IN-FLIGHT ANOMALIES ATTRIBUTED TO ESD'S. RECENT CASES AND TRENDS

Jean-Pierre Catani
Centre National d'Etudes Spatiales
18, avenue Edouard-Belin
31401 Toulouse cedex 9

Abstract

The general problem of charging is usually shared out four domains of physics or technology: astrophysics for the knowledge of environment, materials technology for understanding and prediction of charge build-up, plasma physics for predicting thermal or electromagnetic effects of discharges, and space engineering for assessing effects of transients on the space system.

The environment monitoring at the geosynchronous altitude has been carried out for years beginning with the first launches of NOAA GOES satellites. Their drawback is they provide only local data. The development of Space Weather activities let foresee the possibility of deriving the charging particles content in the immediate vicinity of the space vehicle from a limited set of flight-monitored data. Today, anomalies attributed to charging are fortunately infrequent, making unreliable statistical correlation between environmental data and event occurrence. It can be conclusive only in some cases of surface charging.

The understanding of interaction of materials with a well-representative simulation of environment is a priority in Europe, especially at CNES, the French Space Agency. In a CNES/ONERA test facility in Toulouse the main features leading to both surface and internal charging are simulated for all altitudes. An aim is the characterization of new technologies and new materials: electrical thrusters, active antennas, conductive coatings. Another aim is the issuing of design rules in the frame of the European Space Standardization. The plasma discharge is the source of an electromagnetic field transient. At equipment level an ESD immunity test has been used for now fifteen years. A system level test remains to be defined.

General

The spacecraft anomaly is at the end of a long chain of causes and consequences. At the origin we find the Sun, it is the source of plasma ejected in the zone of space called heliosphere comprising all planets of the solar system and extending much farther. This plasma interacts with the Earth magnetic field and can partially diffuse into the magnetosphere, the zone of space governed by the terrestrial magnetic field. The solar plasma is not emitted uniformly inducing large instabilities of the magnetosphere; it results heating of magnetosphere plasma at hundreds of kiloelectronvolts at the altitude of geostationary spacecraft and megaelectronvolts by orbits of positioning system satellites. The interaction of the satellite body with this hot plasma is frame charging at high negative potentials, also differential charging between insulated parts resulting in electrostatic discharges. The fast release of charges creates high-amplitude electromagnetic fields, then current and voltage transients onto box interconnecting cables. The pulses penetrate inside boxes, propagate along printed-circuit-board tracks, reaching active devices, toggling flip-flops, saturating amplifiers, or fusing lanes inside integrated circuits.

Each step of the process is highly random. Even if we are able to analyze each one, we have no mean to derive the behavior of the system from Sun observation or magnetosphere radiations monitoring, even not from electrical measurement on the spacecraft. On the opposite side, once an anomaly has occurred, it is possible (and useful) to assess the probability of a charging cause. It is the aim of on-orbit investigations.

Investigation

Main steps of investigation

How to know what happens in flight? A Ground Control Center dedicated to a Space System is permanently checking the spacecraft configuration. An alarm or warning is triggered when the spacecraft is getting out of its nominal working state. An electrostatic discharge is not observed itself but only when it has permanent consequences. Telemetry data is never designed for surveying unforeseen events; it is defined for command control and good-health diagnosis. Probes are exceptionally implemented on commercial spacecraft to determine the state of environment at the location of the spacecraft, at the time of the anomaly.

Spacecraft event understanding is the conclusion of three convergent ways of analysis: environmental data monitoring, vacuum charging tests, and electromagnetic immunity tests. Only one criterion is rarely convincing enough.

