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Toward the Use of Electronic Commercial Off-the-Shelf Devices in Space: Assessment of the True Radiation Environment in Low Earth Orbit (LEO)

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Abstract: Low Earth orbit missions have become crucial for a variety of applications, from scientific research to commercial purposes. Exposure to ionizing radiation in Low Earth Orbit (LEO) poses a significant risk to both spacecraft and astronauts. In this article, we analyze radiation data obtained from different LEO missions to evaluate the potential of using electronic commercial off-the-shelf (COTS) devices in space missions. This study is focused on the total ionizing dose (TID). Our results demonstrate that COTS technology can effectively provide cost-effective and reliable solutions for space applications. Furthermore, we compare the data obtained from actual missions with computational models and tools, such as SPENVIS, to evaluate the accuracy of these models and enhance radiation exposure prediction. This comparison provides valuable insights into the true radiation environment in space and helps us to better understand the potential of COTS technology in reducing costs and development times by utilizing technology previously used in other areas. In light of the results, we can see that the radiation values observed experimentally in space missions versus the computer simulations used present variations up to a factor of 30 depending on the model used in the analysis.

Keywords: TID; dosimetry; COTS; radiation; LEO

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1. Introduction

Low Earth orbit missions have numerous advantages, such as their relatively low cost and accessibility, which make them ideal for various applications like Earth observation, remote sensing, telecommunications, and scientific research. For instance, the International Space Station (ISS) operates in an LEO and is used for research and technological development projects. However, LEO missions pose unique challenges, including exposure to ionizing radiation, which implies a significant risk to spacecraft and astronauts. The radiation environment in an LEO is composed of a mixture of charged particles, such as protons and electrons, including those from the South Atlantic Anomaly (SAA), Galactic Cosmic Rays (GCRs), Solar Energetic Particles (SEPs), and Albedo Neutrons. These particles can range from high-energy protons to low-energy electrons and can potentially damage electronics, leading to costly mission failures and affecting human tissues. Examples of electronic failures include single event upsets (SEUs), single event latch-ups (SELs), and single event burn-outs (SEBs) [1]. Therefore, mitigating the effects of ionizing radiation exposure is crucial for the success of LEO missions.

One of the challenges in designing and operating LEO missions is estimating the total radiation dose that the spacecraft and its components will receive. This requires understanding the type, energy, and flux of the particles involved in the radiation environment. Tools like SPENVIS [2] are used to estimate the radiation dose a spacecraft will receive in a given orbit using models like CREME (Cosmic Ray Effects on Micro-Electronics) [3] and SHIELDOSE [4]. Accurately estimating the radiation dose is crucial in ensuring the reliability and longevity of electronic components and systems used in LEO missions, as well as estimating the maximum radiation that astronauts will receive aboard the spacecraft.

The popularity of LEO orbits for telecommunications satellites is increasing due to the deployment of mega-constellations. These initiatives require a drastic reduction in the cost of avionics, which can be achieved through the adoption of commercial parts and industrial processes, as well as by integrating more functions and a better design for testability. However, the use of COTS components in low Earth orbit satellites poses challenges due to radiation-induced outages. In this work, we analyze different missions over the years to compare the data obtained by radiation sensors versus those calculated by different prediction models used in space engineering. This information provides a strong basis for the use of COTS technology in future LEO missions, as it should improve the reliability and availability of space systems and ensure the success and safety of these missions. Thus, in this article we continue and extend the scope of previous studies wherein the ability of certain components to resist ionizing radiation has already been demonstrated [5,6].

2. Radiation in Space and Its Effects on Electronic Components

Once on board the spacecraft, humans and electronic components receive radiation of various types and origins that causes different types of damage. In this section, we first present a summary of all radiations and their effects, and then focus on the different ways in which expected radiation doses can be estimated during the lifespan of space missions.

2.1. Radiation in Space

LEO is a region in space that extends from approximately 160 to 2000 km above the Earth's surface. There, the space environment is strongly influenced by various sources of radiation that pose a significant threat to human health and the functioning of spacecraft systems, as it implies a transference of energy from charged particles to human tissues and electronic components. The amount of exposure depends on the particle's charge, mass, and energy. It is essential to understand the nature and impacts of these sources to ensure the safety of the astronauts and the correct functioning of the systems.

