# SPACECRAFT INTERACTIONS WITH THEIR SPACE ENVIRONMENTS

*Jean-Claude Boudenot*
THALES Communications, 160 boulevard de Valmy, BP 82, 92704 Colombes Cedex (France)
Tel = 33.1.41.30.36.51 ; Fax = 33.1.41.30.36.51 – E-mail = jean-claude.boudenot@tcc.thomson-csf.com

**Abstract**
Radiation belts, solar flares and cosmic rays are at the origin of the space radiative environment. Electrons and protons of the radiation belts as well as protons from the sun coronal mass ejection lead to *total dose effects* on electronic devices. Cosmic rays and heavy ions solar flares are responsible for *heavy ions effects*. Recently two other kinds of effects had to be considered. The first one is the so called *proton effects* and is due to the fact that with the miniaturisation of the devices the lighter ion is now able to affect (indirectly or directly) the electronic. The second one is also due to proton, which, in addition of having ionising effect (leading to total dose effects), may occur *displacement effects* (like neutrons). In the first part of this paper, we will review these radiation effects.
Even though electrostatic charging (we do not address this point in this paper) and radiation effects are the main concern, other aspects of the space environment have also to be taken into account. In the second part of this paper, we will address the *effects of the atomic oxygen* which can affect LEO satellites, the *effects of solar U.V*, as well as the *micrometeoroid effects* and finally the man made space *debris*.

## I Space radiation effects

### I.1 Space radiation environment: Van Allen belts, solar flares, solar wind, cosmic rays

The Earth and its immediate environment are protected by the atmosphere, which acts as a semi-permeable "screen", to let throughout light and heat, while stopping radiation and UVs. Because so such natural protection is available in space, human beings and electronics devices must be able to cope with the resulting set of constraints.
Our analysis is limited here to the main components of radiative phenomena encountered in space, by classifying them into four categories by origin: Radiation belts, solar flares, solar wind and cosmic rays. Though somewhat arbitrary (the four types of phenomena are interrelated), this breakdown is best suited to subsequent study of the resulting effects. Note that the particles of interest here are essentially electrons, protons and heavy ions of various origins, with differing energies. Electrons and protons are responsible for total dose; heavy ions and protons cause a number of specific effects that are grouped under the heading "SEE" (Single Event Effect).

*Radiation belts*
Radiation belts contain trapped electrons and protons. This trapped radiation includes two electron belts. The inner belt contains electrons whose energy is less than 5 MeV. The outer belt contains electrons whose energy may reach 7 MeV, furthermore in the case of outer belt, the electron flux is both more variable and more intense than that of the inner belt. A third belt of electrons was observed after a magnetic storm on March 24, 1991. This belt is located halfway between the first and second belts and its trapped electron energies are significant, reaching as much as 30 MeV.

Trapped radiation also includes an inner proton belt structure. A second such belt, containing high-energy protons (>100 MeV), appeared after the same magnetic storm mentioned above. A violent magnetic storm can therefore generate new radiation belts whose life expectancy, estimated at more than two years is not precisely known.

Like electrons and protons, heavy ions may also be trapped in the magnetosphere. An abnormal situation known as ACR or Anomalous Cosmic Ray has long been identified. In 1991, Grigorou postulated that ion with energies of less than 50 MeV per nucleon could be trapped. This result was confirmed in 1993 by measurements made by the SAMPEX satellite. Ion belts are primarily made up of light ions (He, C, N, O, Ne, etc.) with low energies. These ions are ionised once only, are very sensitive to solar modulation and exhibit low penetration. They have no impact on electronics, but contribute to the radiation exposure sustained by astronauts: their high biological efficiency factor has significant impact on equivalent dose.

*Solar flares*
The 11-year sunspot cycle can be roughly subdivided into four low activity years and seven of high activity, punctuated by ordinary events and those of an exceptional nature. There are two types of events to be considered in relation to the radiation environments being considered here. The first is represented by **coronal mass ejection's**, which last several days and emit mainly high-energy protons (up to several hundred MeV). The "Benchmark" here is the proton eruption that took place in August 1972. This single event provided 84 % of the solar protons with energies of more than 30 MeV that were inventoried at the time of the $20^{th}$ solar cycle. The second types of event fall under the transient or "Impulsive Events" category involving large emissions of heavy ions. These include **solar flares** with high-energy ion emissions (several tens of MeV to several hundred GeV per nucleon) that are often ionised only once and vary in composition from one event to another. The references here are the heavy ion flares of September 1977 and October 24, 1989.

