

ESD triggered solar array failure mechanism

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Abstract. A mechanism is presented which explains recent anomalies on geosynchronous (GEO) communications satellites. The symptoms of the anomalies are low impedance shorts between high and low voltage cells on a solar array string, and shorts between high voltage cells and the array ground. All of the anomalies occurred when other, instrumented, satellites measured a charging environment. In this paper we present a theory and supporting laboratory data, which show how small, low energy, spacecraft charging electrostatic discharges (ESD) on solar arrays can lead to larger, sustained discharges, which permanently damage the solar arrays. While first observed in GEO, this mechanism can also lead to solar array failures in LEO.

1. Background

Recently, more than one geosynchronous communications satellite suffered anomalous events that resulted in failures of solar arrays strings. All of the anomalies occurred when instruments, such as the Los Alamos National Laboratory Magneto Plasma Analyzer [Thomsen, et al., 1994], on other satellites measured a substorm environment in the magnetosphere and spacecraft charging.

Spacecraft charging analysis using the NASA Charging Analyzer Program (NASCAP) identified the solar arrays as the probable site of spacecraft charging initiated ESD. However, these ESD arcs have insufficient energy or currents to lead to permanent damage. Analysis showed that the short duration spacecraft charging arcs could trigger long duration discharges between solar cells supported by the solar array current itself.

These long duration discharges dissipate substantial energy, and can cause permanent damage to the Kapton substrate on which the cells are mounted. The effect on

the Kapton is to turn the high resistance polymer into a low resistance carbonized ash. This process, known as pyrolysis, has previously been reported [Stueber and Mundson, 1993]. The net effect is to short out the string, either between high and low voltage cells, or between high voltage cells and the underlying spacecraft chassis ground.

Tests have been performed in a plasma chamber at NASA/LeRC reproduced the failure symptoms observed on orbit, and have provided insight into the details of the controlling mechanisms.

2. Spacecraft Charging Analysis

The NASA Charging Analyzer program (NASCAP) was used to model the spacecraft charging, and to locate possible discharge sites. The NASCAP model, shown in Figure 1, is typical of modern three axis stabilized communications satellites. The major features are the body, mostly covered with conducting thermal blankets,

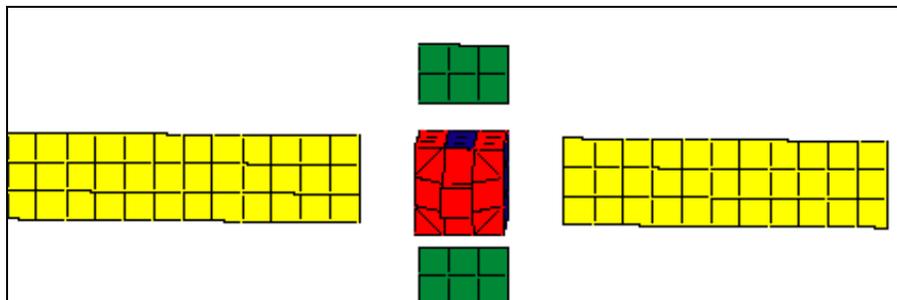


Figure 1. NASCAP model of a GEO communications satellite.

and the large solar array wing, the backs of which are also covered with a black conducting polymer.

Because the actual environments were not known, calculations were performed using the NASA recommended “worst case” charging environment [Purvis, et al., 1984].

$$\begin{aligned} n_e &= 1.12 \times 10^6 \text{ m}^{-3} \\ T_e &= 12 \text{ keV} \\ n_i &= 2.36 \times 10^5 \text{ m}^{-3} \\ T_i &= 29.5 \text{ keV} \end{aligned}$$

Sensitivity studies showed that the spacecraft charges for environments much less severe than the “worst case” environment.

The NASCAP calculations show that the spacecraft charges during substorms, even when in sunlight. The reason is that photo emission from the relatively small conducting area that is sunlit, is exceeded by the charging currents to the large conducting areas on the backs of the solar arrays, which are always shadowed. The spacecraft chassis charges negative at an initial rate of about -5 volts per second, as shown in Figure 2.