In this section, we will examine the main sources of radiation in space and their impacts on human health and technology.

- Cosmic Radiation: CR is a high-energy particle flux originated outside the Solar System. It consists of high-energy protons, alpha particles, and heavy ions with high linear energy transfer (LET) that can penetrate materials and cause ionizing damage to living organisms and electronic systems. The GCRs (Galactic Cosmic Rays) spectrum is a complex combination of fast-moving ions from various elements in the periodic table, with hydrogen and helium ions as the most abundant. However, predicting the space radiation health risk is a challenge due to the broad disparity in energies and species of ions.
- Solar Particle Events: SPEs are short-lived bursts of high-energy particles that are expelled from the Sun and can reach the Earth in hours. They can pose a significant threat to astronauts and satellite systems, especially during periods of high solar activity.
- Van Allen Belts: Van Allen Belts are two regions of charged particles that are trapped in the Earth's magnetic field. These particles can be a threat to electronics and human health during long-duration missions in LEO.
- Atmospheric Radiation: The Earth's atmosphere acts as a shield against cosmic radiation, but it also contains naturally occurring radioactive isotopes that can contribute to the overall radiation dose in the LEO.

- Spacecraft-Generated Radiation: The operation of spacecraft systems and their components can also generate radiation, including secondary electrons and electromagnetic interference. This radiation can impact the performance of electronic systems.

It is important to note that these sources of radiation can have different energies and interact differently with spacecraft materials and electronics. It is essential to understand their properties to effectively mitigate their effects on space missions. For an in-depth study, see [1,7,8] and the references therein.

2.2. Radiation Effects on Electronic Components

Electronic components are critical to the operation of spacecraft systems, but they are also vulnerable to damage from exposure to radiation in space. The effects of radiation on electronic components can range from minor upsets to permanent failure, which may result in reduced performance and increased operational risk. In this chapter, we will summarize the main effects of radiation on electronic components in an LEO.

- Single Event Effects: SEEs are caused by high-energy particles, such as cosmic rays or solar particles, that collide with electronic components and cause temporary or permanent damage. Single event upsets (SEUs) can result in incorrect data or system reset, while single event latch-ups (SELs) can cause permanent damage to the component.
- Total Ionizing Dose: TID is the accumulation of ionizing radiation that damages electronic components over time. It can cause changes in the electrical characteristics of electronic components, leading to a degradation in performance and increased risk of failure. This study focuses on the total ionizing dose in the Earth's orbit, using dosimetry data and predictive models.
- Displacement Damage: DD is caused by the displacement of atoms in the material structure of electronic components caused by high-energy particles, which can cause permanent structural damage. In turn, this can result in a loss of performance or in the failure of the component.
- Single Event Transients: SETs are short-lived electrical signals that can occur in electronic components when exposed to radiation. SETs can cause false signals, generate electromagnetic interference, or cause damage to other components in the system.

It is important to consider these effects in the design and testing of spacecraft systems to ensure a reliable and safe operation in the harsh space environment. It is crucial to implement mitigation strategies and use components tested in radiation environments to guarantee their robustness.

2.3. COTS Electronic Components in Space

Space exploration has historically been associated with substantial development costs and lengthy timelines. However, the integration of commercial off-the-shelf components has emerged as a transformative approach to mitigate these challenges, showcasing their significance in enabling cost-efficient and rapid mission execution. The integration of commercial off-the-shelf components has reshaped the landscape of space exploration. Notable missions, spanning planetary exploration and ISS resupply, have harnessed COTS technology to reduce development costs and accelerate mission timelines. However, it is imperative to acknowledge the technical and reliability challenges associated with adapting commercial components for the space environment. The Mars Science Laboratory mission (2012) in the propulsion and parachute systems included COTS components, ensuring a precise and safe landing on the Martian surface using a Doppler velocity sensor. Aboard the ISS, we can find COTS stand-alone sensors that measure H_2O, CO_2, and O_2 levels in the station (2023). The Ingenuity helicopter (2021), which operates on the surface of Mars, is also equipped with two cameras and a Telecom module (TCB) that relies on commercial off-the-shelf components. In this instance, the selection of COTS components is grounded in their compatibility with military, automotive, or industrial operating temperature ranges.

