

NAIRAS Ionizing Radiation Environment Model

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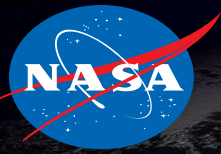
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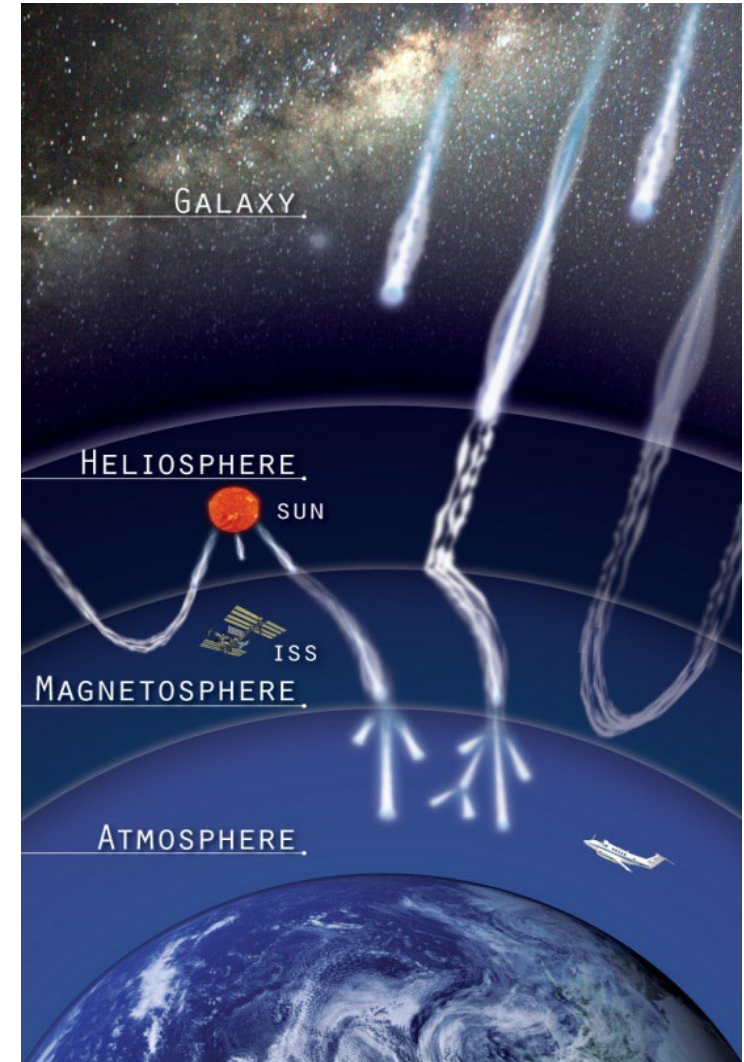
⁴ NASA Marshall Space Flight Center, Huntsville, AL, USA

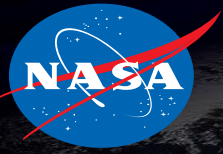
⁵ Jet Propulsion Laboratory, Pasadena, CA, USA



NAIRAS Model

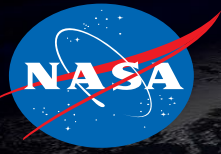
- **Nowcast of Aerospace Ionizing RAdiation System (NAIRAS) Model**
 - Running in real-time on NASA computer cluster since 2011, aviation radiation results hosted publicly on Space Environment Technologies server/website
 - Running in real-time at Community Coordinated Modeling Center (CCMC) since 2020
- **Key (Vintage) Model Features**
 - Physics-based **HZETRN** (High Charge (Z) and Energy TRaNsport) code
 - Real-time inclusion of solar energetic particle (**SEP**) radiation
 - Real-time solar-magnetospheric effects on radiation (cutoff model *by Kress et al. [2004, 2010]*)
- **New/Current Model Developments**
 - Extend from atmosphere to space environment, now including trapped protons (**TRP**)
 - SEP heavy-ions ($Z=2-92$, $A=4-238$) added
 - Single-Event Effects (**SEE**) radiation risk assessment quantities added
 - Run-on-Request (**RoR**) @ CCMC





