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Analysis of Environmentally Induced Spacecraft Anomalies

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This paper outlines an approach for use in spacecraft anomaly analysis. It provides a general decision tree for anomaly investigation and then lists probable causes of environmentally induced anomalies as a function of orbit. Although it is not intended to be a prescription for analyzing particular anomalies, it does provide the reader with an insight to the overall anomaly investigation process that may be of use in designing an "expert system" for anomaly analysis for an operational program.

Introduction

THE space environment is hostile. It is not a benign vacuum into which an object can be placed and be expected to operate exactly as it did when it was designed and tested on the ground. A spacecraft cannot even be stored in space for any significant period without serious degradation of surfaces and electronic components. Numerous adverse interactions occur. A major category is total dose damage to components, both mechanical and electronic, due to the trapped energetic particle environment, solar protons, and cosmic rays.

Spacecraft charging in geosynchronous orbit is a major environmental problem, but other environmental effects can also be severe. For example, during the short period of about one week, the solar proton events of October 1989 resulted in a reduction of power capacity of satellite solar arrays from a few percent (old satellites in geosynchronous orbit or low polar orbit) to over 10% (new satellites such as Magellan, en route to Venus, which suffered an 11% loss).[1,2]

Cosmic rays and relativistic protons also cause single-event phenomena such as circuit upsets, circuit latching, which requires depowering of the circuit to unlatch, and "burnout," in which a circuit element is permanently damaged. Energetic particles also produce heating in cryogenic components, darkening in optical components (such as solar array cover glass, star sensors, and laser light guides), noise backgrounds in low-level sensors, and a number of other undesirable effects. Solar ultraviolet light, x rays, and space plasmas damage thermal control coatings and blankets. Temperature extremes, especially those due to a long umbral passage, have mechanical consequences that are almost uniformly deleterious. At a low altitude, atomic oxygen reacts with surfaces and burns away elements that have a volatile oxide, such as the carbon in Kapton thermal blankets and the graphite in composite structural spars or electrically conducting surface coatings.

An anomaly is any unanticipated condition of a satellite. The term covers the entire spectrum from nonnominal thermal behavior to misoperation or nonoperation of active systems such as power, telemetry, commanding, sensor status, etc. Even the event in which an old U.S. satellite (P78-1) was used as a target for an antisatellite weapon is listed as an anomaly in at least one anomaly catalog. Anomalies can be hardware problems, software errors, commanding "glitches," etc. They can be environmentally induced, vehicle or system design errors, pilot error at the control panel, the result of hostile action, and various other categories. They can even be virtual anomalies, anomalies that are due to analyst error in the data reduction or that are due to hardware or software problems in the ground data processing system. But until the anomaly analysis is completed and a ground source is identified, these nonconforming results that are not due to the satellite itself are considered anomalies. In this presentation, we will not further address virtual anomalies.

The rest of this presentation will be divided into two sections. The first will discuss the anomaly investigation process and provide some examples of results of anomaly analyses and anecdotal material. To assist the reader in following the typically contorted process of the initial stages of anomaly analysis, a number of decision trees will be used. The discussions in the first section will be formulated around these trees. The second section will discuss the various classes of environmentally induced anomalies and provide some insight into the relevance of various orbital and environmental parameters.

Anomaly Analysis Methodology

In this section, the methodology of a typical anomaly analysis effort will be presented. The discussion is at a very fundamental level. Much of the process will be intuitively obvious. I hope, after the discussion, all of it will be so. The primary purpose of this section is to provide additional insight into the depth and scope of the anomaly analysis process. Frequently, far more individuals need to be involved in the process than someone who has not been involved previously in the process would have expected. This section should also provide insight into the necessity for an archive of test data and for the maintenance of contact with the design and test engineers who worked on the system. No one is truly "off of the project" until the satellite becomes permanently inert (dead on orbit, launch failure, museum piece).

