Artemis 1 Radiation Analysis, Modeling, and Dose Assessment

Presented by Diego Laramore Ph.D.

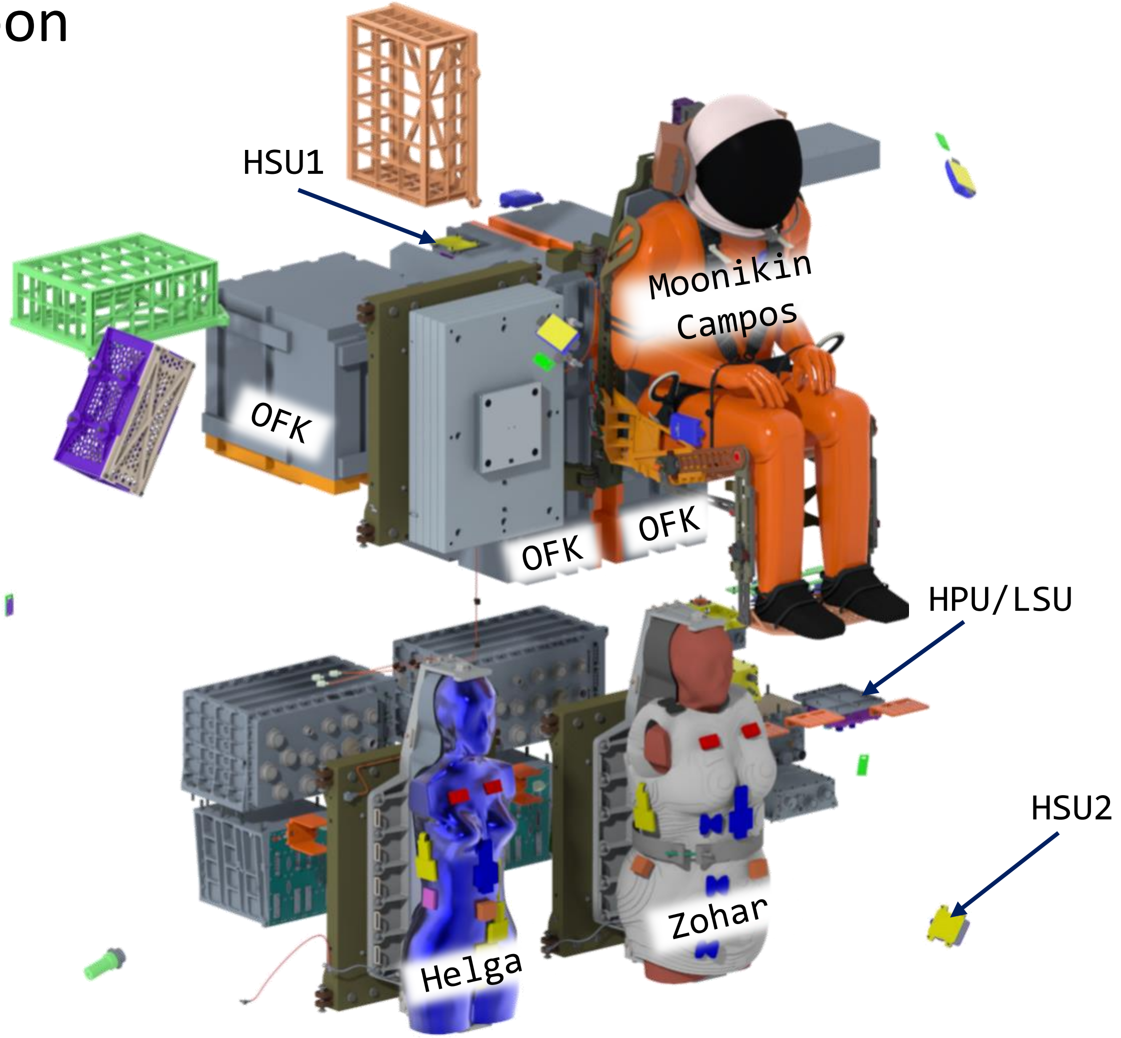
diego.laramore@nasa.gov

Space Radiation Analysis Group (SRAG)

NASA Johnson Space Center, Houston, TX 77058, USA

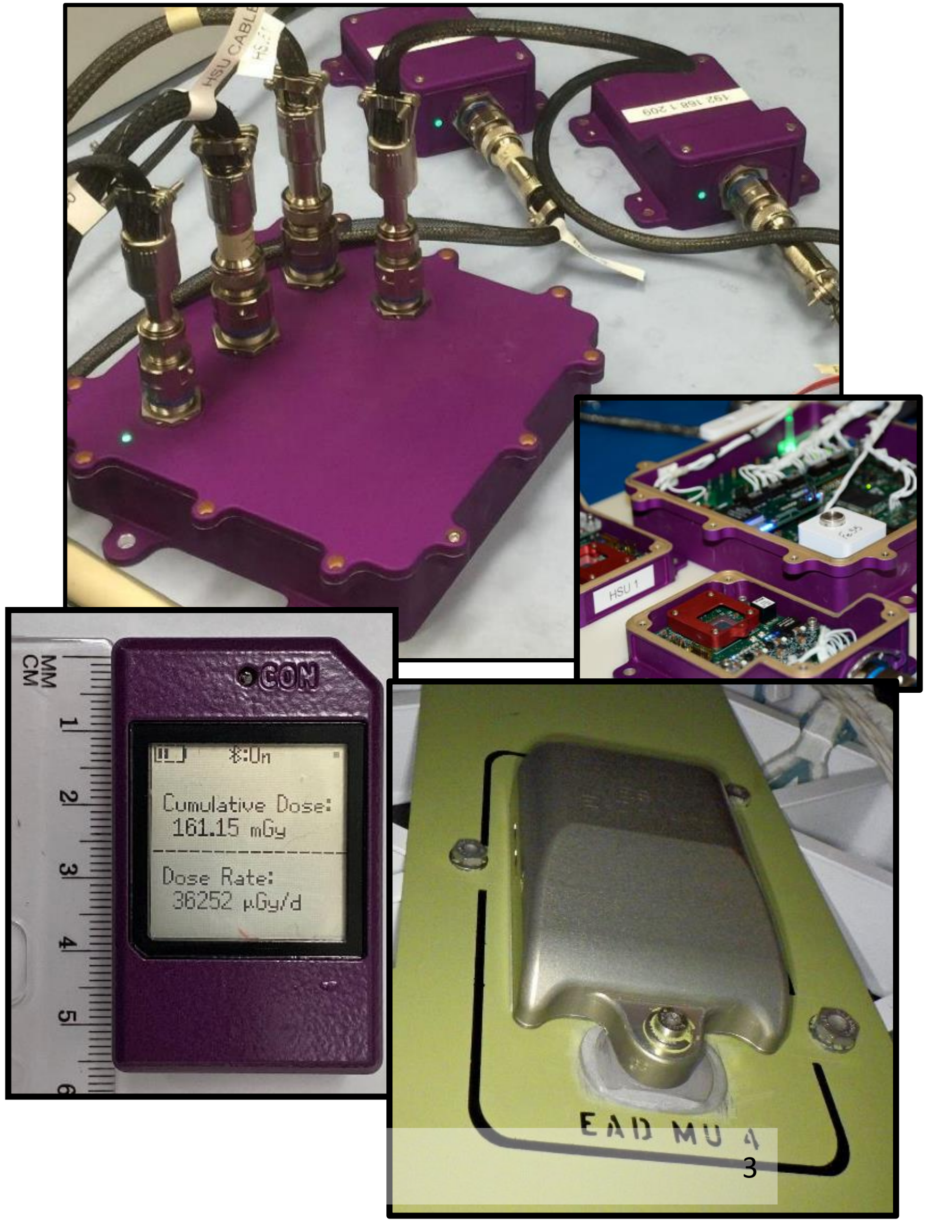
Overview of Artemis 1

- First in a series of Artemis missions to the moon
  - Nov 16, 2022 – Dec 11, 2022 ; ~ 25 days 11 hrs
  - Only Unmanned Artemis Mission
- Vehicle Configuration
  - MPCV Orion
  - ESA Service Module
  - Interim Cryogenic Propulsion System (ICPS)
- Payloads
  - MARE dummies (HELGA and ZOHAR)
  - Commander Campos (Moonikin)
  - <u>Large assortment of Radiation Hardware</u>
  - Official Flight Kit (OFK)
  - Various Instrumentation



Radiation Hardware on Artemis-I

- Artemis I has multiple detectors and payloads for radiation measurement
  - Hybrid Electronic Radiation Assessor (HERA)
    - 3 Timepix based sensor units
    - Active monitor: provides min-by-min dose data
  - Crew Active Dosimeters (CAD)
    - CADs worn by MARE and Campos Dummies
  - Matroshka AstroRad Radiation Experiment (MARE)
  - NASA Passive Sensors: 6 RAMs (TLDs)
  - Various IP sensors: EADs, M-42s, etc…
- Both HERA (as ISS-HERA and AHoSS) and CADs have operated on ISS



