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EXECUTIVE SUMMARY OF THE THESIS

# Multi-mission Comparison of Radiation Effects on the ESA SEU Monitor

LAUREA MAGISTRALE IN PHYSICS ENGINEERING - INGEGNERIA FISICA

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**Academic year:** 2023-2024

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## 1. Introduction

The vast expanse of outer space presents an incredibly challenging environment characterized by extreme temperatures, vacuum conditions, micrometeoroid impacts, and, most importantly, radiation. This radiation, composed of energetic charged particles with galactic and solar origins, poses a significant threat to the electronic systems of satellites and their overall functionality. Survival and successful operation of space systems is ensured by careful consideration of the effects of radiation. **Radiation Hardness Assurance (RHA)**<sup>1</sup> consists of all those activities undertaken to ensure that the electronics of a space system perform up to the specification when exposed to the space radiation environment.

Despite all the standard RHA methods in place, accurately predicting the performance of **Electrical, Electronic and Electromechanical (EEE)** components in the harsh environment of space remains an intricate challenge. This complexity is due to the limitations and approximations within the space radiation environment models, the ground radiation testing and

the prediction models. This, however, does not mean that RHA is irrelevant, quite the opposite, actually. RHA plays a crucial role in assessing the performance and reliability of space hardware, mitigating risks, and ensuring the success of space missions.

It is, however, of fundamental importance to validate the RHA results, i.e., compare the expected performance of a component to the actual in-flight data. Proper assessment of the validity of RHA methods is seldom inquired, which is a critical oversight. Underestimating radiation levels can result in degraded system performance and loss of mission lifetime. Conversely, overestimating radiation levels can lead to excessive shielding, resulting in reduced payload capacity and increased mission costs.

## 2. Objectives

In the thesis, three key topics related to RHA were addressed:

- **RHA Prediction Models Validation:** Data from three different missions with three different orbits was analyzed and compared to the predicted performance in order to validate the standard RHA methods. The different orbits provided a unique

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<sup>1</sup>For a complete list of acronyms used in the thesis, please refer to the Abbreviations Appendix A.

opportunity to evaluate radiation effects in three distinct radiation environments.

In addition, a novel approach was used. Typically, predictions are averaged over the course of the whole mission. This can of course provide a good overall estimate, but time dependence is lost. In the thesis, the comparison was done as a function of time. This methodology enabled us to capture the temporal variations, offering insights into peak periods of vulnerability and potential correlations with specific mission phases.

- **Flight-Heritage:** The second objective of the thesis was to investigate the so-called flight-heritage problem, i.e., whether data from one mission can accurately predict the performance of the same EEE component on another mission. While initial assumptions may suggest a straightforward correlation, the reality may present a more complex picture. In fact, radiation sensitivity is heavily dependent on many factors such as substrate structure, doping of the device and fabrication processes, etc. Consequently, it cannot be unequivocally assumed that the space performance of one component is indicative of the performance of another instance of the same component on a different mission.
- **PyCREME Development:** Another goal of the thesis was to extend the capabilities of PyCREME, a Python toolkit for the prediction of **Single Event Effects (SEEs)**<sup>2</sup> rates in EEE components in space. Thanks to this development, PyCREME was also used to accomplish the other objectives of the thesis presented above.

### 3. Methodology

The most effective way to get data from space, which can be used to validate ground predictions, is to fly a well characterized component. The perfect candidate for this scope is the AT-MEL AT68166F, a commercial radiation hardened **Static Random Access Memory (SRAM)** for space applications. The AT-MEL AT68166F was extensively characterized as part of the ESA Reference **Single Event Upset (SEU)** Monitor

<sup>2</sup>Single Event Effects (SEEs) are disruptions in EEE devices caused by a single ionizing particle striking the device, leading to temporary or permanent malfunctions.

project, which aimed to provide a simple yet effective method for verifying the accuracy of particle beam and test setups during proton and heavy ion component testing. [1]