Initiation of a New Anomaly Study

A new anomaly study automatically begins at that point where some datum from a spacecraft operation deviates from

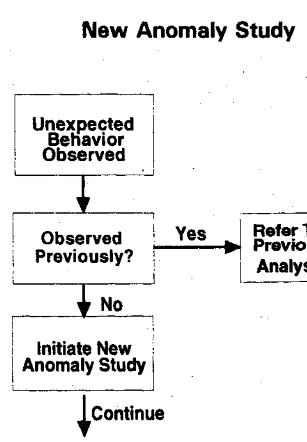

Fig. 1 Initial stage decision tree for spacecraft anomaly investigation.

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that which is expected. A command may be sent and the satellite system fails to respond as expected. A data analyst (which may include software that automatically checks "red line" engineering data as it comes in) observes a nonnominal value. At first contact, a satellite subsystem may be in a mode that is inconsistent with planned operations. Whatever the deviation, an anomaly analysis is in progress until that datum is explained or is logged as analyzed but unexplained. The individuals involved in obtaining an understanding of a low-level misoperation may not even realize that they have been doing an anomaly analysis. The usual path for a formalized anomaly analysis, however, is shown in Fig. 1, beginning with the point at which some unexpected behavior is observed.

The first question that must be answered (in the interests of efficiency of analysis) is: Has misbehavior identical to this been observed previously? If the answer is yes, then this particular anomaly (and its accessory data) can be added to the data base associated with that type of anomaly. If that class of anomaly has already been explained, this anomaly study may be considered completed. This specific event may strengthen the case for a solution that has been proposed for an earlier anomaly. Conversely, the data associated with this particular event may also weaken the case for the preceding explanation. If the origin of that class of anomalies has not been previously identified, this event might also provide just the additional data needed to explain the whole class of anomalies. In any event, if this type of event has been observed previously, it is shunted aside into a previously established anomaly analysis effort. If this type of event has not been observed previously, a new anomaly study must be initiated. Initial guesses as to the cause of an anomaly, when pursued, often lead to more substantial candidates for the cause of the anomaly.

Anomaly Analysis: Commanding

When a new type of anomaly has been observed, the next question (Fig. 2) that must be answered is, Was commanding in progress? This question is of paramount importance because a negative answer to this question severely limits the possible causes of the anomaly. If commanding was in progress, either through direct control or with stored commands, a number of avenues of investigation have to be pursued, usually sequentially, to identify the cause (or to eliminate commanding as the source of the anomaly). The most obvious first step is to review the command sequence in use at the time of the anomaly. Was a valid command sent inappropriately? Was an incorrect command sent through either operator or equipment error? Did the command decoder on the spacecraft interpret a command incorrectly, either through a noisy signal or a hardware or software error in the decoder? Was a stored command executed at the wrong time or interpreted incorrectly? If the spacecraft echoes commands in its data stream, was "spoofing" (unauthorized intentional commanding or sensor stimulation by a hostile party) a factor? If the answer to any of these is yes, and if the resultant state of the spacecraft is what is to be expected from that command, the anomaly has

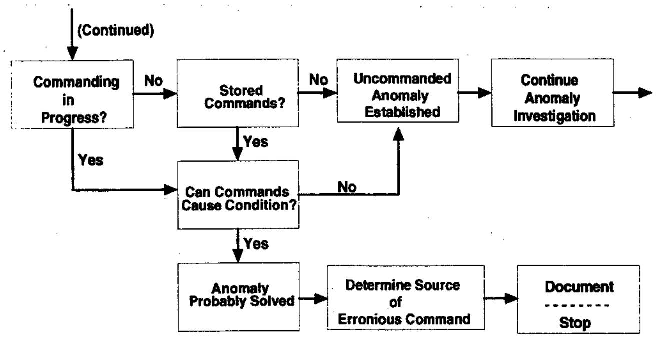

Fig. 2 Establishing that an uncommanded anomaly occurred.