*Solar wind*
The high temperature of the Sun corona (# 2 millions K) inputs sufficient energy to allow electrons to escape the

gravitational pull of the sun. The effect of the electron ejection's is a charge imbalance resulting in the ejection of protons and heavier ions from the corona. The ejected gas is so hot that the particles are homogenised into a dilute plasma. The energy density of the plasma exceeds that of its magnetic field so the solar magnetic field is "frozen" into the plasma. This electrically neutral plasma streams radially outward from the sun at a velocity of approximately 300 to 900 km/s with a temperature on the order of $10^4$ to $10^6$ K. The energies of the particles range from approximately 0,5 to 2 keV per nucleon. The average density of the solar wind is 1 to 30 particles / $cm^3$. The composition of solar wind is approximately : 95% $p^+$ ; 4% $He^{++}$ ; < 1% other heavy ions ; and the number of electron needed to make solar wind neutral.

Major perturbations in the geomagnetic field can occur with changes in the solar wind density (e.g. solar flares), the solar wind velocity (e.g. coronal mass ejection's), and the orientation of the embedded solar magnetic field. The coronal mass ejection's and solar flares cause disturbances of the solar wind, and it is the interaction between theses disturbances and the earth's magnetosphere that causes perturbations called magnetic storms and substorms. The correlation of the number of storm with the level of solar activity is very strong, and the major magnetic storms are closely associated with coronal mass ejection's. During the period of high solar activity, fluctuations in the sun's magnetic field are observed, and these fluctuations result in a compression of the earth's magnetic field lines (geomagnetic storms). When the compression of the earth's magnetic field lines occurs, plasma on the night side of the earth is pushed towards the earth surface. As this plasma pushes closer to the earth, the electrons and ions are deflected by the earth magnetic field and, as a result, spacecraft orbiting between local midnight and 6 a.m will see an abundance of energetic electrons. Consequently, during geomagnetic storms the greatest concern is for spacecraft operating between midnight and 6 a.m.

While at GEO the plasma is quite hot (# 2 keV for electrons and 10 keV from ions on the average) and with a low density (# 10 to 100 $cm^{-3}$) in normal condition, and hot (# 10 keV for electrons and 14 keV from ions on the average) but with a lower density (# 1 $cm^{-3}$) during magnetic storms, the plasma founded at LEO, is colder and incapable of inducing significant charging. However, because energetic particles may move along the magnetic field lines, spacecraft in low altitude polar orbits may encounter the more energetic plasma that is seen to originate at higher altitudes. In situ observations confirm that auroral electrons can be accelerated to several kilovolts, producing a plasma environment capable of more severe charging. This energetic plasma is confined to an annular region near the poles, in the region where the magnetic field lines enter the lower altitudes. Because a spacecraft will only pass through this region periodically during the course of its orbit, charging in the auroral regions is typically of very short duration. Severe charging is more likely when the ambient plasma density is lower because the presence of the low energy ambient plasma acts as a source of neutralising current.

*Solar wind: effects and mitigation*

Differences in the emission and absorption characteristics of materials, differences in sunlight exposure, and localised effects resulting in unequal electron populations produce voltage differences between insulated satellite surfaces (this phenomenon is called differential surface charging). Furthermore, electrons having sufficient energy to pass through the thermal blanket result in internal charging of surfaces and assemblies. Typical insulated objects include cable jackets, ungrounded thermal wrap, thermal paint, component encapsulants, etc. Higher energy electrons penetrating subsystem chassis assemblies may deposit charge onto circuit board and wire insulators, connectors, capacitors, etc. In this process, termed deep dielectric charging, high-energy electrons penetrate circuit elements and devices, leading to trapped charge build-up within the dielectric material.

Mitigation's included the use of filters to prevent the propagation of discharge event created signal transients, the use of surface coatings (paint, etc.) and materials which provide dissipation of deposited charge. Shielding of electronic assemblies to reduce the flux of high-energy electrons impinging on sensitive devices and materials is also recommended to address charging effects.

*Cosmic rays*

Cosmic rays are highly energetic heavy ion nuclei (without the surrounding neutron cloud). In actual fact, these heavy ions only represent 1 % of the nucleonic component of cosmic radiation, which otherwise contains 83% protons, 13% helium nuclei and 3% electrons. The origin of this radiation has not been truly identified; however, we know that part of it (i.e. the most energetic ions) comes from outside the Milky Way Galaxy and the rest from inside it. Ion energies are very high (the most energetic ion ever detected had an energy of $3.10^{20}$ eV, i.e. nearly 50 J !) and the corresponding acceleration mechanisms are not always well understood. Cosmic radiation is nearly isotropic when it arrives in the vicinity of the magnetosphere. However, because the radiation couples to the Earth's magnetic field, its isotropy is not preserved. While its composition is nearly identical to that of matter found in the local galaxy, it does seem to be affected by interaction with interstellar matter. At energies of less than 1 GeV per nucleon, particle flux depends on solar activity.

