NAIRAS Model Nowcasting and Forecasting of the Aviation Radiation Environment

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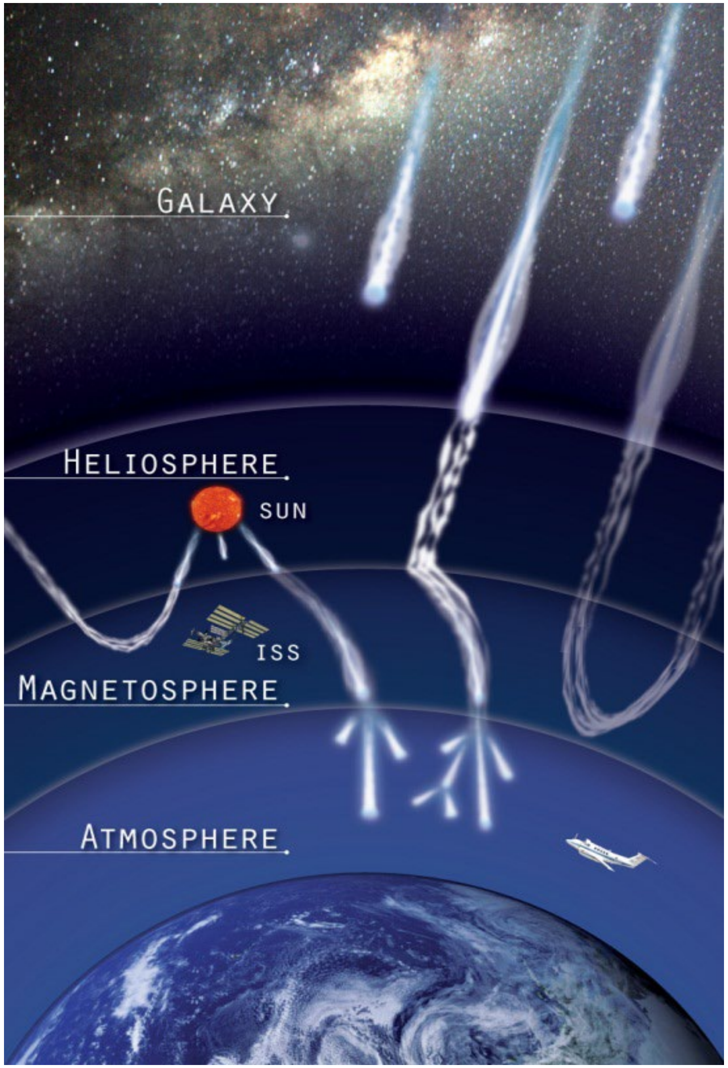
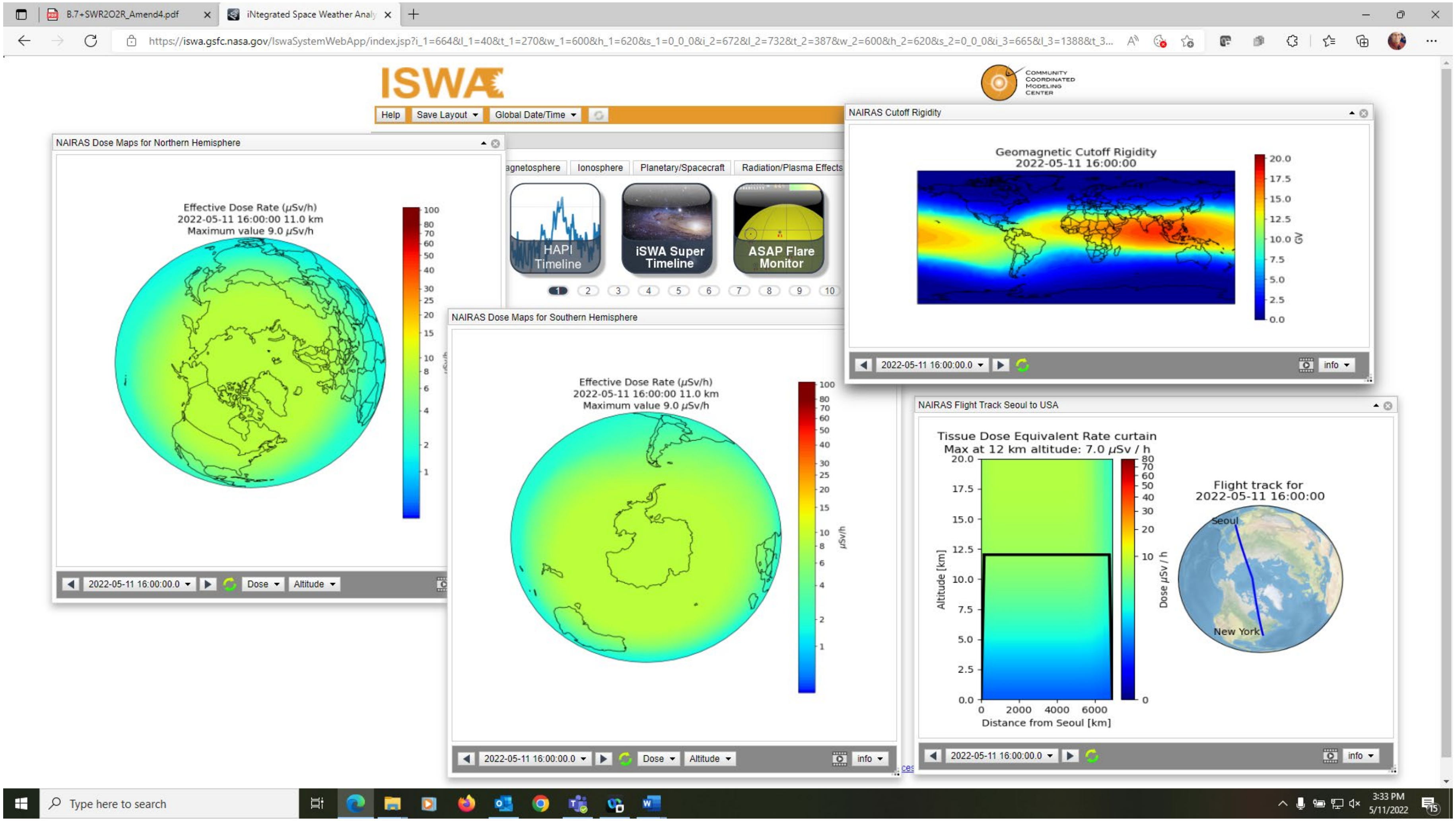
NAIRAS Model