2.4. A Review of Some TID Radiation Test Results on COTS Components

In previous works [9], we determined the TID dose for some COTS components working in an ARM board based on the ESA (European Space Agency) standard by conducting a qualification campaign for the processor. We found a weak behavior of the voltage regulator and a good TID result that was in line with previous tests carried out in the same family of devices [10].

Two recent and extensive technical reports from NASA [11,12] delve into the use of COTS components in space missions and provide recommendations for their validation and usage. Additionally, a more general explanatory course in [13] is also recommended.

In [11], the focus is solely on COTS, and it points out that COTS manufactured using newer CMOS/BiCMOS technologies exhibit robust performance in the face of total ionizing dose radiation. This is attributed to the fact that, in newer technologies, the transistor gate area and oxide thickness are reduced, resulting in a lower total number of trap sites for charges generated during a radiation event. Many of the TID effects in MOS devices occur in the insulator element (SiO_2) and its interface with the semiconductor. The thickness of the dielectric element can vary from 2 nm in the gate to 1000 nm in the field oxide. Djezzar et al. [14] observe how radiation tolerance can be increased by decreasing that thickness from 10 krad with 40 nm to 500 krad with 20 nm.

On the other hand, Hodson et al's work [12] offers a broader scope and extensively addresses the use of COTS and the effects of TID across different technologies, with numerous references provided for further exploration.

In the study conducted by Armani et al. [15], a total of four microcontrollers based on FRAM technology and five operational amplifiers, encompassing both CMOS and bipolar designs, underwent total ionizing dose testing. The findings revealed that, in an unbiased mode, the microcontrollers demonstrated impressive TID tolerance, exceeding 490 krad. However, when configured to operate in deep sleep mode, their tolerance significantly decreased to 7.5 krad. On the other hand, the operational amplifiers exhibited varying levels of radiation resistance, with failures occurring at 25, 130, and 190 krad, while one unit remarkably withstood TID testing up to 350 krad.

In a related study by [16], radiation effects on diverse devices with distinct technologies were investigated at the Goddard Space Flight Center during the years 2020–2021. These devices included those utilizing bipolar, CMOS, and InGaAs/CMOS technologies, subjected to TID testing at levels of 16.3, 17.7, 20, and 50 krad. For the majority of the tested parameters, all devices remained within their specified tolerances, except for one case involving a bipolar voltage regulator. In this instance, the output voltage deviated from the specified range starting at 2.5 krad.

Furthermore, recent research conducted by [17] focused on TID testing of commercial off-the-shelf-based point-of-load (PoL) converters incorporating GaN high electron mobility transistors. A total of nine boards were manufactured and subjected to testing, with notable results. These PoL converters displayed varying degrees of radiation resistance, with failures occurring at TID levels of 20, 30, and 60 krad.

2.5. Methods for Assessing Radiation Exposure in Space Missions

NASA AE8 (Electron Fluxes) and AP8 (Proton Fluxes) radiation models, which were developed in the 1960s using data from 43 satellites, are still widely used in the space industry despite being several decades old (their last revision dates back to the 1980s). Indeed, some researchers have pointed out serious problems with these models, such as errors in coordinate calculations, discrepancies in dose estimates between different NASA models, absurd results in some cases, errors in source code [18], lack of directional models, and over-prediction of electron flux [19].

To address the need for an improved model with better time resolution, three empirical models were developed based on data from the CRRES mission [20]. These models are CRRES-PRO, CRRES-ELE, and CRRES-RAD [21]. However, the major limitation of these models was that they were based on data collected during solar maxima and only covered

14 months. To extend the CRRES-RAD model further, the APEX mission was launched, which gave birth to the APEXRAD model [22]. Also, several alternative models have been developed for modeling geostationary electron flux, such as POLE V1 and POLE V2.

Radiation experts utilize a variety of tools, including computational models, particle accelerator experiments, on-orbit radiation monitoring systems, and software and databases, to accurately estimate the expected radiation levels. These tools, which we summarize below, provide essential information for the safe and successful operation of spacecraft systems.

