The Human Interplanetary Exploration Radiation Risk Assessment System (HIERRAS)

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HIERRAS Stakeholder Team

- Expert consultation group to provide feedback and guidance

We would like to thank all the stakeholder team members!

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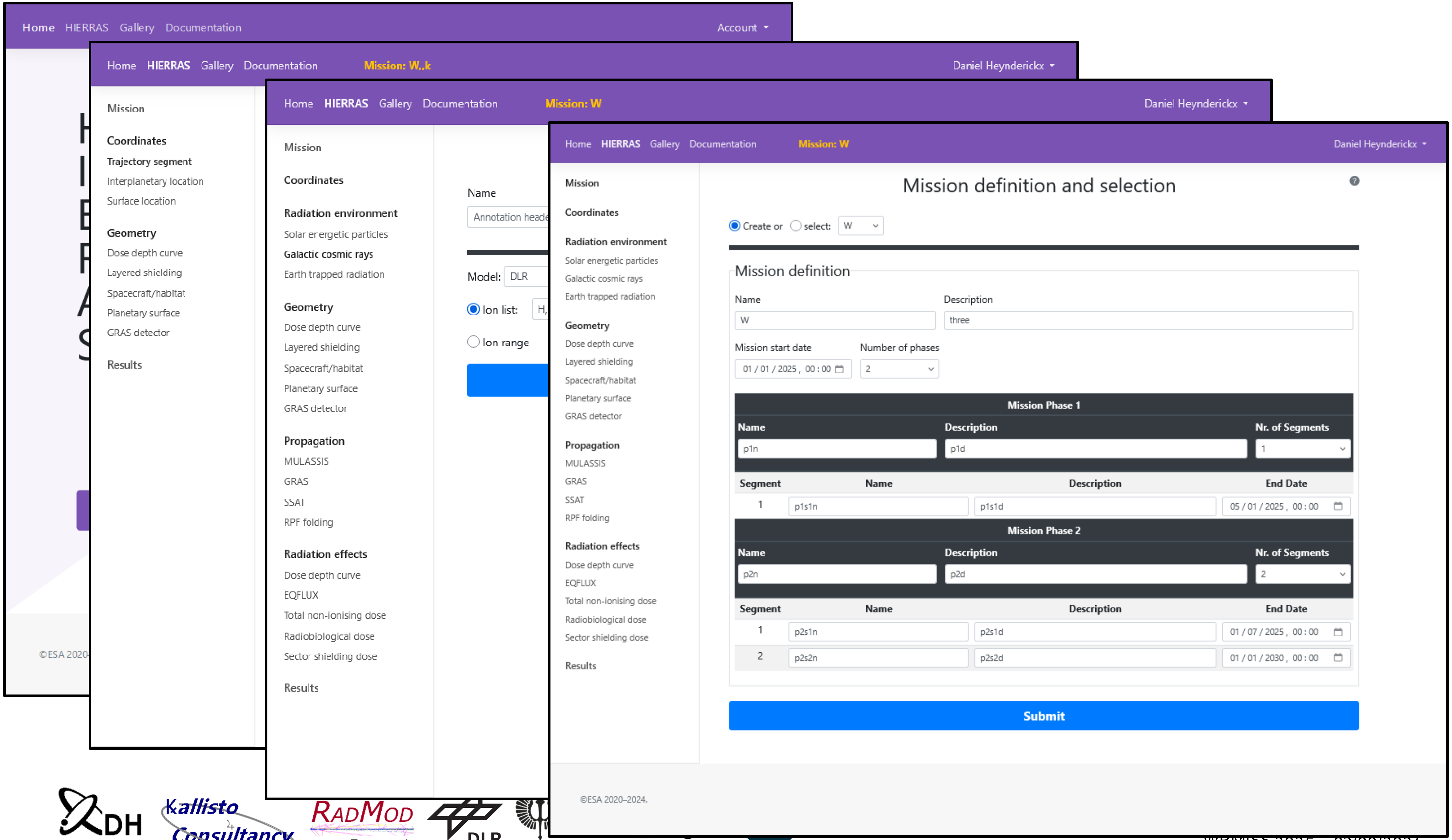
Background and Objectives