First step: Use of environmental monitors

What is the electronic content at time and location of the satellite? Charging fluxes are varying very rapidly, the duration of a charging event is only a few minutes. Since there is no on-board sensor, we can only lean on environmental plots issued by the Space Environment Center of Boulder, CO, USA (0). It is only informative because measurements are not made at the same location of the orbit as the concerned spacecraft. A proton analyzer provides proton flux data from solar flares in three spectral bands: E>10 MeV, E>50 MeV and E>100 MeV. By experience, only the upper band is correlated with upsets (which are not charging effects). Electron fluxes are plotted for two bands: E>600 keV and E>2 MeV. The collapse of high-energy electrons is an effect of substorm mid-energy electron fluxes, an indication of possible surface charging. On the third panel, the H_p magnetic component at GOES location is plotted. The plot would be a clean sine curve in absence of geomagnetic activity. Magnetic noise on this curve witnesses to substorm fluxes of precipitating mid-energy particles. On the lowest panel, planetary K-indices bar-plots confirm occurrence of substorms (when K_p is above 3).

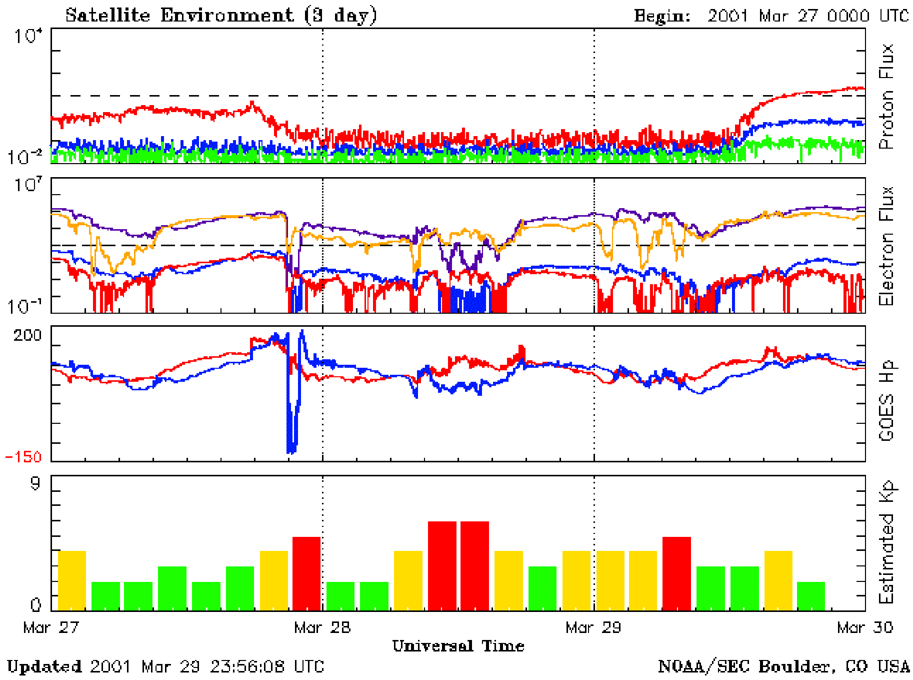


Figure 1. Example of data used for determination of solar and geomagnetic environment. Information from the Space Environment Center, Boulder, CO, National Oceanic and Atmospheric Administration (NOAA), US Dept. of Commerce.

During active periods, during the existence of a magnetic storm, the probability is high for the spacecraft to be impacted by energetic electrons. However even during very quiet periods, charging fluxes are still possible. Moreover we have to take into account a "memory effect". Impinging electrons during active periods become embedded inside dielectric material and can be free some hours, maybe some days, later, resulting into an electrostatic discharge. Electrons of moderate energy (a few 10keV's), buried in surface materials can be responsible of this effect. The discharge triggering may have several causes; for example a local dissymmetry of charge induced by lighting, creates a voltage difference where the voltage was uniform in darkness.

MultiMeV electron fluxes may vary through several decades at different space-time locations. Moreover the charging effect is highly dependent on the spectral signature. They can have a beneficial effect by keeping surface-voltage building-up (radiation-induced conductivity). On the opposite side they are cause of hazardous internal charging.

