Modeling of Environmentally Induced Transients within Satellites

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A technique is described that allows an estimation of possible spacecraft charging hazards. This technique, called SCREENS (spacecraft response to environments of space), utilizes the NASA charging analyzer program (NASCAP) to estimate the electrical stress locations and the charge stored in the dielectric coatings due to spacecraft encounter with a geomagnetic substorm environment. This information can then be used to determine the response of the spacecraft electrical system to a surface discharge by means of lumped element models. The coupling into the electronics is assumed to be due to magnetic linkage from the transient currents flowing as a result of the discharge transient. The behavior of a spinning spacecraft encountering a severe substorm is predicted using this technique. It is found that systems are potentially vulnerable to upset if transient signals enter through the ground lines.

Introduction

IN the early 1970's, geosynchronous spacecraft began experiencing a series of unexplained electronic switching anomalies. These events were initially considered to be nuisances and were corrected by ground commands, logged in the operations records, and forgotten. In June 1973, an Air Force geosynchronous satellite failed and the subsequent review board found that the failure could have been caused by an encounter with a severe geomagnetic substorm.[1]

It had been known for years prior to the failure that substorm environments could charge satellite surfaces to substantial negative voltages,[2,3] but now this charging apparently could be responsible for catastrophic failures. Reviews of satellite operational records established the opinion that such substorms might be responsible for the switching anomalies as well. The term "spacecraft charging" was applied to this process of geosynchronous satellite surfaces being charged by geomagnetic substorm environments.[3]

A cooperative Air Force/NASA technology investigation was launched late in 1975 to evaluate spacecraft charging phenomena.[4] The objective of this investigation was to develop the criteria necessary to control absolute and differential charging of spacecraft surfaces by this substorm environment. This investigation was ambitious in that, over a 5 year period, it was to define the substorm characteristics, develop the computer tools necessary to predict the complex geometry surface charging in that environment, determine the location and characteristics of discharges, compute the transient coupling into the structure and electronics systems, characterize materials, and conduct space flight experiments. Based on this information, design documents were to be issued. The output of this program has been documented in the proceedings of the biennial Spacecraft Charging Technology Conferences[5-7] and in AIAA Conferences.[8,9]

From these published reports, it is apparent that substantial progress has been made, although it has taken longer than anticipated to complete the task. An environment atlas has been published,[10] the NASA charging analyzer program (NASCAP) has been validated against ground test and flight data,[11,12] a preliminary version of a military standard test document drafted (but not issued),[13,14] and a design guideline document issued.[15] However, the study of discharge characteristics and transient pulses coupling into systems has been lagging behind the other areas. A considerable effort went into studying the discharges initiated under a strong voltage gradient—the so-called "big bang" discharges —before it became apparent that such gradients could not exist on spacecraft.[16] Subsequent studies have identified the conditions that could produce lower-energy discharges and have approximated possible characteristics.[17-19]

The problem still remaining is to demonstrate that a discharge occurring on a spacecraft surface could cause an electronic system upset. Previous studies delving into this were either primarily concerned with the mechanics of a discharge or could not demonstrate that an upset hazard existed.[20-25] In this report, it is assumed that a discharge does occur and that this discharge produces a transient within the spacecraft. Simple engineering level modeling techniques are then used to show the effects of these transients on the voltage distributions within the spacecraft and to suggest ways in which transients could couple into the electrical systems.

Approach

The approach used in this study is to employ a technique called SCREENS (spacecraft response to environments of space). This technique really has several elements tied together to satisfy engineering requirements for electrostatic discharge (ESD) survivability.[26] The SCREENS flow chart is shown in Fig. 1. Although this technique has been developed over a period of years and has been validated against tests,[27] it is constantly being updated to incorporate the latest information.

The first step in this procedure is to determine the surface charging. This is done with NASCAP code using the severe environment model given in Table 1. This environment model has been taken from the NASA design guidelines document.[15] The apparent non-neutral density is used to compensate for the ion species expected of these orbits. The NASCAP computes ion currents using only hydrogen ions, but this technique allows for the helium ions as well. The purpose in this step is to determine where the electric fields are concentrated and to compute the total charge stored in the dielectrics. These NASCAP predictions are used to provide an identifiable bound to the charge lost in discharges. This means that the details of the discharge process are not considered and quantifiable procedural rules can be established to treat the transient interactions.

