A REVIEW OF ESD RATES OBSERVED IN ORBIT

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ABSTRACT

Spacecraft manufacturers are required to qualify their designs to demonstrate either immunity to the environments or to derate their designs to accommodate the degradation that will accrue over the mission life. ISO-STD 11221-E describes charging tests that establish degradation due the array arcing and due to any follow-on sustained arcing. A key question for any charging test program is the definition of duration-how many arcs do I expect over mission life with a given design. ESD rates observed on historical spacecraft are reviewed to provide an assessment of the plausible number of ESD events to be expected

1. I. INTRODUCTION

This paper begins with an overview of the estimated number of surface discharges expected on the WIND spacecraft, which is an excellent case study for the process described in ISO-STD 11221-(E). Subsequent close examination of those estimates by independent reviewers uncovered non-physical artefacts in the environment climatology data. When the suspect environment data is rejected, the total yearly arc count dropped significantly. But the reviewers had not repeated the entire discharge count estimating process, and were not able to offer an independent discharge rate estimate. In-orbit data from discharge monitors on three different spacecraft are reviewed in the next section. Average annual arc rate data are estimated from the flight results to provide the range of rates observed in-orbit. The observed rates range span 3 orders of magnitude, which is too wide to provide useful engineering guidance. The conclusion is that the in-orbit data does not provide consistent guidance to solar array test planners.

2. ISSUES WITH ARC COUNTS ESTIMATED USING THE ISO 11221 PROCESS AND LANL CLIMATOLOGY DATA

Spacecraft manufacturers are required to qualify their designs for the environments they will operate in, and to demonstrate either immunity to those environments or to derate their designs to accommodate the degradation that will accrue over the mission life. This includes the effects of charging and the ESD it causes. In the case of solar arrays, AIAA standard S-112 [1] describes the types of testing required to qualify solar arrays. ISO-STD 11221-E [2], which is an applicable document in AIAA S-112, has laid out a rigorous ESD qualification process. It requires testing to establish the ESD threshold voltage (section 6.1), the level of degradation due the array arcing (primary arcs, section 8.1) and due to any follow-on sustained arcing (sections 7.4-7.6).

A key question for any charging test program is the definition of the test duration, that is,-how many arcs do I expect over mission life with a given design, and what percentage of that quantity is required for a subscale coupon qualification test. ISO-STD-11221 recommends a process to answer that question using a combination of analyses and tests (section 6.6 and Annex D).

A case study that combined tests and analyses to determine the expected number of primary arcs and corresponding test duration is the assessment of the WINDS satellite charging performed by Cho et al [3]. A detailed NASCAP model of the spacecraft was analysed using parametric sets of geosynchronous orbit (GEO) plasma number densities and temperatures to determine which combinations result in inverted gradient differential charging on the array over an empirically established breakdown threshold. Climatological frequency of occurrence statistics for the GEO plasma parameters were derived from measurements made by the Los Alamos National Lab (LANL) MPA instrument and archived on the web [4]. The solar array arcs expected over a year was estimated at 2990 arcs total (to be applied to degradation tests of section 8.1) and 2434 in sunlight (to be used for secondary arc testing of sections 7.4-7.6).

Some researchers were surprised by the total number of arcs per year, which was far higher than values reported in orbit (e.g., SCATHA has reported ESD rates of only 76 per year). This motivated them to closely scrutinize the paper. They uncovered non-physical combinations of number density and temperature in the plasma parameters in the LANL raw data set [5]. Per the LANL MPA principal investigator, these are artefacts of the algorithm used to correct the plasma properties for biases introduced by charging of the satellite hosting the MPA instrument. When the arcs predicted using the non-physical parameter sets were removed, the number of arcs/year dropped from 2990 to a range of 105 to 762. However, the researchers were not prepared to repeat the entire analysis of Cho et al. and could not therefore establish a definitive estimate for the total number of arcs. This leaves solar array designers without clear guidance on how to scope their ground ESD qualification tests.

There is an alternative source of ESD counts: the flight history of spacecraft that flew discharge monitors which detected and recorded ESD events. The rates observed in orbit by instruments on three satellites are reviewed in the next section.

