A TID Estimation Tool based on Machine Learning for the Zodiac Pioneer Mission

# A TID Estimation Tool based on Machine Learning for the Zodiac Pioneer Mission

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***Abstract*—We developed a tool for the TID estimation of space missions based on a machine-learning approach. The tool has been effectively used to characterize the radiation environment for the ESA Zodiac Pioneer mission.**

***Index Terms*—TID, Interplanetary Mission, Radiation Effect, Machine Learning, Radiation Environment.**

## I. Introduction

One of the top priorities in ESA's Space Safety Program related to Planetary Defense is the implementation of a class of fast rendezvous satellites to characterize potentially dangerous asteroids for the Earth. The main objective of the ongoing study is to conceive a small satellite baseline design enabling an asteroid scout mission Zodiac Pioneer to a wide range of targets. The ongoing study takes as a starting point the list of known Near Earth Asteroids with high interest for Planetary Defense and reasonable rendezvous possibilities in the next 8 years. When space missions require intercepting asteroid orbits, the spacecraft's trajectories often exhibit large fluctuations in distance from the Sun, occurring in short time intervals. In addition, the duration of the spacecraft's interplanetary cruise can be significant enough to experience transitions in solar activity, going from maximum to minimum or vice versa.

These factors result in a highly variable radiation environment and effects characterizing the spacecraft trajectory. A comprehensive radiation analysis requires characterizing each mission phase with the related radiation environment. However, conventional tools [1] [2] fail to do such an accurate analysis due to the unavailability of defining multi-segment interplanetary missions and adopting a minimum interplanetary mission length of 6 months. This results in an unfeasible evaluation of an effective trajectory-based radiation environment, when the relative distance from the Sun changes within a few weeks.

Furthermore, especially in the preliminary phase of studying the feasibility of a mission, utilizing worst-case scenarios is not significant. Indeed, many trajectory solutions could be under evaluation, sharing the boundary conditions, such as the minimum and maximum distance from the Sun, due to mission design constraints. Additionally, it is frequent that worst-case distances are assumed for very short time intervals (less than 1 month). Consequently, adopting worst-case scenarios for the entire mission case would result in neglecting trajectories' characteristics and overestimating radiation effects.

Hence, we proposed and developed a new comprehensive framework to estimate the total ionizing dose (TID), covering the trajectory-induced variation in the daily dose contribution. The framework is built upon a dose dataset constructed using ESA's SPENVIS tool [1], considering different interplanetary missions with variable durations, Sun distances, and solar activity. Utilizing Machine Learning (ML) algorithms trained on this dataset, the tool takes the point-to-point interplanetary trajectory as input and provides an estimate of the spacecraft's TID. The tool's first use case is the radiation environment characterization and dose estimation for the ESA Zodiac Pioneer mission. Specifically, ESA is assessing the feasibility of a mission to the 99942 Apophis asteroid, Rapid Apophis Mission for SpacE Safey (RAMSES), aiming at characterizing the dynamical and physical properties of the asteroid before, during, and after its close encounter with the Earth, expected by April 13, 2029. In intercepting the asteroid's orbits, various trajectories are currently under study [3] . Even sharing the launch year, due to variations in cruise duration, distances from the Sun, and time spent in solar maximum, the three proposed spacecraft trajectories exhibit highly variable proton fluxes affecting the cruises, resulting in diverse mission dose profiles. The adoption of traditional tools for dose estimation compromises the preservation of individual trajectory characteristics, as they rely on either the average distance value for the entire journey or the worst-case scenario, dictated by Zodiac Pioneer mission constraints.

In contrast, our tool enables the characterization of each trajectory while retaining its unique features, thus allowing for the generation of precise mission dose profiles useful in the final trajectory decision. Still, we compared the mission dose profiles generated by our framework and those derived adopting worst-case scenarios. These last were obtained from both the commercial tool and the developed platform.

Results reveal not only consistency but also the significant superiority of our methodology in accurately estimating doses while preserving trajectory specifics.

The adoption of effective trajectory-based dose estimations introduces radiation sensitivity as an additional metric in the final trajectory decision-making process. This is crucial when as for Zodiac Pioneer, the final objective is to define a baseline platform capable of reaching multiple NEAs, each characterized by different orbit and spacecraft intercepting trajectories to be comprehensively analyzed.

