Review of Artemis I Mission Radiation Challenges and Data for the Crew Module

Charles R. Bailey, Razvan Gaza, Chirag Patel, Joshua M. Pritts, & Kyson V. Nguyen

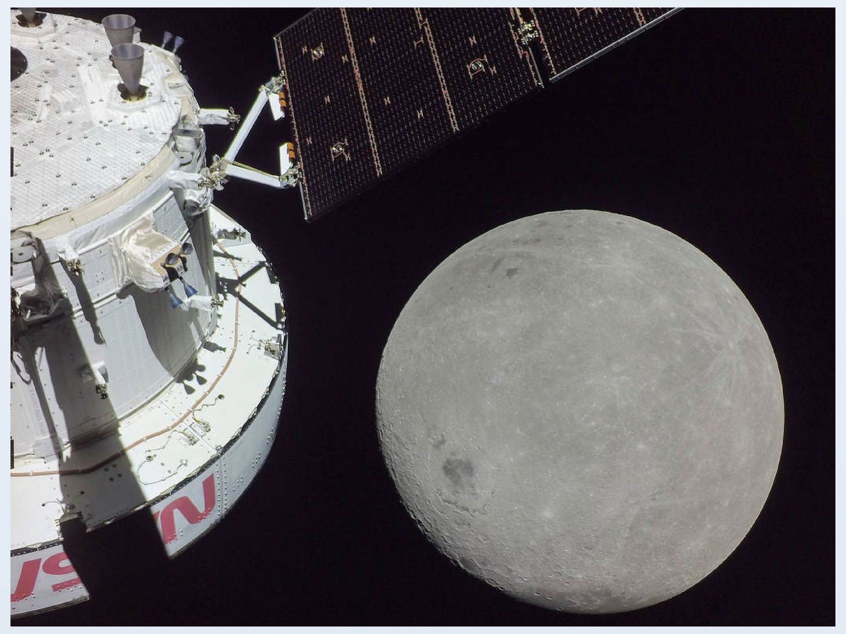
*Corresponding author: charles.r.bailey@nasa.gov

Abstract— We review the Artemis-I mission and corresponding radiation-hardness assurance (RHA) process. We discuss the RHA methodologies employed, design challenges, culture challenges and some flight data vs. rate estimations.

I. INTRODUCTION

Our paper outlines some of the Radiation Hardness Assurance (RHA) techniques, challenges, and lessons learned with an uncrewed demonstration mission.

- The Artemis Program seeks to establish Gateway and Lunar access for astronauts
- Artemis-1 was the first mission in a series of increasingly complex missions
- Launched on November 16, 2022 over a duration of 25 days
- Demonstration test flight, including reentry and water landing
- Provided operations experience with expected single-event effects



II. CULTURE

The culture at NASA JSC surrounding hardware design has changed from supporting the International Space Stations (ISS) alone and supporting ISS and the Moon2Mars initiatives. There were "growing pains" as hundreds of parts were heavy-ion tested by Lockheed-Martin for Orion, but the development process of the uncrewed flight helped to augment the culture change to a deep space development mentality.

For over two decades, we developed hardware for ISS which required thousands of pieces of critical hardware (i.e., flight computers, life support systems), and noncritical hardware (i.e., laptop computers, wireless access points, routers, consumer electronics). For the relatively benign ISS radiation environment in low-earth orbit, medium-energy proton screening proved to be sufficient in order to reduce risk surrounding noncritical hardware. Overly sensitive hardware was not flown to ensure crew time was not wasted due to radiation-related hard failures from the dominant particle.

The radiation environment for the Orion vehicle is much harsher. As a result, proton tests are not a viable verification method for radiation hardness assurance. Our hardware development process was forced to evolve to face the challenges of the 30X worse deep space radiation environment. Heavy-ion testing is necessary for critical and noncritical hardware to ensure functional performance and reliability requirements are met during and after exposure to the mission environment.

III. RADIATION HARDNESS ASSURANCE PROCESS

A. Combination of Risk Avoidance and Risk Quantification

For the Orion vehicle, there were no radiation pass/fail criteria. All active parts required immunity or test data supporting a survival LET threshold of 75 MeV-cm^2/mg with variations for specific types of parts according to current state-of-the-practice RHA methods. Parts that:

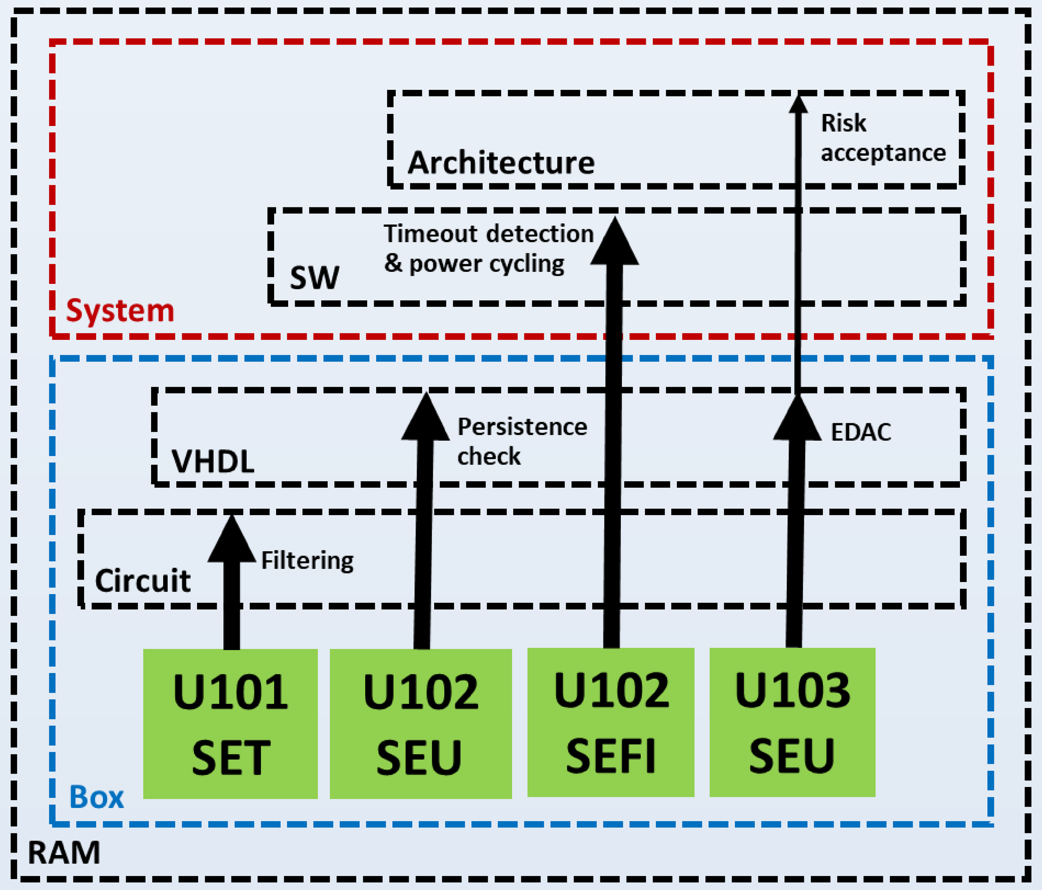
- survived Destructive Single-Event Effects (DSEE) testing were given a failure rate of "0"
- did not survive DSEE testing, rates were considered on a part-by-part basis at system / box level for functional performance / availability during critical phases of flight
- did not meet functional performance / availability requirements and could not be mitigated were removed from the design

SEE were characterized and evaluated vs. worst-case critical mission performance requirements. Reliability/availability quotas were not provided to the contractor. As a result, the analysis was reviewed by safety and reliability groups. The rates are evaluated at the system level to determine the performance of the system during critical phases of flight to ensure safety and mission success. SEE signatures were also evaluated to determine if they passed beyond the boundaries of the system and into other systems affecting the vehicle.

Accumulated dose effects for the inside of the crewed vehicle are minimal due to the thick shielding and short mission duration. Electronics outside the pressurized volume were considered on a part-by-part basis.

B. Integrated Analysis of Radiation Effects

The vehicle-level effects caused by SEE that crossed the system boundary were not initially considered in the contract by NASA or Lockheed Martin. The structure of the contract was that Lockheed Martin had subcontractors, each of which provided radiation analysis for the system they designed. The European Space Agency (ESA) provided an analysis for their designs also.



Early in the avionics development cycle, we recognized that an analysis that considered the radiation effects across the Artemis vehicle – regardless of the developer – was necessary for safety and performance validation. The Program stood up a board to consider these topics with support from NASA and Lockheed Martin management called the EM System Level Radiation Effects Team (EMSLRET). The multidiscipline team included engineering, reliability, safety, operations, and radiation SMEs and others were called to participate frequently to evaluate the vehicle-level radiation analyses. These meetings were incredibly valuable in explaining how radiation effects manifest at the part level and propagate to the system level. Mitigations were considered on both the operational and design fronts, and this gave the flight control team valuable insight into what they may see on console during the mission.

IV. DESIGN CHALLENGES

The bus voltage on the Orion vehicle is 120 VDC to reduce mass of current carrying wires, so N-Channel MOSFETs needed to hold off 180 VDC. There were no commercial options that met size and performance needs. The solution was to use a CREE SiC MOSFET rated to 1200VDC. These MOSFET were built on a CREE prototype line since there were no available parts that met the stringent requirements and qualified by Lockheed Martin by lot, piece-by-piece. During testing, current leakage was noted at higher fluences and higher LETs, but analysis the leakage was deemed negligible risk for the shorter Artemis mission lengths.

