Master in Photonics

MASTER THESIS WORK

RADIATION ENVIRONMENT OVER THE WFM DETECTOR IN LOFT's ESA MISSION

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Radiation environment over the WFM detector in LOFT’s ESA space mission

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abstract. The analysis of the radiation environment to which a space mission is exposed is of great importance given the negative effects that radiation could cause in different scientific instruments. In this work we carried out a detailed analysis of the radiation environment to which one of the instruments aboard The Large Observatory For X-ray Timing (LOFT), selected by ESA as one of the four Cosmic Vision candidate for a "Medium-class Mission" launch opportunity, with a foreseen launch date in either 2022 or 2024, is exposed. We first generated the satellite’s orbit and identified the main radiation contributor. Then, we determined the integral and differential average spectrum of trapped protons and electrons over the orbit according to the AP-8 and AE-8 models. The WFM (Wide Field Monitor) has several cameras, each one consisting of a coded mask, a pyramidal collimator and a detector tray. The geometry of a camera was simulated and finally we used the Monte Carlo simulation Geant4 Radiation Analysis for Space, based in GEANT4, and we calculated some important parameters such as: total (cumulative) fluence, total ionizing dose, no ionizing energy loss, which can be useful in order to estimate the risk and effects over the instrumentation. In order to carried out all the calculations, we used the SPENVIS/GRAS web interface.

Keywords GRAS, GEANT4, LOFT, radiation environment, ionizing radiation.

1. Introduction

Given the recent emergence of launches of space missions new engineering challenges have been generated. It is vital to take into account all the variables that may affect the spacecraft’s performance and its stability as well as the performance of its detectors and instrumentation. One of the major threats is that generated by radiation. Its presence was found during the early years of the twentieth century, a few years before the advent of the first manned missions. The Earth’s radiation belts were discovered by Van Allen in 1958.

The importance of assessing the space environment prior to construction of space systems has shown to be of critical value highlighted by failed missions due to complications arising from effects connected to the space environment [1], [2]. The
assessments of the impact of radiation to spacecraft involves many steps, including the
specification of the radiation environment, the transport of the radiation through the
spacecraft up to the sensitive devices, and the assessment of the effects of the local
environment to the devices.

In this work we mainly pretend to analyze the radiation environment and determine
some parameters related to the impact and risks on radiation devices. We will apply
this analysis to an specific instrument, the Wide Field Monitor which will be part of the
Large Observatory for X - Ray Timing mission.

Firstly will be necessary to establish the satellite’s orbit since this data is critical to
describe the possible sources of radiation, then we proceed to determine the more
predominant radiation environment, we will design using a computational simulation
the geometry of the detector and finally we will find parameters such as: fluence, total
ionizing dose and non ionizing energy loss.

The above calculations will be made using a web interface which uses sophisticated
Monte Carlo codes to find the desired results.

2. The Radiation Environment

The radiation environment close to Earth consists of three main components: trapped
particles, galactic cosmic rays and solar particle events. None of the components are
constant in time, mainly due to variations in the activity of the Sun. Solar activity
influences the Earth’s magnetosphere, which in turn determines the extent of the
trapped particle radiation belts [3].

2.1. Trapped Particle Belts

Interaction of the solar wind flow with the Earth’s magnetic field gives rise to a cavity
in the interplanetary medium known as the Earth’s magnetosphere. Within this cavity
there exists a limited region where the motion of energetic particles is confined by the
earth’s magnetic field. This region comprises the Earth’s radiation belts.

2.1.1. The trapped proton population  The energetic, above 10 MeV, trapped proton
population is confined to altitudes below $2.0 \times 10^3$ km, while lower energy protons
cover a wider region, with protons below 1.0 MeV reaching geosynchronous altitudes.
The region of space covered by higher energy protons diminishes with increasing energies
and the location of the highest intensities moves inward [5].