- **Nowcast of Aerospace Ionizing RAdiation System (NAIRAS) Model**
  - Running in real-time on NASA computer cluster since 2011, results hosted on Space Environment Technologies server/website
  - Running in real-time at NASA Community Coordinated Modeling Center (CCMC) since 2020
- **Key Model Features**
  - Global atmosphere ionizing radiation environment model
  - 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 Development**
  - Improved SEP dose nowcast/forecast
  - Extend to low-Earth orbit (**LEO**) environment
  - Single-Event Effects (**SEE**) radiation risk assessment quantities
  - Run-on-Request (**RoR**) @ CCMC



Real-Time NAIRAS @ CCMC

Integrated Space Weather Analysis (iSWA) System



NAIRAS Run-On-Request User Input

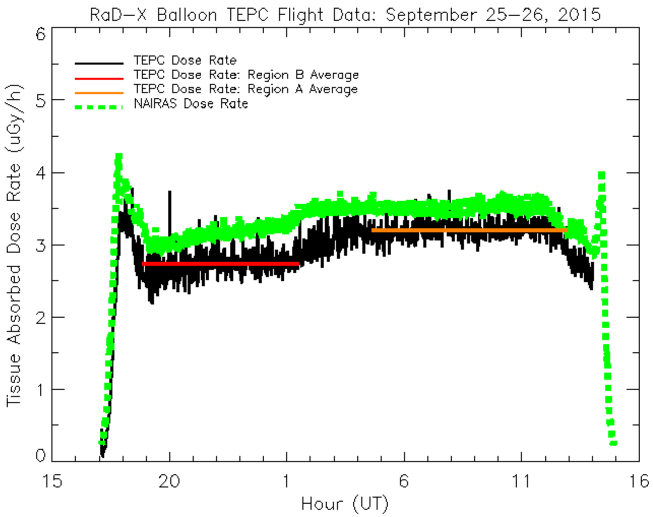
Availability: RoR @ CCMC in Spring 2023

Table: RoR Capability Summary and Description

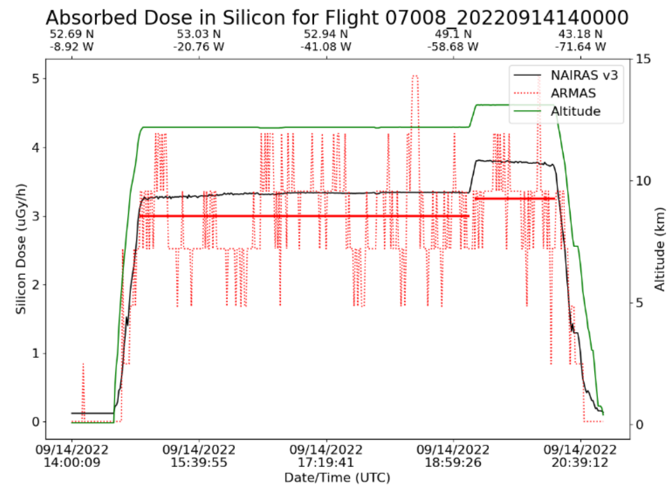
<table>
<tr><th>Run Option</th><th colspan="2">Output Quantities</th><th>User Input</th></tr>
<tr><td>Global Dosimetric</td><td colspan="2">Absorbed dose in silicon, absorbed dose in tissue, dose equivalent, ambient dose equivalent, effective dose</td><td>Start/End Date-Time</td></tr>
<tr><td rowspan="5">Flight Trajectory</td><td colspan="2">Dosimetric & Flux/Fluence</td><td>Trajectory file (date/time/lat/lon/alt)</td></tr>
<tr><td>Dosimetric</td><td>Same as global run</td><td>Shielding depths for dosimetric calculations</td></tr>
<tr><td rowspan="3">Flux/Fluence</td><td></td><td>Shielding depths for flux/fluence calculations</td></tr>
<tr><td>Integral
• GCR LET
• SEP proton
• TRP proton</td><td>Lower LET/energy bounds of integral quantity</td></tr>
<tr><td>Differential
• GCR LET
• SEP proton
• TRP proton</td><td>N/A (full model differential spectra written to output)</td></tr>
</table>

