Enhancing Radiation Resilience in Integrated Circuit Designs for Deep Space Missions

Prepared for:

Dr. Kurt Vogel
Associate Administrator
Space Technology Mission Directorate
National Aeronautics and Space Administration

Prepared by:

Achal Kumar Gupta
Junior Electrical Engineer – Radiation Effects Specialist

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TERMS OF REFERENCE

This report was requested by Dr. Kurt Vogel, Associate Administrator of the Space Technology Mission Directorate at the NASA Headquarters, Washington on April 7, 2025. The report was commissioned to investigate the radiation-induced failure of integrated circuits in deep-space environments and evaluate potential mitigation strategies to implement in next-generation spacecraft to enable them to venture further from Earth, for extended periods of time. The request followed concerns raised to Dr. Vogel about the risk of radiation-induced failure to existing and future deep space missions operating in high-radiation environments.

Dr. Vogel's specific instructions are as follows:

- Identify and explain the primary failure mechanisms caused by cosmic radiation in deep space environments
- Evaluate the effectiveness of currently adopted mitigation strategies, both hardware and software-based
- Investigate emerging technologies and techniques that could improve radiation tolerance in circuits
- Provide recommendations for short and long-term implementation strategies of newer technologies
- Submit the report before the 13th of May 2025 at 11.30 PM SAST (UTC + 2) to the Office of the Associate Administrator at NASA Headquarters, Washington D.C.

SUMMARY

This report concerns the issue of radiation-induced failure in integrated circuits in space, affecting the spacecraft's ability to travel into deep space for extended periods of time.

Background and Motivation

The need for this investigation arose from concerns raised to the Office of the Associate Administrator of the Space Technology Missions Directorate about the risk of failure in current and future missions caused by extended exposure to radiation. Without an investigation into more effective mitigation strategies, future missions will not safely be able to travel further away from Earth for prolonged periods of time.

Objectives and Methodology

The primary objective of this report is to evaluate the tolerance of electronics against the adverse effects of exposure to cosmic radiation. The report investigates three key areas:

- The fundamental mechanisms leading to damage in electronic systems
- The current mitigation strategies adopted in spacecraft design
- Emerging technologies to improve fault tolerance in spacecraft electronics

This investigation is performed through a comprehensive literature review. No simulations or physical tests were performed; insights were drawn from documented mission data, component testing results and industry case studies.

Results of the Investigation

Three principal radiation effects were identified:

- Total Ionising Dose (TID):	Long-term exposure causing degradation to material and device performance over time
- Single Event Effects (SEE):	Instantaneous malfunction of the device caused by a single charged particle
- Displacement Damage (DD):	Structural damage to a component on the atomic level, impacting device functionality

Currently, enforced mitigation strategies vary with mission context. Legacy methods are constrained due to mass, cost, or availability. Newer developments include error detection and correction algorithms, redundancy, and radiation-aware routing. Additionally, the use of materials like Silicon Carbide (SiC) and Gallium Nitride (GaN) are more fault tolerant.

Conclusions

An innovative approach is required to bypass limitations in cost, mass, and functionality. A shift towards the inclusion of predictive modelling, material innovation and software resilience are essential to reduce the risk of failure due to cosmic radiation.

Recommendations

Based on gathered facts and insights drawn, these recommendations are made:

- Account for cumulative radiation damage in spacecraft design
- Apply mitigation strategies consistent with mission context and objectives
- Accelerate maturation of modern technologies to allow for full-scale use