- ESA has several environment and effects modelling suites relevant to component/system radiation effects (*e.g.*, SPENVIS, CIRSOS, SEPEM, ESPREM) – not astronaut exposures
- HIERRAS is a radiation environment specification system for human exploration beyond LEO
- Inclusion of attenuation and secondary production by planetary atmospheres, magnetic fields and material shielding considering realistic spacecraft/habitat geometries and materials
- Determinations of human stochastic (cancer-causing) and tissue reaction (deterministic) dose quantities
- Aid assessment of warning times and hazard level for flux enhancements seen over a mission
- Modular system with clearly defined interfaces
- User-friendly web-based graphical user interface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Account
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Mission: W
Daniel Heyndericka
Mission
Coordinates
Trajectory segment
Interplanetary location
Surface location
Radiation environment
Solar energetic particles
Galactic cosmic rays
Earth trapped radiation
Geometry
Dose depth curve
Layered shielding
Spacecraft/habitat
Planetary surface
GRAS detector
Propagation
MULASSIS
GRAS
SSAT
RPF folding
Radiation effects
Dose depth curve
EQFLUX
Total non-ionising dose
Radiobiological dose
Sector shielding dose
Results
Name
Annotation heade
Model: DLR
Ion list:
Ion range
Mission definition and selection
Create or select: W
Mission definition
Name
W
Description
three
Mission start date
01 / 01 / 2025 , 00 : 00
Number of phases
2
Mission Phase 1
Name
p1n
Description
p1d
Nr. of Segments
1
Segment Name Description End Date
1 p1s1n p1s1d 05 / 01 / 2025 , 00 : 00
Mission Phase 2
Name
p2n
Description
p2d
Nr. of Segments
2
Segment Name Description End Date
1 p2s1n p2s1d 01 / 07 / 2025 , 00 : 00
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Submit
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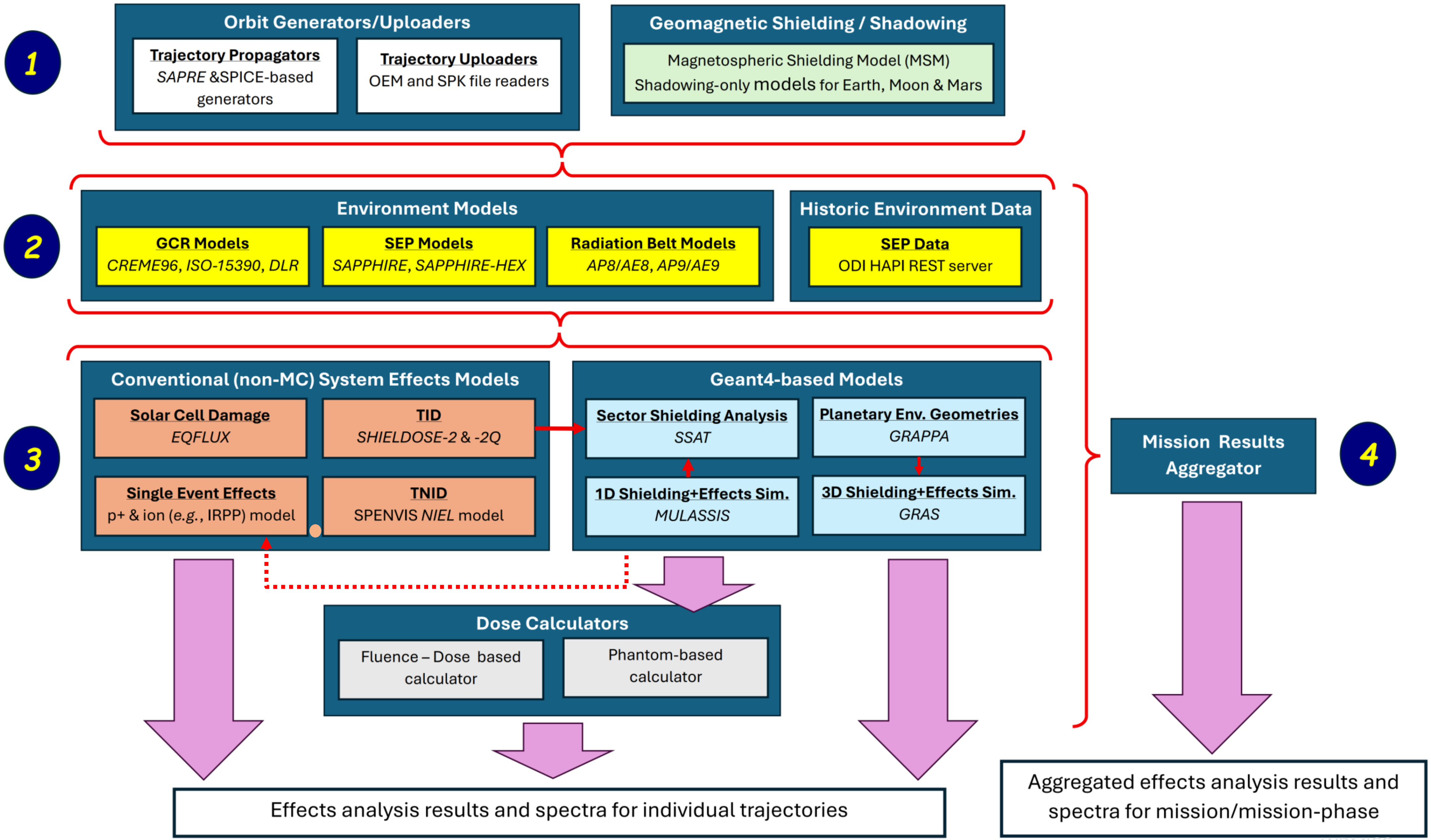
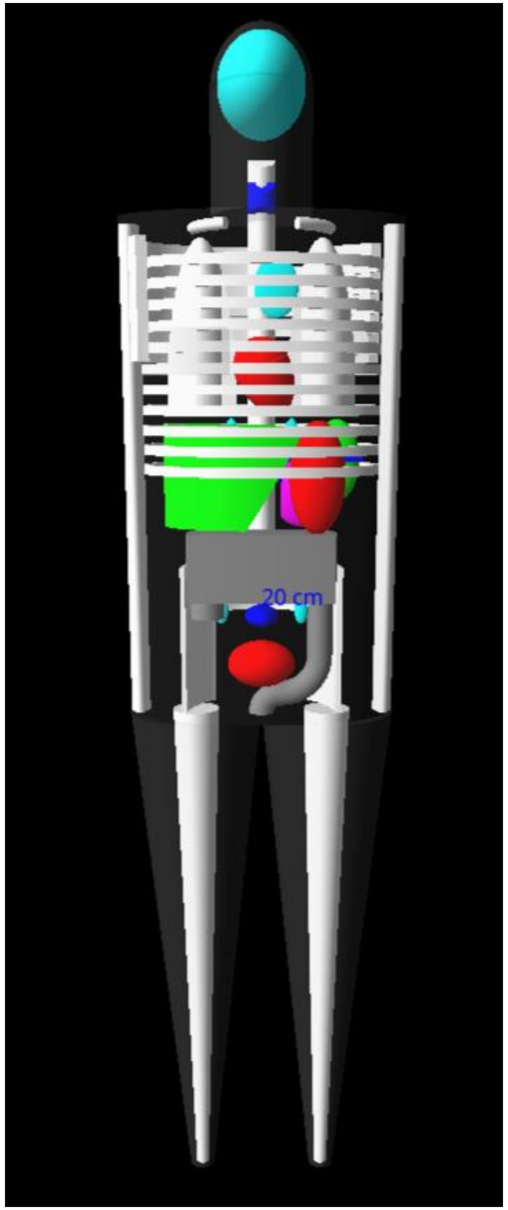
HIERRAS - Models and Analysis Routes



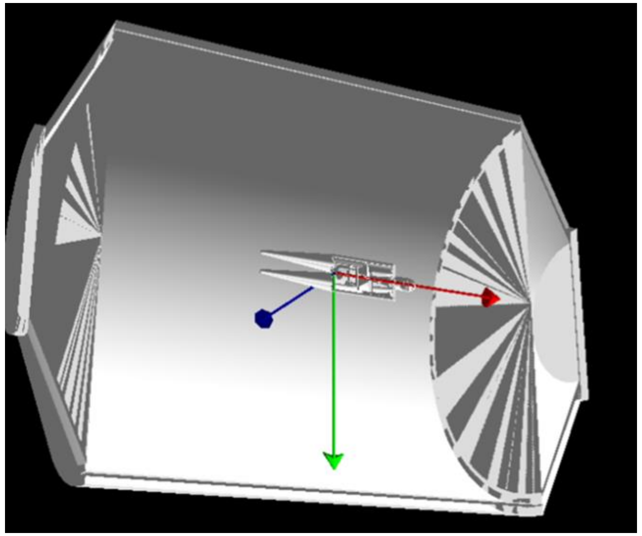
Dose Calculations

- Dose maps, based on fluence-to-dose conversion coefficients:
  - Effective dose, *E* (ICRP-116)
  - Effective dose equivalent, H_E, using Q(L) or NASA NASA Q(Z,E) factors (ICRP-123)
  - Ambient dose equivalent (ICRP-74)
- Volume detectors
  - Cubes or spheres placed by user in geometry
  - Same dose quantities as dose maps using fluence-to-dose conversion
- Phantom-based calculation
  - Gray-equivalent dose, G_T
  - Dose equivalent, $H_{T,Q}$
  - Effective dose, *E*
  - Effective dose equivalent, H_E
  - ORNL's MIRD CSG-based phantom (Snyder *et al*, 1969) available – users may upload better phantoms



Models and Geometries (1)

- Two sources for environment and effects models:
  - ESA's **Network of Models** (NoM) – https://nom.esa.int
    - Provides futureproofing since NoM models well maintained, and suite frequently expanded
  - **SPECTIRES Toolkit** in HIERRAS provides many of the same models
- Spacecraft, habitat, planetary environments, phantoms defined as GDML geometry files
- GRAS v6.0:
  - Multi-threaded
  - Robust and simply commands for relative placements of geometries specified in separate GDML files
- MULASSIS v2.0:
  - Non-MC CSDA simulation for heavy ions – approximation for thin shields and effects on microelectronics



GRAS on ESA ESSR

MULASSIS on ESA ESSR

Models and Geometries (2): What is GRAPPA?