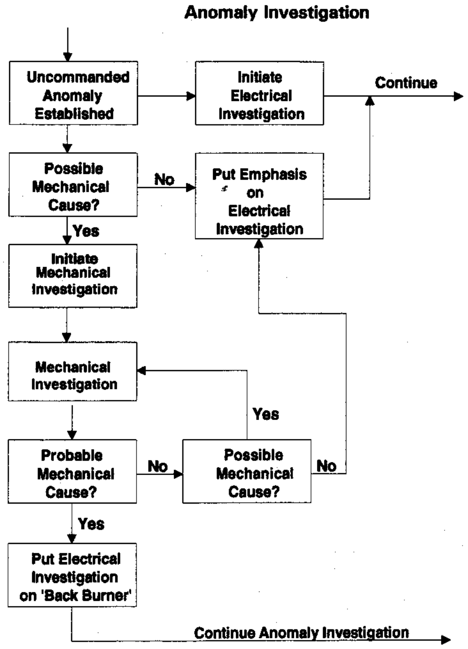

Fig. 3 Mechanical investigation branch of anomaly decision tree.

probably been solved. Note that an unexpected response to a validly issued and executed command does not fall into the category of command anomalies. Prevention of future command anomalies might require corrective action either on the ground or on the spacecraft.

Anomaly Analysis: Mechanical Causes

If commanding, either direct or stored, can be ruled out as a cause of the anomaly, an "uncommanded anomaly" has been established and further investigation is required (Fig. 3). At this point, two avenues of investigation are opened: mechanical causes and electrical causes. The data available from the satellite are used to determine whether a mechanical cause (i.e., spacecraft hardware) is possible. It may require consultation with the design and test engineers, and even the technicians who worked on the satellite and its instrumentation, to get a reasonably positive answer to the question of whether a mechanical problem has occurred. If the answer is no, the electrical investigation is emphasized. If the answer is yes, a more concerted mechanical investigation is initiated (branching to the top of the fourth section of the decision tree, Fig. 4). At this point, the anomaly investigation may be completed: If a very strong case can be made for a mechanical cause, with all observables providing results that are consistent with the mechanical hypothesis, the anomaly may be documented and the anomaly investigation ended.

An example of an investigation in which a mechanical cause was identified is provided by the fate of the OV1-14 satellite (international designation 1968-26B, a small scientific satellite flown in 1968 by the U.S. Air Force Office of Aerospace Research). About two days after launch, the spin rate on the spin-stabilized spacecraft started to increase slightly. No other anomalous effects were reported. The spin rate continued to increase, followed by erratic performance of the vehicle-ground telemetry link. Over a period of two more days, the spin rate continued to increase, and finally telemetry was lost. Postmission analysis of the engineering data showed the following: The bus voltage began to increase abruptly several hours before the spin rate began to change. Battery temperature began to increase shortly after onset of the voltage increase. Then battery temperature began to decrease, and the spin rate began to increase. Finally, the bus voltage began to decrease, followed by telemetry link problems. Operation of all other systems and experiments was nominal.

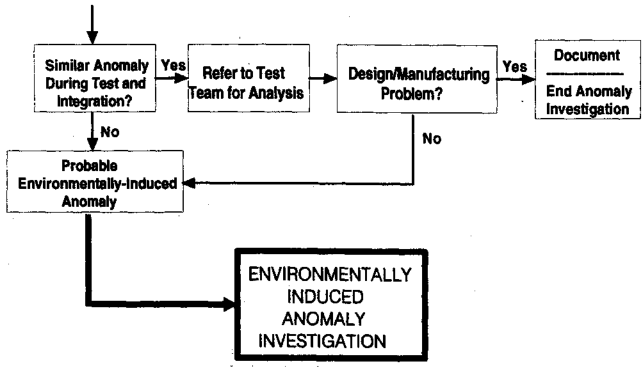

Fig. 4 Establishment of an environmentally induced anomaly.

The ultimate resolution of the anomaly was as follows: A component (probably a power zener diode) failed in the voltage regulator that controlled battery charging by the solar array. This resulted in an overvoltage condition on the power bus and overcharging of the battery. Overcharging of the battery raised its temperature. The increased pressure in the cells due to the elevated battery temperature caused one of the cells to rupture, venting its electrolyte. Venting of the electrolyte cooled the battery and caused the satellite to spin up (mass reaction effect). When sufficient electrolyte had been lost, the voltage on the bus began to drop. The reduced voltage resulted in reduced transmitter power and poor link closure. Eventually, the voltage dropped below the command receiver's operational limit, and control of the vehicle was lost. The anomaly investigation was closed, with a part's failure being identified as the cause. The failure was classified as mechanical because both the spin-up of the satellite and the loss of power and control were directly due to the rupture of the cell.

