Computational tools for modeling the Chasqui A and Chasqui B nanosatellite missions in space weather study

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The complex interaction of ionizing electromagnetic radiation with satellite systems limits their useful life, causing a degradation of the critical properties of structural materials, eroding solar panels, causing interference in communications, among others. This type of radiation increases during a maximum solar cycle, where solar storms are more frequent.

The objectives of this study were to simulate the physical interaction of the nanosatellite projects (Chasqui A and B) with the Plasmaspheric Hiss (PH) and the South Atlantic Magnetic Anomaly (SAMA) respectively.

For the magnetic interaction of SAMA with the Chasqui B nanosatellite, COMSOL software was used, employing finite elements and the magnetic dipole model. A computational model of the payload system was built for the interaction with the weak magnetic field ranging from 17000 nT to 31000 nT.

For the interaction of the PH and SAMA with the Chasqui A and B nanosatellites respectively, Geant4 software was applied, employing the Monte Carlo method and uniform and non-uniform models of the Earth's geomagnetic field. A computational model of the nanosatellites and their subsystems exposed to an ionizing radiation environment with an energy range of 0.4 MeV to 0.8 MeV for PH and an energy range of 10 MeV to 300 MeV for SAMA was built.

The result was the modeling of the payload and its interaction with the SAMA, the measurement of radiation deposition on the nanosatellites and determination of the optimal materials to be used as shielding.

Key Words: COMSOL, Geant4, Plasmaspheric Hiss, South Atlantic Magnetic Anomaly.

1. Introduction

The modeling of nanosatellites is currently the cornerstone to determine the success of any space mission. For this reason, in the Chasqui A and Chasqui B nanosatellite missions, computational tools such as Geant4 and COMSOL are used, which allow visualizing most of the spatial interactive capabilities, thus simplifying reality and allowing the user to understand the structure of the systems selected. Computational modeling also makes it possible to identify improvements in nanosatellites due to the precise simulation of electromagnetic, acoustic, structural mechanical, fluid flow, heat transfer and chemical phenomena in a medium. In this way it is possible to verify the correct structuring of the chosen components and predict the behavior in the real world.

The objectives of the paper are focused on simulating the physical interaction of the South Atlantic Magnetic Anomaly (SAMA) and Plasmaspheric Hiss (PH) phenomena with the payload of nanosatellites to determine a radiation shielding of these payloads; and numerically model the behavior of current density and electric surface density loss in a small coil in the Earth's magnetic field within interplanetary shock-type events located in the South Atlantic Anomaly. Throughout the investigation, the precedents for which the modeling of the Chasqui A and Chasqui B nanosatellite missions have been taken as reference with respect to the study of space weather will be detailed, therefore, in the methodology section, the analysis of the models and simulations regarding the behavior of the flow of trapped protons and electrons, by means of the SPENVIS system, which will also allow the calculation of the dose of ionizing radiation, in order to discuss the results obtained from the modeling of the payload and the simulations of the physical interaction of both nanosatellites alluding to phenomena such as SAMA and PH.

2. CHASQUI-II nanosatellite mission

The CHASQUI-II nanosatellite mission (Chasqui A and Chasqui B) is scheduled to last 1 year from early 2025 when the solar cycle is at its peak.

The Chasqui A mission (3U CubeSat) is designed to fly in a geosynchronous transfer orbit (GTO), with a perigee altitude of ~185 km, an apogee altitude of 35,000 km, an inclination of 18° and a period of 10.26 h. It has an external mechanical structure (boom) where a hybrid magnetometer (HMAG) is located, which works simultaneously as a coil and a fluxgate. Its objective is to monitor the momentary disappearance of the Plasmaspheric Hiss (PH) when interplanetary shocks occur.