- GRAS Preprocessor for Planetary bodies and Asteroids
- Creates GDML geometry representations of Mars and Moon
- Planar and spherical geometries
  - Sim
  - 3D g
- Can be scales
- Treatm
  - Atm
  - Soil
  - Precipitates (CO_2 & H_2O)
  - Magnetic fields (for Mars)

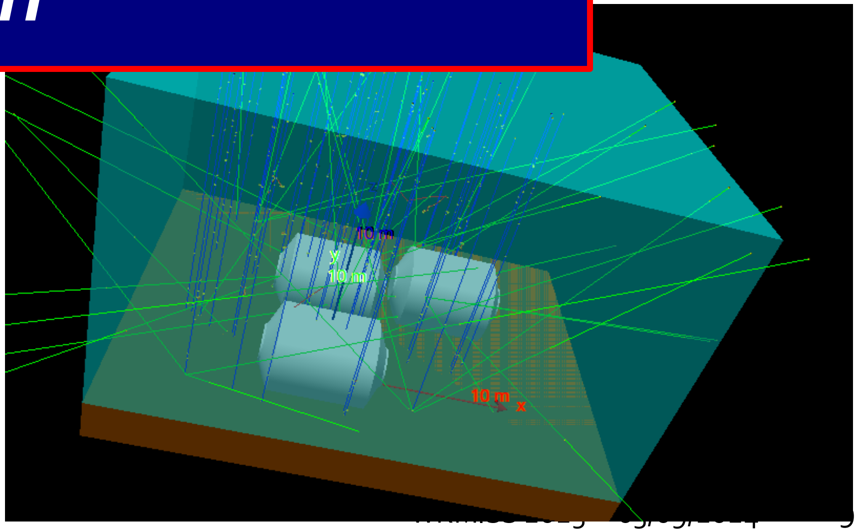
This approach means that GRAS (or another Geant4 application) can be used for 3D MC simulation

- Better maintainability of software

G4 Space Apps docker implementation of all ESA Geant4 applications used:

- **_MULASSIS, GRAS, SSAT, GRAPPA_**
- **_Greatly simplifies installation_**

Local environment with partially-buried habitat modules (additional GDML files) included in GRAS simulation



HIERRAS Response Function (RPF) modes

- GRAS & MULASSIS runs can be lengthy, from minutes to several days
- Conventional results have limited reuse
- **RPF generation module** allow calculation of shielded fluences & doses based on precalculated response functions using MULASSIS or GRAS
  - MULASSIS RPFs: Species, energy, shield-thickness
  - GRAS RPFs: Species & energy
- Allows reuse of lengthy simulation results, *e.g.*, time-dependent environments in subsequent studies

Channel	E_l (MeV/nuc)	E_u (MeV/nuc)	Power Law Index
C1	1.0	10.0	0
C2	10.0	50.0	0
C3	50.0	99.76	-1
C4	99.76	199.05	-1
C5	199.05	397.16	-1
C6	397.16	792.45	-1
C7	792.45	1581.14	-1
C8	1581.14	3154.78	-1
C9	3154.78	6294.63	-1
C10	6294.63	12559.43	-1
C11	12559.43	25059.36	-1
C12	25029.36	50000.0	-1
C13	50000.0	100000.0	-2.7

HDaemon and the Background Job Processor

- BkgProcessor allows asynchronous, parallel GRAS/MULASSIS runs
- Requests are submitted to the BkgProcessor:
  - Application to run and simulation run parameters
  - Start date/time if delay required
  - Dependencies on other jobs completing first
- Monitors progress and sends %-complete to online-user
- Can Email user when complete or if problems occur
- "Super Background Runs"
  - Build radiation shielding response function database
  - Makes use of allocated threads for parallelism
- HIERRAS Administrator can configure:
  - Total processor threads available to BkgProcessor
  - Max threads per user
  - Max job run-time

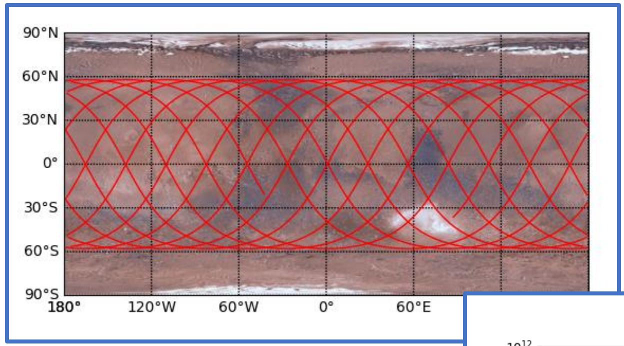
.... and there is an automated cleaner to remove discarded files from failed runs

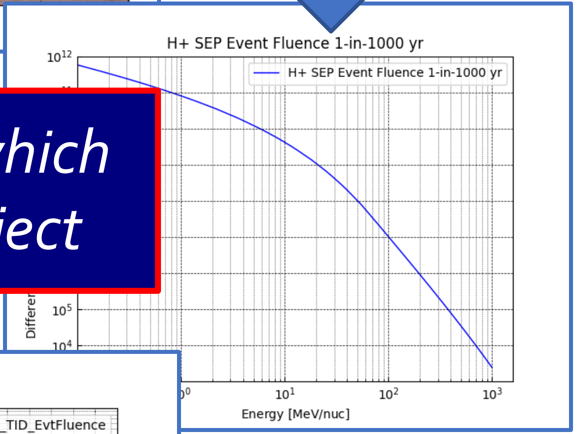
H^2UGOS – HIERRAS Handler for Users, Groups and Object Storage

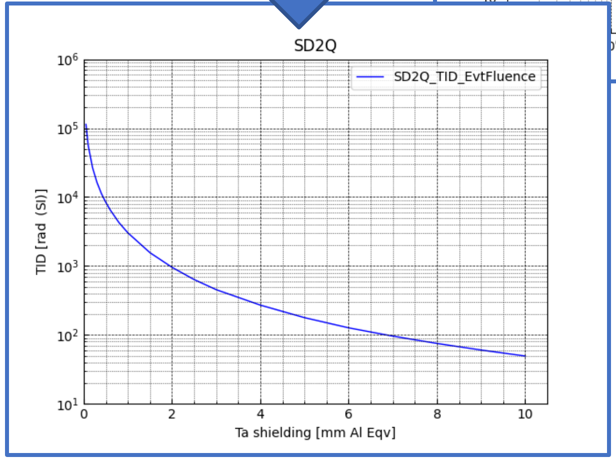
Data Audit Trail Management

- MySQL-based database application
- Manages user registration information and registration access through a user/org whitelist
- Files uploade
  - File owner
  - All associa
    spectrum→shielding calculation etc)
  - Avoid unintended consequences of deleting file which another user has used for input to their run
  - Quick access to auxiliary data
- H^2UGOS stores all requests and responses
  - Review of full model run conditions
  - In future can allow re-run capability.

