

# Enabling Reliable, Fault-Tolerant Autonomous Lunar Habitats with High-Performance Spaceflight Computing

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**Abstract**—The lunar surface presents unfavorable constraints and harsh living conditions. To address these challenges, autonomous habitats will require complex integrated systems that combine advanced software, high-performance hardware, and cutting-edge sensors to ensure sustainability, safety, and operational efficiency. Consequently, maintaining a sustainable presence on the Moon requires reliable infrastructure and efficient development, precise monitoring, and utilization of resources within a lunar installation. These elements are essential not only to ensure that lunar settlement can be long-term, self-sustaining, and resource-efficient, but also to serve as a foundation for future missions and eventual human habitation on Mars. Humans are not native to the Moon; therefore, our survival and ability to thrive will depend on autonomous systems that can foster safety and resilience through high-availability architectures, graceful degradation, and highly fault-tolerant spaceflight hardware capable of continuing operation during failures. This requires advanced human-rated distributed systems architectures with specialized electronics, scalable capabilities, and an integrated design approach. Unlike current practices focused on short-term missions and regularly maintained components, permanent lunar compute systems must be designed for extended operations beyond mission durations. This paper explores the necessity of transitioning toward fault-tolerant, highly autonomous hardware systems designed for multi-year missions. It also identifies critical subsystems that require high levels of autonomy, supported by radiation-hardened processors and extreme thermal loads, which are essential to mitigate long-term degradation and ensure sustainable lunar habitation. Finally, the paper aligns with NASA’s identified Civil Space Shortfalls, particularly in high-performance onboard computing, advanced data acquisition, extreme-environment avionics, radiation monitoring and countermeasures, and autonomous health management. It proposes NASA’s new High-Performance Spaceflight Computing (HPSC) processor as a turnkey solution, delivering 100 times the performance-per-watt of legacy rad-hard CPUs and enabling onboard AI, edge computing, and fault-tolerant features essential for sustained lunar autonomy and beyond.

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## 1. INTRODUCTION

Space-based computing dates back to the 1960s with the Apollo Guidance Computers, which handled critical guidance, navigation, and control tasks for the Apollo missions [7]. Later, each space shuttle carried multiple IBM AP-101 computers built from discrete IC chips. In 2001, BAE Systems introduced the RAD750 – a radiation-hardened, 32-bit microprocessor derived from the PowerPC 750 architecture. The RAD750 processor has served as the reliable backbone of spaceflight computing for nearly twenty years and reached its end-of-life with Psyche and Europa Clipper Missions [6].

Looking at new frontiers, as human and robotic missions push deeper into space, conducting scientific observations and establishing permanent lunar and planetary presence demands highly autonomous systems to fulfill NASA’s research objectives [14]. To maximize scientific return and data output, while ensuring safe operations in space habitats, space vehicles, and containers must be designed with powerful onboard processors, tightly coupled subsystems, optimized energy consumption, and the ability to withstand dynamic conditions and harsh space environments. NASA’s Space Technology Mission Directorate (STMD) leads the development, demonstration, and infusion of transformational technologies that enhance NASA’s efforts to explore the unknown in space, benefit life on Earth, and solve critical stakeholder needs [9]. In recent years, the

research and reported requirements for next-generation space processors by NASA [14] focused on (not limited to):

1. Enhanced Compute and Autonomous Capabilities.
2. High Fault-Tolerance.
3. High-Speed and Advanced CPU Connectivity.
4. Future-Proof Security Measures.

STMD is constantly refining its strategy for prioritizing technology investments, with the goal of evolving into a stronger and more resilient national tech base for civil space, and as a result, released the 2024 Civil Space Shortfall Rankings [9] – described in Table 1. This strategic framework addresses critical technological gaps in avionics, habitation systems, and autonomy and identifies shortfalls that underscore the urgency of developing resilient systems capable of sustaining long-duration missions in the harsh lunar environment. To address these challenging shortfalls in sustaining future space missions, including autonomous Lunar and Martian habitats (ID 1519, 1526, 1527, 1535, 1549, 1550, 1551, 1552, 1553, 1554, 1555), NASA, in partnership with Microchip, developed the High-Performance Spaceflight Computing (HPSC) processor as an emerging pivotal solution [1].