Anomaly Analysis: Electrical Causes

In a sense, the preceding anomaly should be considered to be an electrical anomaly (since the cause of the anomaly was an electrical component's failure), but the change in spin rate was the first noticed deviation from nominal operation, and the anomaly was thus identified as a mechanical one. If no probable or possible mechanical cause is identified in an anomaly investigation, full emphasis is placed on the electrical investigation. Of course, it is possible to reopen the mechanical investigation if evidence points back toward that sphere.

The first stage of an electrical investigation is to determine whether a part's failure is the cause. If the anomaly was a transitory process or a reversible state, it is unlikely that it was caused by a component failure. If it is a permanent effect, then it is more likely that a part has failed, although something else may have caused that part to fail. An initial step in the electrical investigation should be to determine whether a similar anomaly was observed during integration and test of the satellite and its systems (Fig. 4). If the answer is yes, the ground test team must assist in the investigation of the anomaly. (This is one of the areas where one needs access not only to the design and test data but also to the design and test engineers, even years after launch.) If such anomalies were observed during integration and test, the problem is really a design/manufacturing problem and needs to be corrected for future flights. However, at this point the design and test team must also be consulted as to what their corrective procedures were and what recommendations they may have to prevent further occurrences (or to ameliorate the effects of the problem) on orbit. If no similar occurrence was observed during the ground phases of the satellite program, and if failures of mechanical and electrical component parts have been ruled out, the probability is that one has an environmentally induced anomaly, the subject of the next section.

Since an electrical (or even mechanical) part's failure can be induced by the environment, it is usually more efficient to have someone who is an expert on spacecraft-environment interactions review the data at an early stage of the investigation. Sometimes a single discussion with a knowledgeable individual may suffice to focus the investigation down to specific environmentally induced effects.

An example of an environmentally induced electrical failure that was initially thought to be a mechanical failure is the Defense Support Program (DSP) star sensor shutter anomaly case history. The DSP carried a photosensor that had a field of view somewhat wider than that of the star sensor (which was used for attitude determination). The star sensor had a shutter to protect it from direct viewing of the sun. The shutter was activated by the photosensor. The anomaly consisted of erratic operation of the shutter. In some cases the shutter remained closed or closed at inappropriate times. Initially it was thought that the cause was a faulty mechanical assembly. Extensive effort was put into a mechanical investigation, including designing new shutter mechanisms, fatigue testing, thermal cycling, etc.

Ultimately, someone knowledgeable about the particle environment was consulted. He observed that the anomalies were strongly correlated with very large increases in the energetic electron fluxes. The photosensor had a short coaxial cable that was routed external to the vehicle and was thus subject to intense energetic electron irradiation at times. The cause of the anomalies was thick dielectric charging and subsequent damage to the attached circuitry by discharges within the cable. The hypothesis was checked by modeling the circuitry and analyzing its response to cable discharges. The model supported the observations. The problem was fixed by, among other changes, putting a solid shield around the cable.

Environmentally Induced Anomaly Analysis

When a space-environment expert is consulted about an anomaly, his/her first approach will be to determine the status, at the time of the anomaly, of a number of parameters that may be associated with the anomaly, since those parameters act as pointers to possible anomaly mechanisms. The items of prime interest are 1) vehicle orbit and location in the orbit at the time of the anomaly, 2) magnetic activity at the time of and just before the anomaly, 3) local time at which the anomaly occurred, 4) changes in the particle environments near the time of the anomaly, 5) specific details of the anomaly, 6) possible anomalies on other vehicles during the same time period, and 7) previous environmentally induced anomalies on this vehicle.

Selecting potential causes of the anomaly is only a first step, although a very important one, in solving the mystery of an anomaly. After selecting a potential candidate, a detailed analysis of a hypothesized mechanism must be prosecuted. The mechanism of the anomaly has to be detailed at the component level. Circuit drawings, electrical performance data, logic diagrams, mechanical data, etc., must be available to show that the hypothesized mechanism could have produced the observed anomaly. The environmental conditions must also be shown to have been capable of producing the required input to that mechanism.

