Cutting-Edge Strategies for Radiation Effect Estimation on Asteroids Space Mission. Invited Paper

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Abstract

Assessing the reliability of electronic devices in space is crucial, yet current methodologies often lack realism in reflecting actual mission scenarios. State-of-the-art approaches for Total Ionizing Dose (TID) and Single Event Effects (SEE) estimation face limitations in accurately capturing trajectory-dependent radiation exposure and technology-specific device sensitivity. To address these challenges, we propose advanced methodologies that enhance radiation risk assessment through machine learning and empirical data integration.

Our ML-based TID estimation tool predicts radiation dose based on interplanetary trajectory, mission duration, and shielding thickness. Polynomial regression models, trained on a SPENVIS-generated dataset, enable precise dose estimation by discretizing trajectories and selecting the appropriate model for each segment. Additionally, SEE sensitivity is evaluated using cross-section data from publicly available radiation test databases, combined with particle flux estimates from radiation environment toolS, ensuring technology-aware predictions.

Applied to the Zodiac Pioneer mission feasibility study, our approach provides a comprehensive and efficient radiation environment analysis, surpassing traditional methods in both accuracy and automation.

CCS Concepts

• **Hardware → Safety critical systems**; **Transient errors and upsets**.

Keywords

Reliability, Interplanetary Mission, Asteroids, Radiation Environment, Radiation Effects

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1 Introduction

The threat posed by Near-Earth Objects (NEOs) has driven the development of planetary defense initiatives aimed at protecting Earth from potential asteroid impacts. Among the most notable space missions dedicated to this goal are NASA's Double Asteroid Redirection Test (DART)[14] and ESA's Hera mission [7]. These missions serve as critical milestones in humanity's ability to detect, track, and, if necessary, alter the trajectory of potentially hazardous asteroids. The DART mission, launched in 2021, successfully demonstrated kinetic impactor technology by intentionally colliding with the asteroid moonlet Dimorphos of the Didymos system. The mission provided invaluable data on asteroid deflection, proving that such an approach could be a viable planetary defense strategy. Building on this success, ESA's Hera mission, launched in October 2024, will follow up on DART's impact by conducting a detailed post-impact assessment of Dimorphos, gathering high-resolution imagery and physical measurements to refine impact modeling and improve future asteroid deflection strategies. The success of planetary defense missions underscores the advancements in space technology that now enable deep-space operations. Unlike missions in Low Earth Orbit (LEO) or Geostationary Orbit (GEO), deep space missions face significant challenges due to vast distances, long communication delays, and harsh space environments. Despite their classification as "near", NEOs often require spacecraft to undergo interplanetary cruises spanning years before reaching their targets. During these long-duration missions, spacecraft must autonomously perform maneuvers, process onboard data, and withstand extreme environmental conditions, including radiation exposure, thermal fluctuations, and micrometeoroid impacts. Given these challenges, designing spacecraft systems that are robust, fault-tolerant, and capable of autonomous operations is imperative. This paper presents a systematic methodology for verifying the compliance of spacecraft onboard electronics with the space radiation environment, considering the specific mission profile while also comparing state-of-the-art approaches with proposed new methods. The analysis begins with defining the radiation environment, estimating the relevant particle fluxes, and assessing radiation-induced effects, including Single Event Effects (SEEs) and Total Ionizing Dose (TID) with a custom tool. As a case study, we examine an ESA-funded study aimed at developing a small satellite baseline design with high delta-V capability, enabling the Zodiac Pioneer asteroid scouting mission, led by Tyvak International, whose main target of the mission was the 99942 Apophis asteroid.

The paper is structured as follows. In Section 2 details about Zodiac Pioneer and the mission to Apophis are given. Section 3 illustrates state-of-the-art approaches while Section 4 details the proposed methodology to define the radiation environment and effect estimations. Section 5 delves into experimental results while Section 6 illustrates hardness assurance approach. Finally, Section 7 concludes.

