National Aeronautics and Space Administration

Mars Campaign Office

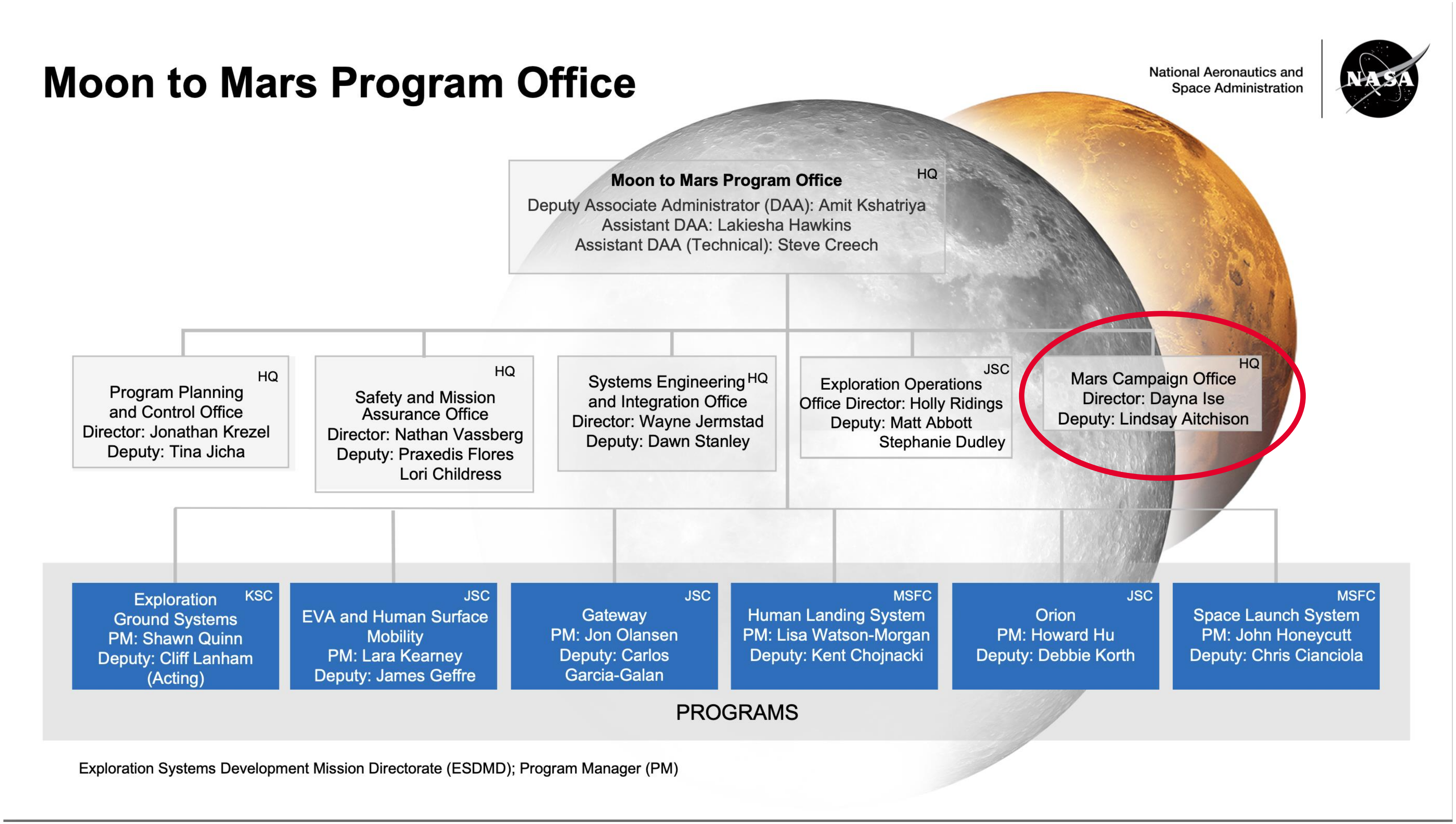
MCO Radworks Portfolio

Eddie Semones

RadWorks Portfolio Lead

WRMISS 2025

September 2025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PM: Lisa Watson-Morgan
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This office is the continuation of the Advanced Exploration Systems (AES) Program started in 2011 - 2012 – Radworks was in the original AES portfolio - sustained budget of ~5M-7M year for over 10 years.

Crew Health & Performance Domain
Jane Gensler, Lead

Earth Independent Operations Domain
Andres Martinez, Lead

Environment Control & Life Support System Domain
Marlon Cox, Lead

Surface Systems & Environments Domain
JJ Edelmann, Lead

Transportation & Vehicle Systems Domain
Vacant, Lead

PORTFOLIOS: (Crew Health & Performance Domain)

Food Systems	Grace Douglas Trent Smith
Countermeasures	Kent Kalogera Scott Wood
Exploration Medical	Kelly Wilkey Moriah Thompson Rahul Saresh
Spacesuits	Cinda Chullen
Spacesuit Physiology	Karina Marshall-Goebel Nick Mustachio
Fire Safety	Courtney Schkurko
Radiation Protection	Eddie Semones

PORTFOLIOS: (Earth Independent Operations Domain)

Vehicle Systems	April Potter
Mission Management	Marc Carbone
Crew Interaction	Megan Parisi
Anomaly Response	Chris Teubert
Data Integration	Christian Ratterman
Communication & Navigation	Ian Maddox

PORTFOLIOS: (Environment Control & Life Support System Domain)

Life Support Sys	Imelda Stambaugh
ISS ECLSS Evolution	Alesha Ridley Erin Skalak
Logistics Reduction	Melissa McKinley

RADWORKS

July 2025

06 Advanced Habitation Systems

Gap type:
K- knowledge, requires scientific research
D – development (TRL 1-4)
T – Technology (TRL 5-9)
E – engineering (TRL 5-9 mission specific)