Allows comprehensive traceability of run results which may be generated by different users within a project



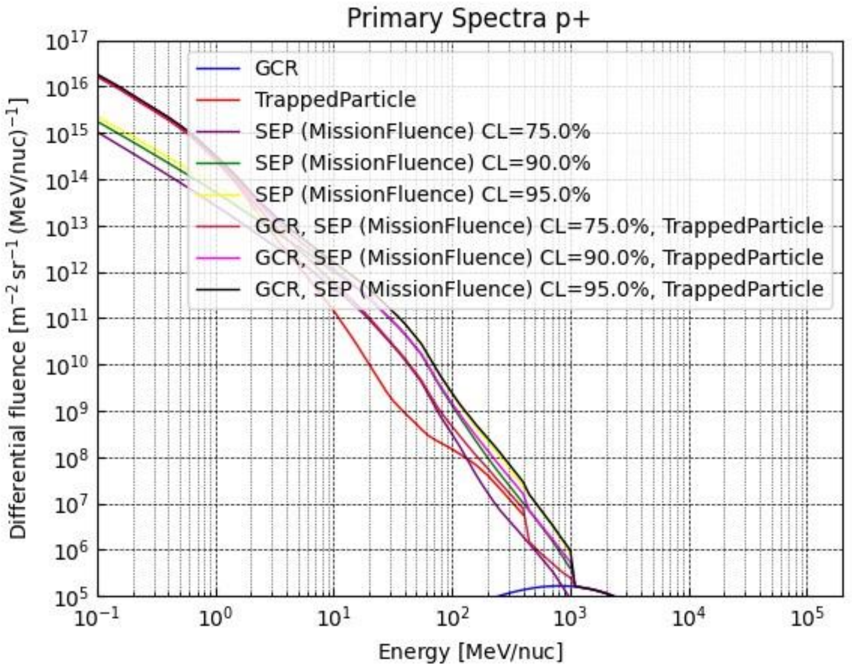


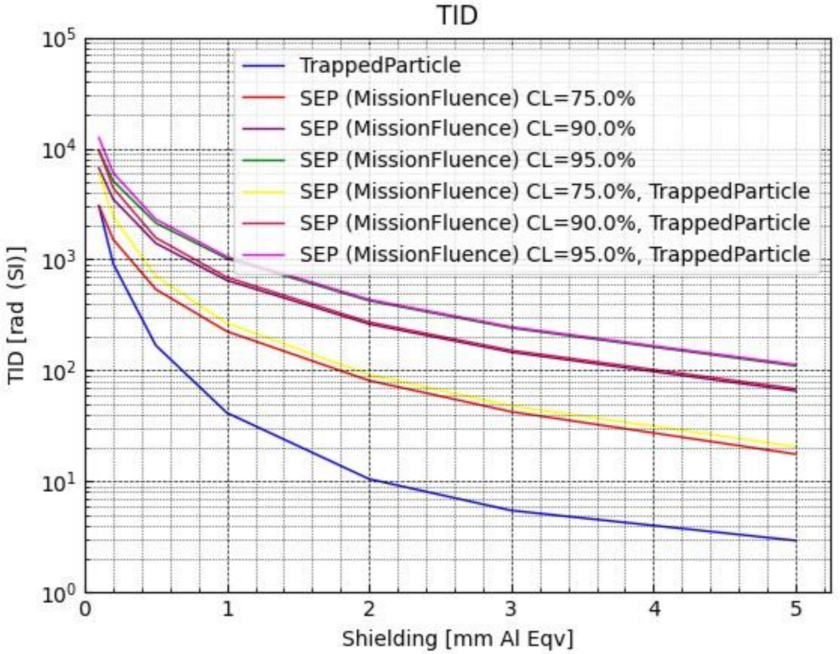


DH CONSULTANCY Kallisto Consultancy RadMod Research DLR sparc

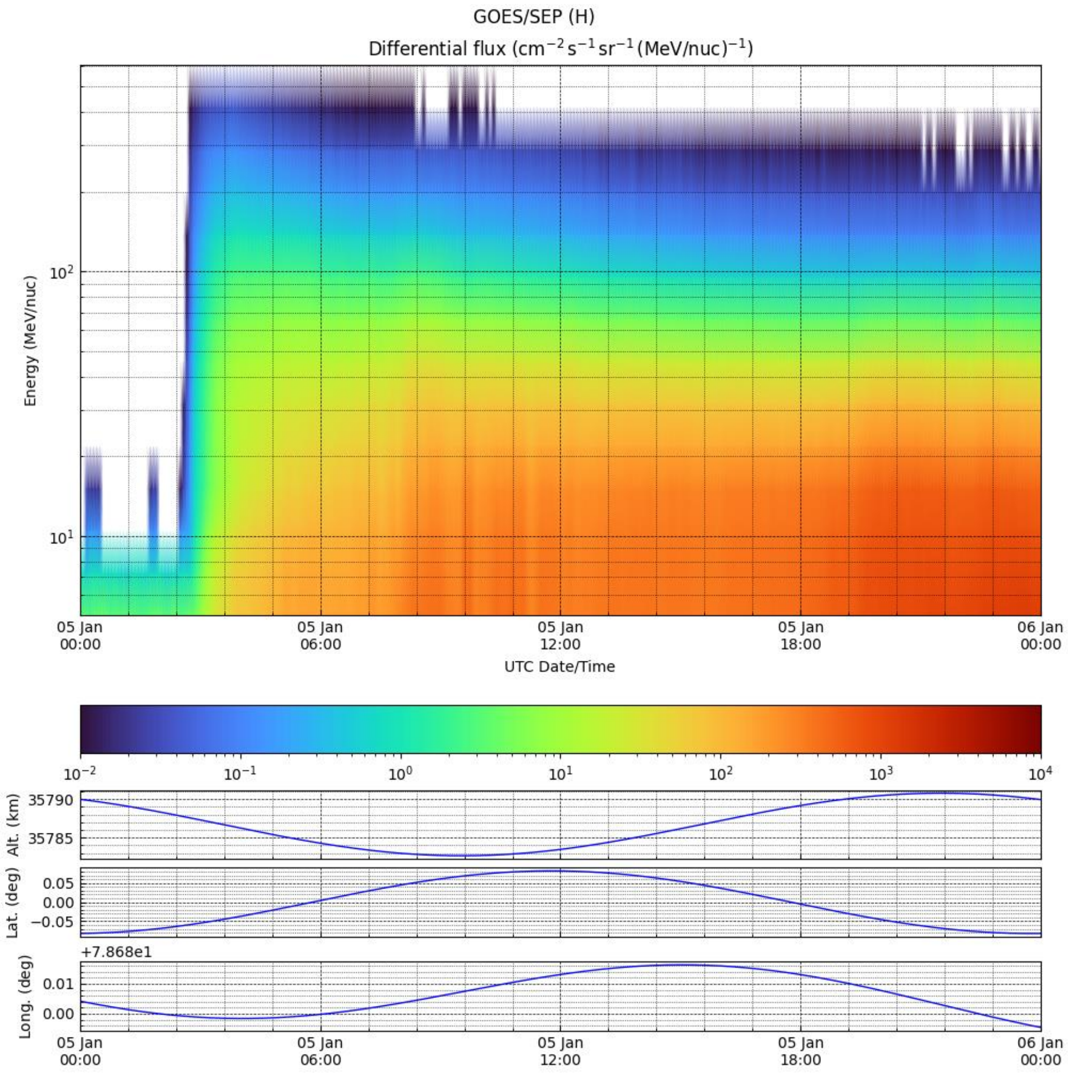
Mission Definition & Aggregation

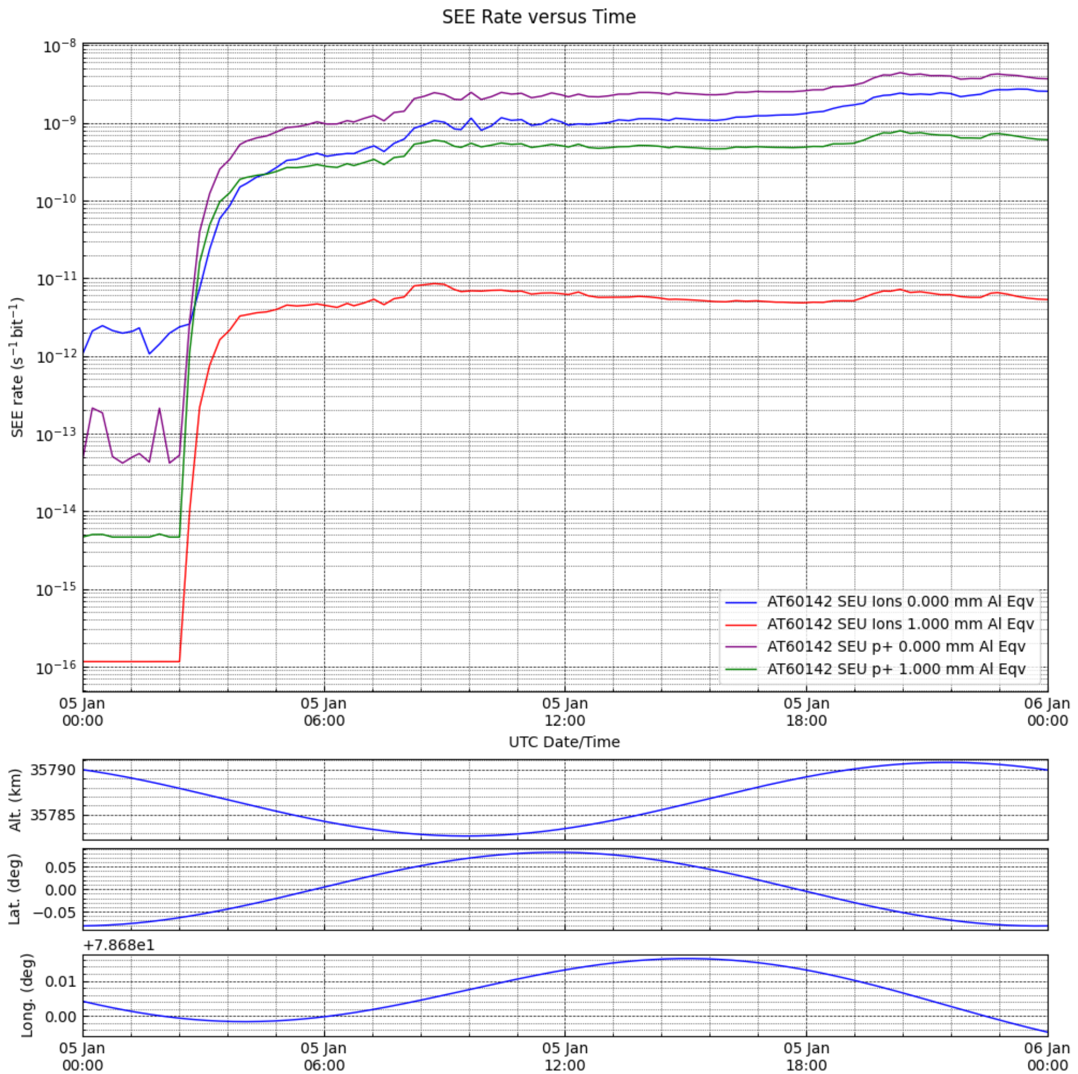
- Missions defined hierarchically:
  - Mission comprises one or more phases
  - Each phase comprises one or more segments
  - Each segment is defined by one trajectory or characteristic orbit
- H²UGOS maintains associations all these objects
- User can request aggregation of all spectra, TID, TNID, EQFLUX results for mission or phase
  - Calculated per radiation source: GCR, SEP, …
  - Summed over all sources
- Aggregator will automatically iterate through the combinations of different confidence levels *e.g.*, in SAPPHIRE, AE9 and/or AP9





Example of time dependent HIERRAS results using SEP





GOES/HEPAD data processing and update to SEPEM Reference Data Set

- High Energy Proton and Alpha Detector (HEPAD) onboard GOES6 to GOES15
- Data cleaning and gap filling
- Bow tie analysis to determine reference energies and geometric factors -> updated datasets

