

Review article

Systematic review of engineering and testing approaches for radiation hardness assurance in commercial space avionics

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ABSTRACT

In this paper, a comprehensive review of the evolving engineering and testing methodologies for radiation hardness assurance (RHA) in commercial-off-the-shelf (COTS) based space avionics, with a focus on recent trends and future directions is provided. The increasing reliance of space engineering on COTS has prompted a shift in RHA strategies, reflecting both technological advances and the complex radiation environments faced by modern space systems. Emphasis is placed on the interplay between traditional RHA frameworks and the integration of state-of-the-art design principles, fault-tolerant architectures and testing approaches. The review highlights how evolving system requirements and accelerated development cycles have influenced radiation testing practices and risk mitigation techniques. Examples are presented of enhancing reliability under radiation exposure, including reconfigurable systems, agile engineering processes and system-level validation. Emerging applications, including intelligent onboard systems and distributed satellite networks, are discussed with attention to their unique challenges and opportunities in RHA. The review concludes with a perspective on the critical gaps and future needs to advance RHA practices in support of increasingly complex and resource-constrained space missions.

1. Introduction

The ongoing evolution of space systems engineering has brought new challenges in ensuring the reliability and robustness of avionics in the space radiation environment. The well-known radiation-induced effects include single event effects (SEEs), total ionizing dose (TID) degradation, and displacement damage (DD) [1–3] which can severely impact system performance, leading to anomalies, mission delays, or even catastrophic failures [4]. As space missions grow in complexity and performance demands rise, particularly for long duration missions and harsh environments, radiation hardness assurance (RHA) has become a critical area of focus. RHA refers to a systematic approach aimed at ensuring that all spacecraft components, including but not limited to avionics, can operate reliably in radiation environments. Although radiation-induced effects are commonly associated with electronic components, they also impact a wide range of spacecraft materials, such as optical components and polymers. Traditionally, radiation hardened components have been used for critical systems. However, the increasing sophistication of space missions, coupled with the drive to reduce costs, has led to the growing use of commercial off-the-shelf (COTS) components. These components offer advantages in terms of performance and availability, as well as size, weight, power and

cost (SWaP-C) effectiveness. However, their potential vulnerability to radiation effects introduces new challenges for RHA programs.

1.1. Motivation and scope

Due to volatility in the supply chain, tighter budgets and rapidly evolving market demands, the space industry is increasingly dependent on COTS components in critical subsystems [5]. There is a growing need for components that offer high performance, scalability and affordability compared to radiation-hardened alternatives, which are often more costly and limited in availability. COTS components and systems that are highly integrated, multifunctional and reconfigurable, often have increased susceptibility to space radiation, posing risks to their operational integrity and longevity in harsh space environments [6]. The shift towards COTS-based solutions introduces new challenges for the engineering, testing and qualification of these systems to ensure their reliability in space.

This paper aims to review current RHA practices and standards related to complex COTS-based space avionics, identify the main trends and challenges in engineering and testing these COTS-based systems

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for space missions and highlight gaps in existing methodologies. In this context, complex refers to highly integrated and multifunctional COTS-based avionic systems that involve intricate hardware-software interactions, extensive interdependencies between components, and sophisticated data processing requirements, all of which amplify the challenges of ensuring RHA in harsh space environments.

While acknowledging the broader relevance of RHA to all spacecraft components, including non-electronic materials such as optical elements and structures, a detailed review of their specific RHA methodologies falls outside the focused scope of this paper on COTS-based avionics. This review goes beyond summarizing existing literature by offering practical guidance for practitioners addressing the challenges of RHA in COTS components. It responds to the growing demand for robust, scalable RHA strategies that support the reliable design, development, and deployment of space systems using commercial technologies.

Using a rigorous systematic literature review (SLR) methodology, this work synthesizes current findings to highlight emerging trends, integrate best practices, and expose critical deficiencies in current RHA methods. It aims to convert technical complexity into decision-ready insights that enhance mission reliability and cost-efficiency amid the increasing adoption of COTS in space.

1.2. Paper overview

The paper is structured as follows. First, Section 2 reviews existing RHA standards and key literature, providing essential background information on the topic. Then, Section 3 outlines the methodology used to conduct the SLR, including the criteria for selecting relevant literature and the scope of topics covered to establish the current state-of-the-art. Subsequently, Section 4 presents the findings categorized by the relevant themes found, relating back to the research questions posed in the methodology. Afterwards, Section 5 discusses the findings and compares insights from existing standards with state-of-the-art research, highlighting gaps and limitations, and future research directions. Finally, Section 6 concludes with a summary of key insights on RHA for complex COTS-based space systems.

2. Generic literature review

This section provides a comprehensive review of research, standards and practices related to RHA for complex COTS-based space systems. Engineering and testing standards are covered, key studies on RHA methodologies examined, and the challenges associated with applying these methodologies to modern space systems are highlighted.

2.1. Space agency RHA practices

RHA is a critical aspect of space system design, particularly for high-reliability missions where component failure due to space radiation could lead to loss of spacecraft, communication failure, or endangered crew safety. Space agencies and defense organizations have developed a variety of standards to guide the development of space systems, covering everything from environmental characterization to mitigation strategies. These standards are essential to ensure that systems can operate reliably in the harsh space environment.

The European Space Agency (ESA) standards, provided by the European Cooperation for Space Standardization (ECSS) initiative, contain a comprehensive set of standards covering major aspects of RHA in space missions:

- ECSS-Q-ST-60-15C: The main RHA standard, specifies requirements for ensuring RHA of space projects [7].
- ECSS-M-ST-80C: Risk management standard, defining the principles and requirements for integrated risk management in a space project [8].

- ECSS-E-ST-10-04C: Defines general models and rules for determining the local induced radiation environment applicable to all types of products [9].
- ECSS-E-ST-10-12C & ECSS-E-HB-10-12A: Covers the methods for the calculation of radiation received and its effects, and a policy for radiation design margins (RDM) [10,11].

These standards collectively define a thorough and conservative approach to RHA. There are still links with other relevant RHA standards, however these are mentioned in the standards themselves. More recently, ESA introduced a mission classification scheme similar to that of the National Aeronautics and Space Administration (NASA), which will provide more flexibility to industry as a function of the mission class [12]. In this scheme, class I is the class where ECSS standards are fully applicable. The generic RHA activity for each mission phase is defined as:

- Phase 0 - Mission analysis and concept studies: Environment specification for mission options, preliminary assessment of sensitivities and availability of components.
- Phase A - Feasibility and technology development: Environment specification for baseline mission, preliminary assessment of sensitivities and availability of components.
- Phase B - Preliminary design: Environment specification update, RHA requirements, detailed analysis of component requirements, identification of sensitivity data, component test plan execution.
- Phase C & D - Detailed design & Assembly, Integration, and Test: Accurate shielding and radiation effects analysis, consolidation of test results, testing.
- Phase E - Operation: Investigation of radiation effects, feedback to engineering groups of lessons learned.

On the other hand, NASA historically managed RHA through project-specific expert teams rather than a formal generic standard, where methods were heavily influenced by the Military Specification (Mil-Spec) standards. Recently, NASA has published a more generic RHA guideline for their own practices. The relevant documents used as reference are:

- MIL-HDBK-814: Provides guidance to the application of piece-part RHA programs for the effects of ionizing radiation dose and neutron damage to semiconductor electronics [13].
- MIL-HDBK-816: Provides guidance and easy-to-follow procedures for the preparation of detailed device specifications for the procurement of microcircuits and semiconductor devices where RHA is required [14].
- MIL-HDBK-817: Provides guidance in establishing survivability requirements, and structuring the RHA program [15].
- NASA/TM-20210018053: An overview of NASA's best practices and guidelines spanning the primary radiation effects, and provides significant content on radiation shielding, testing, and operational monitoring [16].
- NASA-STD-3001, volume 1 & 2: Human spaceflight standard where requirements are stated that could impact mission and systems [17,18].