1. Computational Models, such as the Space Environment Information System (SPENVIS—https://www.spenvis.oma.be/, accessed on 1 July 2023) and the NASA Space Radiation Analysis Group (SRAG—https://srag.jsc.nasa.gov/, accessed on 1 July 2023) models, use algorithms and simulations to estimate the radiation levels in an LEO based on the current and predicted space weather conditions.
2. Particle Accelerator Experiments and ^{60}Co radiation sources, such as the total ionizing dose test facilities [9], are conducted in laboratory settings to simulate the effects of radiation on electronic components and other materials. These experiments provide valuable data that can be used to improve computational models and the design of radiation-hardened components.
3. On-Orbit Radiation Monitoring Systems have been installed on the International Space Station (ISS) and the MIR Space Station, as well as on other satellites including NOAA's Polar Orbiting Environmental Satellites (Space Environment Monitor) and CubeSats, to measure radiation levels in space. The data collected by these systems can be used to validate computational models and improve our understanding of the space environment in an LEO.
4. Software and Databases: Radiation experts use various software tools and databases, such as AE8-AP8, SPENVIS, STK, etc., to analyze and interpret the data collected by on-orbit radiation monitoring systems and particle accelerator experiments.

This study compares the dosimetry data of various LEO missions to gain a better understanding of the radiation environment in this space region. The comparison provides useful information for improving the accuracy of radiation prediction models and for the design of future radiation-hardened spacecraft.

2.6. System Design for Space Missions: Applying RDM (Radiation Design Margin) to Overcome the Challenges of Space Radiation

The design of electronic and electrical systems for space missions is governed by various standards and guidelines to ensure safety, reliability, and interoperability. In Europe, the European Cooperation for Space Standardization (ECSS) provides a framework for space program management (M series), quality (Q series), engineering (E series), and sustainability (U series). The whole set of ECSS regulates the design, development, implementation, and verification of space systems and their components.

In particular, ECSS cover these aspects for Electrical, Electronic, and Electromechanical Components (EEEs), including radiation effects and mitigation, in the Radiation Hardness Assurance (RHA). As for each project the RHA requirements depend on mission profile and hardware design, the standard ECSS-Q-ST-60-15 [23] considers the three radiation types previously mentioned (TID, TNID, SEE), defining how to describe the radiation environment and how to analyze the radiation effects on EEE, and identifies the EEE groups that are potentially sensitive to each type of radiation.

The space environment, including radiation, is defined in the standard ECSS-E-ST-10-04 [24], which provides a preliminary starting point for the mission trade-off when selecting the orbit. The calculation then needs to be refined mainly via Monte Carlo analysis (described in ECSS-E-ST-10-12 [25]) considering spacecraft orientation, geometry, and shielding.

Adherence to ECSS [26] standards is critical for the success of space missions and the safety of crew members. Designing with RDM is one way to meet these standards and ensure that radiation tolerance requirements are met. By incorporating an additional margin of radiation tolerance into the systems (from 1.2 to 2 depending on the mission [27]), RDM helps to mitigate the effects of radiation and ensure the reliability of electronic and electrical systems for the entire lifespan of a spacecraft. EEE components are defined in ECSS-Q-ST-60 , and a tailoring is provided for the commercial parts, also known as commercial off-the-shelf, by ECSS-Q-ST-60-13 [28]. However, the latter standard does not provide an effective relaxation of the RHA requirements, but just a flow down.

As a consequence, under RHA perspective, there is no tailoring available for the New Space business, where COTS are generally used. For this reason, New Space projects are either developed outside the European institutional perimeter, losing the benefit of a good set of ECSS standards, or are required, regardless, to propose a tailoring of ECSS that is difficult to justify, reducing the opportunity of cost optimization for low-budget missions.

2.7. Modeling Radiation Environments in Planetary Missions: Challenges and Approaches

The space radiation environment around Earth is relatively well characterized, mainly due to the significant number of spacecraft orbiting Earth, which provide in situ measurements, specially in the LEO. However, radiation environments in inter-planetary missions, such as Solar Orbiter or the most recent Juice, can pose significant challenges for spacecraft and instrument design. Accurate radiation modeling is therefore critical for mission success. As an example, we compare in this section two different trapped particle models for the Jupiter environment and estimate solar cell degradation for the Juice mission.