Objectives

1. Showcase and contextualize the results from the radiation sensors (HERAs LSU, HSU1, and HSU2) that flew on Artemis 1

2. Demonstrate our current operational ability to model the radiation environment from Artemis 1

3. Provide an estimate of effective dose for a hypothetical crew member.

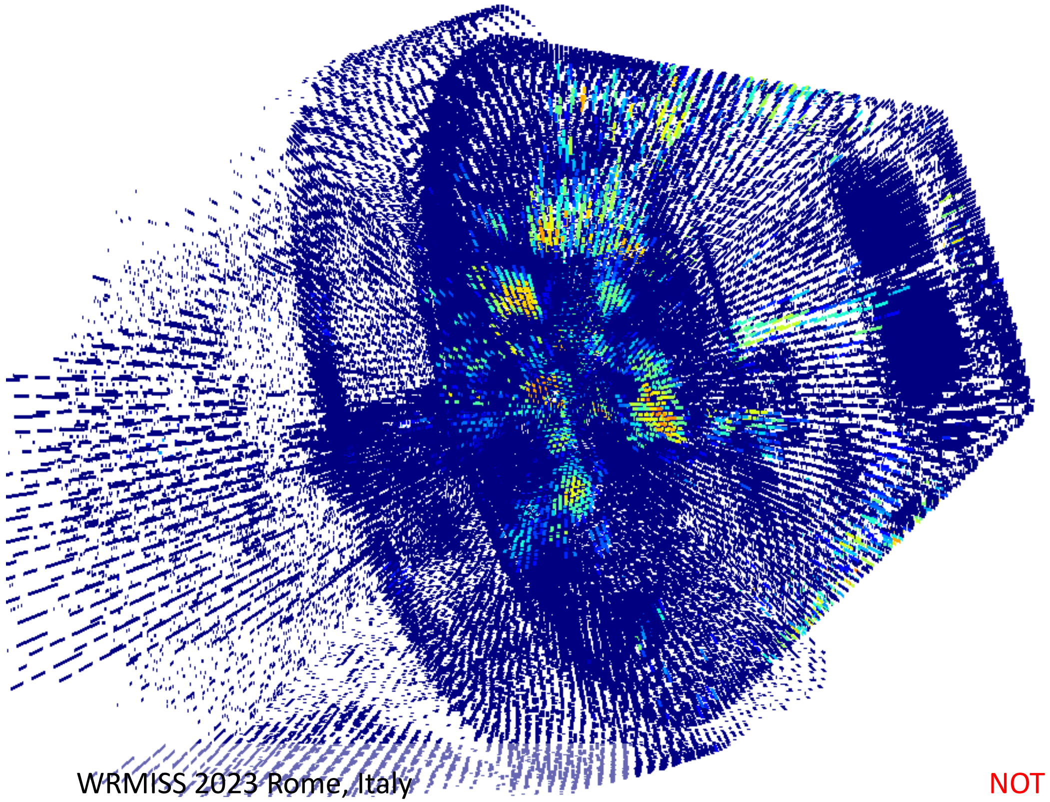
Modeling Artemis 1

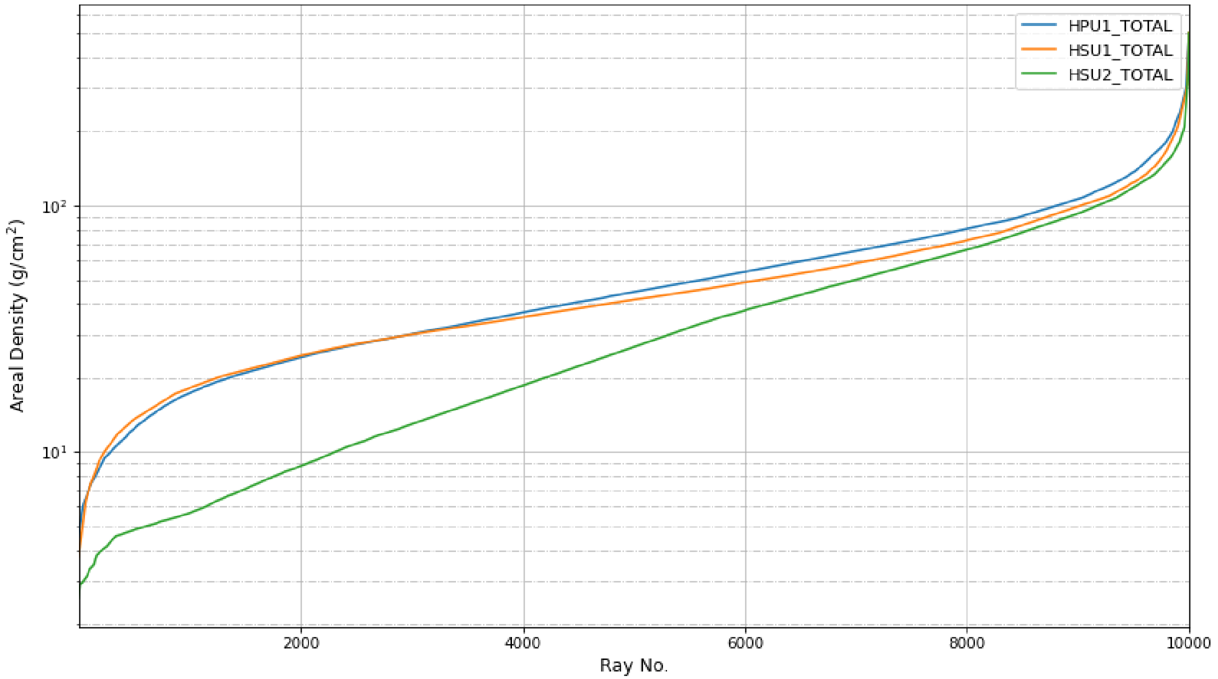
- Mission Segments and Trajectories
  - Outgoing portion – As-flown trajectories (< 10 ER, 0.257 days)
  - Free-space for Trans-lunar-injection and retrograde lunar orbit and return (~25 days)
  - Re-entry portion – As-flown trajectories (< 10 ER, 0.191 days) (may only show freespace GCR)
- Radiation Transport
  - 1DHZETRN, Depth-Dose calculation in Al-slabs per environment, CIMIRAE workflow (OLTARIS-like)
- Environment Modeling
  - Ap9 Trapped protons (Mean), Ae9 Trapped electrons (Median) (IRENE, v1.57.004)
  - GCR: Badhwar-O'Neill 2020 (Slaba and Whitman), GEOFFB-IGRF12 magnetic field for modulation
  - **All environments modeled as isotropic**
- Vehicle and Human Phantom Shielding
  - MPCV CAD model ray-traces (10,000 directions)
  - MAX voxel phantom for tissue doses (Moonikin)
- Effective Dose
  - NSCR 2012 Effective Dose Model, computed in NASA's Radiation Analysis Environment (RAE)

CAD model Raytracing

- Artemis 1 MPCV Orion + SM CAD raytraced to obtain areal density
  - 10,000 ray directions per position (HERAs shown)
  - Converted to 1 layer, aluminum equivalent thickness
  - ICPS not included

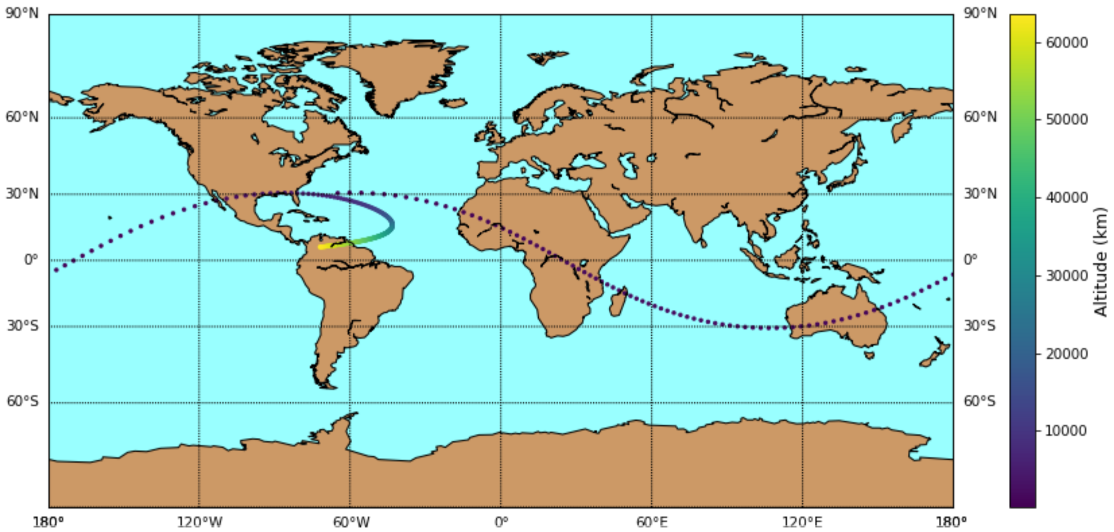
	Mean	Median	10th Ptile	25th Ptile	90th Ptile
HPU1 (g/cm^2)	**56.2**	**44.5**	17.3	27.3	106.7
HSU1 (g/cm^2)	**52.2**	**41.6**	18.2	27.5	97.5
HSU2 (g/cm^2)	**40.3**	**27.3**	5.7	10.8	93.0





Outbound Limb (November 16, 2022)

