NAIRAS Model Improvements to Aviation Radiation Dose Predictions

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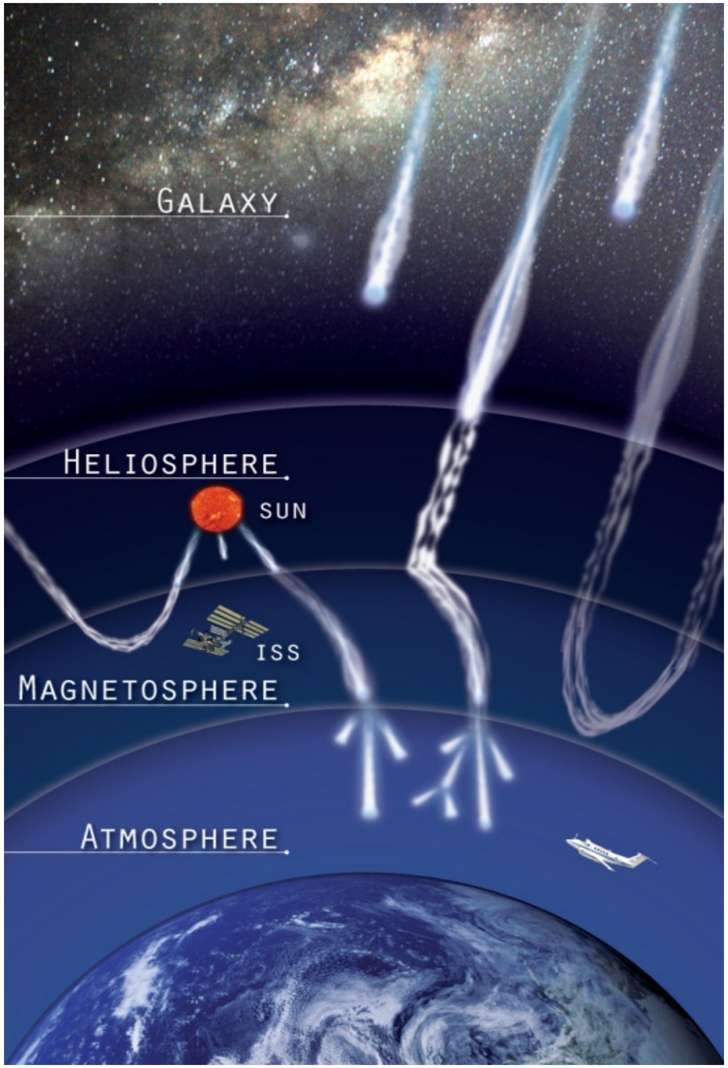
NAIRAS Model

- **Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) Model**
  - Running in real-time on **LaRC** computer cluster since 2011, results hosted on **Space Environment Technologies** server/website
  - Running in real-time at NASA GSFC Community Coordinated Modeling Center (**CCMC)** since 2020
- **Key Model Features**
  - Global atmosphere ionizing radiation environment model
  - Physics-based transport (**HZETRN**)
  - Real-time inclusion of solar energetic particle (**SEP**) radiation
  - Real-time solar-magnetospheric effects on radiation (semi-physics-based cutoff model: **CISM-Dartmouth-NASA**)
- **New/Current Model Development**
  - Improved SEP dose nowcast & forecast
  - Extend to **LEO** environment
  - Single-Event Effects (**SEE**) radiation risk assessment quantities
  - Run-on-Request (**RoR**) @ CCMC