2.1.2. The trapped electron population  The population distribution is characterized by
two zones of high intensities, below altitudes of one Earth radius and above two Earth
radii in the magnetic equatorial plane, respectively, which are separated by a region of
low intensities, called the slot region. The location and extent of the inner and outer
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belts and of the slot region depends on electron energy, with higher energy electrons confined more to the inner belt, and lower energy electrons populating the outer belt to altitudes beyond geosynchronous orbit. Note that at high latitudes the outer electron belt reaches down to very low altitudes.

The general description of the radiation belts above represents what could be called the average particle distributions based on the static NASA models AP-8 and AE-8 [6].

2.1.3. South Atlantic Anomaly

The separation of the dipole center from the Earth’s center and the inclination of the magnetic axis with respect to the rotation axis produce a local depression in the low altitude magnetic field distribution at constant altitude. As the trapped particle population is tied to the magnetic field, the lowest altitude radiation environment, below about 1.000 km, peaks in the region where the magnetic field is depressed. This region is located to the south east of Brazil, and is called the South Atlantic Anomaly (SAA). Proton fluxes are negligible outside the SAA, but electron fluxes can be very high at high latitudes where field lines from the outer electron belt reach down to low altitudes [7].

2.2. Space Environment, Effects and Education System

The ESA SPace ENVironment Information System (SPENVIS), is a www - based tool intended to facilitate the use of models of the spatial environment. The interface includes parameter input with extensive defaulting, definition of user environments, streamlined production of results, background information, and on-line help. SPENVIS has been operational for about three years, with a continuously expanding user community and set of functions. SPENVIS is designed to help spacecraft engineers perform rapid analyses of environmental problems and, with extensive documentation and tutorial information, allows engineers with relatively little familiarity with the models to produce reliable results. SPENVIS was created by the European Space Agency with the collaboration of NASA and other scientific institutions interested in the study of the radiation environment in space, also is freely available upon registration [8], [9].

SPENVIS will be used in this work in order to carry out different simulations since this tool has many kind of procedures for analyzing the radiation environment over a satellite in a determined orbit, also it has a number of tools based on Monte Carlo codes using GEANT4 which is a toolkit for the simulation of the passage of particles through matter.

2.2.1. Geant 4 Radiation Analysis for Space

There is a Monte Carlo code responsible for analyzing the radiation in space called Geant4 Radiation Analysis for Space, GRAS. To access the analysis that allows GRAS, we first need to define a set of parameters (inputs) without which is not possible run the code. The order in which entries must be set as follows: definition of the orbit, trapped particle radiation models, source particles,
source geometry, physics models and the geometry of the detector. GRAS is a Geant4-based tool that provides a general space radiation analysis for 3D geometry models. More specifically, GRAS allows the definition of a multi-volume 3D geometry and incident particle source. Then, using the Geant4 toolkit it simulates radiation transport through the geometry, treating electromagnetic and nuclear interactions [11].

3. LOFT mission

The Large Observatory For X-ray Timing, LOFT, is a medium-class mission selected for the assessment phase of the ESA M3 Cosmic Vision call, intended to answer fundamental questions about the motion of matter orbiting close to the event horizon of a black hole, and the state of matter in neutron stars. LOFT was recently selected by ESA as one of the four space missions concepts of the Cosmic Vision program that will compete for a launch opportunity at the start of the 2020s [12]. The Institute for Space Studies of Catalonia is heavily involved in the feasibility study.

It is important to analyze the radiation environment which will affect the satellite during its mission. To do this, we must define the necessary parameters that will finally run GRAS. We will study one of the mission instruments called Wide Field Monitor, WFM [13].

3.1. LOFT’s Orbit

The satellite will operate in a low equatorial Earth orbit (≈600 km, 5.00° inclination) in order to reduce the background and the radiation damage effect of South Atlantic Anomaly, the duration of the mission will be 4 years. We need to first establish the characteristics of the orbit to perform all subsequent calculations. In a LEO orbit, as is the case, the main radiation environment will be trapped particles in the radiation belts.

3.2. Averaged spectra of trapped electrons/protons along the orbit

From the data set for the orbital parameters is possible to determine using both AP-8 and AE-8 radiation models, the averaged spectra of trapped electrons and protons along the orbit, obtaining the results shown in figure 3.