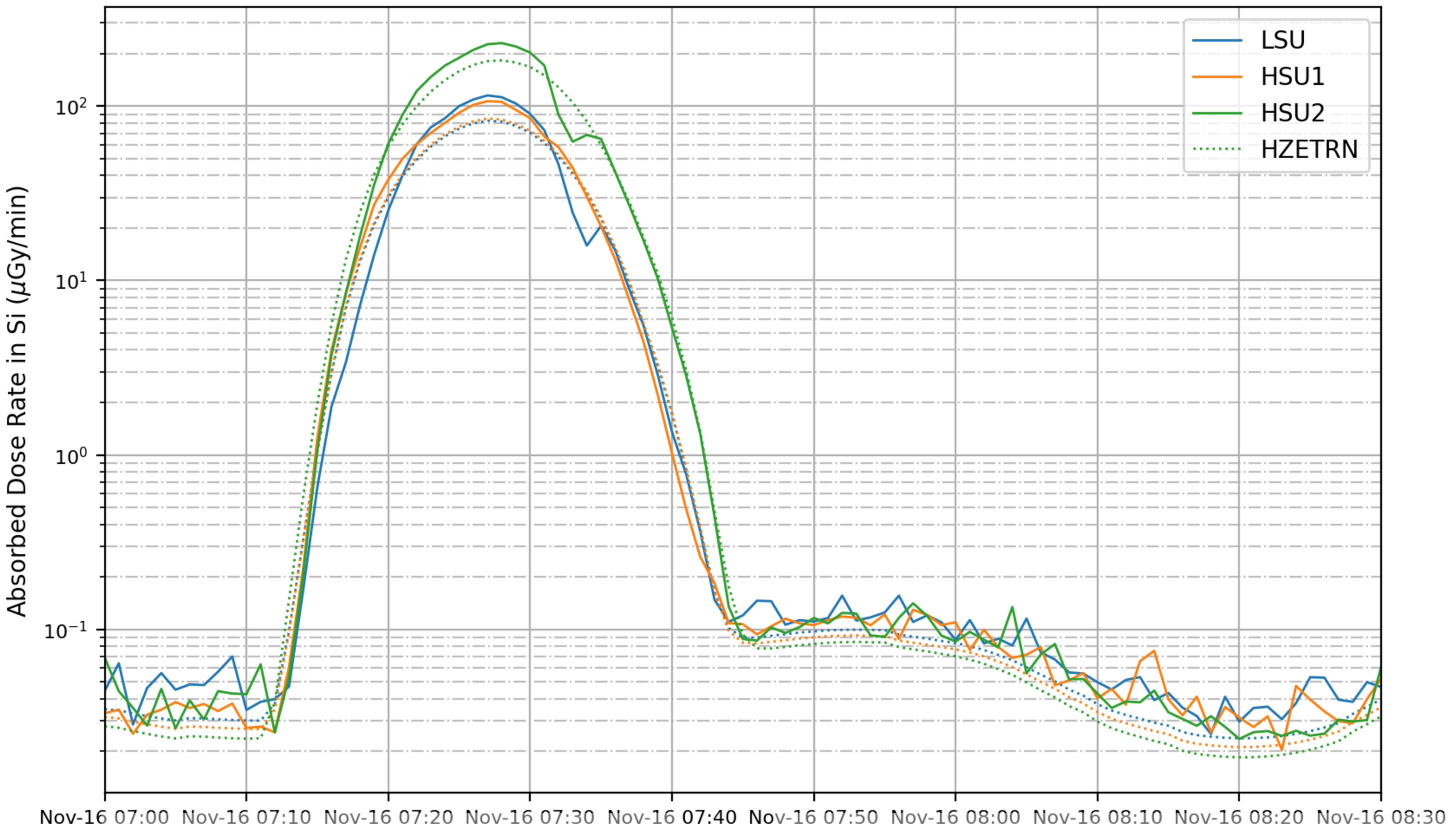
- 6:47:44 a.m. - Liftoff
- 6:49:56 a.m. - Solid Rocket Booster separation (Mission Elapsed Time 00:02:12)
- 6:55:47 a.m. - Core stage main engine cutoff commanded (MET 00:08:04)
- 6:55:59 a.m. - Core Stage/ICPS separation (MET 00:08:16)
- **7:11:11 a.m. – Enters Van Allen Proton Belt (Ap9 est.)**
- 7:40:40 – 07:41:02 a.m. - Perigee Raise Maneuver (MET 00:51:22)
    - 22 seconds in duration
- **7:46:41 a.m. – Exits Van Allen Proton Belt (Ap9 est.)**
- 8:17:00 – 8:35:11 a.m. - Trans-lunar injection (MET 01:38:03)
    - 17 minute, 59 second burn
- **8:27:00 – Enter Van Allen Electron Belt (Ae9 est.)**
- 8:45:20 a.m. - Orion/ICPS separation (MET 02:06:10)
- 10:09:20 p.m. - ICPS Disposal Burn (MET 03:30:10)
- **13:24:11 p.m. - Exit Van Allen Electron Belt (Ae9 est.)**
- 14:35:15 p.m. - Outbound Trajectory Correction-1 burn (MET 07:56:05)



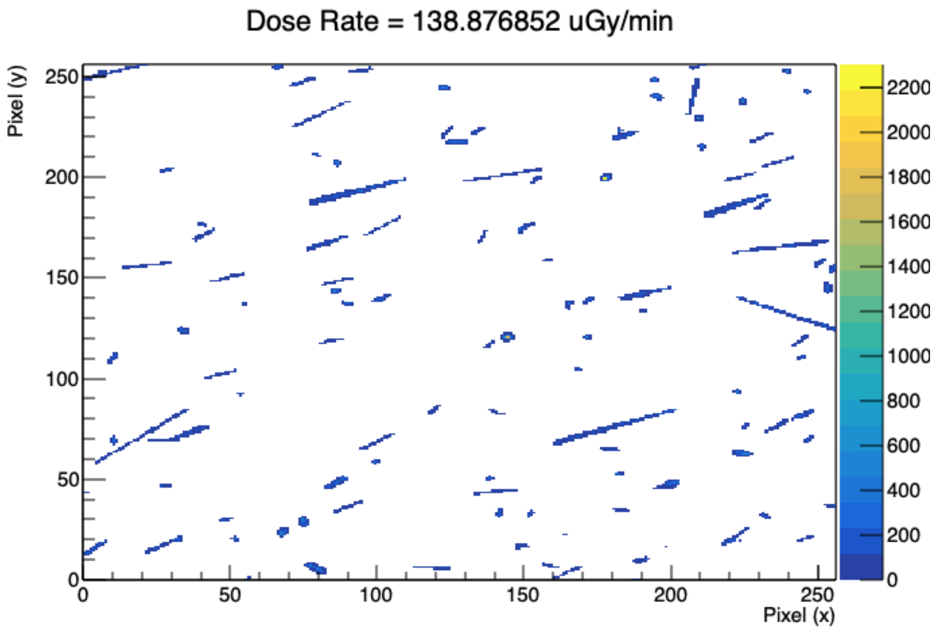
Artemis 1 Modeling and Data

HERAs – Inner VAB

- Transits Inner VAB 7:11am to 7:46am GMT
  - Qualitatively good agreement with Ap9 + modulated GCR dose rates
    - Modelled peak rates are 70%-80% of measured
  - Cumulative dose also in good agreement (Table)



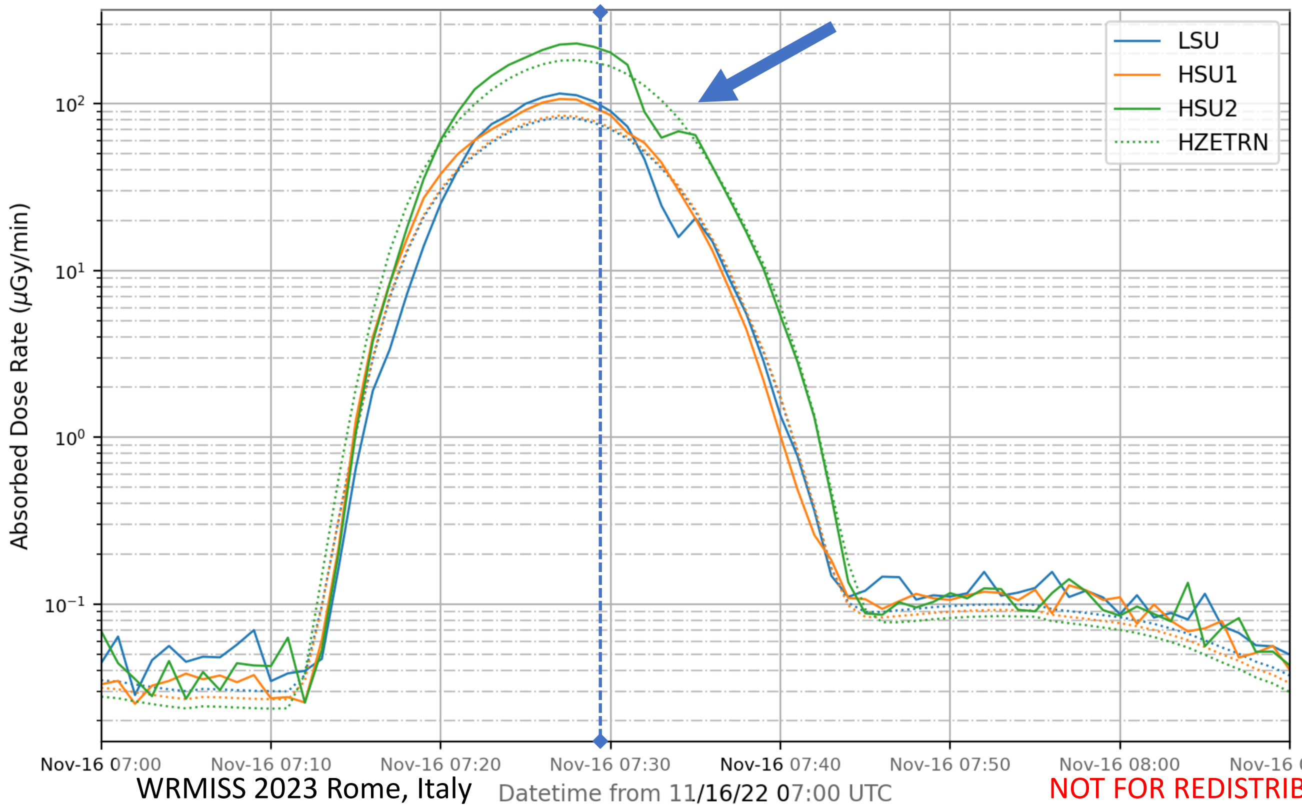
Sensor	Cum. Dose Error
Artemis 1 LSU	-13.8%
Artemis 1 HSU1	-13.9%
Artemis 1 HSU2	-9.4%