Second step: Use of environment simulators

Charging properties of rough materials are more or less known. Bulk and surface resistivity, secondary emission yield to electrons and ions, photoemission efficiency are documented during the spacecraft development for charging assessment. Actually, materials are used in complex assemblies; possible interactions between adjacent materials have an influence on charging balance and discharge processes. Testing flight-representative items in a vacuum facility with a representative charging ambiance is a way for assessing the discharge risk. It provides information on discharge characteristics: duration of the discharge, current amplitude, and associated electromagnetic field. It will also provide information for the design of an electromagnetic simulator.

A set of electron guns generates an electron beam in broad range of energy from 10 keV to 200 keV or more. The item under test is polarized with respect to the chamber walls for simulating the absolute voltage of the spacecraft. UV-light or a proton source simulates locally the positive charging effect of sunlight.

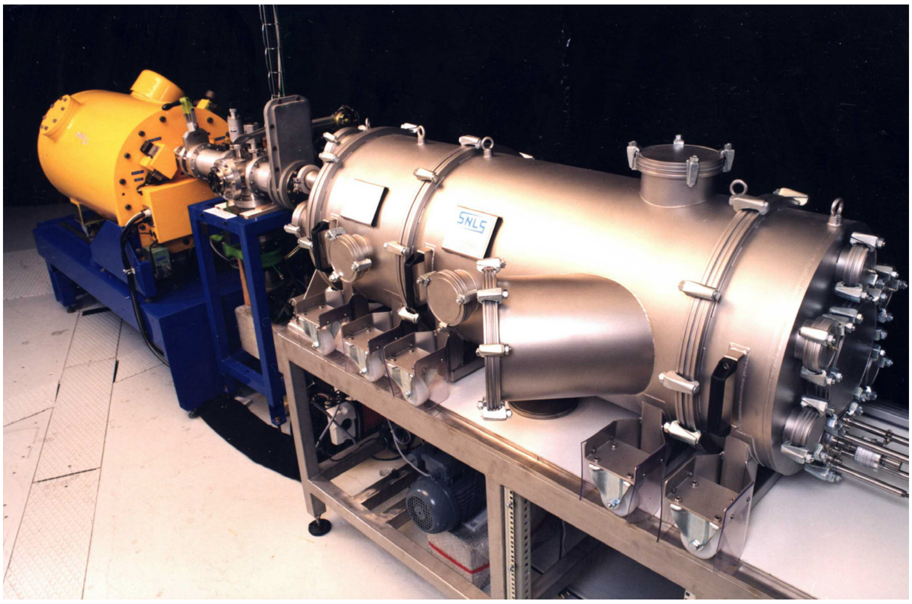


Figure 2. Wide-spectrum charging environment facility SIRENE (photo ONERA)

A NASCAP simulation is useful for preparing the test and defining the voltage configuration (polarization) of the specimen under test and the electron flux.

Third step: Use of ESD simulators

The plasma created by the electrostatic discharge can have primary effects; for example, to trigger a cold arc discharge between cells of the solar generator. However, in most cases electromagnetic effects of electrostatic discharges are preponderant. Two types of electromagnetic sources have been identified.

The discharge process is a transition from a charged state to a discharged one; it is seen as an electric-field transient step. During the transition, a replacement current is flowing in the spacecraft frame; this is one of electromagnetic sources. At the same time, electrons are blown off from the site of discharge, repelled by the negative potential. The charge present at a given time in free space before being recollected (or lost in space) generates an electric field pulse of several tens of kilovolts per meter in the immediate vicinity of the site of discharge, inducing current or voltage pulses onto close wires or bundles.

What is the response of a box to an electrostatic discharge, in other terms is the anomaly a possible response of the box to an electrostatic discharge? Analyzing the electrical schemes or drawings is not conclusive. Immunity or susceptibility is affair of details; it is the consequence of parasitic elements, stray capacitances, bonding inductances, nonlinear effects in active devices, a lot of unspecified parameters. A susceptibility test is the only mean to know the equipment behavior to electrostatic discharges. A numerical analysis is useful to understand the susceptibility mechanism inside the box.