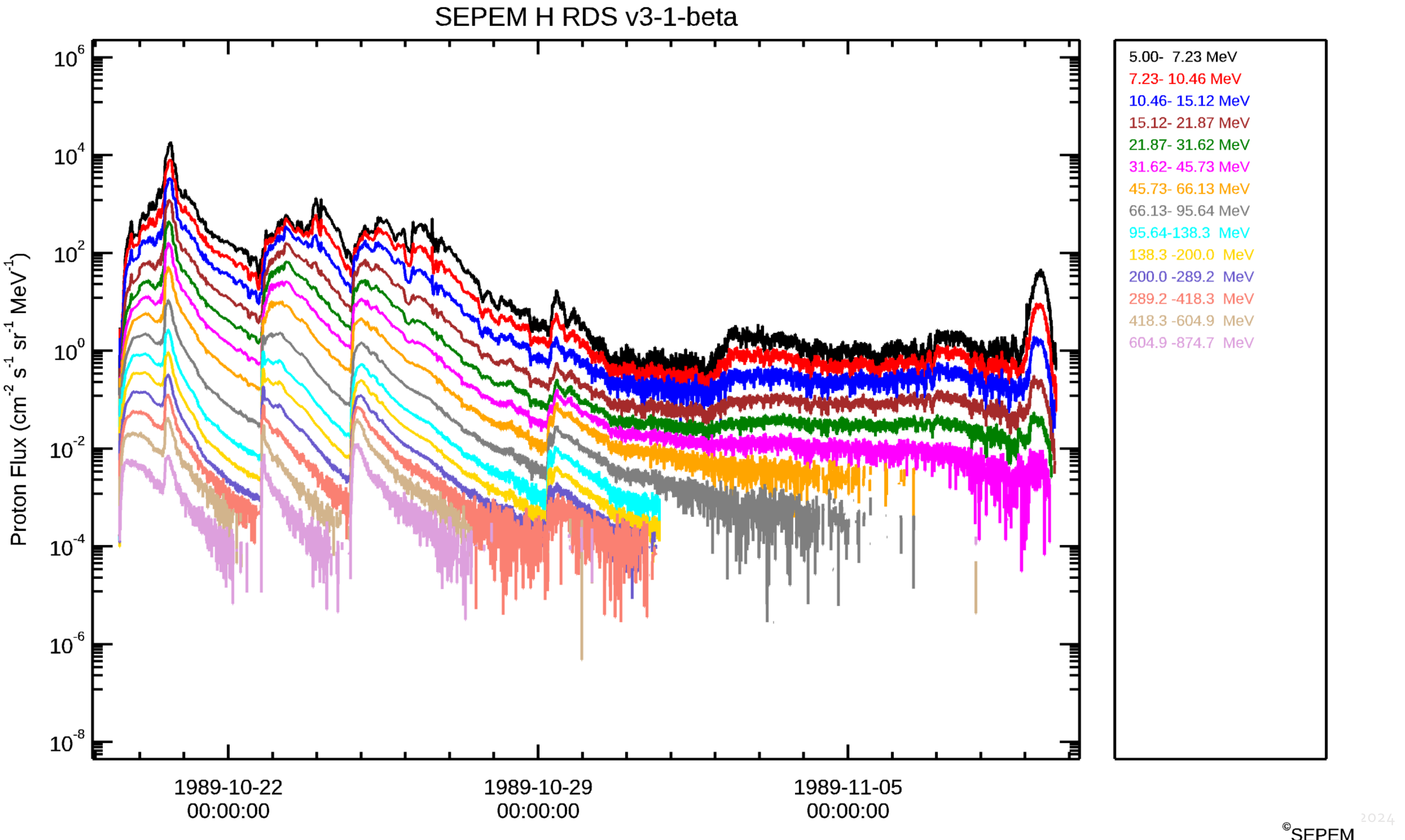
Channel (nominal)	Energy range (MeV) (1986-1994)	Energy range (MeV) (1995->)
P8	355-435	350-420
P9	435-555	420-510
P10	555-760	510-700
P11	>760	>700

Channel (nominal)	$G\Delta E$ (cm² sr MeV) (1986-1994)	$G\Delta E$ (cm² sr MeV) (1995->)
P8	77	67.5
P9	48	67.5
P10	369	162

Channel (bow tie)	E_{eff} (MeV) (1986-1994)	$G\Delta E$ (cm² sr MeV) (1986-1994)	E_{eff} (MeV) (1995->)	$G\Delta E$ (cm² sr MeV) (1995->)
P8FR	405	93.2 (-8.1%, +21.7%)	406	110 (-8.2%, +22.4%)
P9FR	473	84.5 (-2.2%, +6.3%)	457	66.3 (-1.8%, +5.2%)
P10	622	135 (-4.1%, +11.7%)	583	136 (-4.3%, +12.3%)

Extended SEPEM RDS channels

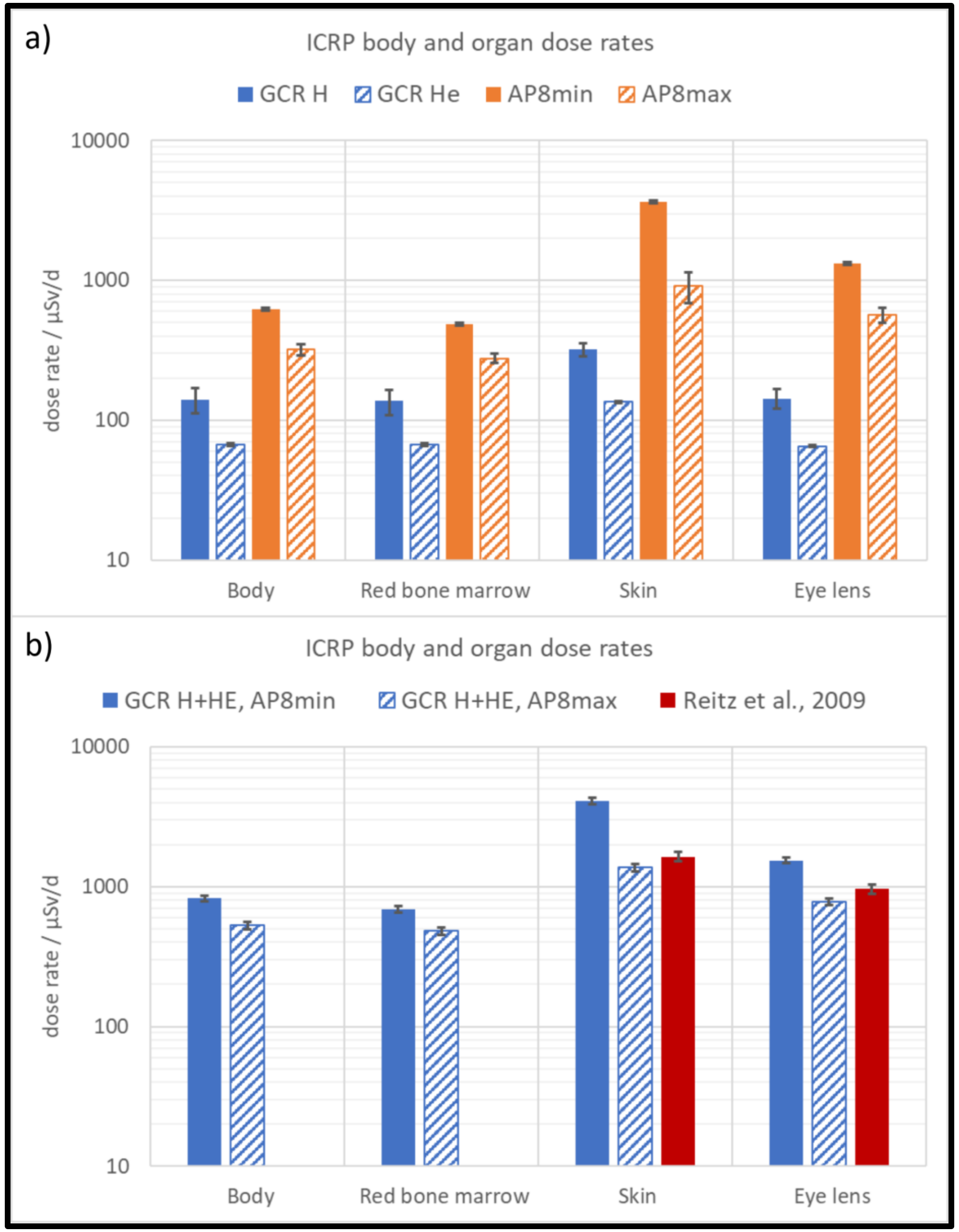
Channel	E_l	E_u	E_c
F1	5.000	7.231	6.013
F2	7.231	10.46	8.695
F3	10.46	15.12	12.57
F4	15.12	21.87	18.18
F5	21.87	31.62	26.30
F6	31.62	45.73	38.03
F7	45.73	66.13	54.99
F8	66.13	95.64	79.53
F9	95.64	138.3	115.0
F10	138.3	200.0	166.3
F11	200.0	289.2	240.5
F12	289.2	418.3	347.8
F13	418.3	604.9	503.0
F14	604.9	874.7	727.4