## II. The Zodiac Pioneer: Defining the Issue

The Zodiac Pioneer spacecraft inherits its payload, flight computer module, and the majority of its components from the MILANI CubeSat, part of the HERA mission[4] . While MILANI will operate within a radiation environment estimated at 6 krad over a 6-month active mission period, it's imperative to meticulously assess the TID for Zodiac Pioneer to ensure the compatibility of components between the two missions.

The characterization of the radiation environment for the Zodiac Pioneer mission is closely tied to the trajectory chosen to intercept the orbit of the asteroid. Again, referring to the first case analyzed with Apophis as the target asteroid, the mission design constraints dictate that the spacecraft must reach Apophis at least two months before the Earth fly-by while maintaining a maximum distance from the Sun of 1.2 AU and a minimum distance not dropping below 0.75 AU. Additionally, a minimum time frame of three years is necessary for spacecraft design and manufacturing, setting the earliest launch date for November 1, 2026. Three candidate trajectories have been identified that comply with the aforementioned mission design constraints [3] . Although all the interplanetary trajectories share the launch date in 2027, the trajectory patterns concerning the Sun, both in terms of distance and exposure to solar activity, vary significantly between one solution and the others.

Table I. Zodiac Pioneer Proposed Trajectories

| | T1 | T2 | T3 |
|---|---|---|---|
| Departure date | May 5, 2027 | Nov 1, 2027 | Oct 27, 2027 |
| Arrival date | Feb. 8, 2029 | Feb 2, 2029 | Dec 3, 2029 |
| Time of Flight [days] | 640 | 459 | 404 |
| Time in Solar Max [years] | 1.53 | 1.03 | 1.05 |
| Time in Solar Min [years] | 0.22 | 0.22 | 0.05 |
| Worst-case Sun distance [AU] | ~0.78 | ~0.76 | ~0.75 |
| Time @ worst-case distance [days] | ~13 | ~30 | ~32 |
| Avg Sun distance [AU] | ~1.0 | ~1.0 | ~1.0 |

The trajectories' specifications are outlined in Table I. As evidenced by the data, extrapolating the radiation environment based on the worst-case scenario, uniform across all potential trajectories and limited to a brief temporal window (approximately 1 month), would not only reduce the comparison exclusively to cruise duration but also induce an overestimation of radiation effects. This overestimation arises not only because the minimum distance is traversed for less than 10% of the overall mission duration, but also because of the inherent limitations in the physical models characterizing the environment available in commercial tools.

Using the ESA SPENVIS[1] tool as an example, despite offering greater flexibility compared to historical tools [2] in defining interplanetary trajectories, it suffers from three significant limitations. (i) Interplanetary trajectories cannot be multi-segmented, meaning one must either utilize the worst-case scenario or the average value for the entire mission. (ii) The minimum duration for interplanetary missions is set at 6 months, thus precluding the possibility of breaking the mission into independent segments at varying distances if they last less than 6 months. (iii) Interplanetary distance is defined through discrete steps, leading to arbitrary approximations.

In the presented worst-case scenario of Table I, rounding down to 0.7 AU will result in an even more critical overestimation of the radiation environment to which the spacecraft will be exposed. On the other hand, assuming that spacecraft will never be closer than 0.8AU to the Sun is an underestimation.

All these aspects are crucial, especially during the early design phases when the primary objective is to identify the optimal trajectory that satisfies all mission requirements.

## III. The Proposed Methodology

Maintaining information regarding spacecraft distances from the Sun and dwell time is crucial, particularly in tailoring the estimation of TID for the mission. Historically, worst-case scenarios were always employed in terms of solar particle events and distances. However, this approach may lead to either eliminating parts that could be acceptable or incurring increased mass and cost to shield some Commercial Off-The-Shelf (COTS) parts. An alternative approach involves examining the mission timeframe within the solar cycles and predicting the sunspot number for the mission period [6] as proposed by the NASA team for the Resource Prospector Mission to estimate the TID on electronic components accurately. Nevertheless, when the spacecraft trajectory varies significantly concerning the Sun, predicting solar activity is merely the initial step in comprehensive dose estimation.

To consider both the fluctuation in solar activity and changes in distance from the Sun, and to address the challenges outlined in points (i) and (ii) from the previous section, we developed a custom TID estimation framework.

The central core of the framework encompasses a fourth-degree polynomial regression model trained on a database of dose values derived from the SPENVIS environment characterization tool.