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The next step is to estimate the discharge pulse characteristics. This pulse is usually treated as an overdamped, double-exponential current transient that accounts for the charge lost. The discharge used in these evaluations assumes that charge is ejected into space, causing the spacecraft to become more positive. The discharge process is assumed to be more rapid than the recharging of the spacecraft by the environment so that they can be treated independently. The rules used to determine the discharge site and charge loss are based on the NASCAP predictions and are as follows:

1) Discharges occur wherever the dielectric surface is 1000 V more negative than the structure.

2) Discharges occur whenever the dielectric surface is 500 V more positive than the structure.

3) The charge lost in a discharge is 10% of the total charge stored in a NASCAP cell.

4) If there is a surface voltage difference between the discharge site and adjacent dielectrics of more than 1000 V, then the charge lost is 30% of the total stored in the NASCAP cell.

These rules are simply guides used to bound a discharge and have not been proved.

The coupling of this transient into the structure and cables is computed by means of lumped-element, circuit analysis models (LEM). For each spacecraft configuration, the value of capacitance, resistance, and inductance has to be computed, measured, or estimated. For most spacecraft, this can be a large, time-consuming task (see Fig. 2 for a simplified version of a spacecraft structure LEM[26]). Selected cable LEM's are included with the structure model to determine the threat to the systems. The model predictions are generated using the SPICE2 computer code. For a quick-response engineering decision, simplified single- and double-path models can be used. These are gross models that agree qualitatively with the detailed ones and are used primarily to determine if detailed models should be used to understand what could be occurring in selected regions or to evaluate possible corrective techniques.

Analysis of Spacecraft Behavior

The use of this SCREENS technique is shown in the following sections. The spacecraft considered is a spin-stabilized, geosynchronous orbit, communications satellite having a despun antenna. The results could be applied equally as well to a three-axis stabilized spacecraft.

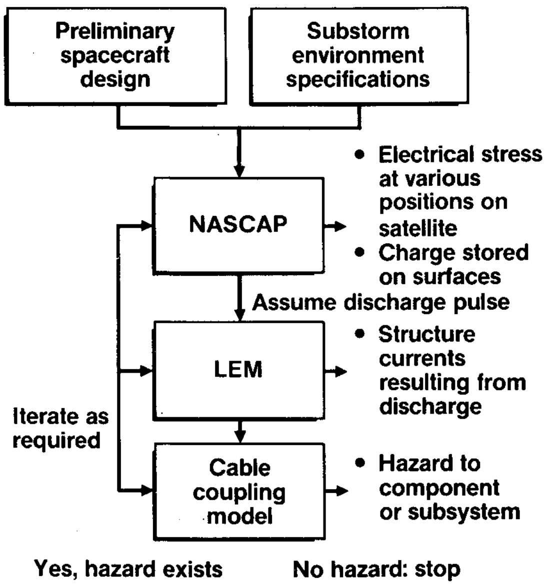

Fig. 1 SCREENS technique flow chart.

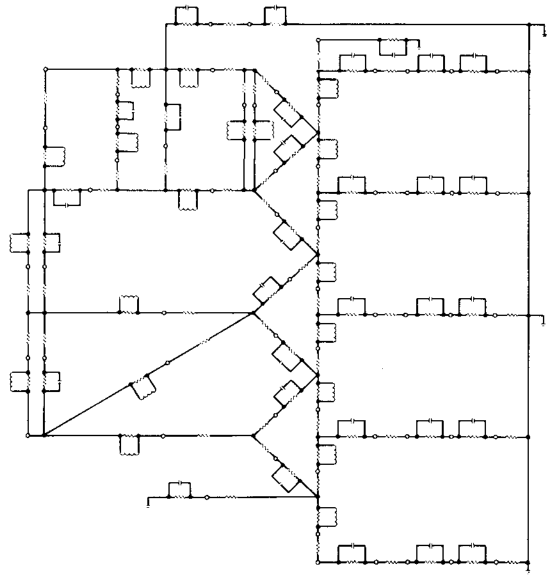

Fig. 2 Spacecraft lumped element model (LEM).

