NASCAP MODELING OF GEO SATELLITES - SPACECRAFT CHARGING IS BACK!

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ABSTRACT

During the last few years of Solar Minimum, GEO spacecraft charging design practices may have become lax because of a paucity of spacecraft charging events. Unfortunately, this has also been the time of great changes in spacecraft design, because of the new emphases on higher power arrays and lower costs. Also unfortunate is the fact that spacecraft charging may lead to failures of solar array strings, panels, or entire spacecraft. One way to prevent satellite failures due to spacecraft charging events is to simulate the effects with a charging code, such as the venerable NASCAP/GEO code. We will discuss the use of NASCAP on the ACTS satellite as well as a newer application dealing with typical recent spacecraft charging anomalies.

BACKGROUND

In the late 1970's and early 1980's, it was commonplace for satellites in geosynchronous Earth orbit (GEO) to undergo mysterious sudden failures. For instance, the Marecs-A communications satellite suffered the loss of much of its solar power during its demonstration news conference. The suspected culprit in these failures was the space environment, and this was confirmed when detailed calculations using spacecraft charging codes such as NASCAP/GEO and laboratory experiments using high fidelity simulations of the GEO environment showed that geomagnetic substorms could lead to sudden differential charging of spacecraft surfaces, followed by large electrical discharges which, when coupled into the spacecraft or solar array interiors, could lead to electronics upsets or failures.

Completion of the NASCAP/GEO computer code in 1984, and simultaneous publication of the Design Guidelines for Assessing and Controlling Spacecraft Charging (Purvis et al, 1984, hereafter called the Spacecraft Charging Guidelines), gave spacecraft designers powerful tools to prevent spacecraft charging and the electrical discharges associated with it. NASCAP/GEO made it possible to make detailed geometrical models of spacecraft and "fly" them in severe substorm conditions inside laboratory computers, thereby making it possible to evaluate the spacecraft charging that would occur and to predict problems before they occurred. The Spacecraft Charging Guidelines gave engineering rules of thumb for materials, geometries, and construction techniques which could be used to prevent charging before the expensive GEO spacecraft were built and launched. Although not perfect, these codes and guidelines have been used by a decade of spacecraft designers with generally positive results. The incidence of spacecraft charging related failures has dropped dramatically.

However, geomagnetic substorms are more common and more severe during the times of solar sunspot maximum. The last maxima were in 1980 and 1989, and we are now just past the time of solar minimum. The next maximum is forecast to be in 1999 or 2000. It is believed that this maximum will rival the last two maxima, which were abnormally strong (Joselyn et al, 1997). That means that for the last several years, spacecraft charging conditions have been somewhat benign, and we are now headed for an upswing in solar activity. Also, the last several years, with the new demands for lower cost, lighter, more powerful communications satellites, have seen the introduction of several new satellite designs, using larger, lighter and more efficient solar arrays, spacecraft bodies made of new composite materials, and new high voltage spacecraft buses. Many of the older engineers who used the Spacecraft Charging Guidelines and NASCAP/GEO during the previous solar cycle maximum have retired or moved upstairs, and the need to prevent spacecraft charging has seemed less urgent. These are very dangerous times for new GEO satellite designers, whose satellites must survive the coming solar maximum.

BASIC SPACECRAFT CHARGING PHYSICS

All spacecraft surfaces in GEO will tend on very short timescales (micro- to milli-seconds) to balance the positive ion and negative electron currents impacting on the spacecraft. Any imbalance will lead to charged surfaces, which will act to repel the charging species and attract the species of opposite charge, thereby discharging the surface. However, insulators tend to local current balance, whereas conductors, which are typically tied together by the spacecraft ground structure and must therefore be at or near the same potential, will tend toward global current balance. In some cases, this may lead to high differential voltages between adjacent spacecraft conductors and insulators. The ambient plasma in GEO is typically of very low density, meaning that the normal, thermal currents of ions and electrons are quite small. Unlike the LEO plasma, which actively tries to maintain all spacecraft surfaces at the same potential, the GEO plasma cannot be relied upon to instantly discharge charged surfaces. GEO spacecraft will tend toward an equilibrium potential which is slightly to moderately negative of the surrounding plasma, because the incoming rapid electrons at zero potential will overbalance the slow moving ions. Current balance is thus achieved when the electrons are being repelled, somewhat. The equilibrium potential (floating potential) will be that which is just repelling a majority of the electrons, and thus depends on the average impacting electron energy.