Orbit

The vehicle orbit, especially the location of the vehicle in the orbit at the time of the anomaly, is the most important parameter in the investigation of a possible environmentally induced anomaly. The potential environmentally induced disruption mechanisms vary with position in the magnetosphere; e.g., Fig. 5 shows the general configuration of the environmental hazards in space. The hazards are not, of course, confined to sharply delimited regions. Of concern are energetic protons from about $L = 1.3$ to 1.8, the energetic electrons from about $L = 3$ to 7, extreme ultra violet (EUV), and cosmic rays everywhere (although at lower altitudes and latitudes there is some shielding from the cosmic rays by the Earth's magnetic field), solar protons at high altitude and over the polar caps, hot plasma at high altitude and high latitude, and atomic oxygen worldwide up to about a 500-km altitude.

At a low altitude, the major causes of environmentally induced anomalies are the energetic protons and cosmic rays (single-event phenomena, dose, backgrounds), plasma effects, atomic oxygen burning, solar uv, the residual atmosphere, man-made debris, and surface glow, more or less in that order of importance. For polar orbits, solar protons and auroral effects (hot plasma, streaming low-energy protons and electrons, magnetic field distortions, and optical emissions) may also be important. At higher altitudes, the dose from trapped energetic particles becomes most significant, followed by thick dielectric charging, surface charging, solar protons and cosmic rays, and solar uv. At geosynchronous orbit, surface charging and thick dielectric charging are the most likely candidates, followed by solar protons and cosmic rays. Solar uv may also be a problem. For highly elliptical orbits, long shadow times are possible, introducing the possibility of thermal effects, in addition to all of the aforementioned effects. For highly inclined orbits, plasma effects can also become important. We will come back to this point by addressing the primary anomaly concerns by orbital groups.

Magnetic Activity

If magnetic activity was high just before or at the time of an anomaly, or if the vehicle was at geosynchronous altitudes, the probability that the environment was involved in an anomaly is enhanced. Figure 6 shows the response of the energetic electron environment to a magnetic storm.[3] The data were obtained by the OV1-19 (international designation 1969-25C, a satellite similar to the OV1-14) a week before a magnetic storm on May 15, 1969, two days after the storm, and again two and three weeks after the storm. The data were obtained in the low-altitude extension of the outer zone but are representative of the fluxes higher on the field line. In the critical (to thick dielectric charging and dose effects) region of 300 keV to 1.5 MeV, there is a flux increase of three orders of magnitude. At energies above 1.5 MeV, which are critical to backgrounds in sensors and optical devices because of their penetrating ability, there is an increase of one and a half orders of magnitude. The fluxes in this energy range are more persistent than the lower energy fluxes, with the >2 MeV fluxes still increasing two weeks after the storm, whereas the 300 keV to 1 MeV fluxes have decreased by two orders of magnitude.

The effects shown in Fig. 6 are the result of a major magnetic storm. Such storms also produce intense heating of the plasma at and beyond geosynchronous altitude and in the auroral regions. This produces an increase in surface charging that in turn causes anomalies when discharges occur. But smaller magnetic storms, called substorms, also produce plasma heating effects, primarily at high altitudes in the midnight and dawn sectors.

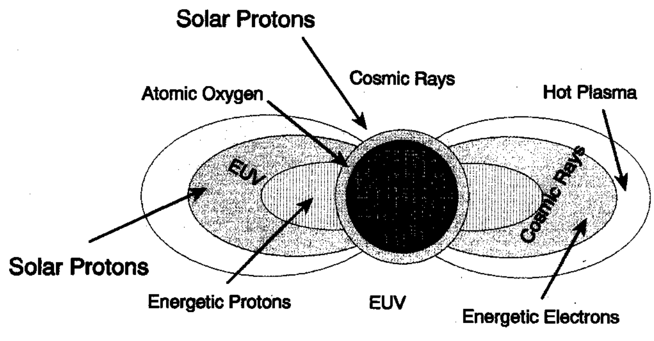

Fig. 5 Environments producing deleterious effects on satellites.

