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MODELING RADIATION LOADS TO DETECTORS IN A SNAP MISSION *

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Abstract

In order to investigate degradation of optical detectors of the Supernova Acceleration Project (SNAP) space mission due to irradiation, a three-dimensional model of the satellite has been developed. Realistic radiation environment at the satellite orbit, including both galactic and trapped in radiation belts cosmic rays, has been taken into account. The modeling has been performed with the MARS14 Monte Carlo code. In a current design, the main contribution to dose accumulated in the photo-detectors is shown to be due to trapped protons. A contribution of primary α-particles is estimated. Predicted performance degradation for the photo-detector for a 4-year space mission is 40% and can be reduced further by means of shielding optimization.

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Abstract – In order to investigate degradation of optical detectors of the Supernova Acceleration Project (SNAP) space mission due to irradiation, a three-dimensional model of the satellite has been developed. Realistic radiation environment at the satellite orbit, including both galactic and trapped in radiation belts cosmic rays, has been taken into account. The modeling has been performed with the MARS14 Monte Carlo code. In a current design, the main contribution to dose accumulated in the photo-detectors is shown to be due to trapped protons. A contribution of primary α-particles is estimated. Predicted performance degradation for the photo-detector for a 4-year space mission is 40% and can be reduced further by means of shielding optimization.

INTRODUCTION

The purpose of the Supernova Acceleration Project (SNAP) is probing dark energy by observations of Type Ia supernovae in a 4-year space-based mission(1). One of the serious technical issues is radiation load to the critical devices such as charge-coupled device (CCD) photo-detectors. Degradation of charge transfer efficiency (CTE) due to radiation damage is a major concern for such highly sensitive photo-detectors as CCD. To predict the CTE degradation, *non-ionizing* energy loss should be determined as a fraction of the energy deposited in the detectors(2,3).

In this paper, the performance degradation is determined for a three-dimensional model of the satellite and radiation environment averaged over the SNAP orbit. The considered cosmic radiation includes both galactic and trapped in radiation belts particles, mostly protons and electrons. Hadronic and electromagnetic showers induced in the apparatus by the cosmic radiation sources are simulated with the MARS14 code(4) in the energy range from 100 GeV/A down to 100 keV/A. The satellite is not considered to be orientation-stabilized and all the source terms are assumed to be isotropic. The CTE degradation is predicted using an approximate separation of energy deposited in the photo-detectors into the ionizing and *non-ionizing* energy loss. Numerical results of the Monte Carlo simulations are presented.

RADIATION ENVIRONMENT AT THE SNAP ORBIT

The orbit of the satellite (inclination 26.3 degrees, apogee 152830 km, perigee 10000 km) is taken into account by means of the codes CREME96(5) and SPENVIS(6). SPENVIS is used to represent electron component of Earth's radiation belts while CREME96 is used to describe galactic cosmic rays (GCR) and solar flares. The most significant limitation consists of the maximum apogee allowed in the code CREME96, namely 10^5 km. Therefore the contribution from GCR is calculated for a restricted orbit with apogee of 10^5 km and scaled to take into account the real orbit. All the spectra of incoming radiation are calculated taking into account geomagnetic shielding in the Earth's geomagnetic field.

The codes used allow us to divide cosmic radiation into four categories:

- Protons trapped in radiation belts.
- Electrons trapped in radiation belts.
- Primary protons and heavy ions.
- Primary electrons.

Calculated orbit-averaged energy spectra for these components are shown in Fig. 1. The contribution from primary electrons is taken from Ref. (7). One sees that trapped protons and electrons as well as primary protons and α-particles are the drivers and needed to be taken into account as source terms. All these components but α-particles are included in the simulations and results are presented below.

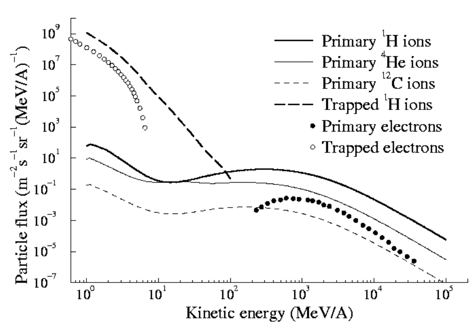

Figure 1. Orbit-averaged particle spectra at solar minimum.

Regular variations in solar activity during a so-called "11-year cycle" give rise to variations in integral particle fluxes of GCR within a factor of two. At solar flares the number of protons emitted from Sun can increase significantly thus disturbing Earth's magnetosphere. It gives rise to variations in orbit-averaged fluxes for both trapped particles and GCR. The GCR spectra for the largest solar flare ever observed (October 20, 1989) are described in the CREME96 database[5]. For a more realistic estimate of absorbed dose, ordinary solar flares of lower magnitudes should be included.

