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Study of the radiation environment of the Serpens-II satellite mission and the necessary protection of electronic components

Estudo do ambiente de radiação da missão Serpens-II e mitigações necessárias para proteção dos componentes eletrônicos

Renan Guilherme Soares Menezes[1], Devison Santos Silva[1], Leonardo Ghizoni[2], Sidney Luiz Alessi Carrara[1]

ABSTRACT

The space environment is very inhospitable; several factors must be considered when designing a satellite so that it can be operated with the desired lifetime and reliability levels. Satellites consist of different subsystems, mostly constituted by electronic components. The incidence of space radiation over such components can cause them to fail or degrade their performance over time. In this paper, we conduct studies to identify the need for shielding to reduce radiation incidence upon CubeSat components. The SPENVIS interface was used for particle flow simulations in the space environment to analyze the radiation deposited in the devices. The more detailed the geometry of the satellite model, the closer to reality will the estimated dose be. We concluded that computational simulations can be a useful tool for dimensioning the radiation tolerance of components in the design phase of a satellite.

Keywords: TID, COTS, CubeSat.

RESUMO

O ambiente espacial é muito inóspito e apresenta diversos fatores que devem ser levados em consideração no projeto de um satélite para operação com níveis de confiabilidade desejados. Satélites são constituídos por diferentes subsistemas, com inúmeros componentes eletrônicos. A incidência de radiação existente no espaço sobre tais componentes pode levá-los a falhar, ou a ter seu desempenho degradado. O objetivo do presente artigo é realizar estudos a fim de identificar a necessidade de blindagens para mitigar a incidência de radiação nos componentes de um *CubeSat*. Utilizamos a interface SPENVIS para simulações do fluxo de partículas no ambiente espacial, analisando a radiação depositada nos componentes. Quanto mais detalhada a geometria do satélite, mais próximos da realidade os resultados obtidos com relação à dose depositada nos componentes. Conclui-se que a simulação computacional pode ser utilizada como um princípio para o dimensionamento da tolerância à radiação de componentes na fase de projeto de um satélite.

Palavras-chave: TID, COTS, CubeSat.

[1]Faculdade de Tecnologia de São José dos Campos – FATEC Professor Jessen Vidal – São José dos Campos/SP – Brazil.
[2]GomSpace A/S – Aalborg – Denmark.
Correspondence author: Renan Guilherme Soares Menezes | Faculdade de Tecnologia de São José dos Campos – FATEC Professor Jessen Vidal | Av. Cesare Mansueto Giulio Lattes, 1350 | CEP 12.247-014 – São José dos Campos/SP – Brazil | E-mail: renan.g.s.meneses@hotmail.com
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INTRODUCTION

Satellites are used for innumerable purposes to make people's lives safer and more convenient. The most common types of satellites are communications, meteorology, Earth observation, navigation and scientific research. Satellites consist of different subsystems, mostly constituted by modules with many electronic devices and components. However, conditions in the space environment are much more severe than those here on Earth; space radiation is one of the main problems for these subsystems, causing logical errors and degradation of the integrated circuits and other electronic components of the satellites.

Therefore, when a satellite is designed, one must consider the mission it will perform, the orbit in which it will operate, and the mission duration, in order to estimate the amount of radiation its electronic circuits will be subject to along its usable life in orbit.

The reliability level of electronic circuits subject to radiation in space can be increased by choosing components with high radiation tolerance (specially fabricated and tested for this purpose) or by shielding to protect them from the radiation incidence. Both options add high costs to space systems: "space-class" electronic components can cost 100 to 1000 times the price of commercial off-the-shelf (COTS) components. Besides, shields add mass, considerably increasing the costs of launching the satellite into orbit.

Simulations of the space radiation environment and its interaction/flow through the several layers and materials of the spacecraft are possible once the mission orbit parameters and lifetime are defined. One useful tool for such study is SPENVIS (Space Environment Information System)[1], a web interface for models of the space environment and its effects, including cosmic rays, Van Allen belt radiation, energetic solar particles, plasma, gases and microparticles[1]. Modeling the satellite geometry allows an analysis of the type and amount of radiation that hits each component, considering its position in the system with respect to other pieces of equipment. One can then identify more or less vulnerable positions and design specific additional protections where necessary.