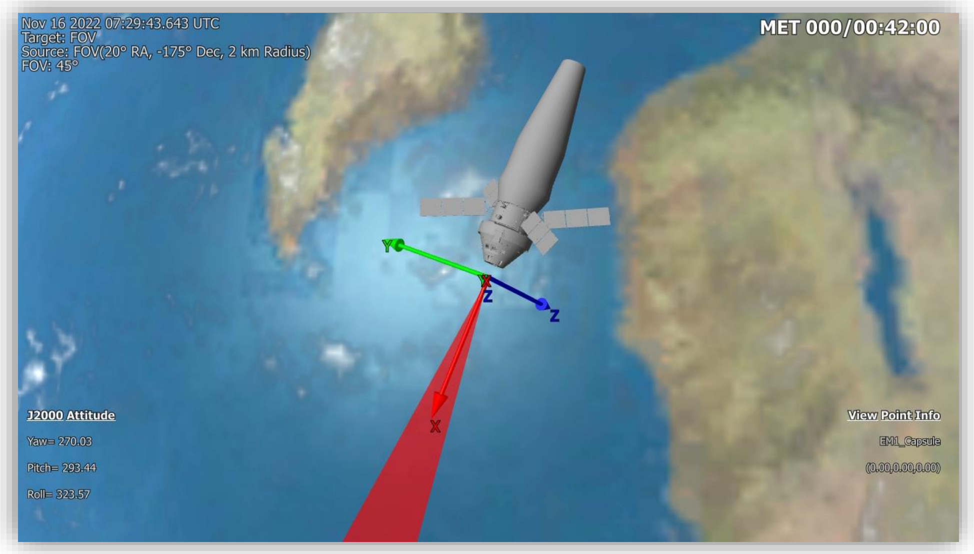


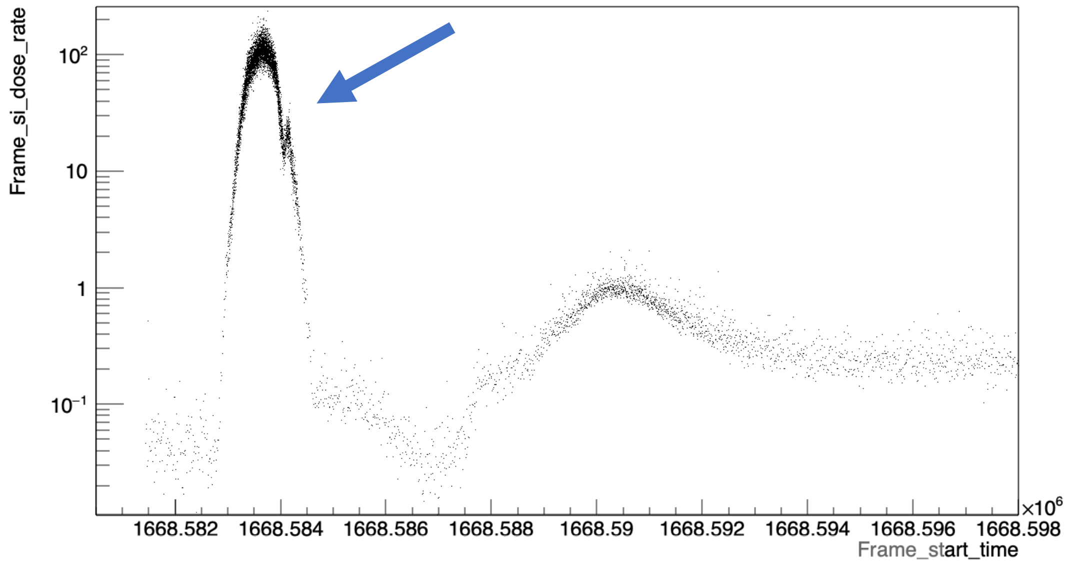
HERA Frame – Inner VAB Belt

HERAs – Inner VAB

- Unexpected anomaly in HERA dose rates
  - Obvious discontinuity (dip) in HERA dose rate and frame rate for LSU and HSU2, not represented in Ap9 model
  - Leading explanation is a drastic change in orientation prior to PRM, combined with anisotropy in proton environment