The Chasqui B mission (1U CubeSat) is designed to fly in a sun-synchronous orbit (SSO), with a perigee altitude of ~533 km, apogee altitude of ~565 km, inclination of ~97.5°, period of 1.59 h and local time of ascent node (LTAN) at 13:41 hours It also has a boom where a 3-axis Fluxgate Magnetometer (FMAG), 3 XEN-1220 units, based on Hall effect is located. Its objective is to monitor the weakening of the Earth's magnetic field in the South Atlantic Magnetic Anomaly (SAMA) when interplanetary shocks occur.

Fig. 1 shows the simulation of the orbits followed by these missions using the Systems Tool Kit (STK) software.

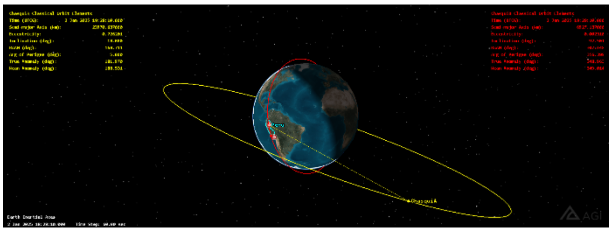

Fig. 1. 3D simulation of the orbits followed by the Chasqui A and Chasqui B missions in STK.

3. Computational tools

The following sections describe the computational tools used to model and simulate the interaction of the Chasqui A and Chasqui B missions with the PH and the SAMA, respectively.

3.1. COMSOL

COMSOL is a software that allows us to model physical processes from a particular point of view, either a model already implemented within the program or modeling through EDP 1). Having an infinite number of applications, one of the applications of our interest is Magnetic Field of a Helmholtz Coil. Its main objective is to design the Helmholtz coils in order to obtain as a result a uniform magnetic field between the coils with the primary component parallel to the axes of the two coils. Where his physical formula for this uniform magnetic field for a coil is:

$$B = \frac{\mu_0 I}{(5/4)^{3/2} r} \qquad (1)$$

The formula has as parameter that the distance of the coils is equal to the radius of the coil, because this configuration has the particularity that the magnetic field along the transverse axis of the coils is uniform B(r=0,Z)=cte 2).

To know the induced current it is first necessary to know what value of magnetic field is needed, in this case the CHAOS-7 model will be used to calculate the magnitude of the desired magnetic field for the study.

3.1.1. CHAOS-7 Geomagnetic Field Model

The CHAOS-7 model of the near-Earth geomagnetic field is time-dependent between 1999 and 2020, based on the magnetic field observations collected by the low-Earth orbiting satellites Swarm, CrtoSat-2, CHAMP, SAC-C and Oersted, complemented by monthly averages of measurements from ground-based observatories. The scientific contributions of CHAOS-7 are the study of the current changes of the geomagnetic field, the study of the South Atlantic Magnetic Anomaly and the rapid field changes in the Pacific region since 2014 3).

3.2. Geant4

Geant4 is a set of tools for simulating the passage of ionizing particles through matter using the Monte Carlo method. The software is based on a solid object-oriented programming (OOP) design written in the C++ programming language, which favors the development of a variety of applications by the community 4). For example, high energy physics, space medicine and radiation.

3.2.1. SPENVIS

The Space Environment Information System (SPENVIS), which is an operational software of the European Space Agency (ESA), developed and maintained by the Belgian Institute of Space Aeronomy (BIRA-IASB) since 1996 5).

SPENVIS is a Geant4-based space radiation database web interface that allows the user to assess the space environment and its effects on spacecraft systems and crews.

The different mathematical models used in this section fulfill the purpose of predicting and describing the radiation environment around the Earth using the orbit parameters and focusing on various particle populations and their characteristics.

For the quantitative analysis of the mission environment we have used the AP-8/AE-8, SAPPHIRE, ISO-15390 models and for the analysis of ionizing radiation dose the SHIELDOSE-2Q model was used.