### I.2 Dose effects: origins, effects on electronic devices, order of magnitude

The total doses sustained in space environments are almost exclusively attributable to trapped particles contained in radiation belts and to protons emitted by solar flares.

*Total Ionising Dose Evaluation*

To evaluate the Total Ionising Dose (TID) on a component, one have to use the "dose profile curve" that indicates the dose received through a shield of varying thickness (most often a hollow aluminium sphere). This curve is often used as a specification, since it depends only on the mission of interest. Then, according to the exact location of the component considered in the satellite, and the various shields that protect it from space (satellite insulation, printed circuit card, housing component, etc.) the TID is computed. One can use for that two methods. The first is an analytical method based on "sectoral analysis", i.e. weighting of the dose profile curve. The second makes use of a Monte-Carlo approach.

*Influence of the orbit*

At Low Earth Orbits (the altitude of LEO satellite is in the range of 300-5000 km), the average space distribution of particles is inhomogeneous: the outer electron radiation belt is close to the Earth at high latitudes (polar horns) and the region centred on the south Atlantic has a high level of trapped particles (electrons and protons). This means that:

- A satellite placed in very low equatorial orbit (300 km) sustains little radiation,
- A satellite in low orbit at an inclination of less than 45° is subjected to the SAA,
- A satellite in low polar orbit at an inclination greater than 55° (e.g. heliosynchronous satellite) is subjected both to the SAA and to the impact of the polar horns,
- A satellite placed at altitude over 1400 km (e.g. constellation satellite) is heavily impacted by dose effects. The proton belt makes a further contribution that sometimes leads to a total dose greater than that received in geostationary orbit.

At GEostationary Orbit (GEO at 36000 km of altitude) and Medium Earth Orbit (the altitude of MEO satellite is in the range of 5000-36000 km) the main source of dose radiation is due to the outer electron belt. As an example, for a 18 years GEO, TID is 100 krad behind 5 mm of aluminium, and 10 krad behind 10 mm. In this kind of orbit it is possible to use some local shielding, like shielded box, because the efficiency of shielding with respect to electron is quite good. (As a comparison a TID received by a satellite placed at 2000 km of altitude is, for 5 years and behind 10 mm aluminium shielding, in the range of 300 krad)

*Dose effects: order of magnitude*

The TID that electronic devices can withstand depends on the technology. Standard CMOS COTS is in the range of 1 to 10's of krad, while CMOS rad hard devices are in the range of 100 krad to 1 Mrad. Standard bipolar is better than standard CMOS and can withstand a TID in the range of 10's to 100 krad. AsGa is intrinsically TID hardened and can withstand a TID of 1 Mrad or even more. But one have to be very careful on these orders of magnitude, because there are a lot of dependence factors on TID effects, like: 1) Dose rate (there is a low dose rate enhancing for bipolar technologies contrary to high dose rate enhancing for MOS technologies); 2) Bias during and after irradiation; 3) Time after irradiation (annealing or rebound) ; 4) Lot to lot dependence ; and so on.

**I.3 Displacement effects: origin, effects on electronic devices, order of magnitude**

Low earth orbits higher than 1400 km are also impacted by the effects of atomic displacement due to trapped proton. This effect, which is a familiar in military situations (due to neutrons) was, up until now, more or less neglected in space applications. Because new orbits are increasingly located in the proton belt, the space industry has now to take into account proton-induced displacements and their inclusion in radiation analysis. The displacement effect is quantitatively measured by its Non Ionising Energy Loss (or NIEL) per opposition to ionising loss measured by the dose deposition (note that proton, which is both charged and massive particle, has the ability to induce both dose and displacement effect).

The order of magnitude of displacement effects are as follow: $10^{11}$ n(eq 1 MeV).cm$^{-2}$ for CCD & optolinks ; $10^{12}$ n(eq 1 MeV).cm$^{-2}$ for bipolar ; $10^{14}$ n(eq 1 MeV).cm$^{-2}$ for MOS ; and $10^{15}$ n(eq 1 MeV).cm$^{-2}$ for AsGa.

