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Modelling of Environmentally Induced Discharges in Geosynchronous Satellites

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Abstract

The NASCAP computer code is used to compute the charging the discharging characteristics of a typical communications satellite in geosynchronous orbit. For the case of a severe substorm, satellite surface differential charging in sunlight is found to be substantially less than that required to produce discharges in ground simulation studies. A discharge process is postulated involving discharges triggered at edges (or imperfection) followed by discharges to space. The characteristics of such discharges are parametrically varied to evaluate the possible effects on the satellite. It has been found that discharge characteristics inferred from satellite monitors could be caused by predicted space discharges, that single cell discharges to space can reduce surface potential over entire satellite, and that low-density electron trajectory computations indicate that discharge generated electrons may not return to the satellite by long trajectories. Current transients predicted do not agree with the available ground simulation results indicating that additional work must be done both analytically and experimentally to understand and fully explain these discrepancies.

Introduction

For the past five years there has been a concerted effort to understand the phenomenon known as spacecraft charging.[1-3] This phenomenon arises when a geosynchronous satellite encounters a geomagnetic substorm, and dielectric surfaces become charged to negative potentials relative to space.[4-5] Since photoemission can play a dominant role in controlling the potentials achieved by spacecraft surfaces, the possibility exists that there could be significant differential charging between shaded insulators and spacecraft ground. That spacecraft charge in this space environment has been shown from ATS-5 and 6 data[6-7] and from Scatha data.[8] That discharges can occur is demonstrated by on-board monitors.[9-11] The questions to be resolved are how the discharges initiate, how they propagate and what the discharge characteristics are.

There have been a significant number of ground based tests conducted on the charging behavior of dielectrics exposed to monoenergetic electron beams.[12-16] Discharge behavior, as well, has been studied.[15-18] Tests indicate that discharges initiate at insulator edges or seams and propagate across the surface. Shielding around the edges of the insulator has been found to be effective in reducing the probability of discharges on smaller samples.[19]

Simultaneously with the ground testing, there has been substantial progress in defining the characteristics of geomagnetic substorm environments[20] and in developing analytical modelling tools.[21] The modelling tools have shown that three-dimensional effects influence the predicted behavior so that complete, three-dimensional, transient modelling is required.

A previous study examined the general charging and discharging behavior of geosynchronous satellites.[22] The present study extends the earlier work, concentrating on an improved simulation of discharges and parametrically evaluating spacecraft response when specified fractions of the surface charge are lost to space.

NASCAP Model of Satellite

NASCAP Description

The NASA Charging Analyzer Program (NASCAP) has been described previously in the literature.[21,23-24] The present version of NASCAP contains the capability of simulating two forms of discharges. The first simulation consists of a charging interruption when the differential voltage between the insulator surface and the conductor underneath exceeds a specified voltage value. When this limit is exceeded charge is transferred from the insulator to the conductor underneath (depth of discharge specified by user) and the charging simulation continues. This simulation characterizes a breakdown in the material capacitor and is representative of a short circuit or punch through type of discharge. The second simulation consists of a charging interruption when the insulator surface voltage relative to space exceeds a specified value. When this limit is exceeded, a specified amount of charge is lost to space (representing charge "blowoff"). It is believed that this loss of charge to space produces the current transients within the satellite. The two types of discharge simulation can be initiated simultaneously, sequentially or independently.

The geosynchronous environment can be defined in terms of single or double Maxwellian distributions[25] by specifying particle temperatures (in electron volts) and number densities. The code outputs a variety of displays showing the model used, the voltage distributions at specified times, currents to each conductor, surface voltages and particle trajectories (if desired).

Satellite Description

The satellite model chosen for this study is shown in Fig. 1. It is representative of a 3-axis stabilized, geosynchronous, communications satellite. It has two large solar array wings and a central spacecraft body. The overall dimensions are 9 meters across the solar array wings by 2.4 meters across the spacecraft. Materials used on this model are specified on the figure. The spacecraft body is divided into 3 conductors, as shown, to allow current transient computations in those regions. These conductors are capacitively coupled but held at zero volt difference.