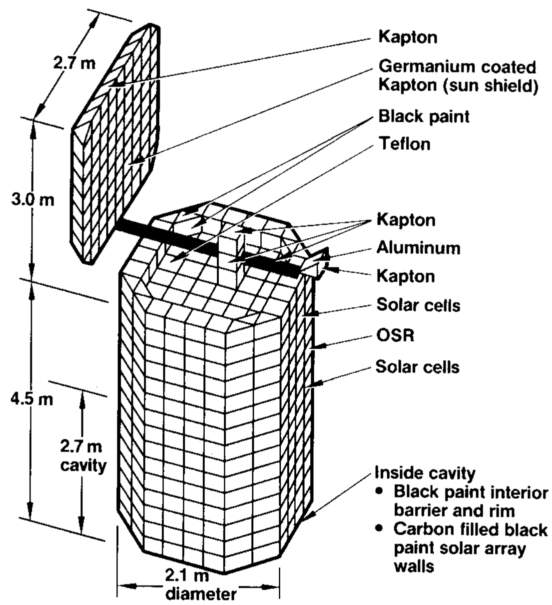

Fig. 3 NASCAP model of spin-stabilized spacecraft.

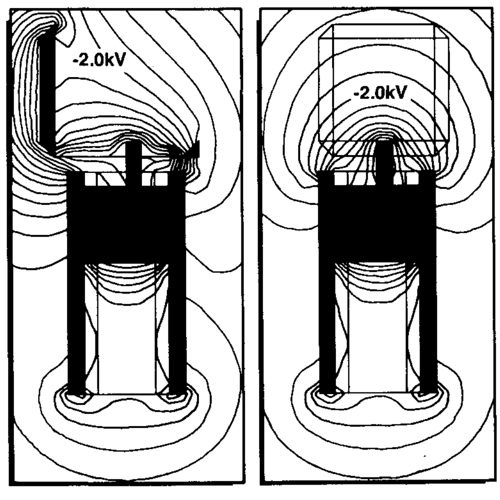

Fig. 4 Predicted voltage distributions around spacecraft, midnight simulation (equipotential lines in 200 V steps).

Table 1 Geomagnetic substorm environment

	Temperature (keV)	Density (cm^{-3})
Electron	12.0	1.1
Ion	20.0	0.1

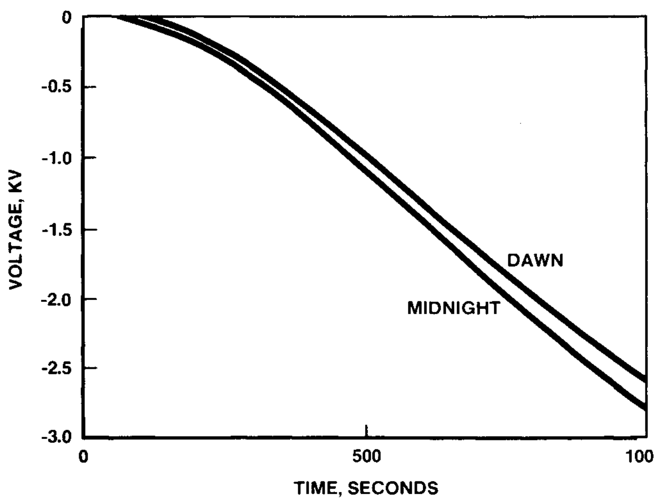

Fig. 5 Predicted structure potentials.

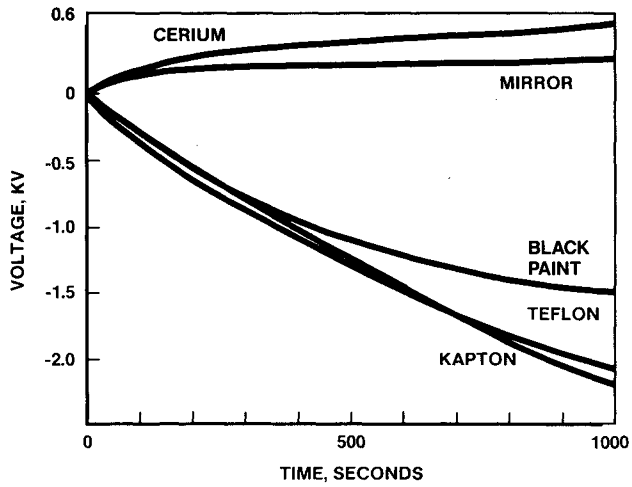

Fig. 6 Predicted differential voltages, midnight simulation.

