 257 ± 5 deg), as were the sun angles on the two days (92 deg on day 294, 90 deg on day 146). These different orientation parameters would have produced different shadowing conditions on the spacecraft surfaces and, most likely, a different discharging location. No correlations have been made between TPM transient pulses and SSPM data for day 294.

Geomagnetic Dependence of Transient Pulses

Figure 8 presents the average number and standard deviation (due to counting statistics of *Kp* events) of candidate natural discharge pulses observed on P78-2 per 3-h *Kp* value.[6] A factor to consider in relating transient pulse rates to geomagnetic activity levels, in addition to the amount of disturbance, is the interaction of the substorm plasma with the spacecraft in the form of spacecraft charging. That is to say that a high *Kp* value may not indicate a space condition conducive of spacecraft changing effects should the substorm plasma be too low in temperature and density, or should the vehicle not be collocated with the region of space impacted by the substorm.

Figure 8 shows a correlation between a disturbed magnetosphere ($Kp > 2^+$) and an increased TPM transient pulse rate. There is also a trend in the plot for higher transient pulse rates at higher values of *Kp*. Both the correlation to disturbed geomagnetic periods and the trend for higher pulse rates are consistent with data presented in Ref. 1.

Due to the limited variation in combinations of *Kp*, orbital location, and plasma conditions, caution should be taken in interpreting the data in Fig. 8. While inconsistencies at *Kp* values of 4 and 5 may be statistically produced (note large standard deviations), the dropoff at values above 6^- may be an indication of the substorm passing through P78-2 altitudes into lower regimes.

TPM Peak Amplitude Data

The largest amplitude signals on the TPM antenna wires observed to date occurred on April 23, 1981. The largest of the measured transients produced an approximately 100 V peak signal across the 100 K Ω impedance of the high-impedance antenna and a 20 V peak signal across the 50 Ω low-impedance antenna. Assuming a 15 MHz antenna resonant frequency (as was measured during prelaunch tests), the first half-cycle of the damped sine wave signals on each of the antennae for this event contained energies of approximately 8 (10^{-9}) and 7 (10^{-8}) J, respectively. These energies are below the damage threshold, but within the upset threshold range for most integrated circuits. This particular transient event produced no detectable signal in the TPM single-point ground sensor.

The other two relatively large transient events detected on that date produced lower amplitude signals on the high- and low-impedance antennae (marginally at the typical integrated circuit upset level), but produced signal amplitudes of several amperes in the single-point ground sensor. This is most likely because the electrical breakdowns that caused these transients occurred at a different location on the spacecraft surface. The differences in these signals again point out that the system responses to spacecraft charging-induced transients are highly dependent on the locations of both the sources and the sensors. Although the several ampere signals on the single-point ground sensor may seem large, on this particular spacecraft transients of tens of amperes are routinely produced at that location during normal vehicle operations such as transmitter turn-ons.

Transient pulse peak amplitude data were recorded by the TPM during preflight space qualification arc-injection tests performed to test vehicle response to electromagnetic discharges. These tests were conducted in accordance with USAF electromagnetic compatability requirements as specified in MIL-STD 1541. TM sensors detected all 11 arc-injections, eight being detected simultaneously by all four sensors. Comparisons of TPM peak amplitude data recorded during these preflight tests and on-orbit (Figs. 9-12) show that for all sensors, maximum on-orbit amplitudes surpass the largest preflight peak amplitudes. Based on these data, it is seen that present MIL-STD 1541 arc-injection test

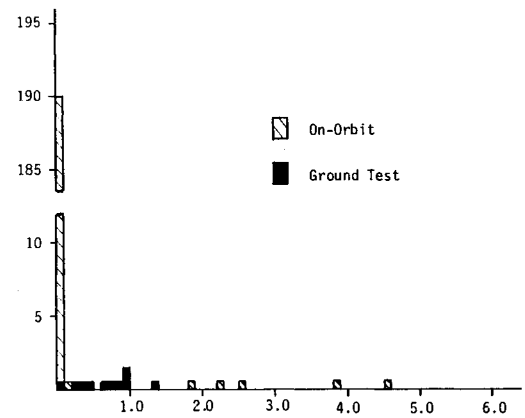

Fig. 12 Ground probe peak amplitude (A) distribution, on-orbit vs ground test.

specifications do not adequately stress vehicle systems to extreme on-orbit discharge pulse amplitudes.