Space Radiation Protection

Physical Mitigation Technologies

1.1 Space Weather Forecasting

- (D) SPE forecasting tools
- (D) Earth – independent alert system
- (K) GCR forecasts: Predictive models of solar cycle modulation

1.2 Radiation Monitoring

- (E) On-board dosimetry systems
- (T) Adv. space radiation env. characterization - missions/systems

1.3 Effective Shielding

- (E) SPE shielding
- (E/T) GCR shielding - passive
- (T) Combined GCR/SPE shielding - active

Biological Effects/Mitigation

1.4 Predictive Models of Crew Health Risks

- (K) Probabilistic health risk models

1.5 Biomedical Countermeasures and Surveillance

- (K) Biomedical countermeasures
- (K) Biomarkers & Technologies for In-flight Monitoring and Health Management

***Major Asset:** Space Weather architecture*

***Major Asset:** NASA Space Radiation Laboratory*

Open Questions

The shift from LEO to deep space has important implications for radiation research and there is the need to improve space radiological protection strategy and risk assessment for astronaut missions:

Radiation Environment Measurement

- Enhance knowledge on radiation environment is fundamental for mission planning and design
- Particle quantities such as energy deposit spectra and fluxes are needed to validate and update models
- Development of new instrumentation

Dosimetry and radiation risk estimation

- For exploration missions, actively powered radiation detectors for the crew are required
- Individual bio-dosimetry combined with the results of radiation detectors are fundamental for the radiation risk estimation

Radiation propagation tools and models

- Radiation propagation tools provide calculated radiation data for a specific planned mission scenario and can be benchmarked with data from sensors
- Transport codes, based on Monte Carlo (GEANT4, FLUKA, PHITS) or on deterministic (HZETRN) codes need further developments including updates for missing data (such as nuclear cross section measurements)

Radiation storm forecasting

- Forecasting SPEs is very important for deep space operations for efficient planning and use of countermeasures complying with the "As Low As Reasonable Achievable" (ALARA) principle for astronaut protection.
- Forecasting from physics based models lacks the accuracy needed for human protection.
- Now-casting, using real-time precursor measurements along with data from past SPEs, is currently the best method available for issuing timely warnings

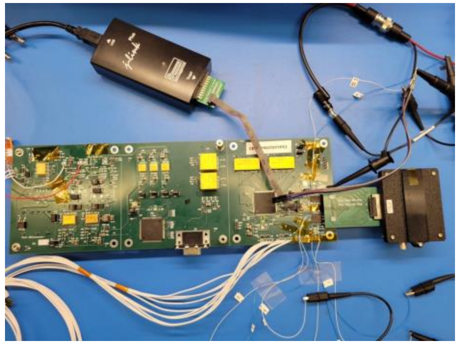
[Fogtman, A., Baatout, S., Baselet, B. et al. Towards sustainable human space exploration—priorities for radiation research to quantify and mitigate radiation risks. npj Microgravity 9, 8 (2023)]

Only through a harmonized and cohesive Scientific Community we will be able to fill these gaps.

Overview

Why is this Portfolio important?

RadWorks advances technologies and develops hardware that supports NASA's Space Exploration efforts to manage and minimize crew radiation risks for Health and Human Performance. Space radiation environments for Lunar and Mars missions must be characterized to determine astronaut crew exposures; information that is vital to influence vehicle design and mission planning. RadWorks builds on existing detection, shielding, and modeling capabilities to provide solutions that inform the design and operations of all aspects of NASA exploration spaceflight missions.



CEPS Flatsat Prototype 2

Current Projects for 2026

- **HZETRN Physics Development**
- **neutron Dose of Unknown Radiation Environments nDURE - derived from Lunar Orbiting and On-surface Neutron Spectrometer (LOONS) project PI Georgia de Nolfo-GSFC**
- **Compact Electron Proton Spectrometer (CEPS) and ARES2**
- **Integrated Solar Energetic Particle Warning System (ISEP)**

LOONS Engineering Model

Portfolio Objectives (and M2M Objectives)

RadWorks Objectives	Connection	M2M Objectives
Update physics models for more accurate space radiation transport calculations	HZETRN enables the design of habitation systems that protect crew from space radiation environments	TH-4LM: Develop in-space and surface habitation system(s) for crew to live in deep space for extended durations, enabling future missions to Mars
Develop/test neutron and charged particle spectrometers and measure fields	Detectors are needed to monitor crew radiation exposure and provide an alert warning system for solar particle events	TH-8LM: Develop systems that monitor and maintain crew health and performance throughout all mission phases, including during communication delays to Earth, and in an environment that does not allow emergency evacuation or terrestrial medical assistance
Validate space weather models and integrate them into scoreboards	Space Weather scoreboards will be used to decide if shelter is needed at the onset of a SPE and to predict clear periods for EVAs	

Note: RadWorks technologies support several other M2M Objectives. See back-up slides.

HZETRN Physics Development – Effective Shielding

Why is this project important?

- An accurate and computationally efficient radiation transport code is needed to support the design of spacecraft that keep radiation exposure As Low As Reasonably Achievable (ALARA) and to verify spacecraft radiation protection requirements. NASA's HZETRN space radiation transport code has a demonstrated ability to analyze highly complex vehicle geometry in space environments and is currently being used for requirements verification for Gateway and HLS. Multiple verification and validation efforts have shown that HZETRN models space measurements well and agrees with much slower Monte Carlo codes as well as they agree with each other, but there are still notable differences between thick shield transport results using the world's best codes. HZETRN's physics models must be improved to support accurate assessment of human exposure in heavily shielded spacecraft needed long duration lunar surface and Mars missions.

FY26 Scope of Work

- Complete investigation into differences in the physics models for individual interactions (cross section models) used by Monte Carlo transport codes to identify the models that need the most improvement, based on accuracy and impact on crew exposure
- Complete cross section models for pion, proton, and neutron interactions, which are known to have a large impact behind thick shielding

SPE Shielding requirement

V1 4031: Radiation Limits - Solar Particle Events NASA-STD-3001 V1

Statement:

The program shall protect crewmembers from exposure to the design reference Solar Particle Event (SPE) environment proton energy spectrum (sum of the October 1989 events) to less than an effective dose of 250 mSv.

