Radiation Environment and Effects Analysis of the Zodiac Pioneer Mission

IAC-24-C2.6.4

Radiation Environment and Effects Analysis of the Zodiac Pioneer Mission

Eleonora Vacca[a]*, Sarah Azimi [b], Luca Sterpone [c], Margherita Cardi[d], Isabella Pappagallo [e], Paolo Martino [f],

[a] *Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Turin, Italy,* eleonora.vacca@polito.it
[b] *Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Turin, Italy,* sarah.azimi@polito.it
[c] *Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Turin, Italy,* luca.sterpone@polito.it
[d] *Tyvak International srl, Via Orvieto 19, 10149, Turin, Italy,* margherita@tyvak.eu
[e] *Tyvak International srl, Via Orvieto 19, 10149, Turin, Italy,* isabella.pappagallo@tyvak.eu
[f] *European Space Agency – ESTEC, Keplerlaan 1, 2201AZ, Noordwijk, The Netherlands*, paolo.martino@esa.int
* Corresponding Author

Abstract

ESA's Zodiac Pioneer mission targets Near-Earth Asteroids (NEAs) with potential rendezvous opportunities within the next 8 years, representing interesting targets for the Planetary Defense roadmap. The mission involves designing a small satellite platform capable of reaching various targets across different interplanetary trajectories, considering the asteroid 99942 Apophis as first case study given its close approach to Earth on April 13, 2029. Throughout the mission, the radiation environment will be highly mutable due to variations in solar activity and changes in the spacecraft's distance to both the Sun and Earth. These variations translate into different radiation sources affecting the spacecraft's onboard electronics. A comprehensive analysis requires characterizing each mission phase with the related radiation environment. However, conventional tools fail to do such an accurate analysis due to the unavailability of defining multi-segment interplanetary missions and adopting a minimum mission length of 6 months. To address this, we developed a new framework to estimate the total ionizing dose along the spacecraft's trajectory. The framework is built upon a dose dataset acquired from ESA's SPENVIS tool, accounting for different mission durations, Sun distances, and solar activity. By evaluating trajectory-specific factors, our method accurately estimates radiation exposure, providing a more tailored and realistic assessment of the dose contribution than conventional tools that rely on worst-case scenarios. This approach avoids TID overestimation and highlights critical differences between potential mission trajectories under study, avoiding generalities.
Keywords: Zodiac Pioneer, Interplanetary Mission, Asteroids, Radiation Environment, Radiation Effects

1. Introduction

One of the next priorities in ESA's Space Safety Program related to Planetary Defense is implementing a class of fast rendezvous satellites to characterize potentially dangerous asteroids. The main objective of the ongoing study is to conceive a small satellite baseline design with high delta-V capability, enabling an asteroid scout mission, Zodiac Pioneer, to reach a wide range of targets. The study, led by Tyvak International and completed in June 2024, takes as a starting point the list of known Near Earth Asteroids (NEA) with high interest for Planetary Defense and reasonable rendezvous possibilities in the next 8 years. One of the most important use cases to be considered is the Earth's close encounter with the 99942 Apophis asteroid, expected by April 13, 2029 [1].

Due to the peculiarity of Apophis getting close to Earth, with the closest distance being 30,000 km, the radiation environment characterization for the Zodiac Pioneer mission initially focuses on this target, proposing a deep analysis of all the mission phases and the related radiation sources that the spacecraft should face. Indeed, by comparing the Apophis proposed trajectories with those proposed for the other NEA targets, it is clear that from an environmental point of view, intercepting Apophis orbit is more challenging with respect to the other asteroids of interest. As will be discussed in detail in the following sections, when reaching Apophis, the Zodiac Pioneer spacecraft is expected to embark on an interplanetary cruise characterized by huge fluctuations in distances from the Sun, oscillating from 0.7 AU up to 1.2 AU while facing a transition between solar maximum to solar minimum environmental conditions, as well as the influences of the Earth's magnetosphere during its Earth fly-by. In contrast, other targets' proposed trajectories are characterized by more homogenous environmental conditions during their interplanetary cruise.