### A. *Model Dataset*

The database was constructed by instrumenting the SPENVIS tool with various mission configurations to encompass all possible scenarios. Specifically, the collected data are categorized into two main blocks, associated with maximum and minimum solar activity. For each solar activity phase, four classes of values are distinguished, linked to four different distances from the sun ranging from 0.7 AU to 1.0 AU. For each distance, under the two different solar conditions, the dose contribution is gathered by generating space missions of increasing duration, starting from the minimum value of 183 days with regular intervals up to a maximum of 1200 days. This value is determined by the fact that beyond approximately 1200 days, there is a transition from minimum to maximum activity in most of the available data on past solar cycles in SPENVIS. Once the mission specifications are set, the SPENVIS tool is configured to calculate the solar proton fluence using the SAPPHIRE model [7] . Subsequently, the TID estimation engine is executed, adopting the Aluminum sphere model and the SHIELDOSE-2 calculation model. For each run, the output is a table of dose values for different shielding thicknesses. These data constitute the database used for training the custom TID framework.

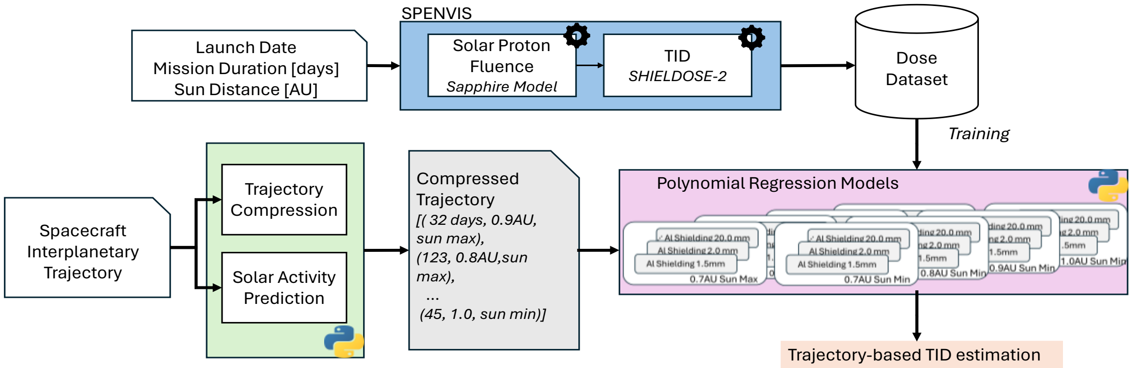


Fig. 1. TID estimation developed framework.

## B. *TID Estimation Framework*

An overview of the system is presented in Fig. 1. The framework receives the spacecraft trajectory along with its launch date as input and translates it into a suitable format for the TID estimation, through the Trajectory Compression module and the Solar Activity prediction one. The custom TID engine is structured as a collection of distinct regression models, taking into account not only the distance from the Sun and solar activity but also the thickness of the shielding. Therefore, the primary input required by the top entity of the TID estimator is the mission segment specified by Sun distance, duration in days, solar activity, and shielding thickness. As output, the tool produces the predicted dose value for the specified conditions. Figure 2 illustrates the regression curve models estimating dose values for Aluminum shielding with a thickness of 2.5mm across various solar activity conditions and distances.

The effectiveness of the proposed model has been validated through test data points (i.e., not used during model training). The predicted dose values are compared with those produced by SPENVIS when set with the same mission conditions. Figure 3.a. proposes some of the obtained results when both tools are configured with an Al shielding thickness of 2.5mm and maximum solar activity, spanning different distances scenarios and mission duration. Moreover, the induced model absolute error for the test data points is proposed in Figure 3.b. As can be appreciated from the proposed plots, the developed model introduces an error smaller than 40 rad for most of the test points adopted. Higher error contribution relates to test points characterized by mission duration over 1000 days, while the model does not fit for missions over 1300 days due to the transition from solar min to max in the data points as explained previously, which is not covered by the tool at this prototyping phase. Due to the tool's development initially tailored to address the environmental characterization requirements of the Zodiac Pioneer mission and the tight deadline, its current limitations notwithstanding, the tool's adaptability and precision align with mission specifications while showing high flexibility.

## IV. Experimental Analysis

The developed tool was utilized to estimate the TID contribution associated with the various interplanetary trajectories proposed in the Zodiac Pioneer mission to intercept the orbit of the asteroid Apophis. The three trajectories are characterized by significant fluctuations in the distance between the spacecraft and the Sun over short time intervals (< 6 months), rendering the use of conventional tools such as SPENVIS impractical without resorting to worst-case scenario assumptions (no multi-segment interplanetary mission allowed).

