TOOLS USED IN SPACE RADIATION OPERATIONS

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BIRA-IASB Visiting Scientist Program

April 24 – May 7, 2023

ABSTRACT

The goal of NASA's Radiation Health Program is to achieve human exploration and development of space without exceeding acceptable risk from exposure to ionizing radiation. The Space Radiation Analysis Group (SRAG) at NASA Johnson Space Center carries out this mission by following the philosophy of ALARA – As Low as Reasonably Achievable. SRAG utilizes a variety of tools to maintain awareness of space weather and to monitor the space radiation environment, both internal and external to the vehicle. SRAG develops and manages a wide variety of detectors that are located on the exterior and throughout the interior of the International Space Station and worn by crew. During Artemis I, SRAG provided detectors distributed within Orion's interior and participated in the MARE experiment, which outfitted female phantoms with thousands of thermoluminescence detectors (TLD) and other dosimeters to better constrain the total dose accrued inside the human during a mission to the Moon. Motivated by the Artemis Exploration Class missions, SRAG and collaborators are developing forecasting capabilities for solar energetic particle (SEP) events and their biological impacts to crew. Tools that have come out of this work include the Acute Radiation Risk Tool (ARRT) and the SEP Scoreboards. This presentation will give an overview of the tools used in SRAG ops and currently under development to support our next steps in human space exploration.

SPACE RADIATION ANALYSIS GROUP (SRAG)

Mission: The protection of humans from impacts of space radiation exposure
Philosophy: As Low As Reasonably Achievable (ALARA) to *accomplish mission goals while minimizing astronaut radiation dose*

- Establish human radiation exposure standards (career/acute)
- Support the Flight Control Team in Mission Control by monitoring the space weather and radiation environment and evaluating impact to crew
- Build and monitor vehicle-mounted and personal dosimeters
- Model the radiation environment in free space and within the vehicle
- Model and assess the biological risks due to radiation
- Develop flight rules that define requirements regarding radiation sources and actions in response to radiation events

Mission Control

Flight Director
Leads FCT

CAPCOM
Communicates with crew

CRONUS
Manages onboard data systems

ADCO
Manages spacecraft orientation

VVO
Manages visiting vehicles

PAO
Interfaces with media

ETHOS
Monitors air quality and temperature

GC
Manages Mission Control hardware

SPARTAN
Manages spacecraft power system

EVA
Manages spacesuit and spacewalk tasks

ROBO
Manages robotic arm

OSO
Manages maintenance systems and logistics

TOPO
Manages spacecraft trajectory

Surgeon
Monitors crew health

PLUTO
Manages portable electronics

ISO
Tracks spacecraft inventory

ISE
Liaison between spacecraft and visiting vehicles

BME
Monitors health-related systems

RIO
Interfaces with international partners

OPSPLAN
Coordinates crew schedule

Radiation
Monitors space radiation environment

"BIG THREE" QUESTIONS ABOUT SEPS TO SRAG OPERATORS

What the Flight Control Team in Mission Control asks	What they mean
1 Will an event occur?	1 Do we need to worry?
2 How intense will the event be?	2 Will we need to stop mission activities so crew can shelter?
3 When will the event end?	3 When can we resume mission activities? When can we stop worrying?

HOW DO WE ADDRESS THESE QUESTIONS?

1. Monitoring/Nowcasting (actions taken if environment surpasses specific limits)
   - SRAG Operators constantly monitoring real time data streams
   - NOAA SWPC calls when a space weather event occurs
   - NASA Moon to Mars Space Weather Analysis Office (M2M) briefings and constant communication
2. Forecasting (no action taken in response to a forecast)
   - SRAG operator intuition
   - NOAA SWPC daily briefings with forecasts for the next 24 hours
   - Acute Radiation Risk Tool (ARRT) to estimate possible biological impacts
   - SEP Scoreboard (with model runs driven by M2M inputs)

MONITORING

International Space Station and Artemis I

Operational Thresholds

Solar Particle Event (SPE)	Energetic Solar Particle Event (ESPE)	Shelter
GOES >10 MeV proton intensity exceeding 10 pfu	GOES >100 MeV proton intensity exceeding 1 pfu	GOES >100 MeV proton intensity exceeding 100 pfu
• Important during EVAs (spacewalks) • Protons start to penetrate spacesuit shielding at these energies	• Important during IVAs (inside the spacecraft) • Protons start to penetrate spacecraft shielding at these energies	• Important for mitigating crew's radiation exposure • Radiation dose becomes significant enough at this level to warrant stopping mission activities

Shelter threshold will be lower for Artemis missions to provide time for crew to build a shelter

SOLAR ENERGETIC PARTICLES AT THE ISS

- Operations on the International Space Station take place in Low Earth Orbit (LEO) inside of the Earth's protective magnetosphere, which reduces the time that the ISS is impacted by SEP events
- SRAG operators support from 8:30am – 12pm CT each weekday, during EVAs, and during a contingency

ISS Orbits only encounter SEPs near the geomagnetic poles during 5-10 minute passes (purple ovals).

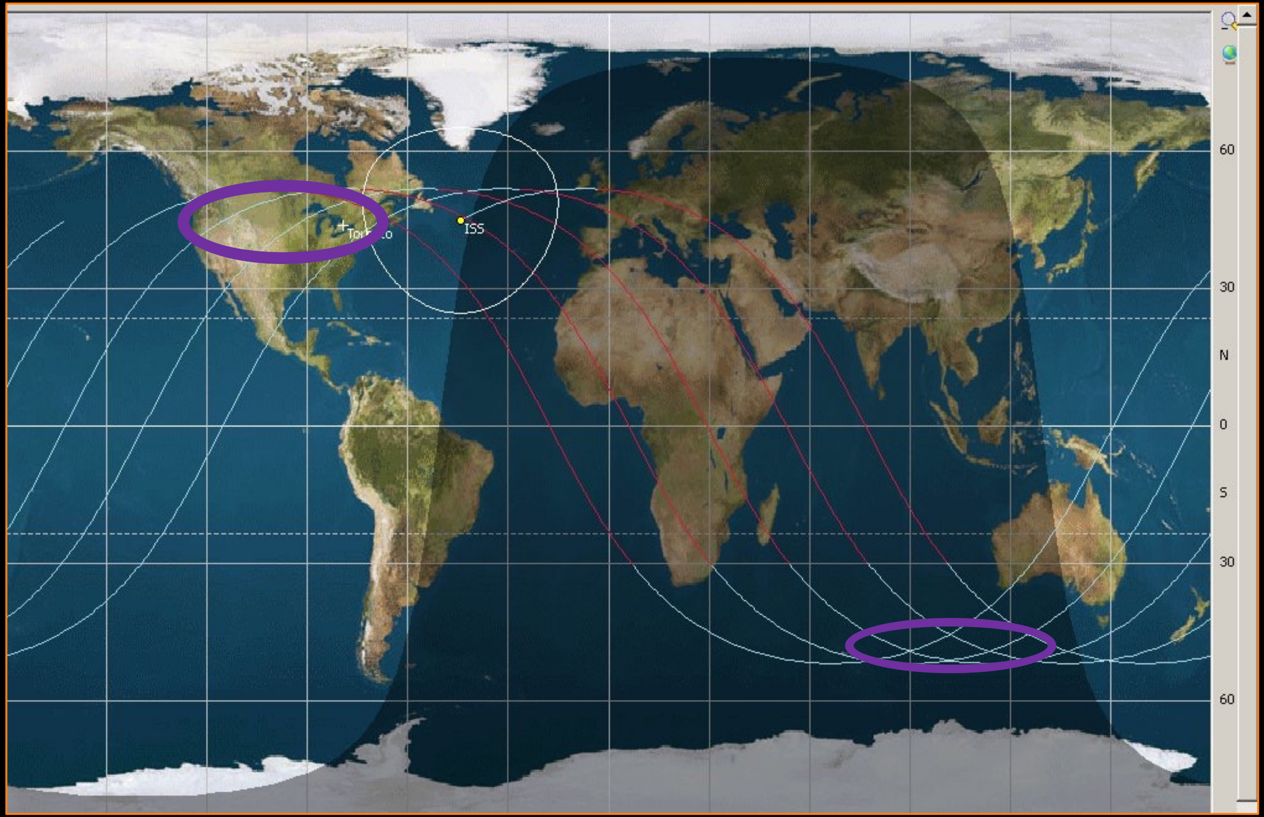
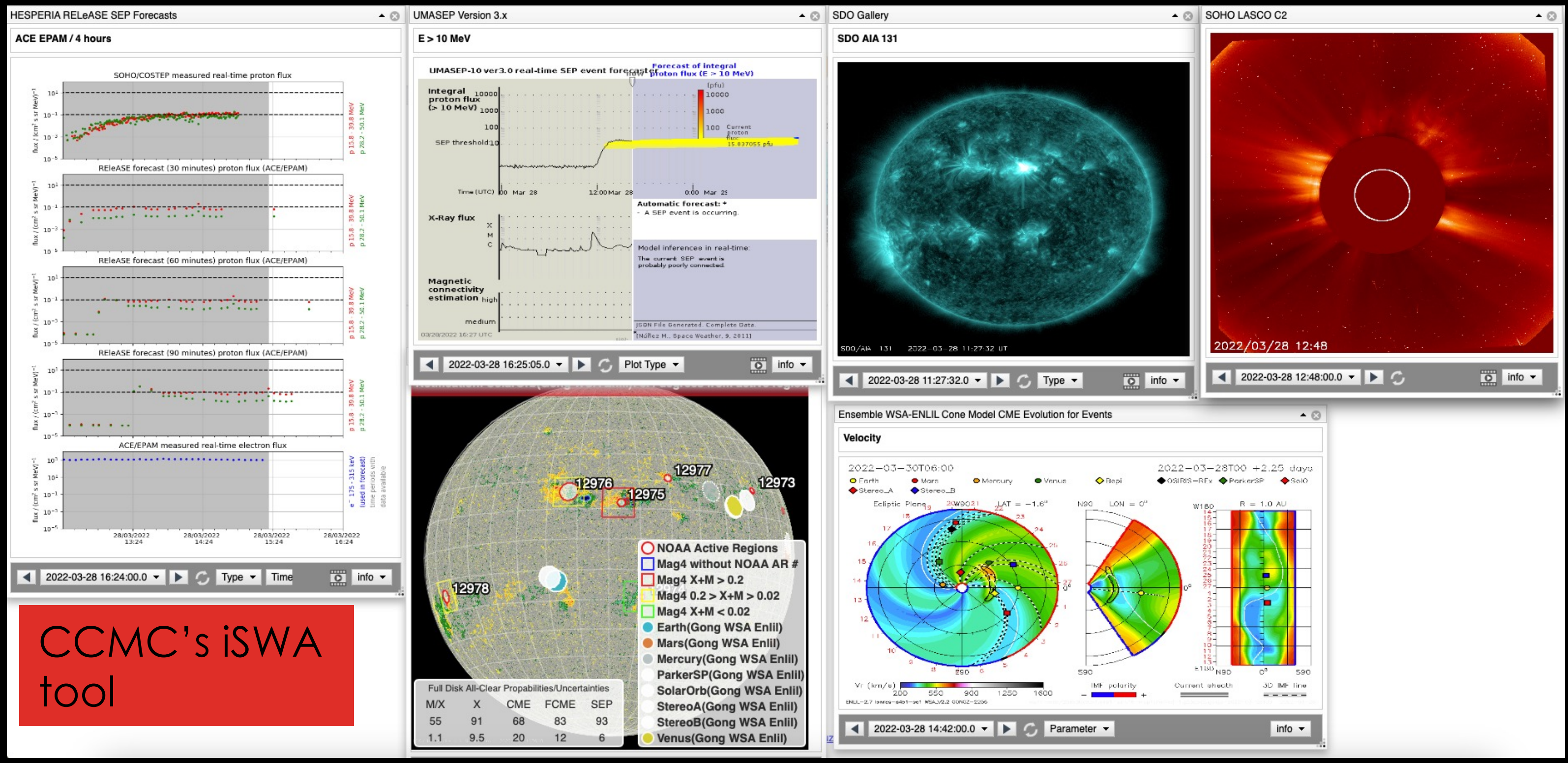


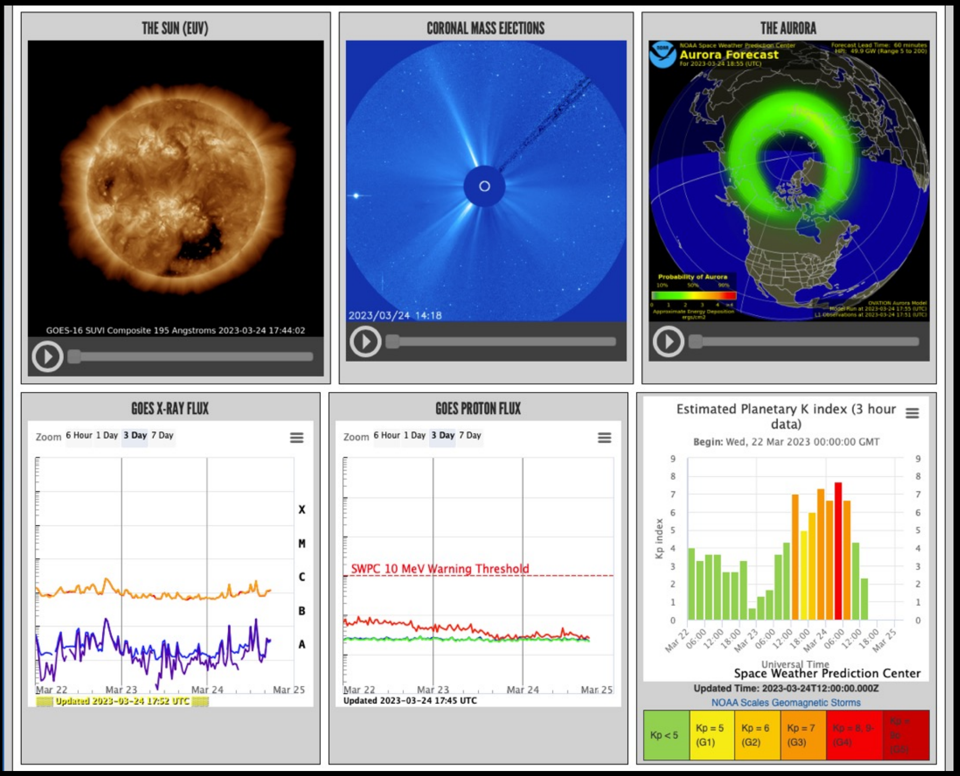
Image credit without ovals: Wikipedia

CURRENT SPACE ENVIRONMENT

CCMC's iSWA Web Tool

NOAA SWPC's Operational Data





RADIATION ENVIRONMENT MONITORS

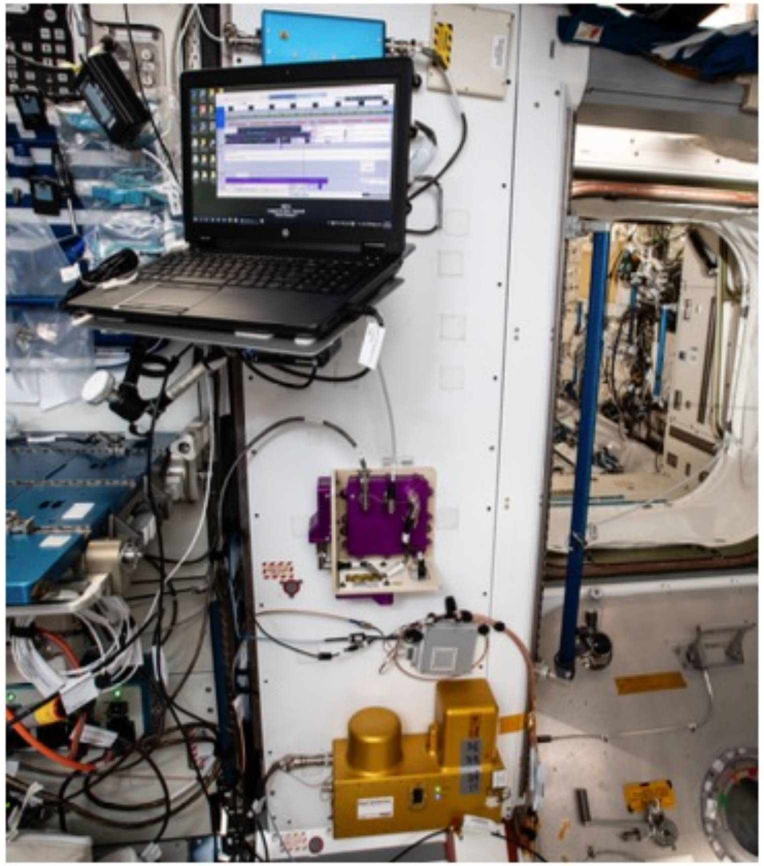


Figure 2: ISS HERA deployed with RAD in Node 2

Dosimeters are mounted throughout the ISS. They are sometimes moved to different modules to measure the radiation environment throughout the Space Station.