One of the factors that are important in determining the charge on GEO spacecraft surfaces is the photoelectric effect, wherein UV sunlight can liberate electrons from some surfaces, and keep them from charging highly negative. At the plasma densities typical of GEO, the photoelectric effect can lead to local electron emission currents greater than the thermal plasma currents. Another effect is secondary electron emission. If an electron within a certain energy range hits a surface, more than one electron may be liberated. As strange as it may seem, it is thus possible for a positive surface to charge more highly positive when it attracts electrons from the adjacent ambient plasma. Backscattered electrons can also impinge on spacecraft surfaces. Still another effect has to do with the "plasma sheath" around a spacecraft. Beyond a certain distance, the spacecraft's potentials will be screened from its surroundings by a rearrangement of the positive and negative charges in its vicinity. In GEO, it is possible for parts of the spacecraft sheath to extend far enough to "bottle-up" or prevent the surroundings from discharging certain surfaces. Such an effect is called a potential barrier. Sometimes, the conductivity of insulators is increased somewhat by impinging sunlight, a property called photoconductivity. Yet another factor is "snapover". Here, secondary electrons emitted from a surface when it is bombarded by high energy electrons hop across the surface, effectively making it a funnel for current to adjacent conductors. In order to determine the potentials to which surfaces will come in a real-life GEO satellite situation, the current balance equations must be solved simultaneously with the electrostatic potential distribution, a problem for which NASCAP/GEO was invented.

Spacecraft surfaces can charge to high potentials when high energy particles impinge on them (as in geomagnetic substorms, when changes in Earth's magnetosphere can accelerate particles to tens of thousands of electron volts). Above about +100 V, some surfaces produce more secondary electrons than impinge on them, and may charge to a potential where this is no longer the case, some few thousands of volts positive with respect to the ambient plasma. Surfaces which don't emit more secondaries than primary electrons can charge highly negative in a flux of high energy electrons, because the floating potential must rise to the point where most of the incoming electrons are repelled. And, if conducting surfaces are shaded, the photoelectric effect can't help discharge them. It is possible for an entire satellite to charge to high potentials relative to its environment. This is called absolute charging. A more dangerous situation is when adjacent surfaces charge to very different potentials. This is called differential charging.

Arcs can occur when dielectric materials are asked to stand off potential differences greater than their breakdown voltage. Solar arrays can arc when the cells are at potentials more negative than about 200 V with respect to the surfaces of their coverslides. If high voltage solar arrays or power system wiring use flexible kapton substrates or insulation, then once an arc occurs, the kapton may pyrolize and produce a conductive path to allow the power source to continue the arc, shorting out an entire power system circuit. And, conductor-insulator junctions can arc at differential potentials of a few hundred volts. The situation seems too complex to allow for many generalizations.

Nevertheless, the Spacecraft Charging Guidelines have some important recommendations to make. First, it is recommended that all possible spacecraft surfaces be coated with conducting material and grounded together. This will absolutely prevent any large differential potentials from existing on the surfaces. The coating material does not have to be highly conducting, but nearly perfect insulators (such as Kapton and Teflon) will not prevent differential charging. Teflon is not a good photoconductor, either, so that impinging sunlight will not allow potential equalization. It may be possible to use electron guns or plasma generating devices to discharge high spacecraft potentials. This solution is being used on the International Space Station, for example. Another tack is to prevent electrical discharges, if they occur, from disrupting satellite electronics. One recommendation is to shield all electronic components inside a Faraday cage, to prevent space plasma and radiated noise from entering. Electrical filtering may be used to protect circuits from the rapid transients associated with electrical discharges. These filters must be capable of filtering out the highest arc currents expected (sometimes in the 10's to 100's of amp range). One recommendation not in the Guidelines is to avoid the use of kapton insulation in high voltage circuits where arcs may occur for any reason. But perhaps the best recommendation is to use NASCAP/GEO to predict, find, and eradicate the problem areas before starting spacecraft buildup.