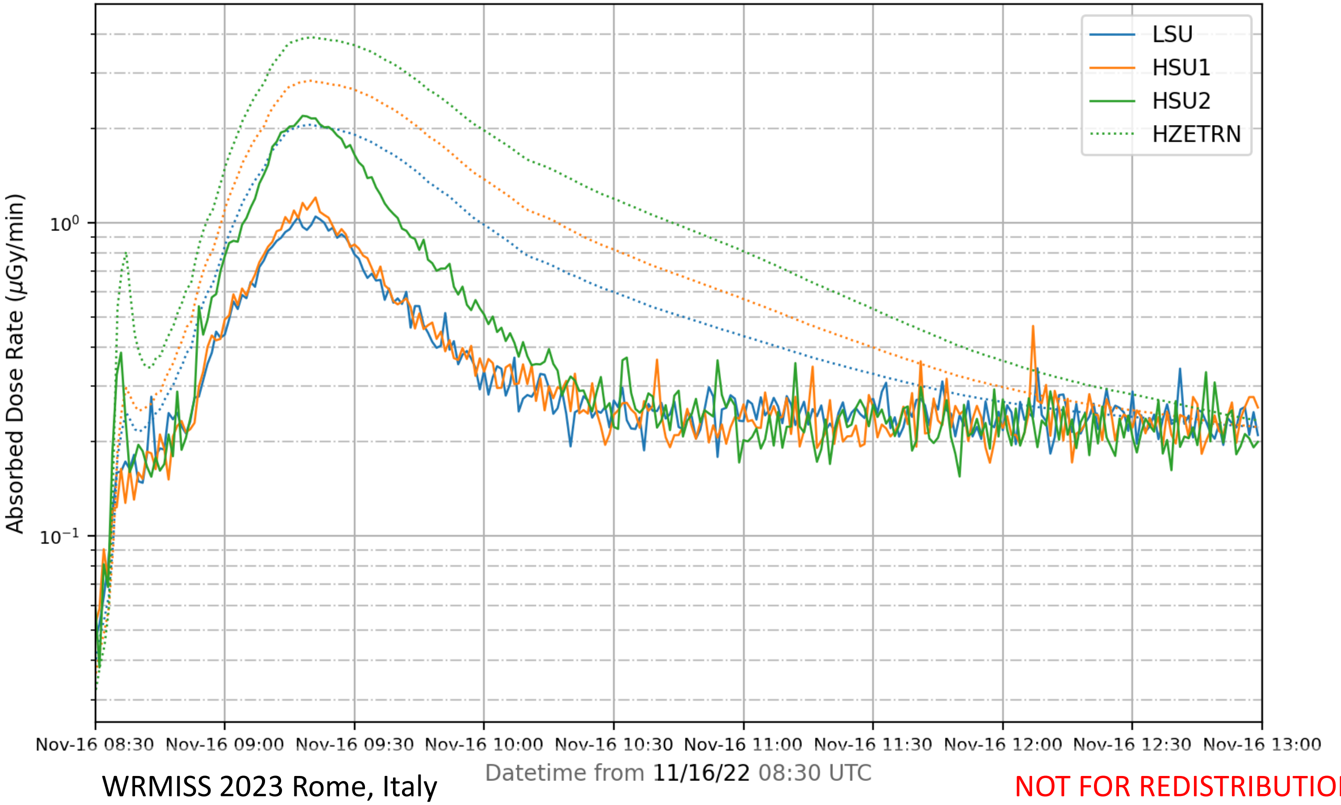


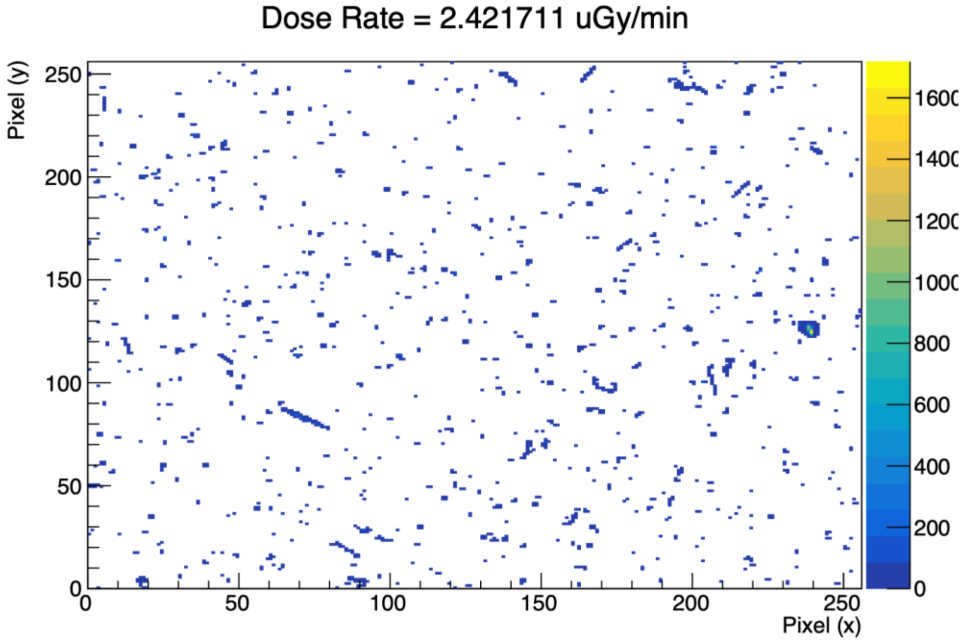


HERAs – Outer VAB

- Transits Outer VAB 8:27:00 to 13:24:11 GMT
  - 1DHZETRN largely overestimated absorbed dose from trapped electrons to point sensors
  - This is expected; 1D HZETRN is poor at modeling stochastic particles like bremsstrahlung photons induced by primary electrons

Sensor	Cum. Dose Error
Artemis 1 LSU	92.5%
Artemis 1 HSU1	152.2%
Artemis 1 HSU2	146.6%



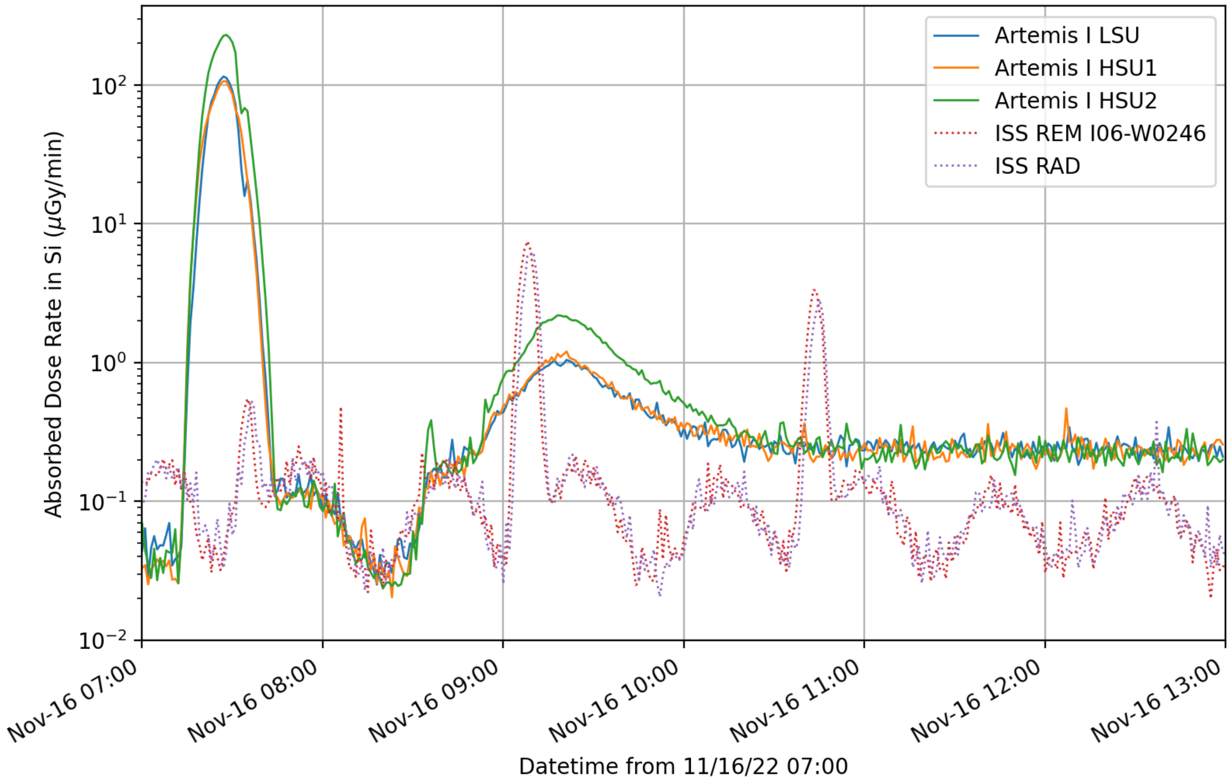


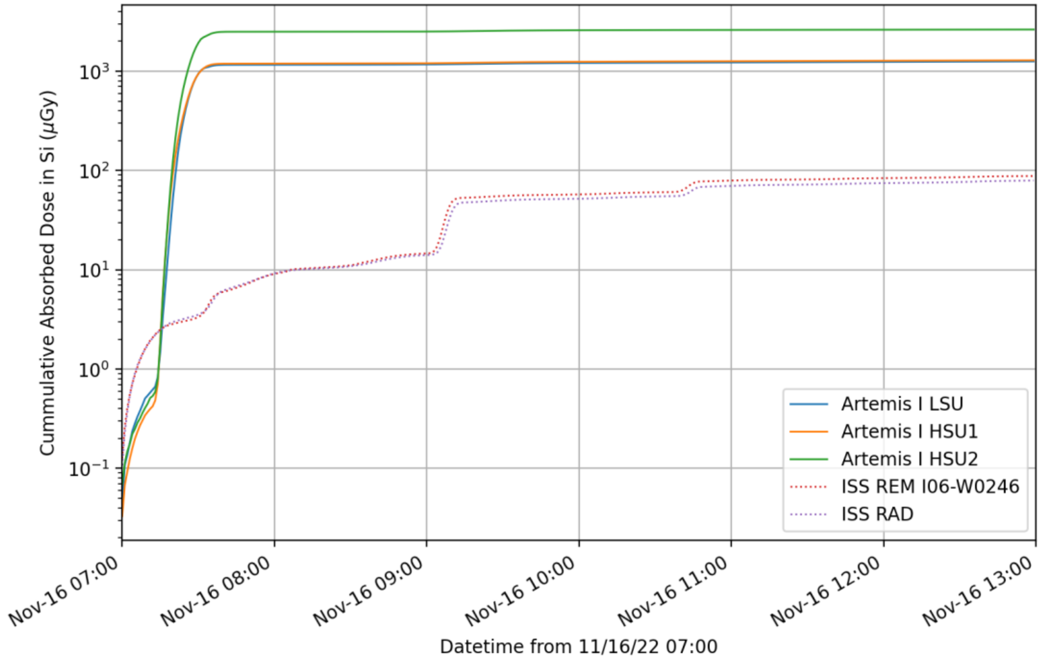
HERA Frame – Outer VAB Belt

Comparing ISS Doses to Artemis

- ISS experienced 3 ascending SAA passes during Artemis 1 Outbound (6hr window)
  - Showing Si dose reported by 2 collocated sensors: ISS RAD and Timepix REM I06 (USLab Overhead-Zenith)

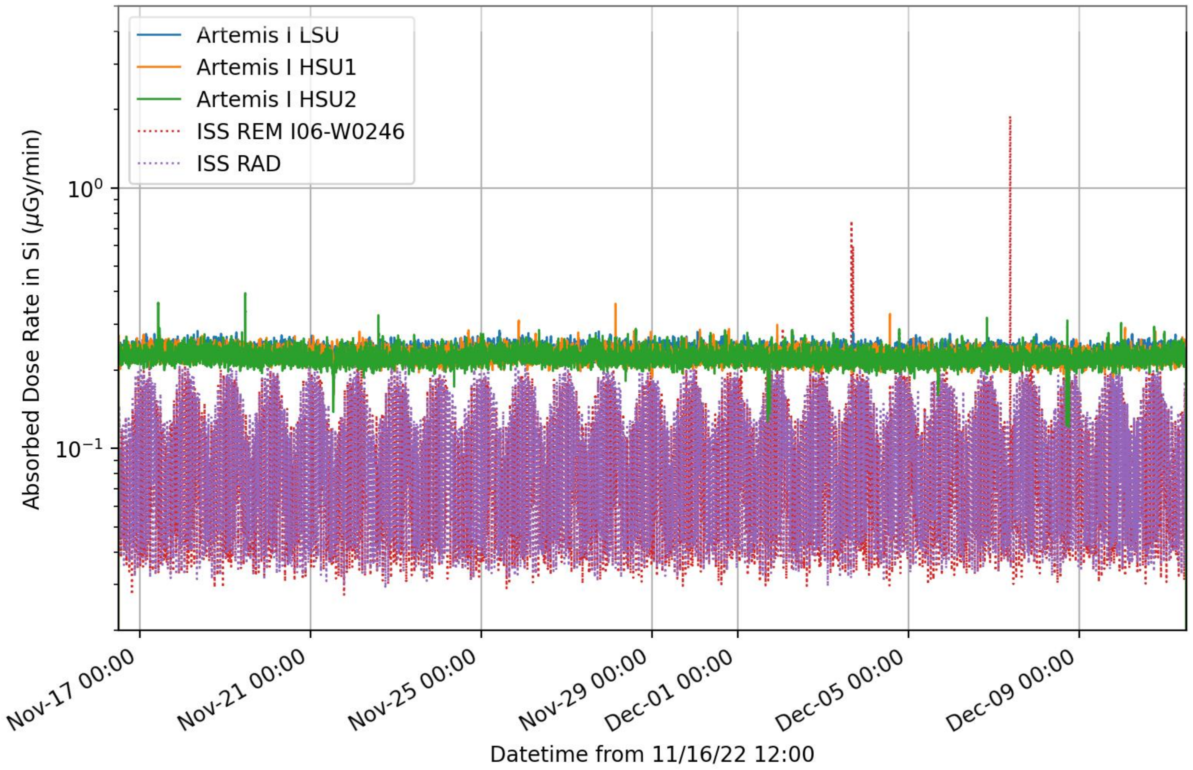
Sensor	Dose in Si
Artemis 1 LSU	1255 µGy
Artemis 1 HSU1	1289 µGy
Artemis 1 HSU2	2633 µGy
ISS I06-W0246	88 µGy
ISS RAD	79 µGy