Image credit: https://wrmiss.org/workshops/twentyfourth/Stoffle.pdf

Crew Active Dosimeters (CAD) are worn by astronauts and show a continuous readout of the current dose rate and the cumulative dose for the mission duration.

Image credit: https://srag.jsc.nasa.gov/spaceradiation/how/how.cfm

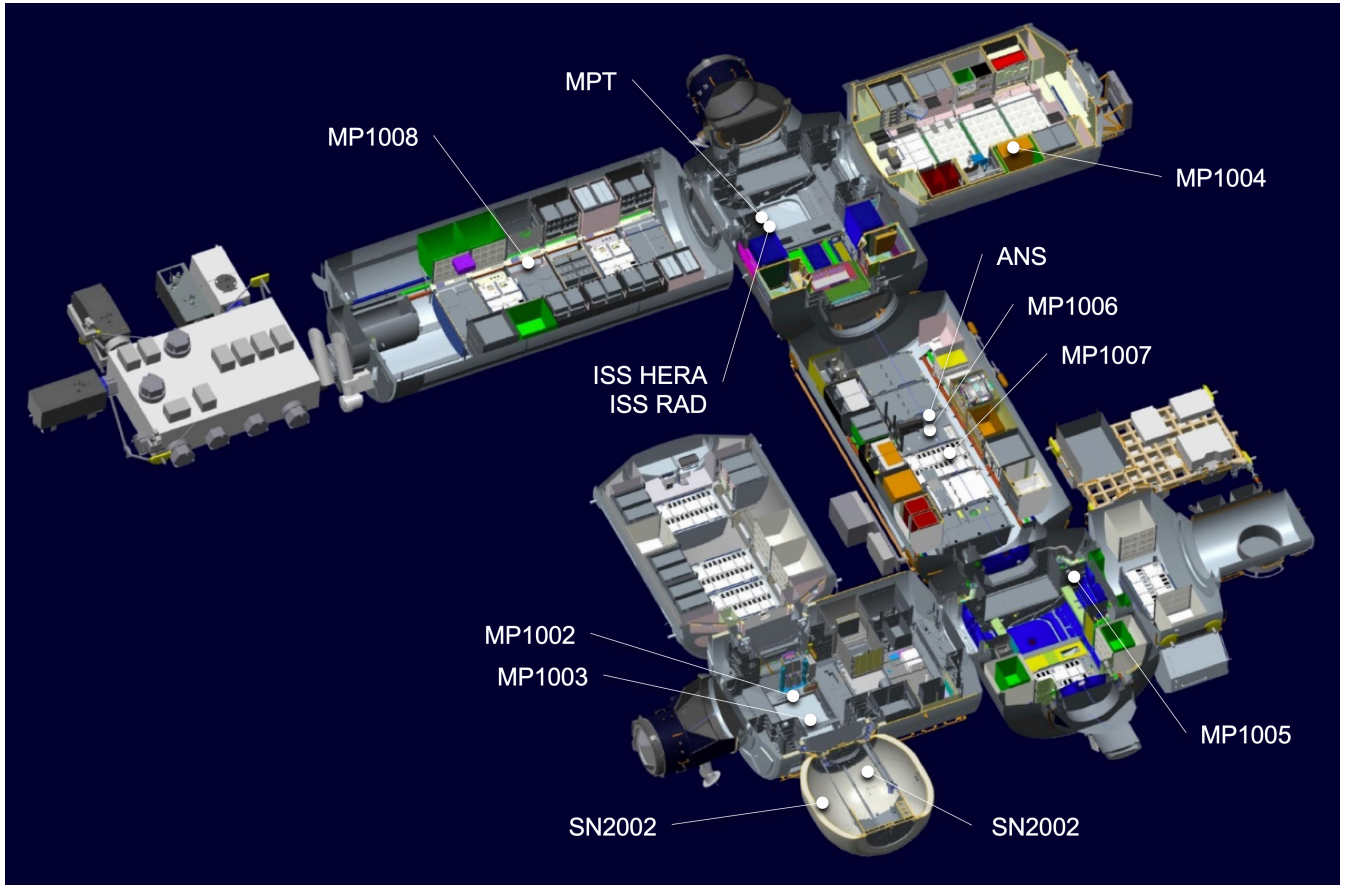
RADIATION ENVIRONMENT MONITORS (REM-2)

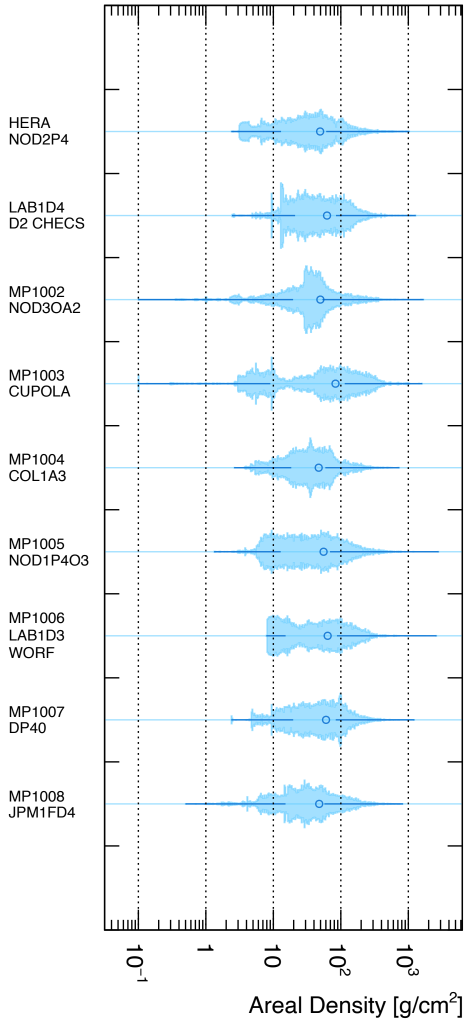
- Deployed on 7 SSCs throughout ISS
- Connected by USB
- Flight software begins data acquisition on bootup
- Launch GUI to view dose rate and current data frame (ion tracks)
- These active units replaced passive area monitors that could only be read post-mission on the ground
- Receive REM data 3x/day

Figure 3: Radiation Environment Monitor.

Image credit: https://wrmiss.org/workshops/twentythird/Zeitlin_S6.pdf

DETECTOR DEPLOY LOCATIONS





ISS hardware and shield distributions as of May 2019

Image credit: https://wrmiss.org/workshops/twentyfourth/Stoffle.pdf

HYBRID ELECTRONIC RADIATION ASSESSOR (HERA)

Exploration Mission monitoring hardware

- → Capable of 4 sensors per system
  - → Local sensor on Processing Unit
  - → Up to 3 remote Sensor Units
- → On-system processing and analysis
- → Active telemetry for crew displays and ground monitoring
- → Caution and Warning capability for crew/ground alerts

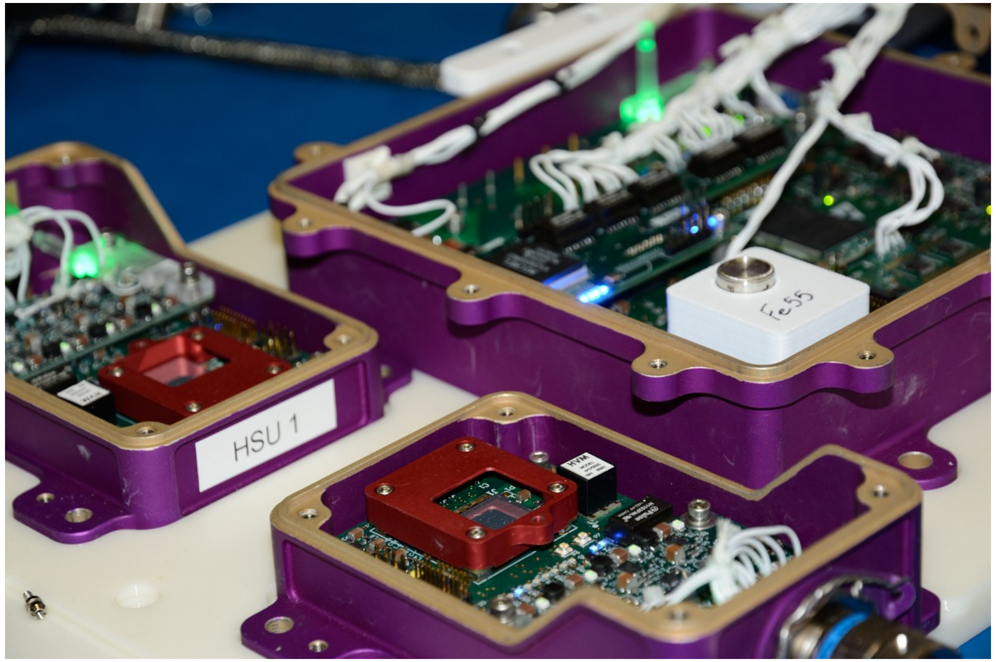
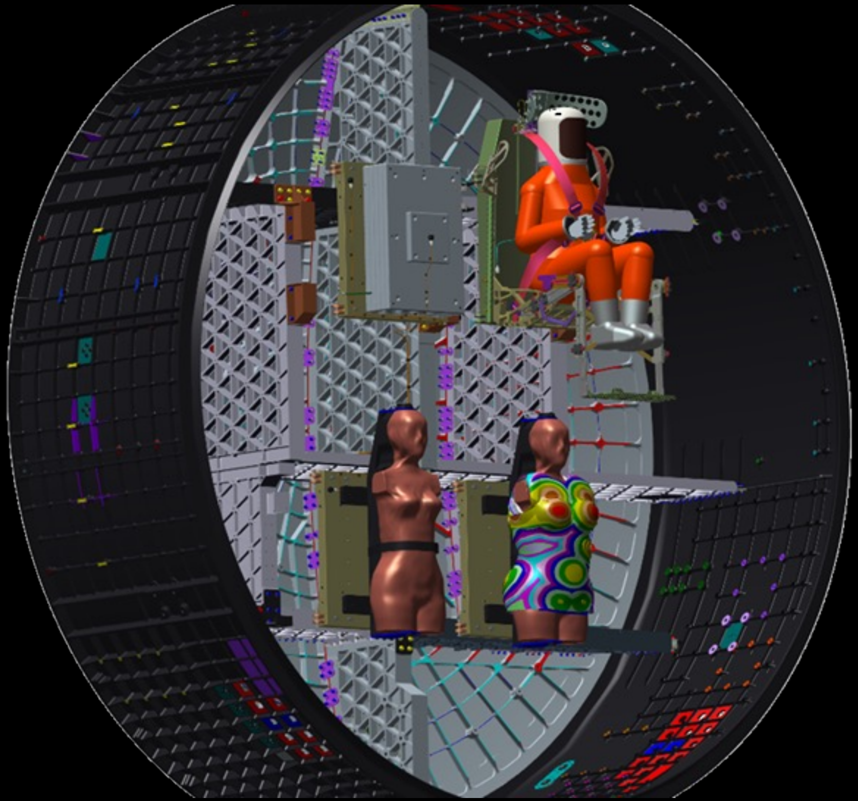


Image credit: https://wrmiss.org/workshops/twentyfourth/Stoffle.pdf

ARTEMIS I – DOSIMETRY EXPERIMENTS

- The uncrewed Artemis I mission was a test bed for our technologies
  - Dosimeters mounted throughout the vehicle (including HERA)
  - Extensive radiation measurements inside two female anthropomorphic phantom torsos (MARE)
  - A radiation-protection vest prototype

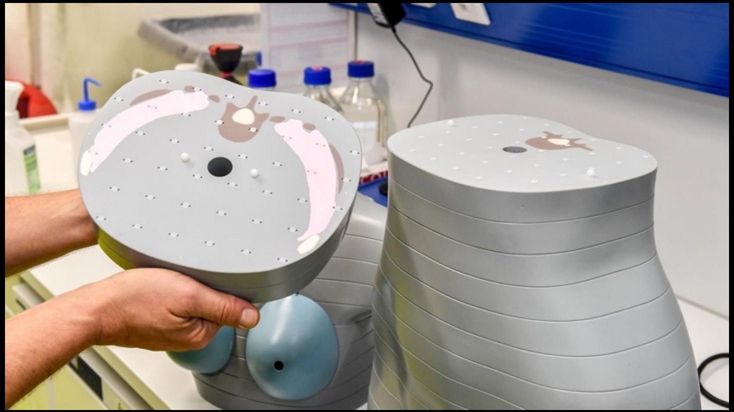


< Photo credit: https://www.dlr.de/content/en/galleries/mare-experiment.html

Photo credits:
https://www.nasa.gov/image-feature/orion-manikins-return-from-artemis-i-mission
https://www.dlr.de/content/en/galleries/mare-experiment.html

MARE (MATROSHKA ASTRORAD RADIATION EXPERIMENT)

- Two female manikins – Helga and Zohar – were equipped with radiation detectors
  - Composed of layers with simulated organs
  - Each layer was outfitted with dozens of tiny radiation detectors, partially contributed by SRAG
  - SRAG will be analyzing thousands of measurements to better understand organ dose and biological risk
- Zohar wore a radiation protection vest to assess any benefit
- Detectors were removed at Kennedy and the torsos returned to DLR for further analysis

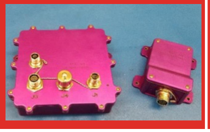
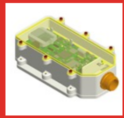
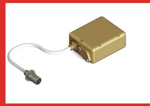




ARTEMIS I – SRAG CONSOLE OPS

- SRAG, SWPC, and M2M tested the operational strategies in place to forecast and mitigate SEP events
  - 24/7 mission support
  - 24-hour office-to-office communications with NOAA SWPC and NASA M2M
  - Monitor and test the Acute Radiation Risk Tool (ARRT)
  - Monitor the new SEP Scoreboards