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GLOSSARY

Bit Flip:	A temporary error where stored data in a computer's memory changes state unexpectedly.
Cosmic Radiation:	High-energy particles from space, such as protons and heavy ions, which can damage electronics onboard spacecraft.
Deep Space:	Regions of space far beyond Earth's atmosphere and protective magnetic field. Radiation in this region of space is often much higher than in space closer to Earth.
Displacement Damage (DD):	Permanent harm to materials in electronics when radiation knocks atoms out of place, leading to long-term performance issues.
Error Correcting Codes (ECC):	A method to detect and correct errors in data, such as bit flips, to ensure data integrity is preserved when storing and processing it.
Fault -Tolerant Design:	Designing systems such that they continue normal operation despite failure of certain parts/mechanisms, using either error-correction methods or backup hardware.
Field-Programmable Gate Array:	An FPGA is a type of computer chip that can be reprogrammed after launch, allowing it to adapt to new tasks or recover from errors.
Immunotronics:	A self-healing technology that works in a similar fashion to the biological immune system, where electronics detect and repair damage autonomously.
Integrated Circuit (IC):	A small electronic chip that houses multiple components, such as transistors, to power computers.
Predictive Simulation Tools:	Software used to model how radiation affects spacecraft parts, allowing for safer system design.
Radiation-Hardened Components:	Electronics built to withstand radiation damage with the use of unique materials or designs.
Redundancy:	Including backup components that can take over if their primary counterparts fail
Triple-Modular Redundancy (TMR):	Using three copies of critical components and voting to pick the correct output if one fails.
Van Allen Belts:	Zones around the Earth containing trapped radiation, shielding here is essential to prevent damage.
Wide-bandgap Semiconductor:	Durable materials that can tolerate high heat and radiation better than conventional semiconductors

1. INTRODUCTION

1.1. Subject of and Motivation for Report

This report concerns and investigation into fault-tolerant design practices and technologies implemented in integrated circuits to withstand prolonged exposure to dangerous cosmic radiation in deep space. Radiation poses a significant risk to the nominal functionality of electronics onboard spacecraft, and this risk compounds with time spent in space and distance travelled. The motivation behind the report is to find more effective strategies to boost the radiation tolerance of electronics onboard future NASA missions into deep space that do not compromise mass, cost, or functionality of the device.

1.2. Background to Investigation

The report was initiated because of concerns raised to the Office of the Space Technology Mission Directorate regarding the longevity and effectiveness of deep space missions due to the prolonged radiation exposure experienced by spacecraft.

Previous missions, such as the Voyager spacecraft, have reported anomalies that have been traced to radiation events – such as unexpected bit flips in memory and processors, and even unexpected system resets. These errors underline the need for fault-tolerant design to mitigate the adverse effects of radiation.

1.3. Objectives of Report

The objectives of this report are therefore to:

- Identify key effects of cosmic radiation on electronic systems
- Analyse how these effects contribute to mission degradation/failure
- Evaluate current fault tolerant measures
- Contextualise mitigation strategies through past examples
- Propose design-based recommendations to enhance the radiation resilience of integrated circuits

1.4. Limitations and Scope of Investigation

This investigation focuses solely on radiation-based faults that may compromise future missions, despite other complications that may also compromise future missions. The report has been given ample time to complete, however due to the recent discovery of the issue at hand, limited resources are available. Consequently, this report synthesises secondary research from publicly available sources.

1.5. Plan of Development

The report begins by outlining the types of radiation damage that integrated circuits can experience. It then examines the various strategies currently adopted in active missions to curb radiation effects, such as radiation-hardened components, redundancy, error correction coding, and watchdog timers. This is followed by an analysis of proposed future technologies and their advantages compared to currently adopted technologies. Conclusions are then drawn based on the gathered information. Recommendations are finally made regarding the improvements that can be made to increase fault tolerance in spacecraft electronics in a practical manner.

1.6. Method of Investigation

This report is based on a review of academic literature, technical papers, and case studies from space agencies such as NASA, ESA, and commercial satellite providers. Sources include journal publications and published articles. Insights are drawn from the synthesis of recurring themes and an evaluation of documented mission anomalies linked to radiation exposure. All conclusions are made based on this literature review, without new experimental data.