NAIRAS Validation @ 0-40 km

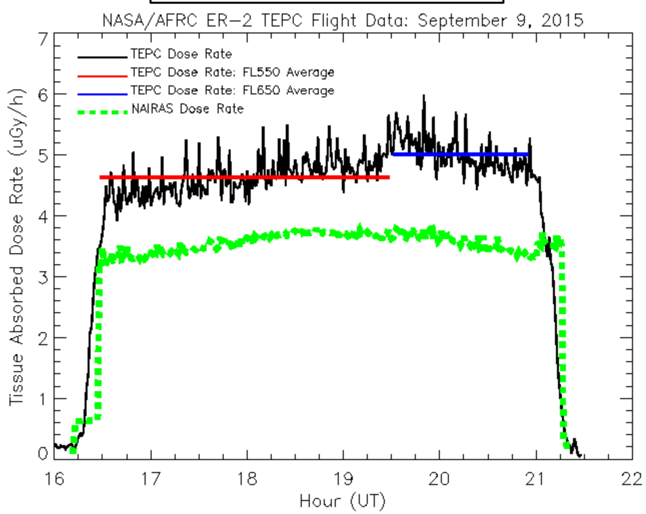
RaD-X Region A: 21 km < Z < 27 km; Region B: Z >32.5 km