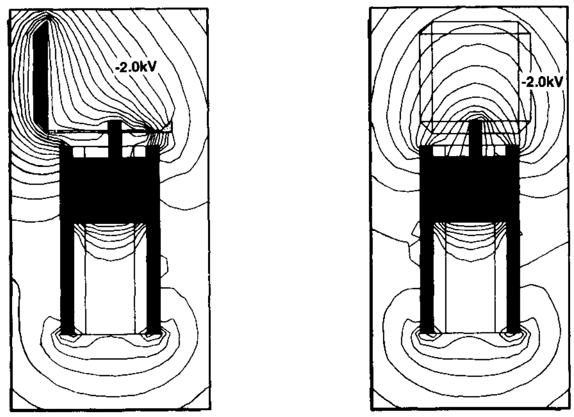

Fig. 7 Predicted voltage distributions around spacecraft, dawn simulation (equipotential lines in 200 V steps).

NASCAP Modeling

Model Description

The NASCAP model of the spacecraft is shown in Fig. 3. This represents a generic spin-stabilized spacecraft with an extendable solar array. The spacecraft is 7.5 m in overall height and 2.1 m in diameter. The antenna is 2.7 m on a side. It has a quasiconductive Earth-facing side with a dielectric back. The spacecraft solar array uses ceria-doped cover glass. Optical solar reflectors (OSR) are used for radiator surfaces. The upper barrier is Teflon and is recessed to be in constant shade. The deployable solar array interior walls are coated with a quasiconductive coating. The closeout barrier in the cavity has dielectric painted surface (black).

Charging Computations

This model was run in both a midnight and dawn sunlight charging simulation using the environment given in Table 1. The code was run in the "spin" mode, which inputs an average value of solar intensity into the cylindrical surfaces. This is a reasonable approach for a spacecraft spinning at a rapid rate compared to the dielectric charging time. The despun antenna materials chosen were such that the normally shaded surfaces had zero photoemission, while the normally sunlit surfaces had three times the standard photoemission values for those materials to produce the equivalent photoemission currents for a surface in constant sunlight. Eclipse charging simulations were not attempted.

The code was run to simulate a substorm environment encounter of 16 min. Historically, it has been found that, while substorms can persist for hours, durations at severe levels are limited. Running the code for this period of time (16 min) has been found to calculate spacecraft ground potentials larger than those measured in the past 15 years in space. Hence, the simulation does evaluate a worst-case condition to evaluate the electrostatic stresses in a proposed design.

Midnight Simulation

The voltage distributions for the midnight simulation are shown in Fig. 4. For this simulation, the sun illuminates the front surface of the feed and antenna, while the back sides of both are dark. The charging history of the spacecraft ground is shown in Fig. 5, which shows that the maximum potential reached in 16 min is -2.5 kV. The differential voltages of selected surfaces are given in Fig. 6. The maximum differential reached is -2.0 kV.

The voltage distribution from the dark Kapton on the antenna extends into the back side of the array. This gives rise to a circumferential voltage distribution around the body-mounted array and OSR's. The body solar array differentials vary from -70 to $+200$ V around the circumference relative to the structure potential. The OSR's vary at $+300$-800 V relative to the structure. This field distortion extends to the deployable array where the distribution ranges from -27 to $+500$ V relative to the structure. Hence, fields from the dark antenna may prevent discharges from the body solar array, but they do not influence the possible discharge on the OSR's and deployable arrays.

Other possible discharge sites of concern are the dark Kapton and the Teflon forward barrier, since they have voltage differentials of greater than 1000 V. Another area of concern is the lower cavity because of a possible hollow cathode effect that could exist there. The lower baffle is very negative (about -1.5 kV relative to the structure), while the rest of the region is essentially field free at a more positive value. Any discharge initiated at the barrier would have its charge accelerated out to space.

A summary of the regions of concern, the charge stored per NASCAP cell, and possible charge lost in any discharge is given in Table 2.