GCR Shielding requirement

V1 4033: Crew Radiation Limits from Galactic Cosmic Radiation NASA-S

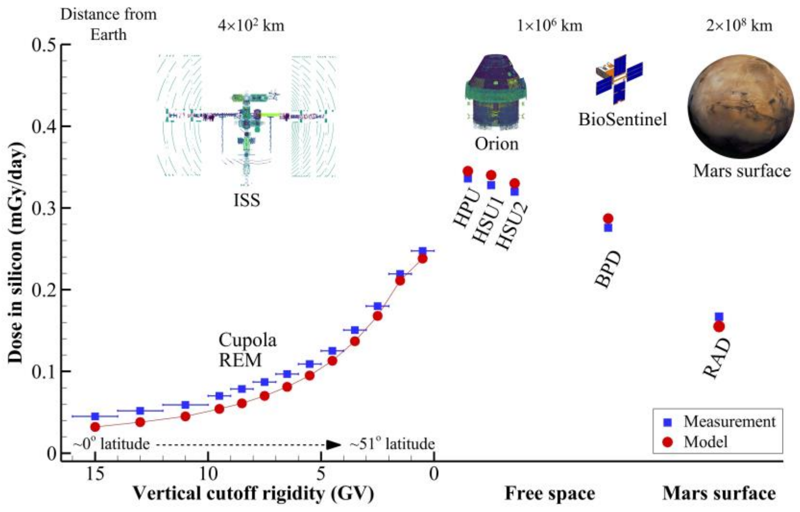
Statement:

For habitable space systems designed to support crew for > 60 days, the program shall protect crewmembers from exposure to the galactic cosmic ray (GCR) environment to less than a NASA effective dose (as defined in NASA-STD-3001, Volume 1 [V1 4030] Career Space Permissible Exposure Limits for Spaceflight Radiation) rate of 1.3 mSv/day for systems in free space and to less than 0.9 mSv/day for systems on planetary surfaces.

Note: To verify the habitable space system design meets the GCR protection requirement above, the NASA effective dose rate is calculated using the 2009 solar minimum Badhwar O'Neill GCR model spectrum and take into account estimated crew time spent at lightly and more heavily shielded locations throughout the habitable space system. If achievable, further measures are to be taken to reduce crew exposure in accordance with the ALARA principle, as set forth in [V1 4029] As Low as Reasonably Achievable (ALARA) Principle.

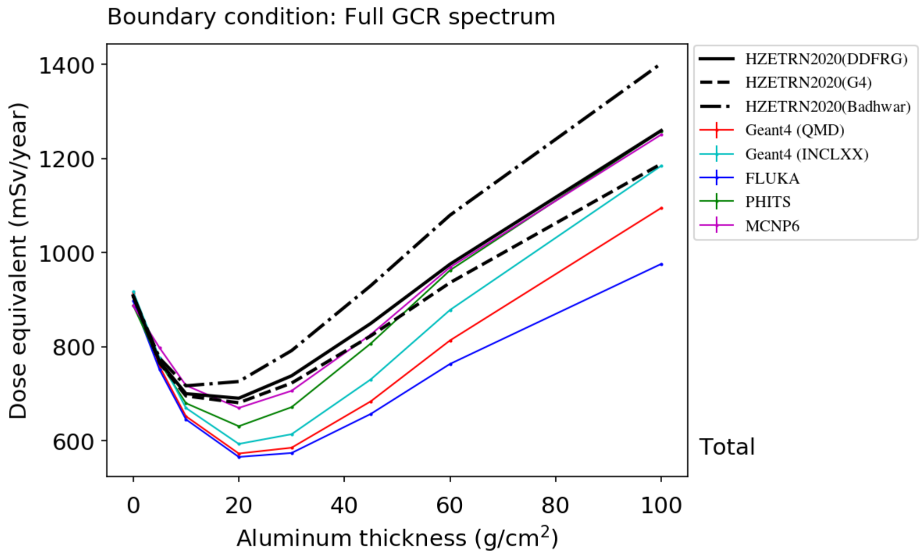
RadWorks HZETRN Physics Project – Completed Work (2020-2024)

- **HZETRN2020 completed and released** (https://software.nasa.gov)
  - Include a new 3D transport algorithm
  - Included an improved heavy ion cross section model: RAADFRG
- **HZETRN2020 integrated into the On-Line Tool for the Assessment of Radiation In Space (OLTARIS)** (https://oltaris.nasa.gov)
- **HZETRN2020 validated with ISS, Artemis-1 Orion, BioSentinel and Mars rover dose measurements**
  - Good agreement in all cases
- **Updated verification of HZETRN with Monte Carlo codes**
  - HZETRN agrees with Monte Carlo codes as well as they agreed with each other
  - ~30% uncertainty in calculated dose equivalent for thick shielding
  - Significant differences in particle spectra for pions, neutrons, and light ions
- **New Double-Differential FRaGmentation (DDFRG) cross section models completed – all showing good agreement with available measurements**
  - Light ions (^{4}He) and heavy ions -> protons and light ions
  - Protons, light ions, and heavy ions -> pions
  - Light ions and heavy ions -> neutrons



Comparison of model calculations to measurement data for the ISS, Orion module, BioSentinel CubeSat, and Mars surface during the Artemis-1 mission

Dose equivalent calculated with multiple transport codes for varying shield thicknesses in front of and behind the dose point



RadWorks HZETRN Physics Project – Current Work

Primary Goal: Improve the accuracy of thick shield transport calculations to support the assessment of crew radiation exposure in heavily shielded spacecraft

- Needed for long duration lunar surface & Mars missions
- Enables vehicle optimization and mission planning