3. SURFACE DISCHARGING RATES OBSERVED IN-ORBIT

3.1. TPM Discharge Counts

In response to anomalies that had occurred on several spacecraft attributed to spacecraft surface charging and discharging, a Transient Pulse Monitor (TPM) instrument was developed. The instrument was coupled to a simple “E-dot” external electric field sensor and installed on a geosynchronous satellite [6]. The E-field sensor was a flat metallic plate, biased at 5.6V negative relative to spacecraft structure ground. Under normal sunlit conditions, the TPM would measure net positive current to the plate, which consisted of the currents of ambient plasma ions minus the plasma electrons collected by the plate, plus the much larger photoelectron current leaving the plate. In eclipse, or when the sensor plate is shadowed, the photoelectron current is near zero and the net current was very small. During strong charging conditions in geomagnetic sub storms, the net current would become negative, even during sunlit operation. During these events, the current was reported as zero in the telemetry because the instrument was designed to only measure positive currents.

The TPM would count voltage pulses on the plate lasting between 0.5usec to 1msec caused by EMI radiation from discharges on the satellite surface. This early version of the TPM was not designed to capture amplitudes or waveforms. Laboratory calibration tests indicated that discharges from thermal control dielectric coupons could be detected out to a 3 foot range. But the instrument did not have a sharp range cutoff and larger discharges anywhere on the spacecraft could be detected.

The TPM and sensor were flown on an unidentified host satellite in geosynchronous orbit. On a magnetically quiet day (Ap index = 5), the current sensor showed only the normal diurnal variation of photocurrent (due to varying sun angle with satellite local time). The current also varied with satellite spin angle, but the authors of [6] only reported the peak current versus spin angle. The diurnal current peaks when the plate surface is closest to normal to the sun, which occurs around satellite local times of 6:00 and 18:00 hours. The current reaches a minimum near local midnight when the sunlight has a grazing incident angle. At local noon the current goes to zero because the spacecraft body shadows the plate.

Despite the quiet magnetic conditions, 217 arcs were detected over 24hrs, for an average rate of ~9arcs/hr. Most arcs occurred around 16:00-22:00 local time. The arcs also occurred within an asymmetric narrow range of spin angles, suggesting a small area was responsible for the discharges. Had the cylindrical solar arrays been discharging, the spin angle distribution should have been more azimuthally symmetric.

On a day of modestly active geomagnetic conditions (indicated by Ap=19), the current collected showed the usual diurnal pattern except for the 3.5 hour drop to zero around local midnight, indicating a high flux of energetic electrons is overwhelming photoemission. There was a significant spike up in the rate of discharges, peaking at ~6arcs/minute, coincident with that high flux. A total of 335 discharges were detected during the 3.5 hour long storm, a rate of 96 arcs/hour. This is an order of magnitude higher than the quiet time background rate. An examination of the discharge timing over a spin period relative to the detector’s orientation to the sun shows a fairly uniform distribution. So discharges during storm time conditions appear to originate all around the spacecraft (and are large enough to be detected far from the TPM sensor).

Low rates of discharges similar to the quiet time response preceded the storm. The total number of discharges during the other 20.5 hours of the disturbed day after the storm totalled 377, for an average rate of about 18 arcs/hour that is twice the background quiet-day rate. The spin modulation distribution of the discharges during that 20.5 period looked nearly identical to the quiet time spin angle distribution, suggesting the same small discharge source region was involved.

Design details for the spacecraft that hosted this instrument are not known. However, the majority of the external surface area of spinners is used for cylindrical solar arrays, and another smaller portion for second surface mirror thermal radiator panels The radiator mirrors and solar cell cover glass typically utilized the same (non-conductive) cover glass, and would be expected to charge and discharge with azimuthal symmetry. The spacecraft top is where payloads are typically located, and the payloads are very asymmetric with regard to spin angle. The rate of discharges outside of storm times is likely due to discharges on the payload because of the asymmetry with respect to spin angle, and therefore is irrelevant to estimating discharge rates for the solar array. The symmetrical angular distribution of discharges during storm times suggests that they occur from the solar arrays or radiator surfaces. Because the surface area of the solar array is typically much larger than the radiator area, we will conservatively assign the entire rate of discharge during storm times to the solar arrays.