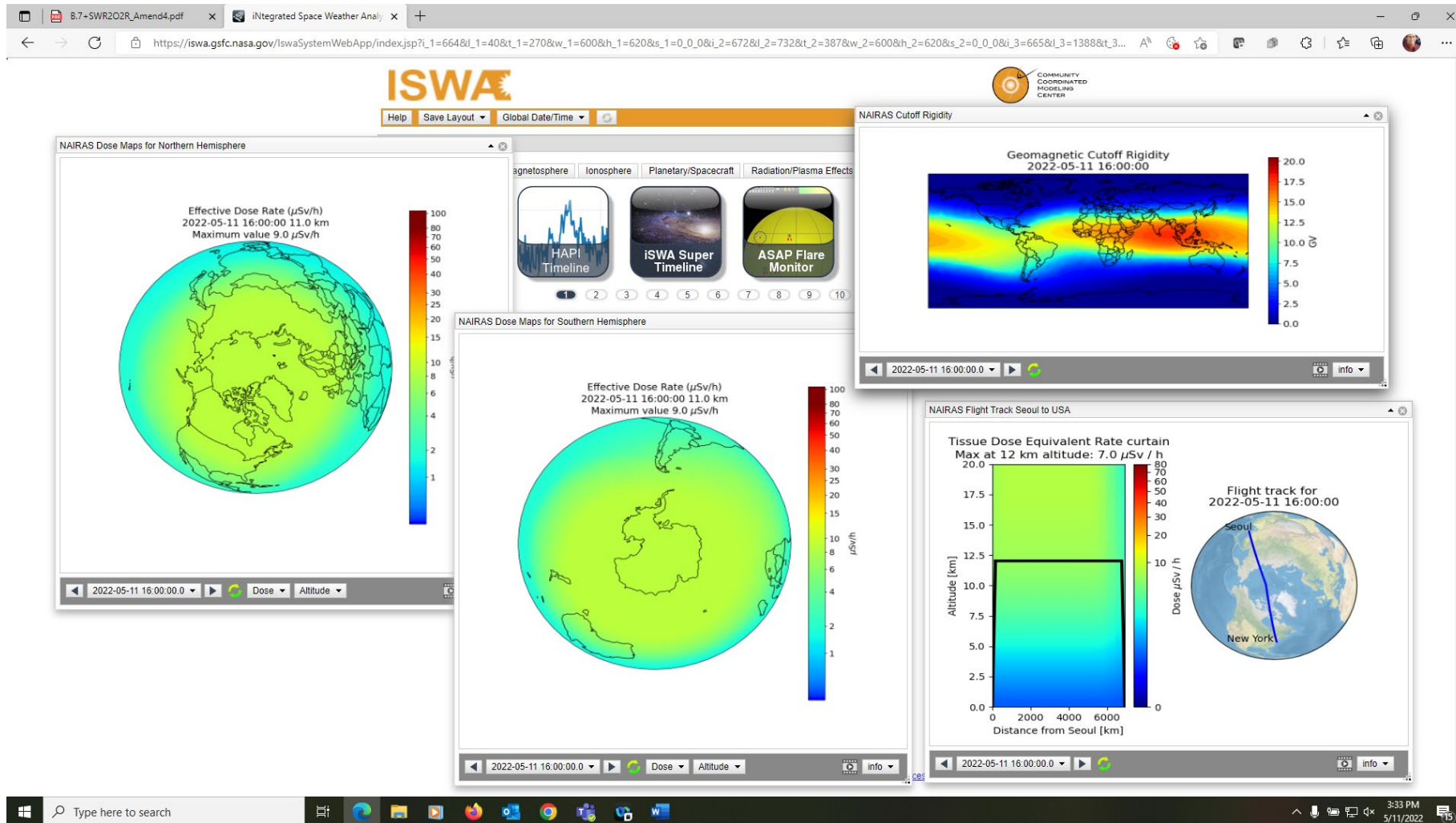
Outline

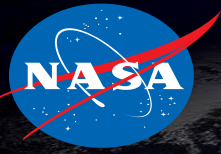
- **NAIRAS Real-Time Interface @ CCMC ([publicly available](#))**
- **NAIRAS RoR Capability @ CCMC ([publicly available](#))**
- **NAIRAS Validation Studies in the Atmosphere**
- **NAIRAS Predictions of Space Radiation**
 - Examples of model outputs for various space weather conditions
 - Preliminary validation in the space environment
- **Summary and Conclusions**



Real-Time NAIRAS @ CCMC

CCMC Integrated Space Weather Analysis (iSWA) System

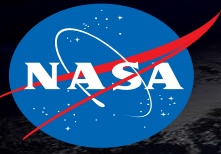




NAIRAS Run-on-Request (RoR) User Input

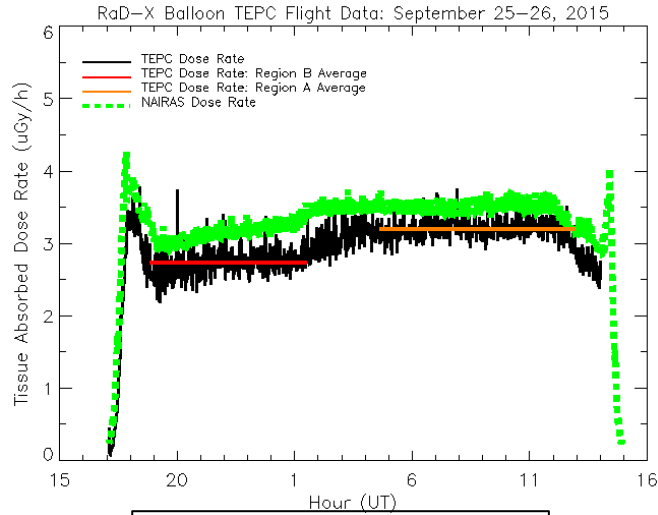
Table: RoR Capability Summary and Description

Run Option	Output Quantities		User Input
Global Dosimetric	Absorbed dose in silicon, absorbed dose in tissue, dose equivalent, ambient dose equivalent, effective dose		Start/End Date-Time
Flight Trajectory	Dosimetric & Flux/Fluence		Trajectory file
	Dosimetric	Same as global run	Shielding depths for dosimetric calculations
	Flux/Fluence	Integral <ul style="list-style-type: none"> GCR/SEP LET (linear energy transfer) SEP proton TRP proton 	Shielding depths for flux/fluence calculations
		Differential <ul style="list-style-type: none"> GCR/SEP LET (linear energy transfer) SEP proton TRP proton 	N/A (full model differential spectra written to output)

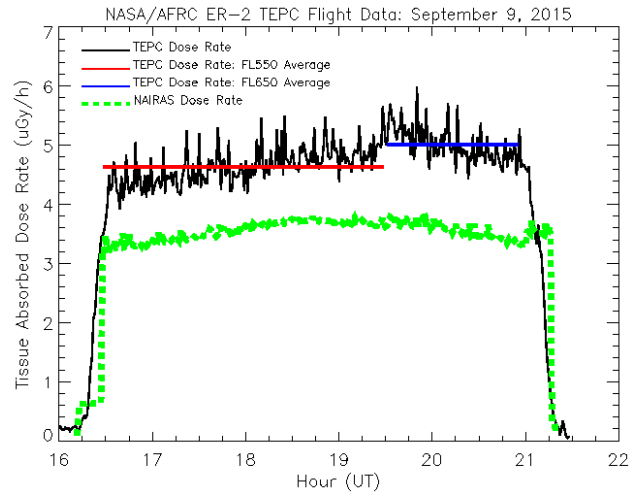


NAIRAS Validation @ 0-40 km

RaD-X Region A: 21 km < Z < 27 km; Region B: Z > 32.5 km



RaD-X ER-2: Z = 17km, 20km



•Legend

- NASA Radiation Dosimetry Experiment (RaD-X)
- Automated Radiation Measurements for Aerospace Safety (ARMAS) semiconductor dosimeter
- Columbia Scientific Balloon Facility (CSBF)
- Tissue equivalent proportional counter (TEPC)

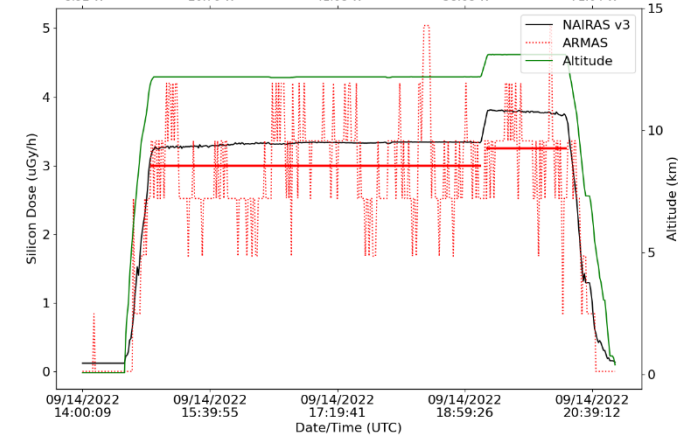
•Absorbed dose rate comparisons

- Tissue (top left, bottom left, bottom right)
- Silicon (top right)
- **Agreement within 30%**

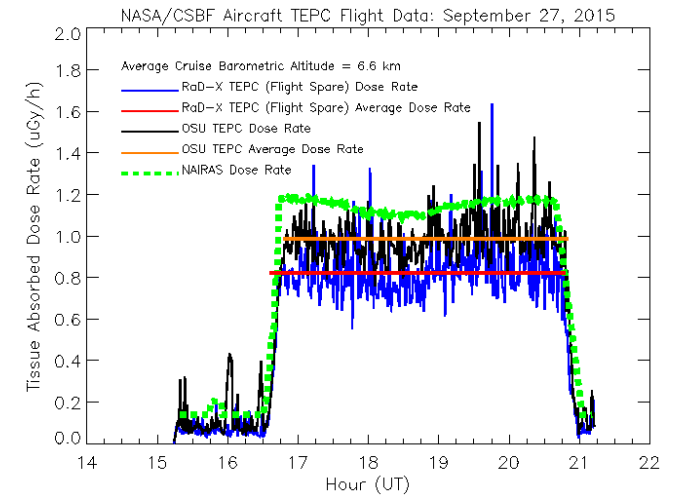
US Corporate Aircraft: EINN-KBDL

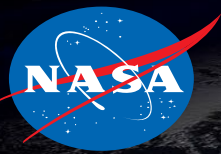
Absorbed Dose in Silicon for Flight 07008_20220914140000