The two models used in this analysis are JOSE (Jovian Specification Environment) by ESA, and GIRE2 or DG2 (Divine and Garrett updated) by JPL. Five different Jupiter radial distances were considered in this comparison (5 Rj, 10 Rj, 15Rj, 20 Rj, and 30 Rj). The MCSCREAM model was used to estimate solar cell power degradation (for AZUR 3G28) for the Juice mission, starting from the available differential fluxes at the five fixed distances and interpolating data.

It can be seen in Table 1 that the differences between the two models can have significant impacts on solar cell performance and the estimated TNID (total non-ionizing dose). The use of the MCSCREAM model to estimate solar cell power degradation provides a valuable tool for mission designers to evaluate the expected performance of solar cells under different radiation conditions.

Table 1. The preliminary estimation of solar cell degradation with the JPL updated model underlines the need of more effort in the solar cells' design and in the Jupiter environment definition.

Cover Glass Thickness	150 μm	300 μm
JOSE (ESA)	85%	90%
GIRE2 (DG2-JPL)	73%	82%

Regarding the TID analysis, the general model used for ionizing dose is SHIELDOSE-2 RD, and an updated version called SHIELDOSE-2Q RD is used for the Juice mission due to its capability to treat higher-energy electrons. The method uses a precomputed dataset of doses from electrons, electron-induced Bremsstrahlung, and protons derived from Monte Carlo analysis. The dose is provided as a function of material shielding thickness. In Figure 1, the dose–depth curve is represented as a function of spherical aluminum shielding thickness, and it shows that the dose is dominated by trapped electrons, as well as that the contribution of trapped protons is insignificant compared to that of solar protons. The accumulated dose of solar energetic protons is shown in the figures with a 90% confidence level that higher doses will not be observed.

As we can see in Figure 1, the expected TID for Juice goes above 1 Megarad for a typical wall thickness of 1.5 mm, considering a mission duration of approximately 12 years. In the case of the Solar Orbiter, the estimated TID for the total mission duration (7 years) is around 100 krad. As it will be discussed in the next section, the expected dose in an LEO mission such as the ISS corresponds to a total dose below 3 Gy/year in the worst case. This is why COTS are gaining ground in the space sector, specially in LEOs. With time, it is likely that COTS may be used in interplanetary or Moon missions, since a 1 kGy (100 krad) TID is achievable with COTS technology.

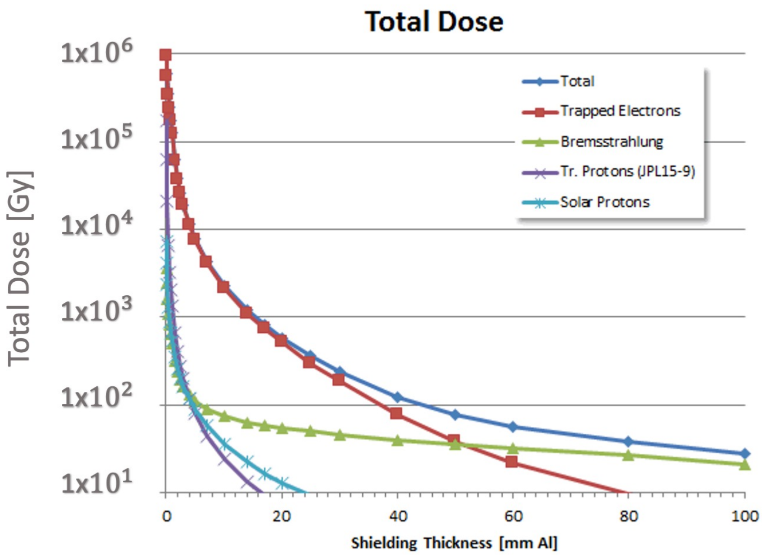

Figure 1. Dose in Si as a function of spherical Al shielding as calculated by SHIELDOSE-2Q for the entire Juice mission [29].

3. Methods and Results

In this study, we used data from multiple LEO missions to estimate the expected radiation levels in an LEO and assess the use of COTS components in these missions. The data collected by various radiation assessment systems on board these missions were analyzed and compared to computational models to estimate the actual radiation levels in the LEO. We then assessed the performance of COTS components in these radiation environments to determine their suitability for use in LEO missions. By combining these data and analysis, we hope to provide meaningful insights into the radiation environment in LEOs and improve our understanding of the use of COTS components in these missions.