At equipment level a susceptibility test has been developed at CNES and used for fifteen years. This is a recommended test of the standard "ISO-14302, EMC for Space Systems. It can be performed by a coupling method using a wire adjacent to the bundle (0). A 100pF capacitor charged at 6kV is discharged through a fast spark gap. The discharge current is electromagnetically coupled to the bundle. This test has been designed to replace the radiated field test from a sparking device and the conducted test by discharging an arc onto the structure, tests defined by the older MIL-STD-1541 standard.

In most cases ESD events and electronic upsets have no consequence at system level due to internal redundancy or logical filtering. A system level test remains to be defined.

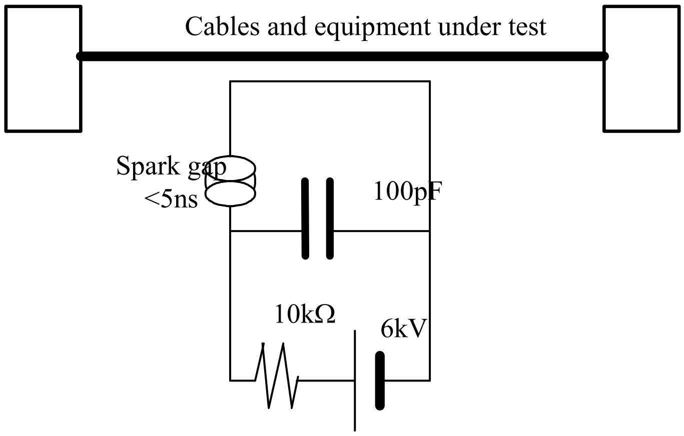


Figure 3. Recommended spacecraft charging ESD immunity test at unit level

Flight Experiences

All anomalies experienced in flight have not the same weight. We used to distinguish at least two kinds of anomalous behavior:

- Major anomalies: malfunctioning (temporary or permanent) with operational consequences (failure, automatic recovery, loss of control, loss of performances)
- Minor anomalies: anomalous functioning without operational consequence.

We give the example of a European program of several satellites, totalizing 22 temporary major anomalies for 38 years of cumulated time in orbit, about one event per satellite every two years. It seems to be a normal rate for the current generation of satellites. The associated outages are well inside the standard requirement and far from hundreds of events experienced in the 70's or 80's which have initiated research programs about charging.

However the fact that anomalies consecutive to charging events are still experienced from time to time is the indication we are at the border-line between safe and weak systems. Most of anomalies occur on subsystems connected to an external equipment, sensor or actuator; this is a noticeable point which helps us to define mitigation techniques and prepare test plans.

First example: Unlocking of a phase-locked loop

The described anomaly is unlocking of a receiver phase-locked loop. Applying the normal procedure of investigation when an environmental induced discharge is suspected, we plot events on a time-date diagram (Figure 4).