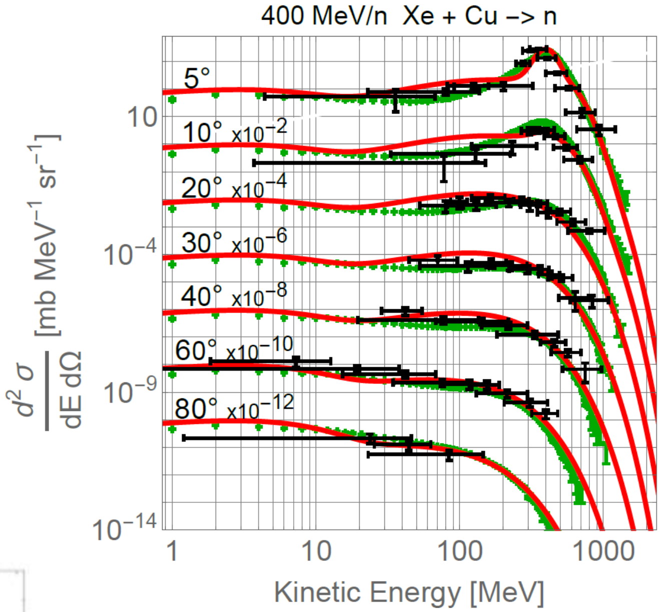
Primary Focus Areas:

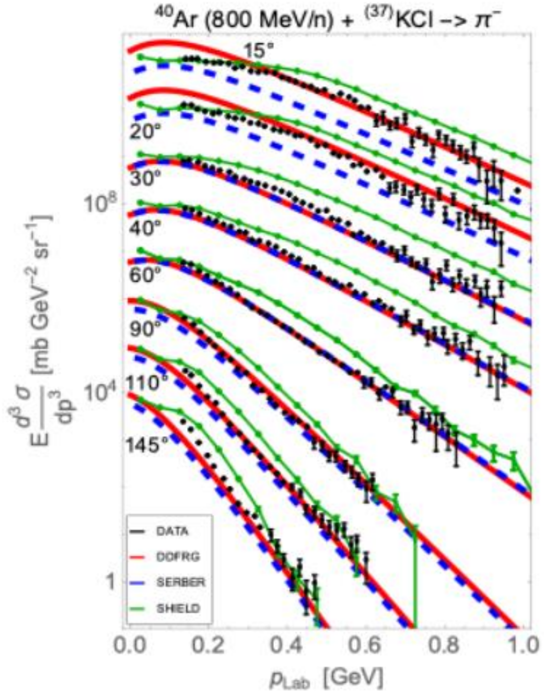
- Development of new DDFRG cross section models pion, proton & neutron projectiles producing pion, proton & neutron fragments
- Examination of existing physics models used by HZETRN and other transport codes

2025 Accomplishments:

- Developed a new uncertainty quantification methods to support model and measurement comparisons
  - Now includes both vertical (y) and horizontal (x) error bars inherent in experimental data and Monte-Carlo models
  - Important because some experiments have large energy uncertainties
- Completed initial comparisons between LaRC developed DDFRG neutron production cross sections and MCNP cross sections
- Completed comparisons between LaRC developed DDFRG pion production cross sections and two other models: a Serber model being developed at LaRC and the SHIELD model
- Completing documentation of HZETRN physics models

Comparison of DDFRG neutron production cross sections (Red) with MCNP cross sections (Green) and measurements data (Black)





Comparison of DDFRG pion production cross sections (Red) with Serber model cross sections (Blue), SHIELD model cross sections (Green) and measurements data (Black)

Alignment to ESDMD Technology Gaps

Gap ID:

- 0308: Radiation Countermeasures
    - 0308-04: Galactic Cosmic Radiation (GCR) effects mitigation

Gap Description:

- This gap addresses the need to mitigate both Solar Particle Event (SPE) and Galactic Cosmic Ray (GCR) radiation environments to reduce the risk of adverse medical impacts on crew. It notes that passive shielding is mass-prohibitive, while active shielding methods have low maturity.

Gap Closure Support:

- Strategies that rely on identifying optimal spacecraft configurations and the placement of multifunctional shielding technologies to reduce crew GCR exposure consistent with the As Low As Reasonably Achievable (ALARA) principle will have to be developed individually for each spacecraft in which astronauts will spend more than 60 days. The ability to evaluate crew exposure behind thick shielding and optimize that shielding hinges on the accuracy of the transport code. <u>This task will improve the accuracy of thick shield transport calculations to enable vehicle optimization assessments by improving the physics models (cross sections) used by the HZETRN transport code</u>. In lieu of more expensive thick shield space measurements, validation of individual cross sections, the integrated transport code, and optimal shield thicknesses will be performed through comparisons with existing measurements and other transport codes. It is anticipated that uncertainty in cross sections for the particles that have the largest impact behind thick shielding (pions, protons, and neutrons) can be reduced by a factor of two.

When Does This Project Finish?

- This task will not close the GCR shielding gap, but it will complete crucial physics model development for HZETRN which will enable accurate vehicle optimization.
- The proposed improvements to the physics models used by HZETRN will be completed by 2030. The improved models will be integrated into the HZETRN code and tested immediately following their development, so the improved transport code will be available for vehicle optimization studies shortly after the new physics models are completed.

neutron Dose of Unknown Radiation Environments (nDURE) and other neutron monitoring advancements

Why is this project important?

- Neutrons may contribute a large percentage to astronaut dose equivalent. However, there is limited higher energy (>20 MeV) experimental data for model development and verification for the purpose of crew health and safety. This drives the need to provide an instrument which can be used to characterize a crewed volume on a deep space mission. nDURE is a neutron spectrometer based on the double-scatter technique utilizing p-terphenyl scintillators.