INSTRUMENT SUITE FOR ARTEMIS EXPLORATION MISSIONS

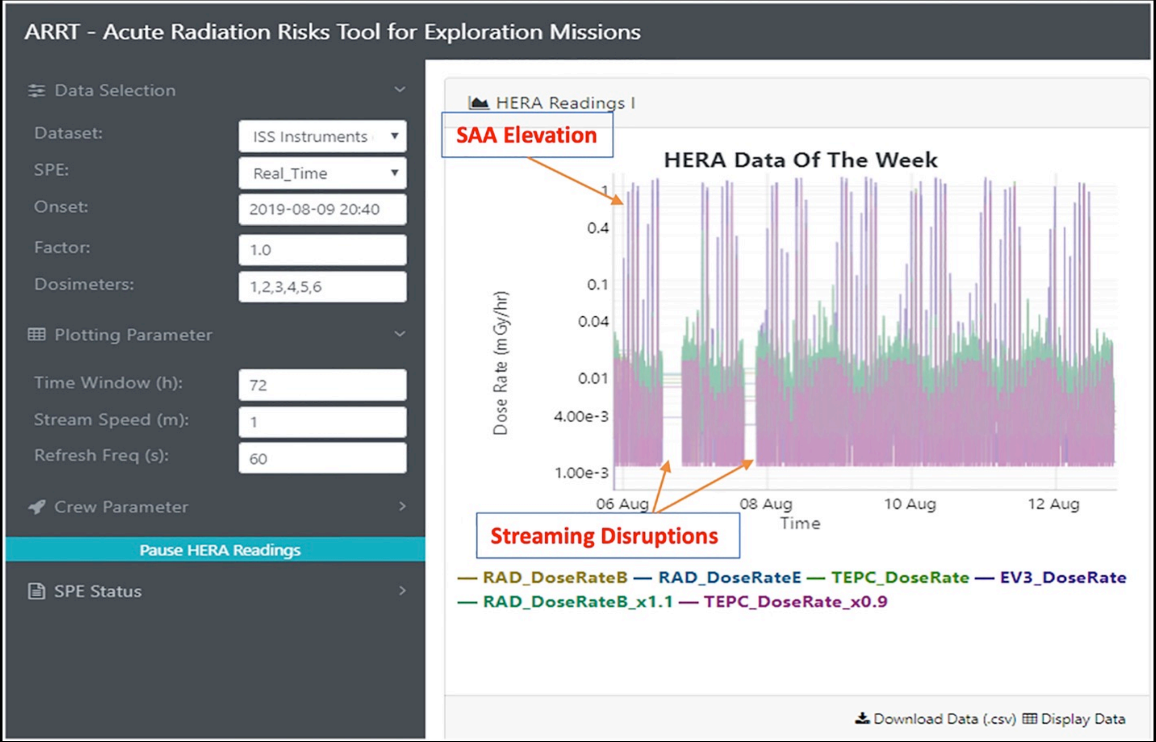
Function	HERA 	CAD 	ARES 	ARD 	Neutron Detector*
Type of measurement/ what is measured	• Charged Particle Detector • Area monitoring of flux/species and dose	• Crew member dose rate/total dose	• Charged Particle Detector • Area monitoring of flux/species and dose	• Crew member dose rate/total dose	• Neutron flux
Proposed mission	• Orion	• Personal dosimeter worn by crew at all times (except for EVA, because of battery & lack of vacuum capability) • Manifested by Orion	• Gateway, Lander • (HERA heritage hw)	• EVA, integrated with xEMU	• Vehicles with crew, including HALO, HLS, Orion
Use	• Real time monitoring • On board alerting	• Real-time dose at crew • Post mission crew risk assessment, re-flight determination	• Real time monitoring • On board alerting	• Real time dose at crew • On board alerting • Post mission crew risk assessment	• Post mission Crew risk modeling, re-flight determination
Mass	• ~3kg	• 35g	• <2kg	• 430g	• 4.25 kg

FORECASTING

Developing new tools and technologies

ALGORITHM OF ACUTE RADIATION RISKS TOOL (ARRT)

- Forecasting of biological effects
- ARRT Functionality:
  - Monitor radiation environment inside the spacecraft via the HERA detectors
  - If an SEP occurs, use modeled results from a precomputed database of GLE/SEP to assess estimated total dose in humans
  - Report possible biological impacts
- During Artemis I, ARRT served as a dashboard to monitor the HERA readings.
- No SEP event occurred during the mission, but ARRT was triggered by a pass through the radiation belts, demonstrating its forecasting functionality.



ARRT is currently reading dosimeters onboard the ISS. During Artemis I, ARRT used HERA detectors onboard Orion as a test for crewed Artemis missions.

Hu, S., Monadjemi, S., Barzilla, J. E., Semones, E., ARRT Development for the Upcoming Human Exploration Missions, Space Weather, Volume 18, Issue 12, article id. e2020SW002586, December 2020, DOI: 10.1029/2020SW002586

Reference:
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020SW002586

PRECOMPUTED DOSE CALCULATION PROCEDURE

Prepared spectral fits for 65 historical GLE/SEP events for each time step during the event

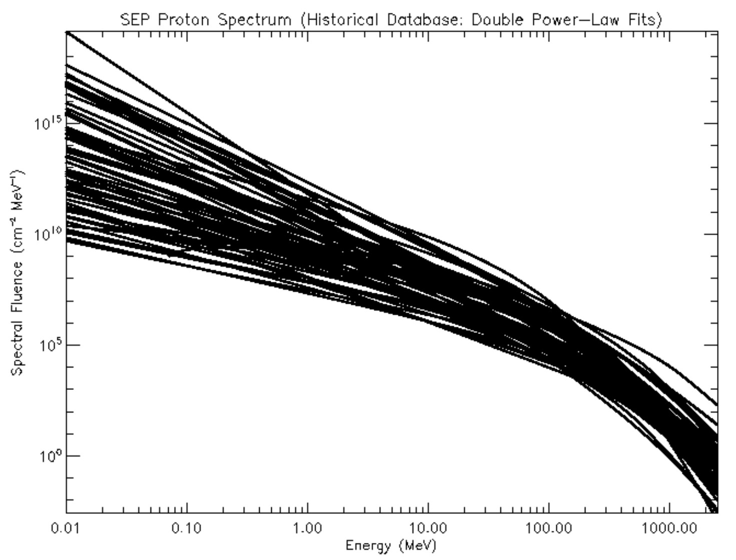
Each event transported through Orion shielding with HZETRN to location of :

- HERA detectors
- Blood forming organs (BFO) inside male/female seated/sheltered crew

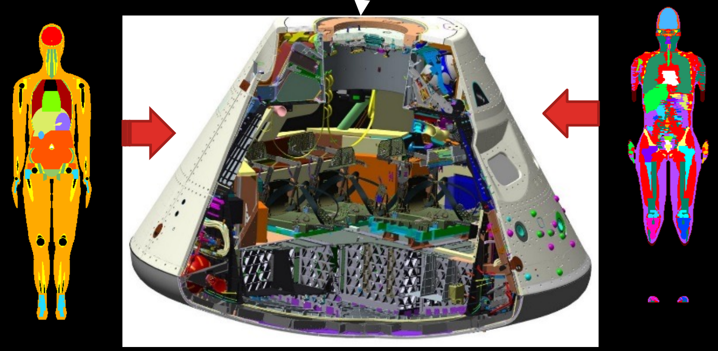
Dose calculated at each location of interest:

- HERA detectors: Si-dose (Gy)
- BFO dose (Gy-eq)
  (average RBE = 1.5 for protons)

SEP Spectra: Historical Database



Transport



Mertens et al. 2018

ARRT REAL TIME OPERATIONS

- SEP Organ Dose Model (Nowcasting)
  - Generate a database of silicon doses at HERA locations and organ doses at crew locations, for 65 historical events with known total spectra.
  - Find the event in database that best matches the spectral shape of the real-time vehicle radiation environment.
  - Find the optimal scaling parameters between HERA measurements and the precomputed dose in silicon at HERA locations for the selected event.
  - Apply the scaling parameters to the database of organ doses to obtain real-time organ doses at the normal and storm shelter crew locations.
- Acute Biological Response Model
  - Input: BFO dose rates from the SEP organ dose model
  - Based on codes developed for ARRBOD and HemoDose
  - Includes neurovascular models (nausea and vomiting, fatigue and weakness), hematopoietic models (lymphocyte, granulocyte, leukocyte, and platelets), and a performance degradation algorithm

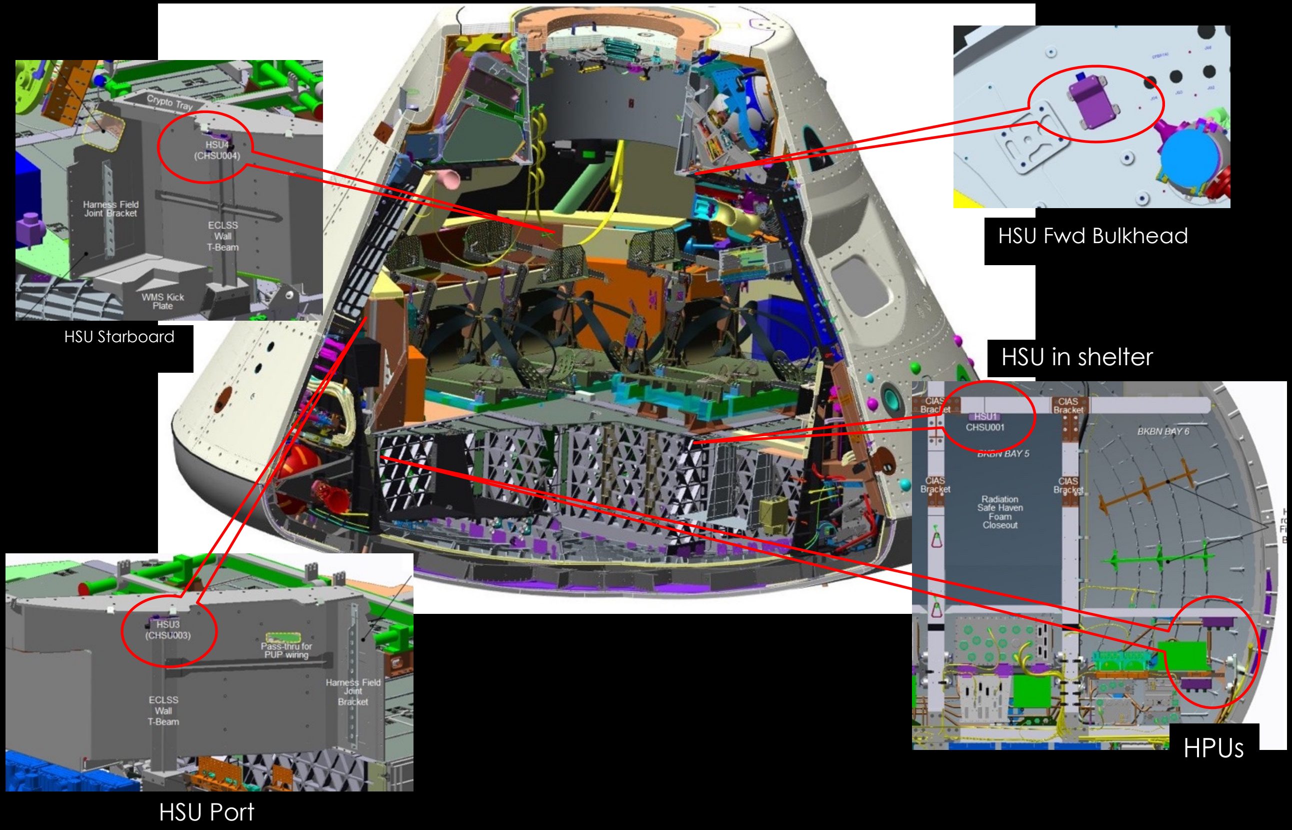
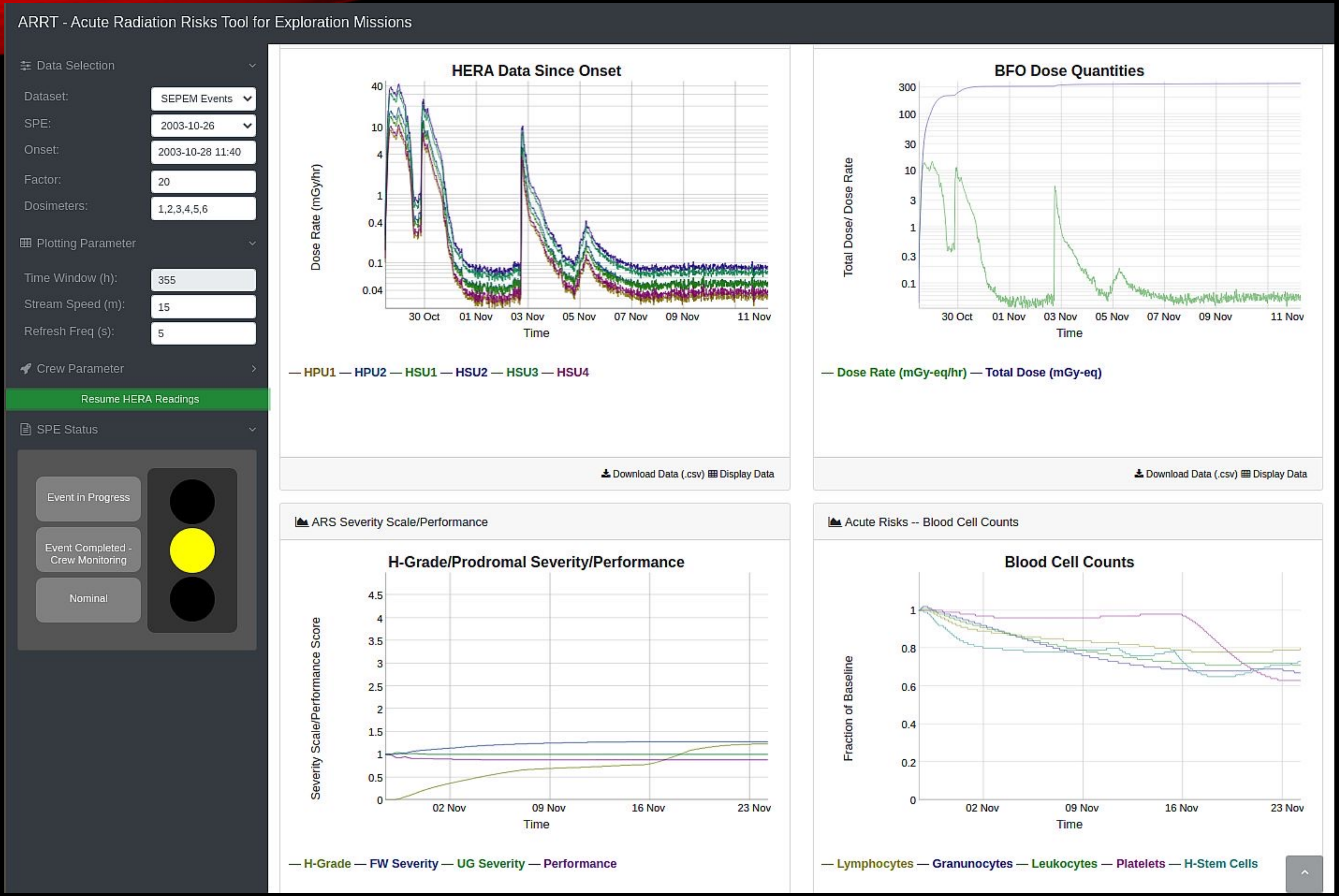