Thanks this extensive characterization, the AT68166F SRAM is the perfect candidate for this scope, and indeed, the SEU Monitor was flown in space onboard three different ESA missions:

- **Alphasat:** the largest European telecommunication satellite ever built. Launched on a **Geostationary orbit (GEO)** with two SEU Monitors onboard on 25<sup>th</sup> July, 2013.
- **PROBA-2:** one of the smallest ESA satellites, dedicated to the demonstration of innovative technologies. Launched on a **Low Earth Orbit (LEO)**, with one SEU Monitor onboard on 2<sup>nd</sup> November, 2009. [2]
- **BepiColombo:** Europe's first mission to Mercury. Launched on 20<sup>th</sup> October, 2018, with one AT-MEL AT68166F as SRAM of the **BepiColombo Environment Radiation Monitor (BERM)**.

The working principle of the SEU monitor experiments is simple: the memory addresses of the AT-MEL AT68166F are written with "01010101b" for even addresses and "10101010b" for odd addresses. This results in a checkerboard pattern of zeros and ones. Once the checkerboard has been written, the system reads all the memory. When a particle strikes the SRAM die, as represented in Figure, 1, the system identifies the bits that have flipped from "0" to "1" or vice-versa, detecting the SEE event, as depicted in Figure 1.

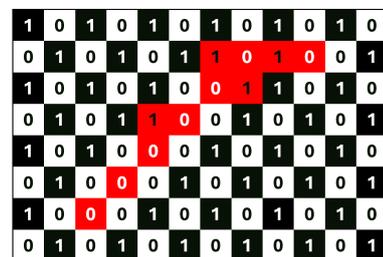


Figure 1: The memory checkerboard pattern with several bits upset by a charged particle.

When an SEE event is detected, the relevant data is stored for further data analysis. Once the raw data from the three missions is parsed and analyzed, the rates of in-flight SEE can be computed.

Subsequently, the predicted SEE rates are computed according to the RHA methodology. This requires following the **E**uropean **C**ooperation for **S**pace **S**tandardization (**ECSS**) standards, which define space radiation environment models, particle-matter transport models, and SEE rate prediction models. [3]

Finally, with both in-flight and predicted SEE rates available, a comparison can be made to effectively validate the standard RHA methods and address the flight-heritage problem.

## 4. Background

Space radiation does not only interact with the surface of a material but may pass through the spacecraft itself. As radiation moves through matter it may displace and/or ionize the material in its path. This, in turn, causes disruptions like spurious signals, material degradation and severe damage to the spacecraft electronics. The type and magnitude of these radiation effects is largely dependent on the type of radiation, which is characterized by the radiation environment encountered by the spacecraft. The two main sources of radiation that compose the space radiation environment in our Solar System are:

- **Galactic Cosmic Rays (GCRs):** A nearly isotropic flux predominantly comprising of extremely energetic protons (89%) and heavier nuclei (11%) coming from outside our Solar System.
- **Radiation belts:** Energetic particles diverted and trapped into toroidal-shaped regions around planets in response to dipolar magnetic fields.

Extremely energetic particles such as GCRs and trapped protons can be so energetic that is nearly impossible to shield electronics inside a spacecraft. This is why, instead of trying to stop them, is of key importance to understand the effects that they can have on spacecraft in order to predict them and mitigate the consequences they can have.

GCRs, however, must first penetrate Earth's magnetosphere, a region dominated by the planet's magnetic field, to reach a spacecraft. The Lorentz force dictates the deflection of charged particles within this magnetic field, with the particle's energy influencing its ability to penetrate. In addition, the presence of the solid

Earth occults part of the solid angle from which particles can arrive at a given location. As a result, the type of orbit plays a crucial role in determining the radiation impact on a spacecraft. A satellite in LEO orbit is protected to some extent from GCRs by Earth's magnetic field, but it is exposed to trapped proton radiation. GEO orbit, and especially the interplanetary one, instead, have little to no geomagnetic shielding and are therefore greatly exposed to GCRs.