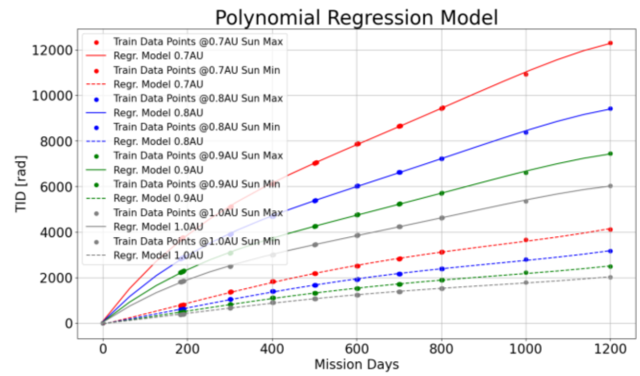


Fig. 2. TID developed model curves for different Sun conditions and distances. Dot points are SPENVIS dose data used during model training.

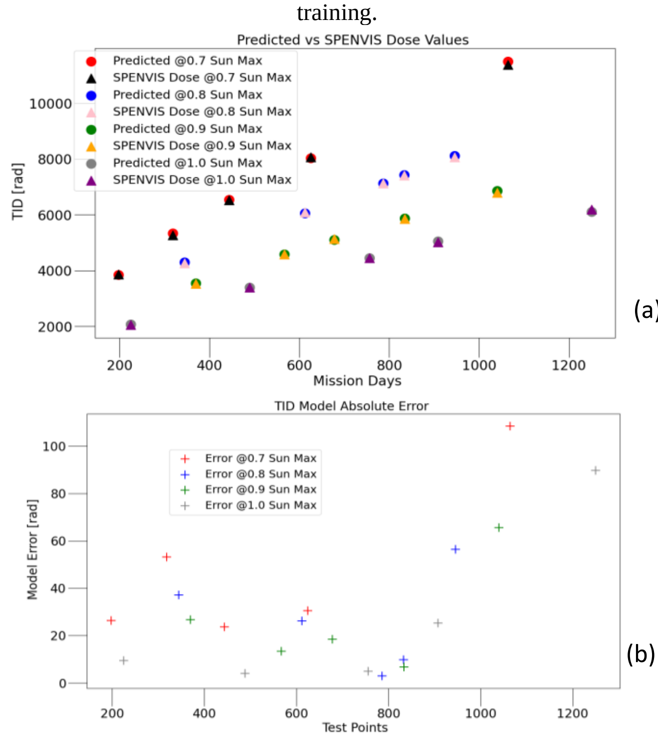


Fig. 3. TID developed framework validation. (a) the model predicted TID values compared to SPENVIS outcomes (b) the absolute error introduced by the model in the TID computation with respect to SPENVIS dose results.