The variable distance to the Sun, coupled with the timing within the solar cycle, significantly impacts the radiation source and its effects. The assessment of radiation effects becomes even more challenging due to the lack of radiation environment tools capable of managing such variable interplanetary trajectories, making it difficult to accurately estimate the radiation impact on the onboard electronics, which is crucial for the success of the space mission. Therefore, to address this challenge, we developed a custom tool to estimate

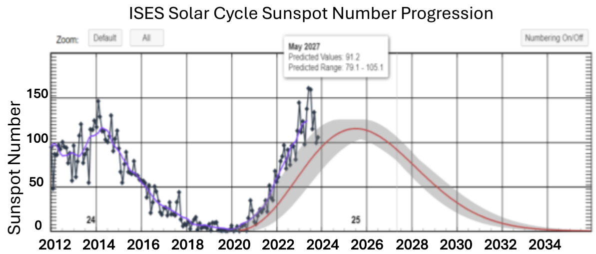

Fig 1. Solar cycle 25 prediction.

the total ionizing dose (TID) for each interplanetary trajectory under study. Additionally, we employed a comprehensive approach to characterize the expected radiation particle fluxes using multiple tools such as CREME[2], SPENVIS[3], and OMERE[4] to perform the analyses and compare results. The Zodiac Pioneer environment characterization includes TID effects and the Single Event Effects (SEE) on the Flight Computer Module (FCM), which combine environment modeling and radiation test data.

The rest of the paper is organized as follows. Section 2 examines the correlation between the mission phases and expected solar activity. Section 3 outlines the modeling of the radiation environment for three different trajectories currently under study to reach Apophis. Section 4 provides the radiation analysis performed, highlighting the TID developed tool and the proposed methodology for estimating SEE.

2. Solar Activity Prediction

Solar activity, marked by maximum and minimum values in the solar radiation and magnetic fields, remarkably influences the near-Earth interplanetary environment. Specifically, it influences the contribution of solar particles and galactic cosmic rays (GCRs). Therefore, the radiation effects on the onboard electronics exhibit significant changes depending on the solar cycle phase and the energetic particles involved. The solar cycle spans approximately eleven years, featuring phases of heightened activity called solar maximum and phases of reduced activity called solar minimum. During solar maximum, the contribution of solar particles, mostly composed of protons, increases, while the solar activity shields from the GCRs generated outside the solar system. In contrast, GCRs can penetrate at the solar minimum.

The launch of Zodiac Pioneer toward Apophis is planned to occur within a timeframe that allows the spacecraft to reach the asteroid before its close encounter with Earth. Politecnico di Milano, part of the Mission Study Consortium, proposed three trajectories with feasible launch dates in 2027, enabling arrival at the asteroid by February 2029 at the latest [5]. We used this trajectory data to assess the expected radiation conditions during this period in

Table 1. Sun Activity Comparative Analysis for Different Trajectories

Trajectory		LEOP	Int. Cruise	CPO
#1	Start - End	05/05/2027–3/06/2027	03/06/2027 – 08/02/2029	08/02/2029 – 13/09/2029
	Duration [days]	30	610	217
	Time in Sun Max [year]	0.08	1.45	0
	Time in Sun Min [year]	0	0.22	0.59
#2	Start - End	1/11/2027 – 30/11/2027	1/12/2027 – 02/02/2029	02/02/2029 – 13/09/2029
	Duration [days]	30	429	223
	Time in Sun Max [year]	0.08	0.95	0
	Time in Sun Min [year]	0	0.22	0.61
#3	Start - End	27/10/2027 – 25/11/2027	25/11/2027 – 03/12/2028	03/12-2028 – 13/09/2029
	Duration [days]	30	374	284
	Time in Sun Max [year]	0.08	0.97	0
	Time in Sun Min [year]	0	0.05	0.78

relation to the current solar cycle. Figure 1, based on data from the National Oceanic and Atmospheric Administration (NOAA) [6], illustrates the solar cycle and projected sunspot numbers for the relevant dates. The data indicate that the solar cycle will still be at its maximum in 2027, with the transition to the minimum expected around November 2028. As a result, much of the interplanetary cruise will occur under solar maximum conditions, exposing the onboard electronics to higher TID effects due to increased solar proton activity. In contrast, the satellite's close proximity operations (CPO), i.e. the scientific phase, around Apophis before, during, and after its Earth flyby will be impacted by high-energy GCRs associated with the transition to solar minimum conditions.