SEPEM H RDS v3-1-beta
Proton Flux (cm^-2 s^-1 sr^-1 MeV^-1)
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-6
10^-8
1989-10-22 00:00:00
1989-10-29 00:00:00
1989-11-05 00:00:00
5.00- 7.23 MeV
7.23- 10.46 MeV
10.46- 15.12 MeV
15.12- 21.87 MeV
21.87- 31.62 MeV
31.62- 45.73 MeV
45.73- 66.13 MeV
66.13- 95.64 MeV
95.64-138.3 MeV
138.3 -200.0 MeV
200.0 -289.2 MeV
289.2 -418.3 MeV
418.3 -604.9 MeV
604.9 -874.7 MeV
©SEPEM
2024

MATROSHKA EVA-related scenario

- 370 km, 51.6° orbit associated with ISS in 2004
- Geomagnetically shielded DLR GCR model for protons and He
- AP8 at max & min
- GRAS calculation of fluences at spherical detector, R=30 cm, surrounded by carbon sphere, R=45 cm, thickness=2.3 mm
- ICRP-123 fluence-to-dose conversion factors:
  - Effective dose equivalent, H_E (column 1, "Body")
  - Dose equivalent, $H_{T,Q}$(columns 2-4)

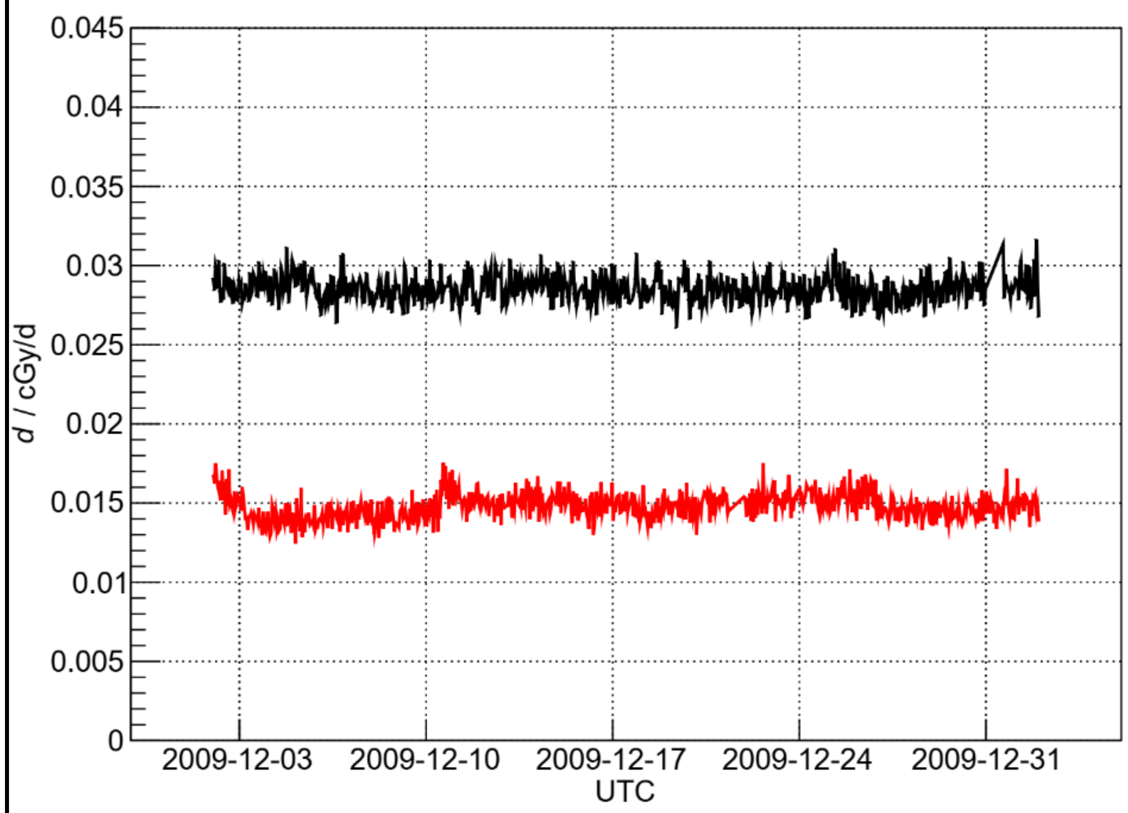


CRaTER Instrument / Lunar Reconnaissance Orbiter (LRO)

- 2-Day 50km lunar orbit
- DLR GCR model proton & He flux with lunar shadowing
- MULASSIS (1D) geometry with:
  - 2 mm spherical Al shield
  - 1 mm spherical Si detector

HIERRAS results (cGy/d):

- Solar minimum:
  - H = 0.0112 ±0.0003
  - He = 0.0044 ±0.0001
- Solar maximum:
  - H = 0.0044 ±0.0001
  - He = 0.0021 ±<0.0001



CRaTER D5/D6 dose rate for solar minimum (2009, black line) and maximum (2015, red line)