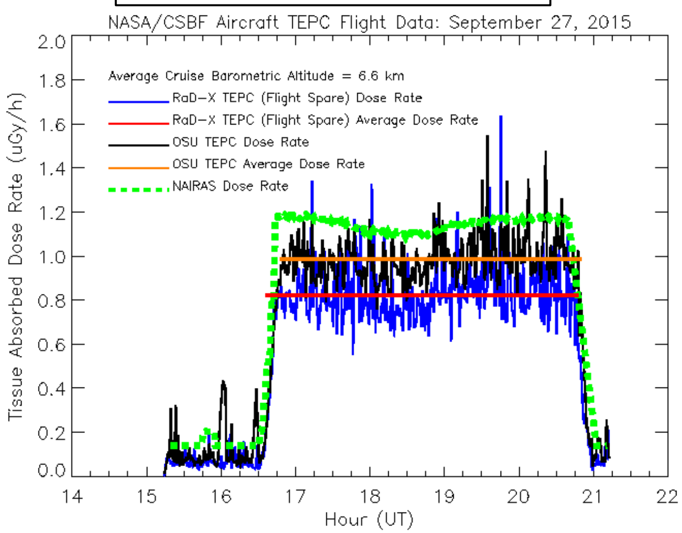
US Corporate Aircraft: EINN-KBDL



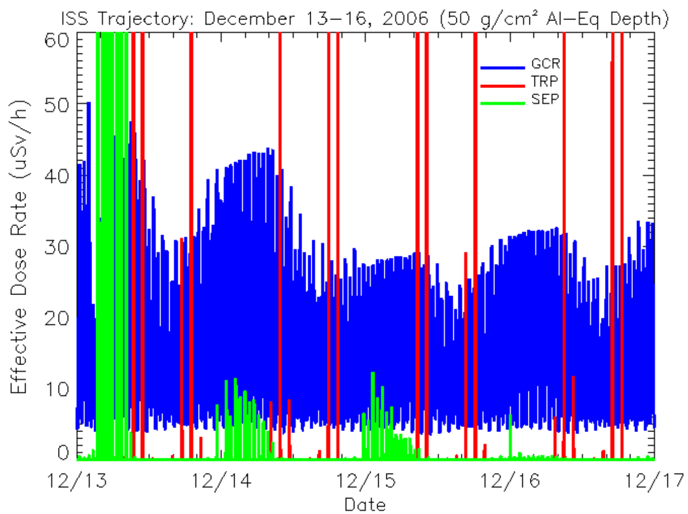
RaD-X ER-2: Z = 17km, 20km



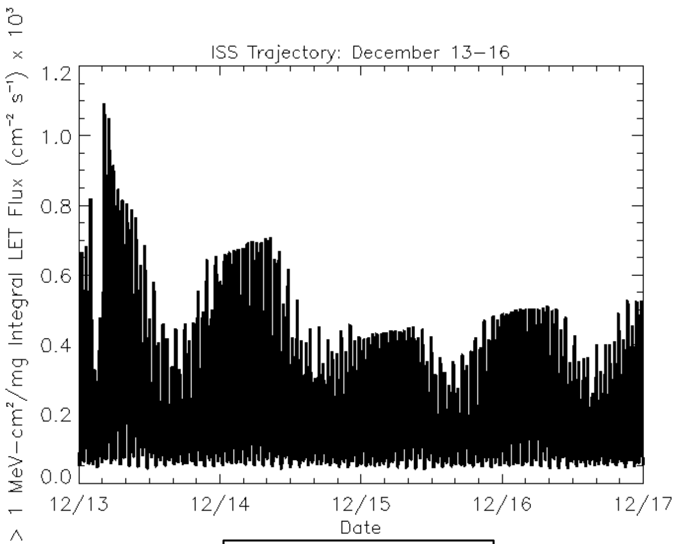
RaD-X CSBF Chase Plane: Z = 6.6 km



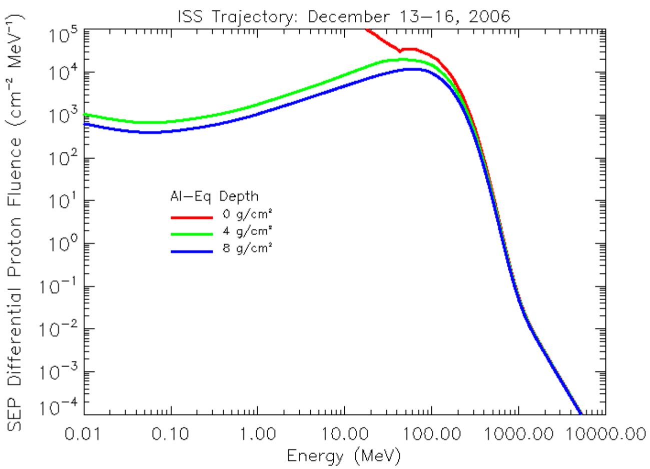
Dec 2006 SEP Events: ISS Radiation

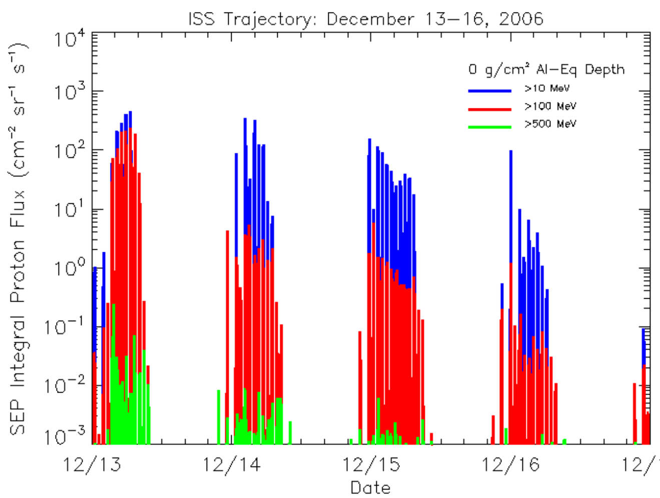


Al Shielding: 50 g/cm²



Al Shielding: 4 g/cm²



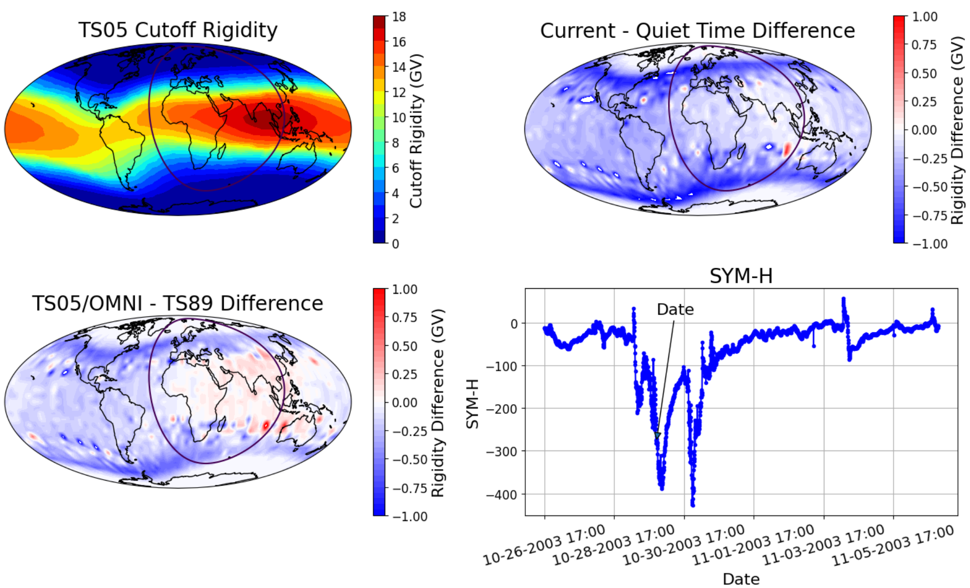


Geomagnetic Cutoff Rigidity Model

- **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

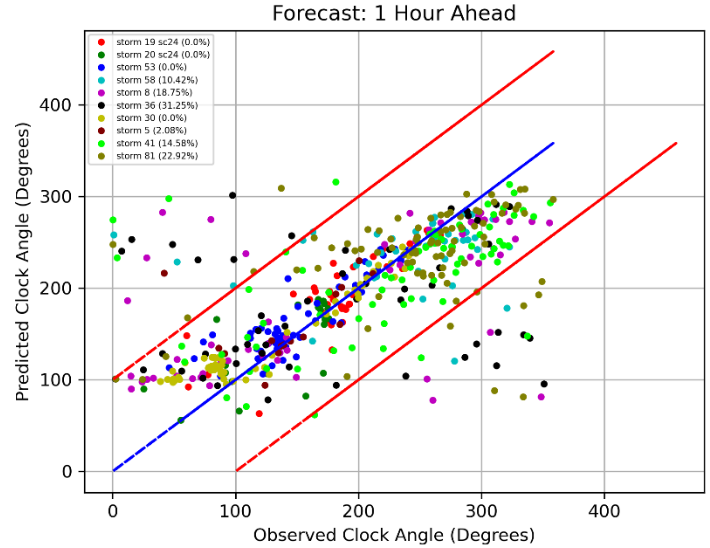


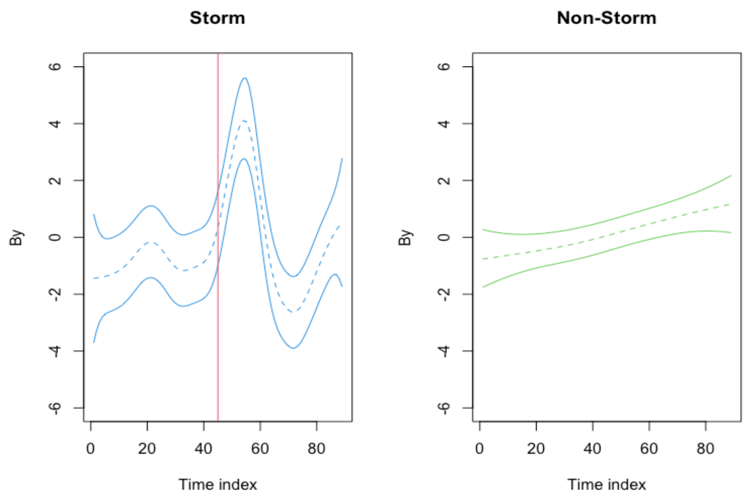
Top Right: Largest suppression of cutoff (~1 GV) (open-closed field boundary) occurs in dusk sector due to max build-up of partial ring current in TS05 (IMF Bz dependent)

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

Machine Learning Kp/Dst-Forecast

- **Kp/Dst-Forecast Approach**
  - WSA-ENLIL-Cone solar wind parameters forecast
  - Empirical formula to get Kp/Dst as function of solar wind speed, total IMF and IMF clock angle (Newell et al., 2007)
  - However, need separate IMF clock angle forecast to improve state-of-art (@CCMC) since WSA-ENLIL-Cone has no internal coronal mass ejection (CME) structure
- **Machine Learning IMF Clock Angle**
  - Trained on Advanced Composition Explorer (ACE) data (solar wind velocity and density, IMF B-components, derived clock angle) from large geomagnetic storms (Dst min < -100 nT) during solar cycles 23 and 24
  - Developed deterministic and stochastic models
  - Forecast 1-12 hours ahead
- **Key Results**
  - IMF clock angle predictions provide improvement over current operational Kp/Dst models at CCMC (top right). However, beyond the first couple hours the performance is unacceptable
  - Improved performance sought using Functional Data Analysis (FDA) methods (bottom right)