2 The mission to 99942 Apophis Asteroid

99942 Apophis [13] is a near-Earth asteroid classified as a potentially hazardous asteroid due to its Earth-crossing orbit and size. With an estimated diameter of approximately 370 meters, and a mass of around 6.1×10^6 kg, follows an elliptical orbit completing one orbit around the Sun in approximately 323.6 days. Its close encounter with Earth on April 13, 2029, will bring it within roughly 31,600 km of the planet's surface, inside the orbits of geostationary satellites, making it one of the closest predicted asteroid flybys for an object of its size. This event presents a unique opportunity for scientific observations and mission studies, particularly for planetary defense and space exploration initiatives. To investigate the impact of Earth's magnetosphere on asteroid 99942 Apophis, ESA has commissioned a mission feasibility study focused on characterizing the asteroid's physical properties before, during, and after its close encounter with Earth. To achieve this, the Zodiac Pioneer mission was designed to intercept the asteroid's trajectory at least two months before its Earth flyby, necessitating an interplanetary cruise beyond Earth's gravitational influence. As a deep space mission, Zodiac Pioneer is exposed to a complex radiation environment, making a precise assessment of radiation conditions crucial to mitigating the risk of system malfunctions caused by radiation-induced effects. During the early mission design phase, multiple interplanetary trajectory scenarios were considered, accounting for variations in launch date, propellant mass budget, cruise duration, and heliocentric position, each of which influences the expected radiation environment. The following sections will present a detailed analysis of radiation effects, emphasizing the key differences between the proposed mission trajectories. This analysis highlights the critical role of early-stage radiation estimations in shaping mission design decisions, particularly in influencing the final trajectory selection.

3 State-of-the-art

The current trajectory analysis approach typically assumes worst-case radiation scenarios across different mission proposals due to shared design constraints. Since the Sun is the primary driver of the radiation environment, conventional methods often consider both peak solar activity—leading to maximum solar energetic particle (SEP) fluxes—and the highest possible Galactic Cosmic Ray (GCR) flux [1]. However, this assumption is flawed, as solar activity directly modulates GCR intensity. During solar maximum, the Sun's magnetic field attenuates GCRs, while during solar minimum, reduced solar shielding allows higher GCR penetration. This unrealistic superposition leads to radiation overestimation, resulting in unnecessary component exclusions or excessive shielding, increasing spacecraft mass and potentially impacting trajectory and propulsion requirements. Another key factor is the spacecraft's varying distance from the Sun during its interplanetary cruise. Current radiation tools like ESA's SPENVIS [4], CNES' OMERE [9], and CREME[3] assume a single mission segment at a fixed distance, making them unsuitable for dynamic trajectories where solar exposure fluctuates over short periods. Conventional methods compensate by using either an average distance or a worst-case scenario, typically the closest approach to the Sun, as existing models do not support distances beyond 1.0 AU. This is particularly problematic for fast rendezvous missions, such as Zodiac Pioneer[6], where rapid changes in heliocentric distance and solar conditions occur, as seen in the Apophis encounter. To overcome these limitations, we propose a novel tool that integrates the spacecraft's actual trajectory with solar activity conditions, enabling a more accurate estimation of the expected radiation dose. By accounting for real-time trajectory variations and solar cycle fluctuations, this approach improves radiation effect predictions, ensuring better-informed spacecraft design and mission planning. Additionally, when considering SEE estimations, the typical approach only focuses on shaping the devices as a generic layer of sensitive material (typically silicon). However, this leads to a too generic approach, masking the effective sensitivity of the device, consequently affecting the screening procedure of the Bill of Material (BOM). As a consequence, we propose a more accurate analysis that combines radiation test data and environment simulation to produce a mission-oriented SEE estimation.

4 Proposed Approach

Accurate radiation estimation begins with determining the solar activity phase at the time of the mission. Given the Sun's 11-year cycle—six years of maximum and five of minimum—forecasting tools such as NOAA [8] predict the expected conditions based on historical and predictive models. Once the solar phase is identified, appropriate radiation models can be selected. Using radiation environment tools such as SPENVIS, it is possible to define the mission by setting a launch date, distance from the Sun and mission lengths (days, months or years). Then, running the engine for particle flux estimation, it is possible to determine the expected amount of solar protons and GCRs for the target mission. Particles' fluxes are necessary to then run the radiation effects estimation engine which will provide useful insight in threshold values of both TID and SEE to be adopted in BOM analysis. However, while LEO and GEO trajectories can be modeled accurately, this is not the case of interplanetary missions that can only assume one single distance from the Sun, which is not a realistic scenario. To overcome this issue, we developed a custom tool that enables TID estimation by only providing trajectory and lunch date as input and provides the expected TID for the entire mission, avoiding the use of general approaches as worst-case distances or average distances.