FY26 Scope of Work

- Complete optimization and derive requirements for nDURE from simulations (energy range, energy resolution, geometric factor, sensitivity, etc.)
- Conduct nDURE SRR
- Limited support for other neutron spectrometer efforts
  - Support discussions with Gateway and/or HLS on possible ANS flight opportunities
  - Support Canadian Active Neutron Spectrometer (CANS) development as requested

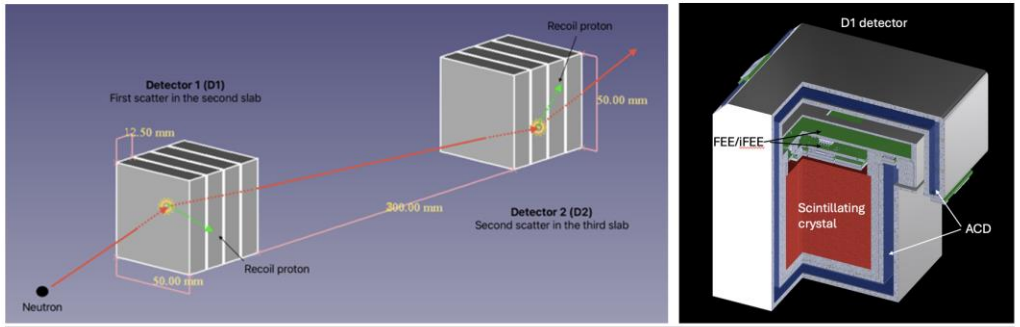


Figure 1: (left) Schematic of the nDURE concept, (right) nDURE mechanical design with surrounding ACD.

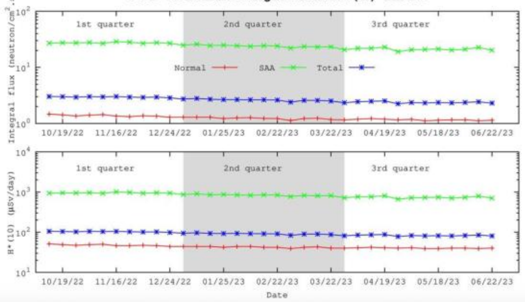
Neutron Measurements at the Lunar Surface MSFC		
Assembly, Integration, and Test	Document No.: ANS-RPT-101	Revision:
	Effective Date: Jan 31, 2020	Page 18 of 18

Final Quarterly Report FY23 Q3

Integral flux and ambient dose equivalent

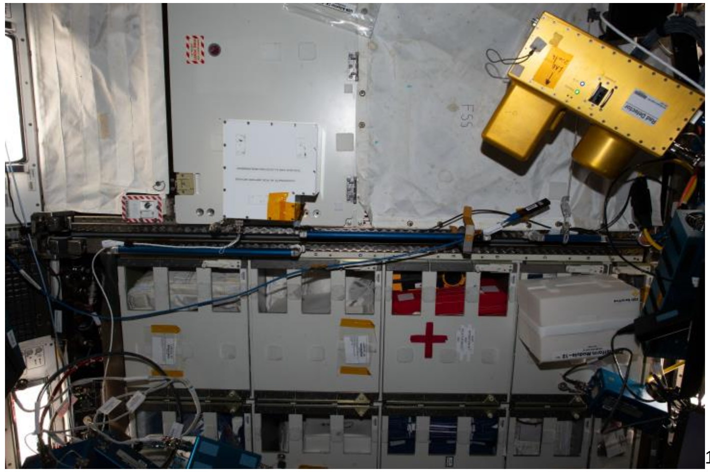
Period	DATE		No. of Days	Location	Normal		SAA		Total
	START	END			Φ (#/cm2.s)	H*(10) (μSv/d)	Φ (#/cm2.s)	H*(10) (μSv/d)	H*(10) (μSv/d)
294	03/29/23	04/06/23	8	USLAB	1.19	41	21.83	761	85
295	04/06/23	04/12/23	6	USLAB	1.22	42	21.88	764	86
296	04/12/23	04/19/23	7	USLAB	1.19	41	22.99	803	87
297	04/19/23	04/28/23	9	USLAB	1.16	40	19.02	663	78
298	04/28/23	05/03/23	5	USLAB	1.18	41	20.58	717	82
299	05/03/23	05/12/23	9	USLAB	1.12	39	20.86	727	81
300	05/12/23	05/18/23	6	USLAB	1.14	39	21.21	739	82
301	05/18/23	05/25/23	7	USLAB	1.16	40	20.34	708	81
302	05/25/23	06/07/23	13	USLAB	1.16	40	21.08	734	82
303	06/07/23	06/14/23	7	USLAB	1.12	39	22.64	789	85
304	06/14/23	06/22/23	8	USLAB	1.14	40	20.25	704	81

FY23 - FNS Neutron Integral Flux and H*(10) - USLAB



Prior success with ISS-RAD and ANS

ANS TechDemo mission ended in June 2023 concluding 3.75 years of reporting the ambient neutron component of the radiation levels on the ISS.



Alignment to ESDMD Technology Gaps

Gap ID:

- 0307: Radiation Monitoring and Modeling
  - 0307-02: Space radiation environment characterization systems

Gap Description:

- This gap addresses the need for technology to characterize space radiation environments. Radiation must be monitored and characterized (identifying particles types and energies) to determine exposure of hardware and assess health impacts to crew on lunar and Mars missions. Neutron production comes from both target fragmentation at lower energies & proton-induced neutrons at higher energies. To date, characterization of induced neutron environments in spacecraft are constrained to relatively lower energies (<20 MeV) with measurements at higher energies (up to >100 MeV) plagued by large uncertainties & systems with excessive mass/volume/power. The energy region between 1 MeV - 1 GeV accounts for most of the neutron induced cancer risk. Validation of model calculations over just the low energy region provides little information on model accuracy at higher energies. An instrument to measure neutrons in the energy range between 1 MeV to 1 GeV with suitable energy resolution on a log-scale to clearly delineate salient features of the spectrum is needed.