Computational Results

Satellite Charging in a Constant Substorm

The satellite model's charging was simulated using a single Maxwellian description of a severe substorm having an electron temperature of 8 KeV, a proton temperature of 16 KeV and a plasma density of one particle per cubic centimeter. The charging response of typical satellite surfaces is shown in Fig. 2. As shown, it required about $2x10^3$ seconds to reach steady-state conditions. The material properties specified are those used to conduct the initial evaluation of the Scatha Surface Potential Monitor data.[26]

A point to be made here is that the maximum differential voltage predicted between the spacecraft structure and shaded Kapton is only about 3 kV. There are no surfaces with larger differential voltages. The differential voltages on the spacecraft are limited by voltage barriers formed by the shaded insulator potentials which restrict photoemission.[27] Ground tests of discharge behavior indicate that differential voltages of at least 10 kV are required to produce breakdowns,[16] so that a 3 kV differentials, no discharges are expected. Comparisons of the NASCAP code predictions to Scatha data indicate that the code is a reasonably valid representation of the charging process.[26&28] Hence, a discharge process has to be postulated in order to generate the breakdowns that are known to occur on satellites from on-board monitors.[9-11]

Discharge Process

The discharge process postulated for this study is illustrated in Fig. 3. First, it is assumed that a short circuit or punch-through discharge initiates the process and this is then followed by a discharge to space. For this study the triggering discharge is assumed to start when the differential voltage across a selected surface exceeds 2700 volts (or when the gradient is 2.7×10^5 volts/cm). As stated previously, the satellite body is divided into three separate conductors (see Fig. 3). Kapton used on the shaded parts of the satellite are separately identified to allow discharges to be triggered at several different points on the satellite.

Discharge Characterization

With this discharge process, the NASCAP code was used to study parametrically the behavior of the satellite when discharges of various depths were triggered at the Kapton sites. While all of the seven possible Kapton discharge sites were examined in this study, the results can be typified by considering the behavior for only Kapton 1 and 2 breakdowns (see Fig. 3).

Effect of depth of discharge. The effect of depth of discharge to space on the overall response of the satellite is shown in Fig. 4. Here, the satellite was exposed to the constant substorm for 1000 seconds. Then a breakdown was triggered and charging was allowed to continue for the next 800 seconds. Whenever the Kapton 1 potential became more negative than -5000 volts, discharges to space were triggered.

When only 10 percent of the charge was lost to space, discharges occurred continually, causing the insulator and spacecraft ground potential to appear to stabilize. This behavior pattern could be similar to that monitored for satellite surface discharges.[9] When 30 and 50 percent of the insulator charge is lost to space, a discharge pattern with pulses 2 to 3 minutes apart appears. This type of pattern is similar to the transient event counter data observed on CTS.[10]

When a discharge to space occurs, the whole potential distribution around the satellite is reduced. The NASCAP code computes the charge lost in a space discharge and recomputes all the surface potentials based on the remaining charge. Only one NASCAP cell need be involved in the discharge process depending on the charge loss and breakdown voltage criteria. The result is a voltage reduction at the discharge site and a smaller voltage reduction on all other surfaces.

The satellite behavior over extended time periods has been investigated with 10 and 30 percent depth of punch through discharge triggers, as well as with simultaneous punch-through and space discharges of the same depth. There are no significant differences in the characteristics under these conditions from the ones discussed above.

Emitted electron trajectories. The understanding of the behavior of charged particles emitted from discharge sites is necessary for the development of a satellite discharge coupling model. Since the NASCAP code computes the electric fields around the satellite due to environmental charging, it can also compute the trajectories of low density (<1 mA) particles in these fields. Such a computation was under taken here to determine the influence of electrostatic fields on emitted electrons.

The satellite potentials and electron trajectories before and after space discharges (500 nsec time separation) for several conditions were computed. Electrons (1 mA) were emitted from the discharge site in all directions. The electron energy range was 0 to 5 KeV. Electrons having energies of less than 2 KeV did not escape; they were suppressed by the voltage barriers. Of those electrons with energies greater than 2 KeV, up to 40 percent of the current would escape to space.