NASA has published one other guideline specifically for RHA [19]. The guideline covers defining the space radiation environment, radiation failure mechanisms, testing strategies and system-level mitigation techniques, such as shielding, redundancy and error correction. It also presents approaches for parts categorization based on radiation tolerance and mission requirements. It also emphasizes iterative risk assessments and emerging challenges in newer semiconductor technologies.

Beyond NASA and ESA, several other space agencies (e.g. Russia, China, India, and Japan) have also developed RHA-related standards or guidelines. However, these documents are generally less accessible due

to language barriers, limited public distribution, or institutional access restrictions. In many cases, such as in Russia and China, radiation test and assurance procedures are documented in national or military standards written in Russian or Chinese, with limited availability outside official channels. The Bureau of Indian Standards (BIS) has recently issued standards that include RHA elements [20], even for off-the-shelf components [21]. Japan’s JAXA provides internal documents on RHA and radiation effects with some English versions available [22,23]. Notably, many of these agencies reference or align with existing ECSS, NASA, or Mil-Spec practices. Other countries such as Brazil, South Korea, and Israel have active space programs that include some level of RHA, but no public national RHA standards have been identified.

2.1.1. Comparison

While ESA’s ECSS standards provide a structured, detailed framework applicable to high-reliability missions, NASA’s reliance on Mil-Spec standards and project-specific guidelines results in a more flexible, case-by-case approach. ESA’s framework tends to emphasize comprehensive risk management and detailed testing, while NASA’s focus varies depending on the mission classification and criticality of the system. This latter approach is being adopted by ESA.

Despite these variations in philosophies, several critical areas of overlap exist, particularly concerning fundamental radiation effects testing and risk management principles. Both agencies universally require TID and SEE testing for electronic components intended for space. The methodologies for performing these tests (e.g., test setup, dose rates, ion species) often draw from similar established practices and international standards, leading to comparable data sets and assessment criteria for certain component types. Furthermore, both frameworks advocate for robust derating policies and comprehensive failure analysis, emphasizing the importance of understanding component vulnerabilities and implementing design margins.

However, the application of these shared principles, especially for COTS components, often reveals critical differences. NASA’s inherent flexibility can allow for more aggressive COTS adoption through extensive mission-specific testing and creative mitigation strategies, potentially reducing costs and integration timelines but shifting more risk to the system level. Conversely, ESA’s more rigid approach, while ensuring higher confidence in component heritage and qualification, can lead to higher costs, longer development cycles, and limited access to cutting-edge COTS technologies. A key point of divergence, for instance, lies in the specific qualification levels or screening requirements for various COTS categories. While both require extensive testing for critical components, the thresholds for acceptance or the extent of additional hardening measures may vary significantly. It implies different trade-offs in terms of performance, cost, and schedule when selecting a component based on adherence to one standard over the other. The absence of strict one-to-one equivalence for all COTS components across both standards necessitates a thorough, critical assessment by engineers to determine the appropriate RHA strategy for a given mission.

An overview of the generic, combined process for both agencies is seen in Fig. 1. The processes flow down from requirements, to design, to validation and to launch. In the case something is not according to specification, it can be revised in the design (e.g. on system level with redundancy and shielding or on mission level with orbit selection).

2.1.2. COTS standards and guidelines

ESA is actively doing work on tailoring RHA for mission classification and giving recommendations for COTS devices. This RHA tailoring is a set of minimum requirements applicable to a specific mission. Problems ESA has encountered in COTS-based projects are late consideration of RHA, misunderstanding of the risks, misunderstanding of the concept of heritage, the RHA impact of scaling from prototype to a recurrent system is not understood and the amount of activities is

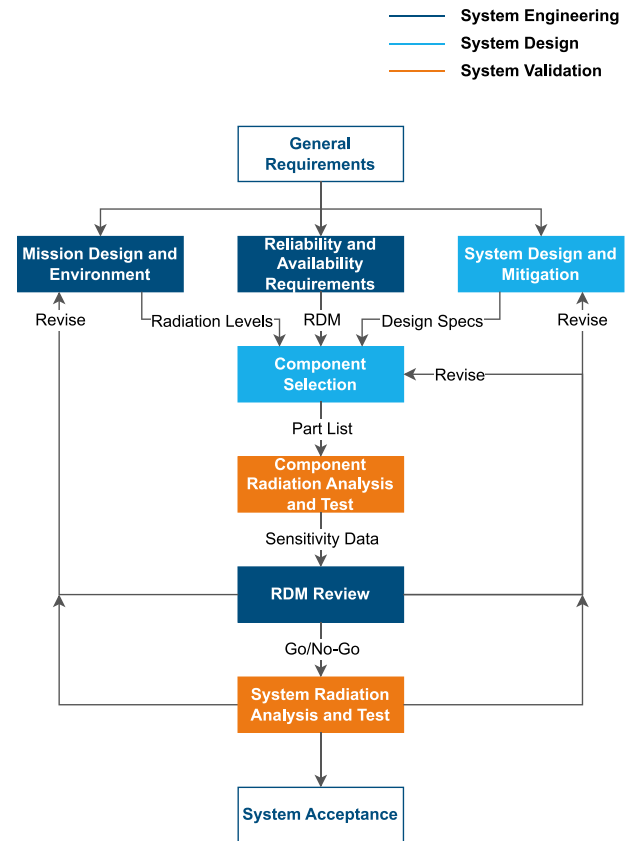


Fig. 1. Simplified illustration of the generic RHA processes as applied in major space agencies. RDM = radiation design margin.

underestimated. Possible considerations to tackle these problems introduced are: understand the RHA impact on project resources (based on mission classification), perform selection of parts and design iterations at early stages of the design (keep it compatible with alternative parts), check propagation of errors in high-risk equipment, be inquisitive when buying COTS, be careful with heritage, and include a radiation expert in the project [24]. More recently, ESA also published a guideline [25], which provides a framework for using COTS components in ESA missions. It categorizes COTS components into different criticality levels based on mission risk, reliability and radiation tolerance requirements. The guideline discusses procurement strategies, reliability concerns, RHA and mitigation techniques at component, module and system levels. It addresses lot homogeneity, risk assessment and qualification procedures to ensure component suitability for space applications.

Efforts have also been made to address these issues through specific guidelines and standards. For example, the ECSS-Q-ST-60-13C standard outlines the requirements for selecting, controlling, procuring and using COTS Electrical, Electronic, and Electromechanical (EEE) components in European space projects. This technical standard emphasizes the need for careful selection and control measures to ensure that COTS components meet the necessary performance and reliability requirements, helping to mitigate the risks associated with their use [26].

