RADIATION-INDUCED INSULATOR DISCHARGE PULSES IN THE CRRES INTERNAL DISCHARGE MONITOR SPACECRAFT SAMPLES

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ABSTRACT

The Internal Discharge Monitor, IDM, was designed to observe electrical pulses from common electrical insulators in space service. The sixteen insulator samples include G10 circuit boards, FR4 and PTFE fiberglass circuit boards, wires with common insulations, FEP teflon, and alumina. Pulsing characteristics differ amongst the sample materials. FEP differs significantly from TFE teflon, and fiber-filled material differs from bulk material. The samples are fully enclosed, mutually isolated, and space radiation penetrates 0.2 mm of aluminum before striking the samples. No bias is applied, the electric fields are generated by trapped spacecharge due to the stopping of high energy space electrons. The IDM results indicate the rate at which insulator pulses occur in space. The pulse rates are compared with space radiation intensities and energy spectra as measured by the CRRES satellite radiation detectors.

INTRODUCTION

The purpose and background of the Internal Discharge Monitor (IDM) are documented [1]. The IDM monitors spontaneous electrostatic discharges on internal insulators in spacecraft caused by penetrating radiation. Ref. 1 reviews test results for IDM sample material under laboratory simulations of the Chemical Release and Radiation Effects Satellite (CRRES) space radiation environment. These test results provided valuable data for determining the final design of the instrument. The samples were chosen because of their generic nature; they are representative of the many materials and device structures used in most spacecraft.

Radiation (mostly electrons) penetrates the skin of a satellite and stops in the insulating materials. High voltages then build up both on and in the insulator materials. Occasional spontaneous discharges of the insulators induce electrical pulses in sensitive satellite wiring. The magnitude of the pulses depends on many parameters including the area of charged insulator surface [2], the radiation spectrum, existing bias levels on adjacent circuits [3], the relative area of the sensitive circuit, the effective impedance of the sensitive circuit, voltages on other adjacent charged insulator surfaces [3], a complicated transfer function between the discharging circuit and the sensitive circuit, etc. The IDM only detects the number of pulses which occur above a threshold level on simple representative generic circuit elements. Thus, it tells us how often such pulses are occurring but nothing about the nature of the pulses.

The CRRES orbit is roughly geosynchronous transfer with an apogee of 33,500 km, a perigee of 348 km, a period of 9 hours 52 minutes, and an equatorial inclination of 18.2 degrees. Thus the IDM is exposed to the inner (usually HE protons) radiation belt for a short time, and to the outer electron belt for a long time. High energy electrons are the dominant cause of IDM pulses.

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THE EXPERIMENT

The sixteen samples were chosen after an extensive testing program [1]. Page limitations force us to refer to the literature [4] for a description of the samples and the electrode geometries. A pulse detector with 50 ohm input impedance is connected to one electrode on each sample. The pulses vary in width from less than 1 ns to as much as 10 nanoseconds [1,5]. Most pulses are between 2 and 5 nanoseconds wide. The threshold for pulse detection is ten picocoulombs for the pulses of shortest duration so that some partial discharge pulses will be detected. Depending on pulse width and sensitivity setting, the voltage thresholds vary from a tenth of a volt to ten volts on the 50 ohm detectors. More information is available on the sensitivity of the detectors [4].

Much larger pulses result from the same phenomena occurring on larger samples or on samples with applied voltage on the electrodes [2,3]. The pulses monitored on IDM samples are assumed to relate both directly and indirectly to the phenomena of satellite anomalies produced by discharges on wiring, solar array insulators, thermal blankets, antenna insulators, circuit boards, feed-thru insulators, and other electrical component insulation.

The maximum pulse voltage measured in ground tests on a 50 ohm line (sometimes 25 ohms) is reported in Ref. 1 for most of the samples, and in Ref. 5 for multilayer G10 circuitboards. For samples of this size (25 square cm.) we expect the maximum voltage to be on the order of 100 volts. Because the pulse voltage is dependent upon many external factors (in this case 50 ohms is important, higher impedance results in higher voltage) it is not the exact voltage which is of interest. The occurrence of a pulse of sufficient energy to interrupt normal circuits is of interest. In different circuits the pulsed voltage, or energy, from the same kind of material could be much larger. We believe that the IDM pulses are the triggers which sometimes create much larger pulses, and the IDM pulse rates are an indication of the maximum rate of occurrence for spacecraft ECIEMP (Electron Caused Internal ElectroMagnetic Pulse) discharge anomalies.