Of particular interest for the thesis is the **S**outh **A**tlanctic **A**nomaly (**SAA**). Earth's magnetic field is not geographically symmetrical but has a tilt of about  $11^\circ$  from the rotation axis. As a result, the radiation belts do not align exactly with the Earth's surface and drop closer to the Earth's surface in a specific region located over South America. This asymmetry leads to a significant increase of energetic particles flux in this region.

## 5. Implementation

The aforementioned ECSS standards define:

- **Space Radiation Environment Models:** In order to compute the effects of radiation on EEE components, the radiation environment must first be defined in terms of particle fluxes.
- **Particle-matter Transport Models:** The space radiation environment models provide particle fluxes outside the spacecraft. However, most onboard EEE devices are not directly exposed to the particle flux but operate inside the spacecraft shell and are protected by the shielding provided by the spacecraft walls and other components. This requires modeling the effect of the shielding on the particle flux, i.e., computing the particle flux at the EEE component.
- **SEE Rate Prediction Models:** Once the particle fluxes at the EEE component are defined, this information is combined with results from ground component testing in order to predict the component performance in space.

These models have been incorporated in many modern software suites, however, while these tools are suited for engineers performing RHA, they present limited scripting capabilities, preventing from performing time series analysis

and/or parametric analysis. This led to the development of a Python toolkit for the computing of SEE rates: PyCREME. [4]

At the current state-of-the-art, PyCREME was able to compute SEE rates caused by GCRs. However, without the possibility of specifying a mission orbit, geomagnetic shielding and Earth shadow effect were not taken into consideration. In the thesis, PyCREME was further developed to extend its prediction capabilities to all the three missions presented above, this extensive work included adding these components:

- **Geomagnetic Shielding and Earth Shadow Effect:** The models defined by the ECSS standards were directly implemented into the PyCREME software.
- **AP8 Model:** An empirical model of the Earth trapped radiation that was derived from measurements accumulated by more than 20 satellites. This model was included into the PyCREME workflow for the computation of SEE rates due to trapped protons.
- **Orbit Definition and Propagation:** Computing the geomagnetic shielding, the Earth shadow effect, and the AP8 proton fluxes, all require the knowledge of the spacecraft's position in space, i.e., its orbit. This capability was added in PyCREME, so that all the three missions previously mentioned could be included.

## 6. Conclusions

### 1. RHA Prediction Models Validation:

During the course of the thesis, SEE rate prediction models from three different missions in three different orbit types were validated. The predictions consistently demonstrated remarkable accuracy, typically falling within a factor of two of the in-flight measured SEE rates.

Furthermore, an innovative comparison approach was introduced, employing time series data instead of conventional mission-averaged values. This analysis unveiled a significant modulation in SEE rates due to variations in solar activity, which impacts the SEE rate by a factor of three.

The RHA prediction models not only demonstrated accuracy in predicting mission-averaged outcomes but also show-

cased proficiency in capturing temporal dependencies, further increasing their validity. This achievement is particularly remarkable given the incredibly complex and dynamic nature of space, as well as the inherent limitations and approximations addressed throughout the thesis.

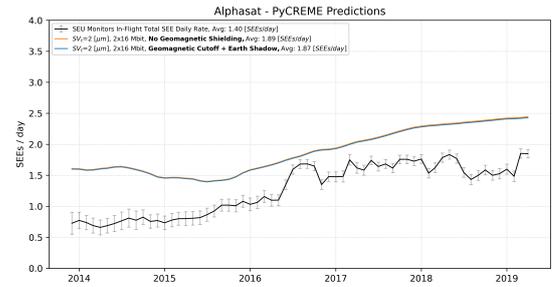


Figure 2: Comparison between in-flight and predicted SEE rates for the Alphasat mission.