At NASA, the use of COTS parts in critical applications has sparked a debate because of varying perspectives on the associated risks. Some centers consider COTS components to be high-risk because of uncertainties in quality and long-term reliability, particularly when compared to the more rigorously controlled Mil-Spec parts. Others believe that, with proper engineering practices, these risks can be mitigated, making COTS a viable option for space missions. A significant challenge in using COTS components lies in part-level verification, as they come

from various manufacturers with differing levels of quality control. Unlike Mil-Spec parts, which have well-documented quality and reliability standards, COTS components lack uniformity, making it difficult to establish a standard verification process. The absence of formal communication or government oversight complicates efforts to ensure consistent quality across suppliers, often leaving agencies with the challenge of determining what evidence is sufficient to verify COTS components for critical space applications. Major recommendations are to select COTS parts from industry leading part manufacturers (ILPMs) with the highest commercial grade, use older technology nodes (2 to 8 years), choose parts that are widely used and select parts with flight heritage. These components can also be referred to as “Established COTS” [27]. NASA is also recommending Mil-Spec screening and non-radiation-related lot acceptance testing to be reduced or eliminated in cases where evidence of sufficient quality and reliability exists for COTS parts. The extent of insight into COTS manufacturers and the amount and nature of the needed evidence will differ by mission, which is likely to be driven by mission’s resources and associated risk posture [28].

Another evolving aspect of COTS usage is reflected in the commercial sector, where traditional RHA practices are being challenged. Commercial missions often rely on novel COTS technologies, new mission architectures and operate with smaller budgets compared to traditional space programs. This shift necessitates a more flexible approach to RHA, where risk is managed using tools like goal structuring notation (GSN) and relative risk analysis, allowing for the acceptance of certain risks where they align with the mission’s overall success criteria. These evolving practices indicate the need for updated standards that can accommodate the rapid development cycles and innovative solutions characteristic of commercial missions [29].

2.1.3. RHA testing standards

Testing is a fundamental aspect of demonstrating means of compliance (MoC) for RHA, ensuring that components and systems can withstand the radiation environments encountered in space. Various standards guide the testing process, specifying procedures for evaluating both cumulative radiation effects and transient effects. These standards are being used by space agencies, sub-contractors and ILPMs. The standards applicable for TID testing are:

- ESCC-22900: Defines the basic requirements applicable to the steady-state irradiation testing of integrated circuits and discrete semiconductors suitable for space applications [30].
- MIL-STD-750/883 1019: Defines the requirements for testing discrete packaged semiconductor devices for ionizing radiation (total dose) effects from a Cobalt-60 (⁶⁰Co) gamma ray source [31,32].
- ASTM-F1892: Provides guidelines and background information for performing ionizing radiation effects testing, particularly total dose testing, of semiconductor devices at dose rates below 300 rad/s [33].

For SEE testing, the following standards can be taken as reference:

- ESCC-25100: Defines the requirements for the testing of integrated circuits and discrete semiconductors for SEE arising from irradiation by energetic heavy ions or protons [34].
- MIL-STD-750 1080: Describes the procedure for conducting heavy ion irradiation of power metal–oxide–semiconductor (MOS) field-effect transistors (FETs) [31].
- JESD-57: Establishes requirements for conducting heavy-ion SEE testing in electronic devices [35].
- JESD-89: Provides a comprehensive overview of the measurement and reporting of alpha particle and terrestrial cosmic ray induced soft errors in semiconductor devices [36].
- JESD-234: Establishes requirements for conducting a proton SEE test in electronic devices [37].

- ASTM-F1192: Provides a standard for testing integrated circuits and other devices for the effects of single event phenomena induced by heavy ion irradiation [38].

Apart from radiation testing, SEEs can in some cases also be tested using a pulsed laser (PL) test method. This method of testing is also maturing in recent years, and has both European [39] and American [40] guidelines. This test method is currently used as part screen method and fault injection. Additionally to ionizing radiation tests, DD testing also has a commonly used standard, ESCC-22500. This guideline defines the requirements applicable to the DD irradiation testing of integrated circuits and discrete semiconductors suitable for space applications [41].

2.2. Key studies on RHA themes

Numerous studies have explored the critical themes of RHA. This subsection elaborates on the effects of radiation on modern electronics, mitigation strategies and testing methods. The studies included have contributed significantly to the understanding of these topics and have been heavily cited.

2.2.1. Radiation effects on modern electronics

Radiation effects on microelectronics have become increasingly significant as technology scales down, posing challenges for device reliability and performance [3]. The primary radiation effects include ionization and atomic DD, with TID response being particularly important in MOS systems [1]. As device dimensions and operating voltages decrease, sensitivity to radiation increases dramatically, affecting both memory and logic circuits [2]. Specific radiation effects mechanisms, such as a dose-rate-induced latch-up, gate oxide charging, DD, and single event upsets (SEUs), limit the radiation survivability of modern electronic systems [42]. These challenges are further exacerbated by technology trends, making radiation effects testing, RHA and response prediction increasingly complex and crucial for future microelectronic devices [3].

2.2.2. Mitigation strategies

To mitigate risks when using COTS systems, researchers propose careful selection processes, suitability analyses and qualification phases [6,43]. Some successful approaches include mixing COTS devices with military and rad-hard components [44] and implementing architectural solutions to address radiation-induced upsets [6]. Despite the challenges, COTS components offer potential benefits for space missions, especially for commercial missions where traditional space-qualified components are less attractive due to high costs and long lead times [45,46]. Design mitigation strategies include redundancy mechanisms, radiation-hardening-by-design (RHBD) and specialized design methodologies for static random access memory (SRAM) based field programmable gate arrays (FPGAs) [47,48]. Emerging memory technologies show promise for rad-hard electronics, offering potential alternatives to conventional complementary (C)MOS approaches [49]. As radiation effects can have system-level consequences, designers must consider radiation tolerance at both the component and system levels to ensure reliability in harsh environments [50,51].

2.2.3. Radiation testing and qualification

RHA testing is crucial for qualifying microelectronics for space applications. The process involves assessing TID effects and SEEs [52]. Key considerations for testing include understanding radiation environments, physical mechanisms and appropriate test methodologies [53]. Advanced techniques like the qualified manufacturers list methodology (from ECSS) can improve efficiency through statistical process control and test structure correlations [54]. Temperature effects must be considered when testing, because devices can show increased degradation at elevated temperatures post-irradiation [55]. Although test standards

ensure best practices, they must evolve with advancing technology and research [56]. Challenges with testing include addressing low-dose-rate sensitivity in linear bipolar devices [57] and potential degradation at low TID levels in some linear integrated circuits [58]. Comprehensive testing across temperature ranges and consideration of both TID and DD are recommended for effective RHA. Testing of complex technology components can be challenging due to their underlying architectural complexity, hence the value of performing functional tests on system-level is increasing [59]. System-level testing is an upcoming trend, with existing demonstrations in mixed-field environments [60].

3. Methodology

This study employs a SLR to investigate the state-of-the-art RHA applications and methodologies for complex space systems using COTS components. The SLR approach ensures a comprehensive understanding of the key developments, challenges and innovations in designing, testing and qualifying COTS-based systems or technologies for space.

3.1. Research question

Based on the generic literature review in Section 2, this review seeks to address the following primary research question:

R0: What are state-of-the-art RHA engineering practices for design and testing of COTS-based complex space systems?

To refine this study, the following sub-questions are considered:

R1: How have system design methods and system architectures evolved to incorporate key radiation mitigation techniques for COTS components in space systems?

R2: How have radiation testing, verification and qualification methodologies adapted to ensure reliability in COTS-based space systems?

R3: What innovative applications and emerging trends are defining the future use of COTS components in space missions?