The flight computers used for Artemis-I were the SX-750, which leverage SOI devices commonly used in space applications. One of the challenges of these units was drop-outs due to SEU since the onset LET was less than 1 MeV-cm2/mg. The rates were evaluated for the varying environments of the flight (deep space, Van Allen Belts, solar-particle event, etc.). This analysis led to another VMC being added. After that calculation was complete, the system was analyzed by system experts to verify that:

- if one computer had a single-event upset (SEU), then it could be "rejoined" with the other computers before one of the other of the 3 computers also had an upset
- if two of the 3 power cycling at the same time, then the vehicle could be lost during some phases of flight

This was an in-depth analysis performed by Lockheed Martin with NASA involvement.

An ASIC was developed by Honeywell for many applications on the Artemis. Testing of this component was difficult due to the thickness of the part. The only viable method to test this part was the Variable Depth Bragg Peak method [2]. Testing was performed by Honeywell [3].

V. FLIGHT ANOMALIES

No flight anomalies during the mission were radiation related. The Star Tracker was considered an anomaly but was not and the Power Control and Distribution Unit had anomalous behavior but radiation is not considered a cause at this time. Overall, the Artemis-1 mission was free of major radiation issues and there are no planned changes for the upcoming manned missions.

VI. SEE DATA COLLECTED

Data were collected across systems to determine the validity of the mitigation techniques.

A. Star Tracker

The Star Tracker from Jena Optronik in Germany has an impressive spaceflight heritage across both NASA and commercial space applications. The unit provided reliable data throughout the mission via error detection and correction (EDAC). The unit sets a bit when the EDAC is exercised When this was observed, the flight control team mistook this EDAC bit to mean a potential data corruption. However, the Star Trackers both indicated the same position throughout the mission. Although the vehicle was never in danger, the miscommunication resulted a tiger team being created to work this perceived anomaly during the flight demonstration. This miscommunication was due to several factors:

- limited information due to export-controlled information and other contractual issues
- long and prestigious spaceflight heritage led to limited resources focusing on other concerns
- radiation team concentrated on hardware designed in-house or with no/limited space flight heritage

These factors lead to the radiation team not briefing the flight control team on what the EDAC bit meant. It also did not occur to the radiation team to check what data could be seen by the flight control team. This was taken as a lessons learned, and both the radiation team and flight control team agreed to work towards better communication on future missions.

B. Flight Main Computer (FMC)

The Vehicle Main Computer (2) is made up of 2 FMC is based on the PowerPC 750FX processor, and there are two processors per FMC. The analysis performed on these units showed acceptable performance during transits through the Van-Allen Belts (VAB) as well as acceptable performance in a Solar Particle Events (SPE). The FMC had two upsets during the flight. One was on flight day 9, and the other on flight day 11 which means both SEU were outside the VAB and were caused by Galactic Cosmic Rays (GCRs). The GCR upset rate of .37/FMC/21-day mission with a 20 second re-sync time. The flight data showed 2 SEU with a 29 second re-sync time. This aligns well with the calculated bounding rates.

C. Global Position Satellite Receiver (GPSR)

The GPSR provides onboard inertial position and velocity state vector updates during low-earth orbit operations and the Entry, Descent, and Landing phases of flight. The GPSR has two antennas for use when the vehicle is below GPS satellites. This system transmits the data via transceivers to various systems and those data packets can become corrupted and lead to EDAC indications. This is not uncommon and was expected but at a higher rate than seen during flight; the calculated bounding rates were overly conservative. Soft reset of the GPSR was an identified potential radiation-related event, but it is at a much lower rate than the EDAC.

Device	Effect	Predicted occurrences	Observed occurrences	Notes
Star Tracker	EDAC bit asserted	Almost daily in deep space	2 during the mission	Not a flight anomaly – discussion about implementation
FCM	EDAC bit asserted	2	2	Not a flight anomaly
GPSR	EDAC bit asserted	1	1/day	Not a flight anomaly
FCM	Reset	2	2	Not a flight anomaly
GPSR	Soft Reset SEFI	1	1 in 363	Not a flight anomaly

VII. LESSONS LEARNED FROM ARTEMIS I

The development RHA methodology and the harsher environment led to some growing pains both among management and engineering personnel. The flight control team also learned that radiation effects are going to be a part of the everyday operation of the vehicle. All parties had to grow together to get the first mission accomplished and be ready for the manned flights in the future.

VIII. CONCLUSIONS

The paper gave an overview of the Artemis-1 mission from a radiation standpoint. The methodology used along with the culture changes needed were discussed. The SEE during the flight were covered as well. The Artemis-1 flight performed well and the lessons learned from the development effort will be folded into the future designs for NASA deep space missions.

ACKNOWLEDGMENT

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