2. RADIATION-INDUCED FAILURE MECHANISMS

2.1. Total Ionizing Dose (TID) Effects

Total Ionizing Dose (TID) refers to the gradual buildup of damage in electronic components caused by exposure to space radiation over time, primarily from high-energy protons and electrons. As these charged particles strike semiconductor material inside electronic chips, they cause a shift in electrical properties, such as the threshold voltage needed to turn the transistor on. This can lead to increased power loss, reduced clarity in signals and, over a sufficiently prolonged period of time, the complete failure of the component, affecting the overall performance and functionality of the integrated circuit [1], [14].

2.2. Single-Event Effects (SEE)

Single-Event Effects occur when a single high-energy particle, such as a heavy ion or fast-moving proton, strike a sensitive part of an integrated circuit [2]. Such a sudden impact results in a surge of electric charge in the specific part of the IC that was struck, affecting the behaviour of the device. The specific nature of the strike can lead to different behaviours, such as the following:

- Single-Event Upsets (SEU): These are temporary bit flips in the data stored either in memory or in logic circuits [2], [3]. They do not affect the overall functionality of the device, however data stored at that location can lead to errors if not reverted to their original value.
- Single-Event Latch-ups (SEL): These are dangerous events that occur when a charged particle strikes a hidden current path inside the IC. This creates a loop in the circuit that draws a large amount of current, leading to permanent damage inflicted to the component, if the current draw is not limited by external controls [2].
- Single-Event Gate Rupture (SEGR): These events are extremely severe in nature and lead to the structure of the device physically breaking down. This event leads to the breakdown of the insulating material that is found in a transistor [11].
- Single-Event Burnout (SEB): These events are similar in nature to SEGR, with the key difference that instead of the insulating material of a transistor being severely damaged, permanent damage to the junctions in power devices is caused [11].

2.3. Displacement Damage (DD)

Displacement Damage is a radiation failure mechanism that occurs when incoming radiation transfers enough energy to dislodge atoms in the lattice of a semiconductor material [4], [12]. Such damage does not directly lead to an electric charge, however the change in material structure affects its electrical properties, consequently affecting how well it carries an electrical signal.

When atoms are moved out of their original positions, they leave behind gaps known as *vacancies* and introduce additional atoms in the wrong spots, known as *interstitials.* These irregularities interfere with the smooth flow of charge through the semiconductor, reducing the device's speed and ability to drive the given amount of current.

In light-dependent components, such as photodiodes and image sensors, this type of radiation damage can hamper the component's ability to interpret light into electrical signals. Additionally, it increases the amount of background signal, known as *dark current*, even when there is no light entering the component.

Displacement Damage has a permanent effect on the device and cannot be corrected through software. Like Total Ionizing Radiation (TID), the damage gradually compounds with time, influencing the long-term behaviour of a spacecraft's onboard electronics.

2.4 Synergistic and Secondary Effects

The above mechanisms can often interact and affect each other. For instance, charges trapped by TID can make devices more susceptible to SEEs, and damage caused by displaced atoms can make TID-related leaks worse [1], [4]. Solar weather events, specifically ones with solar particles involved, cause sudden increases in radiation levels, which accelerates all three types of damage simultaneously. Changes in temperature can further stress these materials, causing cracks and internal damage, compromising the electrical and structural integrity of the device even further.

3. CURRENT MITIGATION STRATEGIES

3.1. Radiation-Hardened Materials and Processes

Special fabrication processes and materials used to make electronic components less sensitive to radiation. For example, the Silicon-on-Insulator (SoI) technology places components on a thin layer of silicon over an insulating base. This reduces the total charge buildup that could occur from radiation strikes, hence lowering the change of unwanted bit flips in memory and prolonging the lifespan of the device [1], [5].

Other approaches include high-resistivity silicon and specially processed gate oxides, which give a device additional resistance to damage from trapped charges. However, these methods involve more expensive materials and more complex manufacturing.