3.2. Search strategy

A structured search was conducted using the Scopus database to identify relevant academic literature to these questions. The search query was formulated to capture relevant studies using keywords from the main questions, including alternative words. The following query was used to search in titles, abstracts, and keywords of publications:

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‘Space’ AND ‘Compl*’ AND ‘System*’ AND ‘Radiation*’ AND (‘COTS’ OR ‘Commercial-Off-The-Shelf’) AND (‘Engineer*’ OR ‘Design*’ OR ‘Test*’ OR ‘Verif*’ OR ‘Qualif*’)
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Each term was included for the following reasons:

- ‘Space’: Ensures the focus is on literature related to space environments or systems.
- ‘Compl*’: Refines the search for complex or complicated systems.
- ‘System*’: Retrieves literature on systems, not just isolated components.
- ‘Radiation*’: Targets research addressing radiation related topics.
- (‘COTS’ OR ‘Commercial-Off-The-Shelf’): Focuses specifically on COTS items.
- (‘Engineer*’ OR ‘Design*’ OR ‘Test*’ OR ‘Verif*’ OR ‘Qualif*’): Captures a broad range of engineering activities, including design, testing, verification and qualification processes.

3.3. Inclusion and exclusion criteria

The review focused on papers published from 2010 onward to capture the most recent developments. The following inclusion and exclusion criteria were applied:

- **Inclusion criteria:** Peer-reviewed journal articles and conference papers addressing the use of COTS components in space systems, RHA methodologies, system design and testing procedures for radiation tolerance.
- **Exclusion criteria:** Non-peer-reviewed sources, incomplete or duplicate records and sources not relevant to avionic space systems.

After applying these criteria, 46 papers were selected from an initial pool of 61 relevant documents revealed by the search query on Scopus.

3.4. Data extraction

Data was collected from textual and graphical content to ensure a thorough synthesis of the findings. The following data points were extracted from each study, which is based on their relation to the research sub-questions:

- Information on design strategies, fault tolerance and system architectures, with a focus on how these have been adapted to mitigate radiation effects in space.
- Information on the various radiation testing approaches used to verify the reliability of COTS components.
- Insights into the challenges, key findings and emerging trends shaping the integration and future adoption of COTS components in space systems.

3.5. Synthesis and categorization

The SLR methodology was chosen not only for its rigor in comprehensively mapping the existing body of knowledge but also for its capacity to systematically extract and synthesize findings into actionable insights and practical implications relevant to the engineering and operational challenges of COTS-based space avionics. The extracted data was systematically categorized into key themes that align with the research questions:

- **Complex COTS-based system design:** Focused on design methodologies and redundancy mechanisms employed to enhance reliability.
- **Radiation testing methodologies:** Explored the evolution of testing approaches and their effectiveness in verifying COTS component reliability under space radiation conditions.
- **Innovative applications and emerging trends:** Synthesis of current applications and emerging trends in the use of COTS components in space systems.

This systematic categorization allowed for a clear alignment between the methodology and the results, ensuring that the data extraction directly supports the research questions and overarching findings of the review. These results can later be used, together with the generic literature review findings, in the discussion for analysis and actionable recommendations.

4. Results

This section presents the synthesized findings from the SLR of research and studies related to RHA for complex COTS-based space systems. The results are categorized into the key themes relating to the research sub-questions.

4.1. Complex COTS-based system design

The design and architecture of complex space systems using COTS components have undergone significant evolution to address the harsh conditions of space. This section's aim is to shed light on research sub-question R1.

4.1.1. Modular and adaptable design strategies

Modular design strategies have become essential for addressing the evolving demands of modern satellite missions. Emphasizing standardization and the effective use of COTS components, these strategies improve adaptability, enhance reliability and optimize cost-efficiency. The modular approach allows isolated testing of subsystems, simplifying the integration process and contributing to overall mission robustness. Additionally, standardizing components promotes design re-use across missions, significantly reducing engineering efforts and accelerating development timelines. In complex space systems, modularity combined with design re-use yields substantial efficiency improvements. For instance, power distribution systems can be effectively scaled to accommodate the diverse requirements of advanced spacecraft without sacrificing cost-effectiveness [61]. Modular enhancements (such as increased service capacity or redundancy) can thus be integrated seamlessly. Furthermore, updating legacy test systems through script conversion and interface modernization leverages existing infrastructure, aligns with modular design principles, which substantially reduces both development time and costs. This demonstrates how modular adjustments and strategic re-use foster reliable and flexible solutions, minimizing non-recurring engineering expenses and streamlining system integration.

A practical example of these strategies is found in lean-satellite development methodologies, where over 28 independent subsystems with dedicated telemetry were successfully implemented [62]. Through standardization facilitated by open-source hardware and software platforms, rapid prototyping and reliable subsystem operations under space conditions were achieved. Moreover, adapting general-purpose COTS components to withstand the stresses of the space environment illustrates how cost-effective and resilient satellite systems can be developed without reliance on expensive space-grade components, delivering comparable reliability. Such modular and adaptable design strategies also significantly contribute to meeting environmental compliance objectives for complex space missions. Critical practices include developing modular systems designed for cross-platform compatibility, ensuring adherence to mechanical, electrical and RF interfaces, while addressing radiation resilience for low Earth orbit (LEO) missions. Employing detailed design analyses and customized testing methodologies efficiently validates system performance across diverse launch scenarios and operational conditions. Standardized testing for interface compatibility further enhances reliability, enabling systems to meet stringent interoperability standards while simplifying compliance processes for multi-system space missions [63,64]. Additionally, adopting a unified modeling language (UML)-based approach furthers modularity, resulting in plug-and-play capabilities that bolster system adaptability and integration flexibility [65,66]. This can be applied to both software and hardware.

4.1.2. Fault-tolerant architectures

A recent systematic analysis compared fault-tolerant mechanisms designed for radiation protection in FPGA-based space electronics [67]. These mechanisms, categorized by redundancy type, are summarized in Fig. 2.

The mechanisms can be quantitatively assessed using statistical fault injection testing and metrics enable the balance of reliability and resource overhead. The architectural vulnerability factor (AVF) in Eq. (1) quantifies how vulnerable a specific chip or circuit is to causing a system-level failure if a radiation-induced error (like an SEE) hits it. The number of fault injections can for example be quantified by the

number of particles that hit the system. A lower AVF implies greater resilience to faults occurring in that particular area.

$$AVF = \frac{\text{Number of Failures}}{\text{Number of Fault Injections}} \times 100 \quad (1)$$

The power-delay-area product (PDAP) in Eq. (2) is a metric to evaluate the resource effectiveness of different hardware implementations, especially for fault-tolerant designs where overhead is a concern. Here, the electrical power consumption of the component, the time it takes for a signal to propagate through the circuit (indicating performance), and the physical silicon area occupied by the circuit are taken into account. A lower PDAP generally signifies a more optimized and efficient design, balancing performance, energy use, and physical size. This metric is critical for assessing the overhead introduced by various fault-tolerance techniques in space-constrained and power-limited systems.

$$PDAP = \text{Power} \times \text{Delay} \times \text{Area} \quad (2)$$

According to [67], informational redundancy methods generally provided superior reliability but required significantly more resources. In contrast, hardware redundancy approaches, particularly triple modular redundancy (TMR), achieved an effective balance between resource efficiency and robust reliability. Thus, selecting an appropriate fault-tolerant mechanism depends heavily on the specific reliability requirements and resource constraints of the target space system. Recent trends indicate growing interest in hybrid fault-tolerance strategies, particularly for complex COTS systems. Such hybrid approaches integrate multiple fundamental mechanisms shown in Fig. 2.