AN EXAMPLE - THE ACTS SATELLITE

The ACTS satellite is in many ways typical of today's modern communication satellite in GEO. It is a 3-axis stabilized box-shaped body, with large solar panels extending from its sides, and antennae mounted on the box. The solar arrays may be moved around alpha joints and, along with control of the body orientation, this allows for a favorable (normal) solar incidence. The ACTS satellite was analyzed for spacecraft charging by Joel Herr (1991). Much of what follows is taken from his paper.

As may be seen in Figure 1, two of the sides of the ACTS body are covered with Optical Solar Reflector (OSR). OSR has a thin coating of silica, a non-conductive material. Thermal control is maintained over much of the spacecraft surface by the use of a metallized multi-layer insulation thermal blanket. In addition to being conductive, these surfaces also have high photoemission, a source of free electrons which may help discharge surfaces.

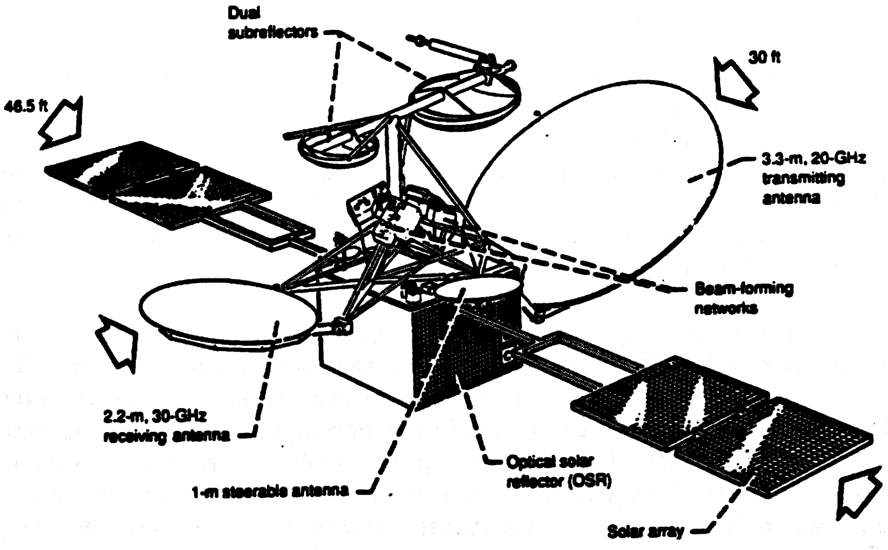

Figure 1. The ACTS satellite.

In Figure 2, we see the NASCAP/GEO model of ACTS, which was used to do the calculations for a spacecraft charging analysis by Herr (1991). In producing the model, it was assumed that the metallized multi-layer insulation was covered with grounded Indium Tin Oxide, a conductive coating, and that conductive paint (cpaint) was used on the antennae. The areas of silver interconnects and silica coverslides were adjusted to represent the approximate areas on the real spacecraft.

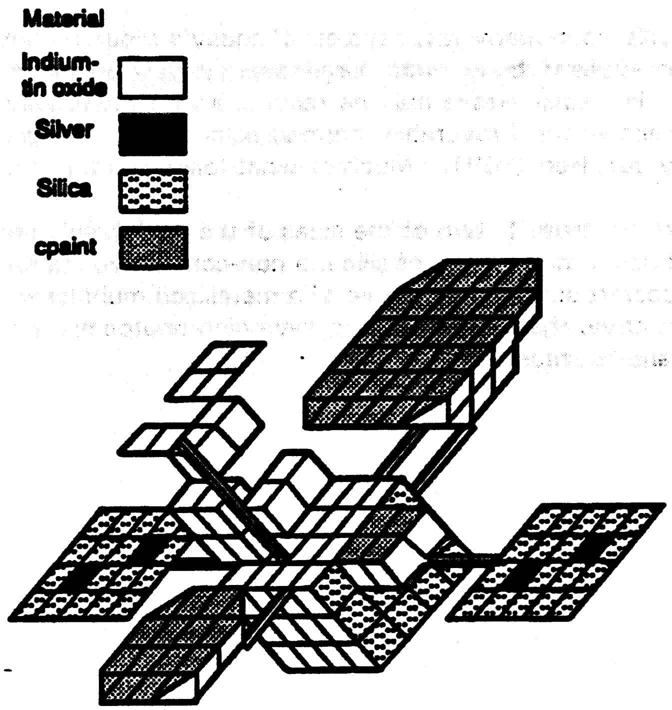

Figure 2. NASCAP/GEO model of the ACTS satellite.