HERAs - Freespace GCR

- Freespace GCR environment for most of Artemis 1
  - 1DHZETRN + Freespace BON2020 GCR model nominally 10% lower than measured. Quality factors also in good agreement
    - Returning leg folded into Freespace portion



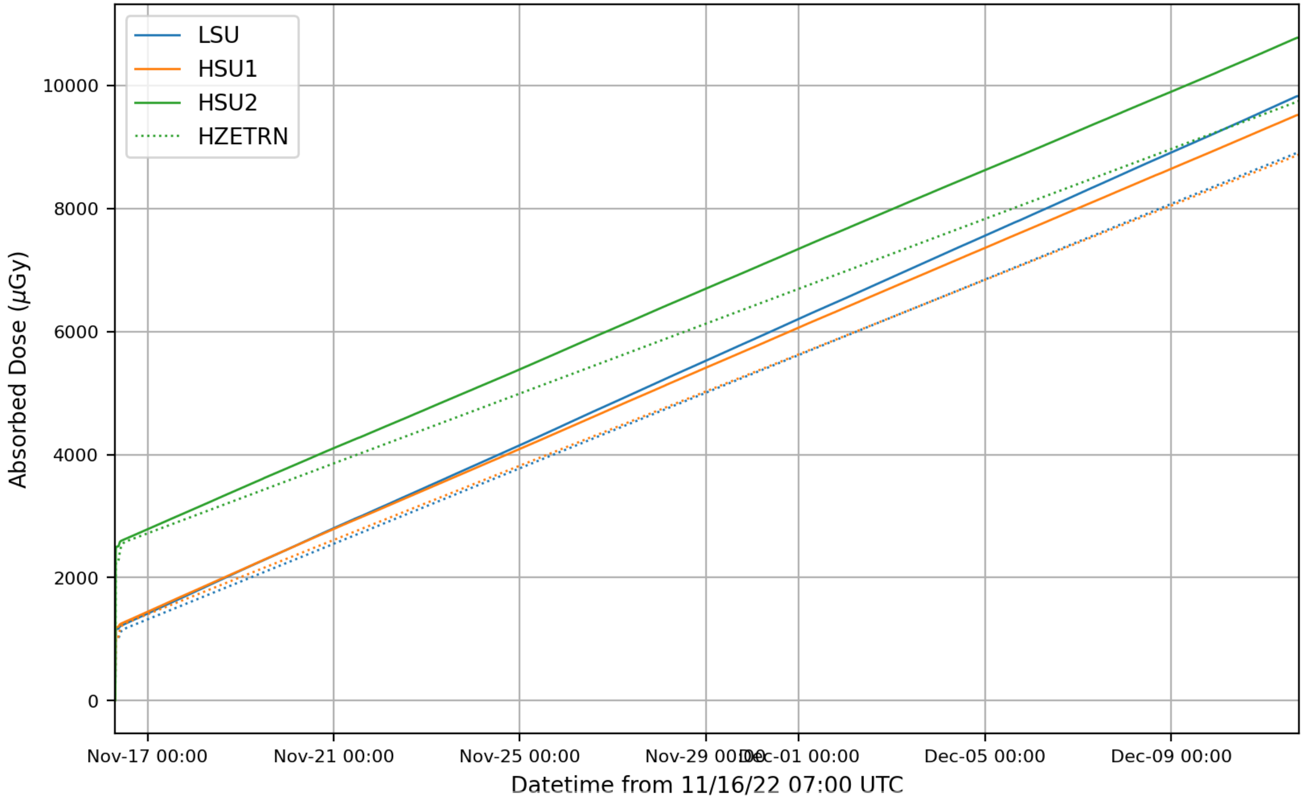
	Measured	1DHZETRN	% Diff
LSU (mGy/Day)	0.336	0.307	-8.5%
<Q>	2.3	2.5	
HSU1 (mGy/Day)	0.328	0.302	-7.9%
<Q>	2.6	2.5	
HSU2 (mGy/Day)	0.32	0.284	-11.3%
<Q>	3.1	3.2	

- HERAs minute data plotted with ISS GCR sensor data
  - Smoothed (10 min. rolling window average)
  - SAA mask applied in plot (B and L cuts)

	GCR Only	GCR+SAA
ISS REM I06 (mGy/Day)	0.129	0.223
ISS RAD (mGy/Day)	0.132	0.208

Full Mission Dose

- Full mission dose model nominally 10% lower than measured
  - Cumulative Dose values dominated by Freespace GCR dose rates
  - No significant VAB dose (measured or modeled) on return
    - Measurements showed Freespace GCR until shutdown before splashdown, no VAB passes in models



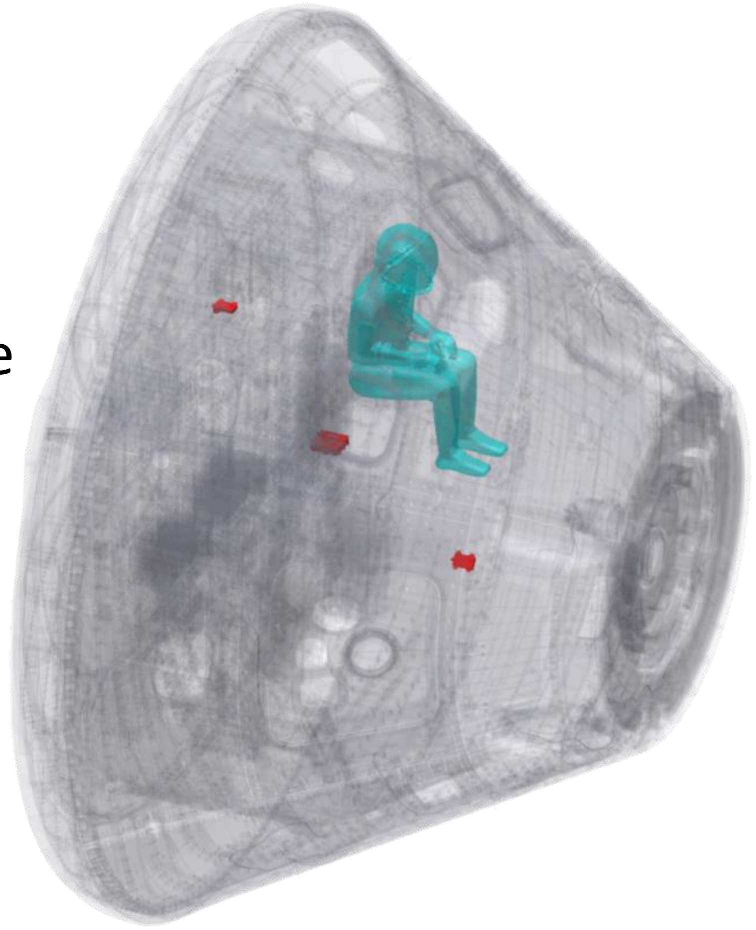
Total Mission Dose in Si			
	Measured	1DHZETRN	% Diff
LSU (mGy)	9.8	8.9	-9%
HSU1 (mGy)	9.5	8.9	-7%
HSU2 (mGy)	10.8	9.7	-10%

Total Mission Dose in Si	
	Measured
Moonikin Campos CAD (mGy)	9.816

Effective Dose Computation

Computing Effective Dose

- On ISS, Radiation Area Monitors and Crew Dosimetry provide reference point measurements in the vehicle
  - Currently, 7 Timepix REM-2s (exclude BEAM) and the RAD detector
  - Dose to sensors can be modeled and compared to measurements
- Transport of GCR and trapped protons through a human phantom (MAX/FAX†) provides modeled tissue absorbed dose
- Both are used Operationally to estimate total NSCR 2012 effective dose to crew member
  - Model GCR + Trapped proton dose to sensors and CADs
  - Normalization factors is computed to scale Trapped proton contribution and minimize error
- Same can be done in Artemis 1 Outbound segment in RAE



†Kramer, Richard & Khoury, Helen & Vieira, J.W. & Loureiro, Eduardo & Lima, V & Lima, Fernando & Hoff, Gabriela. (2004). All about FAX: A Female Adult voXel phantom for Monte Carlo calculation in radiation protection dosimetry. Physics in medicine and biology. 49. 5203-16. 10.1088/0031-9155/49/23/001.