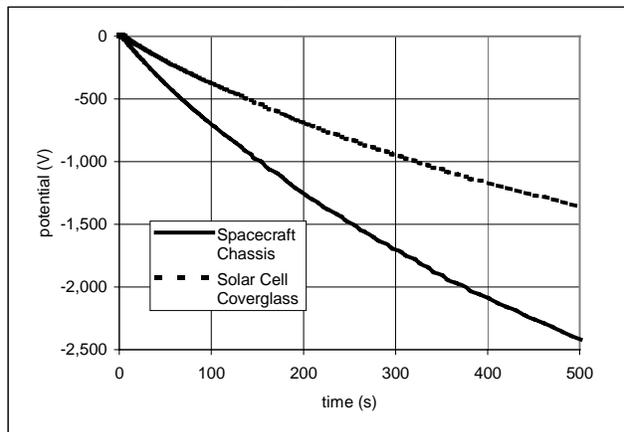


Figure 2. NASCAP calculation of spacecraft charging

The NASCAP calculations also show that inverted potential gradients develop on the solar arrays. An inverted potential gradient is when the solar array coverglass is less negatively charged than the underlying cell material and metallic interconnects. As shown in Figure 2, the potential difference between coverglass and the underlying cell increase at an initial rate of about 3 volts per second. This charging continues only because the coverglass is highly resistive.

Even though their photo emission currents are much larger than their charging currents, the solar cell coverglasses charge negatively because local electric fields prevent the low energy photo electrons from leaving the spacecraft, as shown in Figure 3.

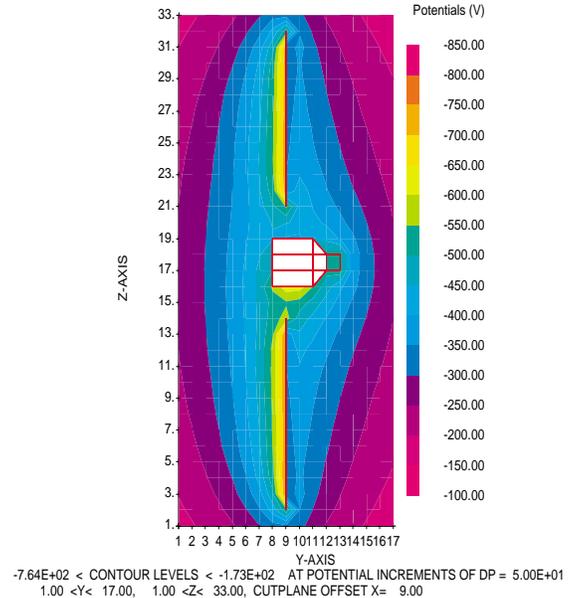


Figure 3. Potentials around the spacecraft showing the barriers that suppress low energy photo emission from the solar cell coverglasses.

The NASCAP calculations show that after a few minutes, the solar array coverglasses are several hundred volts positive with respect to the underlying cell or adjacent interconnects. This magnitude of potential difference is known to cause arcing on solar arrays [Ferguson, 1986; Guidice, et al., 1996].

3. Discharge Scenario

The solar array arcs occur at relatively low potentials, ~500V, and the energy available for discharge, even for a large wing, is the equivalent of discharging a couple microfarad capacitor. The ESD generates a plasma plume which expands over the solar array at velocity of about 30 km/sec [Vaughn, et al., 1994].

$$C = \frac{\epsilon_0 \kappa A}{d} \approx 1.8 \mu F$$

$$Q = C \Delta\phi \approx 5.6 \times 10^{-4} \text{ coulombs}$$

$$E = \frac{1}{2} C \Delta\phi^2 \approx 0.1 \text{ joules}$$

$$\tau \approx \frac{\ell}{v} \approx \frac{1.25}{3 \times 10^4} \approx 40 \mu s$$

$$I \approx \frac{Q}{\tau} \approx 13 A$$

Less than a Joule of energy is released, not enough to burn out components in a multi kilowatt power system. However, it is enough to trigger a secondary discharge, which uses the power system itself, as the energy source to cause permanent destruction of part of the array.