3.2.1.1. Radiation Belt models AP-8 and AE-8

The AP-8 model is a static model for trapped proton fluxes, but it distinguishes the conditions of solar minimum and maximum and covers proton energies from 0.1 MeV to 400 MeV in near-Earth space between 1.15 and 6.6 Earth radii. 6,7). While the AE-8 model for trapped electron fluxes covers energies from 0.04 MeV to 7 MeV in the space between 1.2 and 11 Earth radii for both solar minimum and maximum solar conditions 7,8).

3.2.1.2. Solar Accumulated and Peak Proton and Heavy Ion Radiation Environment model

The Solar Accumulated and Peak Proton and Heavy Ion Radiation Environment (SAPPHIRE) model aims to cover all aspects of the SEP environment required for mission specifications in Earth orbit. It provides outputs for cumulative mission fluence, peak flux, and largest Solar Particle Event (SPE) fluence for solar minimum and solar maximum conditions for solar protons, helium nuclei and heavy ions. The core model covers energies from 5 MeV to 289 MeV, but extrapolated output is available from 0.1 MeV/nuc to 1000 MeV/nuc 9).

3.2.1.3. Cosmic ray model ISO-15390

The ISO-15390 semi-empirical GCR model is based on models from the Moscow State University. It accounts for variations in the GCR flux due to the solar cycle using sunspot numbers and the interaction of GCR particles with the largescale heliospheric magnetic field [10)]. The model covers GCR energies from 10 MeV to 105 MeV for electrons, protons and heavy ions with Z numbers from 2 to 92 in near-Earth space, but outside the Earth magnetosphere [11)].

3.2.1.4. SHIELDOSE-2Q

SHIELDOSE is the name of the program written by Stephen Seltzer to calculate the dose received behind radiation shielding as a function of the depth of the shielding for expected electron and proton fluences in space [12)], SHIELDOSE-2Q is a later version including additional armour materials [13)].

4. Methodology

The following sections show the simulations and modeling of the Chasqui A and Chasqui B missions.

For the Chasqui A mission and its interaction with the PH phenomenon, a radiation shielding analysis was developed using the SPENVIS web interface whose software is based on Geant4, however, for this mission its payload (hybrid magnetometer) was not modeled since this hardware is still under development.

For the Chasqui B mission and its interaction with the SAMA phenomenon, its payload (fluxgate magnetometer) was modeled using COMSOL software, and a radiation shielding analysis was also developed using the SPENVIS web interface.

4.1. Chasqui A Mission

4.1.1. Radiation Shielding Analysis

In this section we analyze the radiation environment to which the Chasqui A mission is exposed, using the computational models described in Section 3, which we will later use to obtain the total absorbed ionization dose with which the radiation shielding was identified, all this using the SPENVIS web interface.

4.1.1.1. Particle environment on GTO

Before analyzing the effects of radiation on satellites and their subsequent protection, the radiation environment must be identified. For this we use the database provided by the SPENVIS web interface to obtain the particle spectra, as described in Section 3. The particle spectrum received by a spacecraft is highly dependent on its trajectory, so an orbit must be specified before a particle spectrum can be generated from the database models. This section was performed in the context of the Chasqui A mission, which is described in Section 2, therefore, the Chasqui A mission parameters and orbit are used as a reference configuration.

4.1.1.1.1. Model for trapped proton and electron spectra

In SPENVIS, the AP-8/AE-8 model is used to analyze the flow of protons and electrons trapped in the mission. The reference parameters used to generate the AP-8 and AE-8 spectra for later use in this mission are shown in Table 1. Due to the date on which the mission will be carried out, a confidence level of 99.865% for the AE-8 model, this refers to the probability of exceptional events such as storms and extreme solar flares, which temporarily increase the flow of electrons.

Table 1. Parameters used to generate the AP-8 and AE-8 spectra for trapped particles in the SPENVIS web interface.

Parameter	**Value**
Proton model	AP-8
Model version	Solar maximum
Threshold flux for exposure	$1\ cm^{-2}\ s^{-1}$
Electron model	AE-8
Model version	Solar maximum
Local time variation	Do not include
Confidence level	99.865 %
Threshold flux for exposure	$1\ cm^{-2}\ s^{-1}$

The Fig. 2 shows the AP-8 and AE-8 spectra generated with the parameters in Table 1, where the particle spectra are shown as integral flux.