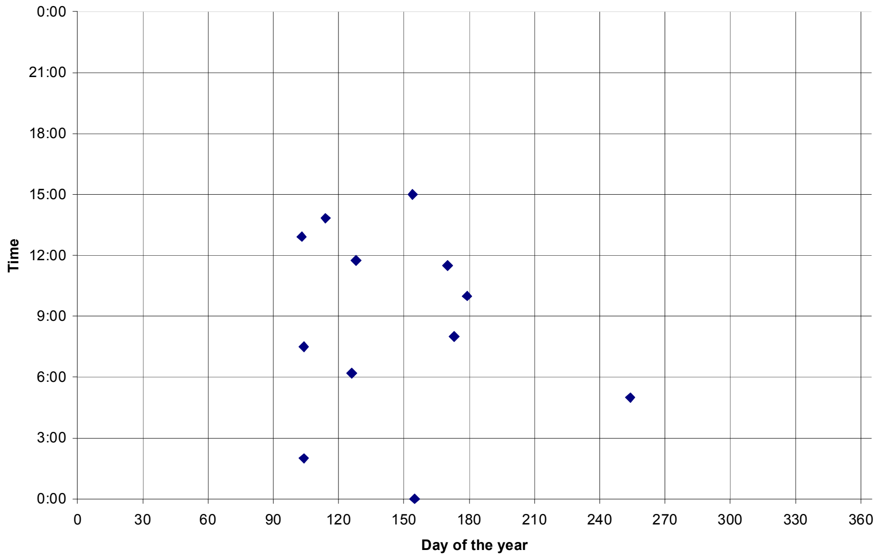
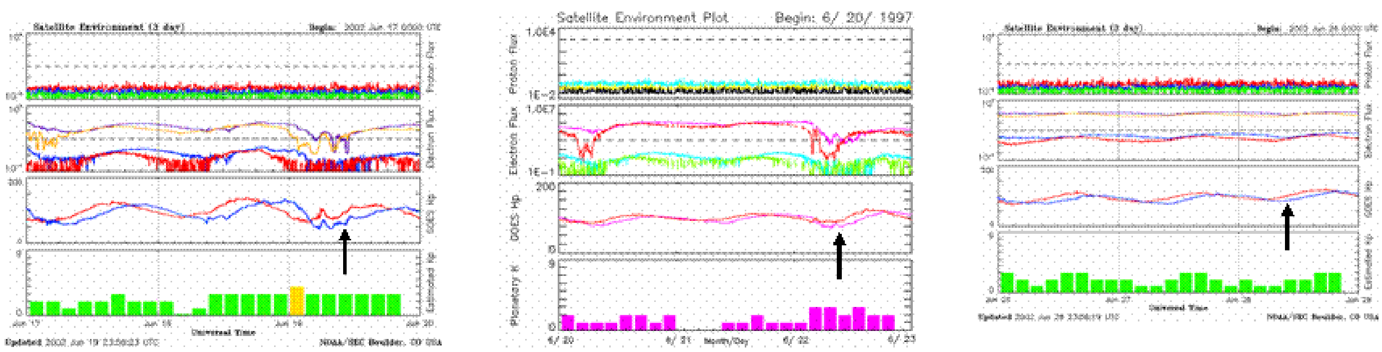


Figure 4. Time-date distribution: seasonal and time dependence (from 12 events in 5 years)

Though the small numbers of events, the dots do not seem randomly distributed, a seasonal and time dependence is visible. Mainly, a majority of events has occurred in the morning where surface charging is more frequent. Views of NOAA diagrams (Fig. 5) sometimes show a correlation between the geomagnetic activity and occurrence of anomalies. The charging event is guessed from ripples on the magnetic field amplitude at the altitude of geostationary satellites. It was true for 11 events not for the twelfth one, on June 28th, 2002. This kind of exception is not infrequent, rendering difficult definite conclusions.



19 June 2001, 10am — 22 June 1997, 8am — 28 June 2002, 10am

Figure 5. NOAA reports for three of the events

As the anomaly was of minor type, reproducing it in under an EMC test was not attempted. It was explained by a voltage spike induced by an electrostatic discharge.

Second example: saturation of an op-amp

The second example is concerning six events in seven years on different satellites using the same type of equipment. One event occurred some days after the coronal mass ejection of January 6th, 1997 when the level of multiMeV electron flux was largely increased. Four events took place in the morning quadrant of local time, two outside. From the environment monitoring it was seen that this anomaly always occurred following a storm when the high-energy content of the magnetosphere had become maximal. Environmental induced discharges were supposed to be the cause of anomalies.

The anomaly is seen as the saturation of an operational amplifier (0) masking the nominal low-level signal (0). It was a temporary malfunction the consequence of which was an outage of the whole subsystem. The electronic anomaly was well-explained by a voltage spike in the vicinity of the op-amp input stage. It was reproduced by an ESD immunity test confirming the hypothesis.