Dawn Simulation

To simulate this condition, the photoemission on one edge of the antenna and the exposed pivot and feed surfaces were increased, while all other antenna surfaces were given a zero value. The voltage distribution resulting from this simulation is shown in Fig. 7. The charging history of the ground potential is given in Fig. 5 and the differential voltages of selected surfaces are shown in Fig. 8. The ground potential reached −1.8 kV here in 16 min, while the maximum differential was again about −2.0 kV on the shaded Kapton.

The principal difference occurring in the dawn simulation compared to the midnight is that the fields around the antenna are more intense since both sides are now charging. The fields still extend into the solar array, giving rise to circumferential variation as before. The distribution within the top cavity is not significantly different and the voltage distribution in the bottom cavity is identical to the midnight simulation.

A summary of the charge stored and the possible losses in discharges is given in Table 2.

Discharge Coupling

In this section, the effects of a discharge triggered on an external surface by some mechanism are considered. This requires that a simulated model of the spacecraft structure be assembled.

As stated previously, the detailed lumped-element models (LEM) for spacecraft tend to be very complicated. Therefore, in order to determine the effects of such coupling, a very simplified model will be used. These results will be compared to the more detailed models at the end of this section.

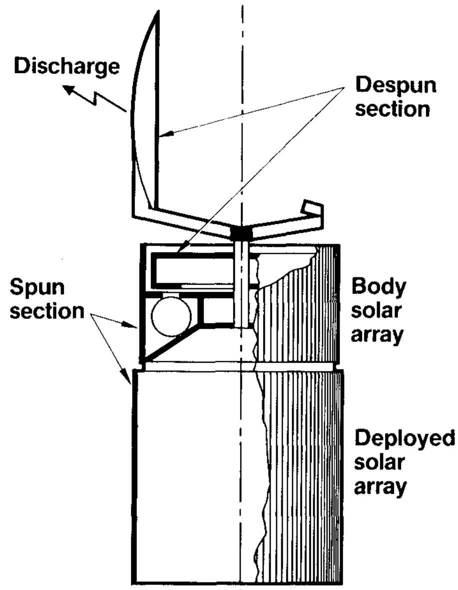

Fig. 9 Spacecraft discharge event.

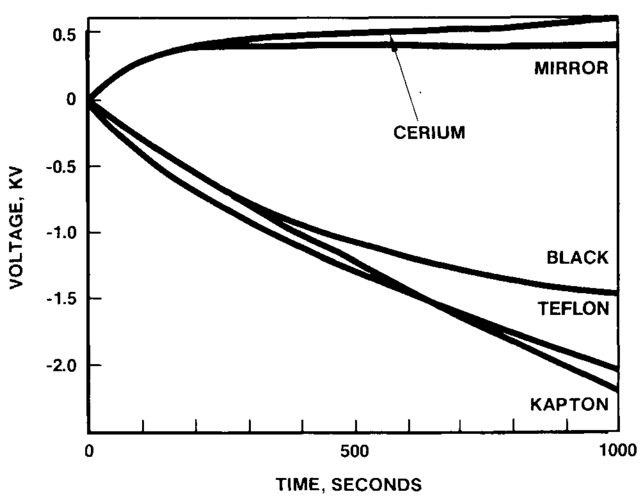

Fig. 8 Predicted differential voltages, dawn simulation.

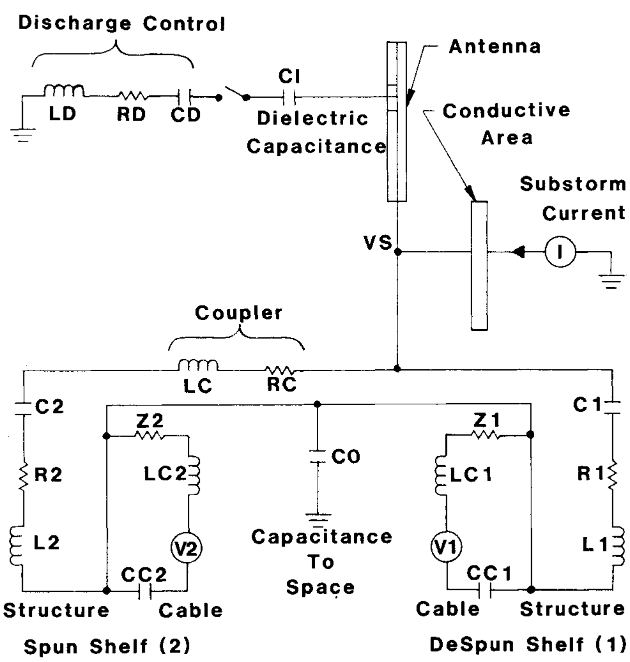

Fig. 10 Simplified spacecraft LEM.