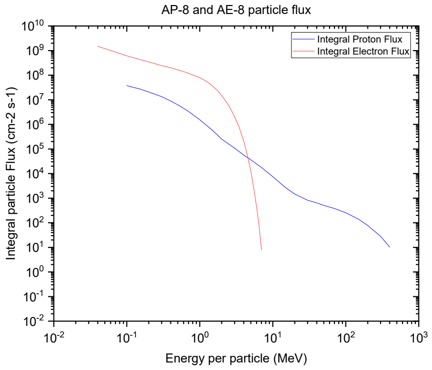

Fig. 2. Average integral flux of trapped protons and electrons at GTO with parameters as shown in Table 1 according to AP-8 and AE-8 models in SPENVIS.

While the main contribution to ionizing radiation doses in Earth orbit are electrons and protons trapped in the Van-Allen radiation belts, there is also particle flux directly from the Sun and cosmic rays.

4.1.1.1.2. Solar particle spectra

In SPENVIS, the SAPPHIRE solar particle model was used to compare the flux of solar particles with the flux of trapped particles. Table 2 shows the reference parameters used to generate the solar particle spectra of Fig. 3.

Table 2. Parameters used to generate the SAPPHIRE solar particle spectra in the SPENVIS web interface.

Parameter	**Value**
Solar particle model	SAPPHIRE (total fluence)
Ion range	Hydrogen to Uranium
Prediction period	Automatic
Offset in solar cycle	Automatic
Confidence level	99.865 %
Magnetic shielding	On (quiet magnetosphere)

This model provides flux data for elements from hydrogen to uranium, but in Fig. 2 only the six types of solar particles with the highest maximum flux are shown.

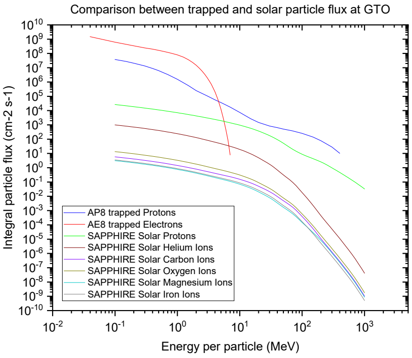

Fig. 3. Comparison between the flux of trapped particles according to the AP-8/AE-8 model and the flux of solar particles according to the SAPPHIRE model in GTO. Only the six types of solar particles with the highest maximum flux are shown.

Analyzing Fig. 3, we identify that the flux of all solar particle species is more than an order of magnitude smaller than the flux of trapped protons over most of the energy range. Therefore, in the calculation of the total dose it was decided not to consider solar particles.

4.1.1.1.3. Cosmic particle spectra

In SPENVIS, the ISO-15390 cosmic particle model was used to compare the flow of cosmic particles with the flow of trapped particles. Table 3 shows the reference parameters used to generate the cosmic particle spectra of Fig. 4.

Table 3. Parameters used to generate the ISO-15390 cosmic particle spectra in the SPENVIS web interface.

Parameter	**Value**
Ion range	Hydrogen to Uranium
GCR model at 1 AU	ISO-15390
Version	ISO-15390 standard model
Solar activity data	Mission epoch
Magnetic shielding	On (quiet magnetosphere)

In Fig. 4, it is observed that the particle flux of the most intense cosmic ray species is several orders of magnitude smaller than the particle flux of trapped protons and electrons. That is, the total energy flux of cosmic particles is negligible compared to the total energy of trapped particles. Therefore, it was decided not to consider cosmic particles in the calculation of the total dose.