RESULTS

The pulsing history of the frequently pulsing samples is provided in Fig. 1. Each sample is designated by its identifying number, its insulating material, the thickness of the insulation, and the type of electrode which is not connected to the 50 ohm pulse detector [4]. GM is a grounded metal electrode, FM is a floating (unconnected) metal electrode, and NM is a free insulator surface on samples which have only one electrode. For example: an insulated hook up wire is a type NM, a coaxial cable with the shield grounded is a type GM, and with the shield floating is a type FM. The samples not shown have pulsed only rarely.

Channel 3 contains a sample of G10 circuit board material [5]. This is a nine layer board without any components mounted. Approximately one quarter of the circuit traces are connected to the pulse detector, the rest of the traces are connected to the instrument ground. The surface of the board is treated with urethane conformal coating. A ground plane is conductively glued to most of the back side of the board. Under electron beam testing, similar circuits were found to produce 20 to 40 volt pulses several nanoseconds wide [5]. Channel 3 experienced only 3 pulses in space. Channel 14 contains a similar sample of G10 board which is covered with "leaky paint", and has not pulsed in space. Samples with leaky paint were seen to pulse only rarely and with pulses less than 1 volt in ground tests [5].

We can outline the results as follows. Pure PTFE (channel 1) is a reluctant pulser, and after sufficient radiation dose it becomes conductive enough that spacecharge electric fields are reduced and pulsing stops. Fiberglass needles in PTFE (channel 16) increase its pulsing response. Pure FEP (channel 9) is a reluctant pulser which requires substantial spacecharge to induce its few pulses. FR4 epoxy-fiberglass pulses occasionally at low fluences, but as the spacecharge density accumulates pulsing becomes very frequent above 0.1 megarads. All discharges are partial, the samples' bulk spacecharge relaxes negligibly during a pulse.

Fig. 2 describes the relationship between instantaneous high energy space electron flux and sample pulses. The data is accumulated into measurement periods. Each period corresponds to the time during which the satellite passes through a shell of the magnetosphere. Arbitrarily we divide the Earth's magnetosphere into shells, each $1/5$ L-shell thick. It takes approximately 10 to 20 minutes for the CRRES satellite to pass through a given $1/5$ L-shell, for example from $L=3.5$ to $L=3.7$. Within any $1/5$ L-shell the flux and energy spectra are approximately constant. If we sum the data over, say, ten orbits then each $1/5$ L-shell is visited 20 times and the total measurement period in that shell is roughly $15 \text{ minutes} \times 20 = 300 \text{ minutes}$.

In Fig. 2 the smooth curve describes the flux of high energy electrons impacting the sample as the satellite orbits the earth. The histogram describes the pulse rate summed over all samples. The dotted curve indicates the magnitude of the pulse rate if there had been only one pulse during each measurement period, and comparison to the histogram shows that during each measurement period there were a few pulses at most. Fiberglass PTFE dominated the pulsing during the first 300 orbits and produced pulses hours after the electron flux decayed. After orbit 600, the FR4 circuit boards dominated the pulsing and responded rapidly to the flux changes.

Ref. 4 indicates that the daily pulse rate summed over all samples mimics the daily electron flux level. This result has been further confirmed by later data where the total pulse count has quadrupled. However, the later data is dramatically different than the earlier data. Summed over all samples, the pulse rate per unit flux has substantially increased. The early data was created almost entirely by two samples of PTFE which did not pulse at later times. The later data was created almost entirely by FR4 circuit boards which pulsed frequently at late times and rarely at early times. If one looks at each sample alone, one might presume that there were ageing effects wherein some samples pulsed more frequently after high fluence while PTFE material pulsed less frequently. We tentatively feel that the PTFE material stops pulsing for the same reason that it does so in laboratory tests. After a total dose accumulation approaching a megarad, PTFE becomes much more conductive and the leakage currents relax the electric field in the material so that it is no longer sufficient to initiate partial discharges.

But FR4 epoxy fiberglass is known to remain insulating, and it is also known from laboratory tests that the electric fields don't reach their maximum steady state value in electron irradiations until the dose exceeds 0.1 megarads. Thus the FR4 pulsing rate is increasing when the PTFE pulsing rate is beginning to diminish. However, we do not know with certainty why the samples began pulsing so early in the flight. Perhaps they had surface flaws such as protruding fiber needles which pulsed readily, especially at the edges and corners of the samples. These results are an excellent example of the fact that pulsing can be sample specific. It is especially noteworthy that bulk electron spacecharge continued to increase over a period of 1 year, thus leakage currents at low electric fields are insignificant relative to space radiation fluxes of 10^6 electrons/cm²-sec.

Fig. 1 Pulsing Histories. A bar of unit height is one pulse per 10 hour orbit. All samples were exposed to the same intensity of space electron flux.

Fig. 2 Pulsing Rate (histogram) and Electron Flux (smooth curve) versus Position Along Orbit.

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