Natural Radiation Environment Definition for Electronic System Design

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Abstract - The natural radiation environment must be defined when designing reliable electronics systems for spacecraft and aircraft. The environment will be described, focusing on new model developments and the use of models to generate mission requirements.

I. Introduction

The complex environment of Sun-Earth space consists of time varying ultraviolet, x-ray, plasma, and high energy particle environments. Variations depend on location in space and on the year in the solar cycle, both somewhat predictable. However, large variations that depend on events on the Sun are not predictable with reasonable certainty and are known only statistically based on past history.

The natural space environment and its solar induced variability pose a difficult challenge for designers of technological systems. The effects of environment interactions include degradation of materials, thermal changes, contamination, excitation, spacecraft glow, charging, communication and navigation errors and dropouts, radiation damage and induced background interference. This paper will focus on the radiation effects.

The accommodation of radiation induced effects is normally accomplished in the design phase of system development. However, the use of radiation soft commercial-off-the-shelf (COTS) components and enabling technologies means that it is difficult and costly to design systems that are completely free from radiation effects. Instead, a level of risk is assumed and minimized in the design phase and during operations. Unfortunately, current models of the radiation environment are not designed for risk analysis or space environment forecasting.

II. Radiation Environment

The natural space radiation environment can be classified into two populations, 1) the transient particles which include protons and heavier ions of all of the elements of the periodic table, and 2) the trapped particles which include protons, electrons, and heavier ions. The transient radiation consists of galactic cosmic ray (GCR) particles and particles from solar events (coronal mass ejections and flares). The solar eruptions periodically produce energetic protons, alpha particles, heavy ions, and electrons. Table 1 lists the orders of magnitude of the maximum energy of the radiation particles. The table shows that much of the environment is high energy, therefore, shielding is not effective for many types of radiation effects. All particles are isotropic and omnidirectional. More complete descriptions of the radiation environment can be found in References 1 and 2.

Table 1: Maximum Energies of Particles

Particle Type	**Maximum Energy***
Trapped Electrons	10s of MeV
Trapped Protons & Heavier Ions	100s of MeV
Solar Protons	100s of MeV
Solar Heavy Ions	GeV
Galactic Cosmic Rays	TeV

* For engineering applications

A. Transient Populations

Figure 1 is a plot of measurements of the abundances of the Carbon-Nitrogen-Oxygen (CNO) group of ions as a function of time. The slowly varying low levels of particles are the GCR population. The effect of the 11-year solar cycle is evident with the peak GCR populations occurring at solar minimum. Superimposed on the GCRs are the unpredictable, sudden rises in the flux levels due to solar storms. Both galactic and solar particles penetrate the Earth's magnetosphere and are particularly hazardous to polar, highly elliptical, and geostationary (GEO) satellites. Because the solar particles increase levels orders of magnitude over the background, there is increasing awareness of the need for a capability to forecast the occurrence of these events.

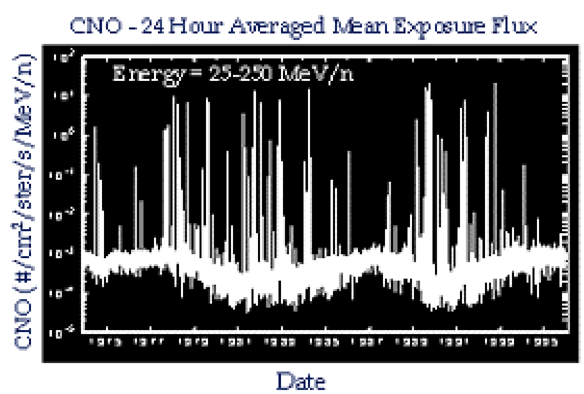

Figure 1: Measurement of CNO ions from 1974 to 1996

B. Trapped Populations

Figure 2 is a drawing of the trapped proton and electron regions around the Earth known for their discoverer, Van Allen. The E > 30 MeV proton fluxes peak at approximately 2,500 km at the equator. The electrons are trapped in two regions, the inner and outer zones. The E > 2 MeV electron fluxes peak at approximately 2,500 and 20,000 km at the equator. The particle levels and locations are highly dependent on particle energy, altitude, inclination, and the activity level of the sun. The displacement of the Earth's magnetic field from the center causes a dip in the field over the South Atlantic Ocean, resulting in a bulge in the underside of the inner belt. This region (~300 to 1200 km) is called the South Atlantic Anomaly (SAA). In spite of the SAA's reputation for plaguing spacecraft, the flux levels there are actually much lower than in the heart of the belts.