Table 2 Summary of charge stored in dielectrics and possible discharge losses NASCAP runs for spin stabilized spacecraft

Simulation	Site	Voltage differential (kV)	Charge stored (μC)	Discharge loss (μC)
Midnight	Kapton (2 mil)	−2.15	101	10
	Ceria solar cells (6 mil)	+0.5	10.5	1
	Optical solar reflectors (8 mil)	+0.8	12.5	1
	Teflon (2 mil)	−2.0	78.5	8
	Black paint-cavity	−1.5	70.6	7
Dawn	Kapton (2 mil)	−2.11	99	10
	Ge-gated kapton (2 mil)	−2.11	99	10
	Ceria solar cells (6 mil)	+0.65	13.6	1.5
	Optical solar reflectors (8 mil)	+0.65	10.2	1
	Teflon (2 mil)	−2.0	78.5	8
	Black paint-cavity	−1.5	70.6	7

LEM Description

The spacecraft event that is being simulated is shown in Fig. 9. A spin-stabilized spacecraft has been charged to the point that a discharge occurs on the antenna. The discharge could have occurred at any of the other regions, but this is the one chosen for illustration. It is assumed that charge leaves the spacecraft, causing a change in the spacecraft potential relative to the space plasma potential.[17] As a result of the loss, replacement currents circulate in the structure. Since the structure is modeled as a series of resistors, capacitors, and inductors, there is a voltage difference throughout the structure. The transient currents generate a magnetic field that couples a voltage into the harnesses. If the cable current transients are large, then they could generate the electronic upset.

The very simplified spacecraft LEM being used is shown in Fig. 10. The despun section is simulated by a single capacitance (C1), resistance (R1), and inductance (L1). There is an unshielded 100 cm cable attached to a shelf. The spun section is likewise treated with parameters labeled 2. The discharge response relative to space is treated with a single capacitance to space. Recharging by the substorm is accomplished by exposing the exposed conductive area to the incident electron current. The parameters to simulate the structural elements are chosen to give an underdamped transient with frequencies in the range of 1-10 MHz for the spun section and 10-20 MHz for the despun. The current induced in the structure is assumed to be related to the discharge current. The division in the structure current between the spun and despun sections is determined by the impedance ratios of the two sections.

The discharge is triggered by closing the switch connecting an R-L-C circuit to the discharge site. The values of RD, LD, and CD are chosen to give an overdamped current transient equivalent to the desired charge loss. It has been found that the discharge currents dissipate in microseconds, which is short compared to the recharging time of the spacecraft by the substorm environment, so that the two processes can be considered independently.

Discharge Coupling Results

The discharge pulse used in this simulation is shown in Fig. 11. The values chosen for CD, RD, and LD (2×10^{-9} F, 50Ω, and 1×10^{-6} H, respectively) resulted in a discharge current transient that reaches 54 A, damps out in about 0.5 μs, and ejects 7.7 μ C to space. This charge loss is a little smaller than desired, but it is difficult to match all conditions perfectly.

As a result of this charge loss, the dielectric potential changes. The spacecraft potential change for the despun section changes very slowly since it is capacitively coupled through the dielectric. The spun section potential changes relative to the despun section primarily due to the coupler impedance (chosen to be about 50 Ω). This differential voltage peaks at about 1230 V and follows the discharge pulse (see Fig. 12).

The currents induced in each of the cables is shown in Fig. 13. The termination impedance of each cable is chosen to be 5 Ω. The transient current in the despun section cable damps out before the discharge pulse ends. The current in the spun section cable has a large spike of 375 mA when the discharge current is a maximum and then rings down as the discharge pulse decays.

The above results were obtained with very simplified models and approximations for the various parameters. However, the trends observed are similar to those obtained in the more detailed LEM studies. For example, a comparison between the ground potential predicted by a detailed model and this simplified version in response to a 2 μC discharge is shown in Fig. 14. The agreement is excellent. The primary difference is that the simplified LEM does not contain the higher-frequency oscillations found using the detailed LEM's. These LEM's also predict that the differential voltages between the interior shelves oscillate relative to each other, producing a bipolar voltage difference that can reach 1 kV before damping out.