The three proposed trajectories are characterized by a different launching date, interplanetary cruise duration, and distance from the Sun. We used this information to characterize each proposed trajectory with respect to the Sun's activity. Table 1 presents an initial comparison of trajectories based on the durations of each mission phase under a specific solar activity condition. The data shows that Trajectory 1 spends more time in solar maximum than the other two trajectories, whose conditions are almost equivalent. This suggests that the absorbed dose during the mission for Trajectory 1 will be greater than that of the other two trajectories due to longer exposure time to higher proton fluxes.

3. Radiation Sources

Considering the proposed trajectories to intercept Apophis orbits, the Zodiac Pioneer spacecraft will predominantly be situated in an interplanetary environment for most of the mission, with variable distance from the Sun, constrained between 0.75 AU and 1.2 AU. During the CPO phase, the spacecraft will briefly enter the Geostationary Earth Orbit (GEO) environment. While following the Apophis orbit after the Earth fly-by, it will remain in an interplanetary environment between 1.1 and 0.9 AU. Consequently, the key radiation sources characterizing these scenarios encompass GCRs, solar protons, and trapped particles when traversing the GEO environment.

3.1 Galatic Cosmic Rays

GCRs are highly energetic particles (up to GeV) originating from outside our solar system, primarily from supernovae and other energetic events in the Milky Way galaxy. These rays consist mostly of protons, with a small fraction of heavier nuclei and electrons. GCR particles entering the heliosphere experience modulation by the Sun's magnetic field and solar wind, which varies in intensity with respect to distance from the source and solar activity. In relation to the data in Table 1, the GCR's contribution is expected to affect the CPO phase of the mission. Indeed, for all the proposed trajectories, the interplanetary cruise mostly occurs during solar maximum activity, which naturally shields the GCRs. In contrast, during the scientific part of the mission, due to minimum solar activity, GCRs penetrate the solar system and may cause SEE that may be disruptive in sensitive devices of the payload.

A traditional tool like CREME96, when employed for interplanetary missions, adopts a general GCRs model that does not consider the distance from the Sun, a critical factor influencing GCR propagation. Therefore, we adopted a comparative approach, analysing GCRs contribution with CREME96 and ESA tool SPENVIS, the latter configured with the CPO mission parameters. Specifically, the CPO phase starts after the spacecraft rendezvous with the asteroid and lasts 6 months. Hence, the satellite's trajectory coincides with that of Apophis, having an average distance from the Sun of 1.0 AU happening during the solar minimum. Table 2 shows the flux of the proton contribution in GCRs. The GCR proton flux is employed to predict the Single Event Upset (SEU) [7] rate in bits per day.

Table 2. GCR Interplanetary Solar Minimum Flux CPO trajectory.

Energy (MeV/nucleon)	**H flux $(m^2\text{-s-sr-MeV/nuc})^{-1}$**	
	CREME	**SPENVIS**
1.00E+00	2.21E+02	3.102E-04
1.02E+01	3.96E-01	3.879E-02
4.92E+01	8.24E-01	4.661E-01
7.04E+01	1.14E+00	6.397E-01
1.01E+02	1.48E+00	8.320E-01
1.99E+02	1.99E+00	1.228E+00
1.05E+03	1.19E+00	1.033E+00
1.01E+04	2.24E-02	2.163E-02
1.00E+05	6.04E-05	5.837E-05

3.2 Solar Protons

Solar protons are high-energy particles emitted by the Sun, particularly during solar flares and coronal mass ejections. These particles can penetrate spacecraft shielding and interact with electronic components, causing issues like SEE and TID . The impact of solar protons is most significant during the interplanetary cruise phase of the Zodiac Pioneer mission to Apophis, especially when solar activity is at its peak. The distance from the Sun modulates the flux of solar protons hitting the spacecraft, meaning the proton flux will vary across the three proposed trajectories. However, the SPENVIS tool cannot support multi-segment interplanetary missions, so the solar proton contribution for the three trajectories can only be estimated based on boundary conditions or the average distance from the Sun. This limitation is important because it hinders the accurate estimation of TID for the mission and prevents a clear comparison of the radiation effects across the proposed trajectories, making it difficult to determine the optimal path. When considering the average distance from the Sun, 1 AU for all three trajectories, SPENVIS results—configured using each trajectory's launch date, cruise duration, and average distance—indicate nearly identical exposure to solar protons, as shown in Fig. 2.