For COTS SRAM FPGAs, self-healing architectures utilizing selective TMR, memory scrubbing, and partial reconfiguration have successfully managed SEUs in real-time. A dual-FPGA setup demonstrated effective SEU mitigation at rates up to two events per second, offering flexibility to adjust scanning frequencies according to anticipated radiation levels. This layered approach supports power efficiency and onboard data processing, making it suitable for high-resilience, low-energy operations in LEO [68]. Alternatively, FPGA-based communication networks have combined dual modular redundancy (DMR) and TMR. A TMR-protected integrity checker monitors both data and configuration errors, providing notifications as necessary. Firmware optimizations significantly reduced FPGA resource usage by more than 50%, enabling practical deployment of DMR within stringent hardware constraints. Fault injection tests confirmed the effectiveness of this setup in preventing silent data corruption [69]. Additionally, employing a combined single error correction–double error detection (SEC–DED) and parity-based coding strategy can effectively manage errors in FPGA-based avionics systems [70].

For multi-core processors and system-on-chip (SoC) designs, heterogeneous core arrangements (HCA) offer effective fault tolerance. One approach pairs a fully protected low-performance (LP) core operating in lockstep with an unprotected high-performance (HP) core, balancing performance, resilience, and hardware optimization. This dual-core architecture allows task partitioning tailored to reduce failure rates and minimize hardware overhead [71]. Similarly, duplex and duplex-TMR (D-TMR) architectures enhance reliability for multiprocessor SoC systems. These architectures employ macro-synchronized lockstep techniques, enabling precise error detection and rollback recovery, especially for softcore co-processors. Proton irradiation testing validated these designs, achieving error coverage rates around 99.3% and significantly reducing error cross-sections [72].

Another promising solution is a dual-pair DMR configuration that pairs processors to detect and recover faults without requiring an external single point of failure (SPF) voter. Processors periodically transmit internal state signatures to a processor voter (P-Voter), facilitating rapid fault recovery. This method presents a versatile alternative to conventional TMR for space-grade applications, addressing some of its limitations [73]. Furthermore, parity-based DMR (PDMR) enhances

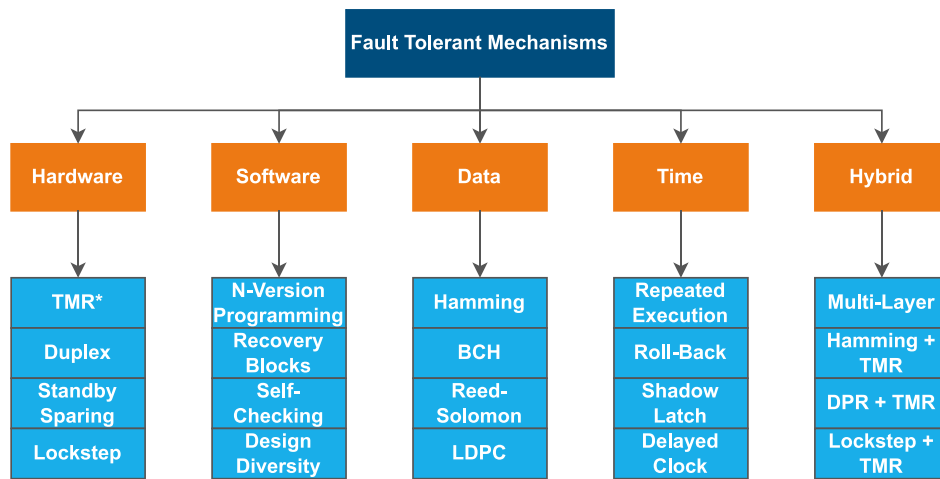


Fig. 2. Classification of various fault-tolerant mechanisms. BCH = Bose–Chaudhuri–Hocquenghem, LDPC = low-density parity check, TMR = triple modular redundancy, DPR = dynamic partial reconfiguration. Source: Adapted from [67]. *TMR is the minimum, M-of-N is an alternative term.

reliability in data transmissions between processors and reconfigurable logic within resource-constrained nanosatellites. By using parity checks for error detection and rollback for correction, this strategy minimizes hardware resources and power consumption, demonstrating viability through SoC testing [74].

An alternative fault-tolerance strategy, not included in Fig. 2, is based on operating system (OS)-level interventions. Integrating software-level error mitigation with hardware protections has shown promise, particularly in Microchip’s PolarFire RISC-V SoC [75]. Proton irradiation tests highlighted clear differences in radiation-induced failure behaviors between bare-metal and real-time OS (RTOS) implementations. The inherent task isolation of a RTOS prevented error propagation across concurrent tasks, increasing system resilience. This study underscored the advantage of combining hardware mechanisms such as built-in cache protection and watchdog timers with software-based strategies, including task redundancy and context isolation. One study highlighted the importance of middleware techniques for radiation resilience, and emphasized combined hardware-software mitigation strategies [76]. Such hybrid solutions significantly enhance reliability and operational continuity drastically in radiation environments.

4.1.3. Systems engineering approaches

Numerous studies emphasize agile or iterative systems engineering methodologies as effective frameworks for developing complex systems that integrate COTS components. These approaches provide flexibility, efficiency and cost-effectiveness in system development. Some of the key strategies identified include [77]:

- Out-of-phase design evolution, allowing independent development of subsystems at varying technology readiness levels (TRLs).
- Flexible testing and selective risk management, addressing uncertainties dynamically as they emerge.
- Early peer reviews and adaptive engineering review boards (ERBs), facilitating real-time design adjustments.
- Interface verification across key subsystems, ensuring smooth integration at the system level.
- Strategic risk management tools, balancing potential risks through partnerships with commercial providers.
- Rapid learning cycles (RLCs), promoting streamlined design iterations and continuous improvement in system resilience and performance.

The RLC strategy, illustrated in Fig. 3, is particularly noteworthy. It supports out-of-phase subsystem development by leveraging

insights gained from early demonstrations and validations. This facilitates the early identification of information gaps and subsequent learning opportunities, and pairs well with modular component designs that require minimal iterative adjustments. Overall, the iterative approach merges agile flexibility with stringent standards, reducing costs and development timelines [77].

RLCs can be effectively enabled through the use of CubeSats, which allow for accelerated testing and flexible design adaptations in response to evolving mission requirements. Scalable architectures, such as distributed nanosatellite networks, significantly improve redundancy and resilience, while modular, reconfigurable systems facilitate real-time adaptability and cost-effective deployment [78,79]. Methods such as error injection testing and hardware-in-the-loop (HiL) validation further enhance these iterative cycles, confirming system resilience even in harsh environments. The continuous feedback loops provided by these testing methodologies substantially improve overall system reliability and robustness [80].

Expanding the scope of systems engineering, one study focused on constellation-level engineering strategies. In propulsion-less CubeSat constellations, custom mission analysis tools synchronize satellite pointing with natural orbital dynamics to optimize coverage, while spring-controlled deployment mechanisms coordinate satellite movement without propulsion. Optimizing relay communication and ground station connectivity further reduces delays, ensuring efficient resource utilization and rapid adaptability to mission requirements [81].

4.2. Radiation testing methodologies

Radiation testing methodologies have evolved significantly to ensure the reliability of COTS-based space systems. This section discusses recent advancements in radiation testing, verification and qualification methodologies, addressing research sub-question R2.