THE SPACE ENVIRONMENT AND ITS EFFECTS ON ELECTRONIC DEVICES

In the space environment near Earth, natural radiation can be considered as coming from three general sources: trapped radiation in the Van Allen belts, composed mainly of energetic protons and electrons; GCRs (Galactic Cosmic Rays), with energies of up to TeV, including all the ions in the periodic table; and solar radiation – a continuous flux of particles plus solar activity with periodic peaks and valleys every 11 years (called solar cycle) – composed of energetic protons, alpha particles, heavy ions and electrons. In a first approximation, all these populations of particles have omnidirectional and isotropic distribution, except those from solar events[2].

The effects of natural radiation on the space environment can be divided into two categories: long-term and short-term. Long-term effects have two distinct concerns: ionizing and non-ionizing damage. Concerns about short-term effects are primarily with ionization by a single particle or formation of secondary particles. It should be noted that even short-term effects can be permanent.

Alternatively, the effects of ionizing radiation on electronic circuits can be seen as two contributions: Total Ionizing Dose (TID) and Single Event Effects (SEE). The two effects are distinct, as are the mitigation requirements and techniques associated with them. The effect of TID is a long-term degradation due to the accumulated energy deposited in a material. Typical effects include parametric failures or variations in device parameters, such as leakage current, threshold voltage, or functional failures. Significant sources of TID exposure in the space environment include trapped electrons and protons, and solar protons. A SEE occurs when a single ion reaches the material, depositing high energy, either through a first shock or by a secondary particle resulting from the shock, causing some effect on the device. The many types of SEE can be divided into two main categories: soft errors and hard errors[3].

THE SERPENS PROGRAM

A program sponsored by the Brazilian Space Agency (AEB), with the participation of several universities, is called SERPENS (Space System for Research and Experiments with Nano Satellites – from the program name in Portuguese). Started in December 2013, the program aims to train Brazilian students, scholars, professors and researchers linked to Aerospace Engineering courses for the development of small, low-cost satellites[4].

The SERPENS-I satellite was launched into orbit on September 17, 2015 through the Kibo JEM module (Japanese Experimental Module) of the International Space Station (ISS), which is in a 408-km orbit and travels at a speed of 27,600 km/h[5].

METHODOLOGY

SPENVIS[1] was the tool used to perform this study. It simulates the flow of particles in the satellite operational environment in orbit, passing particles/radiation through the various materials of the satellite model and analyzing the radiation deposited in the electronic components. The steps to run the computational simulation are:

- Definition of the satellite mission;
- Definition of the models for the flow of trapped particles, solar particles and GCR (Galactic Cosmic Ray) particles;
- Simulation for total ionizing dose;
- Definition of the satellite subsystems geometry (layout);
- Analysis of the dose deposited in each electronic component in each subsystem.

Definition of the SERPENS-II Mission

The environment to be considered in this paper is that of LEO (Low Earth Orbit), between 180 and 2000 km altitude, where most nanosatellites orbit – including SERPENS-II, which is the basis for this study. Table 1 shows the satellite parameters and mission specifications[6]. In this study, the effects of solar radiation pressure and atmospheric drag were not considered.

Table 1: SERPENS-II Satellite Parameters and Mission Specifications.

Description	CubeSat 1U
Approximate Mass	1.3 kg
Approximate Size	10 × 10 × 10 cm
Orbit Type	polar, circular, LEO
Altitude	360 km
Inclination	98 deg
Duration	1 year

DEFINITION OF PARTICLE FLOW MODELS

Model for trapped particles

The models used for trapped particle simulations in the Van Allen belts were the AP8 and AE8 maps. These models consist of omnidirectional fluxes for electron flow (AE maps) in the energy range of 0.04 MeV to 7 MeV, and proton flux (AP maps) in the range of 0.1 MeV to 400 MeV. These maps are based on data from more than 20 satellites from the early 1960s to the mid 1970s[7]. The model version chosen was that of maximum solar activity for both electrons and protons, with a confidence level of 99.865%. Figure 1 shows the mean spectra for trapped protons and electrons.

Model for solar particles

The model used for solar particle simulations was the JPL-91[8]. This model is based on terrestrial surface and atmosphere measurements performed with riometers, rockets and balloons between 1956 and 1963, and measurements of spacecraft in Earth vicinity between 1963 and 1985. In total, about 200 experiments are considered. The confidence level established for this model is 99%, and the presence of solar storms is considered. Figure 2 shows the fluence of solar protons.