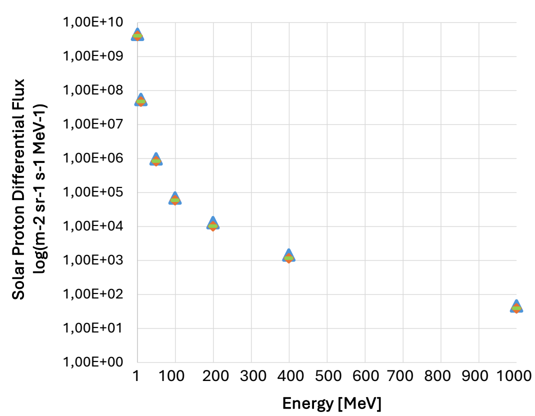

Fig. 2. Solar proton flux at the trajectories average distance.

However, this assumption is inaccurate. Consequently, in the following radiation analysis section, we will outline our proposed methodology for accurately estimating the TID induced by solar protons, considering the actual spacecraft trajectory. This approach will emphasize the key differences among the trajectories despite their shared average distance and boundary conditions, which are mission design constraints.

3.3 Trapped Particles

The Zodiac Pioneer mission to Apophis holds significant importance due to the asteroid's close approach to Earth expected on 13/04/2029, with its closest distance being approximately 30,000 km from the Earth's surface—the same region dedicated to geostationary telecommunications satellites. This proximity underscores the critical need to study Apophis both before and after it enters Earth's sphere of influence to understand how its properties may change during this close encounter. In GEO orbits, spacecraft are largely exposed to GCRs and solar flare particles, while the contribution of trapped particles is lower than in LEO or MEO environments. Indeed, the only trapped protons present have energy levels below those required to initiate nuclear events in the materials surrounding sensitive regions of devices to cause SEEs. Moreover, protons having energy below approximately 40-50 MeV are typically geomagnetically attenuated. Conversely, the outer Van Allen Belt is electron-rich, contributing to the TID effect.

The effective distances between Earth and Apophis are considered to assess the environment characterizing this mission phase. Given that the outer Van Allen Belt extends from 13,000 to 60,000 km above Earth's surface, our analysis includes only the trajectory points of Apophis that enter this range. Table 3 provides the time and distance of the asteroid relative to Earth, which were used as inputs for the characterization tools.

Table 3. Apophis-Earth distances during the asteroid fly-by

Epoch	Apophis – Earth Distance [km]
2029-04-13 19:45:00.000	60991.44255
2029-04-13 20:45:00.000	45015.02736
2029-04-13 21:45:00.000	38021.84143
2029-04-13 22:45:00.000	44866.62215
2029-04-13 23:45:00.000	60777.86527

We exploited two different tools to evaluate the radiation effects of this mission phase. Specifically, we compare the results obtained with SPENVIS with those achieved utilizing the OMERE tool from TRAD-CNES. Considering the data in Table 2, we must model the spacecraft trajectory as a multi-segment geostationary orbit. However, in SPENVIS, the minimum duration for each segment is 0.1 days, approximately 2.4 hours. Conversely, the data available on Apophis trajectory is at 1-hour intervals. For this reason, we configured SPENVIS with a single GEO-type mission with a duration of 0.2 days, covering the time interval of interest. As orbit parameters, we selected the asteroid's maximum distance point inside the outer Van Allen belt (approximately 61,000 km) as apogee, while the minimum distance (approximately 38,000 km) as perigee.

On the other hand, in the OMERE tool, it is possible to provide the GEO orbit file with discrete trajectory points expressed in km and discrete time expressed in seconds. Hence, we can evaluate the effective spacecraft trajectory. We run both tools to evaluate trapped proton and electron spectra, whose values are reported in Table 4. Since SPENVIS uses a GEO orbit to model the asteroid trajectory, particle fluxes' values are higher than those of OMERE, which instead refers to the effective Apophis-Earth position.