As an example the level of displacement damage is between $10^{12}$ n/cm$^2$ to $310^{12}$/cm$^2$ for a LEO orbit which altitude is comprised between 1400 km and 2000 km. This level is almost independent of the thickness of the shielding. So for this kind of orbit the problem of displacement effects has to be taken into account mostly for high analogic devices such as CCD or optolinks.

**I.4 Heavy ion effects: origin, effects on electronic devices, order of magnitude**

When a heavy ion pass through matter it goes straight a line. The more it is heavy, the more the ionisation along ii pass is important. In fact we measure the effect of heavy ions by its Linear Energy Transfer, that is the ionising energy it loss per unit length (roughly the LET increases with the Z of the ion). It is possible to compute the LET from various ions from various energy, by doing so, we have to notice that the maximum LET it is in the order of magnitude of 100 MeV cm$^2$ mg$^{-1}$. When an ion pass trough the active volume of an electronic device it deposes a charge along it's trace and this charge is collected per the electric field of the device. The associated "iono-current" can induced several effects such as :

- SEU (Single Event Upset) which is a transient effect, affecting mainly memories,
- SEL (Single Event Latch-up), which can destroy the component, affecting mainly CMOS structure
- SEB (Single Event Burnout), which has destructive impact; affecting mainly power MOSFET

- SEGR (Single Event Gate Rupture), which is also potentially destructive, affecting mainly submicronic structure,
- SHE (Single Hard Error), yet another destructive effect.

Two parameters are needed to quantify the vulnerability of an electronic device to heavy ion. The first one is the threshold LET, the second one is the cross section. If the LET is greater than a threshold, the energy deposition can triggered the effect. Furthermore the device offer a cross section which represents the probability for an ion to hit a sensitive volume of the component. The higher the cross section is, the more sensitive the device is. From technology point of view all kind of technology may be sensitive to SEE, but the larger the active volume the more sensitive the device. This is the reason why the bipolar technology is more sensitive than the MOS bulk, and the MOS bulk is more sensitive than the MOS SOI technology. Increasing use of electronics in onboard systems and enhanced circuit integration have revolutionised things to such an extent that, today, allowance for heavy ions is of vital importance in selecting components.

The environment itself is characterised by a LET spectra : that is to say the number of ion which LET is greater than a given LET. GEO orbit corresponds to the maximal constraint because it doesn't benefit of magnetosphere shielding. As the altitude of the orbit decreases, and as the inclination of the orbit decreases to, the magnetosphere shielding is more and more effective and the flux of cosmic rays decreases. Due to this shielding effect, one can have several orders of magnitude differences between orbit (e.g. GEO and low altitude, low inclination LEO)

### I.5 Proton Effects: Origin (direct & indirect), effects on electronic devices, order of magnitude.

The first observation of single event upset induced per proton was made 10 years ago, in 1990. As for heavy ion we can distinguish non destructive effects, like SEU, and destructive effects, like SEL or SEB. Furthermore we have to distinguish indirect effects, due to the interaction between incident proton and a nuclei of the component (spaliation reaction ), and direct effect due to ionisation induce per the proton inside a sensitive volume of the device.

Based on the critical energies currently encountered in electronic components, it is clear that direct upsets are only exceptionally produced by protons. By contrast, nuclear reaction of these particles with silicon is possible and can lead to recoil of the heavy residual nucleus (together with emission of lighter fragments) or to formation of two ions of similar masses, by fragmentation of the silicon nucleus. These "secondary" ions then cause the indirect SEE.

The three main sources of indirect heavy ion events are:

- Proton-emitting solar flares, for geostationary and low polar orbits,
- Trapped protons for medium orbits (MEOs),
- The SAA for low earth orbits.

As for heavy ions, the magnetosphere offers a natural screen against protons. Its degree of "screen effect" depends on the type of orbit and the date of the mission. This effect is weak for geostationary and highly inclined low orbits (polar areas) but very strong for low orbits with small inclinations. Moreover, proton flux, as heavy ion flux, is weakest during periods of maximum solar activity, since the concomitant increase in interplanetary magnetic fields accelerates scattering of ions before the latter reach the magnetosphere. Note that the relative significance of heavy ion-induced direct effects and indirect effects depends on the type of orbit and, for a given orbit, on the type of component considered.

## II Other effects

### II.1 Atomic oxygen: origin and effects

The Atomic oxygen is the main specie of the atmosphere from 200 km; the associated density is in the range of $10^9$ – $10^{10}$ atoms/cm$^3$ at 200 km, and in the range of $10^5$ atoms/cm$^3$ at 800 km. The density varies with solar activity (e.g. $10^4$ (minimum) to $10^8$ (maximum) atoms/cm$^3$ at 800 km). The oxidation power of atomic oxygen is enhanced by it relative velocity of 8 km/s and it's temperature (800 K equivalent to 5 eV energy).