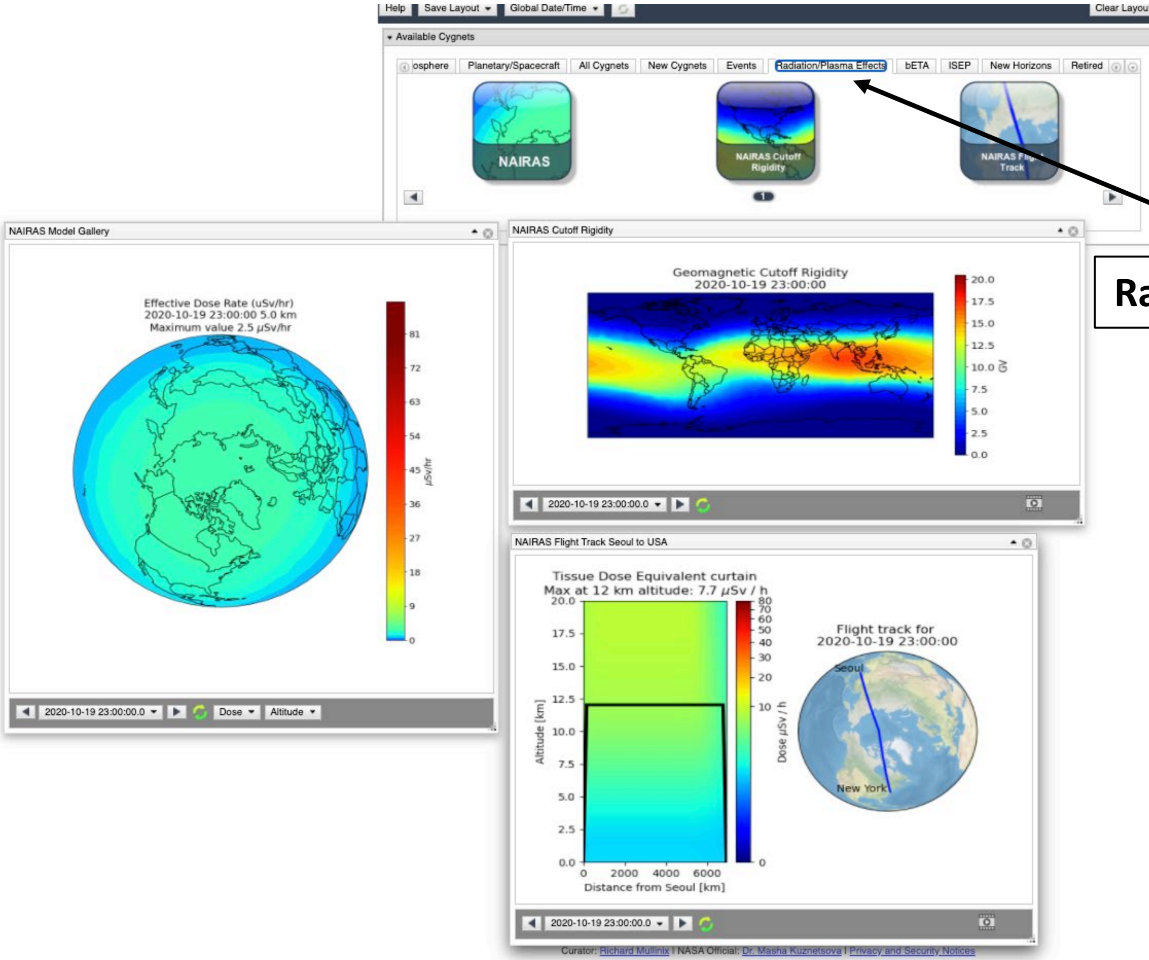


Outline

- **NAIRAS Real-Time Interface @ CCMC (publicly available)**
- **NAIRAS Run-on-Request (RoR) Capability @ CCMC (coming soon)**
  - Model updates and improvements
  - Expanded output products
  - LEO orbit example
  - Comparison to NASA RaD-X balloon flight measurements
- **SEP Improved Nowcast and Forecast Developments (under development)**
  - Geomagnetic cutoff rigidity
  - SEP Proton Spectral Fitting
- **Summary & Conclusions**