While it cannot be claimed that this low-density emitter computation is an actual simulation of discharge generated particles, it does indicate that the electric fields around the satellite do not cause electron trajectories that sweep along long paths to return to the satellite. These computations indicate that the emitted electrons will either be retained locally by voltage barriers or be lost to space.

Current transients. The current transients computed for conductor number 4 due to space discharges in Kapton 1 are shown in Fig. 5. In Fig. 5(a) discharges were triggered by a 10 percent charge transfer punch-through discharge followed by a 10, 30, or 50 percent charge transfer to space. For these computations 500 nanosecond time steps were used. The actual charge lost can be computed by multiplying the current by the time. This charge loss is constant and can be scaled to whatever time interval desired.

In Fig. 5(b) the influence of starting a discharge with a 30 percent charge transfer punch-through discharge is illustrated. The current losses to space here are diminished because there is less charge stored on the insulator surface after the punch through. In Fig. 5(c) the effect of a discharge in Kapton 1 triggering a space discharge in Kapton 2 is illustrated. This has the effect of lengthening the discharge pulse in a decaying fashion since less charge remains on the insulator surface after each successive space discharge.

These current computations indicate that the predicted transients are relatively small compared to the 50 to 150 A, 500 to 4000 nsec pulses observed in ground tests.[16-18] This discrepancy is probably due to the lack of very large differential voltages on the space model predictions. Hence, if the space model predictions are reasonable, then perhaps the ground simulation testing is studying phenomena not found in space. There are some ground test results obtained with the substrate ground isolated that do indicate rather low current pulses similar to those predicted for this satellite.[29] More work on discharge phenomena must be accomplished before a complete understanding is possible.

Concluding Remarks

The NASA Charging Analyzer Program (NASCAP) has been used to study charging and discharging response of a geosynchronous communication satellite in a severe geomagnetic substorm. It has been found that the maximum differential voltage predicted between shaded insulators and spacecraft ground is less than that voltage found necessary for breakdown in ground tests. A discharge process is postulated that assumes discharges are initiated by a short-circuit or punch-through discharge that transfers charge from the surface to the conductor beneath (neutralizing polorization charges), followed by a charge loss to space (space discharge). This loss of charge to space in a specified discharge time results in a current surge through the structure. Spacecraft response to such discharges is then studied parametrically.

Small charge losses to space per discharge (~10 percent) are predicted to produce almost continual discharges which tend to hold the spacecraft ground at a constant potential. Thirty to fifty percent charge loss to space produces larger but less frequent potential excurisons. The repetitive pulses have been observed on satellite surfaces while the less frequent pulses have been seen on satellite harness noise counters. Hence, on-board monitors seem to indicate that both small and large charge loss discharge can occur. When a space discharge occurs, the code predicts that the potential around the whole satellite is reduced.

Electron trajectories have been computed using the low-density particle emitter routines available in NASCAP. It has been found that electrons are either suppressed at the discharge site or escape to space. The electric fields around the satellite do not cause large, sweeping trajectories returning the electrons to various parts of the satellite.

The return current pulse from the space discharge has also been studied parametrically. It has been found that the currents predicted tend to be small. These predictions do not agree with the low impedance or grounded substrate ground test return current data. Although there are indications of agreement with tests conducted with high substrate impedance to ground.

This study indicates that there is still additional work to be done before an understanding of satellite discharge phenomena can be attained. First, the completion of the NASCAP code validation against space data must be accomplished. Additional ground testing must be conducted to investigate characteristics of discharges generated at lower differential voltages. With both these results then it is hoped that a valid spacecraft discharge model can be made available.