The effects of atomic oxygen are various:

- Material erosion. The reaction efficiency depend on the material :
  - very low for Al or Au
  - high for Kapton (# 3 $10^{-24}$ cm$^3$ / atom) : 500 µm for ISSA for 30 years
  - very high for silver (# 10.5 $10^{-24}$ cm$^3$ / atom)
- Electrical interconnects oxidation
- Mirror reflectivity decrease
- Thermal parameters ($\alpha_s$ ; $\varepsilon$) evolution
- Luminescence

Mitigation provisions for atomic oxygen environment effects include the choice of altitude which reduces the exposure, choice of materials which are resistant to chemical degradation and exhibiting high sputtering threshold, the use of coatings to protect surfaces, orienting sensitive surfaces and devices away from the ram direction, and reducing aerodynamic drag by reducing the space vehicle cross section.

### II.2 Sun U.V: origin and effects

The Sun spectra is a black body with temperature of 5600 K. In absence of atmosphere there is no U.V filter (ozone layer filters $\lambda < 0.3$ µm) and so spacecraft has to withstands U.V ray. Due to high energy of U.V (e.g. 9.2 eV for 0.13 µm ; 3.2 eV for 0.39 µm) chemical bonds may be broken. As an example the energy needed to break some classical chemical link is list here:

- C≡C (0.14 µm) ; C≡N (0.13 µm) ; C≡O (0.16 µm)
- C=C (0.20 µm) ; C=N (0.19 µm) ; C=O (0.16 µm)

• C-C (0.36 µm) ; C-N (0.39 µm) ; C-O (0.33 µm)

The associated effects included:

- Fibber degradation
- Optical darkening (creation of "colour centres")
- Thermal parameters ($\alpha_s$ ; $\varepsilon$) evolution ($\Delta\alpha_s$ = 0.01 for many material during typical spacecraft lifetime)
- Weakening.

### II.3 Micrometeoroids: origin and effects

The origin of micrometeoroids is twofold 1) a continuous background (omnidirectional and sporadic) ; 2) a meteor shower (directional and periodic) like Perseid and Leonid meteor shower and many others. Typical characteristics of such a micrometeoroids are a mass in the range of $10^{-10}$ g to 1 g, a density comprised between 0.5 to 2 $g.cm^{-3}$ and a velocity in the range of 10 to 70 km/s (with an average of 17 km/s). The micrometeoroids effects included:

- Erosion of surface materials
- Changes in thermal control properties : $\Delta\alpha_s$ ; $\Delta\varepsilon$
- Contamination of sensitive surfaces
- Tank perforation hazard
- These effects are very dependant on diameter :

• 0.1 mm ⇒ erosion

• 1 mm ⇒ serious damage

• 3 mm particle moving at 10 km/s carries the kinetic energy of a bowling ball moving at 100 km/h

• 1 cm particle has a kinetic energy of a 180 kg safe

### II.4 Orbital debris: origin and effects

Due to their origin, orbital debris is present in the most often used orbits, and will impact spacecraft mainly in the ram direction, with velocities which are less than micrometeoroids. The orbit debris population is influenced by the solar cycle through increased aerodynamics drag effects.

- The source of orbital debris are mainly :

• Non operational spacecraft, boost vehicles, spacecraft explosion

•Break-ups, collisions

• Solid rocket fuel particulates, surface erosion particulates

The number of these orbital debris is continuously increasing:

• 30.000 to 100.000 pieces of debris > 1 cm

• 20.000 pieces of debris > 4 cm

• 7000 pieces of debris > 10 cm

Due to mass and velocity (0 to 16 km/s with an average of 11 km/s) the orbital debris has a significant effects as:

- Tank perforation hazard
- Changes in thermal control properties : $\Delta\alpha_s$ ; $\Delta\varepsilon$
- Contamination of sensitive surfaces
- Erosion of surface material

Mitigation provisions for the micrometeoroid and orbital debris threat is to choose altitude and inclination orbit architecture with minimal presence of orbit debris, locate critical devices and structures away from the ram direction, and the use of a layered "bumper" structure to protect critical elements.

### Reference

Concerning radiation effects there are two major conferences, both with short course and proceeding published by IEEE/NS. These conferences (NSREC = Nuclear and Space Radiation Conference, and RADECS = RADiation Effets sur les Composants et Systèmes), constitute an immense bibliographical data base. In addition some review books exist on this field :


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