Gap Closure Support:

- This task will support the primary goal of developing hardware that is capable of measuring neutron spectra onboard exploration spacecraft.
- The LOONS detector is expected to improve upon the current State Of the Art (SOA) for neutron spectrum measurements by extending the upper bound of the energy range for the measurements from ~20 MeV to =>100MeV, with no more than a factor of 4 increase in mass/power/ volume over the current SOA of ~5kg, ~25cm x 25cm x 15cm, and ~6W.

When Does This Project Finish?

- This task does not close this gap, which addresses charged particle detection and neutrons, but it will complete crucial steps in ensuring that NASA has a space-ready neutron spectrometer for lunar and Mars missions.
- A neutron spectrometer for use inside spacecraft will be build, tested, and calibrated by mid-FY29. This unit will include the detectors, the main electronics card, the front-end electronics, and the bias power voltage unit. The remainder of FY29 and FY30 will focus on identifying a flight opportunity and the corresponding requirements and defining a plan to integrate flight avionics, a processor, and low-voltage power card.

Compact Electron Proton Spectrometer (CEPS) Development

Why is this project important?

- **CEPS** is a space weather early warning instrument designed for missions beyond low Earth Orbit. It provides high precision proton and electron measurements used for space weather event forecasting. Using the ReLEASE predictive model, these measurements can provide up to 30 minutes of early warning of hazardous solar energetic particles. It also enables early prediction of the peak flux and dose rates, improving crew safety and mission planning. This capability is enabled by a pixelated Timepix2 CdTe sensor and custom-designed rad hard electronics. **ARES2**, an internal variant of CEPS, uses its radiation-hardened avionics to deliver a high-reliability radiation monitor with a 10+ year operational lifetime for spacecraft and habitat interiors.

FY26 Scope of Work

- Overall goal is delivery of “Compact Electron Proton Spectrometer” instrument for long term space weather and radiation monitoring
- Two instruments with common avionics – CEPS External to Vehicle (CEPS-EV) and CEPS Internal to Vehicles (**ARES2**)
- FY26 goals:
  - Build and test a CEPS-EV EDU and complete Preliminary Design Review (PDR)
  - Develop ARES2 PTRS and run SRR
  - Develop and test ARES2 flatsat prototype

Name	Flight Date	Mission	Location	Objective	Vehicle	Number Timepix
REM*	2012	ISS	LEO	Demo	ISS	5
BIRD	2014	Orion ETF-1	LEO/MEO	Demo/Science	Orion	2
MPT	2017	ISS	LEO	Science	ISS	2
ISS-HERA	2018	ISS	LEO	Demo	ISS	3
REM2*	2018	ISS	LEO	Ops	ISS	7
Biosentinel	2020	ISS	LEO	Science	ISS	1
AHOSS*	2022	ISS	LEO	Demo/Ops	ISS	3
HERA EM-1	2022	Artemis I	Lunar Orbit	Ops	Orion	3
Biosentinel*	2022	Artemis I	Heliocentric Orbit	Science	Cubesat	1
HERA EM-1	2024	Polaris Dawn	LEO/MEO	Science	Crew Dragon	1
LETS 1	2024	Astrobotic 1	Lunar Surface	Science	Peregrine	1
HERA EM-2**	2024	Artemis II	Lunar Orbit	Ops	Orion	6
HERA EM-2	2025	Artemis III	Lunar Orbit	Ops	Orion	6
ARES	2026	Artemis III	Lunar Surface	Ops	HLS	>1
LEIA	2025/6	CLPS Lander	Lunar Surface	Science	TBS Lander	>1
LETS 2	2027	Beresheet 2	Lunar Surface	Science	Berensheet 2	1
ARES	2028	Artemis IV	Lunar Surface	Ops	Gateway	>1

Table 1: Flown, flying, and manifested Timepix based radiation measurement hardware produced by NASA AES Radworks. *Presently flying/operating, **Installed in vehicle. LEO refers to Low Earth Orbit, MEO to Medium Earth Orbit.

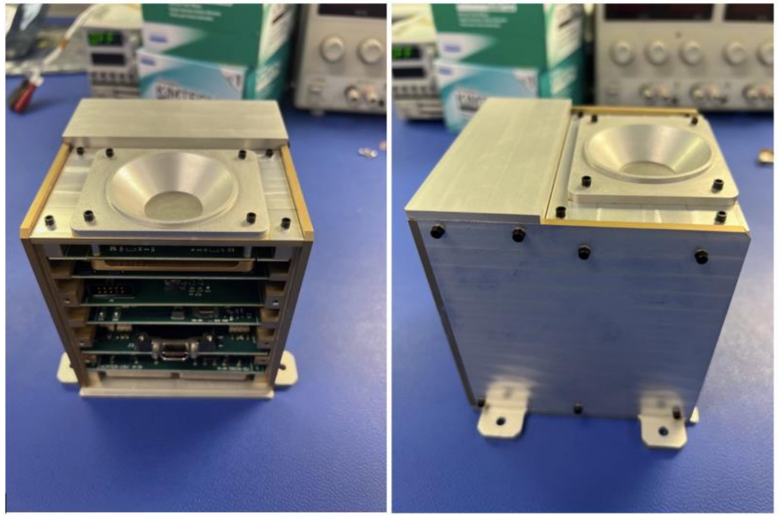
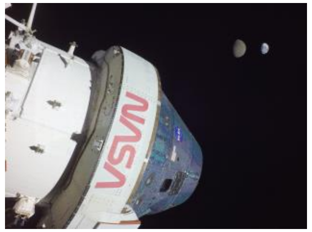