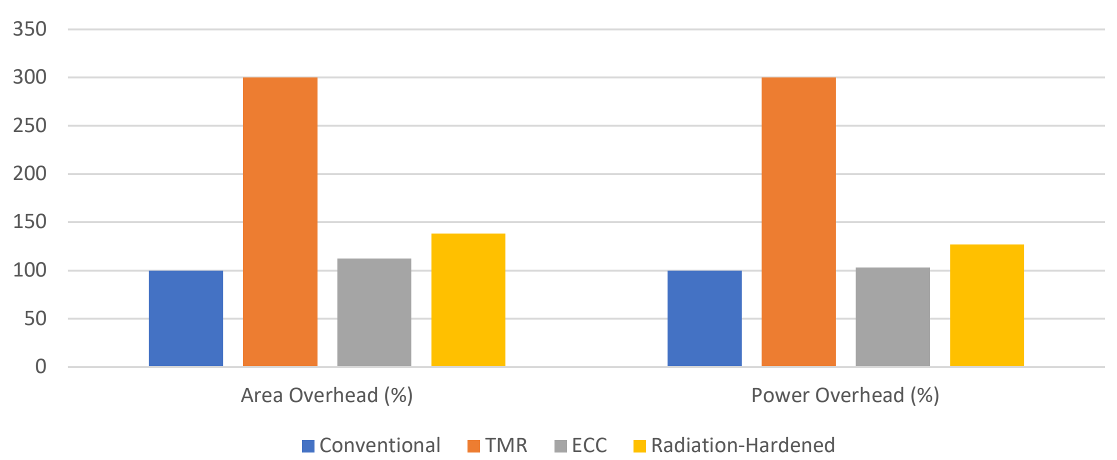
3.2. Design-Level Handling

During the design phase of the circuit, physical layouts are used to alleviate the effects of radiation. For instance, guard rings and enclosed transistors stop unwanted currents from forming during radiation strikes.

In digital circuits, the use of Triple-Modular Redundancy (TMR) allows the system to maintain normal functioning despite damage to a component. TMR triplicates critical parts of a system, and a majority vote decides the actual output, hence a faulty vote will not affect the overall outcome, strengthening the resilience of the device to radiation-induced damage. Similarly, Error Correcting Codes (ECC) are applied to memory such that errors can be found and corrected [2], [3].

These methods are extremely effective against bit flips but are at the cost of chip area and power consumption, as seen in the normalized overhead graph (Baseline = 100%) Figure 1 below [17]:

Figure 1: Normalized Overhead for Various Techniques



3.3. Physical Shielding

Blanketing electronic components with physical material helps block lower-energy radiation. Commonly, thin layers of aluminium or polyethylene are used, however each millimetre of aluminium adds 0.5 to 1 kg per square metre [1]. This form of shielding is particularly effective against particles in the Van Allen belts around Earth but provides limited protection from fast-moving cosmic rays and other deep space radiation.