The reason that a secondary discharge is possible, is that adjacent solar cells can have large potential differences. Since each solar cell generates only a fraction of a volt, a hundred or more cells are strung in series to achieve the desired operating voltage. A typical arrangement is for a string to start on one edge of a panel, run to the other edge, with constantly increasing voltage, and to run back parallel to the starting edge, as shown in Figure 4.

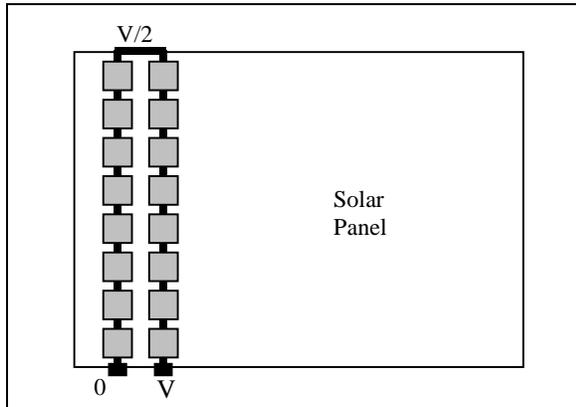


Figure 4. Typical solar array layout showing voltage is generated by stringing cells in series.

In this type of arrangement, the gap between the first and last cells has the full operating voltage of the array. The plasma from the spacecraft charging “trigger” arc provides a current path through which the string current can flow [Levy, et al., 1990]. If the array voltage and current are high enough, the string current can sustain the discharge for seconds or longer. This discharge heats and damages the cell material and the exposed Kapton sufficiently that the polymer breaks down into a carbonized, conducting material, which provides a permanent shunt across the string. This sequence of events is shown in Figures 5 to 7.

4. Laboratory test results

Tests in a chamber at NASA/LeRC were performed to validate the mechanism and to determine the sensitivity to string voltage and current. Due to the difficulty in reproducing the GEO environment, the tests were performed using a low earth orbit (LEO) like plasma to maintain a differential between the cells and the coverglasses. Small test coupons were used with just a few cells at the high and low voltage ends of a single string. The string current and voltage were generated using a solar array simulator. Trigger arc and array simulator currents were measured, as was the potential of the coupon with respect to the chamber wall. The array

voltage and current were increased slowly, to collect data without destroying the coupon.

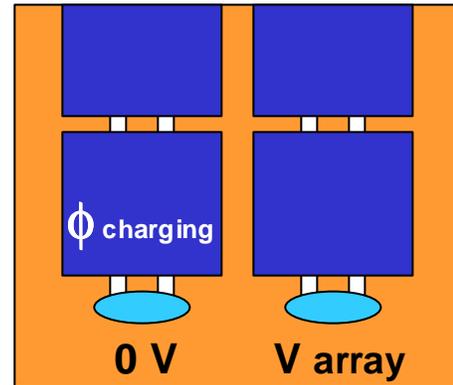


Figure 5. Solar cells charged prior to a spacecraft charging arc.

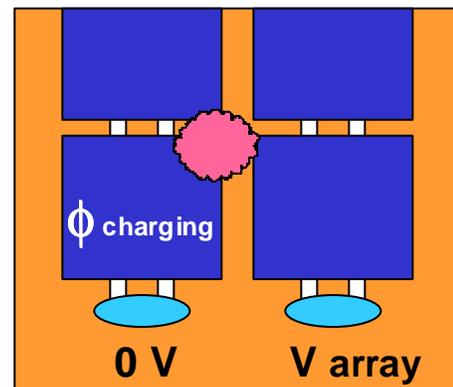


Figure 6. Spacecraft charging causes a small arc to occur in the gap between solar cells on the same string.