GEOMETRY AND MARS MODELING

In order to simplify the model, a judgment was made regarding which parts of the SNAP satellite would be most significant in terms of interacting with incoming cosmic radiation. Information about the SNAP conceptual design was taken from Ref. (8). The material through which a particle from the sun-side would pass would most likely consist of, at minimum:

- Multi-layer insulation (MLI) consisting of 30 layers of about 6-micron thick mylar, at a density of 15 layers per cm. The MLI also includes a very low-density spacer (polyimide) between layers of mylar.
- The optical bench, consisting of layers of 2-mm thick carbon-fiber "tooling plates".
- The conical shield, material and thickness to be optimized within mass, space, structural and thermal constraints.

A few things are added to the above items in front, depending on the angle of approach:

- The spacecraft deck (if the angle is from below) consisting of two layers of carbon-fiber composite 1-mm thick each and a 51-mm thick layer of aluminum foils.
- If the angle is from above, one has the following sequence: MLI, baffles (which are 1-mm thick aluminum), main mirror, optical bench box, and shield.

From the side opposite the Sun the situation is quite different: the thermal radiator is the main piece of material and appears to be essentially the only material. The present thermal radiator concept is 1.25-cm thick aluminum.

A geometry model used in the simulations is shown in Figures 2 and 3. The satellite axis is along the z-axis. The three-layer deck and optical bench box are modeled according to the description given above. The conical shield is represented by an aluminum cone 2-cm thick. The cold plate is described as a molybdenum hexagon 2.5 cm in thickness. The opening in the optical bench box for incoming optical radiation is modeled as a circular (R=30 cm) hole in the box (in xz-plane) with a center at y=-63 cm and z=75 cm (see Fig. 2). The array of CCD photo-detectors is modeled as a 200-micron thick silicon disk placed on a substrate (see Fig. 3).

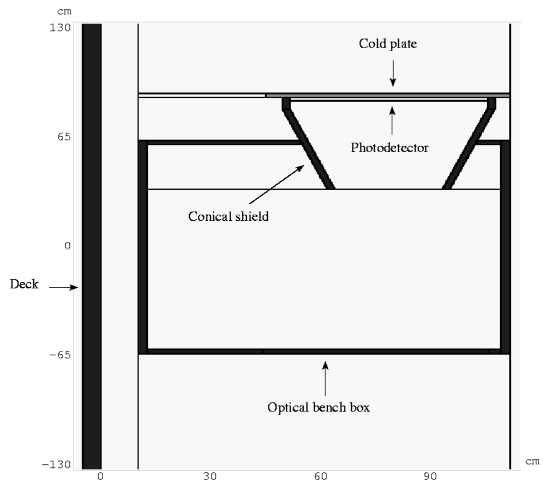

Figure 2. A fragment of the SNAP satellite MARS model (y-axis is up and z-axis is to the right).

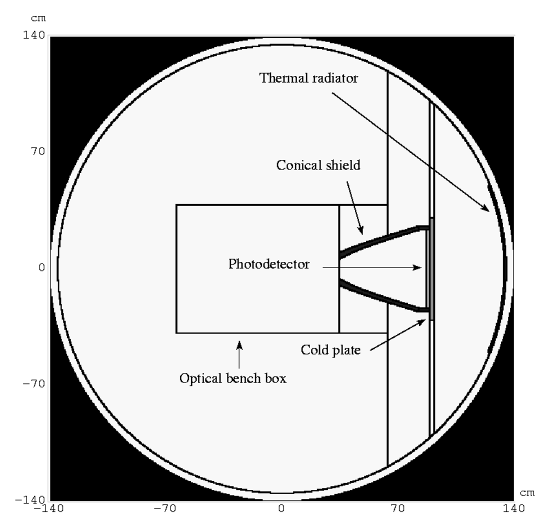

Figure 3. A fragment of the SNAP satellite MARS model (x-axis is up and y-axis is to the right).

PARTICLE FLUXES AND DOSE IN CCD

Distributions of particle fluxes over the system were calculated for all the considered source terms. The distribution of galactic protons is almost isotropic and reproduces the well-known level[9] of about 4 $cm^{-2}s^{-1}$. Secondary neutrons are generated mostly in the cold plate, thermal radiator, and spacecraft deck by galactic protons. Neutron generation by low-energy protons, trapped in the radiation belts, is significantly lower than that due to galactic protons and occurs mostly in the thermal radiator and deck. Figure 4 shows that the thermal radiator serves as an absorber of the low-energy trapped protons. Hadron fluxes in the vicinity of the CCD due to trapped and galactic protons are noticeably different - approximately 10^3 and 10 $cm^{-2}s^{-1}$, respectively. The dose absorbed in the CCD during the worst day due to the largest solar flare equals to 0.04 Gy, *i.e.* about 50% of the yearly dose due to primary protons at solar minimum (see Table I).