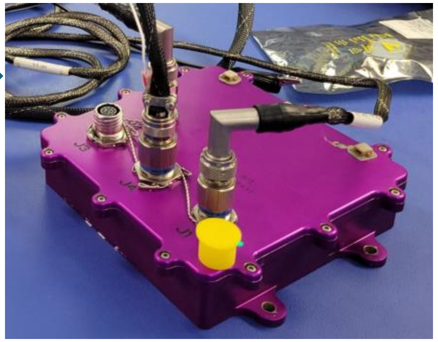
Figure 16 – CEPS Full System Prototype

HLS-ARES Heritage

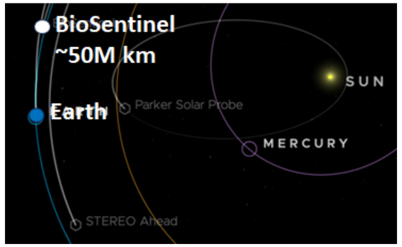
Artemis HERA on Space Station (2021-Present)

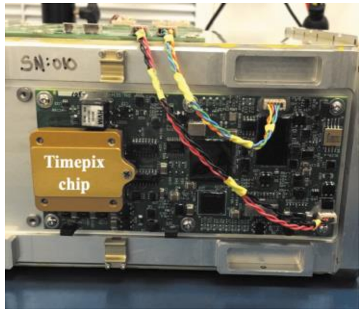
**HERA Artemis 1 and 2 (11/2022)
Polaris Dawn (9/2024)
FRAM2 (2025)**



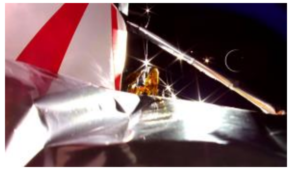


BioSentinel (11/2022-Present)

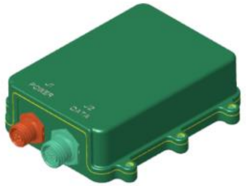




LETS Peregrine 1 (2/2023)



**HLS-ARES
Gateway-ARES**



Alignment to ESDMD Technology Gaps

Gap ID:

- 0307: Radiation Monitoring and Modeling
  - 0307-02: Space radiation environment characterization systems
  - 0307-03: Earth-independent space weather forecasting

Gap Description:

- This gap addresses both radiation detection and monitoring needs and needed improvements to space weather forecasting capabilities. Radiation must be monitored to determine exposure of hardware and assess health impacts to crew on lunar and Mars missions. Radiation monitors are also needed to provide early warning of SPEs, which are hazardous to astronauts and can impact mission operations. Space weather models must be improved to provide more accurate predictions of event onset, duration, intensity, energy spectrum and intensity-time profile.

Gap Closure Support:

- This project will provide an external instrument on the vehicle that can monitor the electron levels to support predictive responses for upcoming SPE events, which will expand the time crew has to prepare for large solar events. When used with space weather modeling tools, this detector is expected to increase warning time from zero minutes for Earth-Independent missions, if no external space weather monitor is provided, to 30 minutes.
- CEPS is expected to be an improvement over State Of the Art (SOA) external space weather measurement systems, NASA's HERMES and ESA's ERSA instrument, by significantly reducing mass, size, and power requirements:
  - Mass (HERMES): 25 kg -> CEPS Target <1 kg
  - Size (HERMES): 0.5m x 0.5m x 0.5m (stowed) -> CEPS Target 1U CubeSat
  - Power (HERMES): 16.5 watts -> CEPS Target 3W + survival heater

When Does This Project Finish?

- This task does not close this gap, but it will complete the development and testing a space weather observation monitor that can be deployed external to the spacecraft.
- This task will be "finished" when a flight instrument has been flown and shows the ability to monitor both electrons and protons in an external environment of a crewed vehicle. Expect a technology demonstration to occur in FY29 or FY30, possibly on Gateway.

Why is this project important?

- Advancement of SPE/flare prediction models and user interface design enables mitigation of crew impacts from radiation exposure
- Increased warning times and improved accuracy of forecasting is needed to inform crew of radiation hazards following development of SPE events, and more accurate models are needed to predict all clear periods.

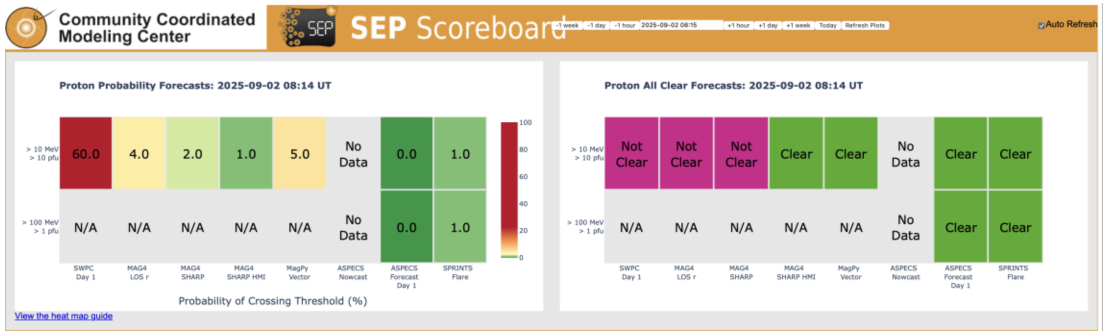
FY26 Scope of Work

- Updates to Concept of Operations defining use of Space Weather Scoreboards for Artemis-III
- Ongoing validation of Space Weather models
- Ongoing incorporation of new and/or improved Space Weather models into Scoreboards for Probability, Intensity, and All-Clear Forecasting
- Initiate development Earth of Independent Operations (EIO) alert system
- Assessment of model updates and product pipeline developed under CLEAR project