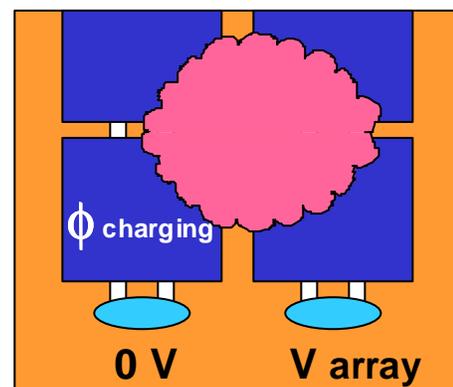


Figure 7. The spacecraft charging arc triggers a sustained discharge driven by the array string current and voltage.

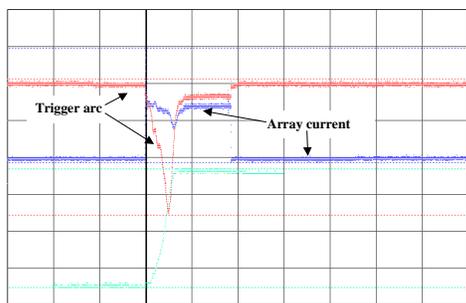


Figure 8. Laboratory data showing an arc triggering current in the solar array simulator circuit, which in turn lengthens the duration of the arc.

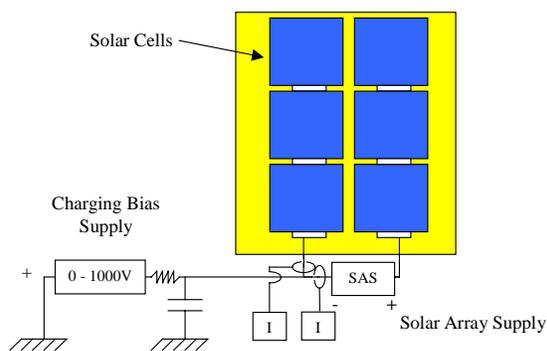


Figure 9. Circuit diagram of the chamber test configuration. Ground is in reference to the chamber walls

Depending on array voltage and current limit, a variety of results were observed. When the string voltage was below 50V, when a charging arc occurred, no current was observed to flow in the solar array simulator circuit. When the voltage was increased, currents up to the current limit were observed to flow in the simulator circuit. If the voltage and/or current limit were high enough, this array current lengthened the arc duration, as shown in Figure 8.

In several cases, the arc was lengthened beyond the recording range of the scope (~2 milliseconds). In a few cases, near the actual operating point of the arrays in space, the discharges continued for many seconds, permanently damaging the coupon, and leaving a low impedance path between cells and/or the array structure. This damage was consistent with the on-orbit damage, as inferred from the satellite telemetry.

5. Discussion

Analysis, laboratory experiments, and the flight data are all consistent with the mechanism described above. However, a complete, predictive theory of the array damage has not been developed. Some progress has been made to understand how the trigger arc plasma is generated, under what conditions it will carry array

current, and how much current it can carry. These efforts are based on the resistive current flow through a collisional plasma, and on probe like current collection by neighboring cells. Little progress has been made in quantifying the transition from current collection to a self sustaining discharge. Understanding the parameters that control the transition to self sustaining discharge is necessary to provide guidelines to array designers.

The trend to higher voltage, higher power solar arrays makes this type of destructive arcing more probable. It is important to note that even though this investigation undertaken because of failures in GEO, the mechanism is equally likely in LEO. Indeed, the laboratory testing was in a LEO like plasma environment. While in GEO, the array charging is caused by magnetospheric substorms, in LEO, charging is caused by the solar array voltage and plasma collection.

While not complete, our present understanding is being applied to design changes that will enable the safe operation of high power, high voltage, solar arrays. These arrays will be designed to prevent coupling of array currents through charging arcs and thus prevent subsequent array damage.

6. References

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