Image credit: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020SW002586

ARRT OUTPUT



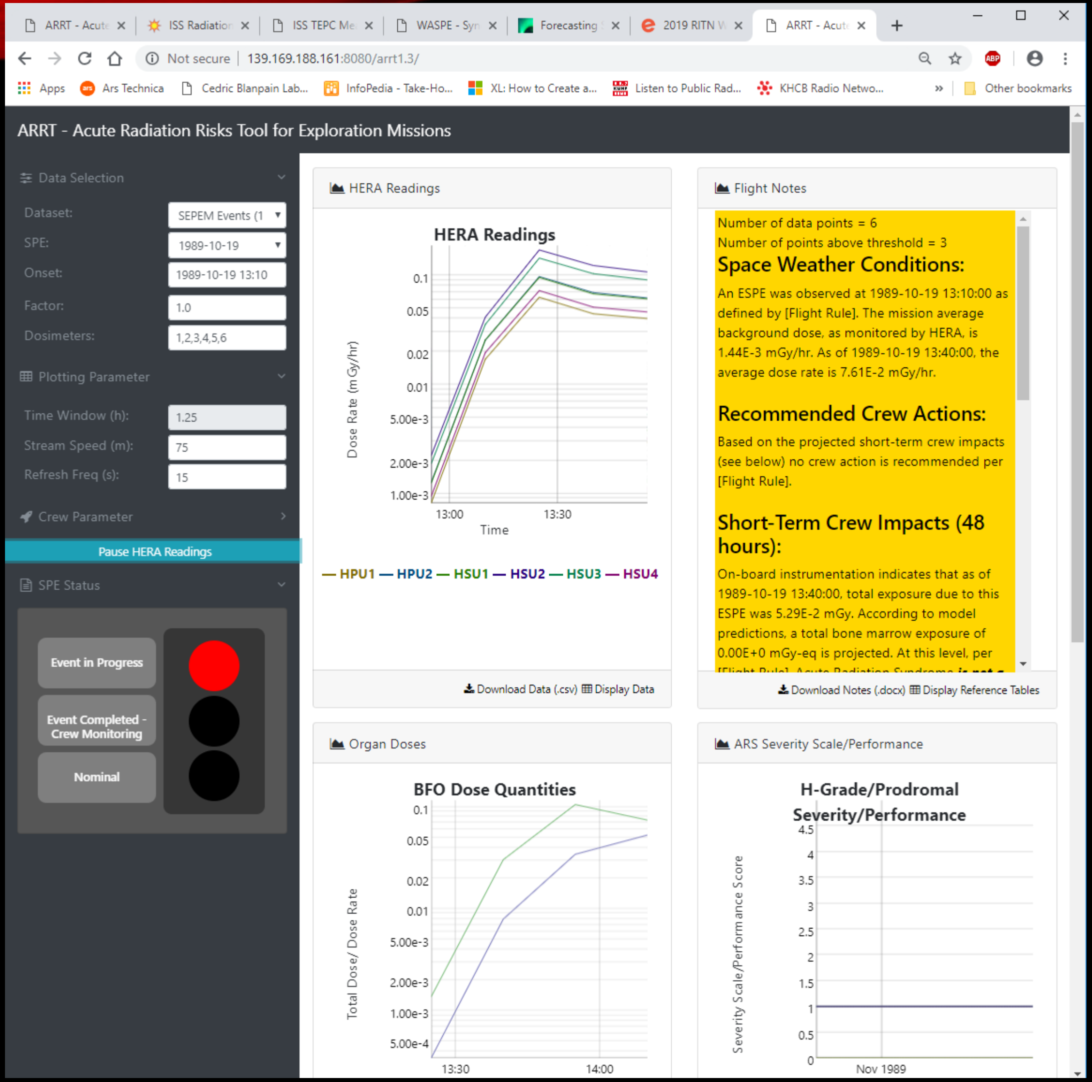
ARRT reads HERA measurements during an SEP event, matches the measurements to a historical database of SEPs, estimates total astronaut organ dose, and predicts the potential biological outcomes as a result of the dose absorbed during the SEP event.

Example response to the October 1989 series of events shown here.

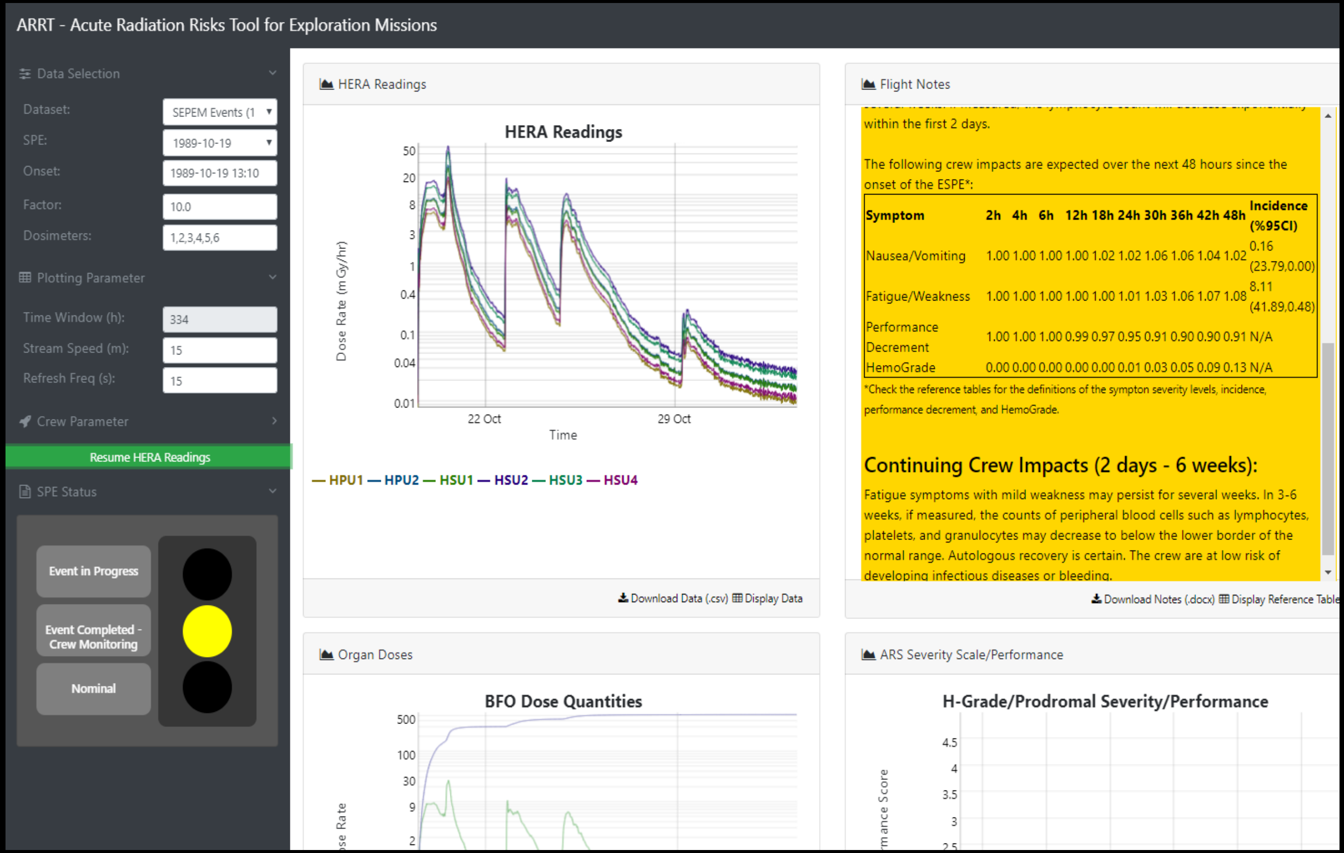
Reference: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020SW002586

ARRT OUTPUT

Oct 1989 Events from SEPEM v2.0 Data Set



Oct 1989 Events x 10 to see acute effects



HERA readings, flight note inputs, results of BFO dose projections, H-grade/ Prodromal Severity/ Performance, Blood cell count projections can be downloaded and viewed online.

After the end of an event, the first 48 hours' prodromal symptom severity and incidence as well as performance decrement are available. ARRT projects anticipated effects over the next 6 weeks.

Reference:
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020SW002586

SPACE WEATHER FORECASTING AND SEP MODELING

- **With Exploration class missions in free space, improvements to current forecasting capabilities become vital**
- NOAA SWPC provides NASA with space weather forecasting services, including the primary space weather forecasts for Artemis
- Additional operational tools and support will be utilized for fast response to Mission Control
  - The Moon to Mars Space Weather Analysis Office (M2M) at NASA Goddard supports the real time implementation and analysis of new space weather models serving as an operational testbed
  - The Integrated Solar Energetic Proton Event Alert/Warning System (ISEP) project, a collaborative effort between SRAG, M2M, and the Community Coordinated Modeling Center (CCMC) develops the SEP Scoreboards for SRAG's needs

THE ISEP PROJECT

Collaborators: SRAG, CCMC, M2M

CCMC's Mission: To enable, support, and perform research for next generation space science and operational space weather models through an interagency partnership.

M2M's Mission: To support SRAG by providing novel capabilities to characterize the space radiation environment. To work as the proving grounds and testbed for the capabilities that will eventually transition to operational agencies. Support NASA robotic missions with space weather notifications and anomaly assessments.

Purpose:

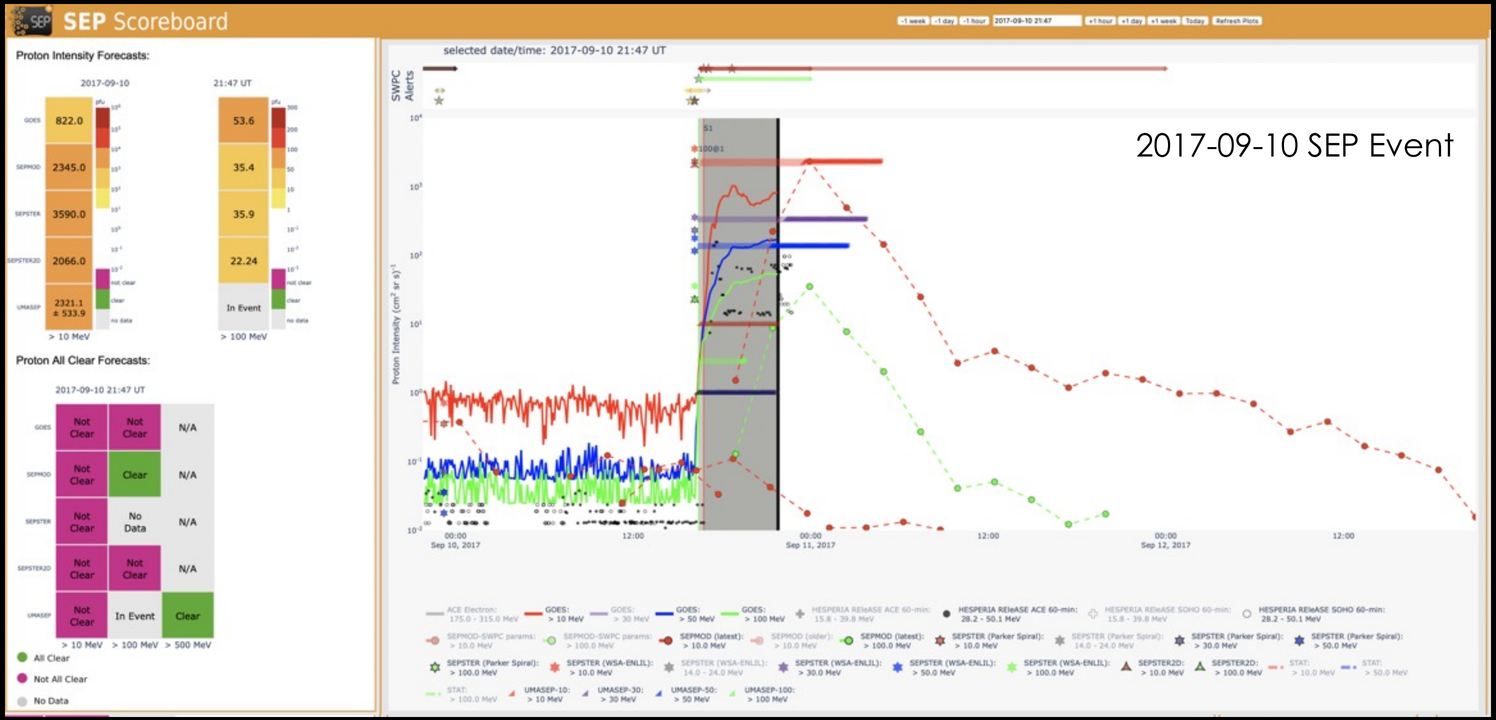
To transition space weather models of interest in human spaceflight from research to operational (R2O) use to support forecasting needs for exo-LEO missions

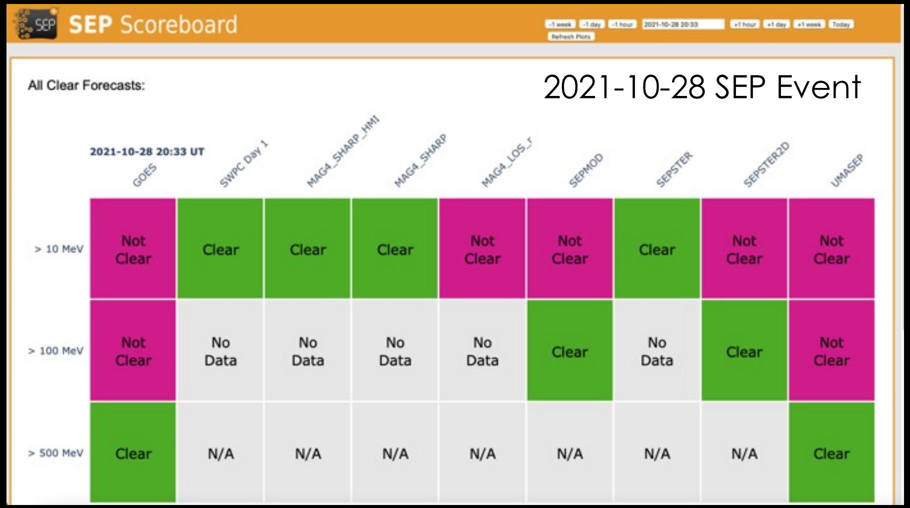
Approach:

Assemble a collaboration between SRAG, CCMC, and M2M to leverage each group's unique capabilities and resources to develop software tailored to SRAG's needs (SEP Scoreboards) and work with SEP model developers to identify, transition, and evaluate models in an R2O2R process.