Model for galactic particles

The model for GCR simulations is the ISO 15390, which is the international standard for estimating the impact of this type of radiation on pieces of hardware and biological objects while in space. The model explains variations in GCR particle flux due to changes in solar activity and large-scale heliosphere magnetic field (the polar magnetic field of the Sun) during the 22-year cycles[9]. For the simulation, all elements of the periodic table were considered, in the presence of solar storms. Figure 3 shows the GCR proton fluence (atomic number Z = 1).

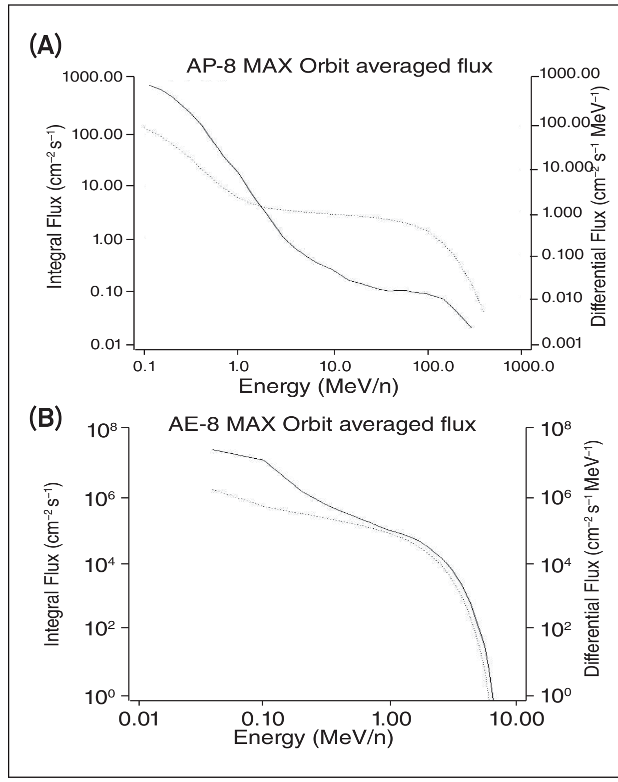

Figure 1: Mean spectra for trapped particles (A) Protons and (B) Electrons.

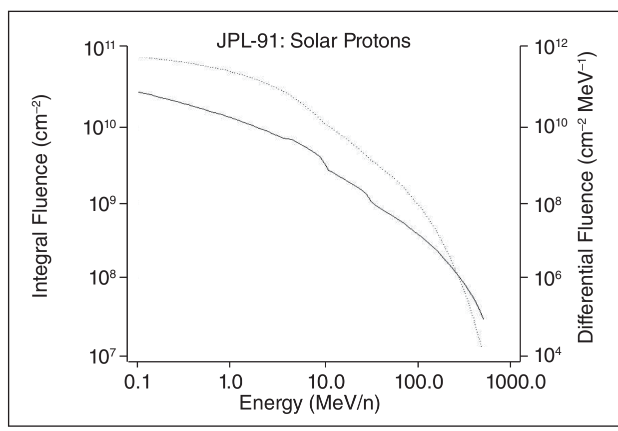

Figure 2: Fluence of solar protons.

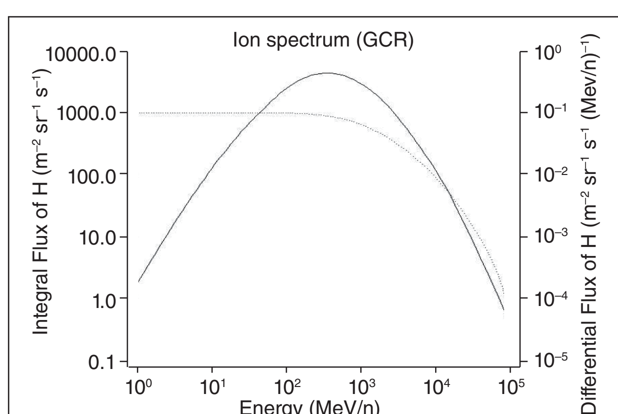

Figure 3: GCR proton fluence for Z = 1.