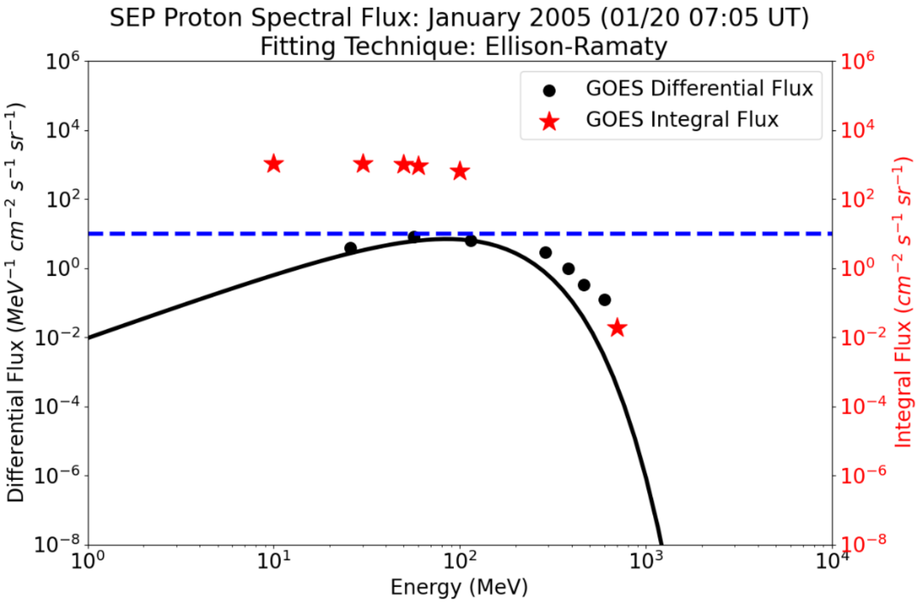




Functional means with 95% uncertainty bands. Vertical line marks storm onset

Update to SEP Spectral Fitting

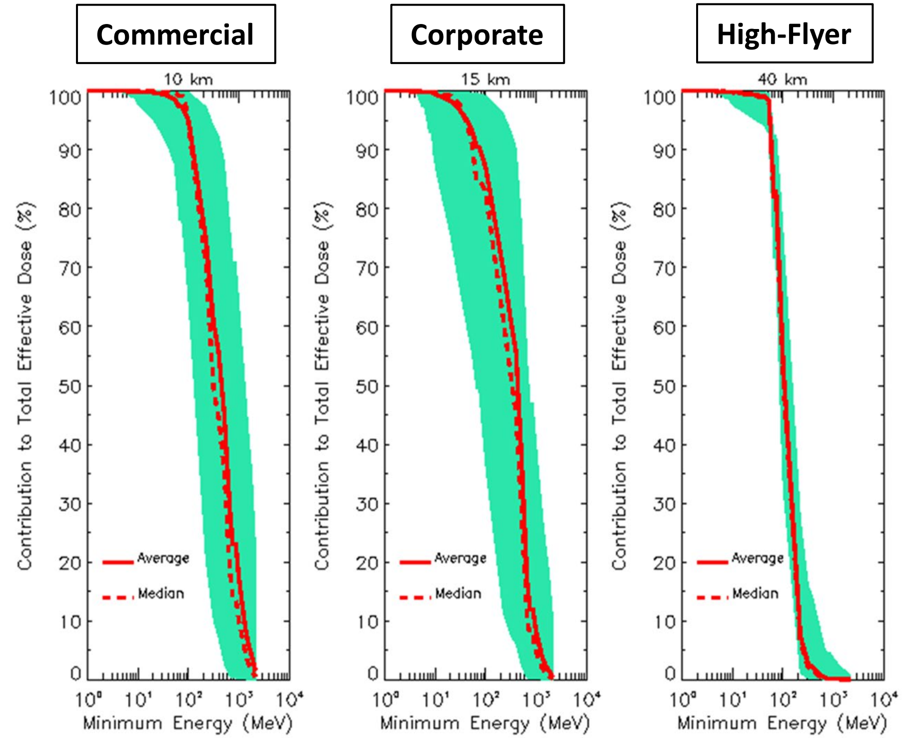
- **New Approach**
  - Fit spectrum to Geostationary Operational Environmental Satellites (GOES) integral proton flux rather than differential flux measurements
  - Fit four functional forms to GOES integral proton flux
  - Choose solution with minimum chi-square
- **Benefits**
  - Improved robustness
    - Difficulty fitting GOES differential channels at event onset and for weak-to-moderate events
    - Extrapolation beyond highest differential energy channel (~500 MeV) requires introducing arbitrary and subjective criteria
    - 50% or more of SEP effective dose at large material depths (aviation altitudes) comes from > 500 MeV protons
  - Preliminary simulations using neutron monitor data suggest fitting to GOES integral proton flux may better represent the relativistic protons during GLEs
  - New integral flux fitting approach provides a pathway to develop a SEP proton spectrum forecast by coupling NAIRAS with UMASEP



SEP proton spectrum (black line) fit to GOES integral flux and comparison to GOES differential proton flux. Horizontal blue line indicates NOAA/SWPC SEP event threshold for >10 MeV proton flux.