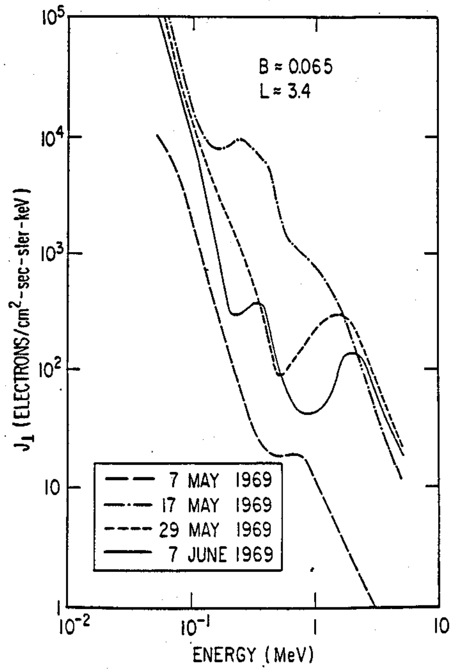

Fig. 6 Energetic electron flux response to a major magnetic storm.

The large magnetic storms can have a direct effect on satellite operation: e.g., on-board use of the magnetic field vector for orientation purposes, such as during operations involving dumping of excess torque from momentum wheels via an interaction with the magnetic field, can result in apparent anomalous operation, especially in the midnight sector where the magnetic field perturbations are greatest.

Local Time

As mentioned earlier, certain local times are more likely than others to produce particular types of anomalies. Anomalies induced by magnetic field fluctuation are more likely to occur at midnight local time. The reason for this is that in the midnight sector the Earth's magnetic field is drawn out into a low-field tail structure by the solar wind. The tail field lines are extensions of auroral and polar field lines. Variations in the solar wind dynamic pressure produce corresponding variations in the Earth's magnetic field. In a process that is not yet well understood, plasma in this tail region is heated and flows earthward, producing effects down to as low as about $L = 5$ in the equatorial region and all the way down to the atmosphere in the high-latitude region. The field configuration, direction, and extension in the tail change. The plasma flows and tail reconfiguration produce the effects that show up as substorms.

The hot plasma flows can also produce intense surface charging on shadowed surfaces that they encompass. Sunlit surfaces produce photoelectron currents that limit surface charging. Figure 7 is a histogram of the probability of charging as a function of local time and magnetic activity as measured by the SCATHA satellite in a near-geosynchronous orbit.[4] Thus, local time is an important parameter in an analysis of a suspected surface charging anomaly.

Local time is also a parameter of interest in thick dielectric charging. The most energetic electron flux intensities peak in the vicinity of $L = 4$, with decreasing intensities to higher and lower L. The energetic electrons drift along L shells that are distorted by the action of the solar wind on the magnetic field in the noon sector. As a result, a geosynchronous satellite passes through its lowest L shell at early afternoon in local time. Because of this gradient in intensity as a function of L, geosynchronous satellites (and other high-altitude satellites) see a variation in intensity of the energetic electrons as a