4.2.1. Adaptations of traditional testing approaches

Recent studies have explored alternative radiation sources, such as the ⁹⁰Sr/⁹⁰Y electron source, comparing it with traditional ⁶⁰Co gamma sources for TID testing of complex SoC components. Electron-based sources simplify test setups and provide directional irradiation, achieving comparable TID thresholds to ⁶⁰Co sources with greater efficiency and reduced cost. Methodologies employing ⁹⁰Sr/⁹⁰Y include sequential irradiation with functional monitoring, continuous irradiation to determine maximum tolerance levels, and post-irradiation annealing to assess component recovery [82]. Another adaptation involves the application of ⁹⁰Sr/⁹⁰Y electron sources for on-chip irradiation of

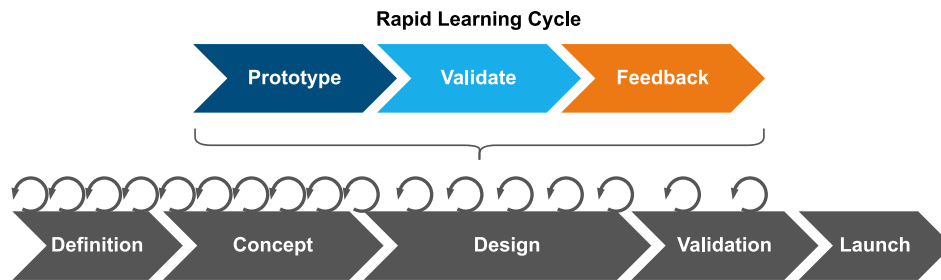


Fig. 3. Rapid learning cycles facilitated by early demonstration and validation.
Source: Adapted from [77].

SRAM-based FPGAs, particularly advantageous for smaller technology nodes (<28 nm). Complemented by on-chip sensing methods, such as custom ring-oscillator networks, this approach enables precise spatial characterization of TID-induced degradation. Integrating classical voltage and current monitoring, processor checks, memory read-back, and frequency scaling into extended-duration remote testing demonstrates the reliability and practicality of $^{90}\text{Sr}/^{90}\text{Y}$ as an alternative to traditional gamma sources [83]. Additionally, ultra-high energy heavy-ion beam testing at facilities like CERN's super proton synchrotron addresses challenges unique to advanced SEE testing of miniaturized multi-processor SoCs (MPSoCs). Conducting tests in-air minimizes interference from auxiliary circuits, and preliminary findings indicate strong single event latch-up (SEL) resilience in specific flash and SRAM-based FPGAs. Ongoing tests aim to quantify single event functional interrupt (SEFI) cross-sections and AVF estimates, providing valuable insights into the reliability of miniaturized systems [84].

However, alternative radiation sources have not replaced traditional testing entirely. Several studies still rely on rigorous up-screening protocols, including evaluations according to the ESCC standards for semiconductor devices like diodes, transistors and memory components. These established methodologies continue to guide the selection of radiation-tolerant COTS components, identifying potential failure mechanisms that may require additional protective measures such as shielding or redundancy [5].

4.2.2. System-level radiation testing

System-level radiation testing methodologies have become increasingly important for evaluating resilience in integrated COTS-based solutions such as single-board computers (SBCs). For example, system-level assessments of the NVIDIA Jetson Orin AGX module using proton and ^{60}Co gamma sources demonstrated distinct resilience characteristics. While the central processor remained functional up to 135 krad(Si), peripheral components exhibited vulnerabilities at lower doses [76]. Mixed-field system-level testing methodologies, capturing hard and soft error cross-sections, have proven essential for comprehensive fault-tolerance analysis. Testing entire subsystems such as on-board computers (OBC) and imaging sensors revealed the efficacy of reboots in mitigating hard errors and the general correctability of soft errors, which typically cause minor operational interruptions [85]. Additionally, system-level testing uncovered interface compatibility issues and software faults not evident in isolated component testing, highlighting potential TID-induced degradation in watchdog circuitry beyond typical LEO radiation levels [86,87]. Mission-specific system-level methodologies have also been applied effectively [88], such as radiation tolerance testing in CubeSat payloads with imaging systems. This approach combines ground-based system-level radiation tests with in-flight functional verification, employing thermal performance assessments and signal-to-noise analyses during rigorous radiation exposure.

4.2.3. Radiation testing for complex socs

Testing methodologies tailored explicitly for complex SoCs, such as RISC-V software processors, have been developed to address increasing computational demands in space missions. One structured approach integrates hardware and software validation strategies within realistic neutron radiation environments, systematically assessing the impact of SEUs and SEFIs [89]. This method emphasizes precise event classification, minimizing test-fixture failures and ensuring robust event logging. A dual-method approach combining bare-metal and OS-based testing has been developed to handle the complexities of modern MPSoCs. Bare-metal testing provides detailed, component-level failure data via self-test software, while OS-based testing utilizes customized kernel-level logging for broader insights into component interactions under radiation exposure. Early results confirm both methods' effectiveness in capturing radiation sensitivity and suggest further improvements in component-specific and multi-core testing methodologies [90].

4.3. Innovative applications and emerging trends

The increasing adoption of COTS components in space missions has led to a new set of innovative applications and emerging trends. This section highlights these applications and trends, providing valuable insights for research sub-question R3.

4.3.1. CubeSat and COTS communication systems

As mentioned before, CubeSat platforms have become valuable tools for cost-effective, iterative experiments. This is again exemplified by the Argus campaign, which refines predictive models using frequent, low-cost flights [78]. Similarly, formation-flying nanosatellites provide scalable space situational awareness (SSA), leveraging COTS-based networks to improve reliability, resilience and data relevance while reducing mission costs [79]. Additionally, CubeSat networks have demonstrated promising potential for planetary exploration missions, providing modular, scalable architectures for planetary science and exploration support [91].

Advanced COTS communication components like software-defined radios (SDRs) and RF SoCs offer enhanced flexibility, adaptability and cost-efficiency for nanosatellite communications. Radiation-tested SDR platforms have demonstrated reliable multi-band operation in LEO, facilitating emerging applications such as RF interference monitoring and geolocation [92,93]. Furthermore, terrestrial COTS receiver technologies have been successfully adapted for space telemetry and telecommand systems, showcasing effective radiation tolerance and robust performance [94].

4.3.2. Reconfigurable and intelligent onboard systems

Reconfigurable architectures, particularly using SRAM-based FPGAs, have been explored for enhanced radiation tolerance through dynamic reconfiguration. Fault injection studies indicate substantial

robustness gains, especially when combined with distributed or integrated memory configurations tailored to specific radiation environments [95,96]. Additionally, active mitigation strategies such as in-flight reconfigurations and memory usage monitoring have effectively countered radiation-induced failures, improving mission resilience [97].

The increasing autonomy in satellites driven by onboard machine learning (ML) further advances mission responsiveness and reliability. Radiation-resistant FPGAs have emerged as preferred platforms for reliable in-space neural network deployment, with ML techniques increasingly utilized for failure detection, isolation and recovery (FDIR) in constrained environments [98,99]. Embedded processor-FPGA solutions have demonstrated significant performance improvements for computationally intensive tasks like search and rescue (SAR) image processing and advanced multispectral tracking, highlighting the potential for hybrid computing architectures in autonomous onboard operations [100,101]. Autonomous navigation systems combining visual and inertial sensors offer robust performance for GPS-denied environments and planetary landing scenarios [102].

4.3.3. Radiation-tolerant components and emerging materials

The integration of advanced COTS materials such as gallium nitride (GaN) FETs and magnetoresistive RAM (MRAM) provides improved radiation tolerance for power electronics and memory components, respectively. GaN-based converters have demonstrated stable high-efficiency performance suitable for demanding LEO applications, presenting a viable alternative to traditional silicon MOS-FETs [103]. Despite their promise, certain materials like silicon germanium (SiGe) heterojunction bipolar transistors (HBTs) and GaN high electron mobility transistors (HEMTs) exhibit specific radiation vulnerabilities, highlighting the continued need for tailored shielding or redundancy measures [5].