52.69 N	53.03 N	52.94 N	49.1 N	43.18 N
-8.92 W	-20.76 W	-41.08 W	-58.68 W	-71.64 W



RaD-X CSBF Chase Plane: Z = 6.6 km





NAIRAS SEP Spectral Fitting

• Protons

- Fit spectrum to GOES integral proton flux
- Fit four functional forms
- Choose solution with minimum chi-square

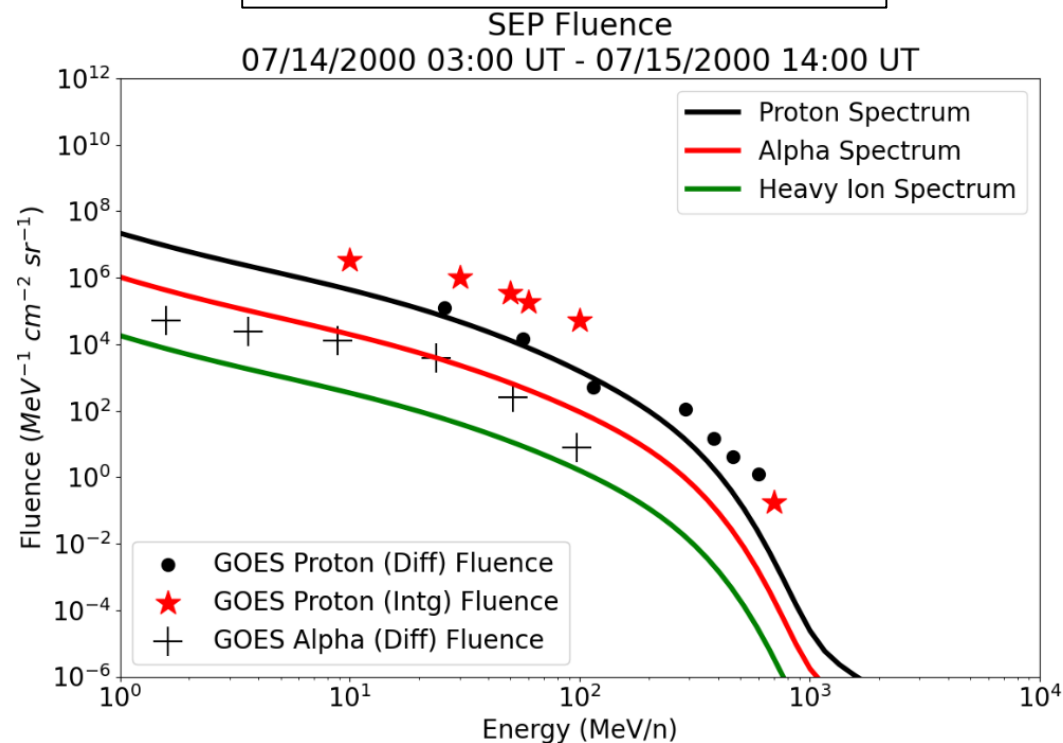
• Alpha

- Retain proton spectral shape from previous step
- Scale proton spectrum by optimal normalization factor using GOES alpha differential flux

• Heavy-Ion ($Z > 2$)

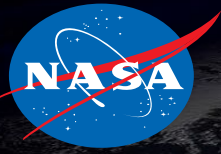
- Scale alpha spectrum from previous step using element/alpha abundance ratios
- *Major heavy-ion abundance ratios*: using GOES alpha and ACE Solar Isotope Spectrometer (SIS) element flux measurements (Xapsos et al., 2007)
- *Minor heavy-ion abundance ratios*: using ACE/SIS and International Sun-Earth Explorer-3 (ISEE-3) element flux measurements (Reames, 1998)
- *Remaining heavy-ion abundance ratios*: using photospheric emission measurements with a scale factor of 4 if the first ionizing potential is less than 10 eV (Grevesse, 2019)

Bastille Day SEP Event Fluence



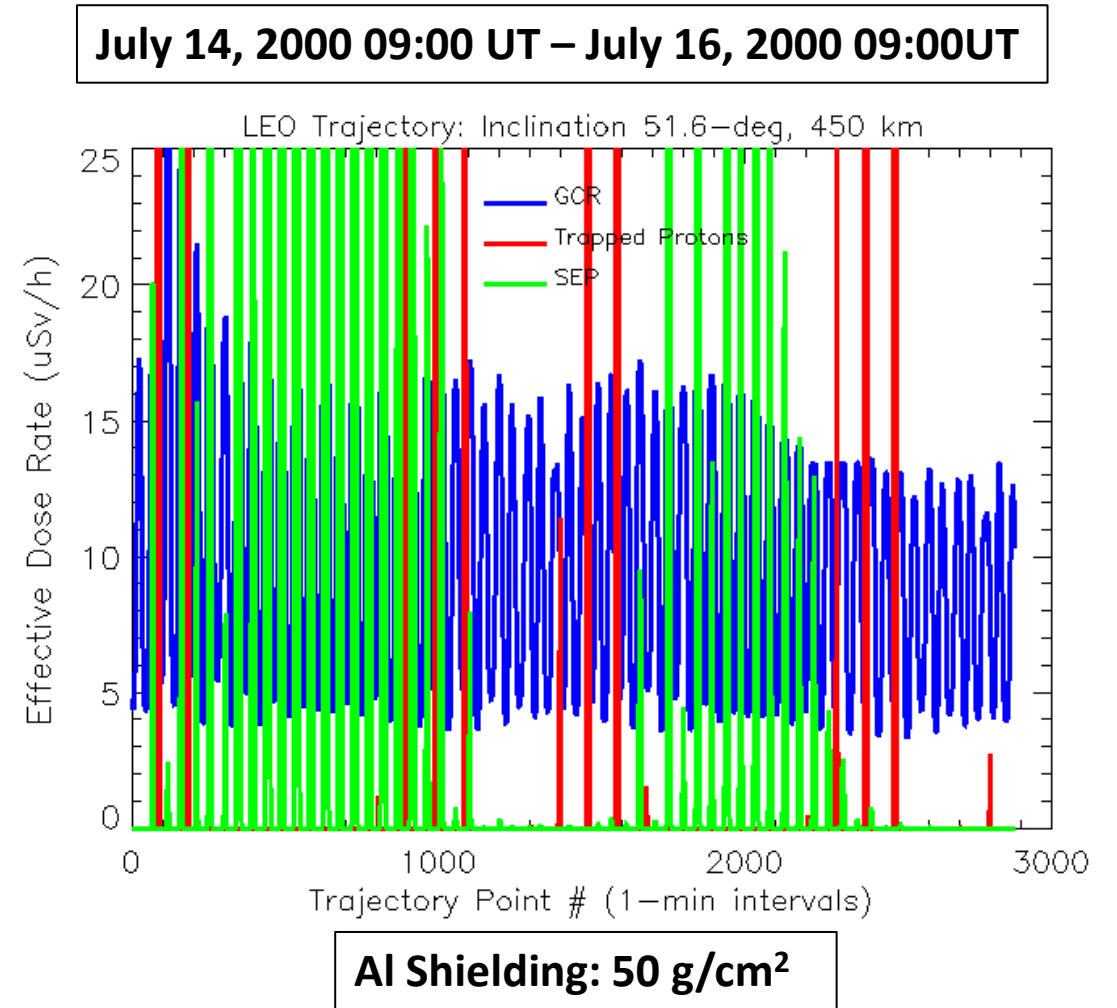
SEP proton spectrum fit to GOES integral proton flux. GOES differential proton flux shown for comparison.