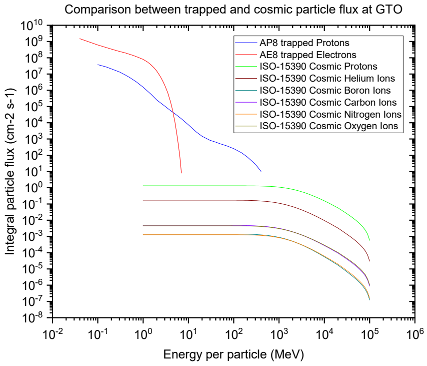

Fig. 4. Comparison between the trapped particle flux according to the AP-8/AE-8 model and the cosmic particle flux according to the ISO-15390 model in GTO. Only the six types of cosmic particles with the highest maximum flux are shown.

4.2. Chasqui B Mission

4.2.1. COMSOL

The initial parameters to consider for simulations in COMSOL are:

Table 4. Parameters used to generate a small coil.

Parameter	**Value**
Number of Laps	8
Larger Radius	6000 μm
Smaller Radius	100 μm
Pitch axial	400 μm
Pitch radial	0

Table 5. Parameters used to generate Helmholtz Coil.

Parameter	**Value**
Radius	150 mm
Distance between Helmholtz coil	150 mm

The simulations will take place in three interplanetary collision events: October 8, 2013, February 27, 2014 and December 19, 2015.

In order to vary to the desired event, we only need to vary the current intensity parameter, which is dependent on the event to be simulated, according to the CHAOS-7 model described in Section 3.1.1.

4.2.2. Radiation Shielding Analysis

Using the SPENVIS web interface, the radiation environment to which the Chasqui B mission is exposed was analyzed using the computational models in Section 3, with which the total absorbed ionization dose was obtained and the radiation shielding was identified.

4.2.2.1. Particle environment on SSO

Analogous to the analysis performed in Section 4.1.1.1, this section was performed in the context of the Chasqui B mission, which is described in Section 2, therefore, the Chasqui B mission and orbit parameters are used as a reference setting.

4.2.2.1.1. Model for trapped proton and electron spectra

Similarly, to the analysis performed in Section 4.1.1.1.1, we use the reference parameters from Table 1 to generate the spectra of particles trapped in SSO as shown in Fig. 5.

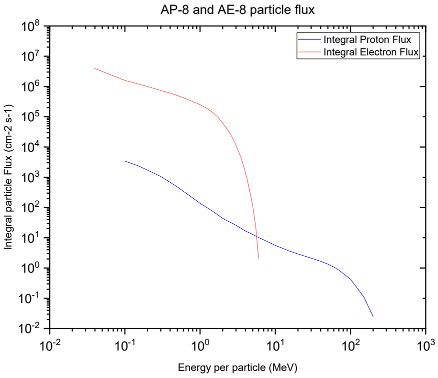

Fig. 5. Average integral flux of trapped protons and electrons at SSO with parameters as shown in Table 1 according to AP-8 and AE-8 models in SPENVIS.

We also analyze the solar and cosmic particle flux.

4.2.2.1.2. Solar particle spectra

In the same way as the analysis carried out in Section 4.1.1.1.2, we used the reference parameters of Table 2 to generate the spectra of solar particles in SSO as shown in Fig. 6, where only the six types were shown. of solar particles with the highest maximum flux.

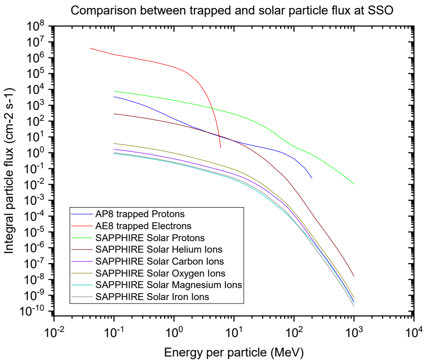

Fig. 6. Comparison between the flux of trapped particles according to the AP-8/AE-8 model and the flux of solar particles according to the SAPPHIRE model in SSO. Only the six types of solar particles with the highest maximum flux are shown.