We first performed a deep search for LEO missions that carry reliable and calibrated in situ radiation monitors with an output in terms of doses (mainly rads or Grays). The goal was to compare the measured dose with the one provided by the computational models. It is important to remark that the TID endurance of an electronic part is given in rads (Si) in its datasheet. For this reason, we did not analyze particle fluxes. This posed a problem, since most of the missions we found carried some sort of particle detector, but not dosimeters. The selected missions are ISS, MIR, PROBA-V, and FOTON-M4.

Next, the same orbit, shielding thickness and time period were modeled in Spenvis (https://spenvis.oma.be/, accessed on 1 June 2023) and Satellite Tool Kit from Ansys (https://www.ansys.com/products/missions/ansys-stk, accessed on 1 June 2023). STK is capable of modeling the space radiation environment thanks to the Space Environment and Effects Tool (SEET). The STK SEET Radiation Environment incorporates the APEXRAD, CRRESRAD, CRRESELE, CRRESPRO, NASAELE, and NASAPRO models. In order to compare the modeled results against experimental results, we transformed the doses in a common unit of uGy per day, assuming the worst case scenario. The orbit is modeled using two-line element (TLE) data for the given period.

3.1. ISS and LEO Dosimetry

The optimal radiation monitoring instrument should be sensitive to as much environment radiation as possible and have good charge, energy, and LET (linear energy transfer) resolution to identify different particles and to assign appropriate values of quality factors. Differences in dose were measured between different locations within the same time period, reflecting differences in shielding [30]. For fixed-oriented spacecraft such as the ISS (International Space Station), differences in the directionality of the primary radiation field will also lead to large differences in the measured dose throughout the habitable volume. Two types of dosimeters are commonly used: passive and active. Passive dosimeters, which include thermoluminescent, optically stimulated, and radiophotoluminescent dosimeters, accumulate the total radiation dose over time. In contrast, active dosimeters, which employ semiconductor materials such as silicon diodes or metal-oxide-semiconductor field-effect transistors, provide real-time measurements of radiation exposure. This information is critical for radiation protection, as it enables the development of effective countermeasures to minimize radiation exposure and establish safe exposure limits for astronauts and equipment. The use of dosimeters on the ISS has provided invaluable data on the expected radiation dose in LEOs, facilitating the development of strategies to mitigate the risks of ionizing radiation in space. Personal dosimetry is also necessary for each astronaut, and area dosimetry is often carried out at different locations within the spacecraft.

3.2. Experimental Results

Numerous experiments have been conducted in low orbit aboard the ISS (both within and beyond the confines of the station) and on satellites such as the Foton-M2 to M4. Passive radiation detectors have been predominantly used in these experiments and have been the subject of further analysis both on the ISS and on the ground.

Table 2 compares the absorbed dose rate measurements obtained from experiments aboard the ISS, such as PADLES [31], BRADOS-1 [32], LIULIN-5 [33], DOSIS and DOSIS3D [34], and the ISS-RAD experiment [35] with predictions made by the Systems Tool Kit (STK) and SPENVIS (AE8-AP8 and CRRES) models.

Table 2. Comparison of absorbed dose rate measurements aboard the ISS and in other satellites and predictions from SPENVIS (AE8-AP8 and CRRES) and STK models with 12 mm of aluminum shielding thickness for the same period of time. Based on the results, we can observe a significant difference between the data from the models and those obtained through actual dosimetry.

Experiment	Period	Days	Orbit (km)	Measured Dose Rate (uGy/Day)	STK (uGy/Day)	SPENVIS AE8-AP8 (uGy/Day)	SPENVIS CRRES (uGy/Day)
PADLES	June 2008 to March 2009	301	352	247–360	1275	455.89	6449.32
PADLES	March 2009 to Sept 2009	180	350	220–329	1313	366.85	5657.53
DOSIS	July 2009 to June 2011		350	195–270	1877	428.77	5928.77
DOSIS3D	2012 to 2015		410	260–360	2491	1053.70	8249.32
BRADOS-1	Feb 2001 to October 2001			208–275	1352	1635.34	7145
LIULIN-5	July 2007 to Feb 2009		350	180–220	1048	863.56	7490.41
ISS-RAD	Jan 2016 to Jan 2017	365	411	255	2444	1120.82	8813.70
ISS-RAD	Dec 2019 to Dec 2020	358	426	361	2824	1284.93	8813.70

Other experiments, summarized in Table 3, show similar results. Note that the shielding in the case of the SATRAM-Timepix experiment is 0.5 mm and that the CRRES simulations can only be carried out with a 2 mm aluminum thickness. In the case of the sensor aboard the FOTON-M4 mission, the author [36] observes the same radiation value obtained during the same period of time in the Dosis-3D/5 experiment aboard the ISS.