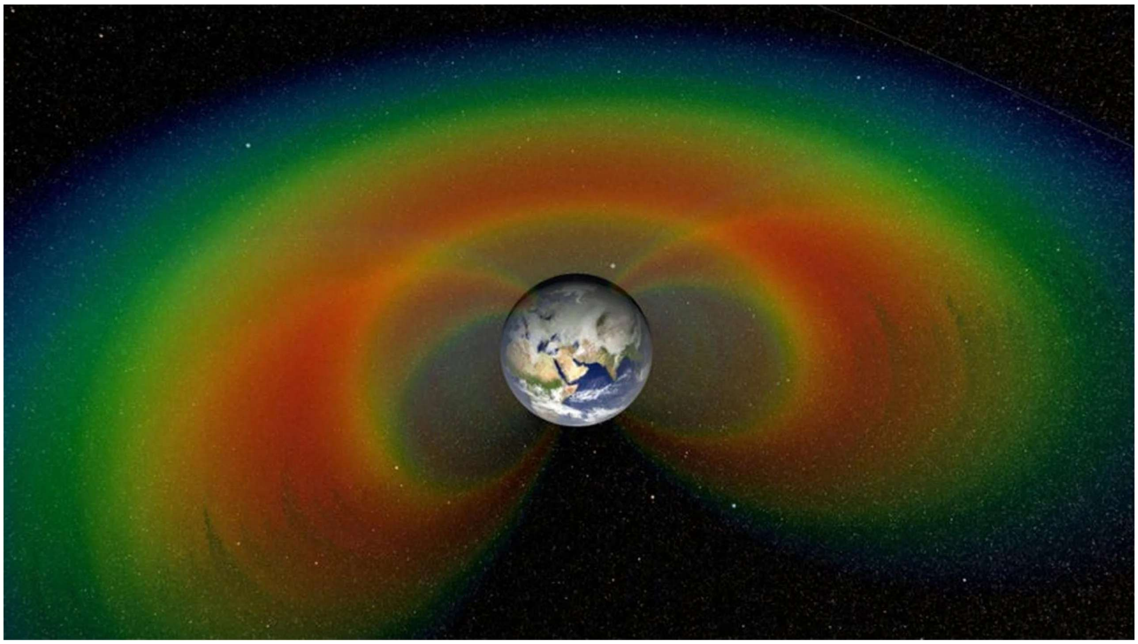


Figure 2: Visualisation of the Van Allen Belts

3.4 Process and System-Level Controls

Prevention against radiation management also takes place during the mission planning and testing stages. Spacecraft can be designed to enter low-power modes during higher zones of radiation and sensitive operations can be scheduled to occur during lower exposure to radiation. On Earth, particle accelerators are used to expose components to simulated radiation environments and measure their overall radiation tolerance [6]. These results can predict the longevity and lifespan of the spacecraft under similar conditions, far from Earth.

Whilst these methods contribute to cushioning the impact the radiation damage does to ICs, they are increasingly limited the further a spacecraft travels from Earth, due to ever higher levels of radiation exposure, and exponentially longer periods of time that the spacecraft spends in those environments.

4. EMERGING FAULT-TOLERANT DESIGN APPROACHES

4.1. Wide-Bandgap Semiconductors

New types of semiconductor materials, such as Silicon Carbide (SiC) and Gallium Nitride (GaN), show promisingly strong resistance to radiation. They boast wider band gaps, courtesy of their stronger atomic bonds, leading to a lower amount of damage caused by trapped particles and atomic displacements, when compared to currently used semiconductor materials.

SiC power devices can retain a sizeable portion of their performance and functionality after being exposed to doses of radiation that would cause irreversible failure in conventional silicon semiconductors [5], [13]. GaN devices have a higher operating temperature range than conventional semiconductors, reducing the need for large cooling systems.

4.2. Self-Healing and Reconfigurable Circuits

Electronic systems now include built-in fault detection and can reconfigure themselves to continue nominal operation. They utilize on-board monitoring systems to detect anomalous functioning and isolate the area that is malfunctioning. Preliminary versions of self-healing Field-Programmable Gate Arrays (FGPA) have shown potential in recovering from radiation events, with a minor power and size overhead [6], [10].

Immunotronics is another advanced approach that can be used for self-healing. It is a form of biomimicry, using learning algorithms to identify and respond to fault, in similar fashion to the biological immune system.

4.3. Advanced Predictive Simulation Tools

Currently, tools that merge particle simulations with models of semiconductor behaviour are in development. These design tools can estimate the absorption, response, and failure trends of a device exposed to a given amount of radiation. These predictions show close alignment with real mission data within experimental error and are being used in the earlier phases of spacecraft design to guide choices of material, layout and shielding [1], [15].

4.4 Hybrid Architectures

New system designs combine many of the strategies mentioned above, creating more robust electronic systems that are not significantly more power hungry or have a larger size than similar devices built with conventional design techniques [15].

5. CONCLUSIONS

Based on the foregoing information, the following conclusions have been drawn.