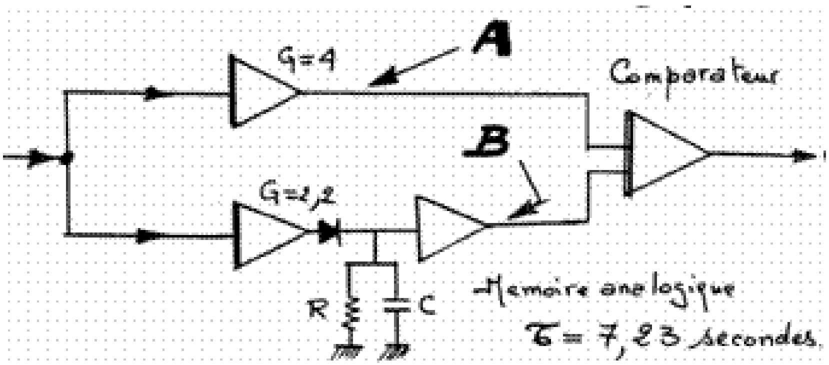


Figure 6. Simplified scheme of the comparator

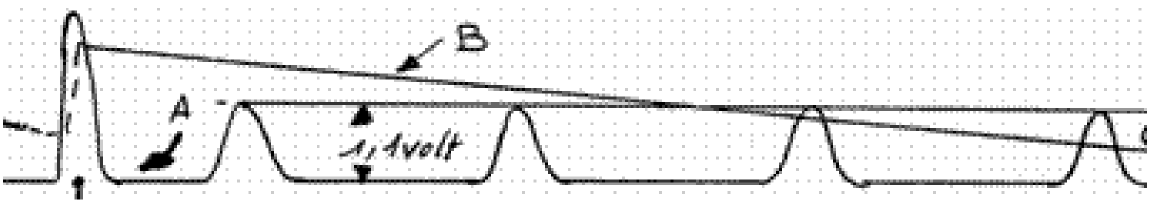


Figure 7. The recurrent pulse on channel A is masked by the low response to the transient on channel B

Towards an ESD-free program

A design and development objective would be a zero-failure mission. In most cases programs are not actually affected by environmental induced discharges. This is a pretext to decrease the costly effort of implementing mitigation techniques with respect to the charging risk. However, any manufacturer has been, is or will face major problems related to charging. The first effort consists of convincing management the risk is not overestimated. The spacecraft provider has to lean on experimented staff. It is not so easy since various domains of physics and technology are involved. The subject needs a continuous funding even when there is an apparent absence of risk in periods free of anomalies.

Mitigation techniques for lowering the charging risk follow two convergent ways. Everything is done for decreasing the number of discharge sources, in the same time, any equipment potentially exposed to charging has to be submitted to an electromagnetic immunity test. Visual inspection and knowledge of materials is primarily used for identifying possible discharge sites.

Design rules have not to be too numerous if we want their strict implementation. Main rules are zero floating-conductor (disregarding the size), the main frame must be a screen to electromagnetic interference and to high-energy electrons, external cables (in the sense they are submitted to electric transients) will be shielded. Any external equipment (equipment outside the shielded main frame) is supposed to be exposed to EMI, so an immunity test will be applied to it.

At a higher level of technical management, continuous Research & Technology activities will be carried out for characterizing new technologies (concerning charging), and possible evolution of older technologies. A systematic investigation of every in-flight anomaly (major or minor) is necessary.

Problems of Qualification and Verification

Qualification at equipment and subsystem level is possible and actually carried out. However representative tests at equipment level are always difficult to achieve. It is never ensured that cables are similar to the flight model, or that same controls are used during the test as on flight telemetry. We know equipment passing successfully ground tests, experiencing charging anomalies in flight.

At system level, no verification test is sure enough to prove the ability of a given S/C to sustain a charging environment. Often we are relying on methods and procedures, and visual inspection.

Trends

Charging and consequences at the altitude of geostationary satellites are well understood; mitigation techniques are known and generally applied. Standardized guidelines will be issued at end of 2004 in Europe (ECSS-E20-07).

Though the number of events becomes low, manufacturing processes are in permanent evolution, causing bad surprises: components supposed to be safe become dangerous.

New technologies (electrical propulsion, high-voltage bus bars, very low-voltage logics, active antennas) are causes of unexpected problems.