Table 4. Trapped particles during asteroid fly-by

Energy [MeV]	**OMERE**		**SPENVIS**	
	Differential flux [cm-2.s-1.MeV-1]		**Differential flux [cm-2.s-1.MeV-1]**	
	Trapped Protons	*Trapped Electrons*	*Trapped Protons*	*Trapped Electrons*
0.1	1.25599e+06	6.54068e+07	1.4583E+06	1.8727E+08
0.25	1.48757e+05	1.31377e+07	1.4295E+05	2.8044E+07
0.75	1.65748e+04	4.26260e+05	5.9491E+03	1.0859E+06
1.00	2.67286e+03	1.44208e+05	1.2062E+03	4.7513E+05
2.00	3.82077e+02	7.20325e+03	9.3748E+00	2.0687E+04
3.00	0.00000e+00	4.57799e+02	0.0000E+00	1.2681E+03
4.00	0.00000e+00	1.01398e+02	0.0000E+00	2.5950E+02
5.00	0.00000e+00	1.21438e+00	0.0000E+00	1.5535E+01
6.00	0.00000e+00	0.00000e+00	0.0000E+00	0.0000E+00

4. Radiation Analysis

This section evaluates the radiation effects expected for the Zodiac Pioneer spacecraft in the mission to Apophis. Two key aspects are evaluated: the TID effects and the SEU sensitivity of the flight computer module (FCM).

4.1 Total Ionizing Dose

At this mission phase, where feasibility studies are conducted, evaluating the implications of radiation effects related to the different proposed trajectories is crucial. However, as shown in Section 3.2, solar proton contributions, the main source of TID [8], cannot be successfully estimated considering trajectory characteristics due to limitations in modeling multi-segment interplanetary missions in conventional tools. Moreover, adopting the approach of manual trajectory fragmentation into independent segments having a constant distance from the Sun and evaluating them separately is impractical. This is because tools like SPEVINS require a minimum segment duration of 6 months, which is incompatible with trajectories, such as those being analyzed for the mission to Apophis, where the distance from the Sun fluctuates over short periods (a few months or weeks). To overcome this challenge, a custom framework has been developed. Drawing upon experimental data from SPENVIS, this framework can generate a dose profile that accommodates all variations in the spacecraft's trajectory distance to the Sun and the diverse solar activity conditions characterizing each trajectory segment.

The developed framework is based on constructing a dose value database extracted from SPENVIS using the SHIELDOSE-2 model. This constructed database considers the variation of parameters such as distance from the Sun, different mission lengths in 100-day increments ranging from a minimum of 183 days (minimum mission duration allowed in SPENVIS) to 1200 days, varying solar activity levels (sun max, sun min), and different shielding thicknesses.

Based on this database, the framework's core is a polynomial regression engine modeling the TID effect with a set of functions for each distance and shielding thickness. The framework inputs each point's effective spacecraft trajectory in AU and solar activity conditions. These data are processed and converted to a format compliant with the regression model. The tool returns the total mission dose for a specific shielding thickness.

The developed tool has been used to compare the three proposed interplanetary trajectories to Apophis. Moreover, to validate the consistency of the dose values reported by the tool, we also evaluated the TID related to nominal and worst-case scenarios estimated by the developed tool and by SPENVIS. In the nominal case, the SPENVIS tool, for each trajectory, is configured with an interplanetary mission occurring at the trajectory average distance from the Sun and with mission length the interplanetary cruise duration. Similarly, it considers the trajectory point closest to the Sun for the worst-case scenario.

Dose profiles were evaluated, taking into account different aluminium shielding thicknesses. Specifically, the selected values range from 1.5mm to 5mm. Results are shown in Fig. 3.

The worst-case dose values for trajectory 2 and trajectory 3 present two minimum distance values, 0.8 AU and 0.7 AU, depending on whether the trajectory's minimum distance point (approximately 0.75 AU) is rounded up or down. This underscores the criticality of adopting worst-case scenarios, as the dose values in the two approximation cases differ by about 2 krad for all the shielding thickness values while also being one order of magnitude higher than the effective trajectory-based estimation. Adopting the worst-case scenario could negatively impact the electronic component selection, leading to the exclusion of devices that are actually compliant with mission characteristics.

Fig. 3. TID for the different interplanetary trajectories to Apophis obtained with the developed tool and with SPENVIS.