SIMULATION FOR TOTAL IONIZING DOSE

The simulation to obtain the total ionizing dose deposited in a simple geometry was done with SHIELDOSE[10], which is a computer code for space-shielding calculations. It determines the absorbed radiation dose as a function of depth in aluminum shielding material of spacecraft, given the electron and proton fluences encountered in orbit. The code makes use of pre-calculated, mono-energetic depth-dose data for an isotropic, broad-beam fluence of radiation incident on uniform aluminum plane media. Furthermore, the restriction to these rather simple geometries has allowed the development of accurate electron and electron-bremsstrahlung data sets based on detailed transport calculations rather than on more approximate methods.

SHIELDOSE calculates, for arbitrary proton and electron incident spectra, the dose absorbed in small volumes of different detector materials for the following aluminum shield geometries:

- In a semi-infinite plane medium, as a function of depth; irradiation is from one side only (the assumed infinite backing effectively insures this);
- At the transmission surface of a plane slab, as a function of slab thickness; irradiation is from one side only;
- At the center of a solid sphere, as a function of sphere radius; irradiation is from all directions. The solid sphere model is the most widely used due to the omnidirectional particle fluxes.

SHIELDOSE is used as a first approximation of the absorbed dose in a given mission when the geometries and materials of the spacecraft have not yet been defined. Since it considers a spherical shielding in 4π steradians, and therefore not the real geometry of the system, the computed dose gives a very conservative approximation of the real-life values. Figure 4 shows the total dose deposited on a silicon (Si) target located in the center of an aluminum sphere (Al) using SHIELDOSE, for the SERPENS-II mission.

One can see that, for an aluminum shield thicker than 14 mm, the total dose deposited in the Si target caused by electrons is practically zero. The dose caused by trapped protons, solar protons, and bremsstrahlung (secondary radiation) is attenuated less efficiently for thicknesses above 4 mm. However, considering the development and manufacturing of a nanosatellite, weight considerations are important and should be seriously taken into account. Generally, protection of satellite components is made with 2 to 3.5 mm thickness of aluminum. With thinner shields, besides reducing weight, the interaction of very energetic particles with the protective material is lessened. Such interactions can generate secondary radiation sometimes more harmful than the primary particles.

Definition of Satellite Geometry

The exact configuration of the SERPENS-II has not yet been defined. For the present study, we will consider generic electronic modules or subsystems. The geometry of the satellite was modeled using the Geometry Description Markup Language (GDML) and was based on the SERPENS-II dimensions: a 1U-CubeSat (10-cm edge cube). In Table 2 we have two examples of hypothetical structures, basically composed of modules that are pieces of equipment or subsystems present in a generic satellite, and external and intermediate aluminum plates (between the modules), which will play structural, electrical shielding and thermal conducting roles, as well as radiation protection.

Figure 5 shows a representation of the structure I mentioned in Table 2.

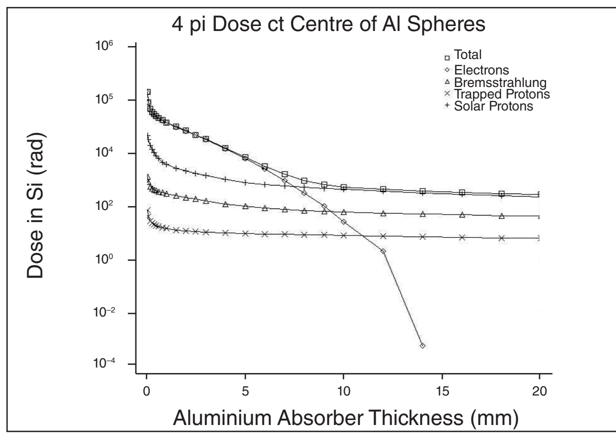

Figure 4: Total dose deposited in the SERPENS-II mission, estimated by SHIELDOSE.

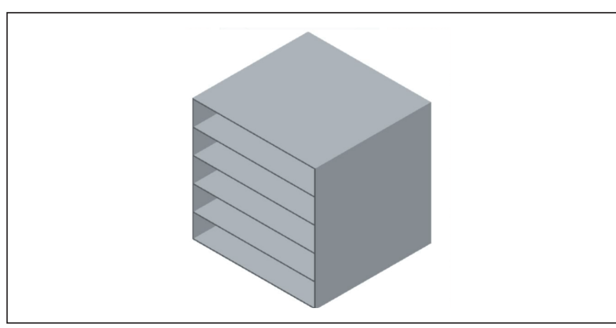

Figure 5: SERPENS-II hypothetical structure I.