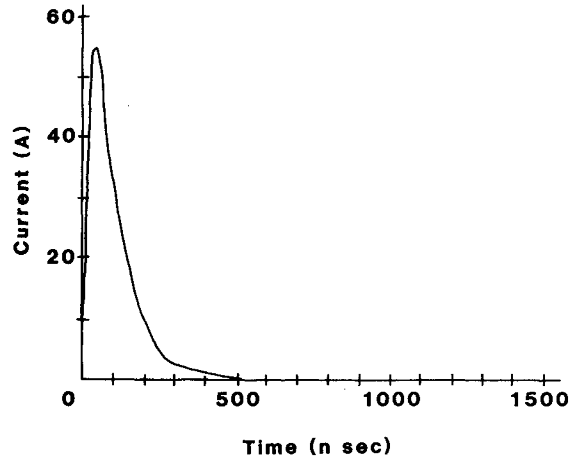

Fig. 11 Discharge pulse characteristics.

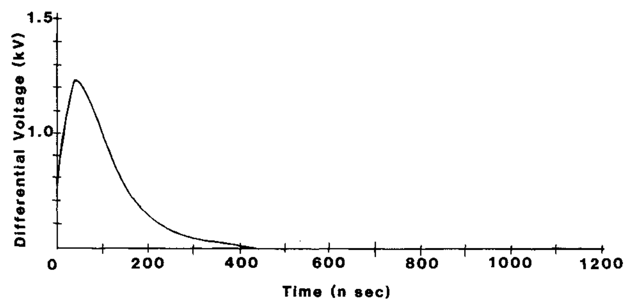

Fig. 12 Differential voltage, spun-to-despun section.

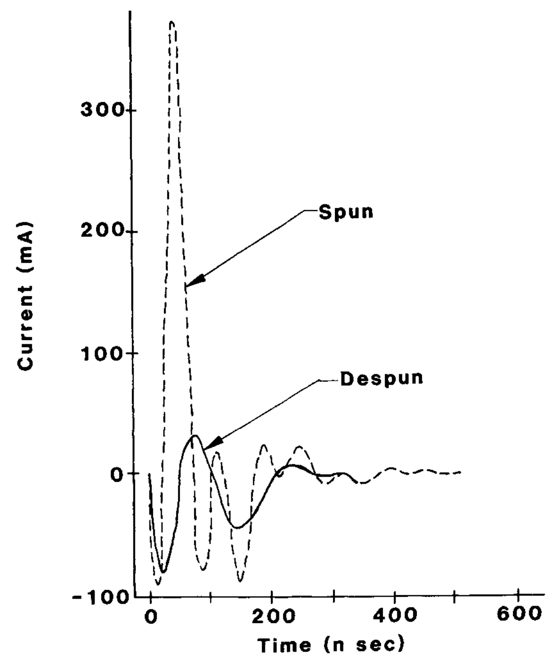

Fig. 13 Current coupled into cables.

Circuit Design Implications

The transient currents predicted in cables by this study tend to be high-frequency signals of relatively low amplitude. Such signals can be suppressed by shielding or filters. Figure 15 illustrates a typical filter as a buffer on a circuit and Fig. 16 the frequencies transmitted. No high-frequency noise penetrates through to the output. As a result of this study and others of a similar nature, it has become evident that the spurious anomalies probably do not enter the system through simple command cable coupling; these are usually well protected by

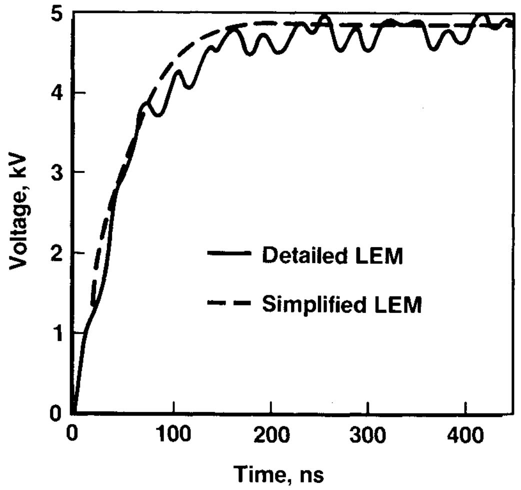

Fig. 14 Comparison of simple to detailed LEM results.