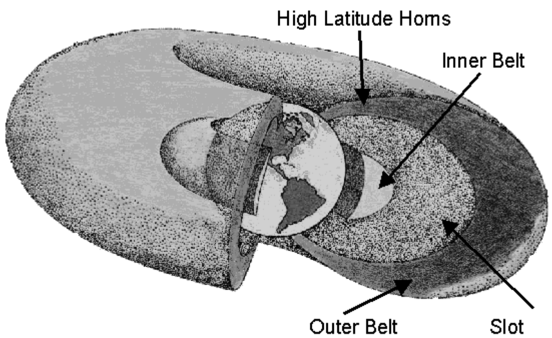

Figure 2: Drawing of the trapped particle populations

The trapped particle population is highly dynamic, especially in the slot region between the inner and outer zones and in the outer zone. Storms can induce sudden variations that are several orders of magnitude higher than the average populations. Figure 3 is a plot of measurements of trapped electrons which shows the extremely dynamic outer zone (L > 2.8) and the slot region (2 < L < 3) filling with storm electrons. Due to their complex distribution and dependence on long- and short-term solar variability, the trapped particle populations are difficult to model and forecast.

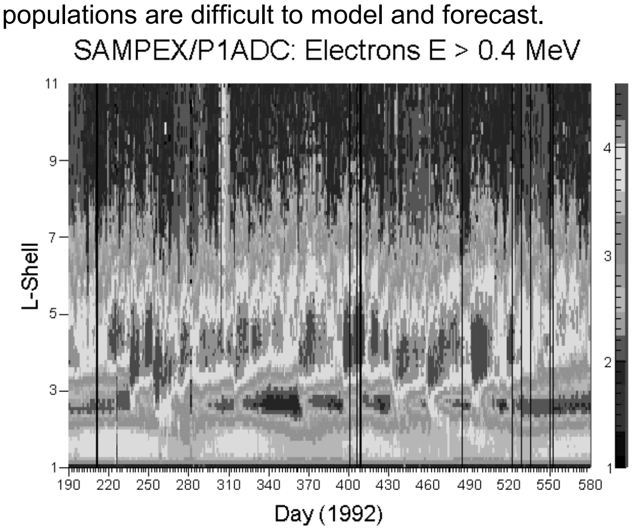

Figure 3: Measurement of trapped electrons which show the extremely dynamic outer zone at L > 2.8 and the slot region (2 < L < 3) filling with storm electrons

To avoid exposure to the trapped radiation environment, missions are planned for low earth orbits (below the belts) or for geostationary (outside of the highly energetic trapped proton and electron regions). To increase observation capabilities, there is growing interest in flying in middle earth orbit (MEO) regions. Due to the lack of experience in MEO, little information is available on the accuracy of radiation environment models in MEO.

III. Definition of Environments

Radiation effects that are important to consider for instrument and spacecraft design fall roughly into four categories: degradation from total ionizing dose (TID), degradation from non-ionizing energy loss (NIEL), single event effects (SEEs), and spacecraft charging/ discharging. Each effect requires a different environment definition depending on the physics of the effect and the interaction model used to predict the rate of occurrence.

A. Total Ionizing Dose

Total ionizing dose (TID) is cumulative long term damage caused by solar and trapped protons and trapped electrons. In microelectronics, TID causes threshold shifts, leakage current, and timing skews. The effect first appears as parametric degradation of the device and can ultimately result in functional failure. When a manufacturer advertises a part as "rad-hard", he is almost always referring to its TID characteristics. Rad-hard does not usually imply that the part is hard to non-ionizing dose or SEEs.

It is possible to reduce TID with shielding material that absorbs most electrons and lower energy protons. As shielding is increased, shielding effectiveness decreases because of the difficulty in slowing down the higher energy protons. TID levels are calculated from the solar and trapped particles incident on the spacecraft and are given as a function of dose versus aluminum shield thickness for a simple geometry. The geometry model generally used is the solid sphere, which gives an upper bound for the dose inside an actual spacecraft. This value is used as a top-level requirement. Figure 4 plots the total ionizing dose for several spacecraft orbits.

In cases where parts cannot meet the top-level design requirement and a "harder" part cannot be substituted, it is beneficial to employ more accurate methods of determining the dose exposure to qualify the parts. One such method is solid angle sectoring/3-dimensional ray tracing. An accurate computer model of the electronics box and/or spacecraft is produced and average path lengths through sectors are calculated. With that information, total doses can be obtained for any location. the value of dose mitigation measures can be accurately evaluated by changing the model and recalculating the total dose. Doses obtained by sectoring methods must be verified for 5-10% of the sensitive locations with full Monte Carlo simulations of particle trajectories through the structure for many histories.