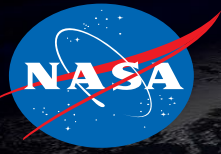
SEP spectra fit to GOES 5-min data. Fluence is 5-min fitted-spectra summed over event.



NAIRAS LEO Dose: Bastille Day SEP Event

- **NAIRAS effective dose: 2 g/cm² (EVA)**
 - **GCR:** 790 uSv
 - **TRP:** 4 mSv
 - **SEP:** 168 mSv (max dose rate = 198 mSv/h)
- **NAIRAS effective dose: 50 g/cm² (inside ISS)**
 - **GCR:** 498 uSv
 - **TRP:** 612 uSv
 - **SEP:** 1.5 mSv (max dose rate = 1.6 mSv)





SEP Heavy-Ion Effective Dose in LEO

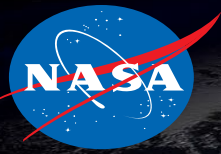
LEO Trajectory: Inclination 51.6-degree, 450 km

SEP Event Date	Start Time (UT)	Duration (Hours)	Shielding Depth: 2 g/cm ²		Shielding Depth: 50 g/cm ²	
			Total Effective Dose (mSv)	Total Effective Dose Ratio (heavy/proton)	Total Effective Dose (mSv)	Total Effective Dose Ratio (heavy/proton)
10/19/1989	12:00	48	40.4	2.02	0.20	1.16
07/14/2000	09:00	48	168.0	2.33	1.52	1.52
11/08/2000	22:00	24	158.2	2.10	1.05	1.34
09/29/1989	09:00	48	23.4	2.59	0.08	1.28
10/28/2003	10:00	48	140.3	2.73	0.96	1.52
11/04/2001	16:00	48	173.0	1.70	1.18	1.21
01/20/2005	06:00	24	17.7	1.84	0.04	1.42
03/07/2012	01:00	48	52.3	2.04	0.06	1.37
04/15/2001	13:00	48	4.7	1.90	0.14	1.53
08/12/1989	14:00	48	17.3	1.66	0.01	1.20

Event Selection: 10 largest SEP events with respect to free-space event dose (Minow et al., Space weather architecture options to support human and robotic deep space exploration, NASA Langley Research Center, Hampton, VA, USA, Tech. Mem. TM/2020-5000837, Apr. 2020.)

Take Away 1: 5 of 10 events SEP heavy-ions increase effective dose by ~40% (**blue**) to ~50% (**red**) at 50 g/cm²

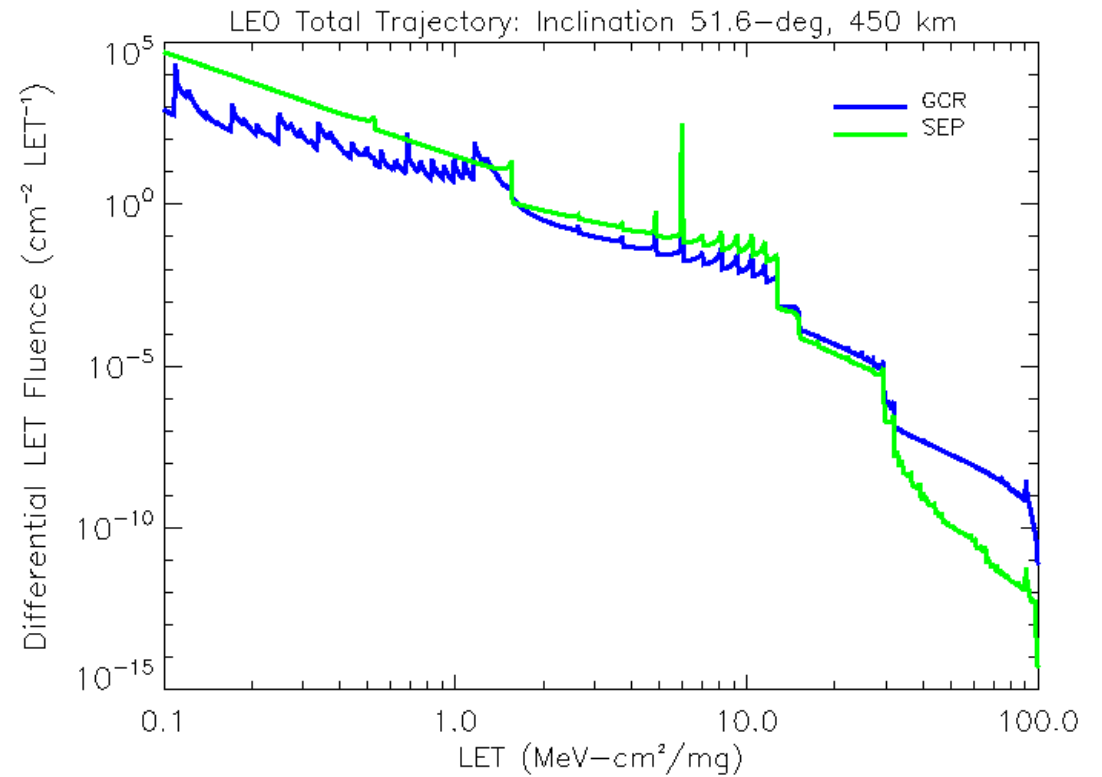
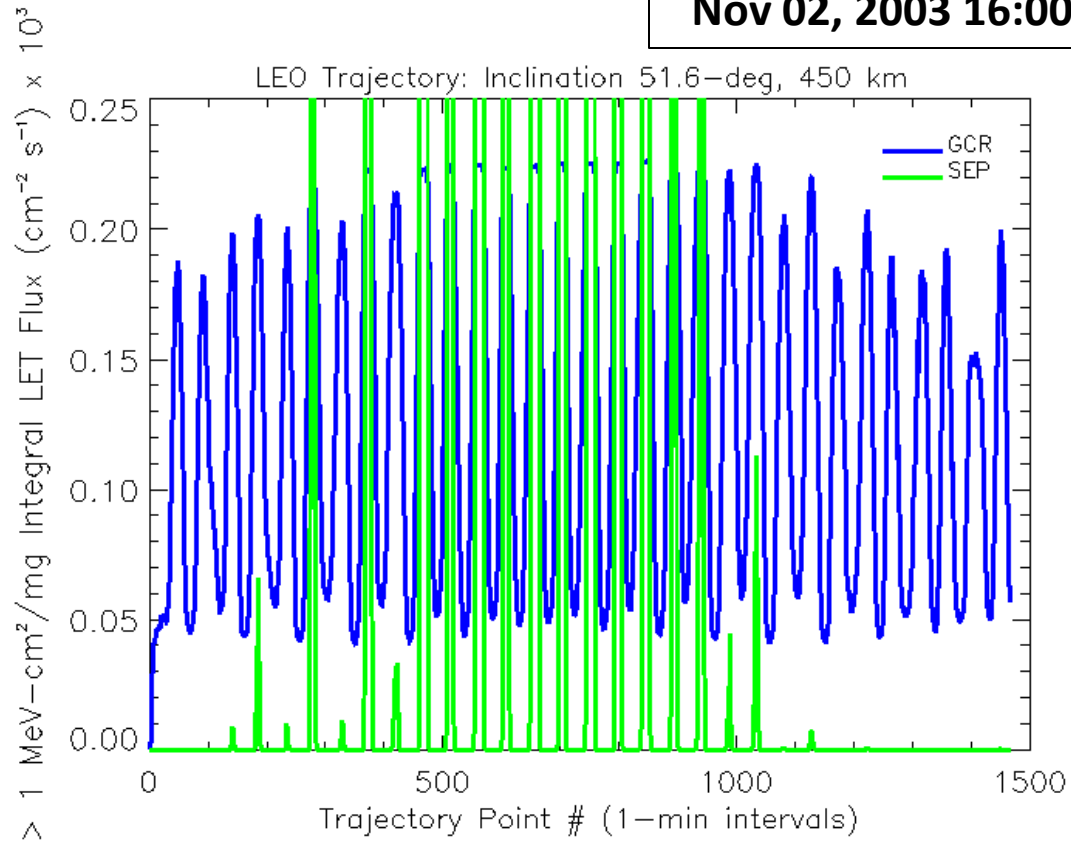
Take Away 2: Nearly all events SEP heavy-ions increase effective dose by factor 2-3 at 2 g/cm² (EVA)