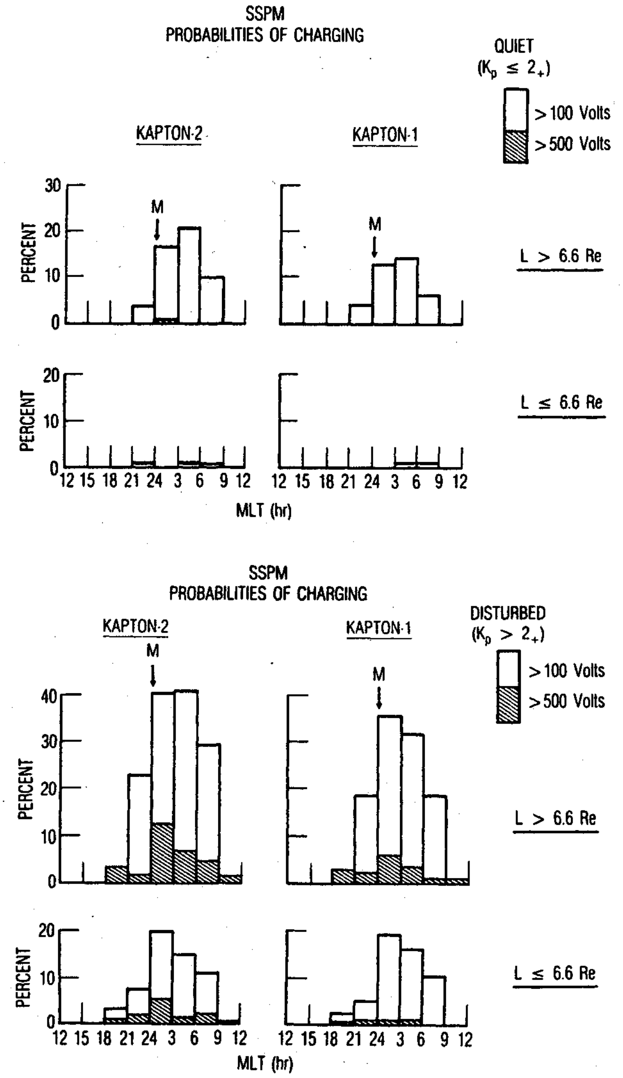

Fig. 7 Probabilities of charging vs magnetic activity.

function of local time, with the peak intensity being encountered in the early afternoon.

Details of the Anomaly

In an anomaly investigation, the details of the anomaly usually give clues to the source of the anomaly. If the anomaly is a temporary change of status or mode and is recoverable by commanding, the anomaly probably was caused by a "false command," where the false command may have been produced by several avenues. The first avenue is an actual command that has been sent inappropriately or a stored command that has been executed at an inappropriate time. Both of these are the result of operator error and require no further analysis. Another avenue is a misinterpretation of a valid command. This behavior is harder to diagnose; usually it is not confirmed until a history of malfunctioning decoder events has been generated. A single occurrence is usually not confirmable unless commands are echoed in the telemetry stream as executed.

A second avenue is the generation of a false command within cables or circuitry by either a surface discharge or a discharge within a dielectric. Surface discharges can produce spikes in cables of over 100 V or currents of kiloamperes, depending on the impedance of the cable terminations. There is sufficient energy to produce permanent damage in components to which the cables connect. Thick dielectric discharges are low-level events and usually do not include enough energy to produce damage in components. They appear as signals on cables and leads. A thick dielectric discharge usually affects a single circuit, whereas a surface discharge can produce spurious signals in many circuits simultaneously.

A third avenue of generating false commands is by the deposition of energy within the sensitive volume of an electronic component by an energetic particle. A heavy cosmic ray can have a high enough linear energy transfer (LET) to produce an effect directly. However, energetic protons can also produce such effects if they disrupt a nucleus and produce energetic spallation products (sometimes call "star" events). Because the direct deposition of energy by a particle is a localized event, usually only one circuit is affected. The anomaly looks very much like the thick dielectric charging anomaly. However, if an unshielded cable, external to the vehicle, is connected to the affected subsystem, the thick dielectric discharge is a very likely cause (especially if the vehicle traverses the outer zone energetic electron belt). Conversely, if the anomaly occurs in a circuit buried deep within the satellite with no direct connection to the outside environment, an energetic particle (cosmic ray or relativistic proton) is the more likely causative agent.

When the anomaly is a permanent failure or degradation of a subsystem, other causes must be considered. Although a false command can produce permanent damage, and surface discharges can produce surface defects or burn out electric components, random parts failure must also be considered. Also, design error can lead to mechanical anomalies. Thermal cycling, aging of polymers, EUV degradation of surfaces, and other effects can all have a cumulative effect that eventually produces an anomaly. Again, the details of the anomaly almost always give clues to the cause of the anomaly.