4.1 The proposed TID tool

The developed TID estimation tool integrates multiple machine-learning algorithms to predict the radiation dose as a function of the distance from the Sun and the duration spent at that distance. The employed machine-learning models are fourth-degree polynomial regression algorithms, chosen for their simplicity and effectiveness. These models are trained on a custom dataset of radiation dose values generated using ESA's SPENVIS tool. The tool processes an interplanetary trajectory as input, applying pre-processing techniques to account for trajectory variations, and outputs the estimated TID for the entire mission. By incorporating

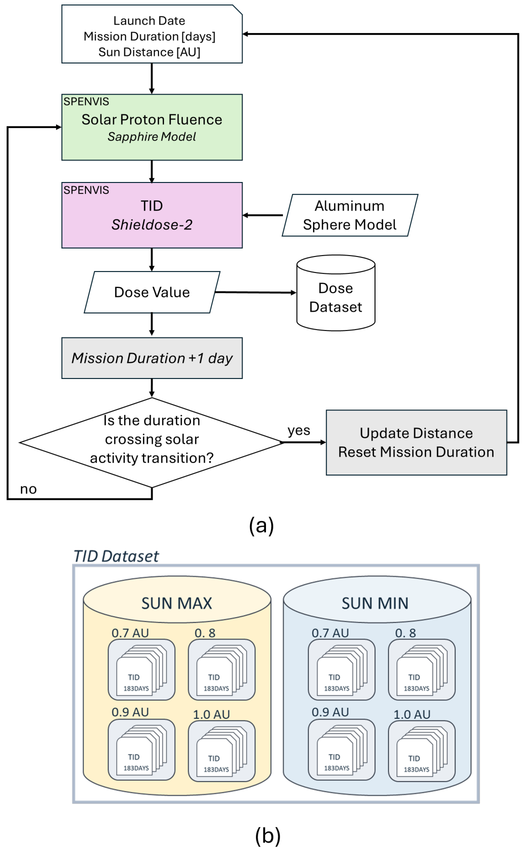

Figure 1: The adopted flow for TID dataset building using SPENVIS tool in (a) while the dataset content in (b)

trajectory dynamics, the tool provides a more accurate and comprehensive assessment of radiation exposure over time, surpassing the capabilities of traditional estimation methods.

The dataset construction followed an iterative process within SPENVIS, simulating various interplanetary mission scenarios to cover a range of relevant conditions. Specifically, for each discrete distance from the Sun—expressed in Astronomical Units (AU) and supported by current particle models—an interplanetary mission was simulated with an increasing duration in one-day increments. For each distance, duration, and solar activity condition, SPENVIS was used to extrapolate the solar proton fluences. Then, the fluences are used as input for the SHIELDOSE-2 TID estimation engine provided in SPENVIS, set with the aluminum sphere geometry model to evaluate omnidirectional incident particles. This process continued increasing mission duration until reaching the transition between solar maximum and minimum activity, starting from a minimum mission duration of six months, which is the lower limit imposed by the current models. Consequently, for each pair of distance and solar activity level, a dataset of dose values was generated, capturing the time-dependent nature of TID variations as mission duration increases. A schematic representation of the dataset construction workflow is shown in Fig. 1.

The dataset was utilized to train the TID estimation tool, which consists of a series of polynomial regression models. Specifically, the tool comprises separate models for each combination of solar activity level, distance from the Sun, and shielding thickness. The shielding material is typically aluminum, with thicknesses ranging from 0.1 mm to 20 mm.

The tool takes as input the spacecraft trajectory and the shielding configuration to be evaluated. The first processing step involves discretizing the continuous trajectory into discrete segments through a rounding process. Each segment is characterized by three key parameters: solar activity, distance from the Sun, and duration. Once the segments are obtained, the characteristics of each segment are used to select the appropriate TID model from the pre-trained set. Unlike conventional tools, which typically assume a single uniform segment for an entire mission, this tool supports multi-segment trajectories.