Table 3. Comparison of absorbed dose rate measurements for SATRAM-Timepix and FOTON-M4 experiments, and predictions from SPENVIS (AE8-AP8 and CRRES) and STK models with 0.5 mm of aluminum shielding thickness for SPENVIS and 2 mm for CRRES. Based on the results, we can observe a significant difference between the data from the models and those obtained through actual dosimetry.

Experiment	Period	Days	Orbit (km)	Measured Dose Rate (uGy/Day)	STK (uGy/Day)	SPENVIS AE8-AP8 (uGy/Day)	SPENVIS CRRES (uGy/Day)
SATRAM-Timepix	August 2015	30	820	80.64	530	1260	1180
FOTON-M4	2014	44	250 × 571	0.048	4.55	26.6	51.20

Missions aboard the MIR space station collected data for several years [30] using TLDs at various locations within the station. Table 4 presents the collected values of dose rate and the comparison using SPENVIS (AE8-AP8 and CRRES) and STK models. The results are comparable to the ones obtained in the ISS, with similar differences between measurements and models for the same orbit and duration.

Table 4. Comparison of absorbed dose rate measurements aboard the MIR, and predictions from SPENVIS (AE8-AP8 and CRRES) and STK models with 12 mm of aluminum shielding thickness. As in the ISS case, substantial differences between the modeling and the dosimetry are observed.

Experiment	Period	Days	Orbit (km)	Measured Dose Rate (uGy/Day)	STK (uGy/Day)	SPENVIS AE8-AP8 (uGy/Day)	SPENVIS CRRES (uGy/Day)
Mir-10	Feb 91	175	402.2	289	749	865	7745.21
Mir-11	March 92	146	405.8	272	987	917.26	7887.67
Mir-12	July 92	190	414.5	360	1237	1000.27	8339.73
Mir-13	Jan 93	180	405	474	1033	886.58	7495.89
Mir-14	July 93	197	403.7	452	1103	910.96	7791.78
Mir-15	Jan 94	183	405.6	508	1170	910.68	7172.60
Mir-18	March 95	115	293.7	295	1099	401.64	3802.74
Mir-21	Feb 96	195	389.8	339	1169	1444.66	7139.73
Mir-22	Aug 96	198	382.3	379	1151	1292.60	6553.42
Mir-23	Oct 97	187	386.8	329	1146	1351.23	6736.99

Some experiments have been carried out on nanosats such as Timepix [37] or iMERSA-R [38], and on cubesats with experiments such as Lucky7 [39], where active radiation sensors were installed. These missions have demonstrated their ability to detect and accurately determine the flow of protons and electrons. Although the amount of data they carry is not excessively large, it represents an important step toward the design of more reliable and precise detectors to be used in future missions.

4. Challenges in the Creation of Predictive Models

Obtaining accurate predictive models of radiation in space is a significant challenge due to the complexity of the space environment, lack of precise and complete data, modeling difficulties, and uncertainty in predictions.

The simulation of solar energetic particle fluxes is a multi-level process. The maximum possible fluxes and energy spectra of solar energetic protons are defined, but these values are not enough to determine radiation exposure for long-term space missions with repeated occurrences of large solar events. Hence, knowledge of the solar event distribution function is also necessary. A model of particle fluxes should be probabilistic in nature and take into account all relevant factors, such as mission duration, solar activity, and particle composition. Nymmik [40] developed the SINP MSU model of SEP fluxes and pointed out that other known models are not sufficiently complete due to issues in SEP event selection, assigning solar activity, and constructing a particle flux model for the selected energy value.