ISS Normalization Using Passive Sensors

- Assume the measured dose of detector i is $D_{M,i}$, and is modeled ideally by the sum of modeled GCR dose $D_{m,i}^{GCR}$ and modeled normalized Trapped dose $c^{Trp} D_{m,i}^{Trp}$ for N detectors. The squared sum error of this model is

$$\epsilon = \sum_{i=1}^{N} \left\{ D_{M,i} - \left(D_{m,i}^{GCR} + c^{Trp}\, D_{m,i}^{Trp} \right) \right\}^2$$

- Minimizing error ϵ with respect to changing normalization factor c^{Trp} gives the following

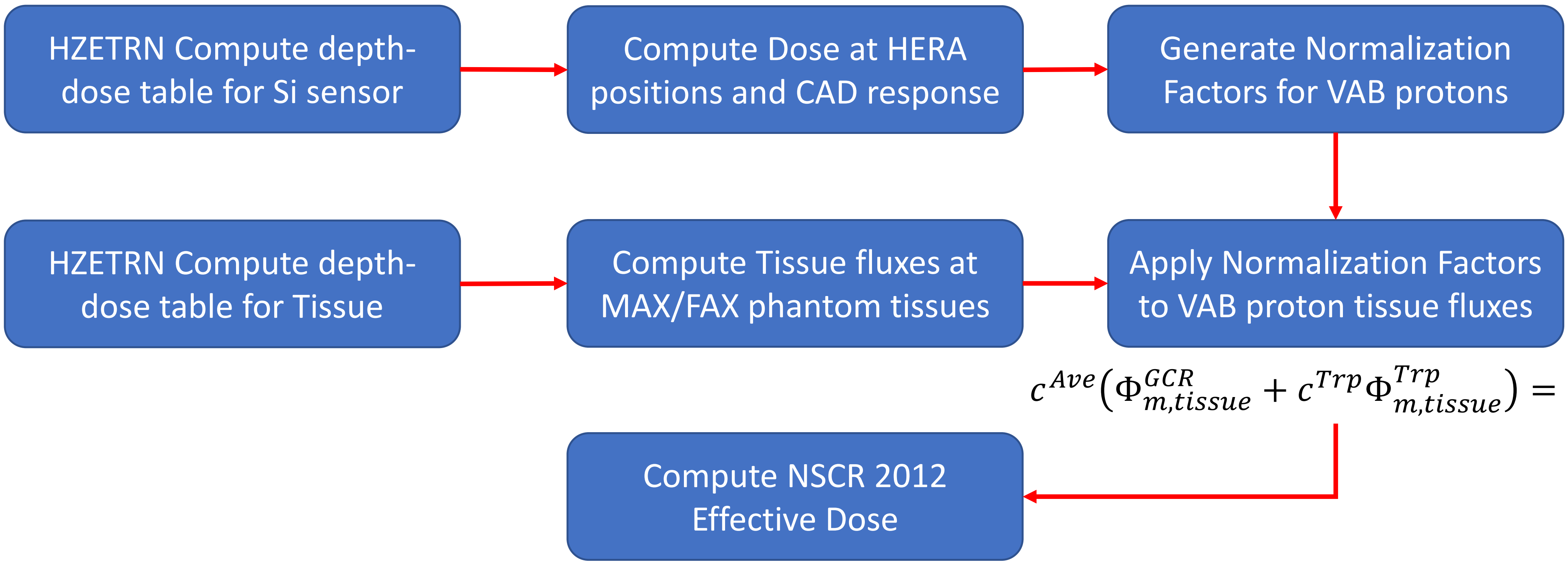
$$c^{Trp} = \frac{\sum_{i=1}^{N} D_{m,i}^{Trp} \left[D_{M,i} - D_{m,i}^{GCR} \right]}{\sum_{i=1}^{N} \left[D_{m,i}^{Trp} \right]^2}$$

- The final normalization constant c^{Ave} is the average ratio of measured dosimeter (CPD) doses $D_{M,CPD}$ and simulated CPD doses with trapped normalization applied, for all N positions

$$c^{Ave} = \frac{1}{N} \sum_{i=1}^{N} \frac{D_{M,CPD}}{D_{m,CPD,i}^{GCR} + c^{Trp} D_{m,CPD,i}^{Trp}}$$

Computing Effective Dose

- Simplified look at how we determine effective dose to humans in LEO



$$c^{Ave}\left(\Phi_{m,tissue}^{GCR} + c^{Trp}\Phi_{m,tissue}^{Trp}\right) = \Phi_{m,tissue}$$

- This normalization method applies to LEO where measurements are available only (GCR + Trapped) i.e. only the Artemis Outbound limb. Freespace GCR is not currently normalized

Campos "Occupational" Dose

- RAE Mission parameters for Moonikin Campos Artemis 1 crew dose report

Astronaut Parameters

Body Model Settings

Gender: Male **Body Model:** Adult voXel **Rays:** 10000

Age at mid-mission: 35 **Smoker Status:** Never Smoker

Mission Parameters

Mission Segment Details

Transport calculations will be completed for the following potential segments of a lunar mission. A separate fluence file will be returned for each segment, allowing for the evaluation of various dose and risk scenarios.

Segment Label	Shielding	Trajectory	Duration (d/h/m/s)			
Seg1-LEO Outbound Trapped+GCR	MPCV_CAMPOS_ARTEMIS1	artemis1_outgoing_asflown	0	06	14	00
Seg2-Outbound Freespace GCR	MPCV_CAMPOS_ARTEMIS1	N/A	0	00	01	00
Seg3a-Lunar Surface GCR	MPCV_CAMPOS_ARTEMIS1	N/A	25	01	43	00
Seg3b-Freespace GCR	MPCV_CAMPOS_ARTEMIS1	N/A	Same as 3a			
Seg4-Return Freespace GCR	MPCV_CAMPOS_ARTEMIS1	N/A	0	00	01	00
Seg5-Return Trajectory Trapped+GCR	MPCV_CAMPOS_ARTEMIS1	artemis1_returning_asflown	0	01	39	00

Dosimetry Parameters (input as dose in H_2O)

Crew Active Dosimeter (CAD) Measurements

Segment	Badge Dose (mGy)	Error (mGy)
Seg1-LEO Outbound Trapped+GCR	1.62	
Seg2-Outbound Freespace GCR	0	
Seg3a-Lunar Surface GCR	0	
Seg3b-Freespace GCR	10.6	
Seg4-Return Freespace GCR	0	
Seg5-Return Trajectory Trapped+GCR	0	

GCR Normalization

Select mode for Active Detectors: Disable (Off)

Campos "Occupational" Dose

- Generated a mock dose report for Commander Campos in RAE using MAX

Organ equivalent doses (mSv) per mission - mean values:

Mission	Oral Cavity	Esophagus	Stomach	Colon	Liver	Lung	Skin	Prostate	Bladder	Brain	Thyroid	Leukemia	Other
1520 [-] Hide	26	24.5	24.7	24.4	24.2	25.4	31.8	23.4	23.8	26.9	26	13.5	24.2
1520-Seg1	*2.18*	*1.77*	*1.84*	*1.71*	*1.67*	*2.02*	*4.05*	*1.43*	*1.54*	*2.41*	*2.18*	*1.18*	*1.69*
1520-Seg3b	*23.8*	*22.6*	*22.8*	*22.6*	*22.4*	*23.3*	*27.6*	*21.9*	*22.2*	*24.4*	*23.8*	*12.2*	*22.4*
1520-Seg5	*0.0995*	*0.0947*	*0.0953*	*0.0947*	*0.0939*	*0.0976*	*0.116*	*0.0915*	*0.0929*	*0.102*	*0.0995*	*0.0514*	*0.0938*
Total	26	24.5	24.7	24.4	24.2	25.4	31.8	23.4	23.8	26.9	26	13.5	24.2

NASA Effective Dose (mSv)*: [-] Click to Hide

Space Missions	Point Estimate	Mean
1520-Artemis 1 Nov22 (preliminary) [-] Hide Segs	18.9	22.3
Seg1-LEO Outbound Trapped+GCR	*1.42*	*1.68*
Seg3b-Freespace GCR	*17.4*	*20.6*
Seg5-Return Trajectory Trapped+GCR	*0.0731*	*0.0861*
TOTAL EFFECTIVE DOSE	18.9	22.3
EFFECTIVE DOSE - SPEL*	N/A	24

Re-entry not normalized (segment badge dose = 0)

* Effective doses are presented for informational purposes only. These values are not used in the estimation of REID or REIC. NASA Effective doses are estimated using tissue weighting factors generated by NASA. When adjusted, effective dose for a male is similar to that of a female, for comparison with the SPEL.