2. **Flight-Heritage:** Despite the inherent complexities of the flight-heritage problem, this investigation has provided valuable insights. The study highlighted critical factors influencing the issue. The analyses underscored the significant role of the shielding and sensitive volume thickness  $SV_t$ , a parameter used in the SEE rate models.

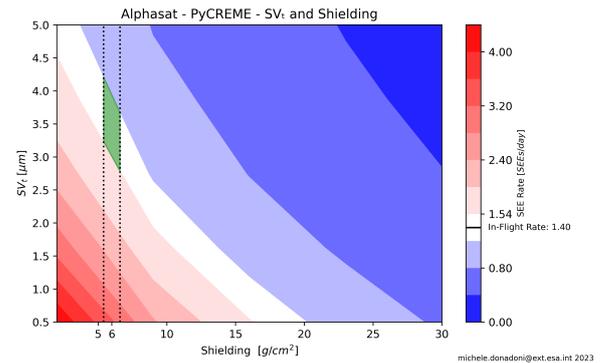


Figure 3: Analysis on the dependence of shielding and sensitive volume thickness  $SV_t$  on the SEE rate of the Alphasat mission.

### 3. PyCREME Development:

PyCREME was further developed to extend its prediction capabilities to all the three missions analyzed in the thesis. Both fluxes and SEE rates were compared with standard software, resulting in negligible difference, as illustrated by the example in Figure 4. This

confirmed the validity of all the added components: orbit propagation, geomagnetic shielding, Earth shadow effect, and the AP8 model integration.

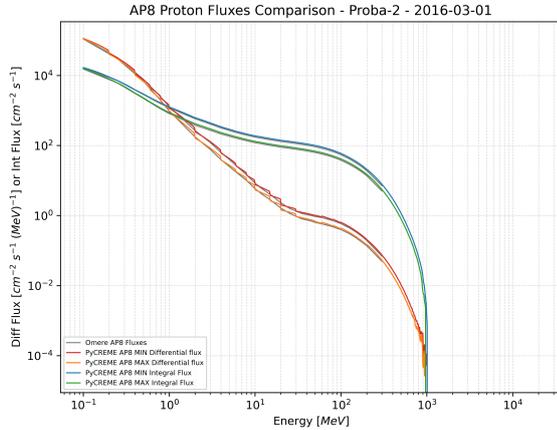


Figure 4: Comparison of AP8 fluxes generated using PyCREME (colored) with those from standard software (gray, shown in the background).

As research often yields unexpected results, these were not the only outcomes of the thesis:

4. **SAA Drift Rate:** The long-term data gathered by the SEU monitor on PROBA-2 allowed to study the drift of the SAA. As shown in Figure 5, the analysis of this data demonstrated a westward drift at a rate of  $0.27^\circ$  per year, consistent with the current state-of-the-art results. This analysis revealed that the radiation effects in EEE components can be utilized for scientific measurements, demonstrating that these effects are not merely detrimental but can provide valuable data for scientific research.

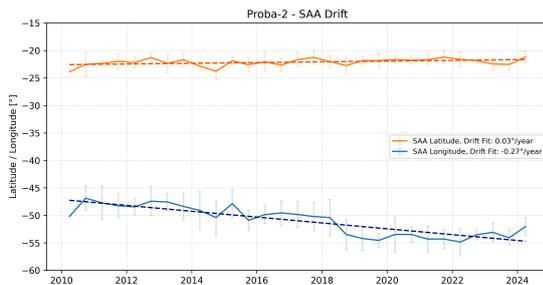


Figure 5: Study on the SAA drift, as measured by the SEU monitor on PROBA-2.

5. **Long-Term Experiments Importance:** Outcomes 1, 2 and 4 couldn't have been performed without the possibility to study long-term data. This shows the importance of missions like PROBA-2, which has been reliably collecting data for 14 years. [5]
6. **Multi-Mission Analysis Importance:** Having the possibility of comparing data from three different missions proved of key importance to validate RHA methods across three different orbits, and to study the flight-heritage problem.

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