Jiggens et al. [41] discuss the importance of space radiation in the design of spacecraft and missions, with a focus on the solar energetic particle (SEP) population as the dominant source of particle radiation over short timescales. The authors highlight the difficulty in determining a worst-case SEP spectrum for all spacecraft components, as different components have different characteristics and shielding geometry. The study defines a worst-case event based on the mission duration and a user-defined confidence level, which provides a more coherent statistical approach to determine the worst-case event fluence. The study concludes that probabilistic models provide a more reliable method for determining the worst-case event fluence than taking a single historical example event.

The current forecasting models are under review by multiple authors, highlighting the need to incorporate new data and calculation methodologies into the existing models. Jiggens et al. [41] propose using SAPPHIRE to replace existing standards in ECSS as a new tool for estimating the radiation environment in space, particularly the proton component. It includes results for different energy levels during solar minimum and maximum. Compared to other models, the cumulative fluence model of SAPPHIRE shows a lower estimated fluence, especially at 100 MeV. The SAPPHIRE model is validated for use in applications such as solar cell degradation estimation. The model can also be used to estimate radiation for heavier ions.

5. Discussion

In this article, we have carried out a comparative analysis between the data obtained by radiation dosimeters in several experiments in space and computer simulations of predictive models used in aerospace engineering.

On average, the models used in the simulations show a factor of 3 as the smallest difference between the measurements and the modeling, and a factor of 30 as the highest. Computational models provide an ideal solution for manned missions with a wide safety margin and a worst-case scenario approach, as well as for missions with critical design specifications. If radiation models overestimate the radiation that components may receive during a mission, and an additional design factor (RDM) of 1.2 to 2 is applied, we may greatly limit the use of high-reliability COTS components in non-critical space applications.

A different approach is necessary to assess the utilization of COTS electronic components for space applications, relying on analytical data rather than depending exclusively on engineering judgment and best-practice experience [42].

The use of reusable launchers greatly reduces the cost-per-kilogram placed in orbit, which makes it possible to launch more missions that can update previous ones. Currently, satellite constellations such as Starlink or Oneweb use COTS components in their satellites, allowing for significantly cheaper devices and the use of proven technologies on Earth to improve performance and provide better services to their customers.

Currently, NASA and ESA are betting on hybrid technologies that combine a COTS electronic system with typical supervision based on space-specific design devices. It is a bet that can guarantee complete system reliability, but leads to designs that increase costs and move away from the New Space paradigm and the use of mature and sufficiently tested technologies in terrestrial applications.

The use of disruptive technologies in the space environment and the analysis of their performance will determine their qualification for the New Space business model that will allow science and technology to advance by leaps and bounds in the future.

6. Conclusions

In this comparative study, we have assessed the alignment between data collected by radiation dosimeters in various space experiments and the predictive models used in aerospace engineering. The results highlight significant discrepancies between measurements and computational model predictions and their propensity to overestimate radiation levels, which can impact mission design and component selection.

Computational models continue to play a pivotal role in space missions, particularly those with stringent safety requirements and manned missions. They provide a worst-case scenario-based approach and offer a substantial safety margin. However, it is crucial to acknowledge their tendency to overestimate radiation levels, which can have implications for mission design and component choices.

In 2019, the European Space Agency initiated a series of comparative studies aimed at the analysis of automotive components adhering to AEC-Q standards. These studies sought to establish parallels with ECSS standards and identify additional tests necessary to qualify these components for use in space applications, with radiation-related considerations excluded.

Based on the data presented in this work, components subjected to total ionizing dose testing have demonstrated robustness in operating within the radiation environment of a low Earth orbit. While certain components may exhibit heightened sensitivity, this challenge can be effectively addressed through a preliminary selection process aimed at identifying potential vulnerabilities to TID. The availability of a pre-qualified list of commercial off-the-shelf components suitable for deployment in space environments (similar to a Preferred Part List, but for COTS) may prove invaluable in expediting the adoption of this technology in low Earth orbit missions.

In conclusion, the findings underscore the potential for integrating COTS components into space missions, particularly in LEO missions, where TID testing has shown promise. The establishment of stringent selection criteria for such components can mitigate any sensitivity concerns and facilitate their seamless integration into space technology, thereby advancing innovation and exploration in the realm of space science and technology.

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