**Table 1. Civil Space Shortfall Description**

Shortfall ID	Shortfall Title
1519	Environmental Monitoring for Habitation
1526	Radiation Monitoring and Modeling (Crew and Habitat)
1527	Radiation Countermeasures (Crew and Habitat)
1535	Autonomous Vehicle, System, Habitat, and Infrastructure Health Monitoring and Management
1549	Advanced Data Acquisition Systems for Diverse Applications
1550	Crew Audio/Visual Interfaces for Long Duration Missions Beyond LEO
1551	Distributed Avionics to Enable Improved Performance and Size, Weight, and Power (SWaP) Efficiency
1552	Extreme Environment Avionics
1553	Foundational Technologies for Future Avionics Devices and Systems
1554	High Performance Onboard Computing to Enable Increasingly Complex Operations
1555	Next Generation Avionics Architectures

HPSC is a fault-tolerant, radiation-hardened, multicore System-on-Chip (SoC) designed to meet the computational demands of future space missions, including those on the Moon and Mars. Its architecture supports advanced autonomy, enabling real-time decision-making and system

management without reliance on Earth-based control [1]. Figure [1] below shows the evolution of commercial processors post the Apollo era, leading us to the RISC-V-based multi-core processor in 2025 – HPSC.

Microchip's PIC64-HPSC microprocessor was designed for intelligent edge and autonomous computing in space with state-of-the-art fault-tolerance techniques. Inherently enabling sustainable strategies and technologies that ensure continuous operation and data integrity within microprocessors for sophisticated autonomous space systems.

## 2. LUNAR SURFACE ENVIRONMENT EFFECTS

The lunar surface subjects systems to intense radiation from cosmic rays and solar particles – typically with dose rates (~1.37 mSv/day) with no geomagnetic shielding [16], extreme temperature swings from over 100 °C by day to –173 °C at night, and the challenges of vacuum, such as outgassing, cold welding, and poor heat transfer. In addition to high-velocity micrometeoroids and abrasive, electrostatically charged regolith dust that continuously threaten to erode and jam critical components, set strict system design requirements. Considering these environmental factors, autonomous lunar habitats must require specialized and robust designs for reliability, thermal control, and material durability against these hazards [11]. Each component must ensure the habitat's immediate survival and functionality, while accounting for prolonged exposure to heightened radiation and extreme thermal cycling, where resources for maintenance are limited or non-existent.

Preliminary results reported in [17] present measurements from the Chang'e-4 Lunar Lander Neutrons and Dosimetry (LND) instrument, providing the first long-duration, in-situ characterization of the lunar surface radiation environment using silicon detectors. Under quiet solar conditions on the lunar far side, LND measured an average absorbed dose rate in silicon of ~13.2 μGy/h (~0.32 mGy/day), corresponding to the direct energy deposition relevant to electronic components. The measurements confirm that the lunar surface radiation environment is dominated by unmoderated galactic cosmic rays, with additional contributions from secondary particles generated in the regolith.

Converting the absorbed dose in silicon to a total ionizing dose (TID) accumulation rate yields approximately 11.56 rad/year or 0.0116 krad/year, under unshielded conditions representative of the LND measurement site. When compared against typical krad(Si) TID limits, these results imply a relatively slow accumulation of ionizing dose in silicon over mission timescales. However, the suitability of permanent lunar surface habitats remains strongly dependent on accurate predictions of single-event effects (SEE) rates.