THE SEP SCOREBOARDS

- The SEP Scoreboards are running in real time and are being used by SRAG operators for ISS and Artemis
  - Probability *(MAG4, SWPC, ASPECS, SPRINTS)*
  - Proton Intensity *(SEPSTER, SEPSTER2D, HESPERIA REleASE, SEPMOD, UMASEP, ASPECS)*
  - All Clear *(all models)*
- All models are welcome to participate in the SEP Scoreboards; https://sep.ccmc.gsfc.nasa.gov/intensity/



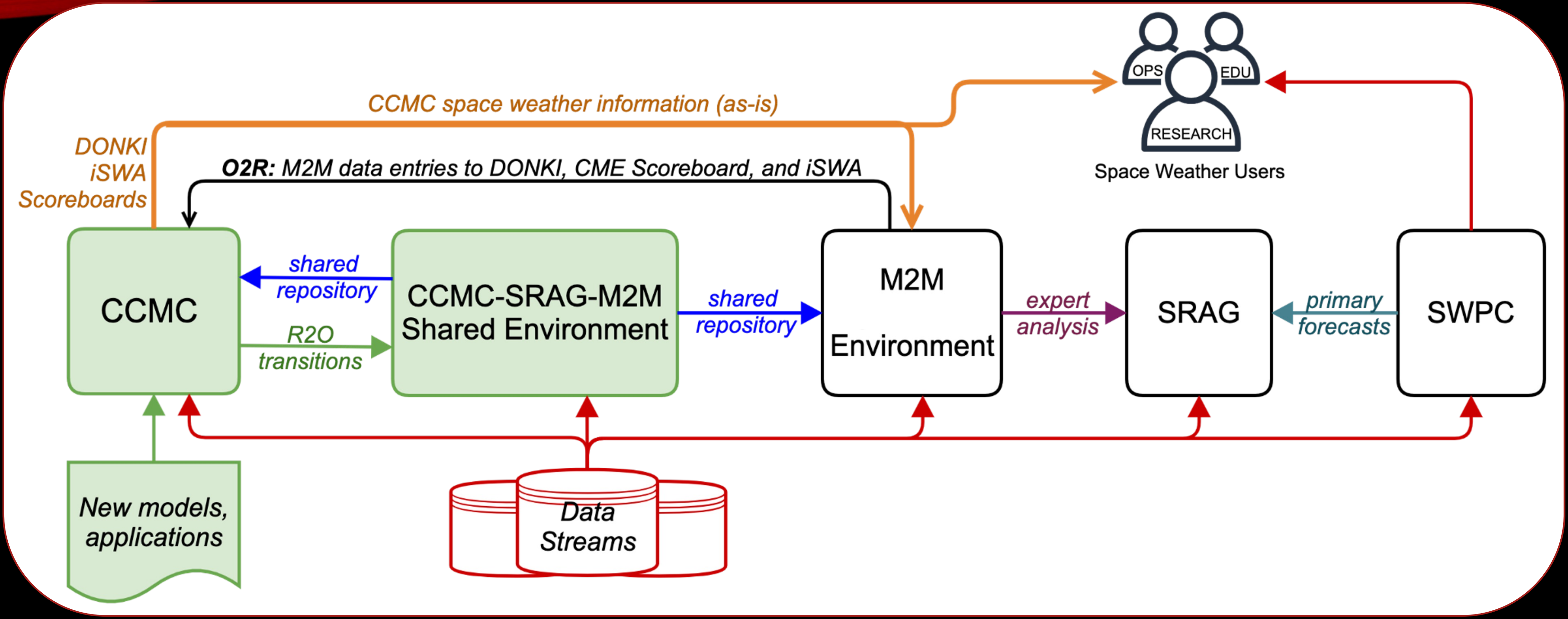


^ All Clear SEP Scoreboard
< Peak intensity and time intensity profile scoreboard
[*https://ccmc.gsfc.nasa.gov/challenges/sep.php*](https://ccmc.gsfc.nasa.gov/challenges/sep.php)

THE SEP SCOREBOARDS WORKFLOW

- CCMC develops the SEP Scoreboards and onboards new models
- M2M analysts provide human-in-the-loop inputs required by the forecasting models, such as coronal mass ejection (CME) measurements and simulations, which are entered into DONKI
- CCMC ingests observational inputs and runs the models automatically by also using the data ingested by the M2M analyst to populate the SEP Scoreboards
    - Models running in real time elsewhere routinely upload their predictions to an anonymous ftp
- SRAG operators monitor the SEP Scoreboards during mission support and provide feedback on useability as well as report issues
- M2M and CCMC provide support for troubleshooting and maintenance of the models
- SRAG, CCMC, and M2M work directly with model developers to communicate needs
- SRAG, CCMC, and M2M have an ongoing effort to develop infrastructure to validate SEP models

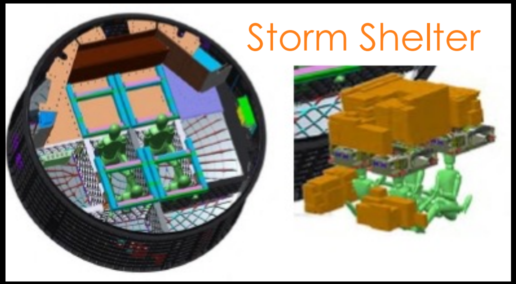
CCMC – M2M partnership: NASA in-house R2O2R pipeline in Support of Human Exploration

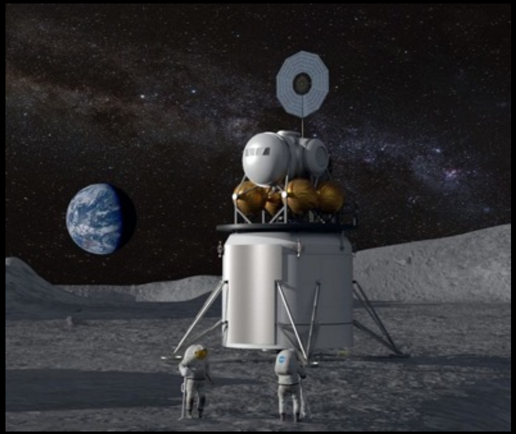


- CCMC transitions ISEP models/software to the shared environment. M2M staff then transitions the models/software from the shared environment and maintains them within the M2M environment, serving SRAG as proving grounds of the capabilities in real time.

OPERATIONAL RELEVANCE OF SEP FORECASTS

- Operational relevance stated here is presented from the perspective of SRAG for space radiation impacts to humans
- Limited SEP impact on the ISS in Low Earth Orbit due to the protection of the Earth's magnetosphere
- Astronauts onboard Artemis will be able to build a shelter within 30 minutes
- Astronauts performing a lunar EVA are required to stay within a 1-hour radius from the lander (life support systems requirement)



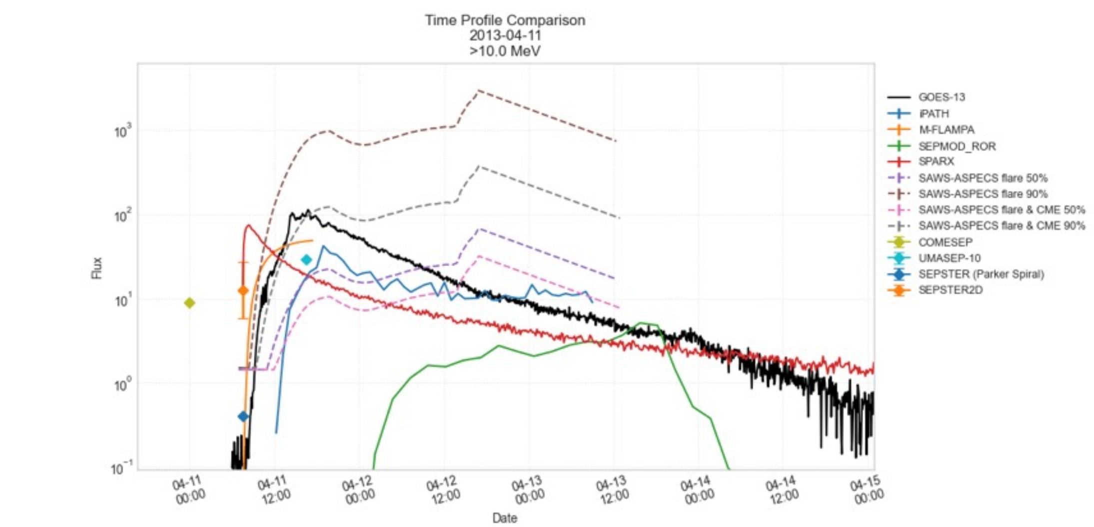


- ➢ Astronauts can respond to an SEP event within a 30 – 60-minute timeframe. Therefore, regardless of All Clear status, if an eruptive event has not yet occurred (flare, CME), it is advantageous to carry out planned EVAs or other important tasks as the task could be completed prior to an eruption. If an SEP event does occur, astronauts can respond quickly.
- ➢ Two types of useful SEP forecasts:
  - ➢ All Clear or probability prior to an eruption (issued every 6, 12, 24, 48, etc. hours)
  - ➢ All Clear and forecasts of all kinds (timing, peak, time profile, fluence) immediately following an eruption to enable quick response

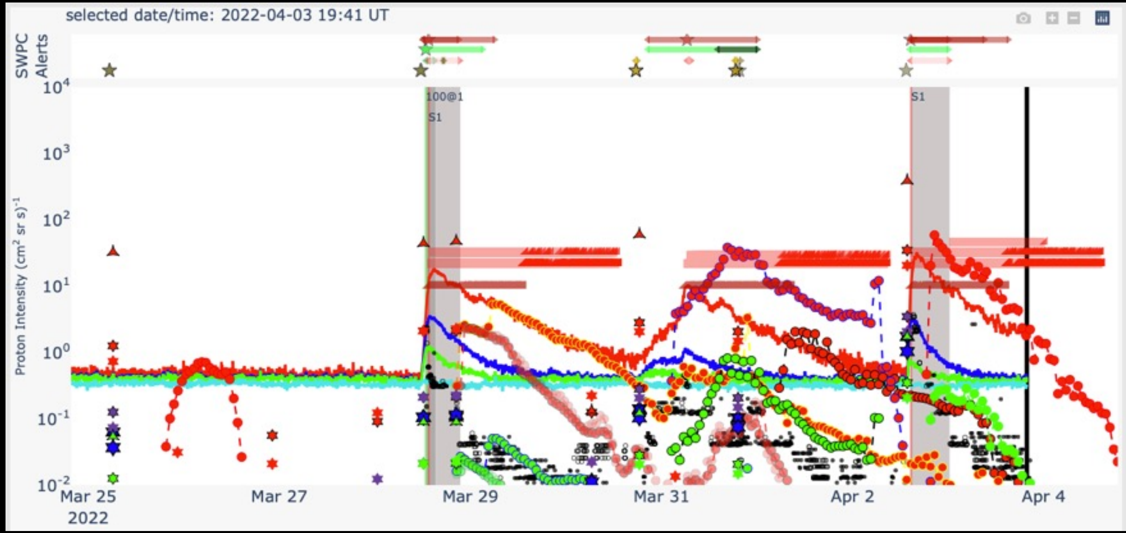
SEP SCOREBOARD VALIDATION

- SRAG, CCMC, and M2M are collaborating through the ISEP project to validate SEP models
  - A community validation effort to validate a set of historical “challenge” events has been ongoing through SHINE/ISWAT/ESWW
  - Validation of the real time forecasts being produced on the SEP Scoreboard
  - Assessments of how model performance is impacted by availability of real time data and human-in-the-loop analysis

Curated Community Validation Effort



Real Time Forecasts in the SEP Scoreboard



SEP MODEL VALIDATION CHALLENGE

Completed	Current	Next
First Phase – *quantitative comparisons with observations* SHINE 2019 & ISWAT 2021 Collect forecasts for 10 Challenge SEP Events	**Second Phase** – *test for false alarms & correct negatives* SHINE 2022 Collect forecasts for 14 periods when no SEP was observed	**Third Phase** – *Statistically significant metrics and cross-model comparisons* Validation with statistically significant number of SEP events and non-events using standardized set of inputs and strict requirements

Final validation code product – *Integrated into CAMEL with assistance from CCMC*

- Third phase – ISWAT team will provide:
  - List of challenge events and non-events (~solar cycle 24 & 25)
  - CME and other input parameters
  - Time stamps after which no data may be used

- **Working Meeting Sept. 5 -7, 2023 in SWRI San Antonio, TX**
- **Working Meeting Nov. 18, 2023 prior to ESWW in Toulouse, France**

PARTICIPATING MODELS 2019 TO 2022

- **ASPECS** (Papaioannou et. al.)*
- **COMESEP** (Dierckxsens et al.)
- **HESPERIA REleASE** (Posner, Malandraki, Kuhl) *
- **iPATH + ZEUS** (Li, Hu)
- **MAG4 SEP** (Falconer, Khazanov)*
- **MagPy** (Tidesse, Falconer et al.) *
- **MEMPSEP** (Dayeh et al.)
- **M-FLAMPA** (Sokolov, Zhao)
- **PHSVM** (Hosseinzadeh)
- **PPS** (AFRL)
- **SEPCaster** (iPATH + AWsoM) (Li, Jin)
- **SEPMOD + ENLIL** (Luhmann) *
- **SEPSTER** (Richardson, I.) *
- **SEPSTER2D** (Bruno) *
- **SPARX** (Marsh, Dalla, Swalwell)
- **SPRINTS** (Engell et al.) *
- **STAT** (MAS + EPREM) (Linker, Schwadron)
- **UMASEP** (Núñez) *

***Running in real time on the SEP Scoreboard**

CALCULATE METRICS

- All validated quantities are output into pdf reports organized by energy channel
- Future work: Active interface to visualize and interpret validation results

COMESEP Validation Report

Report Information

Date of report: 2022-09-22T17:36:27
Report generated by sep-validation > validation.py.
This code may be publicly accessed at: https://github.com/ktindiana/sep-validation

Validated Quantities

This model was validated for the following quantities. If the model does not make predictions for any these quantities, they will not be included in the report.
All Clear or threshold crossed/not crossed
Onset Peak Flux
Maximum Flux
Channel Fluence
Start Time
End Time
Onset Peak Time
Maximum Flux Time
Threshold Crossing Time
Time Profile
Advanced Warning Time

All Clear Skill Scores

Thresholds Applied:
Energy Channel = >10 MeV
Observations Threshold = 10.0 pfu
Predictions Threshold = 10.0 pfu

Instruments and SEP Events used in Validation
N = 10

Validation Events				
Observatory	SEP Date	Prediction Window	Observations	Predictions
GOES-13	2012-03-07 05:10:00	2012-03-07 00:00:00	False	False
GOES-13	2012-05-17 02:10:00	2012-05-17 00:00:00	False	False
GOES-13	2012-07-12 18:35:00	2012-07-12 00:00:00	False	False
GOES-13	2013-04-11 10:55:00	2013-04-11 00:00:00	False	True
GOES-13	2014-01-07 19:00:00	2014-01-06 00:00:00	False	True
GOES-13	2014-01-07 19:00:00	2014-01-07 00:00:00	False	False
GOES-13	2017-07-14 09:00:00	2017-07-14 00:00:00	False	False
GOES-13	2017-09-10 16:45:00	2017-09-10 00:00:00	False	False
GOES-13	2017-09-05 00:40:00	2017-09-04 00:00:00	False	False

GOES-13	2017-09-06 12:00:00	2017-09-06 00:00:00	False	False

Skill scores derived directly from model's native All Clear predictions or defined using threshold crossed/not crossed predictions. Note that All Clear True = No Event, All Clear False = Yes Event