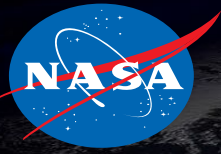
NAIRAS LEO LET: Halloween 2003 SEP Event

Differential and Integral LET Quantities

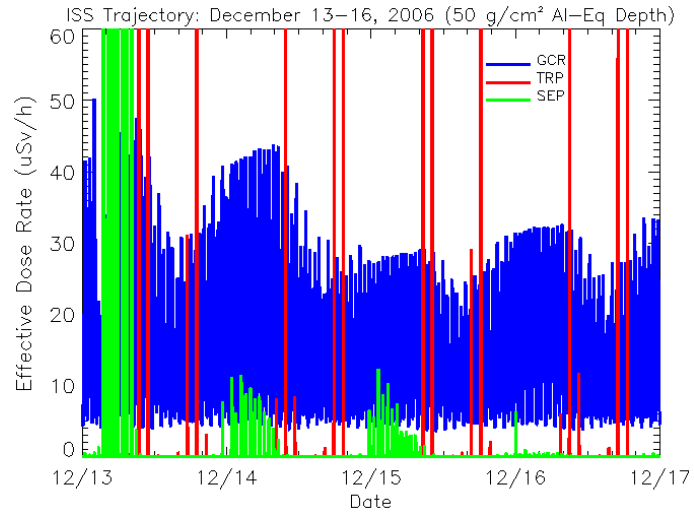
Nov 02, 2003 16:00 UT - Nov 03, 2003 16:00 UT



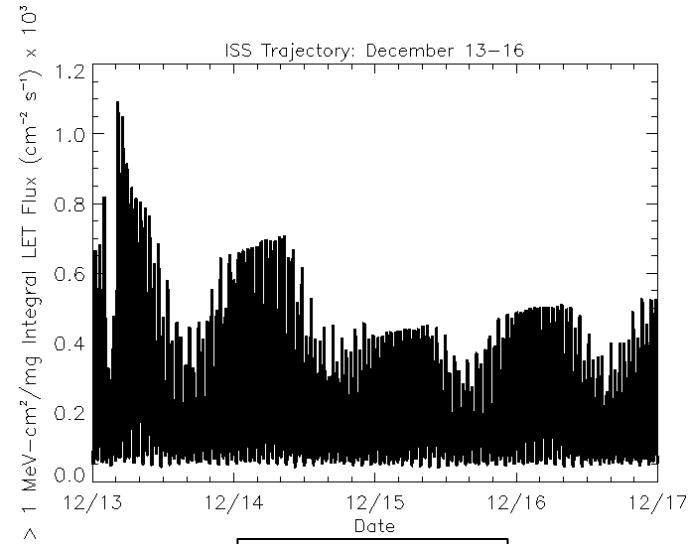
Al Shielding: 4 g/cm²



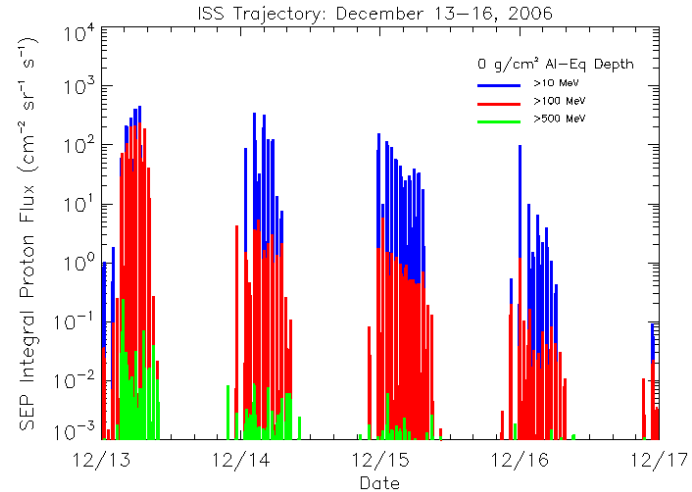
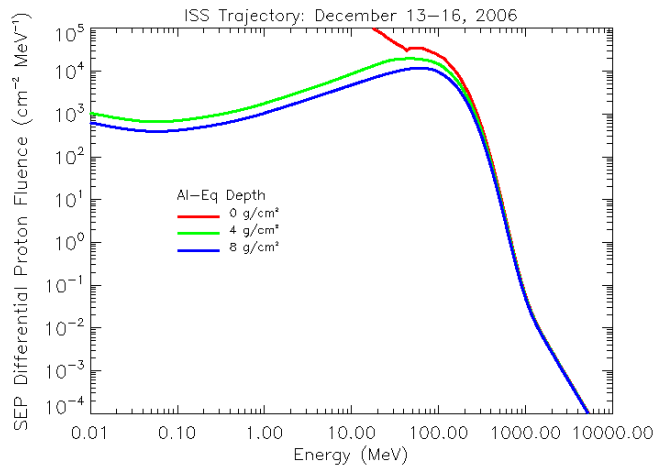
Dec 2006 SEP Events: ISS Radiation