Real-Time NAIRAS @ CCMC/iSWA

iSWA: Integrated Space Weather Analysis System



Radiation/Plasma Effects Tab

https://iswa.gsfc.nasa.gov/IswaSystemWebApp/

NAIRAS Model Improvements

- **LEO radiation environment (trapped protons)**
- **Extend GCR model to ultra-heavy nuclei (Z=29-92,A=64-238) for SEE assessment from high-LET processes**
- **RoR Capability**
  - **Output**: **(1)** global dosimetric quantities and **(2)** flight trajectory dosimetric and flux/fluence quantities
  - Differential/integral flux/fluence quantities useful for SEE assessment
  - Generic input flight trajectory capability (aircraft, balloon, spacecraft)
  - Improved atmospheric transport: off-zenith directions included
- **Expanded geomagnetic cutoff rigidity model to use either TS05 (previous version) or T89 magnetospheric magnetic field models**
- **Improved SEP proton spectral fitting to address**
  - Representing relativistic protons during GLEs
  - Overall algorithm robustness in real-time operation

NAIRAS RoR Output Products

1. **Global Atmospheric Dosimetric Quantities**
    - **Dose rate products**: absorbed dose in silicon, absorbed dose in tissue, dose equivalent, ambient dose equivalent, and effective dose
    - **Model grid**: 1 x 1 lat/lon, 0-90 km @ 1km increments, and 1-hour time cadence
    - **Input**: Start/End Date-Time
    - **Application**: global context and situational awareness of the atmospheric radiation environment; enable retrospective analysis and verification and validation of the real-time version of the NAIRAS model

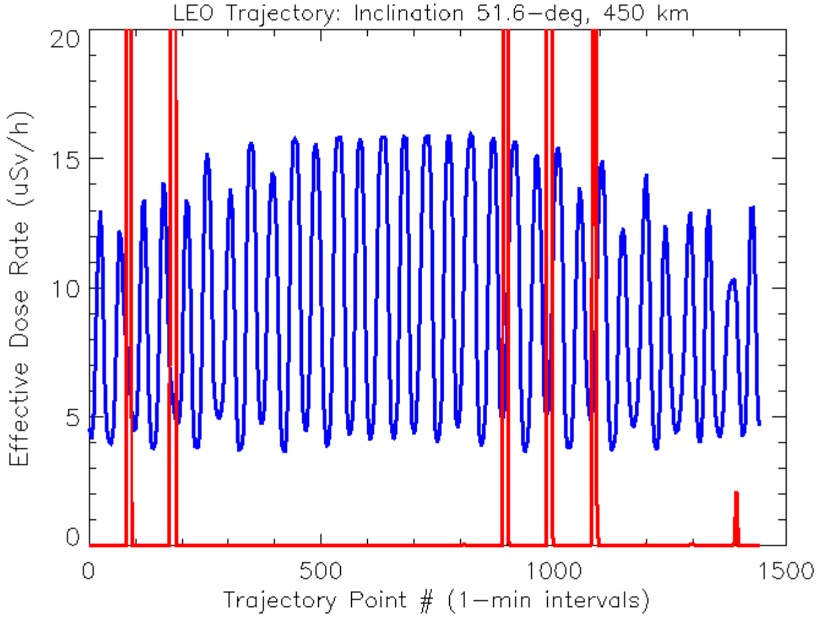
NAIRAS RoR Output Products

2. **Trajectory Dosimetric, Differential and Integral Flux and Fluence Quantities**
   - **Dose Quantities (same as for global products)**
     - Dosimetric quantities at each trajectory point
     - Time-integrated dosimetric quantities
   - **Integral Flux and Fluence Quantities**
     - GCR LET and trapped/SEP proton flux/fluence
     - **Input**: lower LET/energy bounds of integral quantities
   - **Differential Flux and Fluence Quantities**
     - GCR LET and trapped/SEP proton flux/fluence
   - **Input**: trajectory file, separate set of shielding depths for dosimetric and flux/fluence quantities
   - **Application**: detailed flight analysis and radiation environment characterization of individual microelectronic components and SEE assessment

NAIRAS GCR/TRP LEO Trajectory

- **NAIRAS Total Trajectory Effective Dose (per day)**
  - **GCR**: 215 uSv
  - **TRP**: 163 uSv
  - **Total**: 378 uSv
- **ISS Total Effective Dose (per day)**
  - **GCR**: 233 uSv (Wu et al., 1996)
  - **TRP**: 166 uSv (Wu et al., 1996)
  - **Total**: 438 uSv (Cucinotta, 2008)