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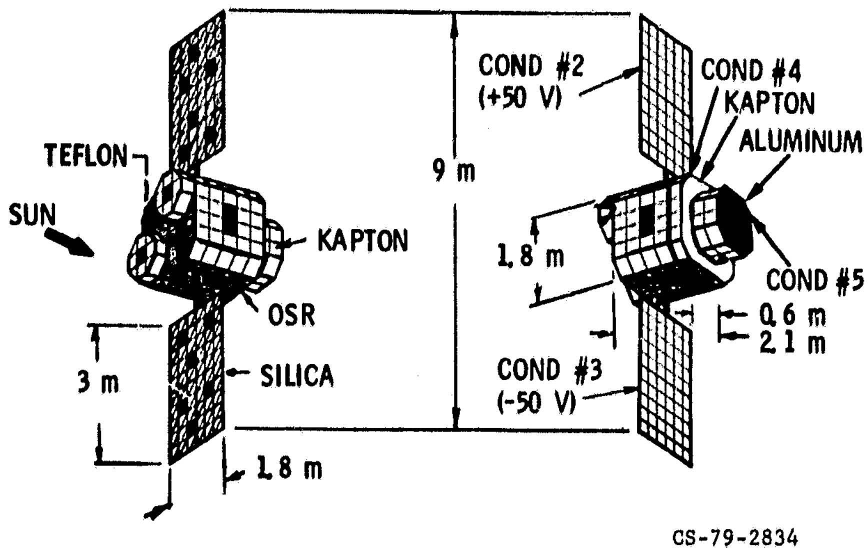

Figure 1. - Typical geosynchronous communications satellite.

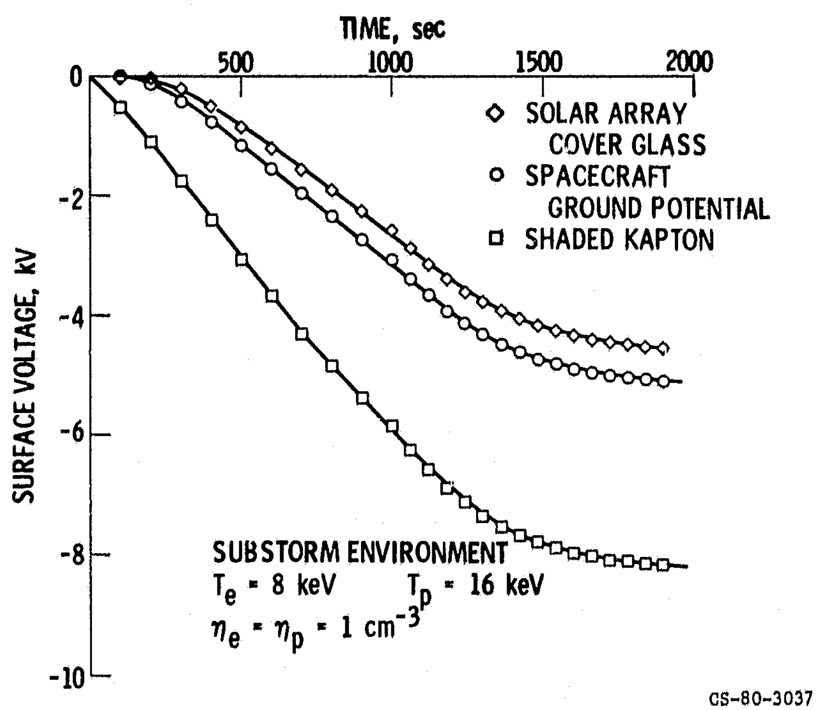

Figure 2. - NASCAP predicted satellite response. Constant substorm environment - no discharges.