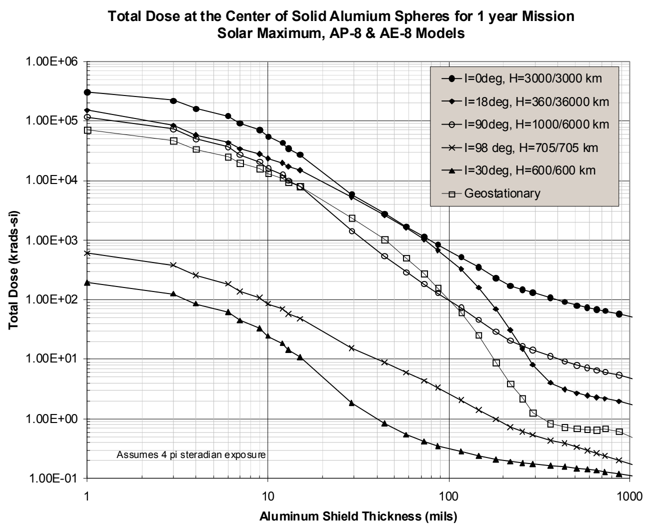

Figure 4: Total ionizing dose for near-earth orbiting spacecraft

B. Damage from Non-ionizing Energy Loss

Damage from non-ionizing energy loss (also known as displacement damage) is cumulative non-ionizing damage in optical materials caused by solar and trapped protons and trapped electrons. Secondary neutrons that are produced in shielding materials or the atmosphere or neutrons from external sources can also cause displacement damage. The particles produce defects that result in charge transfer degradation. It affects the performance of optocouplers (often a component in power devices), solar cells, CCDs, and linear bipolar devices. Shielding has limited effectiveness against the damage. Coverglasses over solar cells reduce damage by absorbing the low energy particles, but they cannot absorb the high energy protons. Shielding is not usually effective for optoelectronic components because the high-energy protons penetrate most realistic spacecraft electronic enclosures. CCDs are heavily shielded, however, secondary particle production can become problematic. Displacement damage effects are calculated from total particle fluence levels. The example in Figure 5 shows that adding shielding has little effect on the high energy trapped protons.

C. Single Event Effects

Single event effects are due to ionization when a single charged particle passes through a sensitive junction of an electronic device. They are caused by galactic cosmic ray and solar heavier ions, but for some devices, trapped and solar protons can induce SEEs. SEEs can be induced by direct ionization by protons, but in most instances, proton induced effects are the result of secondary particles that are produced when the proton collides with a nucleus of the material in the device. Some SEEs are non-destructive, as in the case of single event upsets (SEUs), single event transients (SETs), multiple bit errors (MBEs), single event hard errors (SHEs), single event transients (SETs), etc. SEEs can also be destructive as in the case of single event latchups (SELs), single event gate ruptures (SEGRs), and single event burnouts (SEBs). Figure 6 shows a plot of single event upsets on the SEASTAR flight data recorders. The upsets that occur in the poles are caused by transient particles. Because the recorder is also susceptible to proton-induced effects, the proton region of the SAA is clearly mapped out by the SEU occurrences.

The severity of the SEE can range from noisy data to loss of the mission. The severity is dependent on the type of SEE and the criticality of the system in which it occurs. Shielding is not an effective mitigator for SEEs because they are induced by very penetrating high energy particles. The preferred method for dealing with destructive failures is to use SEE-hard parts. When SEE-hard parts are not available, latchup protection circuitry is sometimes used in conjunction with failure mode analysis. For non-destructive SEEs, mitigation takes the form of error-detection and correction codes (EDACs), filtering circuitry, etc.

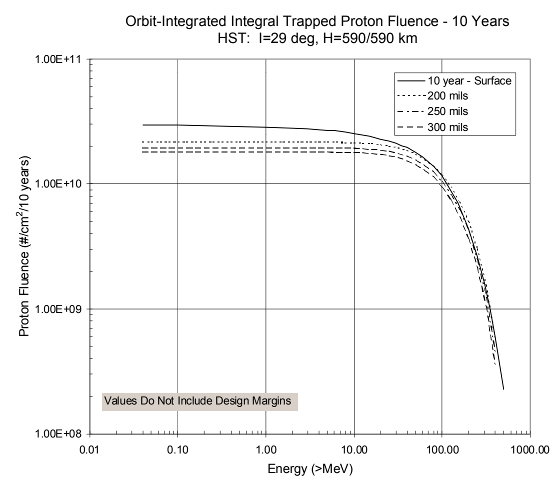

Figure 5: Surface incident and shielded trapped protons responsible for displacement damage

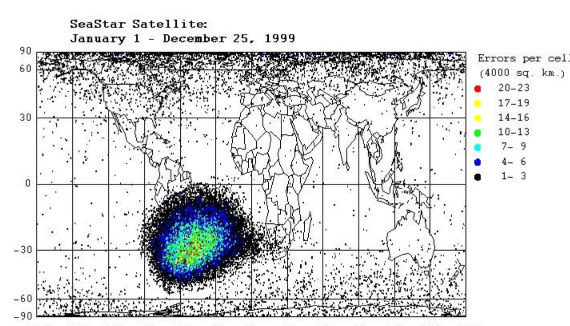

Figure 6: Single event upsets on a flight data recorder

The cosmic ray and solar heavy ion single event effects are evaluated using the linear energy transfer (LET) metric. LET is a measure of the energy deposited along the path of the particle. Figure 7 shows LET values at 1 AU (applicable to geostatioary orbits). Rather than LET, the proton energy spectra are more appropriate for the evaluation of proton induced events (see Figure 5).