https://ccmc.gsfc.nasa.gov/scoreboards/sep/

https://sep.ccmc.gsfc.nasa.gov/probability/

https://sep.ccmc.gsfc.nasa.gov/intensity



Recent ISEP Accomplishments

Research

New work on established models

10+ SEP models transitioned to Scoreboards

Scoreboard Development

Small Businesses, Domestic/International Universities Collaborations

Operations

ISS and Art-I support

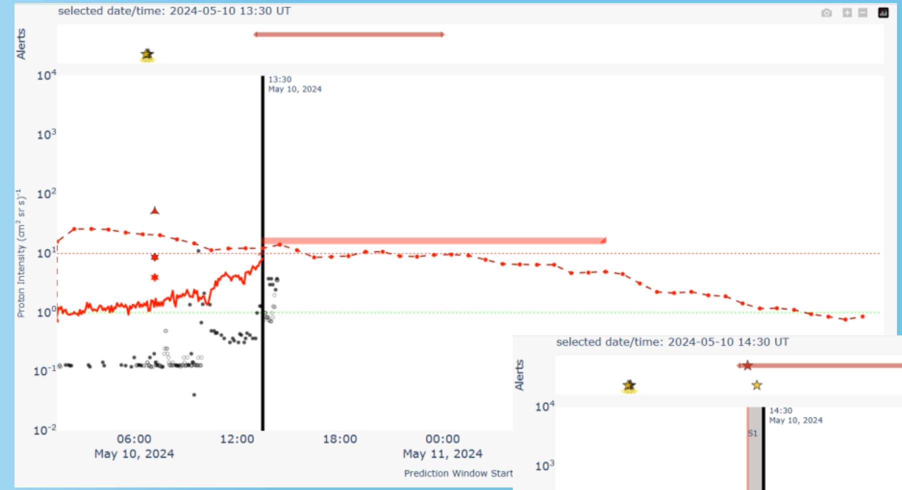
Art-II+ Concept of Operations + Flight Rules

NOAA/SWPC Testbed support (Apr/May 2025)

Continuous iteration of design and function with end user

SRAG Operator Training

JHU/APL Tabletop support (May 2024)



Model Development

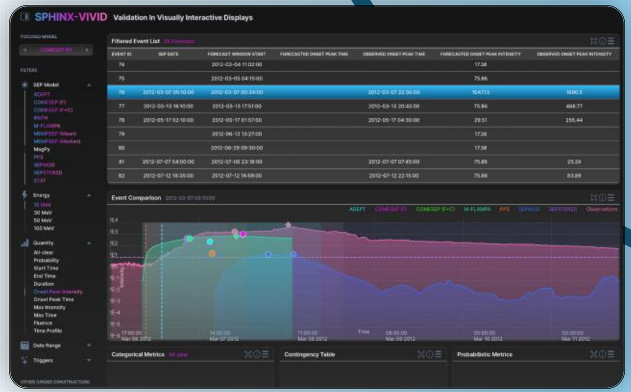
Mission Support

Community-wide effort to validate models (2025)

Establishment of M2M SWAO

SPE Model Review paper (Whitman et al, 2023)

NOAA SWPC Artemis Support – Embedded



Validation

SPHINX/VIVID Development

Alignment to ESDMD Technology Gaps

Gap ID:

- 0307: Radiation Monitoring and Modeling
  - 0307-01: Forecasting and radiation models for solar particle events
  - 0307-03: Earth-independent space weather forecasting

Gap Description:

- This gap addresses both radiation detection and monitoring needs and needed improvements to space weather forecasting capabilities. Radiation must be monitored to determine exposure of hardware and assess health impacts to crew on lunar and Mars missions. Radiation monitors are also needed to provide early warning of SPEs, which are hazardous to astronauts and can impact mission operations. Space weather models must be improved to provide more accurate predictions of event onset, duration, intensity, energy spectrum and intensity-time profile.

Gap Closure Support:

- This task integrates the best space weather models into a suite of scoreboard interfaces for flare forecasting, SPE peak flux prediction, SPE time profile prediction, and "All-Clear" forecasting and validates these models with historical event data and new solar observations as they occur.
- This effort is expected to improve SPE prediction over the current State Of the Art (SOA), based on NOAA Space Weather Prediction Center (SWPC) forecasting, in the following ways:
  - Increase the reliability of 24-hour SPE prediction by 10% (current SOA is True Skill Score (TSS) = 0.61)
  - Develop a 7-day SPE time profile prediction capability, which is not currently measured by SWPC
  - Increase warning time for SPE onset to 6-24 hours (current SOA is 88 min.) – needed for short-term planning
  - Increase warning time for Energetic SPE (ESPE) to 60 min (current SOA is 10 min.) – needed for shelter deployment

When Does This Project Finish?

- This task does not close this gap, but it will complete the crucial steps of incorporating existing models into an integrated set of Scoreboards, validating all of the models in a uniform way with space measurements, and guiding the development of improved models.
- An initial set of Scoreboards will be completed by the end of FY27 and validation of those Scoreboards will be completed by the end of FY29. An initial SPE prediction tool for integration into crew systems for Earth-independent operations will be completed by the end of FY30.

Summary

- SRAG is final preparation for Artemis 2 utilizing 3 Radworks technologies
- **Developed zero-mass solution for Orion's SPE storm shelter and pre-mission dose estimates underway (HZETRN)**
  - Note long-duration habitats must meet GCR shield standard
- **Completed integrated SPE scoreboards to inform Artemis Operations with M2M SWAO support**
- **Artemis 2 HERA strings are installed and ready in Orion**
  - Artemis I – provided 1 HERA string for operational checkout flight
- Tested 3 and still operate 1 Artemis dosimetry systems (2 flight HERAs, and ANS) on ISS
  - **ARES is next in line for ISS demonstration**
  - **AHOSS running in JPM on ISS**
  - ANS could support Gateway as needed with CANs
- Helped support characterization of Mars radiation surface environment over a solar cycle (AES provided MSL RAD Science team support)
- Building compact space weather observation package (CEPS) for potential use on NASA's Extravehicular Activity and Human Surface Mobility Program (EHP), Multipurpose Habitat (MPH), or Mars transfer vehicle
- Artemis III efforts underway
  - ARES to be delivered, developing EVA flight rules and concept of operations, SPE sheltering for HLS vehicle is being evaluated