In Figure 3, the potential contours calculated by NASCAP/GEO (Herr, 1991) are shown for a time shortly after ACTS comes out of eclipse, the time most likely for differential charging to develop. Here, it is easy to see the potential barriers which have developed over the solar arrays, and could lead to discharges.

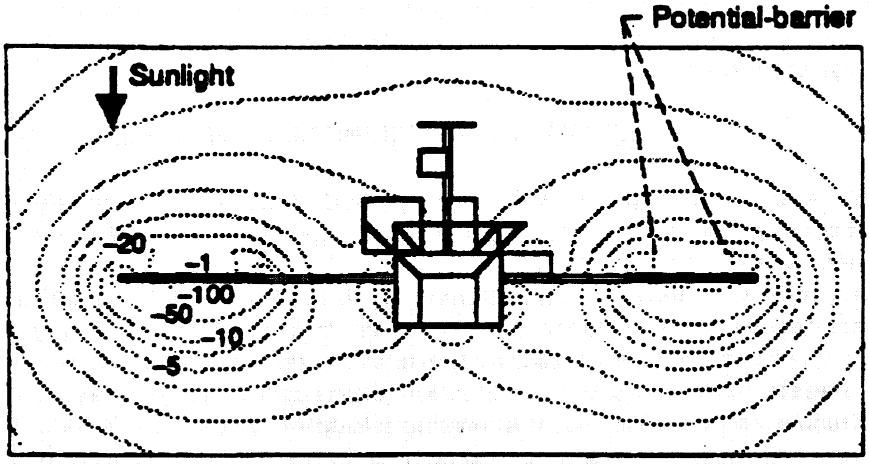

Figure 3. Potential barriers have formed over the ACTS solar arrays.

Finally, Figure 4 shows the time history of differential charging on ACTS calculated by NASCAP/GEO (Herr, 1991) for an eclipse period and shortly thereafter. Here we see that an assumed punchthrough (dielectric breakdown) discharge threshold is exceeded on the array substrate for times about an hour after emergence from eclipse under the conditions assumed for this analysis.

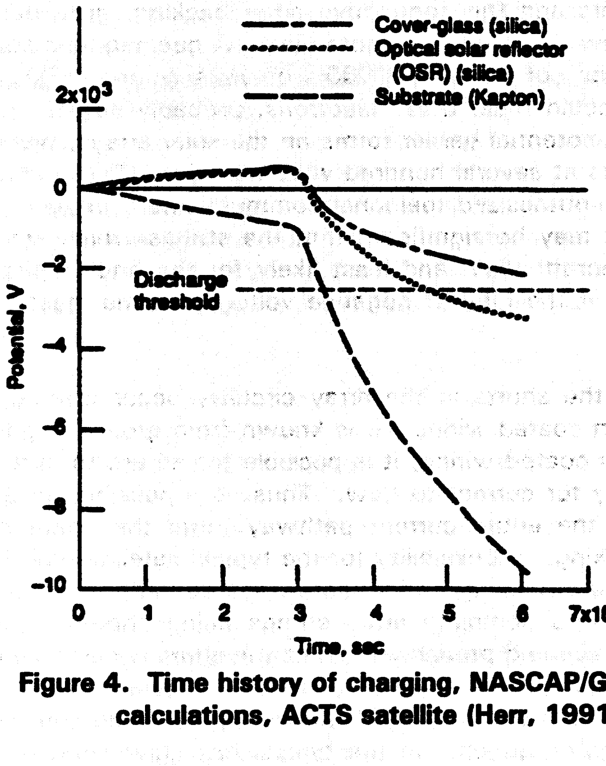

Figure 4. Time history of charging, NASCAP/GEO calculations, ACTS satellite (Herr, 1991).

These figures are presented not as a criticism of the ACTS satellite, but to show the kinds of analyses it is possible to do with NASCAP/GEO. For further details on the ACTS analyses, see Herr (1991).

It is imperative that the materials and material thicknesses used in the NASCAP/GEO analysis of a spacecraft accurately reflect the true spacecraft. In the case of the ACTS satellite, the analysis was done by a person not directly connected with the ACTS project, who found it difficult to find out the details of the geometries and materials used on ACTS from project personnel. They apparently believed that the NASCAP/GEO analyses could be used by ACTS opponents to find fault with the spacecraft, and might lead to its funding demise. As it turns out, some features of ACTS were found to be advantageous in preventing spacecraft charging (such as the use of highly photoemissive materials on the spacecraft body) and the analysis showed that they would make spacecraft charging only a minor problem for ACTS, if a problem at all. Other spacecraft are not so lucky.