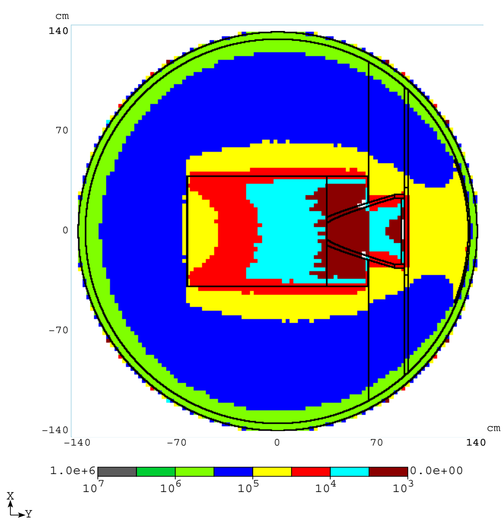

Figure 4. Hadron flux isocontours ($cm^{-2}s^{-1}$) in the model (xy-view) due to trapped protons.

VERIFICATION

The CREME96 code[5] includes, in particular, routines for estimation of radiation attenuation by a shielding layer and absorbed dose in a silicon target. One of the routines, TRANS, keeps track of nuclear fragments produced by cosmic-ray projectiles. It does not track, however, low-energy and short-range fragments produced from target nuclei in shielding material itself. The results can be used for comparison with the detailed MARS calculations. Using the CREME96 built-in routines, an absorbed dose was estimated in a silicon target shielded with a 3-cm aluminum layer. The yearly dose in such a target due to primary protons equals to 0.047 Gy according to CREME96 and should be compared to the value of 0.08 Gy in Table I. Taking into account all the differences between the two models – simplified shielding in CREME96, different sensitive elements and different physical models employed for particle interactions and transport in the two codes – we conclude that the agreement is quite reasonable. The primary α-particles increase the yearly dose by about 40% resulting in total dose in CCD, induced by primary radiation, of 0.11 Gy. Taking α-particles into account is mandatory for orbits and models where/when the contribution from primary cosmic rays dominates.

Table I. Yearly absorbed dose (Gy) in CCD.

Radiation source	Absorbed dose
Primary protons	0.08
Primary electrons	0.003
Primary α-particles	0.03
Trapped protons	207
Trapped electrons	78
Total	285

ESTIMATE OF CHARGE TRANSFER EFFICIENCY DEGRADATION

Degradation of charge transfer efficiency due to radiation damage is a major concern for such highly sensitive photodetectors as CCD. Table II gives predicted CTE degradation based on an approximate separation of energy deposited in the detector into the ionizing and *non-ionizing* energy loss (NIEL). It is NIEL that gives rise to atomic displacements and generation of effective charge traps responsible for the CTE degradation. For the estimate, the fact was used that 1 rad is approximately equivalent to 10^{-5} *non-ionizing* Gy for proton radiation in such an environment[2,3].

Table II. Predicted performance degradation (%) of a CCD photo-detector with 1024×1024 pixels for a 4-year mission. The optimistic and pessimistic estimates refer to ΔCTE equal to 9.6×10^{-14} and 2.5×10^{-13} g/MeV, respectively. The degradation is defined by the expression $1 - CTE^{1024}$.

Radiation source	Optimistic estimate	Pessimistic estimate
Trapped protons	40	73

For neutrons NIEL is less than that for protons at the same energy in the region from 100 keV up to 10 GeV while for electrons NIEL is less than that for neutrons, at least, by a factor of ten(10). Taking all that into account and using the data from Table I, one obtains the yearly non-ionizing absorbed dose in the CCD of about 0.21 *non-ionizing* Gy (only major radiation contribution due to trapped protons is considered). Finally, the degradation rates specific to the two best devices developed at LBNL were used: standard high-resistivity devices and notch high-resistivity devices with ΔCTE equal to 2.5×10^{-13} and 9.6×10^{-14} g/MeV, respectively(11). Devices with higher degradation rates were not considered in the paper.

CONCLUSIONS

The performed analysis enables us to get the first estimate of radiation load to the SNAP CCD and performance degradation in a three-dimensional model for the realistic radiation environment at the orbit. The contribution to the dose accumulated in the CCD detectors due to trapped protons can be reduced by means of further optimization.

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