Analyzing Fig. 6, we identify that only the flux of solar protons and solar helium ions are relevant compared to the flux of trapped particles, all other species are irrelevant. For the calculation of the total dose, it was decided not to consider solar particles.

4.2.2.1.3. Cosmic particle spectra

Similar to the analysis performed in Section 4.1.1.1.1.3, we used the reference parameters in Table 3 to generate the cosmic particle spectra in SSO as shown in Fig. 7, where only the six cosmic particle types with the highest peak flux were shown.

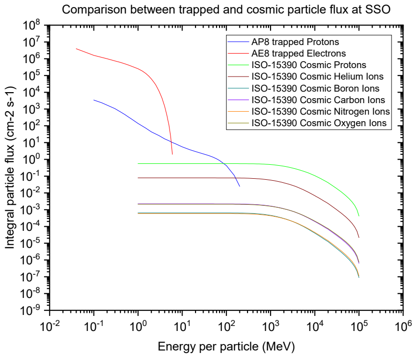

Fig. 7. Comparison between the trapped particle flux according to the AP-8/AE-8 model and the cosmic particle flux according to the ISO-15390 model in SSO. Only the six types of cosmic particles with the highest maximum flux are shown.

It is shown that the total energy flux of the cosmic particles is less than the total energy of the trapped particles. Therefore, it was decided not to consider cosmic particles in the calculation of the total dose.

5. Results and Discussion

5.1. Modeling of the fluxgate magnetometer

From the analysis of Section 4.2.1, using Tables 4 and 5, we will give the simulation results of a small coil (fluxgate magnetometer) that will be perpendicular to the simulated magnetic field respectively with a magnitude that was determined at three approximate interplanetary shock events.

5.1.1. Event of October 8, 2013

In this event the magnetic field was 17626.1069 nT, we evaluated this data in Eq. 1 to obtain the electric current, which gives us 2.9403 A as a result. Its simulation is shown in Fig. 8.

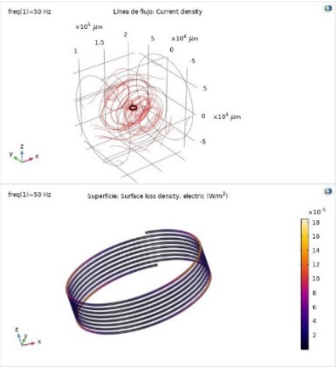

Fig. 8. Modelling of a small coil in the October 8, 2013 event, where the upper image shows us the flux lines as the current density while in the lower image the electrical surface loss density.

5.1.2. Event of February 27, 2014

In this event the magnetic field was 17616.1373 nT, this data is evaluated in Eq. 1 to obtain the electric current, which results in 2.9387 A. Its simulation is shown in Fig. 9.

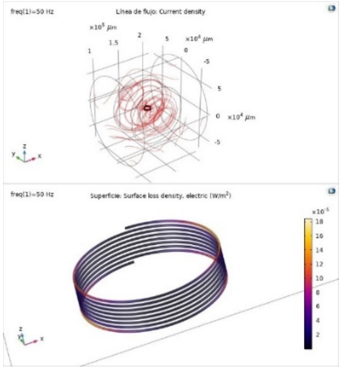

Fig. 9. Modelling of a small coil in the February 27, 2014 event, where the upper figure shows us the flux lines as the current density while in the lower image the electrical surface loss density.

5.1.3. Event of December 19, 2015

In this event the magnetic field was 17577.5075 nT, this data evaluated in Eq. 1 to obtain the electric current, resulted in 2.9322 A. Its simulation is shown in Fig. 10.

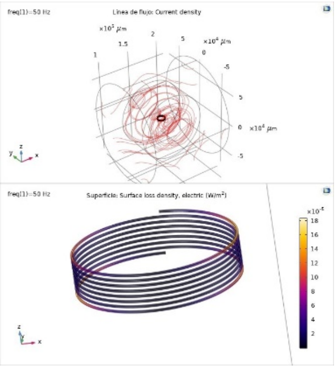

Fig. 10. Modelling of a small coil in the December 19, 2015 event, where the upper figure shows us the flux lines as the current density while in the lower image the electrical surface loss density.

