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

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*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

The Artemis missions are NASA Johnson Space Center's first foray back into deep space since the Apollo missions of the 1960s and 1970s. This paper outlines some of the radiation hardness assurance techniques, challenges and lessons learned with the first demonstration (Artemis-1) mission which was uncrewed.

The Artemis-I mission was launched on November 16, 2022 and lasted about 25 days. This is the first of a series of ever more complex missions providing Gateway and Lunar access to astronauts. The objectives of the first mission were a flight test demonstration including reentry and water landing. The mission was uncrewed but had many of the components of the Artemis-II manned mission. The Artemis-1 mission was a complete success with all objectives met for radiation performance plus building a familiarity with the vehicle operations and expected Single Event Effects (SEE).

## II. CULTURE

NASA has been developing hardware and payloads for the International Space Station (ISS), for many years and those hardware development methods are well understood and have proven to be very effective for that vehicle and environment. The ISS required thousands of pieces of non-critical hardware of all kinds. Many of these were non-critical electronics such as computers, wireless access points, routers, consumer electronics, etc. Pat O'Neill/NASA ret. developed a high-energy proton screening method[1] to ensure inexpensive avionics did not fail or waste crew time with Single Event Effects (SEE). Since Total Ionizing Dose (TID) inside ISS is minimal, this method was a very effective screen for ISS and became a standard test for non-critical avionics developed at JSC. JSC engineers and management became used to inexpensive and available high-energy proton testing as the go-to for non-critical avionics.

The Artemis vehicle is required to perform in the much harsher ionizing radiation environment and proton testing is not a viable test for that environment other than as a screen. The hardware development process had to evolve to face the challenges of the 30X worse deep space environment. Part of this evolution was the realization that heavy-ion testing is mandatory to ensure performance. Scheduling uncertainties in heavy-ion facilities was another stumbling block. There are many less heavy-ion facilities than high energy proton facilities which led to schedule issues versus previous developments. De-lidding parts and building complicated fixtures were just two of the added costs along with scheduling challenges associated with testing using heavy-ions. Additionally, JSC designers and radiation effects engineers had limited experience heavy-ion testing or doing the associated analysis. There were "growing pains" all the way from the rank-and-file engineers to the Artemis program office making the development of the first Artemis flight vehicle challenging.

Hundreds of parts were heavy-ion tested by Lockheed-Martin for Artemis and the development process of the uncrewed flight helped to augment the culture change to a deep space development mentality.

## III. RADIATION HARDNESS ASSURANCE PROCESS

### A. *Combination of Risk Avoidance and Risk Quantification*

For Artemis, there were no radiation pass/fail criteria for electronic parts. All active parts required immunity or test data to a survival Linear Energy Transfer (LET) threshold of 75 MeV-cm$^2$/mg with variations for specific types of parts according to current state-of-the-practice methodologies for Radiation Hardness Assurance (RHA).

Parts that survived Destructive Single-Event Effects (DSEE) testing were given a failure rate of "0". Parts that did not survive DSEE testing, rates were considered on a part-by-part basis at the system/box level for performance/availability during critical phases of flight. Parts that did not meet 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

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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 were minimal due to the thick shielding and the 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 design also. Early on it in the avionics development cycle, it was recognized that an analysis that considered the radiation effects across the Artemis vehicle – regardless of the developer – was necessary for safety and performance validation (figure 1). The Artemis program office agreed and stood up a board to consider these topics with support from NASA and LM management called the EM System Level Radiation Effects Team (EMSLRET). It was realized that radiation engineers did not have the background in vehicle design to evaluate the effects at the vehicle level. A multidiscipline team which 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 very valuable for explaining how radiation effects manifest at the part level and at the system level. Mitigations were considered on both the operational and design front. This also gave the flight control team valuable insight into what they may see on console that was both in and out of family.