Each segment contributes a specific radiation dose to the overall mission, and the analysis accounts for the time elapsed between segments, ensuring an accurate representation of TID accumulation, which is inherently nonlinear over time. The final output of the tool is the total TID for the entire mission, derived solely from the input trajectory. This approach not only provides a more precise estimation of radiation exposure based on the spacecraft's actual spatial and temporal position but also significantly enhances computational efficiency. By automating key steps—such as orbit definition, fluence calculation, and final TID estimation—the tool eliminates the need for manual intervention, making the process both faster and more reliable.

4.2 Accurate SEE Estimation

Another critical parameter for screening onboard electronics is the estimation of SEEs[12][11], particularly in the most critical and sensitive components. A reliable assessment requires incorporating the physical characteristics of the device under analysis, which involves either modeling the device—specifically its technology node—or using empirical metrics such as the SEE cross-section obtained from previous radiation tests. The first approach, based on device modeling, is highly challenging due to the proprietary nature of technological details. Therefore, an alternative methodology is proposed, leveraging cross-section data to estimate SEEs.

The first step involves acquiring the cross-section data associated with the component. This can be done using official databases from ESA and NASA, which collect results from high-energy particle radiation tests—commonly known as radiation testing—conducted to simulate the space environment. The outcome of these tests are typically a cross-section curves as shown in Fig. 2, which serves as a sensitivity metric for the component with respect to a specific type of radiation-induced event. This cross-section data can then be used as input for environmental analysis tools. State-of-the-art tools such as OMERE and SPENVIS allow SEE rate estimation by defining the mission parameters, including orbit, duration, and launch date, and computing the expected flux of energetic particles (GCR, solar protons, or trapped particles). These tools provide SEE predictions either using default parameters—where the only adjustable setting is the technology node size (e.g., 28 nm, 16nm)—or by directly incorporating cross-section data from previous radiation tests. It is important to highlight that the cross-section describes the sensitivity of the component as a function of particle energy for a given fluence. Environmental analysis tools use this information in combination with the estimated particle flux for the mission, where the flux is defined as a function of energy. Through interpolation methods, these two data are combined to generate an average SEE rate per day of mission time. For instance, in the case of a memory device, the cross-section represents the sensitivity of a single memory cell. Consequently, the estimated SEE rate is associated with a single bit. To obtain a realistic assessment of the overall impact, the SEE rate must be scaled according to the total number of sensitive elements (e.g., the number of bits in a memory device). It is also crucial to note that, under identical test conditions (same particle flux and energy), the underlying semiconductor process technology significantly influences the component's sensitivity. As shown in Fig. 2, the cross-sections of two different SRAM devices—one fabricated using a 28 nm CMOS process and the other using a 16 nm FinFET process—exhibit substantial differences, highlighting the impact of technology scaling on radiation susceptibility.

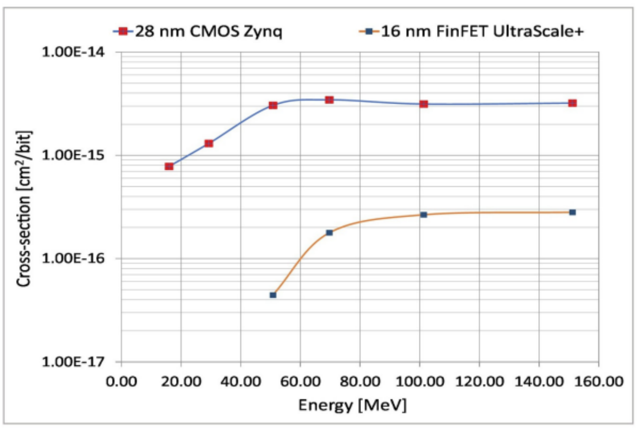

Figure 2: The SEE cross-section data for different technology.

5 Experimental Analysis

The methodologies outlined in the previous section were applied to define the radiation environment for the Zodiac Pioneer mission, described in Section 3. As previously mentioned, in the feasibility study for the mission to the Apophis asteroid, three different interplanetary trajectories to intercept the asteroid orbit were evaluated. Although these trajectories share the same boundary conditions with respect to the Sun, their spatial and temporal evolution differs significantly, as shown in Fig. 3.