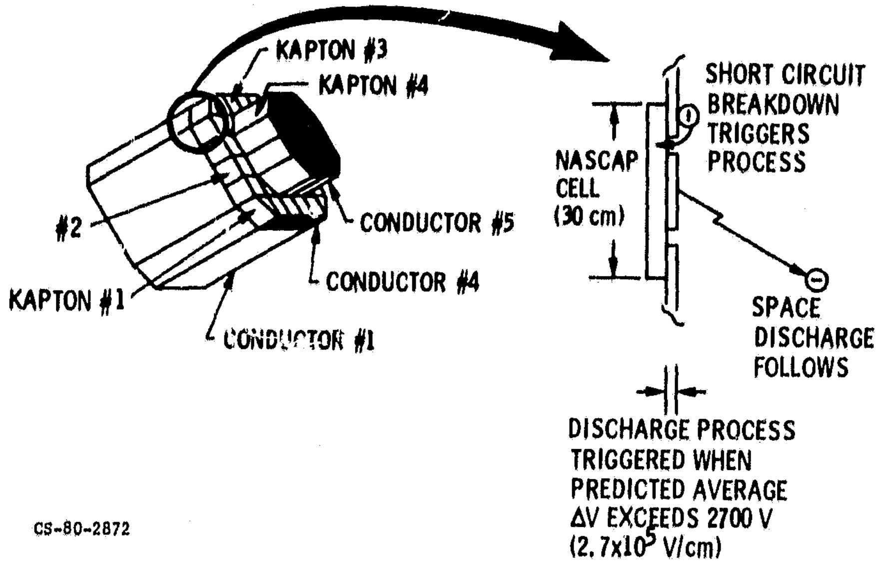

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Figure 3. - Discharge process model and surfaces considered.

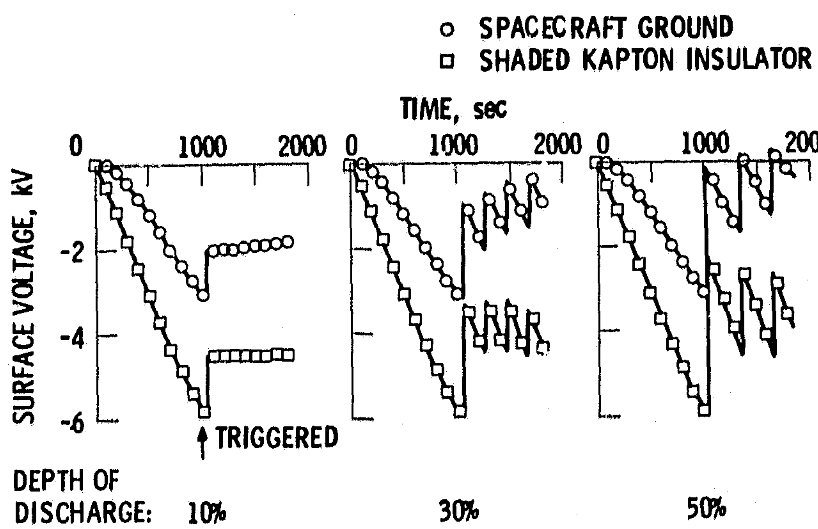

Figure 4. - Satellite discharge characteristics effect of depth of discharge. Sunlight charging in constant substorm. (T_e = 8 keV, T_p = 16 keV, $\eta_e = \eta_p = 1\ cm^{-3}$.)

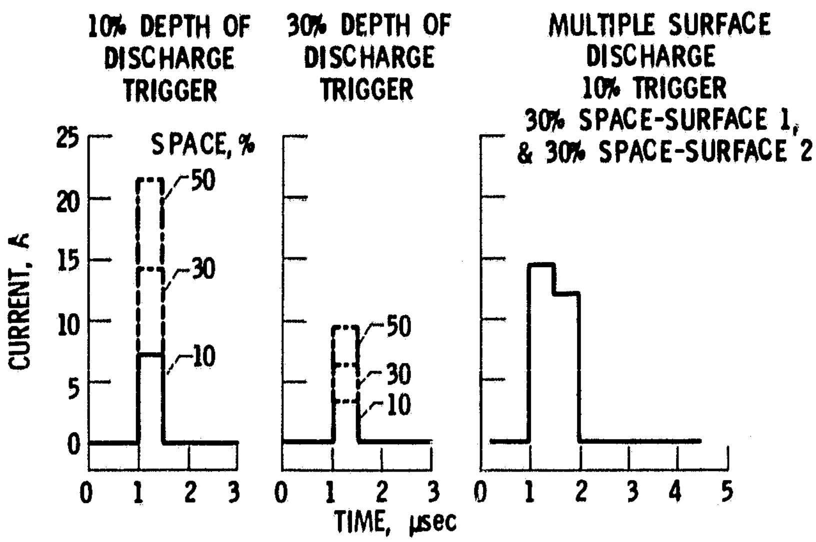

Figure 5. - Typical current transients in conductor due to space discharges. Effect of trigger discharge and number of surfaces.

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