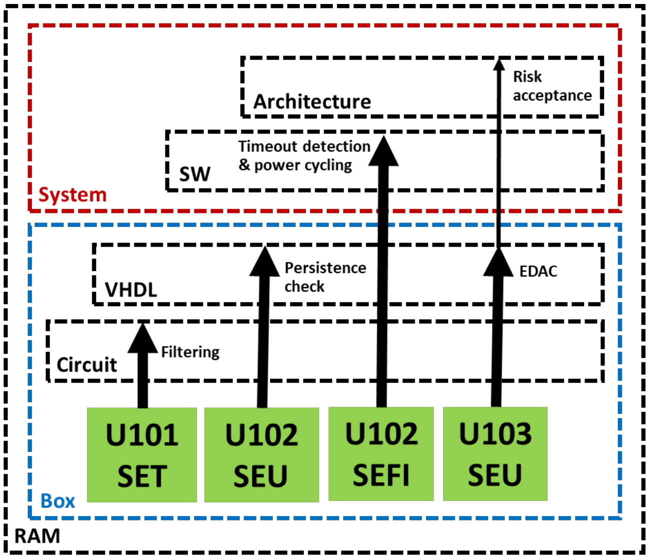

Figure 1 RAM description

## IV. DESIGN CHALLENGES

The bus voltage on the Artemis vehicle was set to 120 VDC to reduce weight of current carrying wiring. This meant that the N-Channel MOSFETs were required to hold off 180VDC the radiation performance. There were no commercial options that met the size and performance requirements. The solution was the use of a CREE SiC MOSFET rated at 1200V. These MOSFET were built on the prototype line at CREE since there was not a commercial part that met the stringent requirements. The piece parts were qualified to space grade by Lockheed Martin by lot, piece-by-piece. During testing, current leakage was noted at higher fluences and higher LETs, but analysis showed the part to be acceptable for the design for the Artemis missions. Overall, there would be no leakage 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-cm$^2$/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 the 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 Application Specific Integrated Circuit (ASIC) was developed by Honeywell was used for many applications on the Artemis. Testing of this component was difficult due to the thickness of the part. The only method to test this part is the Variable Depth Bragg Peak method [2] The testing and use of this part was performed by Honeywell and was documented in [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 was collected across systems to determine the validity of the mitigation techniques. Below are the rates for several of the tracked parameters (figure 2).

| 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 due to SEFI | 1 | 1 in 363 | Not a flight anomaly |

Figure 2

### Star Tracker

The Star Tracker was purchased by Lockheed Martin from Jena Optronik in Germany and has an impressive space heritage across both NASA and commercial space applications. The unit provided reliable data throughout the mission. The unit sets a bit when the EDAC is exercised. This is normal for these units and just shows the EDAC has been used. The flight control team took this EDAC bit to mean there was a potential data corruption. Operationally, there are two Star Trackers and the data from those are compared if there is a question about the validity of the data. The Star Trackers showed the same position during the mission. Although the Artemis vehicle was never in danger, this miscommunication caused the flight and ground teams to work this as an anomaly which. Time and resources were used ineffectively.

This miscommunication was due to several factors. One was that the vendor is European and the information on the product was somewhat limited due to export control and contractual issues. Also, this unit has a long and prestigious history in space and the radiation team was concentrated more on hardware that was designed in-house or had limited space flight heritage. These factors lead to the radiation team not briefing the flight control team on what the 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.

### 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. There was a lot of analysis performed on these units to show acceptable performance during transits through the VAB as well as performance in Solar Particle Events (SPE) should any occur during flight. The FMC had 2 SEU during the 21-day 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 rate for GCR SEU 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 predictions.

### Global Position Satellite Receiver (GPSR)

The GPSR is used to provide onboard inertial position and velocity state vector updates during Low Earth Orbit (LEO) operations and the Entry, Descent, and Landing phases of flight. It has two antennas and is usable when the vehicle is below the GPS constellation of 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.

Soft reset of the GPSR was an identified potential radiation related event but it is at a much lower rate than the EDAC. The radiation team will review the data analysis to verify the calculated rates are correct.

## VII. LESSONS LEARNED FROM ARTEMIS I

The development 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 a part of the everyday performance 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 gives 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.

## IX. ACKNOWLEDGMENT

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## X. REFERENCES

[1] P. M. O'Neill, G. D. Badhwar and W. X. Culpepper, "Internuclear cascade-evaporation model for LET spectra of 200 MeV protons used for parts testing" *IEEE Trans. on Nucl. Sci.*, vol. 45, no. 6, pp. 2467-2474, Dec. 1998.

[2] S. Buchner, N. Kanyogoro, D. McMorrow, C.C. Foster, P. M. O'Neill and K. V. Nguyen, "Variable Depth Bragg Peak Method for Single Event Effects Testing" *IEEE Trans. on Nucl. Sci.*, vol. 58, no. 6, pp. 2976-2982, Dec. 2011.

[3] L. Hoffmann and V. Lam, "Qualification of an Automotive-Grade, State-of-the-Art ASIC for Natural Space Applications" *2013 IEEE Radiation Effects Data Workshop*", San Francisco, Ca., 2013, pp. 1-8.