Historical SEP Events

- **Free-Space SEP Spectra**
  - Spectral Fits to 65 historical GLE/SEP events (*Raukunen et al., SWSC, 8(A04), 2018*)
  - Fits based on GOES differential proton flux and neutron monitor data
  - Event-accumulated spectra
- **Contribution to event-accumulated SEP effective dose from energies > minimum energy**
  - Commercial and private business jet altitudes: 50% or more of the effective dose is due to proton energies > 500 MeV
  - High-flyer aircraft or stratospheric balloon altitudes: 50% of more of the effective dose is due to proton energies > 100 MeV

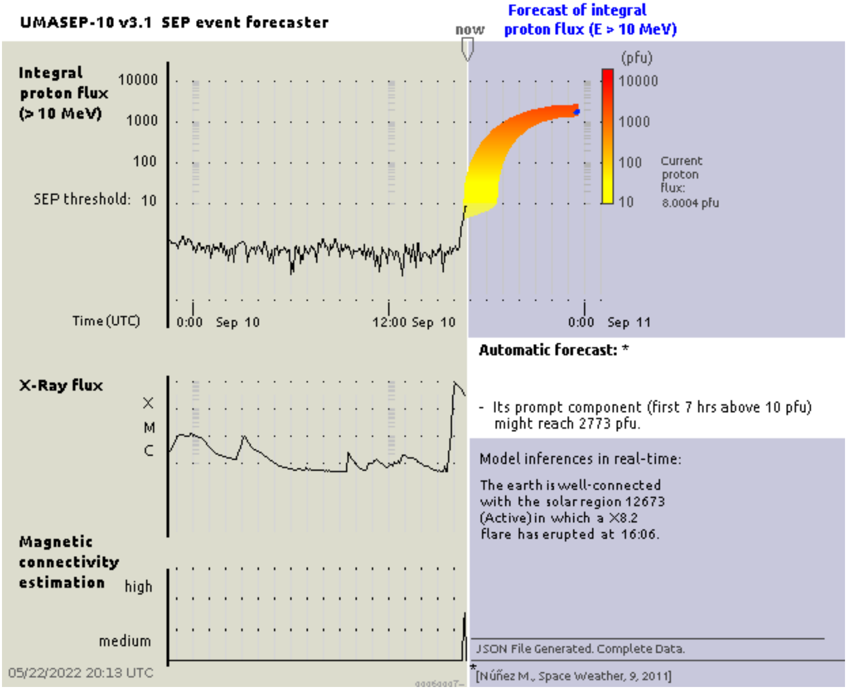


Effective doses computed at the pole (zero cutoff)