To ensure an accurate assessment of the radiation environment for TID estimation, the machine-learning-based tool was employed. By taking the three trajectories as input, the tool generates the total radiation dose as a function of the shielding thickness, providing a precise evaluation of the mission's radiation exposure. Dose profiles were evaluated, taking into account different aluminum shielding thicknesses. Specifically, the selected values range from 1.5 mm to 5.0 mm compliant with the spacecraft mass budget.

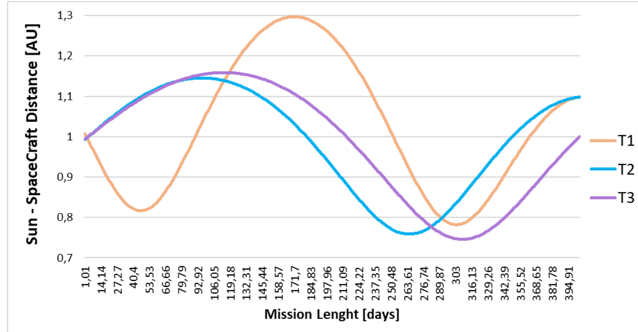

Figure 3: Interplanetary cruise trajectories to Apophis.

Table 1: Interplanetary Crusise TID Estimation

		Trajectory1[rad]	
Al Thickness	Traj-based	Worst Case	SPENVIS Worst Case
1.5	8.44e+03	1.16e+04	1.15e+04
2.5	4.36e+03	6.01e+03	5.95e+03
3.0	3.42e+03	4.72e+03	4.66e+03
4.0	2.30e+03.	3.20e+03	3.13e+03
		Trajectory2[rad]	
Al Thickness	Traj-based	Worst Case	SPENVIS Worst Case
1.5	6.48e+03	1.21e+04	1.20e+04
2.5	3.34e+03	6.25e+03	6.19e+03
3.0	2.62e+03	4.91e+03	4.85e+03
4.0	1.76e+03	3.32e+03	3.25e+03
		Trajectory3[rad]	
Al Thickness	Traj-based	Worst Case	SPENVIS Worst Case
1.5	6.42e+03	1.18e+04	1.17e+04
2.5	3.31e+03	6.08e+03	6.02e+03
3.0	2.59e+03	4.78e+03	4.72e+03
4.0	1.74e+03	3.24e+03	3.17e+03

The computed dose values are compared against those obtained using the SPENVIS tool, configured with worst-case distances as in the state-of-the-art approach, as well as with the one produced by our tool sets in the same conditions. In these scenarios, SPENVIS models the trajectory using a single-segment approximation—maintaining a constant distance from the Sun throughout the entire cruise—since it does not support multi-segment interplanetary trajectory modeling. The results, presented in Table 1, highlight the limitations of this approach.

When using worst-case distances, the individual characteristics and variations among the different trajectories are lost. In contrast, the trajectory-based dose estimation method preserves the distinctions in distance from the Sun and mission duration, leading to a more representative radiation exposure assessment. Notably, T1 exhibits the highest dose, as its extended cruise duration results in prolonged radiation exposure. Conversely, T2 and T3, despite approaching the Sun more closely, accumulate a lower total dose since they spend less time in periods of maximum solar activity compared to T1.

Once TID has been estimated for the different trajectory, the SEE estimation approach has been conducted on the Flight Computer Module (FCM) of Zodiac Pioneer which is implemented on Zynq-7030 System on Chip (SoC). The Zynq-7030 integrates an ARM-based processing system (PS) with an SRAM-based FPGA, combining both hardwired processing capabilities and programmable logic resources. The FCM leverages both the PS and FPGA fabric, enabling flexible and efficient system implementation.

A key characteristic of FPGA devices is their reconfigurability, achieved through the bitstream file loaded into the Configuration Memory (CRAM). This bitstream defines the hardware functionality by configuring the logic, interconnections, and embedded memory resources to implement the desired circuit. However, SRAM-based FPGAs are particularly vulnerable to radiation-induced Single Event Upsets (SEUs)[10][5]. When a high-energy particle strikes a memory cell within the CRAM, it can cause a bit flip, potentially altering the configuration and modifying the circuit's structure, which may lead to functional errors or even system failure. As a consequence, a comprehensive SEU evaluation related to an effective spacecraft environment is a must.