Contingency Table

	Observed Yes	Observed No
Forecast Yes	8	0
Forecast No	2	0

SKILL SCORES	
Hits (TP)	8
Misses (FN)	2
False Alarms	0
Correct Negatives	0
Percent Correct	0.8
Bias	0.8
Hit Rate	0.8
False Alarm Ratio	0.0
False Alarm Rate	nan
Frequency of Hits	1.0
Frequency of Misses	0.2
Probability of Correct Negatives	nan
Detection Failure Ratio	1.0
Frequency of Correct Negatives	0.0
Threat Score	0.8
Odds Ratio	nan
G Skill Score	0.0
True Skill Score	nan
Heidke Skill Score	0.0
Odds Ratio Skill Score	nan

Probability Metrics

Thresholds Applied:
Energy Channel = >10 MeV
Observations Threshold = 10.0 pfu
Predictions Threshold = 10.0 pfu

Instruments and SEP Events used in Validation
N = 23

Validation Events				
Observatory	SEP Date	Prediction Window	Observations	Predictions
GOES-13	2012-03-07 05:10:00	2012-03-07 00:00:00	1.0	0.25
GOES-13	2012-05-17 02:10:00	2012-05-17 00:00:00	1.0	0.82
GOES-13	2012-07-12 18:35:00	2012-07-12 00:00:00	1.0	0.25
GOES-13	2013-04-11 10:55:00	2013-04-11 00:00:00	1.0	0.47
GOES-13	2014-01-07 19:00:00	2014-01-07 00:00:00	1.0	0.79
GOES-13	2017-07-14 09:00:00	2017-07-14 00:00:00	1.0	0.67
GOES-13	2017-09-10 16:45:00	2017-09-10 00:00:00	1.0	0.79
GOES-13	2017-09-05 00:40:00	2017-09-04 00:00:00	1.0	0.82
GOES-13	2017-09-06 12:00:00	2017-09-06 00:00:00	1.0	0.79
GOES-13	0	2012-06-13 13:27:00	0.0	0.0
GOES-15	0	2013-06-07 22:59:00	0.0	0.286
GOES-13	0	2014-10-24 07:58:00	0.0	0.286
GOES-15	0	2014-11-06 03:56:00	0.0	0.125
GOES-15	0	2014-11-07 17:36:00	0.0	0.2
GOES-15	0	2014-12-17 05:01:00	0.0	0.474
GOES-15	0	2014-12-18 22:08:00	0.0	0.474
GOES-13	0	2014-08-01 18:22:00	0.0	0.261
GOES-13	0	2015-03-10 00:03:00	0.0	0.474
GOES-13	0	2016-07-23 05:26:00	0.0	0.286
GOES-16	2021-10-28 17:40:00	2021-11-01 01:55:00	0.0	0.2
GOES-16	2021-10-28 17:40:00	2021-11-02 03:01:00	0.0	0.261
GOES-16	2022-01-20 08:00:00	2022-01-18 17:54:00	1.0	0.2
GOES-16	0	2022-04-17 03:44:00	0.0	0.2

Metrics for probability predictions.

Onset Peak Flux Metrics

Thresholds Applied:
Energy Channel = >10 MeV
Observations Threshold = N/A
Predictions Threshold = N/A

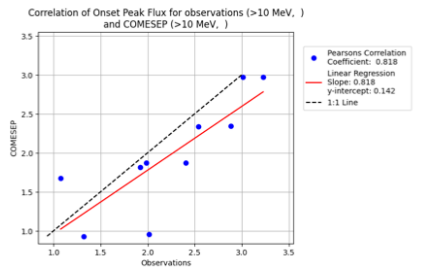
Instruments and SEP Events used in Validation
N = 10

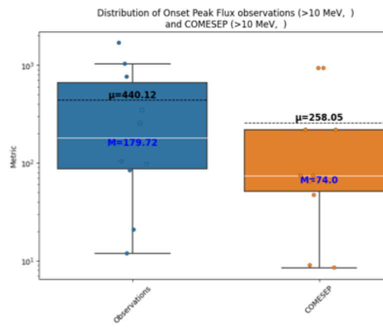
Validation Events				
Observatory	SEP Date	Prediction Window	Observations	Predictions
GOES-13	2012-03-07 05:10:00	2012-03-07 00:00:00	1690.5	933.0
GOES-13	2012-05-17 02:10:00	2012-05-17 00:00:00	255.44	74.0
GOES-13	2012-07-12 18:35:00	2012-07-12 00:00:00	83.893	65.0
GOES-13	2013-04-11 10:55:00	2013-04-11 00:00:00	104.01	9.0
GOES-13	2014-01-07 19:00:00	2014-01-07 00:00:00	761.16	219.0
GOES-13	2017-07-14 09:00:00	2017-07-14 00:00:00	11.886	47.0
GOES-13	2017-09-10 16:45:00	2017-09-10 00:00:00	1031.1	933.0
GOES-13	2017-09-05 00:40:00	2017-09-04 00:00:00	96.978	74.0
GOES-13	2017-09-06 12:00:00	2017-09-06 00:00:00	345.45	218.0
GOES-16	2022-01-20 08:00:00	2022-01-18 17:54:00	20.785435	8.511380382023766

Metrics for log10(model) - log10(observations). Positive values indicate model overpredictions. Negative values indicate model underprediction.

r_lin and r_log indicate the Pearson's Correlation Coefficient calculated using values or log10(values), respectively.

Metrics	
MLE	-0.26623538510276695
MedLE	-0.2290311173852977
MALE	0.3856478115054723
MedALE	0.3229463246290171
RMSE	306.239576336202
RMSLE	0.4851016323356237
r_lin	0.9244170153793853
r_log	0.8181708303652133

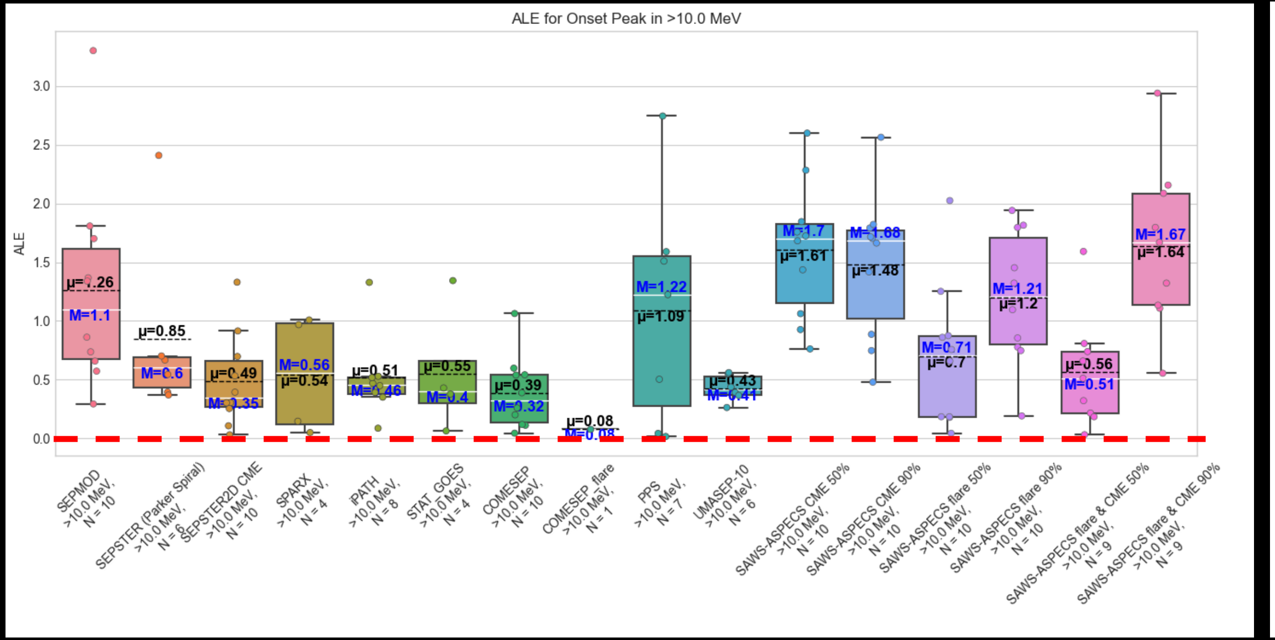




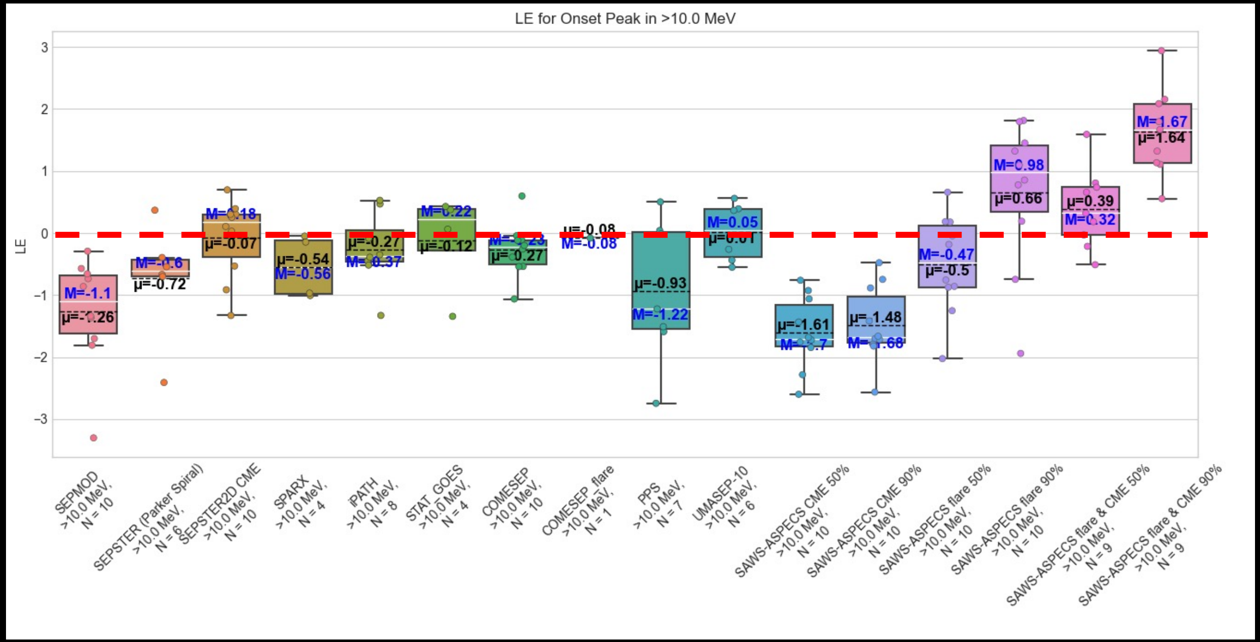
CROSS-MODEL VALIDATION
ONSET PEAK RESULTS FOR >10 MEV

- Compare forecasts with observed onset peak derived for SEP events
- Need to do this carefully, but code and infrastructure being built to allow it

Distribution of Absolute Log Error of Max Flux, >10 MeV

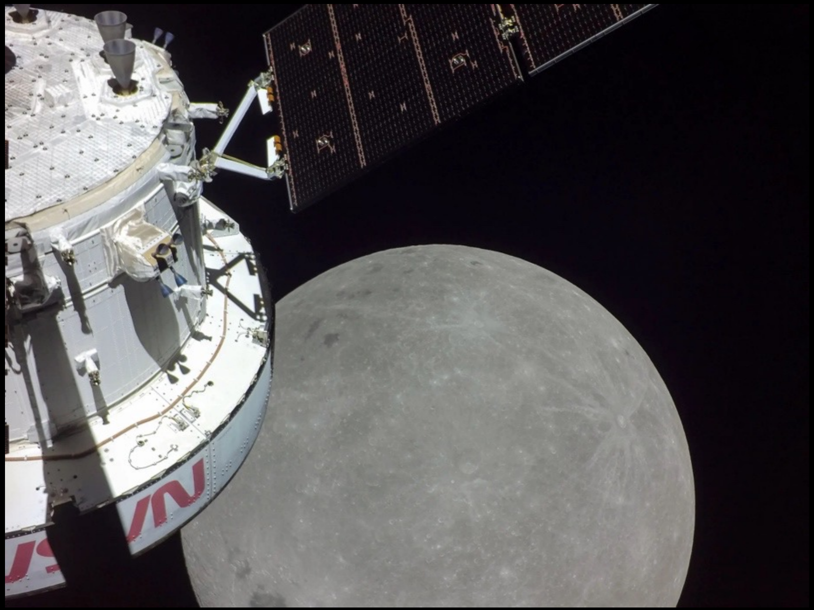


Distribution of Log Error of Max Flux, >10 MeV



CONCLUSIONS

- SRAG operations focus on monitoring a wide array of measurements required for situational awareness
- The newly developed ARRT tool will estimate biological impacts in real time from SEP events during exploration class missions
- The ISEP Project has begun implementing forecasting capabilities in preparation for NASA's Artemis missions
- CCMC developed the SEP Scoreboards to run SEP forecast models in real time
- M2M provides the real time human-in-the-loop space weather analysis activities and model support
- Infrastructure to validate SEP models is being built through ISEP
- Artemis I served as a testbed for all technologies that will be used for crewed Artemi missions, including hardware, projection tools, the SEP Scoreboards in SRAG's console operations and 24/7 support provided by SRAG, SWPC, and M2M



Artemis I

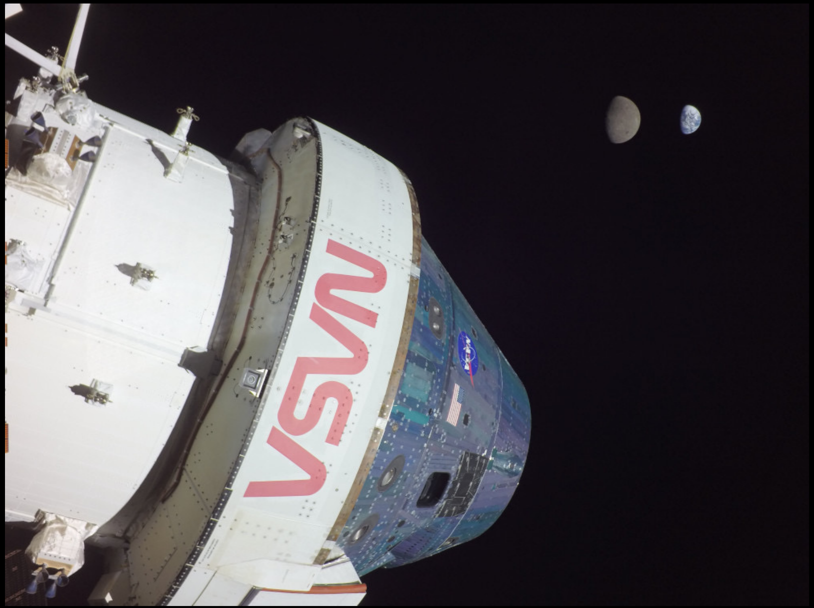


Image credits: NASA

BACK UP SLIDES

COMMUNITY COORDINATED MODELING CENTER (CCMC)

Mission: To enable, support, and perform research for next generation space science and operational space weather models through an interagency partnership.

- CCMC was established to enhance basic solar-terrestrial research and to aid in the development of models for specifying and forecasting conditions in the space environment.
- CCMC assembles, validates, and tests space weather models that can eventually be adapted for operational use by NOAA and the DoD.
- CCMC performs real-time space weather activities including developing real-time systems, running real-time simulations, automatic ingesting and serving information through CCMC's space weather portals and perpetual archives:
  - **iSWA** - integrated Space Weather Analysis system
  - **DONKI** - Database of Notifications, Knowledge, Information
  - **Scoreboards** – pre-event forecast collection, comparative display, and database

https://ccmc.gsfc.nasa.gov/faq/

MOON TO MARS SPACE WEATHER ANALYSIS OFFICE (M2M)

Mission: The Moon to Mars Space Weather Analysis Office (M2M) is established to support NASA's Space Radiation Analysis Group (SRAG) with human space exploration activities by providing novel capabilities to characterize the space radiation environment. M2M will work as the proving grounds and testbed for the capabilities that will eventually transition to operational agencies*. M2M also supports NASA robotic missions with space weather notifications and anomaly assessments.