Anomalies on Other Vehicles

If anomalies have occurred on other vehicles in similar orbits during the same general time period, this may be an indication that the environment caused the anomaly. Significant changes in the environment, especially in hot plasma and energetic electron fluxes, should be considered. If environmental sensor data, such as the GOES particle spectrometer data, are available for the period of interest, they should be examined to determine whether major changes occurred just preceding and during the anomaly period. If such data are not available, magnetic field activity may be a good proxy, especially for geosynchronous orbit.[5,6]

Changes in the Particle Environments

If data from plasma detectors on geosynchronous satellites indicate that the hot plasma environment was unusually severe—hot plasmas with a very low density cold plasma component or frequent injections of hot plasma—surface charging should be suspected in geosynchronous satellite anomalies. If there has been a large increase (order of magnitude or more) in the 300 keV to 1.5 MeV electron flux intensities at any time during the 24 h preceding a "false command" anomaly, the probability that the anomaly was caused by a thick dielectric discharge is high. It has been estimated that perhaps as high as 50% of the charging-induced anomalies are caused by thick dielectric charging, with the remainder caused by surface charging.[7] If an intense relativistic solar proton event was in progress, there is always an enhanced probability that an anomaly was caused by the relativistic protons. Other changes in the particle environments could also result in anomalies. The key here is "changes." The movement away from an equilibrium condition results in the anomaly.

Anomalies vs Orbits

Although almost any type of anomaly can occur in almost any orbit, there are certain types of anomalies that are more probable in a particular orbit. In the next paragraphs we briefly discuss the most likely causes of environmentally induced anomalies. The orbits that will be addressed are: 1) geosynchronous, 2) highly inclined, half-geosynchronous (Molniya), 3) circular, half-geosynchronous global positioning system (GPS), 4) low altitude, polar, and 5) low altitude, low inclination.

Other orbits will not be discussed because there are too many possibilities. Most of them encompass combinations or portions of the aforementioned orbit types, and considerations discussed for the specific orbits will apply to those special orbits.

Geosynchronous

The most probable causes of environmentally induced anomalies on geosynchronous orbit satellites are 1) surface charging, especially near midnight local time and particularly during umbral entrance and exit; 2) thick dielectric charging, especially for the 11:00 to 15:00 local time sector; 3) single-event upset if a solar proton event is in progress; and 4) total dose, especially for older satellites with large accumulated doses and soft circuits. Other possible causes are 5) thermal, especially if the anomaly occurs after umbral passage; 6) EUV, plasma heating, etc. (to be invoked only when other possibilities are eliminated); and 7) single-event upset due to cosmic rays.

Molniya

In Molniya-type orbits, virtually all of the environmental effects that occur in other orbits can also occur here, since the Molniya orbit passes through all of the environments encountered in the other orbits except for the environment at the geomagnetic equator at geosynchronous altitude. The most probable environmental causes of anomalies in the Molniya-type orbits are 1) surface charging, especially near apogee; 2) thick dielectric charging, especially in midorbit when the satellite is passing through the heart of the outer electron zone; 3) single-event upset at perigee or during a solar proton event; and 4) total dose, particularly if an anomaly occurs during a descending or ascending leg. Other possible causes are the same as for the geosynchronous orbit.

GPS

The GPS orbit period is somewhat less than half-geosynchronous, but the following applies to all orbits that spend most of their time in the outer zone energetic electron belt: 1) thick dielectric charging, especially near the equator or immediately after a large magnetic storm; 2) total dose; and 3) surface charging at high latitudes. Other possible causes are the same as for the geosynchronous orbit, plus single-event upset from a solar proton event.

Low Altitude, Polar

Satellites in the low-altitude polar orbit spend most of their time in a benign orbit. To a great extent, the location of the satellite at the time of an anomaly is the best clue as to the type of cause of the anomaly. Probable causes are 1) single-event upset, particularly during polar and South Atlantic anomaly (SAA) passages; and 2) total dose, usually during a solar particle event or after an SAA passage.

Low Altitude, Low Inclination

This is the most benign orbit of all, hence its use for manned missions. The most probable causes of environmentally induced anomalies are 1) single-event upset, primarily during an SAA passage; and 2) total dose, again primarily during and immediately after an SAA passage. Both this and the low-altitude polar orbit may be exposed to significant atomic oxygen. Surface effects due to atomic oxygen erosion and solar EUV may result in anomalies.

Acknowledgment

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