As mentioned in the previous section, estimating particle fluxes and knowledge of the technology node size is not enough, while cross-section data is needed. Therefore, to properly evaluate sensitivity respect to mission profile, we used the radiation test data available in the literature.

In this study, we derived cross-section data for the Zynq-7045 SoC, which, although not the specific target device, belongs to the same FPGA family and is fabricated using the same semiconductor process. Based on this similarity, we utilized user-defined inputs in the SPENVIS tool to estimate the SEU rate on the FCM over the course of a one-day mission. These estimations were performed under varying radiation environments, reflecting differences in the spacecraft's trajectory.

Specifically, the analysis considered a range of heliocentric distances and levels of solar activity. For each combination of distance and solar condition, the impact of different shielding thicknesses was also taken into account. Proton-induced effects were evaluated exclusively, as the available cross-section data was obtained from a proton irradiation campaign. The SEU rate results for heliocentric distances between 0.7 AU and 1.0 AU are presented in Fig. 4.

As illustrated in the chart, the worst-case operating condition corresponds to the spacecraft being at 0.7 AU from the Sun during a period of maximum solar activity. However, among the considered mission trajectories, this specific scenario does not occur, as the spacecraft's minimum distance from the Sun is 0.75 AU, and this proximity is maintained only for a limited duration.

Nonetheless, a conservative design approach should account for the possibility that, even during brief passages through regions closer to the Sun, the spacecraft may be exposed to elevated levels of radiation capable of inducing SEEs. Consequently, fault injection campaigns incorporating SEU accumulation—based on the maximum estimated SEU rate under various shielding conditions—should be carried out. These tests aim to determine the average number of SEUs in the FCM that can lead to system failure and to identify the appropriate shielding thickness required to attenuate the SEU rate to levels that ensure mission safety under all expected conditions.

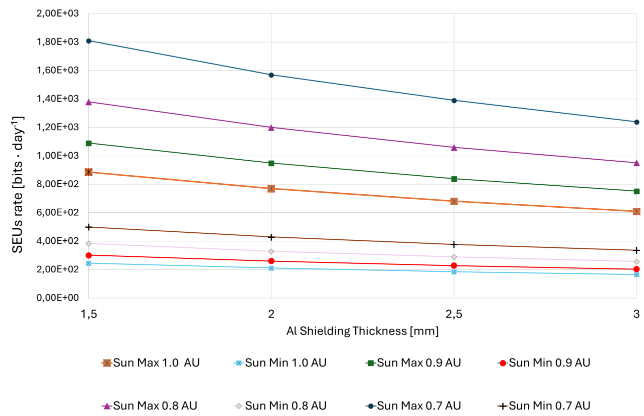

Figure 4: SEU rate estimation on the FCM for different radiation environments.

6 Hardness Assurance Approach

Following the radiation analysis, Trajectory 1 was identified as the most critical case, with an estimated TID of about 9 krad behind 1.5 mm of aluminum shielding. In parallel, the SEU rate on the Flight Control Module was estimated, showing that depending on the implemented logic, the system may need to tolerate up to 1000 SEUs in the configuration memory. This highlights the necessity for robust design-level mitigation techniques, such as TMR, configuration scrubbing, and error detection mechanisms. Beyond the FCM, the rest of the COTS-based architecture—particularly power-critical subsystems like the battery management and avionics—must be evaluated for susceptibility to disruptive Single Event Latch-up (SEL)[2]. Dedicated component-level screening and protective circuitry (e.g., current limiting and automatic power cycling) are essential to ensure mission resilience under the expected radiation conditions.

7 Conclusions

This work presented a methodology for accurate radiation environment analysis tailored to interplanetary missions involving fast rendezvous with asteroid targets. Such missions pose unique challenges, as their trajectories often exhibit large variations in heliocentric distance, exposing the spacecraft to highly dynamic radiation environments.

To address this, we developed a tool for TID estimation and a structured flow for SEE rate evaluation, enabling early-stage assessment of radiation risks. These methods were applied to the Zodiac Pioneer mission targeting Apophis, identifying critical mission phases and guiding the definition of design-level mitigation strategies.

Overall, the proposed approach provides a practical and scalable framework for radiation analysis in similar fast-response deep-space missions, supporting robust and resilient spacecraft design despite the use of COTS components.

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