A CASE TYPICAL OF RECENT GEO ANOMALIES

Recently, GEO spacecraft have started suffering sudden shorts in their power system circuitry, leading to the loss of some spacecraft power. The general design of these satellites is similar to the ACTS satellite above, but with some significant differences. First of all, the array area is significantly greater, in keeping with the trend toward higher and higher power GEO satellites. This is important not so much for the total area, but that the array wings extend to very great distances from the body, and are outside the range of the photoemitted electrons generated on the body materials. Secondly, the array string voltages are higher, again to negate losses in power distribution efficiency on large arrays at low voltages. The array substrate are flexible kapton, and the array wiring is kapton insulated. Thirdly, the backbias bypass diodes on the solar array strings, originally incorporated to prevent string damage when parts of a string were shadowed, have been eliminated, even though they also provided some arcing protection. Finally, many materials are being used which have no counterparts in the NASCAP/GEO databases, so their charging properties are essentially unknown. All of these factors may be important in the typical recent anomaly, presented below.

To the best of the limited analysis that has been done to date, it appears that photoemission on the solar cell coverslides is enough to keep the coverslides at the local plasma potential, whenever they are in sunlight. The array conductors and the conductive array backing, grounded at the negative end to the structure, respond to and follow the spacecraft potentials. A geomagnetic substorm suddenly showers the satellite with numerous electrons of 100's to 1000's of volts energy. The spacecraft body responds by taking on a potential which could repel these electrons, probably several hundred volts negative of the surroundings. At this point, a potential barrier forms on the solar arrays, with the coverslides at near zero, and the cells and interconnects at several hundred volts negative. These conditions can lead to arcing on the solar arrays, and it was hypothesized (personal communication, Snyder, 1997) that this has occurred on GEO spacecraft arrays. It may be significant that the strings which are damaged are typically those farthest away from the spacecraft body, and least likely for the body's photoemitted electrons to reach them. The parts of the array at the highest negative voltage are the most likely places for the arcing to occur.

It is not known how the shorts in the array circuitry occur after the initial arcs, but a possible hypothesis involves the kapton coated wiring. It is known from ground experiments that if a high voltage source is connected to kapton coated wiring, it is possible for an arc to pyrolize the kapton in its vicinity, providing a continued pathway for current to flow. Thus, it is possible for an arc to propagate along the kapton-coated wire, charring the entire current pathway, until the entire circuit is shorted at near its source. This is called arc-tracking. A possibility for the typical satellite now being discussed is that an arc at the solar array can lead to arc-tracking on its kapton coated wiring, and the high voltage array supplies the necessary current, leading to complete array strings being shorted (personal communication, Katz, 1997). Backbias bypass diodes would probably prevent the short circuit scenario during an arc, leading to increased array viability after arcing. The exact details of any scenario depend on the details of spacecraft design. However, the lessons are clear. NASCAP/GEO analysis should come first, before finishing satellite construction, and certainly before launch. In the typical case given above, several mitigating strategies could be followed. The structure could incorporate lots of photoemissive material in the solar direction, so that the body charge could bleed off. The solar cell coverslides could be coated with conductive material

(Indium Tin Oxide, for example), and grounded to the structure, so that the differential potentials causing the arc could not develop. Or, the high voltage wiring could be been insulated with another, less volatile, insulator.

At the present time, NASCAP/GEO is available through COSMIC, the NASA software distributor, or for different platforms, through its developer, Federal Division of Maxwell Laboratories in San Diego, California. It is hoped that it can be modified, for new spacecraft materials, new geometries, and new computers, by the Photovoltaic and Space Environments Branch at the NASA Lewis Research Center. One of the desperately needed steps is to attain laboratory measurements of the photoemission, photoconductivity, and secondary electron emission characteristics of new spacecraft materials to incorporate into the NASCAP/GEO database. A NASCAP/GEO analysis of a GEO satellite will cost less than one man year of time and money, and may save a $100 million satellite from failure.

REFERENCES

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