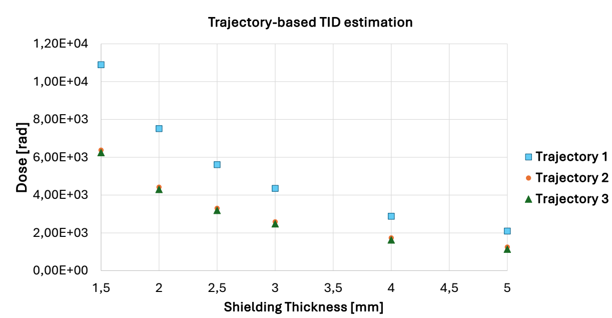

Fig. 4. Trajectory-based TID estimation.

In Fig. 4, the comparison between the dose estimation related to the three different trajectories is proposed. These dose values reflect the effective spacecraft

trajectory proposed by Politecnico di Milano and achieved with our developed TID framework.
As can be seen from the data, trajectory 1 presents higher exposure to radiation dose. The reason can be found in the fact that this trajectory has both the longest duration and longest exposure to maximum solar activity. Indeed, even if trajectories 2 and 3 have the closest point to the Sun at almost 0.75 AU while trajectory 1 is at 0.8 AU, the impact of solar activity in TID is higher since the spacecraft assumes these closest points for just a few days. The value of the dose of trajectory 1 considering 1.5mm Al shielding has been selected as the worst-case scenario for radiation hardness assurance of spacecraft on-board COTS.

4.2 Single Event Upset on Flight Computer Module

The spacecraft FCM, heritage from the MILANI CubeSat [9] of HERA mission, is implemented on the Zynq7030 system on chip (SoC). This SoC comprises an ARM processing system (PS) and SRAM-based FPGA. The FCM exploits both the hardwired PS and the programmable logic of the FPGA.

The peculiarity of FPGA devices is the reconfigurability of the logic resources. Indeed, designs are implemented through a bitstream file loaded in the configuration memory (CRAM), whose content configures the device resources (logic, interconnection, and memory) to implement the target circuit. These kinds of devices are particularly sensitive to radiation-induced SEU. When a high-energy particle hits the memory cell, it may cause an SEU in the CRAM, altering the memory content and inducing structural changes in the implemented circuit, eventually provoking system failure[10][11]. In addition to shielding, hardening techniques such as redundancy and memory scrubbing should be utilized to mitigate this risk. Tuning the frequency of the memory scrubbing operation can be related to the expected SEU rate per mission day and the implemented design's Mean Time to Failure (MTTF). Consequently, characterizing the FCM module about this aspect is deemed extremely important.

The SEU sensitivity is strictly technology-dependent. To correctly estimate the expected SEU rate affecting the mission, it is necessary to relate the predicted protons and heavy ions fluxes with the SEU cross-section of the CRAM per square centimeter per bit (cm^2/bit). The literature provides various radiation tests for the Zynq 7000-SoC family. Still, the Zynq7030 device has not been characterized yet. The closest device is the Zynq7045, which only differs in resource quantities (LUT, DSP, BRAM) and I/O while sharing the same 28nm CMOS technology process. SEU cross-section for Zynq7045 is detailed in Table 5. Figure 5 schematizes the overall procedure adopted to obtain the SEU rate estimation related to the FCM device.

Table 5 Proton-induced SEU Cross Section per Bit

Energy [MeV]	**XC7Z045 CRAM cross section per bit [cm^2/bit]**
30	1.699E-15
50	4.284E-15
100	5.047E-15
150	5.701E-15
200	5.865E-15

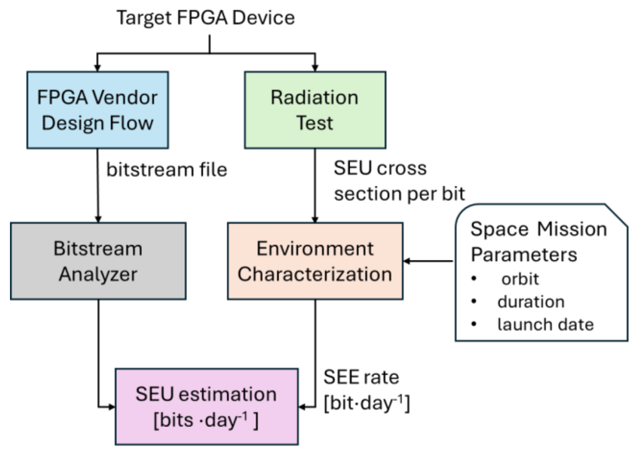

Fig. 5 Overview of SEU estimation methodology.