The graphs indicate the integral and differential flux. The integral flux represents the number of particles of given energy present along the orbit per unit area and unit time, while differential flux, is the number of particles per unit area, unit time and unit energy. This information is very important to then calculate the amount of the particles that reach the detector.

For protons, AP-8 model considers energies between 0.1 to 400 MeV, for the case of electrons AE-8 model considers a range between 0.04 to 7 MeV.
3.2.1. The Geometry of WFM LOFT’s Detector: The LOFT baseline WFM is a coded aperture imaging experiment. Coded mask instruments work by having two parallel plates, one a sensitive detector and the other a coded mask with a given pattern (distribution of opaque and transparent zones). The mask is made of dense, high Z material to completely stop incoming photons, with open slits which leave the photons pass through. A known pattern is thus projected onto the sensitive plate, and by comparing this with the detected pattern a source angle can be found. In addition there is a collimator made of 4 walls, which closes the camera.

The mask shadow recorded by the position-sensitive detector can be deconvolved by using the proper procedures and recover the image of the sky, with an angular resolution given by the ratio between the mask element and the mask-detector distance. The sensitive detectors in the WFM are silicon drift detectors [14]. In the case of our simulation, the 2D 150$\mu$m thick, square coded mask of tungsten of total dimensions of 300 x 300 mm$^2$, is composed by identical elements of dimensions 16 mm x 2 mm, and has an open fraction of 0.75 (although the real open fraction will be 0.25), the coded mask will be placed at 200 mm above the 200 mm x 200 mm silicon detector plane which has a thickness of 450 $\mu$m, below the silicon detector we placed an 1.5 mm aluminum plate as a shielding. The geometry was designed using the Geometry Description Markup Language (GDML) and is exhibit in figure 2.
4. Results

Last data concerning to the orbit, the flux of particles along the orbit and the geometry of the detector, are the main elements required by the GRAS Monte Carlo code in order to determine some analysis parameters. Besides this it is necessary to determine a number of particles for the simulation* which for this case was equal to a million particles.

Finally it is necessary to define the geometry of the source, which must contain the entire detector and for the proposed case we consider a sphere centered at the Si detector which is the object to be analysed.

Once generated the environment or the necessary entries, we proceeded to run the program in order to compute the number of particles that reach the detector, the deposited energy (total ionizing dose) and the NIEL parameter (non ionizing energy loss).

4.1. Fluence

The first important parameter to obtain is the amount of particles per unit area reaching the detector. The fluence, it means, the integral flux integrated over time (duration of the mission) give us this information. The proton fluence spectrum with initial kinetic energies between 0 to 400 MeV is shown in figure 3a and the electron fluence spectrum with initial kinetic energies between 0 to 7 MeV is shown in figure 3b. The energy ranges were fit according to the established by the models used to determine the radiation

* The number of the primary particles to simulate is a parameter of the simulation and has no physical meaning. This number will define the accuracy of your Monte Carlo simulation. The higher this number is the smaller the statistical errors are.
source. It is clear from the above analysis that the total fluence is the sum of all values in the different energy ranges. Table 1 shows the total cumulative fluence of protons and electrons.

**Table 1.** Total fluence at the selected silicon detector.

<table>
<thead>
<tr>
<th>Type of Particle</th>
<th>Fluence (particles/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>((7.0 \pm 0.2) \times 10^7)</td>
</tr>
<tr>
<td>Electrons</td>
<td>((2.9 \pm 0.1) \times 10^8)</td>
</tr>
</tbody>
</table>

### 4.2. Total Ionizing Dose

Ionization is the process of adding or removing electrons (or other charged particles) from atoms. The creation of electron-holes pair in the material cause long term effects in the oxide (charge trapping). An important consequence of the ionization is the alteration of the electronic devices.