Conclusions

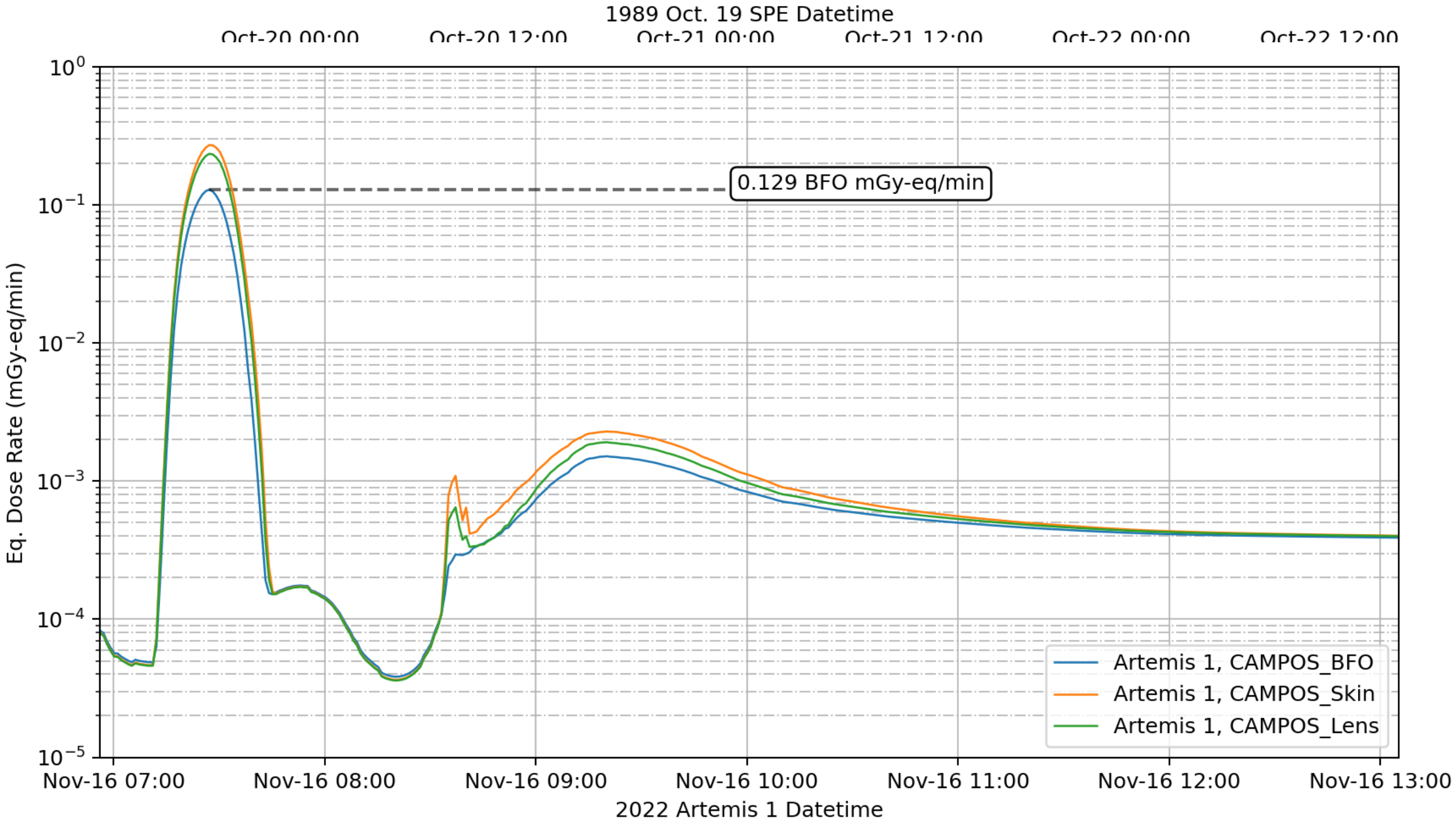
- Artemis 1 mission radiation exposure would not pose a significant acute or chronic health risk to crew members
  - 22.3 mSv against astronaut career limit of 600 mSv
- Dose modeling methods used on ISS are sufficient for Artemis missions
  - Pure models nominally 10% lower than measurements, VAB protons normalized
- Improvements can of course be made to models
  - 3DHZETRN results from Langley Research Center (LaRC) for Freespace GCR calculations have been promising!
  - Incorporate attitude information and consideration of non-isotropic VAB primary particle modeling improve 1DHZETRN error
  - Normalization for Freespace GCR dose (exists, but not operationally implemented)
  - Monte Carlo for dose calculation from VAB electrons

Thank You

Tissue Specific Equivalent Dose

- Tissue Specific Equivalent Dose for MAX phantom in Campos position
  - Relative Biological Effectiveness factors applied (1.5 for protons, 2.5 for A > 1)

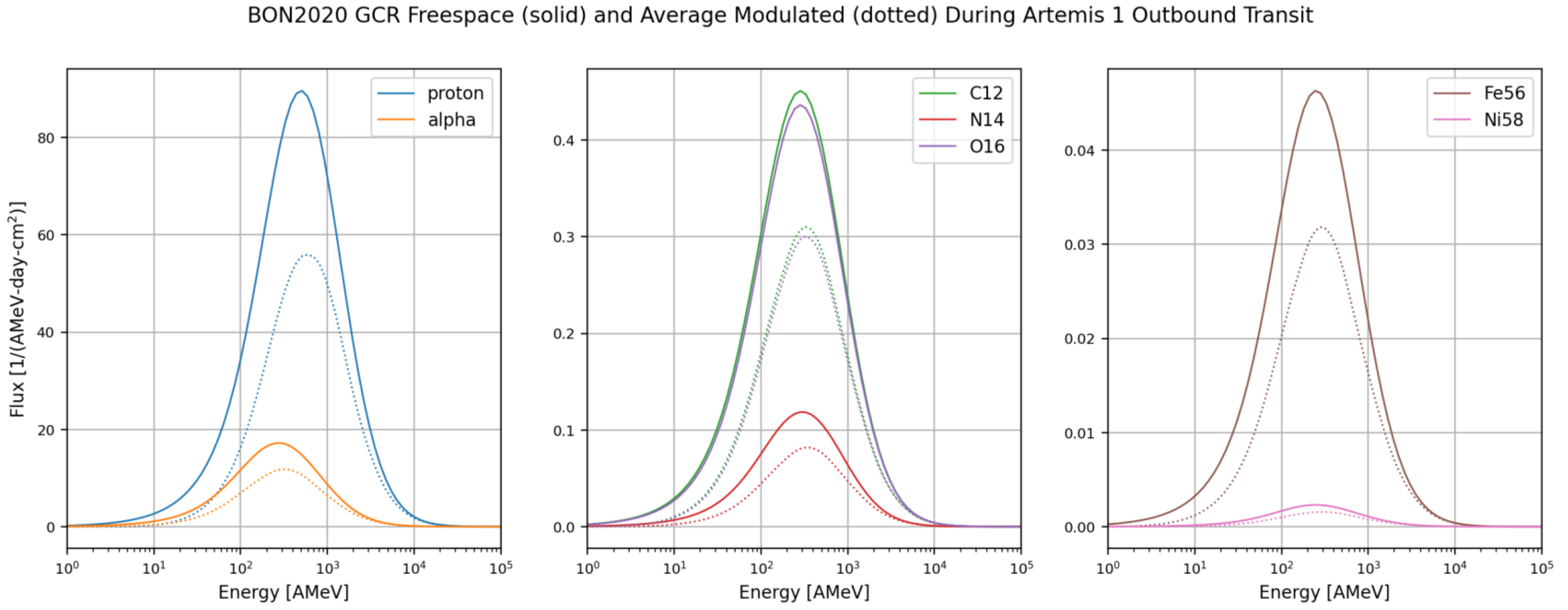
- Blood Forming Organ (BFO) Gy-eq used as acute effects metric i.e. bone marrow syndrome
  - Dose is well below threshold for any acute effects (NASA 30-day PEL – 250 mGy-eq)
- Peak BFO dose rates for VAB transit and ’89 SPE nearly identical
- Outgoing limb – As-flown trajectories (< 10 ER, 0.257 days)

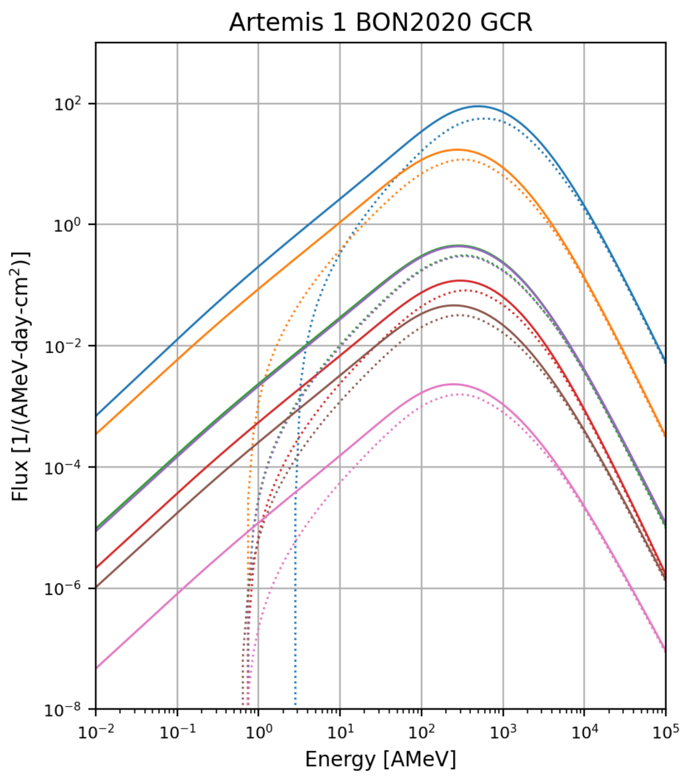


*Time axis are NOT on same scale

BON2020 GCR Model

- BON2020$_{SSN}$ model[1] used to generate GCR particle fluxes
  - Updated local interstellar spectrum (LIS) from BON2014
  - Rigidity derived from monthly smoothed SSN values during Artemis 1 timeline





[1]Slaba, Tony & Whitman, K.. (2020). The Badhwar-O'Neill 2020 GCR Model. Space Weather. 18. 10.1029/2020SW002456.