Table 2: Descriptions of two hypothetical structures for the 1U CubeSat studied here.

Structure I			Structure II		
Components	Thickness	Qty	Components	Thickness	Qty
External plates	1 mm	6	External plates	1 mm	6
Intermediate plates	1 mm	4	Intermediate plates	1.5 mm	4
Modules	19.2 mm	5	Modules	18.8 mm	5
Weight	270 g		Weight	324 g	

DOSE ANALYSIS

Analysis of the deposited total ionizing dose (TID) is done through GRAS, which is a Geant4-based tool that deals with common types of radiation analysis (TID, NIEL, Fluence, SEE, among others) in generic models of 3D geometry[11].

The GRAS tool simulates an omnidirectional flow of particles based on the radiation spectrum expected to be present in the previously defined mission environment.

RESULTS

Figure 6 shows a representation of the events generated in the simulation with electrons. Due to time constraints and the use of central processing unit (CPU) memory for generating this representation, the number of particles was adjusted to a maximum of 100 events for incident particle views. On the other hand, a total of 10^6 events were used for parameter analysis to reduce statistical errors in the deposited dose estimation.

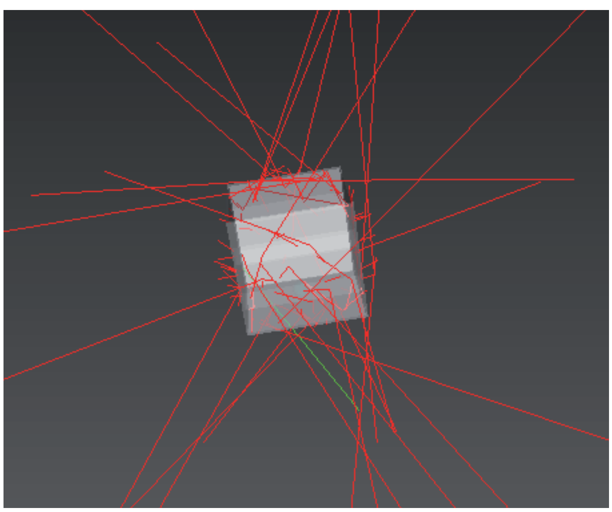

Figure 6: Representation of events with incident electrons.

Table 3 shows the dose deposited on Si targets positioned in each subsystem (cavity), according to its location in the structure. The results provided by GRAS are in units of 0.01 J, making it necessary to correct the results by dividing the dose estimated by SPENVIS by the mass of the target in kg to obtain the dose in rad.

Table 3: Dose deposited in the components of each subsystem.

Structure I		Structure II	
Components	TID (krad)	Components	TID (krad)
Module 1	18.4 ± 1.3	Module 1	16.9 ± 1.2
Module 2	8.3 ± 0.8	Module 2	6.5 ± 0.7
Module 3	8.4 ± 0.9	Module 3	6.8 ± 0.8
Module 4	7.9 ± 0.8	Module 4	7.6 ± 0.8
Module 5	19.0 ± 1.3	Module 5	17.3 ± 1.2

One can see, as expected, that the dose varies according to the target position within the cube; the closer to the center, the lower the dose (TID) deposited due to the shielding provided by the greater total thickness of aluminum and other materials around the target. Based on this, the specifications of the components to be used should be checked in order to assess whether they have the capability to withstand that amount of deposited dose. To decrease the dose, one can add more protection (specific shielding for one or another component), or relocate specific components, placing the most sensitive to radiation in a position that receives less deposited energy.

CONCLUSIONS

In the present article, we performed an initial simulation to guide the choices of position and ionizing radiation tolerance of components and modules to be used in the SERPENS-II nanosatellite. The use of Commercial off-the-shelf (COTS) components, much less expensive than space-qualified components, can significantly reduce the cost of a space mission. COTS components can typically withstand doses of hundreds of rad to a few krad, and can operate in inhospitable environments, such as in space, providing they are properly protected.

Using SPENVIS as a tool for the analysis of ionizing radiation deposited in electronic components of satellites, especially low-cost CubeSats, is a good starting point for their design. The more detailed the satellite geometry representation, the more accurate the simulation results.

Next steps in this work include considering the shielding effect of specific CubeSat SERPENS-II modules, especially batteries, and their radiation tolerances, to specify additional protections eventually needed for more sensitive components.

ACKNOWLEGMENTS

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