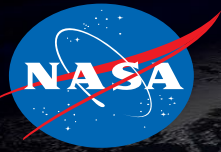


Al Shielding: 50 g/cm²

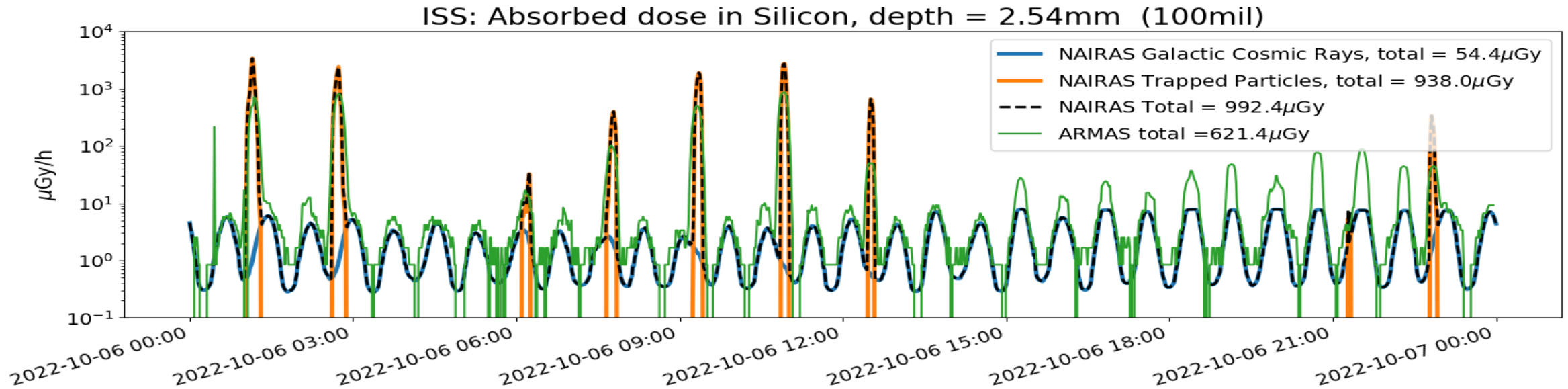


Al Shielding: 4 g/cm²

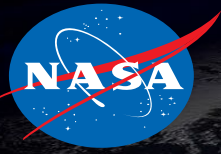




NAIRAS/ARMAS ISS Comparison (Oct 6, 2022)



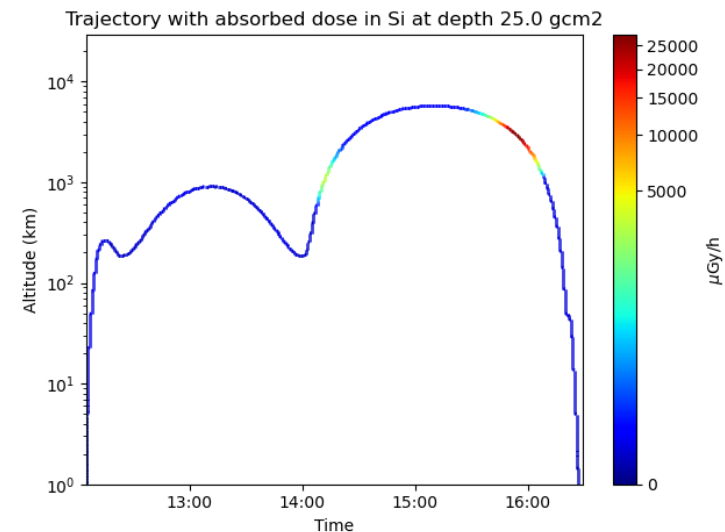
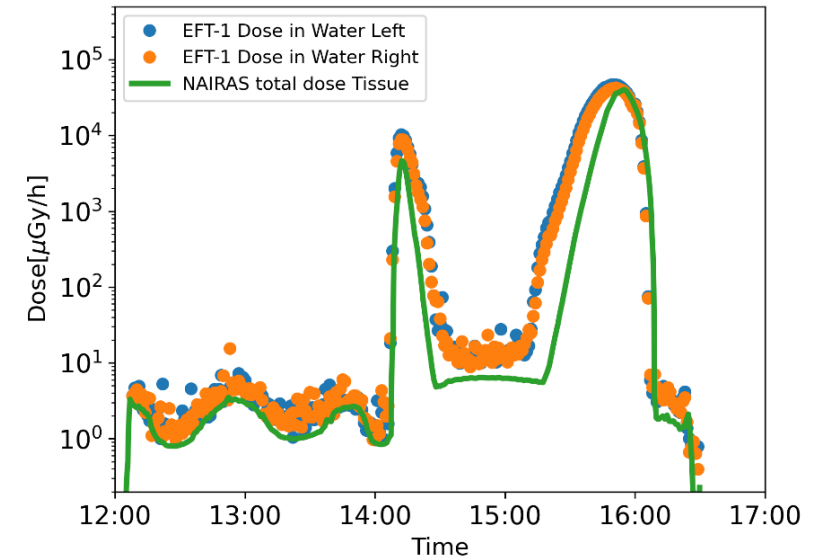
- NAIAS underestimates ARMAS within 30% for GCR, except sometimes at high-latitude ...
- ... NAIAS underestimation of ARMAS at high-latitude likely due to outer-belt electrons
- NAIAS overestimate ARMAS in SAA by factor 2
- NAIAS overestimate ARMAS accumulated daily dose by 60%, which is consistent with the other 208 days of ARMAS data on ISS

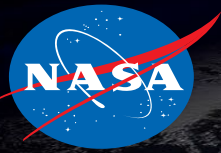


NAIRAS/BIRD Comparison on NASA EFT-1 Flight

- **NASA Orion Exploration Flight Test-1 (EFT-1)**
 - Unmanned flight of NASA Orion Multi-Purpose Crew Vehicle (MPCV)
 - Orbital inclination: 28.6 degree
- **Battery-operated Independent Radiation Detector (BIRD)**
 - Two BIRD active semiconductor detectors (called Left/Right): Timepix technology
 - Data analysis algorithm converts dose in silicon to dose in water (proxy for tissue)
- **NAIRAS/BIRD Comparison**
 - NAIRAS underestimates BIRD by 60% in GCR region (before 14 UT) and TRP region (later than 14 UT)
 - BIRD overestimates total flight dose of other onboard dosimeter systems by 20%.
 - Considering BIRD biased by 20%, NAIRAS underestimates BIRD by 40%
 - NAIRAS uncertainty for GCR known to be within 30%