A supplemental source of lunar surface radiation data is NASA's Radiation Tolerant Computer (RadPC) technology demonstration aboard the Blue Ghost Mission 1 Commercial

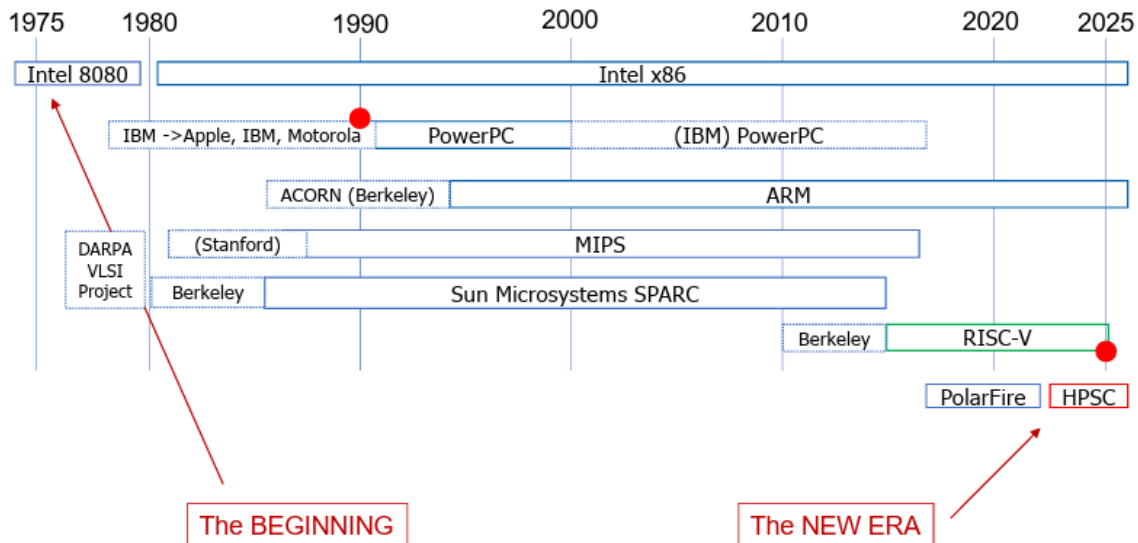


Figure 1. Central Processing Unit (CPU) Evolution [5]

Lunar Payload Services (CLPS) lander [10]. Although the data have not yet been made public, this demonstration is expected to provide critical comparative data that can inform trade studies for future Artemis surface infrastructure.

### 3. AUTONOMOUS HABITAT SYSTEMS

Besides key environmental considerations, autonomous habitats rely on complex and tightly integrated systems to ensure the safety and well-being of their occupants, which not only perform their primary functions but also monitor, protect, and respond to threats in real time. According to [12], NASA's major key habitat components include:

1. Environmental Control and Life Support Systems (ECLSS): These systems manage air quality, temperature, humidity, and waste, creating a livable environment within the habitat.
2. Electrical Power System (EPS): Power distribution and management functions. Nuclear radioisotope generators or solar panels and energy storage systems provide the necessary power for all habitat functions, with redundancy to ensure continuous operation during lunar nights or dust storms.
3. Thermal Control Systems: These systems regulate the habitat's temperature, protecting both equipment and crew from the Moon's extreme temperature variations.
4. Communication Systems: Reliable communication with Earth and other lunar modules and installations, essential for coordination and data exchange.
5. Navigation and Transportation Systems: For habitats that include mobility, such as rovers or movable modules, precise navigation systems are required.
6. Robotic Systems: Autonomous robots can perform

maintenance tasks, conduct scientific experiments, and assist with construction and resource extraction.

7. Radiation Protection and Safety Systems: Active shielding approaches with advanced sensors and shielding materials. Monitoring and emergency systems for real-time exposure monitoring with shelters and evacuation protocols.

The integration of these components into a cohesive, self-sustaining habitat is critical for the success of long-term lunar missions. Each of these systems contains complex autonomy elements that must be incorporated into their design to enable the ability to monitor their own performance, detect and respond to anomalies, and coordinate with other systems within the habitat. This inherently requires systems to implement subsystem-level redundancy, autonomous fault management, integrated health management, and long-term prognostics.

Following Future Artemis missions, NASA is planning to build a permanent lunar outpost over the next two decades. The lunar outpost will consist of numerous modules delivered individually and assembled on the surface, creating a network of interdependent subsystems that must be continuously monitored and managed [12]. The goal of the habitat is to have significant crew autonomy from ground controllers, reducing the ground control staffing requirements. Additionally, it will require a level of autonomy that has not yet been demonstrated in space systems when the lunar outpost is uncrewed. This new level of complexity, due to the number of interacting systems, incremental build-up, and light-time delay between the Moon and the Earth, will impose significant challenges on the onboard avionics systems.