Summary

- HIERRAS System is already a comprehensive web-based environment to predict human radiation exposure quantities for complete missions, addressing:
  - Trajectory definition & environment specification from models and historic *in situ* data
  - Geant4 1D and 3D radiation transport simulation in spacecraft, habitats and planetary/lunar environments
  - Dose calculations based on fluence/dose coefficients, or absorbed doses in phantom
  - TID, TNID, solar cell degradation and SEE rates
- Comprehensive and user-friendly GUI
- The system includes:
  - Modularised with well-defined interfaces – improves upgradability
  - Use of Network of Models – makes future adaptation to alternative/newer models easier
  - Can treat analyses at fine-detailed levels & aggregate results to mission-level
  - Background processing of lengthy Geant4 runs with notification to user of progress
  - Results data traceability – audit trail

Future Developments for TRL > 4

- Further work required to extend/complete the intended range of analysis
  - Time-dependent radiobiological dose analysis
  - Completion of aggregation analysis:
    - Treatment of astronaut occupancy levels
    - Human exposure quantities for different phases
  - Error analysis – incl. propagation through each calculation stage
  - Update to be compatible with G4 11.3-based ESA apps and latest NoM
  - Improve/optimize CPU load-balancing for multi-threaded + multi-user cases
- SEP forecasting models
- Improve focus of output quantities relevant to human exposures for S/C design, mission planning, and mission operation
- Improve and test general useability, robustness, & consistency of system/results required for higher TRL levels

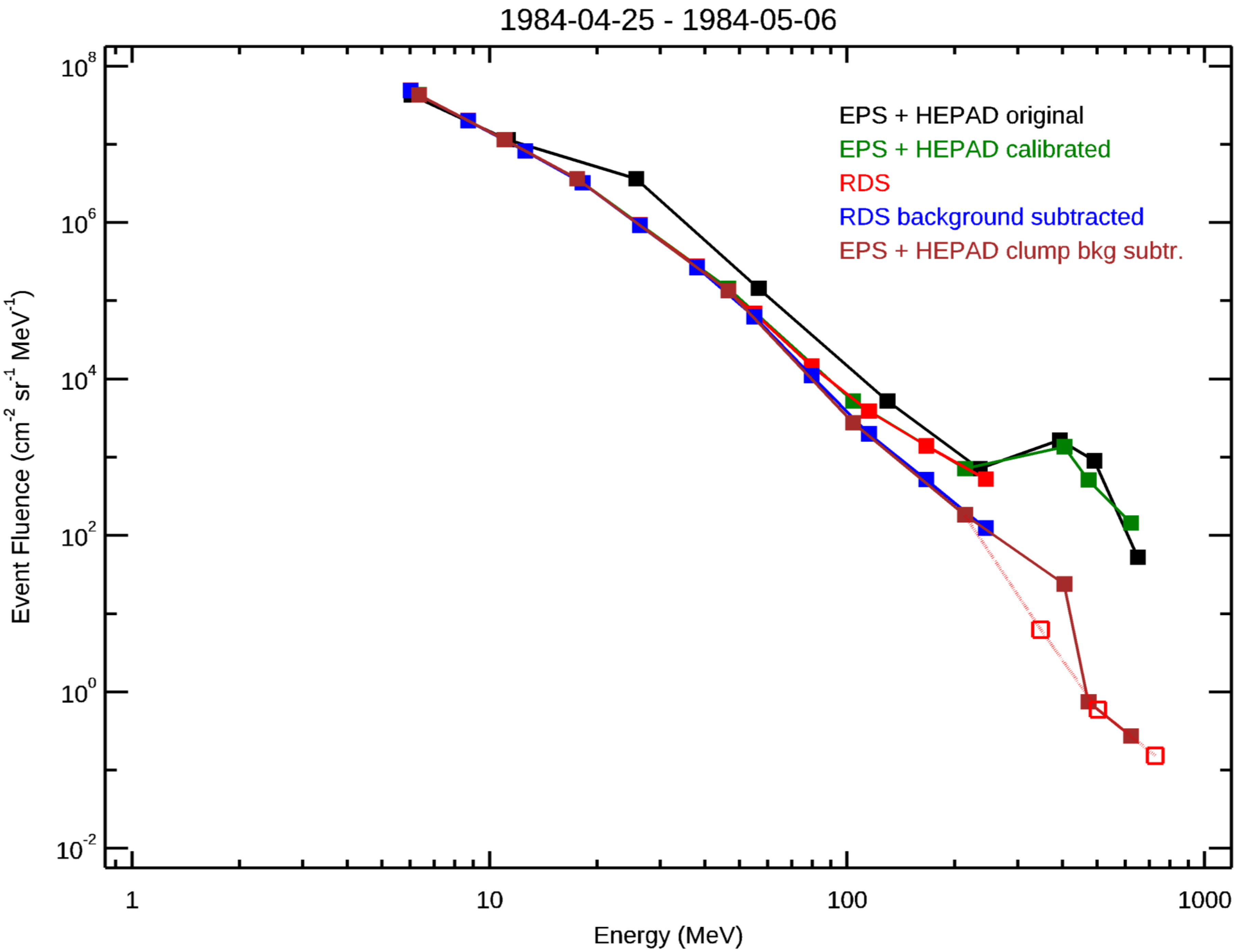
Thank you for your attention!

Additional Material

G4 Space Apps Docker

- Installation of Geant4 and ESA G4 models can be a challenge!
- G4 Space Apps: Highly portable Linux virtual machine
  comprising:
  - Geant4 toolkit and data files
  - ESA Geant4 tools:
    - GRAS (3D shielding and effects simulation)
    - MULASSIS (multi-layered 1D shielding simulation)
    - SSAT (sector shielding analysis)
    - CIRVis (interactive 3D geometry visualisation)
    - MAGNETOCOSMICS
    - GRAPPA with MCD v5.3
  - All system libraries to run these applications
- Very easy to distribute, install and run on Windows or Linux OS
- HIERRAS and NoM System use of G4 Space Apps Docker

- Example cases
  (for those who speak 'dockerese'):
  - MULASSIS:
    - *docker run --rm -it -v "<<host_vol>>:/opt/g4pub" --name g4exe g4_space_apps mulassis <<macrofile>>*
  - GRAS:
    - *docker run --rm -it -v "<<host_vol>>:/opt/g4pub" --name g4exe g4_space_apps gras <<macrofile>>*
  - Execution of docker in "server mode" on a Linux docker host
    - *docker run --rm -it -v "<<host_vol >>:/opt/g4pub" --name g4_exe g4_space_apps server*
    - *sshpass -p g4user ssh g4user@<<g4_exe_IP>> 'cd /opt/g4pub; mulassis <<macrofile>>'*



1984-04-25 - 1984-05-06
EPS + HEPAD original
EPS + HEPAD calibrated
RDS
RDS background subtracted
EPS + HEPAD clump bkg subtr.
Event Fluence (cm^{-2} sr^{-1} MeV^{-1})
Energy (MeV)
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
1
10
100
1000