The procedure requires knowledge of the effective amount of unmasked bits composing the Zynq7030 CRAM, which may provoke system failure if affected by SEU. However, since the FCM module bitstream is encrypted, we implemented a custom dummy design targeting the same FPGA device to produce a bitstream file. The Zynq7030 bitstream file is further analyzed to retrieve all the required information. In parallel, the SEU cross-section provided in the literature and reported in Table 5 is used to estimate the device SEU per bit per day. Our estimation covers different mission parameters. Specifically, we targeted the maximum and the minimum of solar activity as environmental conditions considering different distances from the Sun (0.7 AU, 0.8 AU, 0.9 AU, 1.0 AU). In the SEU estimation, we only considered the contribution of protons. Indeed, despite the availability of the heavy-ion SEU cross-section, both the OMERE tool and SPENVIS require not only the cross-section data points but also the memory cell depth, which is technology information not known. Still, protons represent the higher contribution of high-energy particles in space. SEU estimation results are reported from Fig. 6 to Fig. 9.

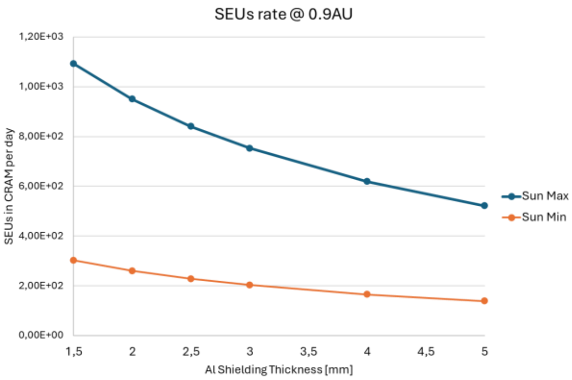

Fig. 6 FCM device SEU estimation at 1 AU.

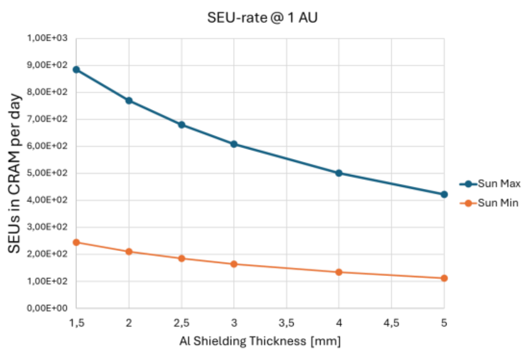

Fig. 7 FCM device SEU estimation at 0.9 AU.

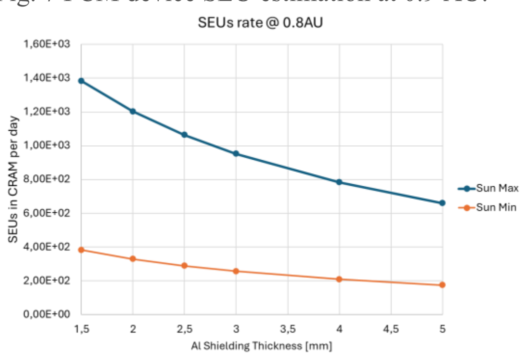

Fig. 8 FCM device SEU estimation at 0.8 AU.

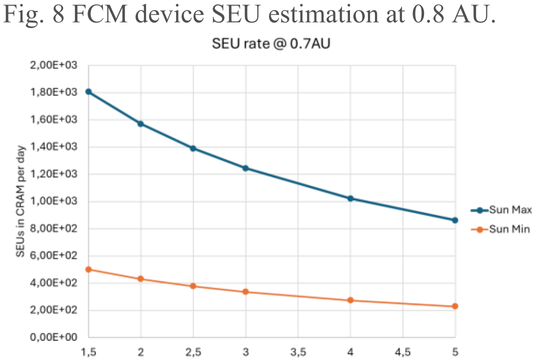

Fig. 9 FCM device SEU estimation at 0.7 AU.