Alongside industry partners, this effort is planned to use several key strategies for developing sustainable avionics systems for lunar habitats [15], prioritizing the following:

1. Radiation Hardening.
2. Thermal Management.
3. Modular Design.
4. Redundancy and Fault-Tolerance.
5. Autonomous Monitoring and Control.

Lunar space environmental effects are unforgiving and accelerate cumulative damage, thermal fatigue, and software aging. However, the right combination of strategies and architecture with the advanced avionics systems can support long-term lunar habitation, withstand the Moon's harsh environment, and operate autonomously for extended periods.

#### 4. CURRENT SPACEFLIGHT HARDWARE & LIMITATIONS

The RAD750 has been instrumental in numerous NASA missions, including the Deep Impact, the Mars Curiosity Rover, the James Webb Telescope, and recently, Psyche and Europa Clipper [6]. Current avionics systems used in space missions, such as those on the International Space Station (ISS) and Mars rovers, provide valuable insights but also highlight limitations when considering long-term lunar habitation. Common techniques for radiation mitigation are often limited to some tolerance, physical separation of hardware, redundancies, voting, encasing materials and under-clocking hardware. The ISS benefits from regular maintenance and the ability to replace faulty components, an option not always available for lunar habitats. Additionally, Mars rovers, like Perseverance and Curiosity, utilize radiation-hardened electronics (RAD750) [8], but these systems are based on older technology with limited processing capabilities and are currently at their end-of-life.

According to JPL mission surveys [6], mission system size has been increasing since the 1980s. Figure 5 in [6] indicates a steady increase in the size and complexity of JPL's software systems over time, which calls for effective and advanced practices since increasingly complex systems require larger software running in parallel at higher rates. Similarly, lunar habitat processors must only possess enhanced computational power, AI edge capabilities, high-speed connectivity, power efficiency, and advanced security measures. Signifying the introduction of the PIC64-HPSC microprocessor to mark a transformative advancement in the future of space computing.

The closest reference to space-based habitat is the International Space Station (ISS). ISS avionics – radiation hardened 386SX and Pentium CPUs [13], survive by planned maintenance and lower LEO doses where avionics operate within Earth's magnetosphere ( $\approx 0.1\text{--}0.3$  mSv/day), use line-replaceable units with on-orbit spares, and undergo periodic maintenance or EVA replacements. Currently existing systems are not designed for prolonged exposure to the harsh lunar environment. The limited processing power of radiation-hardened components can restrict the

implementation of advanced autonomous functions. Additionally, the inability to perform maintenance or replace parts on the Moon necessitates systems that can operate reliably for years without intervention. Although individual components may be radiation-hard for TID and SEE, qualification tests typically span hundreds or thousands of hours, sufficient for replaceable systems but not for decades-long, unserviceable habitats. Lunar habitats need a fundamentally different, endurance-based avionics design qualified and tested for multi-year, unserviceable operation in a far more intense radiation and thermal-cycling environment. This requires a paradigm shift from merely qualifying radiation-hardened components for mission durations to rigorously testing entire integrated systems for multi-year endurance. To address these limitations, new approaches are needed that combine the robustness of radiation-hardened systems with the processing capabilities of modern electronics. Especially with a highly fault-tolerant processor that can compromise the need for multiple computers that function in dual- or triple-modular redundancy [4]. This includes the development of modular electronics architectures that allow for longer durability, easier upgrades, and the integration of commercial off-the-shelf (COTS) components that have been adapted for the lunar environment.

The Radiation Hardened Electronics for Space Environments (RHESE) project [3] outlined a broad set of approaches for electronics that must survive extreme space environments including materials, design, software, and processor hardening methods. It emphasized moving from hardened components toward fully hardened high-performance processors for long missions such as lunar outposts and Mars missions. The results of this effort, specifically through the High-Performance Processors (HPP) and Reconfigurable Processors tasks [2], have fundamentally influenced the technical requirements of HPSC and its development.