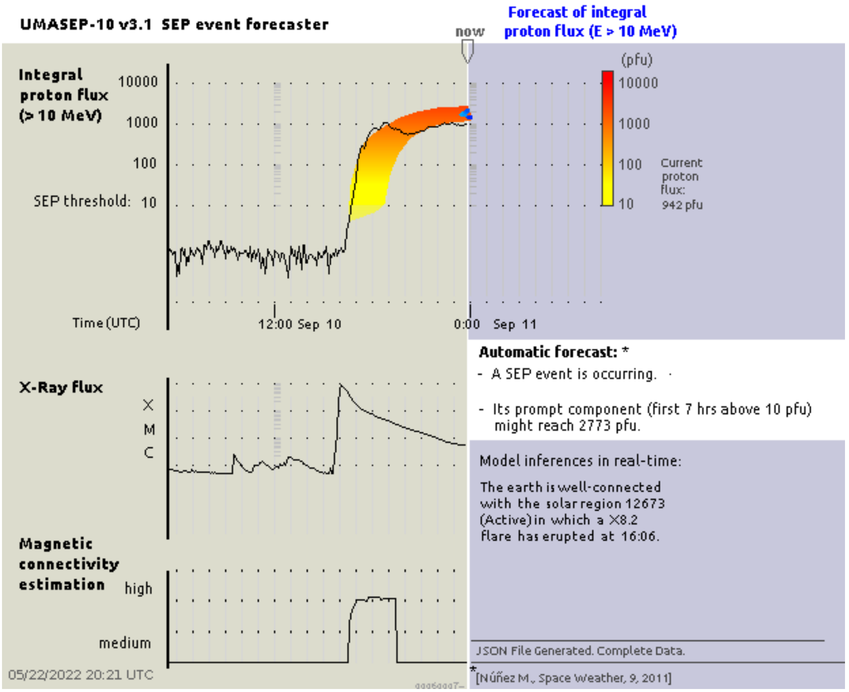
UMASEP Forecast: September 2017

Example Below: >10 MeV Peak Integral Proton Flux

Forecast Issue Time 09/10/2017 16:40 UT



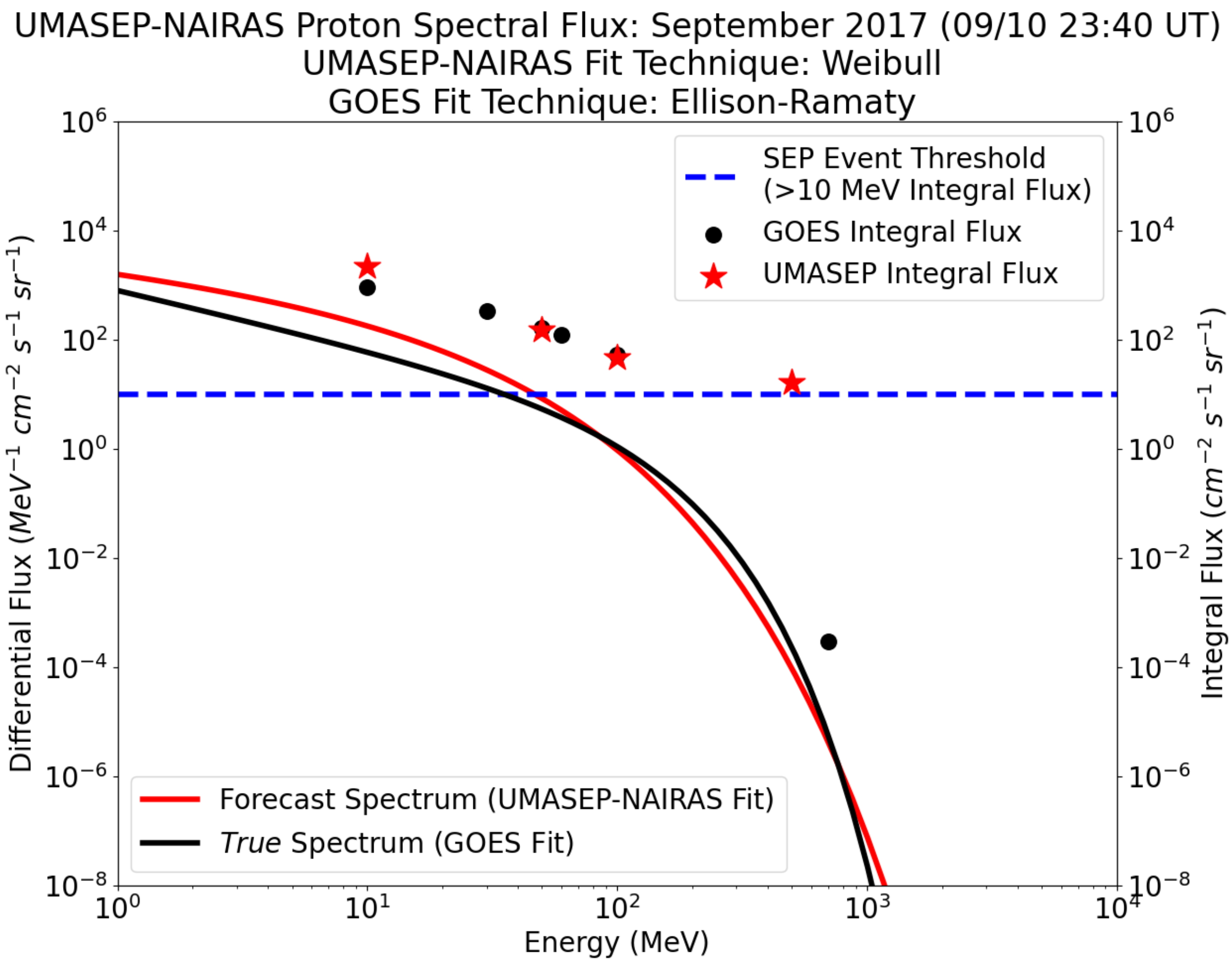
Forecast Window: Issue Time + 7 hours



Other UMASEP Peak Integral Proton Flux Forecast Products: >50 MeV, >100 MeV, >500 MeV

UMASEP-NAIRAS SEP Forecast

7 hours after UMASEP >10 MeV integral proton flux forecast issue time



Summary and Conclusions

- **Major NAIRAS Code Deliverables to CCMC**
  - **NAIRAS Real-Time Global Dosimetric Quantities (Publicly Available Now)**
  - **NAIRAS RoR Capability (Publicly Accessible in Spring 2023)**
  - **NAIRAS Improved SEP Proton Spectral Fitting Algorithm (Running in Both RoR and Real-Rime Versions)**
- **Significant Improvements/Extensions to NAIRAS**
  - **Model domain extended from Earth surface to space**
  - **Model applications extended to assess both human radiation exposure and SEEs in avionic system**
- **NAIRAS Validation Against RaD-X Flight Campaign Observations and Corporate Aircraft ARMAS Measurements (GCR Conditions)**
  - **All dosimetric quantities agree within 30% from 0-40 km**
- **SEP Dose Forecast Development**
  - **Geomagnetic Cutoff Rigidity Forecast Model (Under Development)**
  - **UMASEP-NAIRAS Coupling for SEP Proton Spectrum Forecast (Under Development) → Preliminary results encouraging**