5. Strategy for Radiation Hardness Assurance

Zodiac Pioneer spacecraft mainly equips COTS components. As metrics to scrutinize the BOM to detect critical components to be either radiation tested or replaced with parts compliant with mission specification, we selected the radiation analysis results of trajectory 1 environmental condition, being not only the worst-case scenario of harsh environment to reach Apophis but also for the other NEAs targets being analyzed for the Zodiac Pioneer mission, not detailed in this work. Considering the minimum shielding thickness of 1.5mm, COTS should tolerate at least 12 krad of radiation dose. Regarding single-event effect testing methodologies, it is essential to evaluate the sensitivity of COTS components to destructive effects (such as burn-out and gate rupture) and those that could reduce system availability, such as single-event latch-up and functional interrupt. This evaluation aims to ensure that the mitigation and recovery measures implemented in the system can adequately handle these scenarios. A radiation test campaign using high-energy protons with a minimum energy of 200 MeV is recommended.

6. Conclusions

The Zodiac Pioneer mission aims to study NEAs main reasonable rendezvous possibilities in the next 8 years. One of the most important use cases to be considered is the Earth's close encounter with the 99942 Apophis asteroid. At this time of the mission feasibility study, three different interplanetary trajectories are evaluated, each characterized by different environmental conditions. Solar protons have been identified as the major source of radiation effect during the interplanetary cruise to reach Apophis, while GCRs will predominantly affect the close proximity operation. To characterize the mission with respect to the TID effect, a custom framework has been implemented to comprehensively perform trajectory-based mission dose estimation to distinguish the different proposed trajectories having the same boundary conditions in distances from the Sun, which are mission design constraints. From our estimation, trajectory 1 is the most critical. Therefore, we selected the radiation analysis results for trajectory 1 of 12krad related to 1.5mm Al shielding as the TID threshold value in the COTS analysis. Additionally, we performed SEU rate estimation on the FCM module, considering technology sensitivity retrieved from the proton SEU cross-section combined with the environment characterization. Further analysis will be performed to characterize critical COTS against disruptive SEE through radiation test campaign.

References

[1] Bancelin, Colas, Thuillot, Hestroffer, Assafin, Asteroid (99942) Apophis: New predictions of Earth encounters for this potentially hazardous asteroid, 2012, Astronomy and Astrophysics. 544. 15-.

[2] A.J. Tylka, James H. Adams, Jr., Paul R. Boberg, Buddy Brownstein, William F. Dietrich, Erwin O. Flueckiger, Edward L. Petersen, Margaret A. Shea, Don F. Smart, and Edward C. Smith, CREME96: A Revision of the Cosmic Ray Effects on Micro-Electronics Code, 1997, IEEE Transactions on Nuclear Science, 44, 2150-2160.

[3] M. Kruglanski et al., Last upgrades and development of the space environment information system (SPENVIS), European Conference on Radiation and Its Effects on Components and Systems, Brugge, Belgium, 2009, pp. 563-565.

[4] P. Peyrard, T. Beutier, O. Serres, C. Chatry, R. Ecoffet, G. Rolland, D. Boscher, S. Bourdarie, C. Inguimbert, P. Calvel, R. Mangeret, 2004, OMERE - A Toolkit for Space Environment.

[5] A. Morelli et al. "Initial Trajectory Assessment of the RAMSES Mission to (99942) Apophis", Advances in Space Research, 2024.

[6] National Oceanic and Atmospheric Administration (NOAA) https://www.swpc.noaa.gov/products/solar-cycle-progression/

[7] F. Jain, J. Vasi, R. K. Lal, SEU reliability analysis of advanced deep-submicron transistors, 2005, in *IEEE* Transactions on Device and Materials Reliability, vol. 5, no. 2, pp. 289-295.

[8] L. Chevas et al., Investigation of Scaling and Temperature Effects in Total Ionizing Dose (TID) Experiments in 65 nm CMOS, 2018, 25th International Conference Mixed Design of Integrated Circuits and System (MIXDES), Gdynia, Poland, 2018, pp. 313-318.

[9] F. Ferrari, V. Franzese, M. Pugliatti, C. Giordano, and F. Topputo. Preliminary mission profile of Hera's Milani CubeSat. Advances in Space Research, 67(6):2010–2029, 2021.

[10] E. Vacca, S. Azimi, L. Sterpone, Failure rate analysis of radiation tolerant design techniques on SRAM-based FPGAs, 2022, Microelectronics Reliability.

[11] E. Vacca, S. Azimi, L. Sterpone, Analyzing the SEU-induced Error Propagation in Systolic Array on SRAM-based FPGA, IEEE Radiation and its Effects on Components and Systems (RADECS), 2023.