A single modest geomagnetic storm produced 335 arcs, roughly half of the yearly discharges predicted by the reduced LANL data set. More severe storms would be expected to produce a greater number of discharges. We need to estimate how storms there are a year at various intensity levels to project the yearly discharge count for this satellite. Table 1 summarizes the calculations we performed to estimate the average number of arcs per year we should expect at each Kp level and then total.

The authors of [6] found a roughly linear trend in arc rate versus the Ap index: rate ~(11+34*Ap/50) arcs/hr. rate. Because the quiet day arcs show azimuthal asymmetry, we concluded they are not from the cylindrical arrays and we ignore their contribution to the solar array arc rate. We estimate that the active day rate trends as: active_rate=(34*Ap/50) arcs/hr. We have applied this relationship to the Ap disturbance levels, which correspond to integer Kp levels [7], to derive the estimated arc rates per hour shown in the third column of Table 1

Table 1. Derived yearly ESD counts

Kp	Ap	Counts /hr	events /cycle	Arcs /cycle	Ave. Arcs /yr
0	0	0	Assumed all discharges for Kp<5 are from background asymmetric discharging & not array discharges		
1	4	0			
2	7	0			
3	15	0			
4	27	0			
5	48	33	1700	41,616	3,783
6	80	54	600	24,480	2,225
7	132	90	200	13,464	1,224
8	204	139	100	10,404	946
9	400	272	4	816	74
					8,253

The Space Weather Prediction Centre (SWPC) at the National Oceanographic and Astronautic Administration (NOAA) has ranked the severity of geomagnetic disturbances (by Kp index) and has given the expected number of occurrences over an 11 year average solar cycle in their geomagnetic storm index scales[8], which we show in column 4 of Table 1. Note that the SWPC scales focus on Kp $\geq$ 5 (Ap $\geq$ 48), so we have ignored any arc count estimates for Kp < 5, assuming they do not occur on the array.

The number of arcs expected per solar cycle is derived by multiplying the number of ESD arcs/hour times 3 hours per event (the duration of each value of Kp) and times the number of geomagnetic disturbance events per solar cycle divided by 4. This approach assumes that the solar array arcs will only occur during exposure to geomagnetic sub storms between local midnight and dawn (00:00-06:00 SLT). A GEO spacecraft therefore has a 25% probability of being in the right local time quadrant to experience the high sub storm flux. Finally, the arcs per solar cycle are divided by the 11 year average cycle duration to obtain the average yearly arc rate. The estimated ~8300 arcs/year is 1-2 orders of magnitude higher than the 105-762 arcs/year estimated for WIND using the reduced LANL parameter set.

The satellite carrying the TPM had another instrument which suffered anomalies [9]. The anomalies had two distinct telemetry signatures. The principle investigator for the instrument was able to replicate the telemetry signatures by injecting pulses of the type observed in ground tests [10] of typical spacecraft materials. This provided further evidence that ESD was occurring on the host spacecraft, but clearly, if the estimates of the yearly discharge counts are correct, most must be too small or too far away to affect this other payload instrument.

Satellite design has changed significantly over the decades. As described in [3], WIND utilizes dissipative black kapton thermal blankets and ITO coated radiator cover glass. The solar array panels still use conventional non-conductive glass, but the cells are mounted on graphite fibre composite panels. So, significant areas of the spacecraft surface were static dissipative. Satellite design in the 1970s utilized all nonconductive surface materials, so it is plausible that the rate of charging and discharging could have been much higher back then.

3.2. Discharge Counts on P78-2 (SCATHA)

The P78-2 spacecraft, more widely known as SCATHA, was conceived to study the near geosynchronous orbit charging environment, the build-up of voltages on several different materials, and to detect the occurrences of discharges.

The mission, instruments and spacecraft are described in detail in the literature [11],[12],[13]. SCATHA was a cylindrical spacecraft with large numbers of experiments mounted on booms, along the central body band and on the top. It was spin stabilized at 1 rpm and oriented to keep the spacecraft top out of the sun. Unlike the other spacecraft described in this paper, SCATHA was designed for immunity to spacecraft discharges. The structure was designed in large part to provide an RF shielded enclosure. Wires were individually shielded, and wire bundles outside the RF enclosure received an additional aluminium foil overwrap. Power and signal lines carrying more than 10nA were routed with returns for magnetic cancellation, and the solar array panels were back wired for magnetic cancellation (one of the experiments was a magnetometer intended to measure the ambient field, which is ~100nT at GEO). Pairing signal and returns will reduce differential mode radiation of any signals carried on those pairs. The power system was also designed to maintain a low impedance <20milliohms from DC to 10MHz. A bare gold band at the bottom of the spacecraft (plus some ITO coated glass on the bellyband), which would be exposed to an average of $1/\pi$ suns of sunlight would provide a reference potential for the spacecraft.