Significant TPM Data Periods

In addition to SCATHA time periods previously mentioned, other noteworthy TPM days have been:

1) April 28, 1979 through May 2, 1979 (SCATHA days 118-122). These days, which included the final three days of the Spring 1979 eclipse season, had the highest daily pulse frequencies observed in the TPM data. Days 118 and 120 were especially active, recording 21 and 19 pulses per day, respectively. All of the pulses recorded on these days occurred in sunlight between the local times of 20.8 and 4.4 h. There was high geomagnetic activity during this timespan (*Kp* variation between 3^+ and 5^+). These data are consistent with that presented in Ref. 1 in which the highest transient pulse rates were observed in sunlight during geomagnetically disturbed periods. Approximately 91% of the transient pulses occurred while SSPM charging was present. Though many of the pulse events on these days were coincident with changing surface potentials, no pulses were determined to have been produced by an SSPM discharge.

2) June 14, 1980 (SCATHA day 2166). On this day the P78-2 spacecraft experienced the only observable natural anomaly of its 3-yr mission. While the spacecraft was at a low altitude, approximately 5.5 *Re*, and in the noon-to-dusk quadrant of local time, the SC11 bandpass filter spuriously switched modes. The TPM recorded a transient pulse within 1 s of the time of the switch. Though there had been high levels of SSPM charging on the previous days, in addition to a number of TPM candidate natural discharge pulses and an anomaly on another USAF spacecraft, there was no surface charging measured at the time of this anomaly. There had also been intense high-energy electron flux (>1 MeV) seen by P78-2 spectrometers during the three days prior to the SC11 anomoly.[7] This flux may have deposited sufficient energy within a spacecraft material to cause a transient pulse to be produced through an embedded change breakdown process. Therefore, within the limits of SSPMs to accurately monitor charging levels on the P78-2 surface, it appears that the lone P78-2 anomaly may have been the result of a nonsurface (i.e., embedded) charge breakdown.

3) April 23, 1981 (SCATHA day 3113). As was previously mentioned, the transient pulses recorded on this day had the highest peak amplitude signals observed in the TPM data. The four pulses on this day occurred while the spacecraft was passing through the Earth's penumbra and while surface and vehicle potentials were changing. These pulses are believed to be associated with surface, rather than embedded, charge breakdowns. Noteworthy among the characteristics of one pulse is that it was detected by the single-point ground sensor in addition to the low- and high-impedance antennae. Though the peak amplitude signal recorded by the ground sensor was less than those seen during transmitter power-on and -off command executions, the amplitude is significant because it is the largest recorded by the ground sensor for a candidate natural discharge pulse. No spacecraft anomalies were observed on this day despite the large peak amplitudes recorded by TPM sensors.

Conclusions

Data from the TPM show that there are two distinguishable candidate natural discharge pulse-producing mechanisms present at near-synchronous altitudes. The first is associated with surface charging in the presence of a disturbed magnetospheric condition. Pulses recorded under these conditions are highly localized, favoring the premidnight-to-dawn sector of the orbit. This mechanism is seen to be the dominant factor in the production of P78-2 candidate natural discharge pulses. Additionally, data from the TPM verify transient pulse data from a previously flown experiment which identifies these conditions as those which produced the largest pulse rates.

The second candidate natural discharge pulse-producing mechanism present in the TPM data causes a uniform distribution of transient pulses throughout all local time and satellite attitude conditions without the presence of measured surface charging. Though TPM and SSPM data alone cannot reveal the causes of these transient pulses, the data does substantiate predictions of such uniform distributions. P78-2 data reveal that the lone observable spacecraft anomaly occurred coincidently with a TPM transient pulse not associated with a surface charging event. This indicates that such nonsurface charging conditions may have produced anomalies observed on other high-altitude spacecraft.

As with most electromagnetic interference phenomena, the problem of spacecraft charging-induced electrical transients involves an electromagnetic noise discharge source and a susceptible "victim" circuit. Through attenuation, the particular design details of a spacecraft will greatly effect the amplitude of the noise seen by each circuit for a given source. Data quantifying P78-2 attenuation factors for specific coupling paths from probable discharge points to subsystem circuits and sensor location is not available to make estimations of discharge amplitudes based on TPM or SC1-8B recorded peak amplitude data. It is seen, however, that ground-test discharge simulations currently specified in MIL-STD 1541 do not adequately stress spacecraft systems to extremes in on-orbit discharges. Further studies in the area of ground simulation of space discharges are needed to insure that future spacecraft are tested against representative noise sources so that the hazards of spacecraft charging may be minimized.

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