Recent developments in radiation-tolerant microprocessors, such as the PC7448, have combined high-performance COTS architectures with rigorous qualification standards, enabling their use in demanding Earth observation (EO) and SAR missions across various orbital regimes [104]. Additionally, initiatives like the open source satellite programme (OSSAT) continue validating low-cost, high-performance microprocessors for space applications, identifying promising candidates capable of operating reliably in radiation-intensive environments [105].

5. Discussion

This section discusses the main findings from the SLR, shows their relevance to the research questions and examines their implications on the state-of-the-art RHA practices for COTS-based complex space systems. By addressing the primary research question R0, the section explores key insights into system design, testing methodologies and emerging applications, while comparing findings with established standards and guidelines from space agencies and identifying challenges and future directions in this field.

5.1. Overview of key findings

This systematic review highlights significant advancements and emerging trends in RHA practices for complex COTS-based space systems, directly addressing the research sub-questions R1, R2, and R3. The key insights identified from this analysis include:

- **System design:** Modular design strategies and fault-tolerant architectures are increasingly recognized as foundational for enhancing RHA in complex COTS-based systems. Modular designs facilitate subsystem isolation, targeted protection of radiation-sensitive components and flexible system scaling. Fault-tolerant mechanisms, particularly hybrid redundancy approaches, optimize reliability and resource usage, while agile and iterative engineering methodologies support dynamic adaptation to evolving RHA and system requirements.

- **Radiation testing:** Customized and mission-tuned radiation testing has become critical for accurately evaluating component- and system-level radiation resilience. Emerging methodologies, including the use of alternative radiation sources and mixed-field system-level assessments, ensure thorough validation of COTS components' ability to meet reliability standards in realistic radiation environments.
- **Applications and trends:** New applications and technological innovations significantly enhance RHA capabilities. Notably, distributed nanosatellite networks employing COTS technologies improve fault tolerance and mission robustness. Additionally, intelligent and reconfigurable onboard systems utilizing ML and autonomous diagnostic techniques enable real-time radiation effect mitigation and enhance system adaptability in operational environments. The integration of advanced radiation-tolerant materials, such as GaN-based electronics and MRAM, can substantially enhance component resilience.

5.2. Comparison with standards and guidelines

The findings from the SLR demonstrate significant alignment with, as well as extensions beyond, existing RHA standards and guidelines provided by major space agencies. ESA's ECSS standards present a structured and comprehensive framework for RHA that encompasses all mission phases, ensuring rigorous and standardized risk management. Conversely, NASA's historically flexible, mission-specific approach, derived from Mil-Spec guidelines, emphasizes adaptable RHA strategies that align closely with the varying criticality and risk profiles inherent to different missions. The SLR findings reinforce and expand this transition towards mission-tailored RHA approaches, resonating with ESA's recently implemented mission classification scheme and NASA's contemporary guidelines advocating customized risk assessments and testing protocols adapted to specific mission profiles.

Critically, the SLR highlights the necessity of incorporating RHA considerations at the earliest stages of COTS-based system design, aligning with ESA's identified challenges and recommended practices. ESA's guidelines underscore proactive part selection and maintaining compatibility with alternative components, reducing risks associated with late-stage modifications. Similarly, NASA's recommendations on selecting established COTS from ILPMs, emphasizing proven commercial reliability and flight heritage, validate the SLR's assertion of early and rigorous RHA-focused risk mitigation. One topic not specifically touched upon in standards, but highlighted in the SLR, is the iterative systems engineering approach with RLCs to enhance system radiation resilience.

In radiation testing methodologies, the review findings advocate a structured, multi-tiered testing strategy consistent with current ESA and NASA standards. Moreover, the review identifies novel and supplementary testing methods, such as alternative radiation sources or system-level testing methods, for which standards currently lack coverage. However, the adoption of PL testing by agencies as a complementary RHA practice, reflects the relevance of alternative test methods. Advanced methodologies provide early-stage, cost-effective insights into radiation sensitivity, further supporting tailored testing protocols. Both ESA and NASA are progressively integrating innovative testing methods into their RHA processes, demonstrating alignment with the evolving mission-specific classifications and highlighting a shared recognition of the value in flexible, efficient and comprehensive radiation evaluation techniques.

5.3. Implications

The findings of this systematic review have substantial practical implications for RHA across multiple stages, including system design, testing methodologies, and adoption of emerging technologies in complex COTS-based space systems. Specifically, the systematic analysis of

current RHA practices and research reveals several overarching themes and actionable insights crucial for effective implementation, guiding practitioners in their decisions:

- **Early integration of RHA in design phases:** The review highlights that proactive RHA considerations from the initial design stages are paramount for COTS integration. This includes rigorous component selection, architecture choices that inherently tolerate radiation effects, and early application of design-for-radiation principles.
- **Adaptive and agile RHA processes:** Given the rapid evolution of COTS technology and supply chains, the review points towards the increasing necessity of adaptive and agile RHA processes. This involves continuous monitoring, staying up-to-date of new techniques, and developing flexible testing approaches.
- **Tailored testing methodologies:** No single testing approach fits all COTS components or mission profiles. The literature emphasizes the need for tailored testing strategies, moving beyond generic qualification. This includes a balance of ground-based testing, advanced simulation, and possibly leveraging flight data for validation.
- **System-level hardness and validation:** As COTS integration pushes towards system-level complexity, hardness and validation efforts must extend beyond individual components to the entire system. Fault tolerant strategies like design diversity, or hybrid fault tolerant approaches can be applied.

These insights signal a broader shift in RHA strategy, from relying primarily on inherently radiation-hardened components towards a more dynamic, system-level assurance approach. This approach is better aligned with the realities of integrating COTS technologies, where adaptability, life cycle awareness, and cost-effectiveness are critical to achieving mission resilience under evolving space system demands.

Employing modular and standardized design strategies is critical for creating flexible, scalable architectures that enhance radiation tolerance. For complex COTS-based systems, modularity directly aids RHA by isolating radiation-induced faults to specific modules, thereby preventing their propagation across the system. It also simplifies the identification of radiation-sensitive components, allowing for focused testing and selective hardening efforts, which is crucial when full system-level testing is impractical due to complexity and cost. Furthermore, modularity facilitates easier interchangeability or upgrades of radiation-susceptible COTS components without requiring a complete system redesign, contributing significantly to the overall radiation resilience of complex systems. Although modularity is a strong tool to tackle complexity in systems, other options might be available that were not found in the SLR. Object-oriented design (OOD) utilizing SysML effectively supports these strategies, as demonstrated by the SysML implementation example shown in Fig. 4. This example underscores essential OOD principles such as modularity, polymorphism, and standardized interfaces, which facilitate adaptable system architectures in complex domains like space avionics. For instance, defining a standard contract through the Communication Interface, which includes key operations such as `sendData()` and `receiveData()`, ensures that various modules (like the general Communication Module or the specialized Laser Communication Module) can seamlessly integrate into the broader Space System. Such approaches significantly simplify the interchangeability of radiation-sensitive components, encourage component reuse, and align smoothly with simulation and testing environments. Additionally, distributed and fault-tolerant designs deliver robust real-time error correction, crucial for improving overall system resilience. Recent research often implements hybrid fault-tolerant methods tailored specifically to each system, indicating the necessity of individual assessments and optimizations of fault tolerance strategies. Furthermore, agile and iterative methodologies using RLCs effectively facilitate rapid prototyping and validation; however,