- Real-time space weather activities that require human-in-the-loop analyses and training have transitioned from CCMC to Moon-to-Mars (M2M) Office
- The M2M team populates CCMC's DONKI and CME Scoreboard during their real-time analysis of space weather conditions and sends real-time simulation results to iSWA.
- SRAG, CCMC, and M2M partner together on model validation. After a space weather event, M2M, in conjunction with SRAG and CCMC, runs an evaluation of the model output to include any forecast delays and the reasons for them.

OCHMO Radiation Standards

Astronaut's total career effective radiation dose (In 3001, Vol 1 Rev B) — **600 mSv**

Universal for all ages and sexes, 3% mean risk of cancer mortality, effective dose calculated using 35-year-old female

An individual astronaut's total career effective radiation dose due to space flight radiation exposure shall be less than 600 mSv.

Galactic Cosmic Radiation (GCR) (only under consideration) - achievable with ~$10 g/cm^2$ Al

For missions beyond low Earth orbit, vehicles and habitat systems shall provide sufficient protection to reduce exposure from galactic cosmic radiation (GCR) by 15% compared with free space such that the effective dose from GCR remains below 1.3 mSv/day for systems in free space and below 0.8 mSv/day for systems on planetary surfaces.

250 mSv

20 mSv

Solar Particle Event (SPE)

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).

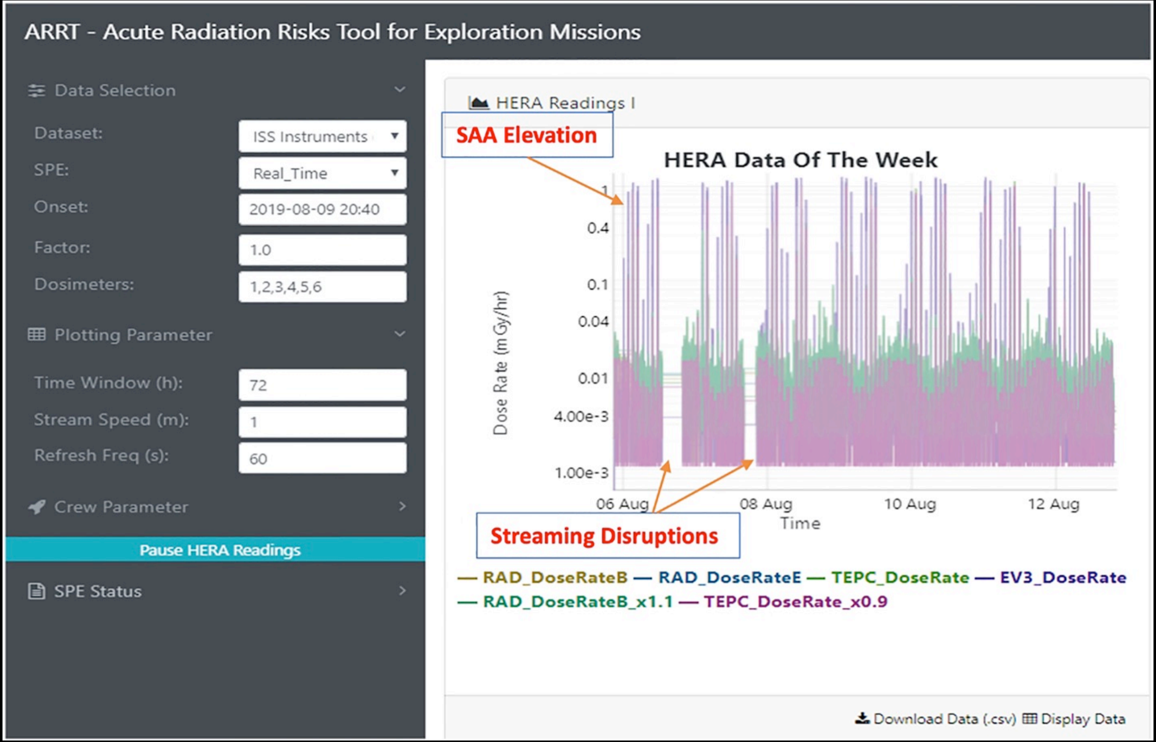
Nuclear Technologies

Radiological exposure from nuclear technologies emitting ionizing radiation (e.g., radioisotope power systems, fission reactors, etc.) to crew members shall be less than an effective dose of 20 mSv per mission year (prorated/extrapolated to mission durations).

ALGORITHM OF ACUTE RADIATION RISKS TOOL (ARRT)

During Artemis I, ARRT served as a dashboard to monitor the HERA readings. No SEP event occurred during the mission, but ARRT was triggered by a pass through the radiation belts, demonstrating its forecasting functionality.

- SPE radiation environment → Transport through shielding → Biological impacts
- Real-time SPE organ dose projection
  - Real-time vehicle dosimeter measurement
  - A precomputed database of dose quantities calculated from the HZETRN radiation transport code
  - A fitting procedure to get organ doses
- Acute biological response models
  - Blood cell kinetics models
  - Prodromal models and performance decrement model
  - Hematopoietic injury model and METROPOL (MEdical TREatment ProtocOLs) scale
- Built-in historical SPEs with a calculated HERA dose

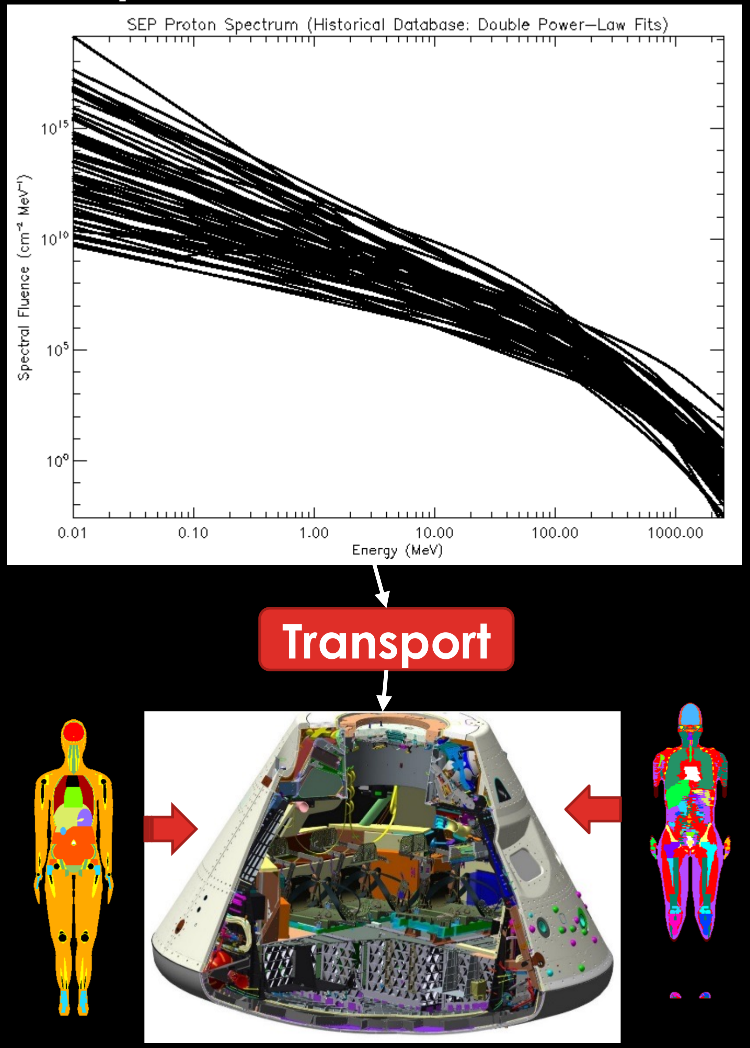


ARRT is currently reading dosimeters onboard the ISS. During Artemis I, ARRT used HERA detectors onboard Orion as a test for crewed Artemis missions.

DOSE CALCULATION PROCEDURE

- Free-space SEP proton spectra (top)
  - Boundary condition for radiation transport through Orion
  - Spectral Fits (**Tylka band fits**) to 65 historical GLE/SEP events (*Raukunen et al., SWSC, 8(A04), 2018*)
- Shielding thicknesses along each (10k) raypath originating at each target point covering 4π sr in direction
- Target points
  - 6 x HERA detector locations
  - Blood Forming Organs (**BFO**) at crew locations (**seated/sheltered**) in the male (**MAX**) and female (**FAX**) human body models
- Numerical solution of 1-D Boltzmann transport equation along each raypath using HZETRN code
- Calculate dose quantities at each target point (bottom)
  - HERA detector locations: Si-dose (Gy)
  - Crew locations (**seated/sheltered**): BFO dose (Gy-Eq) (average RBE = 1.5 for protons)

SEP Spectra: Historical Database

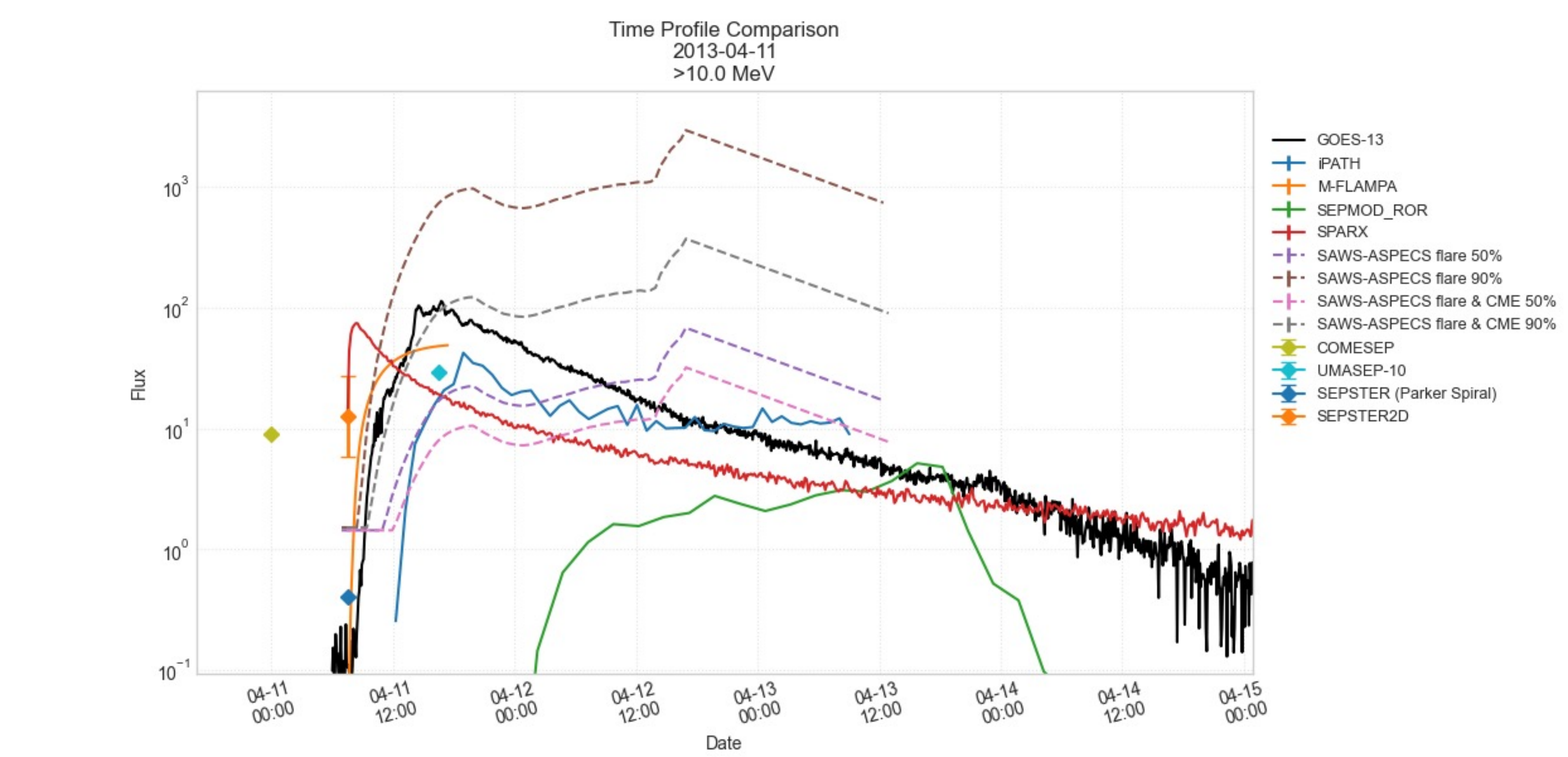


Mertens et al. 2018

SEP MODEL COMMUNITY VALIDATION EFFORT

PARTICIPATING MODELS:

- **ASPECS** (Papaioannou et. al.)
- **COMESEP** (Dierckxsens et al.)
- **HESPERIA REleASE** (Posner, Malandraki, Kuhl)
- **iPATH + ZEUS** (Li, Hu)
- **MAG4 SEP** (Falconer, Khazanov)
- **M-FLAMPA** (Sokolov, Zhao)
- **SEPMOD + ENLIL** (Luhmann)
- **SEPCaster** (iPATH + AWsoM) (Li, Jin)
- **SEPSTER** (Richardson, I.)
- **SEPSTER2D** (Bruno)
- **SPARX** (Marsh, Dalla, Swalwell)
- **STAT** (MAS + EPREM) (Linker, Schwadron)
- **UMASEP** (Núñez)



VALIDATION:

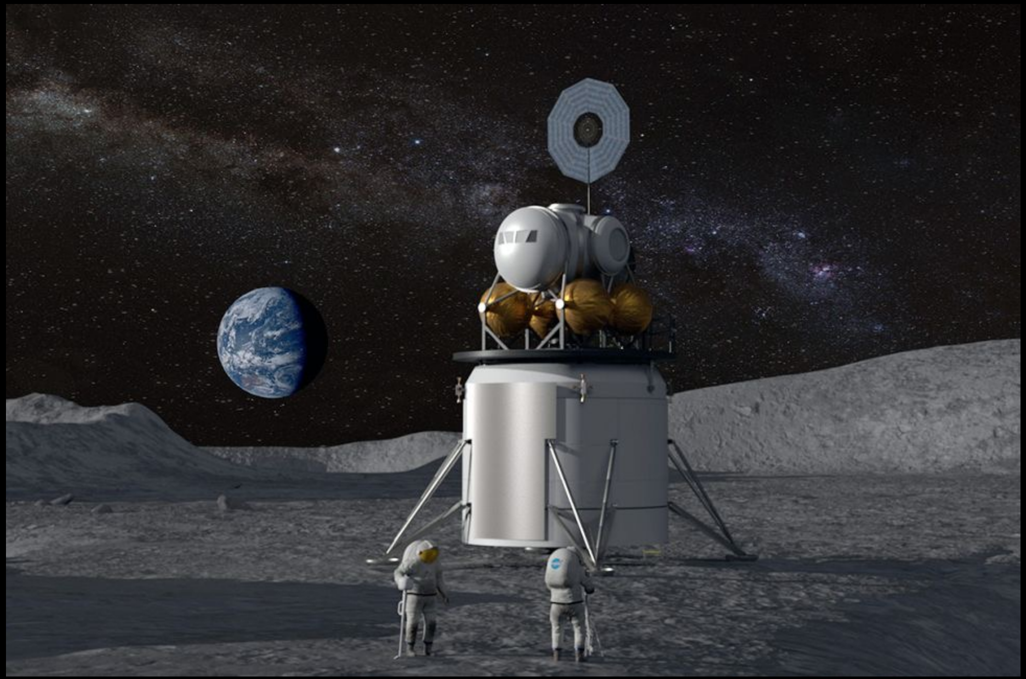
- Historical forecasts for a small selection of 10 SEP events
- SHINE 2022: Focus on forecasting for a small number of “non-events” to test for false alarms