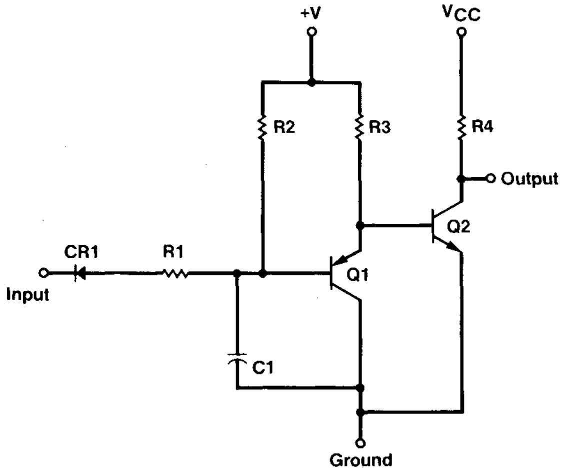

Fig. 15 Typical buffer circuit.

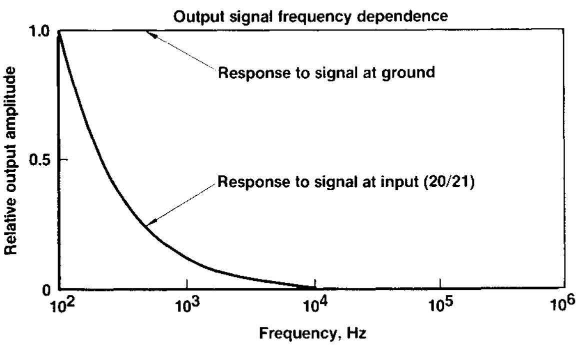

Fig. 16 Noise rejection results for buffer circuit.

noise suppression techniques. Since anomalies still happen, albeit less frequently, then other possibilities should be evaluated.

One alternative path could be transient coupling through the ground lines. Noise input into the ground side of the transistors in Fig. 15 can be transmitted to the output as shown in Fig. 16; whatever amplitude exists can be transmitted into the circuit.

Current designs call for use of the structure for both power and signal return. Care is taken to insure that the designated ground paths have very low dc resistances, but ac impedance rarely is considered. In spin-stabilized spacecraft, there is substantial mutual inductance between the spun and despun sections and modeling is showing this to be important. This implies that concern should be taken to evaluate grounding techniques; the power ground is in the spun section, while the large power users (the payloads) are in the despun section. Regulated power levels could be generated with reference to one ground, while the user systems would be referenced to a different ground value. There are systems with sensors that are remote from their electronics (e.g., attitude control systems). The sensors are usually wired directly to the electronics and these wires can act as antennas conducting pulses into the electronics. The ground return wire is usually considered to be safe. However, these wires can carry pulses directly into the electronics.

Finally, there are those spacecraft that incorporate a variation of the single-point ground philosophy. These use ground wires to connect various electronic systems to a point on the structure. These ground wires then can couple transients directly into the various electronic systems.

Since each system tends to be unique, it is difficult to show the effects of the above concepts on a generalized spacecraft model. However, this ground loop coupling concept seems to agree with experimental work using transients injected into spacecraft.[27]

Conclusions

Spacecraft charging phenomena have been under investigation for the past 10 years. Considerable information has been gathered and documents published. However, anomalies still occur on geosynchronous satellites. There is still no accepted method to evaluate spacecraft system designs for susceptibility to environmental charging effects.

The approach suggested here for evaluating spacecraft designs for susceptibility to electronic upsets is to analyze the system response to substorm environments. This approach is based upon a technique using NASCAP to determine quantifiable surface charging levels. These levels are then used to bound discharge current pulse characteristics. The charge loss transient then generates a current in the structure that couples into the electronics. Hence, a set of transients, which should bound those expected in space, are obtained and used to evaluate electronic system performance.

The input sections of most systems can be reasonably well protected from cable coupling noise by use of simple filters. There is, however, a voltage difference in the various parts of the structure that can give rise to ground loop coupling into the systems. These paths can easily be overlooked and, it is believed, could result in upsets.

Acknowledgment

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