NAIRAS computation for EFT-1 (weighted shielding)
Launched on 2014-12-05

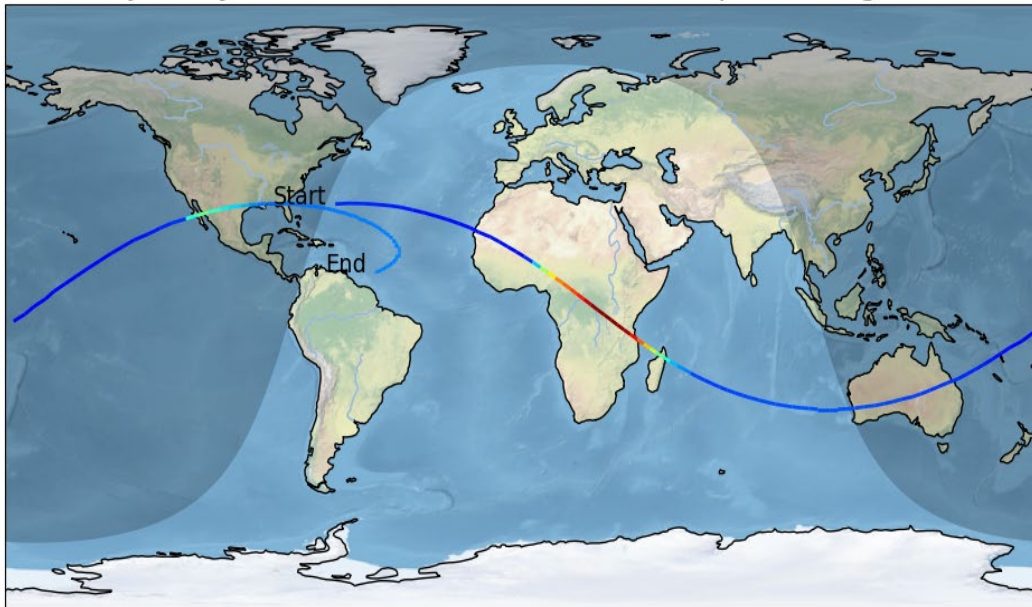




NAIRAS Dose: NASA Artemis-1 Mission

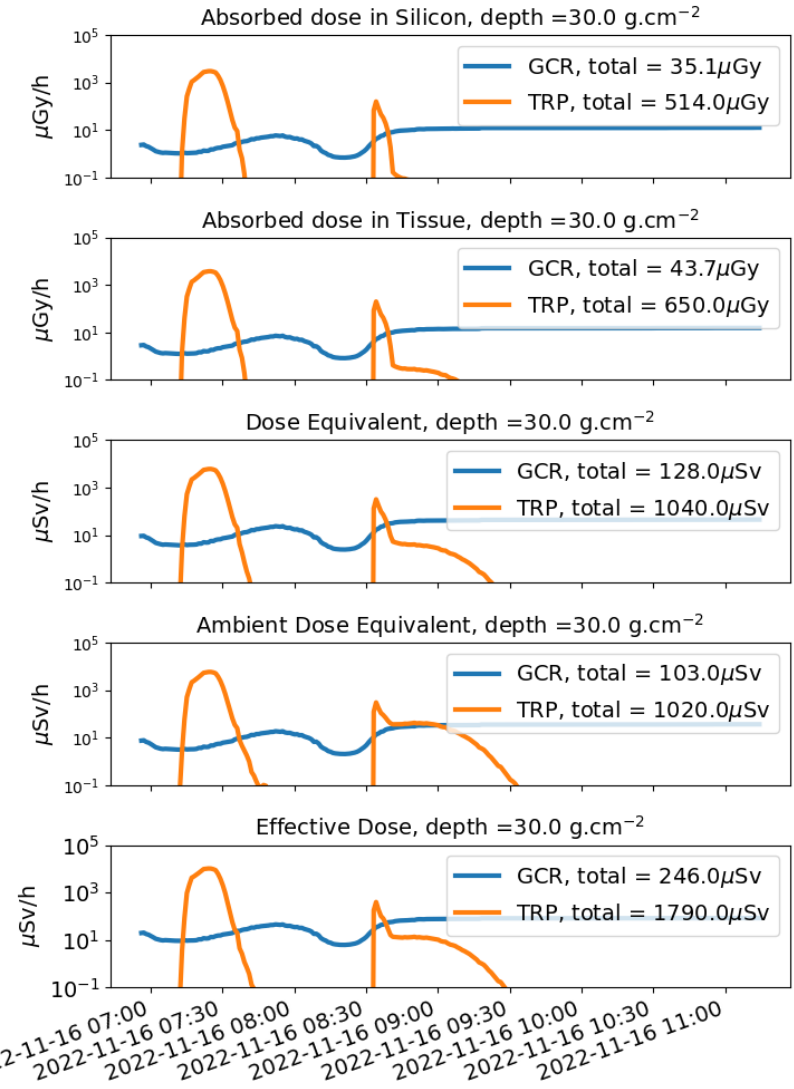
November 16, 2022

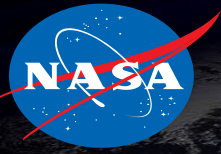
Trajectory with absorbed dose in Si at depth 30.0 g.cm^{-2}



NAIRAS Free-Space Dose Rates (30 g/cm^2)

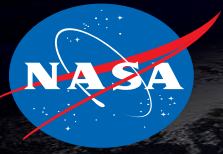
- Absorbed dose in silicon: 12-13 $\mu\text{Gy/h}$
- Effective dose: 80 $\mu\text{Sv/h}$