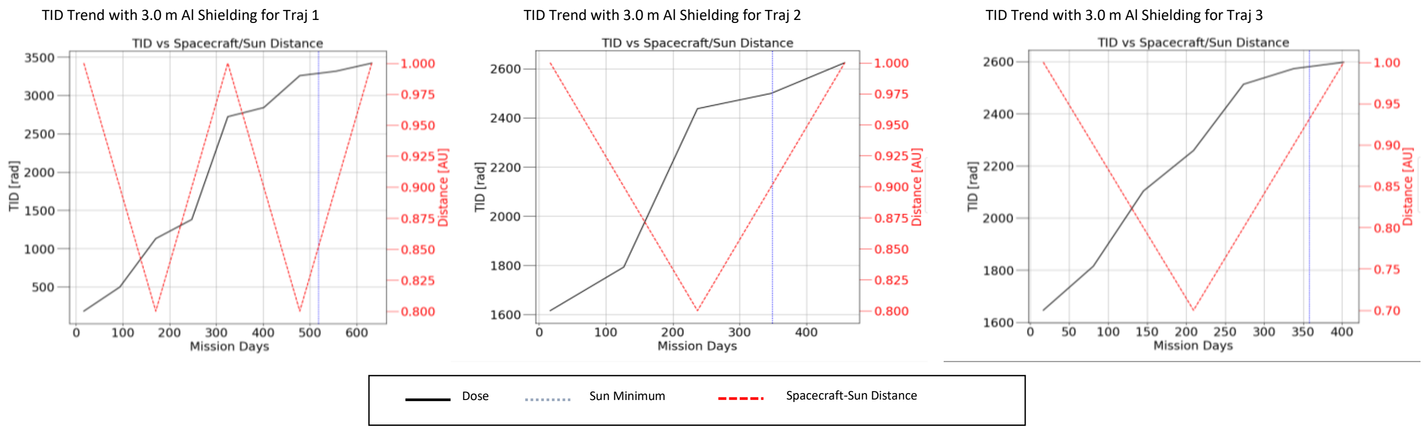


Fig.3 Developed tool TID estimation for the three different trajectories solution when selecting 3.0mm of Al shielding.

However, in this exploratory phase of the mission, relying solely on the worst-case scenario, as previously explained, would restrict the comparison of trajectories solely based on their duration and exposure time during solar max. The three trajectories are available as a set of points defined by (distance, time). Distance relates to the Sun, while the time step between two consecutive points is about 1.2 days.

To exploit the developed tool, each trajectory needs to be *compressed* into discrete segments defined by common average distance, overall duration (which could be smaller than 6 months), and sun activity. The latter is estimated by exploiting the solar cycle prediction tool available in the National Oceanic and Atmospheric Administration (NOAA)[8] as proposed by authors in [4] . Once the trajectory is defined as a multi-segment discrete trajectory, it is given as an input to the tool along with the desired Al shielding thickness. The developed tool produces the estimated TID, as well as dose trend increment along the trajectory. Figure 4 shows the obtained results for the three Zodiac Pioneer trajectories when selecting 3.0 mm of Al shielding. Moreover, for the three trajectories, the worst-case scenario has been evaluated using both the developed tool and SPENVIS. Results are reported in Table 2 which shows that the values generated by our custom tool for the worst-case scenario lightly exceed those generated by SPENVIS. This variance can be attributed to the fact that SPENVIS automatically adjusts for the transition from solar maximum to minimum, causing a change in its dose contribution even with a constant distance from the Sun. In contrast, our tool lacks this feature in its model, resulting in the obtained outcome being consistently based on the worst-case distance during solar maximum. Conversely, the trajectory-based estimation yields significantly lower results compared to the worst-case scenario for all proposed solutions. This means that all proposed solutions comply with the MILANI legacy (designed to tolerate up to 6 krad), even with a thinner shielding choice than required for the worst-case scenario.

## V. Conclusion

In this study, we introduced a tailored framework for estimating TID along interplanetary trajectories featuring rapid and significant variations in distances from the Sun within short timeframes. Our tool tackles the limitations of commercial software, which do not support the definition of multi-segment interplanetary trajectories. Applied to the Zodiac Pioneer space mission, our framework demonstrated superior accuracy in dose estimation compared to the adoption of a worst-case scenario approach.

TABLE II. Interplanetary Cruise TID Estimation

| | Trajectory 1 TID [rad] | | |
|---|---|---|---|
| Al Thickness | Traj-based | Worst Case | SPENVIS Worst Case |
| 1.5 | 8.44e+03 | 1.20e+04 | 1.15e+04 |
| 2.5 | 4.36e+03 | 6.23e+03 | 5.95E+03 |
| 3.0 | 3.42e+03 | 4.88e+03 | 4.66E+03 |
| 4.0 | 2.30e+03. | 3.27e+03 | 3.13E+03 |
| | Trajectory 2 TID [rad] | | |
| Al Thickness | Traj-based | Worst Case | SPENVIS Worst Case |
| 1.5 | 6.48e+03 | 1.29e+04 | 1.20e+04 |
| 2.5 | 3.34e+03 | 6.67e+03 | 6.19e+03 |
| 3.0 | 2.62e+03 | 5.22e+03 | 4.85e+03 |
| 4.0 | 1.76e+03 | 3.50e+03 | 3.25e+03 |
| | Trajectory 3 TID [rad] | | |
| Al Thickness | Traj-based | Worst Case | SPENVIS Worst Case |
| 1.5 | 6.42e+03 | 1.19e+04 | 1.17e+04 |
| 2.5 | 3.31e+03 | 6.18e+03 | 6.02e+03 |
| 3.0 | 2.59e+03 | 4.84e+03 | 4.72e+03 |
| 4.0 | 1.74e+03 | 3.24E+03 | 3.17e+03 |

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