It was possible to visualize in the results that the surface density of electrical losses inside the coil remains constant due to its small size, it is fulfilled that while the size of the coil is larger, the surface density of electrical loss does not tend to be constant. It is also because our coil is induced perpendicularly by the uniform field of the Helmholtz coils. And it is necessary to consider that the main task of the coil is to provide the magnitude of the Earth's magnetic field, so if our coil were in parallel with the Helmholtz coils it would measure undesired values and the sense of its mission would be lost.

5.2. Radiation Shielding

Through the SPENVIS simulation of the mission, with a duration of 1 year.

5.2.1. Radiation shielding in the Chasqui A mission

The spectra generated from the radiation models in Section 4.1.1 are used as input for particle-matter interaction simulations. We use the SHIELDOSE-2Q model accessible through the SPENVIS web interface to estimate the total absorbed ionization dose (TID), with silicon (Si) being the target material for the selected component and defining the center of an aluminium sphere (Al) as the shielding configuration.

The target is to receive less than 10 krad during the one-year mission as marked on the TID plot shown in Fig.11.

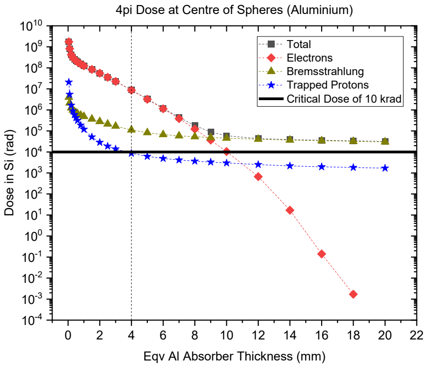

Fig. 11. Total Ionizing Dose (TID) with Aluminium (Al) solid sphere shielding and Silicon (Si) detector for a one-year GTO mission.

Analyzing Fig. 11, it is observed that with a 4 mm thick aluminium shield, the TID is less than 10 krad, fulfilling the objective of receiving less than this radiation dose.

5.2.2. Radiation shielding in the Chasqui B mission

Using the spectra generated from the radiation models in Section 4.2.2 as input parameters, we follow the procedure in Section 5.2.1. The target is to receive less than 0.6 krad during the one-year mission as marked on the TID plot shown in Fig. 12.

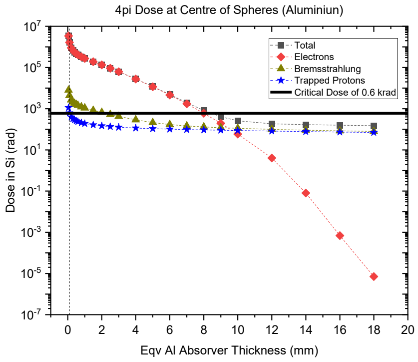

Fig. 12. Total Ionizing Dose (TID) with Aluminium (Al) solid sphere shielding and Silicon (Si) detector for a one-year SSO mission.

Analyzing Fig. 12, it was identified that with a shield of aluminium with a thickness of 0.1 mm, the TID is less than 0.6 krad, fulfilling the objective of receiving at most this radiation dose.

6. Conclusions

It is concluded that, when analyzing the simulations regarding the conceptual approach of the fluxgate magnetometer and studying its behavior in the space environment, it performs the function of a small coil through COMSOL and highlights that the surface density of electrical loss remains constant within of the coil.
Finally, from the radiation analysis, through SPENVIS, it was identified that for the Chasqui A mission and its interaction with the PH, an aluminium shield with a minimum thickness of 4 mm is needed and for the Chasqui B mission and its interaction with the SAMA an aluminium shield with a minimum thickness of 0.1 mm to protect the silicon components within the missions.

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