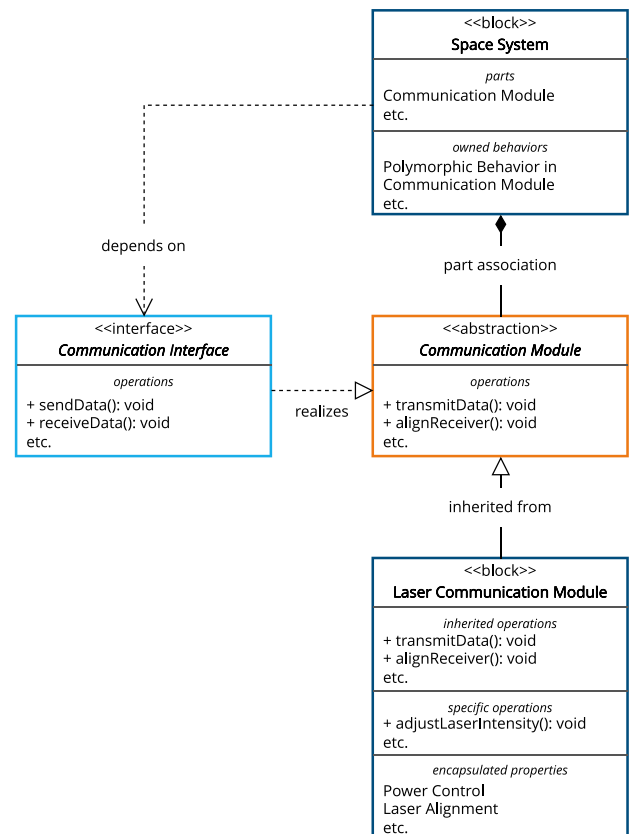


Fig. 4. Illustrative example of OOD using SysML for modularity and re-use.

managing performance variability in COTS components remains an ongoing challenge. Applying these approaches enhances risk management and enables real-time adjustments, factors critical for successfully designing complex COTS-based space systems. Complementary strategies, such as concurrent engineering (CE), also represent valuable methods for integration into these workflows.

The systematic review identifies a significant shift towards multi-layered, customized approaches in radiation testing, addressing various levels of system complexity. Utilizing diverse radiation sources enables precise assessments that closely match the conditions of specific mission profiles. Given the growing range and uniqueness of space missions, no single radiation testing standard can fulfill all requirements; instead, testing protocols must be individually tailored to meet specific mission demands. Additionally, radiation testing now closely integrates with iterative design processes, emphasizing early and frequent validation through radiation tests or fault-injection techniques, adjusted according to test facility availability. This proactive approach significantly reduces development risks and enhances overall system reliability. A notable emerging trend within these tailored testing methodologies is the increasing utilization of repurposed testing facilities, often derived from medical instrumentation (e.g., linear accelerators, proton therapy facilities). These facilities offer more accessible and cost-effective alternatives to traditional, dedicated space radiation test facilities, making them particularly attractive for initial screening and rapid validation of COTS components where full space-qualified testing might be prohibitive due to budget or schedule constraints. Recent research demonstrates the usefulness of these facilities in analyzing component behavior under radiation exposure [106–108], and in characterizing beams for space application testing [109,110]. While these facilities may not always replicate space environments perfectly and may necessitate careful interpretation of results, their accessibility supports

iterative design cycles and allows engineers to quickly assess the radiation sensitivity of COTS candidates, contributing significantly to agile RHA workflows.

Emerging trends in COTS-based space systems introduce significant considerations for improving radiation resilience and mission flexibility. The increasing deployment of distributed satellite constellations emphasizes the need for fault-tolerance strategies evaluated at the constellation scale, including careful management of redundancy and the mitigation of failure propagation across the entire system. Additionally, incorporating advanced radiation-tolerant materials offers promising opportunities to enhance overall system robustness; however, their limited flight heritage necessitates thorough validation processes similar to those required for newly adopted COTS components. Furthermore, the rising use of intelligent onboard systems leveraging advanced AI and machine learning algorithms creates greater dependence on high-performance COTS processors, underscoring the importance of targeted research into efficient, radiation-tolerant computing architectures specifically designed for computationally demanding tasks in radiation-intensive environments.

5.4. Gaps and limitations

Although substantial advancements have been made, several critical gaps and limitations remain:

- **Insufficient in-orbit validation:** A shortage of flight heritage and in-orbit data restricts validation of emerging design and radiation-hardening techniques.
- **Satellite-level fault tolerance:** Fault-tolerance strategies predominantly focus on individual satellites, neglecting constellation-level resilience.
- **Rigid testing frameworks:** Existing radiation testing frameworks lack flexibility, challenging adaptation to evolving mission and requirements.
- **Costly testing facilities:** Conventional radiation testing methods are expensive and less accessible (scheduling or location), limiting frequent testing opportunities.
- **Limited validation of advanced materials:** Promising radiation-tolerant materials lack extensive validation, affecting their adoption.
- **Processor vulnerability:** Dependence on advanced COTS processors for intelligent onboard systems remains vulnerable without radiation-hardened architectures.

Addressing these gaps will be essential to strengthening radiation resilience in complex space systems. In parallel, it is important to recognize that the findings of this review are also subject to methodological constraints inherent to systematic literature reviews, such as publication bias, limited coverage of gray literature, and potential exclusion of emerging research due to scope or terminology differences.

5.5. Future directions

To effectively address the limitations or support current trends, future research efforts should prioritize the following areas:

- **Standardized modular architectures:** Adoption of open-source standards (e.g., RISC-V) to enhance modularity and system adaptability.
- **Flexible testing frameworks:** Integration of modular frameworks with iterative methodologies (e.g., RLCs) for faster and adaptive validation processes.
- **Accessible radiation testing methods:** Inclusion of cost-effective techniques (e.g., PL testing) in standard frameworks to enable frequent assessments.

- **Extended flight validation:** Long-term in-orbit demonstrations to validate novel technologies and methodologies comprehensively.
- **Constellation-level fault tolerance:** Development of fault-tolerance strategies addressing redundancy and failure propagation at the constellation scale.
- **Rigorous material validation:** Comprehensive ground and flight validation campaigns for advanced radiation-tolerant materials.
- **Radiation-hardened intelligent architectures:** Research on efficient, fault-tolerant computing architectures suitable for AI/ML tasks under radiation conditions.
- **Expanding to non-electronic materials:** Investigate the engineering and testing approaches for RHA of non-electronic materials, such as optical components (mirrors, lenses), thermal control materials, and structural elements.

These future directions provide a structured roadmap to advance RHA practices, enabling reliable and efficient use of complex COTS-based systems in diverse space environments.

6. Conclusion

This review systematically explored state-of-the-art RHA practices for complex COTS-based space systems, addressing how design strategies, testing methodologies and applications have evolved. The findings reveal that modular design, hybrid fault-tolerant architectures and agile engineering methods are now central to enhancing system reliability and adaptability. Radiation testing has shifted towards mission-specific approaches, integrating alternative sources and system-level assessments to ensure accurate validation of COTS components under space conditions. Innovative applications, such as reconfigurable systems, distributed constellations and intelligent onboard processing, are redefining the role of COTS in space missions, supported by advances in materials like GaN and MRAM. Despite progress, gaps remain in in-orbit validation, constellation-level fault tolerance and accessible testing methods. Future work should focus on flexible testing frameworks, open-source modular architectures and radiation-hardened solutions for AI-driven systems, ensuring robust RHA strategies that keep pace with evolving mission needs.

CRedit authorship contribution statement

Jasper Dijks: Writing – original draft. **Sybren de Jong:** Supervision. **Alessandra Menicucci:** Writing – review & editing, Supervision. **Iklım Akay:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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