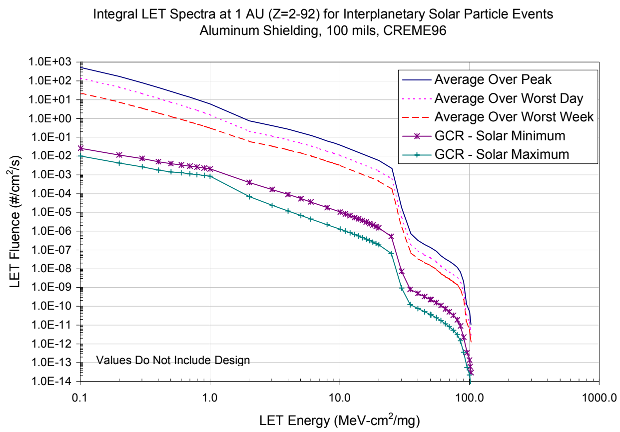

Figure 7: Integral LET spectra are shown for galactic cosmic ray and solar ions, hydrogen through uranium

IV. D. Spacecraft Charging and Discharging

Differentials in electron environments can contribute to spacecraft surface charging and discharging problems [3,4]. Sudden storms in the outer zone electrons produce "hot plasmas" that are responsible for spacecraft surface charging. Also, increases occur in higher energy electrons during storms. These penetrate to dielectric surfaces inside the spacecraft and build up to levels that cause discharges. Spacecraft in GEO and geostationary transfer orbits (GTO) are particularly vulnerable to these effects. Electron fluence levels in MEO are also high enough to cause charging problems. Electron accumulation profiles for a mission must be estimated and analyzed for possible surface and deep dielectric charging effects. A useful tool for evaluating charging environments is the NASCAP 2K model [5].

V. Development of New Environment Models

Reference 1 provides a discussion on the available models of the radiation environments. All of these models have shortcomings that impose problems for current spacecraft design and operations requirements. With the use of COTS and emerging technologies, it is not possible to design spacecraft systems that are completely hardened to radiation effects. As missions assume more risk, models that have better time resolution on long and short time-scales, are more accurate, and provide statistical variations in radiation levels are necessary. Efforts have begun to develop updated models. Solar proton models, including the new ESP [6], provide fluences and fluxes as a function of confidence level. A new trapped proton model [7] calculates inner zone proton levels as a function of a constant time variant over the 11-year solar cycle. This is an important improvement over the AP-8 model, which is averaged over entire solar cycle phases (minimum or maximum). A problem common to modeling efforts is the lack of very low and high energy measurements. In addition to models that specify the space environment, there is an increasing need to be able to forecast environments for spacecraft operations.

NASA's Living with a Star (LWS) Program has identified model deficiencies and is defining science missions along with a Theory and Modeling program that will construct the next generation of space environment models. The models will be based on physical understanding of the environment and will be targeted toward better specification of the environment for spacecraft design, nowcasting for rapid anomaly resolution, and forecasting for more reliable operations. The LWS Theory, Modeling, Data Analysis program issues yearly research announcements beginning in 2000. The LWS Program also includes a Space Environment Testbed Project that will perform research to understand environment interactions with COTS and emerging technologies.

VI. Conclusions

The changing spacecraft design environment requires new radiation environment models that are more representative of the actual environment. NASA's Space Environment and Effects Program (http://see.msfc.nasa.gov/see/dmia/models.html) and Living with a Star Program (http://lws.gsfc.nasa.gov/) are investing in model developments targeted for present and future requirements.

VII. References

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[4] A. R. Frederickson, "Upsets Related to Spacecraft Charging," IEEE Trans. on Nucl. Science, Vol. 43, No. 2, pp. 426-441, April 1996.

[5] Space Environments and Effects Program, NASCAP 2K, http://see.msfc.nasa.gov/see/dmia/models.html.

[6] M. A. Xapsos, J. L. Barth, E. G. Stassinopoulos, G. P. Summers, E.A. Burke, G. B. Gee, "Model for Prediction of Solar Proton Events", to be published in Proceedings of the 1999 Space Environment and Effects Workshop, Farnborough, UK.

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