There were two key instruments to detect and characterize discharges, the TPM and the SC1 Transient Pulse Shape Analyser (PSA). This TPM is an upgraded version of the TPM previously discussed. It is an electronic processor with 4 sensors: 2 are current probes and 2 are long wire antennas: 1 current probe is on one wire connecting a solar array circuit to the power conditioning unit, the other is on one of 7 return wires connecting the PCU to structure single point ground [11]. Both sensors have 1mV/1mA sensitivity, though the ground sensor has a 20dB 50 ohm attenuator. The long wires are unshielded insulated wires tied to the outside of the foil shield on the main vehicle wire harness (height above "ground" is undefined). These 2 wires run parallel to each other and run half way round the inner structure tube and have differing terminating impedances; one is low impedance (hard ground at far end and 50ohm input, with 20 dB attenuator, at the monitor end), and the other is high impedance (100kohm at far end and 10kohm in series with 50 ohm TPM input). The TPM monitors all 4 signals continuously and outputs the pulse count, (+) and (-) peak amplitudes and (+) and (-) integrals once per sec.

The SC1 Transient Pulse Shape Analyser (PSA) measures a signal pulse shape in time domain from 7ns to 3.7msec. It samples 4 sensors: (1) a loop antenna around the primary command distribution unit, (2) a wire outside a typical cable bundle, (3) an external short dipole antenna at end of 2m boom (shown as SC1 in Figure 1), (4) digital command line from the CDU to pulse shape analyser. The TPSA polls each sensor for 16 seconds, and then switches to next sensor. If a signal exceeding a commandable threshold occurs, the signal amplitude is sampled 16 times, either linearly or logarithmically in time. The log time scale covers 7ns to 492usec, linear spacing is 0.16, 0.24, 1.0, 3.8, 30 and 250usec. The amplitude dynamic range is 3mV to 1.84V at min attenuation, and 3.46V to 1910V at max attenuation.

Discharge data was periodically reported out in the literature by Koons et al. [14],[15],[16]. In the first report, 4640 pulses were detected on 20 of 447 days analysed, but only 34 transients (<1%) were attributed to discharges. The vast majority of events were attributed to normal satellite responses (i.e., a command pulse occurred within the 1 second reporting window, so the transients were ignored) or they occurred during e-beam and ion beam experiment operation, and were also ignored. The average discharge rate was 0.076/day, or about 28 discharges/year. The authors reported that the local time distribution showed the majority of the discharges occurred between midnight and dawn, as expected.

In the second report, the total number of days of data analysed had risen to 822 days, and 147 pulses attributed to electrostatic discharges had been detected. The average daily rate had risen to 0.18/day, or 65 discharges/year. A cluster of 29 discharges occurred on a single day (Sept. 22, 1982), along with three different spacecraft anomalies. The discharges were locked to nearly the same rotational phase angle, suggesting that a single location on the spacecraft was arcing. (This is similar to the quiet time arc spin angle phasing on the spacecraft discussed in the prior section.)

In the third report, the total number of days of data analysed had risen to 1527 days, and 316 pulses attributed to electrostatic discharges had been detected (of a total of 8389 transients). The average daily rate had risen to 0.21/day, or 76 discharges/year. The distribution of surface discharges versus satellite local time showed a strong propensity for arcs to occur between 23:00 and 6:00 local time.

The SCATHA rate of 76 discharges per year is only 2.5% of the initial discharge rate estimated for WIND, and is an order of magnitude under the upper rate estimated for WIND from the reduced LANL data set. It is two orders of magnitude below the rate observed by the earlier TPM instrument.