5.1. Radiation Mechanisms Create Compounding, Long Term Threats

The radiation environment found in the vacuum of space adversely affects spacecraft electronics through several mechanisms such as TID, DD and SEE. Not only can each mechanism individually cause damage, but they can superimpose to compound their total effect on the electronics of a spacecraft. Mechanisms like Total Ionizing Dose and Displacement Damage cause long term, lasting damage; TID morphs the behaviour of transistors, increasing power draw and signal distortion, and DD degrades the structural quality of the physical material in the circuits, reducing reliability. Other mechanisms cause instantaneous damage, such as Single-Event Effects which trigger functional failures. When combined, their compounded effect accelerates the failure of radiation-tolerant systems.

5.2. Existing Mitigation Strategies Are Limited by Trade-offs

Currently adopted strategies include radiation-hardened components, physical shielding, and design-level redundancy. They have proved to be effective, allowing multiple previous missions to be deemed a success, yet they are constrained by strict cost, mass and performance demands. Physical shielding adds mass to the craft, TMR increases the size of the chips almost threefold and radiation-hardened components fail to perform to a similar standard as their conventional counterparts.
Additionally, initiative-taking measures such as Earth-based testing fail to accurately model deep-space environments, leading to gaps between expected and obtained device performance and lifespan.

5.3. Though Promising, Emerging Solutions are Underdeveloped

Technologies such as the wide-bandgap semiconductors, self-healing logic devices and advanced predictive modelling show strong potential to curtail current mass, cost, and performance thresholds. Materials such as Silicon Carbide and Gallium Nitride perform better under radiation than conventional semiconductor materials and the use of adaptive architecture can assist in recuperating from faults autonomously.
Despite the promise they offer, they are currently early in development and have not been widely adopted, being limited only to secondary and experimental systems. Without large-scale validation in various mission profiles, they cannot be reliably used to replace conventional materials and techniques in critical hardware. A great deal of testing is still necessary to ensure confident integration into spacecraft design pipelines.

6. RECOMMENDATIONS

On the basis of the above conclusions, the following recommendations are made.

6.1. Design for Cumulative and Interacting Radiation Damage

Allocate resources to develop system architectures that can treat the effects of TID, SEE and DD together rather than as isolated effects. Include components that have proven resilience to specific mission profiles, as well as resilience against compounded radiation damage, such as wide-bandgap semiconductor materials. Incorporate radiation monitoring systems onboard to allow the craft to adapt to extreme radiation events such as high-radiation zones or solar storms, protecting vital circuitry. Account for degradation with the use of redundancy, with copies of critical components that activate only when their primary counterpart is out of service, preserving power yet extending mission life.

6.2. Apply Mitigation Strategies Based on Mission Context

Strongly consider and plan for the exact radiation environments that a specific spacecraft would experience throughout its life cycle and prioritise mitigation strategies that work best for each spacecraft, striking the balance between real world mission constraints and spacecraft lifespan. For instance, in high flux environments like geosynchronous Earth orbit, focus primarily on shielding. In environments such as Low Earth Orbit (LEO), prioritizing software-based fault handling is more appropriate. By adopting mission-aware design practices, the best forms of radiation tolerance can be integrated into a spacecraft.

6.3. Accelerate Maturation and Integration of Emerging Technologies

Increase deployment of newer, untested technologies like wide-bandgap semiconductors and reconfigurable FGPAs into low-risk subsystems of upcoming missions to gather data on the real-world handling and performance of these devices, with conventionally built backups onboard as well. Develop qualification protocols with semiconductor partners like TSMC to ensure that large scale production of these technologies can begin in a reliable fashion. Introduce predictive modelling into the early phases of satellite design processes and measure its effectiveness in reducing prototype cycles and specific design choices. As more information and experience is obtained surrounding these technologies, they will improve, until enough experience and metrics are gathered about them to begin full scale integration into future spacecraft.

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