Various RHESE tasks [2] used modeling and simulation to predict the effects of space radiation on electronics at both the device and system levels. Particle transport codes, including Monte Carlo simulations, model interactions of galactic cosmic rays and solar particles with shielding and electronic components to estimate TID and linear energy transfer (LET) spectra. Circuit-level simulations are then used to predict the impact of TID on transistor threshold voltages, leakage currents, and timing, while SEE cross-section data are used to estimate single-event upset and latch-up rates. A similar methodology can be expanded and applied to HPSC for lunar habitat electronics to guide system-level reliability analyses and ensure safe, continuous operation in the lunar radiation environment. Peripheral components may require separate consideration due to differing radiation sensitivities.

## 5. HIGH-PERFORMANCE SPACEFLIGHT COMPUTING (HPSC)

NASA’s STMD has launched a “Game Changing Development” initiative to advance space-qualified computing [14]. As part of this effort, it funded the High-Performance Spaceflight Computing (HPSC) program in partnership with Microchip Technology and other industry collaborators. HPSC leverages NASA’s and Microchip’s combined expertise in autonomous systems and fault-tolerant design to deliver next-generation onboard computing, tailored for edge AI and autonomy, as well as the rigorous reliability demands of human exploration and operations [11].

Microchip’s PIC64-HPSC ushers in a new era of high-performance computing for space exploration and commercial space endeavors as a viable solution required to design and implement more resilient, reliable, and efficient edge-computing systems for mission-critical applications. The PIC64-HPSC series delivers radiation-hardened, fault-tolerant 64-bit MPUs described in figure [2], which are built around eight RISC-V cores and optimized for AI and Machine Learning workloads. The chip also offers deterministic high-speed I/O connectivity via TSN Ethernet and PCIe interfaces, plus post-quantum cryptography for robust security [1] fused with distinct multi-layered fault-tolerance features described in [5].

The HPSC technology is geared toward high fault-tolerance to enable next-generation avionics with Dual-Core Lockstep (DCLS) – flexible core partitioning for mixed and safety-critical tasks, WorldGuard hardware isolation – error prevention, containment, and mitigation. Additionally, its compatibility with modular and scalable system architectures further supports the development of reusable and maintainable avionics. This approach not only enhances the resilience of lunar habitats but also contributes to cost-effectiveness by reducing the need for custom hardware solutions for each mission. In many ways, HPSC opens new frontiers for space science and missions by enabling compute capabilities that bring true high-performance computing, real-time networking, and advanced security to the demanding nature of space exploration.

A major gap in advanced space computing is identified through Shortfall ID 1554: High Performance Onboard Computing to Enable Increasingly Complex Operations [9]. Given the processor’s capabilities to facilitate the integration of sophisticated autonomous functions, such as health monitoring and adaptive system control, essential for long-duration missions where maintenance opportunities are limited, HPSC mostly bridges this gap. Moreover, integrating advanced computing into lunar habitat systems addresses critical shortfalls in high-performance onboard processing, next-generation avionics architectures, and extreme-environment electronics. By leveraging these capabilities, NASA can build a robust computational foundation for autonomous operations in the challenging

lunar environment.