Total ionizing dose is defined as the amount of energy deposited by ionization or excitation in a material per unit mass of the material. The *Gray* is the SI unit for absorbed dose. If the MeV units are used, GRAS provides as output the deposited energy in the specific volume. Figure 4a and 4b show the amount of deposited energy by protons and electrons with initial kinetic energies in the range considered. Table 2 shows the total dose, it means, the total deposited energy by both trapped protons and electrons.
Figure 4. Deposited energy as a function of the primary kinetic energy. Left: Deposited Energy by protons. Right: Deposited Energy by electrons.

Table 2. Total Ionizing Dose in Silicon Detector.

<table>
<thead>
<tr>
<th>Type of Particle</th>
<th>Dose (deposited energy) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>$(1.55 \pm 0.07) \times 10^8$</td>
</tr>
<tr>
<td>Electrons</td>
<td>$(6.7 \pm 0.4) \times 10^7$</td>
</tr>
</tbody>
</table>

4.3. Non Ionizing Energy Loss

Non Ionizing Energy Loss, (NIEL), is defined as the part of the energy, lost per unit length by a particle moving in the material, through Coulomb (elastic), nuclear elastic, and nuclear inelastic interactions thereby producing the initial displacement damage and excited phonons. This displacement damage creates defect energy levels in semiconductors that can act as trapping and recombination centers.

NIEL is a quantity that describes the rate of energy loss due to atomic displacements as a particle traverses a material, this parameter plays the same role to the displacement damage energy deposition as the stopping power to the total ionizing dose. This concept has been very useful for correlating particle induced displacement damage effects in semiconductor and optical devices. Many studies have successfully demonstrated that the degradation of semiconductor devices or optical sensors in a radiation field can be linearly correlated to the displacement damage energy, and subsequently to the NIEL deposited in the semiconductor devices or optical sensors [15]. If we know that the NIEL for one proton is $6.9 \times 10^{-3}$ MeV cm$^2$/g, then we can calculate the total NIEL, multiplying by the total cumulative fluence. In Table 3 is shown the NIEL factor in units MeV/g for the case of protons.
### Table 3. Non Ionizing Energy Loss.

<table>
<thead>
<tr>
<th>Type of Particle</th>
<th>NIEL (MeV cm$^2$/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>$(4.8 \pm 0.1) \times 10^6$</td>
</tr>
</tbody>
</table>

#### 4.3.1. Displacement damage energy deposition

The product of the NIEL and the particle fluence gives the displacement damage energy deposition per unit mass of material. Displacement damage is the damage to the bulk structure of a semiconductor device caused by the impact of energetic neutrons and/or protons. This effect can be generated by trapped particles. The result of this irradiation is usually either device performance degradation or failure. Table 4 presents the result of the displacement damage induced by protons.

### Table 4. Displacement damage.

<table>
<thead>
<tr>
<th>Type of Particle</th>
<th>Displacement Damage (MeV/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>$(3.4 \pm 0.1) \times 10^{14}$</td>
</tr>
</tbody>
</table>

### 5. Conclusions

It is essential to conduct a study about the radiation environment to which a space mission will be exposed, in order to prevent some risks, potential threats and determine the background. Given the importance of this analysis, a Monte Carlo coded specialized in the space radiation analysis has been developed by the European Space Agency, which was used in all simulations carried out.

In order to carry out the study of the radiation environment over a particular instrument located within the satellite, it was necessary to perform a series of steps beginning with the generation of the satellite’s orbit, specification of the radiation source, trapped proton and electron fluxes in each point of the orbit, design of the geometry of the instrument. With the above data set, finally we proceeded to implement GRAS based in GEANT4 which is a tool designed to determine the passage of particles through various materials according to certain physical processes.

With the help of specialized software the geometry of WFM’s camera was simulated, whose silicon detector was the analysed interface.

We identified that trapped protons and electrons are the main contributor radiation for a satellite in a LEO orbit, taking the more significative values at points corresponding to the South Atlantic Anomaly.

Finally with the help of GRAS were calculated some parameters such that the particle fluence to the silicon detector, it means, the integral flux during the duration of the
mission, likewise we found the deposited energy in the detector and the NIEL parameter. All results can be useful at the time of final construction of the instrument and will serve as a starting point for future studies.

6. Acknowledgements

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7. Bibliography