3.3. Discharge counts on CTS

The Communication Technology Satellite was an experimental high-power RF payload spacecraft that was 3-axis stabilized and had large planar blanket arrays [17], [18]. Per those sources, the design had features common to the 1970-71 period: non-conductive thermal blankets were used to close the top and bottom spacecraft body openings; non-conductive solar cells, optical solar reflectors (OSRs) and Ag/Teflon were used on the s/c exterior. All of these materials were expected to charge and discharge. A transient event counter (TEC) instrument was added to the spacecraft late in the program to detect ESD pulses coupled into the spacecraft harness. The TEC utilized 3 sensor wires that were coaxial cables with 60 cm of the shield removed and which were laced to harness bundles of interest. Consequently, external ESD had to induce signals in the harness and then cross-couple to the TEC sensor wires. Ground tests with a pulser indicated the 5V threshold would easily be exceeded.

The TEC sensor locations were:

1. Channel 1 (ACS) was attached to the attitude control system harness, which was expected to pick up discharges from the dielectrics on the forward platform, including thermal blankets and silvered Teflon radiators
2. Channel 2 (SA instrument) was attached to the solar array instrument harness just inside the spacecraft at the slip rings; the instrument harness is unshielded and runs down the centre of the blanket array
3. Channel 3 (SA power) was attached to the solar array power harness just inside the spacecraft at the slip rings; power lines are unshielded and run down both sides of the blanket array

The electronics had a single telemetry channel, so each sensor would count pulses for 1 second in turn, and on the 4th second, a calibration signal was sampled. The detection threshold was 5V, and the count scale coding ranged from 0-63 pulses and an overflow indicator representing greater than or equal to 64 pulses. A built in delay of 5 microseconds was imposed to suppress counting long duration ringing pulses multiple times.

The TEC captured nearly 3000 arcs in 91 days. The A1 sensor captured 942 arcs, the A2 sensor (array signal lines) captured 1411 arcs and the A3 sensor on the array power lines captured 640 arcs. (Note: the count detected on the power line harness was consistently lower than from the array instrument harness. This was explained by the fact that the power control electronics attached to the power harness filters the power lines, and since the power circuitry is lower impedance than instrument circuitry, fewer power line transients could reach the 5V detection threshold.)

The total yearly count of all the arcs detected by the 2 solar array sensors is projected to be roughly 8200 arcs/year, about a factor of 3.4 higher than originally estimated by analysis for WIND and 1-2 orders of magnitude higher than the estimates based on the reduced LANL data set.

The CTS 3-axis stabilized spacecraft body and sun tracking planar array are more representative of current spacecraft designs. And since the TEC sensors are sampling the solar arrays directly, these estimates appear more applicable. Post launch, an ESD charging test was performed on a solar cell coupon that confirmed that ESD pulses should occur when exposed to sub storm type electron fluxes [19]. Note however, the solar array arcs occurred at all local times, and not just between local midnight and dawn. So charging and discharging may be occurring at different local times.

4. CONCLUSION

It was originally hoped that surface discharge rate data collected by discharge monitors on satellites in GEO or near GEO orbits would provide a consistent picture of the discharge rate one could reasonably expect on future spacecraft, and would also provide an independent benchmark for the rates estimated for the WIND satellite, which followed the process promulgated by ISO-STD 11221-(E). Unfortunately, the observed discharge rates cover a wider range than the analytically estimated rates. Rates derived from data obtained on 2 spin stabilized spacecraft ranged from a low of 76/year (SCATHA) to a high of ~8300/year from early TPM data. Rates based on data from CTS, which is a 3-axis stabilized spacecraft like WIND, are ~8200/year, which is roughly factors of 3.4-4.6 higher than the original rates estimated for WIND, and are 1-2 orders of magnitude higher than the reduced rates arrived at after rejecting discharges predicted using non-physical LANL parameters.

Some differences in rate would be expected due to differences in spacecraft design (e.g., size). Significant differences in discharge monitor sensitivity (sensor locations and sensitivity to ESD fields or currents) are likely a greater factor. Since standard, calibrating ESD pulse tests of these satellites were not performed, relative comparisons of monitor sensitivities cannot be made. Since most of the available data reports a count of discharges (SCATHA is the exception), comparison of discharge amplitude distributions cannot be made. So there is no clear way forward to synthesize a reasonably narrow estimate of annual discharge rate from this body of data.

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