SPACE RADIATION DURING HUMAN EXPLORATION MISSIONS OUTSIDE OF LOW EARTH ORBIT

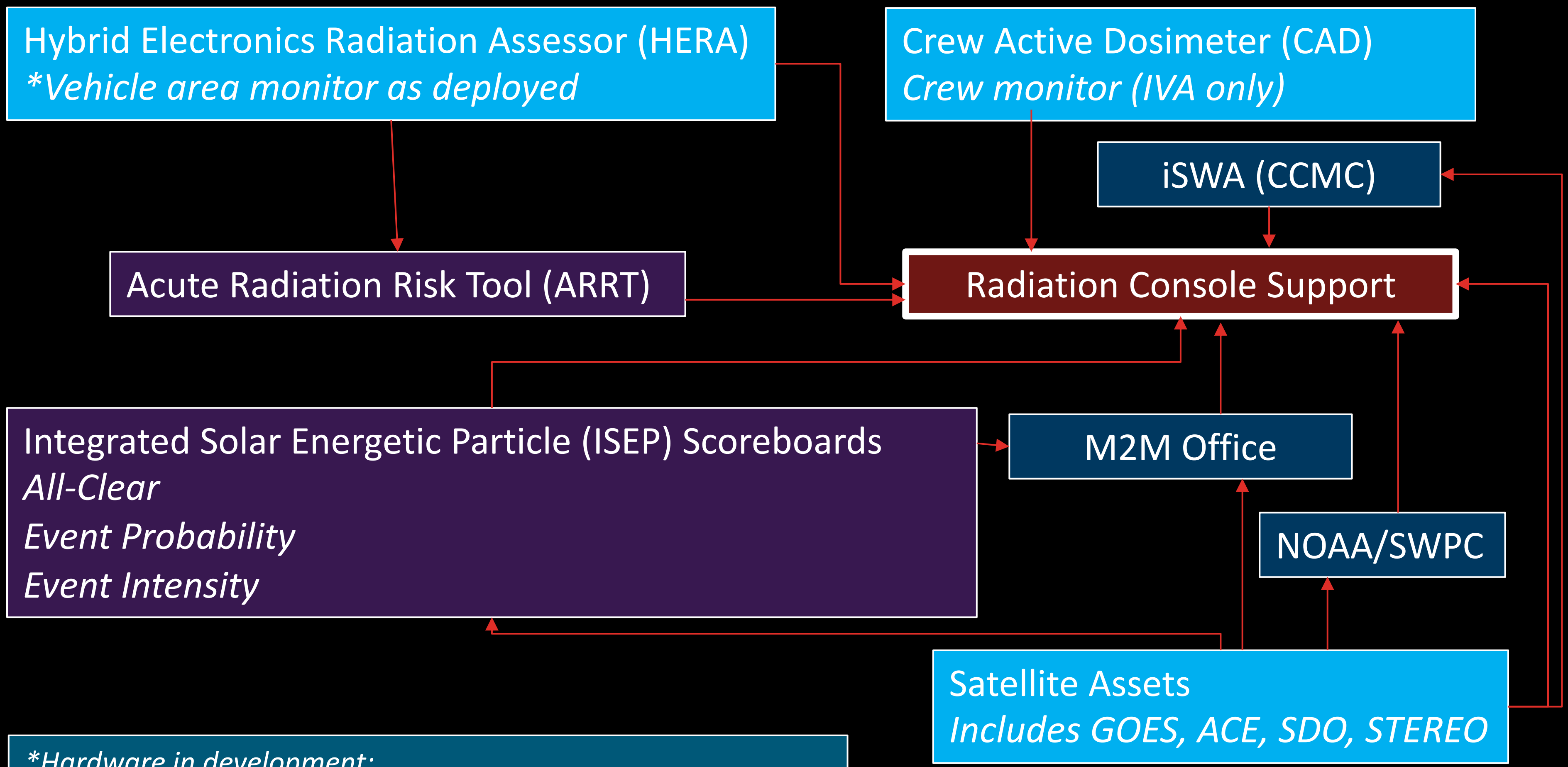
Missions beyond LEO where crew-vehicle system spends substantial time in ‘free-space’ the scenario is very different:

Human-vehicle will see full extent of SEP event.

Image credits: NASA



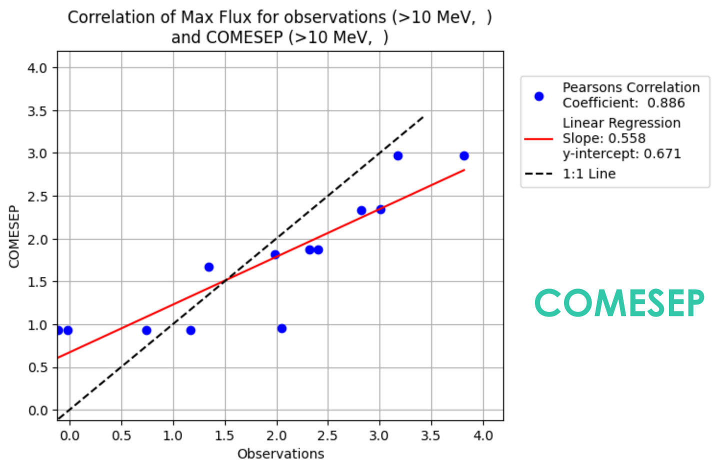
ARTEMIS OPERATIONAL ASSETS



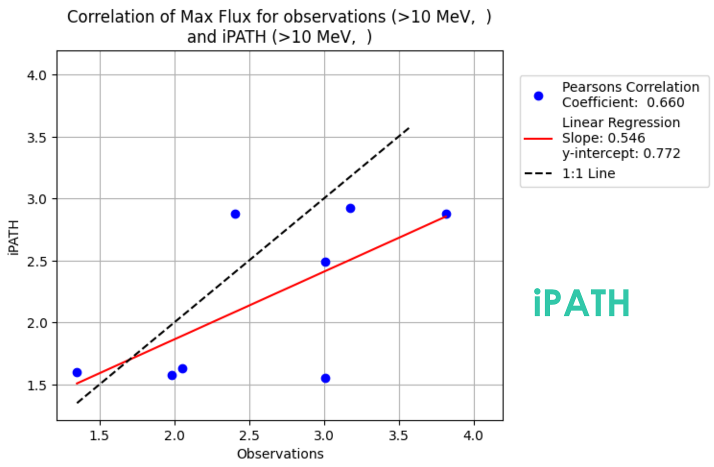
**Hardware in development:*

- *Active Radiation Environment Sensor (ARES)*
- *Exploration Extravehicular Mobility Unit (xEMU) Active Radiation Detector (ARD)*

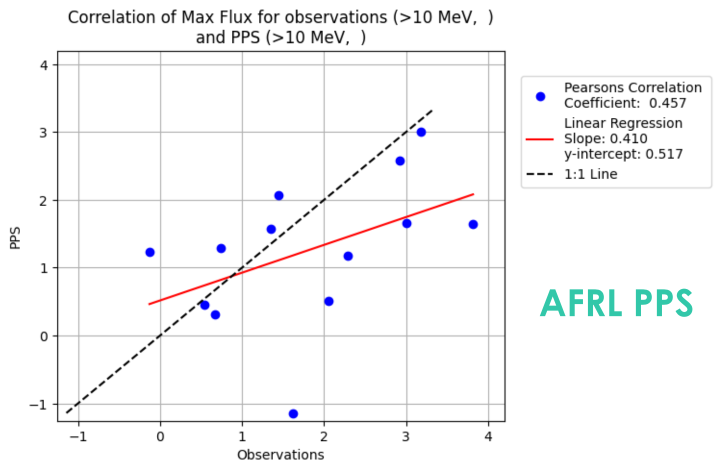
Max Flux



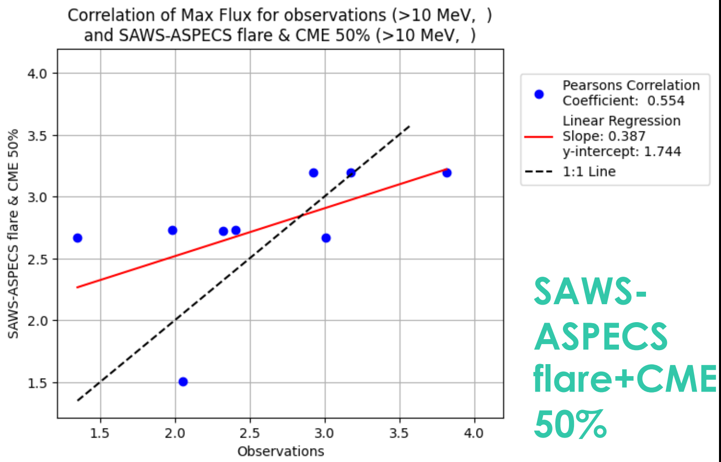
COMESEP



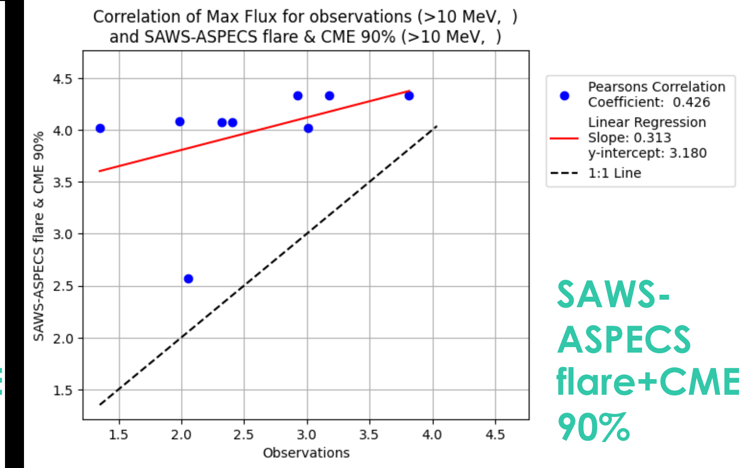
iPATH



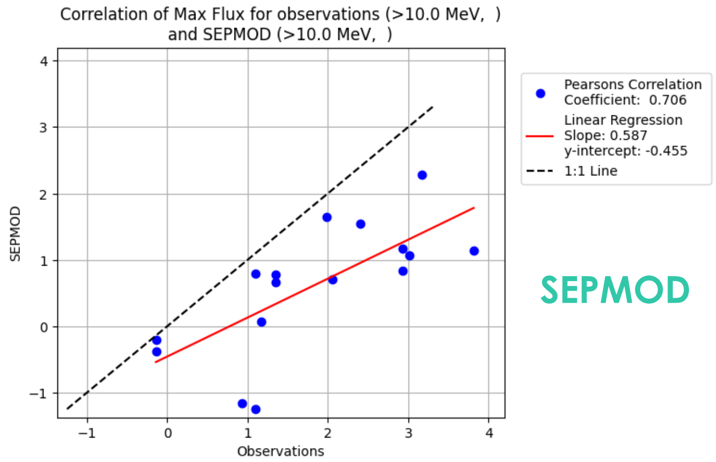
AFRL PPS



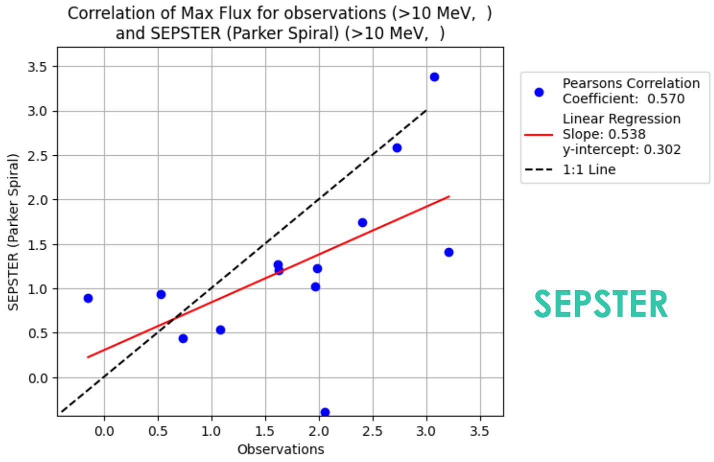
SAWS-ASPECS flare+CME 50%



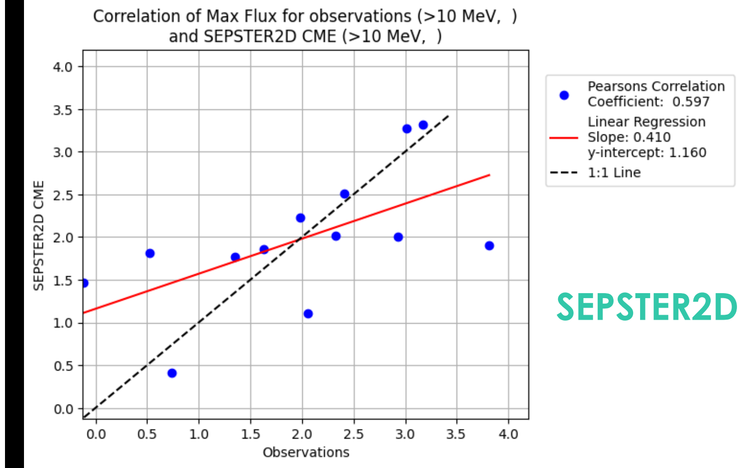
SAWS-ASPECS flare+CME 90%



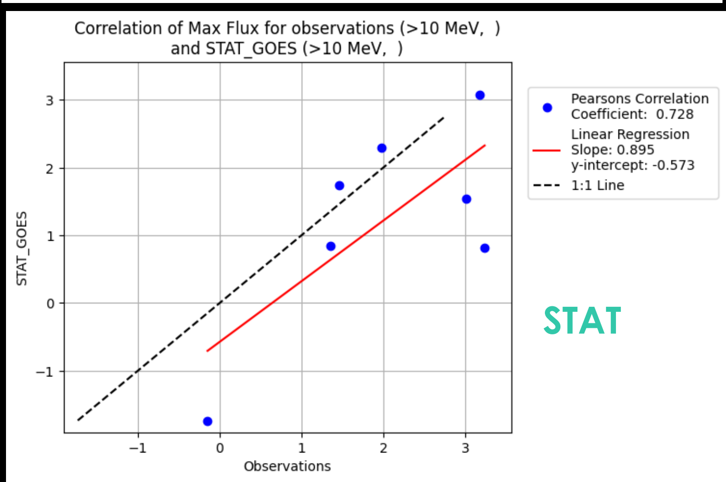
SEPMOD



SEPSTER



SEPSTER2D



STAT