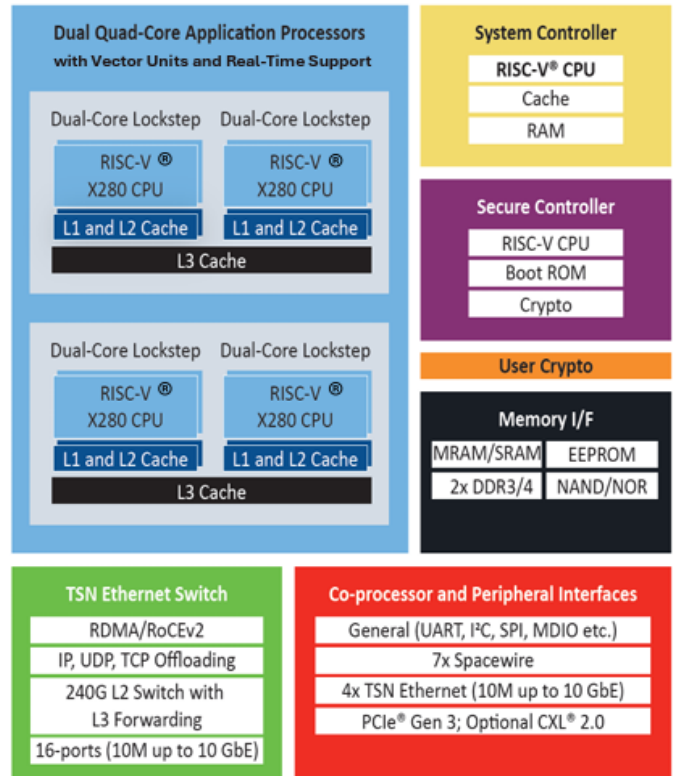


Figure 2. PIC64-HPSC Architecture [1]

## 6. AUTONOMY & FAULT TOLERANCE

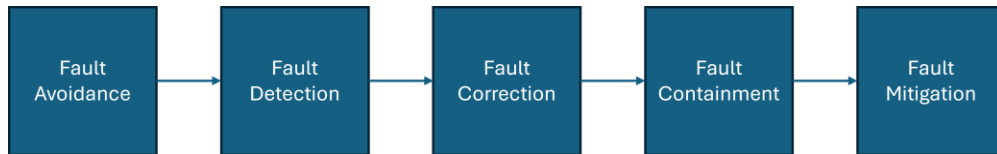
Fault-tolerant engineering is a rigorous process; on a high level, it focuses on minimizing failure likelihood, removing single points of weakness, and keeping systems running as long as possible. Computer processors are the core of electronic systems, especially in mission-critical, autonomous, and edge computing. The fault resilience for microprocessors is crucial as they set the standard for reliability and availability of a system. A fault in the CPU subsystem could result in a catastrophic failure, halting the operation of the entire embedded system.

Faults in microprocessor operations fall into two main categories. (1) Hardware-induced faults stem from physical component failures such as broken circuits, processor malfunctions, or defective memory modules. (2) Non-hardware-induced faults arise from software bugs, malicious code, or human mistakes. While software- and human-related faults are harder to predict or prevent, robust hardware architectures can effectively isolate and contain them. Faults can also be categorized as external from Total Ionizing Dose (TID) effects and Single-Event Effects (SEE). TID – represents cumulative damage over time, unique to space that degrades device performance, SEE – arises when a single high-energy particle (cosmic ray, proton, neutron, alpha) strikes a sensitive region, it involves Single-Event Upset

(SEU) – a bit flip or transient error in memory or logic, Single-Event Latch-up (SEL), and Single-Event Transient (SET) anomalies.

Designing for fault tolerance must span the processor’s architecture, its implementation, and even its fabrication. Only a comprehensive, balanced strategy covering fault prevention, detection, correction, containment, and mitigation can ensure dependable operations. The HPSC family, by design, is optimized for high-radiation space environments, meeting a 200 krad(Si) TID tolerance and incorporating Radiation-Hardened-By-Design (RHBD) techniques to mitigate SEEs. It offers an extensive set of fault-tolerant capabilities, as described in figure [3], making this processor ideal for space computing missions in challenging environments from Low Earth Orbit (LEO) to deep space. The PIC64-HPSC robust fault-tolerant scheme proceeds through the following five key phases described in figure [4]:

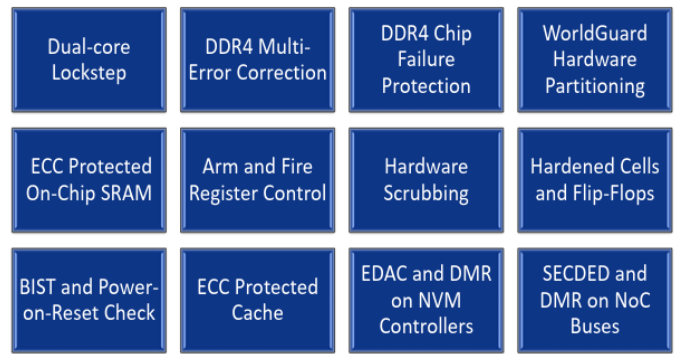
1. **Fault Prevention:** Proactively design, implement, and manufacture systems to avert defects before they arise.
2. **Fault Detection:** Since no design is perfect, rapidly identify any emerging errors so they can be addressed before escalating.
3. **Fault Correction:** Once a fault is flagged, apply the necessary remedies, whether algorithmic, hardware-based, or procedural, to restore correct operation.
4. **Fault Containment:** Isolate the error within a confined region of the system, preventing it from propagating and impacting other components.
5. **Fault Mitigation:** If a fault cannot be fully rectified, execute measures (e.g., graceful degradation or safe-state transitions) that limit its adverse effects on overall functionality.



**Figure 4. HPSC Fault-Tolerance Scheme [4]**

NASA’s Europa Clipper spacecraft was designed to be fully autonomous; the project utilized the following common mitigation strategies to manage radiation-induced failure risks and avionics degradation in Jupiter’s highly radiative environment [6]:

1. Radiation-hardened electronics (RHBD technologies, shielding).
2. Redundant architectures (TMR and voting logic).
3. Error detection and correction (EDAC/ECC) memory.
4. Fault-tolerant software architectures with frequent system state checks and automated recovery.
5. Real-time diagnostics and periodic maintenance algorithms



**Figure 3. HPSC Fault-Tolerance Features [4]**

In this instance, the flight software assists in radiation management by supporting and maintaining radiation-hardened hardware. It can prevent damage but rarely reverses it. However, crewed missions, such as those in the Artemis program, have a higher certification rating (Class 1A – Safety-Critical) and demand even higher functional safety and Fault-tolerance standards. Subsequently, a highly fault-tolerant processor like HPSC can supplant the need for multiple computers that function in dual- or triple-modular redundancy, yielding considerable savings in Space, Weight, and Power (SWaP).

A trade space exploration may identify alternatives for certain elements of a distributed system architecture. Lunar habitat electronics must account for radiation exposure but may leverage radiation-tolerant commercial components combined with heavy shielding and system-level mitigation. In this context, a radiation-tolerant PIC64-HPSC1100-RT (50 krad(Si) TID tolerance) chip [1], or similar parts, may be sufficient. This approach can reduce cost and, in some cases, improve performance, but it introduces increased vault mass

and higher integration risk compared to the purpose-built, radiation-hardened PIC64-HPSC1000-RH with modest shielding.

Future missions will only extend in length and complexity, necessitating enhanced computational capabilities. The vast amounts of data acquired by sensors and imaging devices require in situ processing to enable autonomous decision-making. It is impractical to rely on Earth-based resolutions with limited downlink bandwidth and significant communication delays. Instead, onboard autonomy will play an essential role in navigation, pathfinding, and automated scientific analysis for lunar landers, terrain vehicles, and space habitats. These advanced workloads typically require

computational speeds at the scale of Giga or Tera Operations Per Second (GOPS/TOPS), representing a performance higher in orders of magnitude than that of RAD750.

## 7. CONCLUSION

Computing has been crucial for the success of space missions. The increasing complexity and the need for greater autonomy of future missions require next-generation processors. HPSC realized the RHESE strategy [3] by combining modern high-performance computing with radiation-tolerant design principles and layered fault-management to produce mission-capable electronics suitable for habitats, landers, and deep-space systems. To ensure multi-year operations, lunar habitat electronics must first be highly fault-tolerant, then shift from a parts qualification mindset to a system endurance mindset – testing the integrated stack under combined radiation and thermal cycling, equipping it for graceful degradation, and embedding health-monitoring agents that anticipate and mitigate aging-related failures. HPSC represents a significant advancement in space-qualified computing technology. It improves the quality and quantity of science data return for future missions, and its design addresses the needs of advanced missions with greater reliability and efficiency. Lastly, HPSC addresses ten identified civil space shortfalls, and through this prioritization effort, STMD improves its ability to advance U.S. competitiveness, drive economic growth, and foster diverse talent and expertise to establish permanent lunar presence and solve our nation’s toughest technology challenges.

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