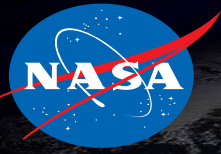


Summary and Conclusions

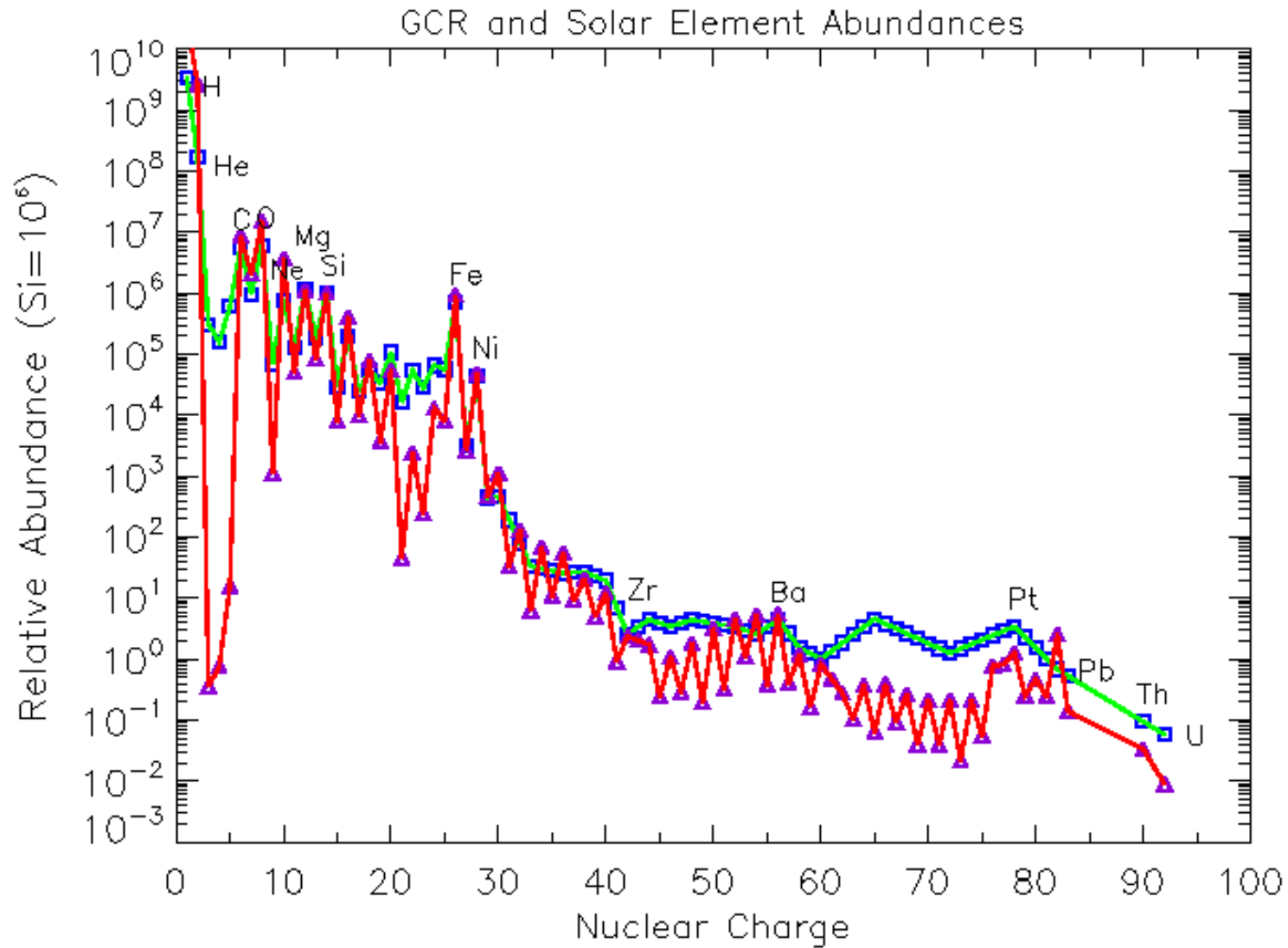
- **New NAIRAS RoR Capability (publicly available since Feb 2023)**
 - Users can run the model for customized scenarios and perform scientific and engineering analysis of the atmospheric and space radiation environments
 - **Global dosimetric run option:** context and situational awareness
 - **Flight trajectory run option:** detailed human flight radiation exposure characterization, detailed comparisons with onboard dosimeters, provide inputs to radiation effects models to assess SEE in aircraft and spacecraft flight electronics
 - **Usage Metrics:** 392 user jobs submitted so far in 2023
- **NAIRAS agrees with measurements to within 30% from 0-40 km**
- **NAIRAS comparisons with measurements in the space environment are encouraging (generally less than 60%)**
 - ISS low-Earth orbit (LEO)
 - NASA EFT-1 medium-Earth orbit (MEO)
 - NASA Artemis-1 cislunar orbit
- **Next Steps**
 - Add outer-belt electrons (AE8 with solar modulation)
 - Comprehensive validation studies: (1) Publish comparisons with 1000+ ARMAS aircraft flights, (2) Publish comparisons with RaD-X campaign measurements, and (3) 208 days of ARMAS-ISS data



Backup Slides



SEP Heavy-Ion Model



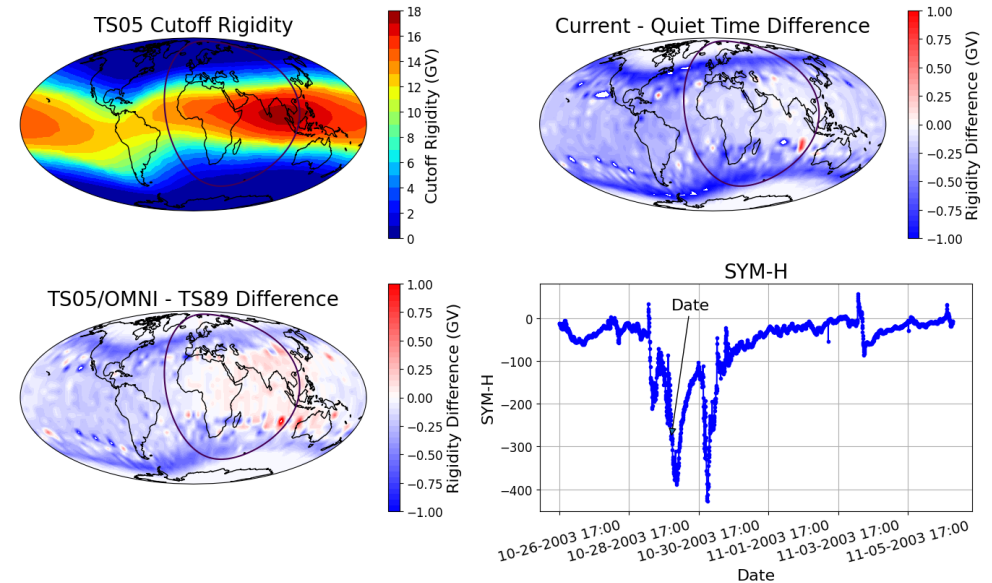


Geomagnetic Cutoff Rigidity Model

- Based on CISM-Dartmouth model with TS05 magnetospheric B-field (*Kress et al., 2010*)
- Added multiple magnetospheric B-field selection capability
 - TS05 → parameterized by solar wind quantities, interplanetary magnetic field (IMF), SYM-H/Dst, and other derivative solar wind quantities
 - T89 → parameterized by the planetary K-index (Kp)
- The TS05 better represents magnetospheric responses to interplanetary disturbances
 - but real-time solar wind parameters available from ACE/DSCOVR 1995+
- Benefits of T89 option
 - NAIRAS can simulate any historical solar-geomagnetic storm event
 - Extend/enhance validation capabilities
 - Provide initial step in forecasting cutoff via Kp-parameter forecast

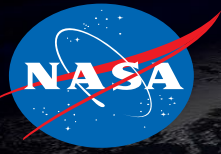
Halloween 2003 Geomagnetic Storm

Date: 10/29/2003 2100 UT



Top Right: Largest suppression of cutoff (~ 1 GV) (open-closed field boundary) occurs in dusk sector due to max build-up of partial ring current in TS05 (IMF B_z dependent)

Bottom Left: T89 doesn't well represent max cutoff suppression and cutoff in dusk sector



GCR Model (H-BON10) Solar Modulation Potential