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

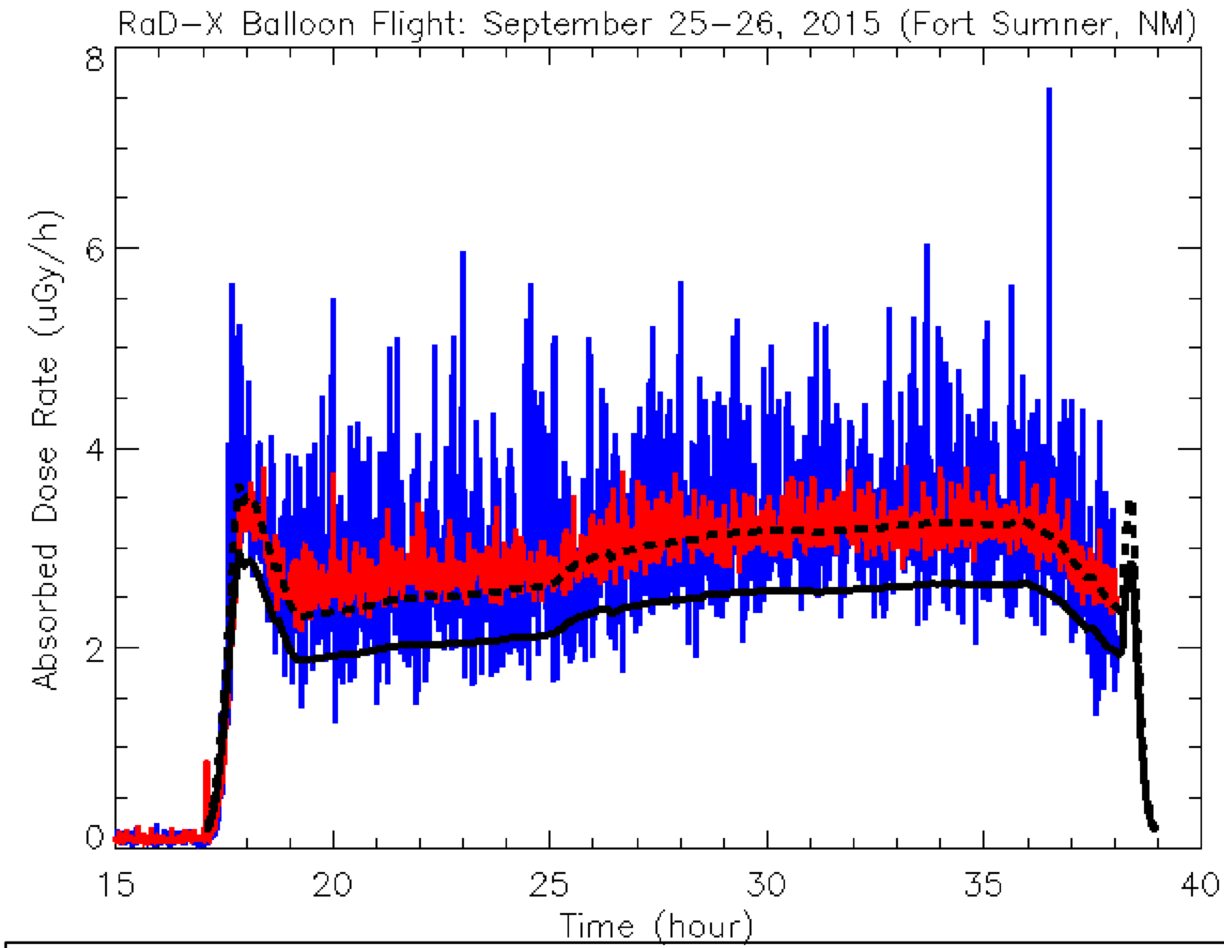


Blue: GCR effective dose rate

Red: TRP effective dose rate

Al Shielding: 50 g/cm^2

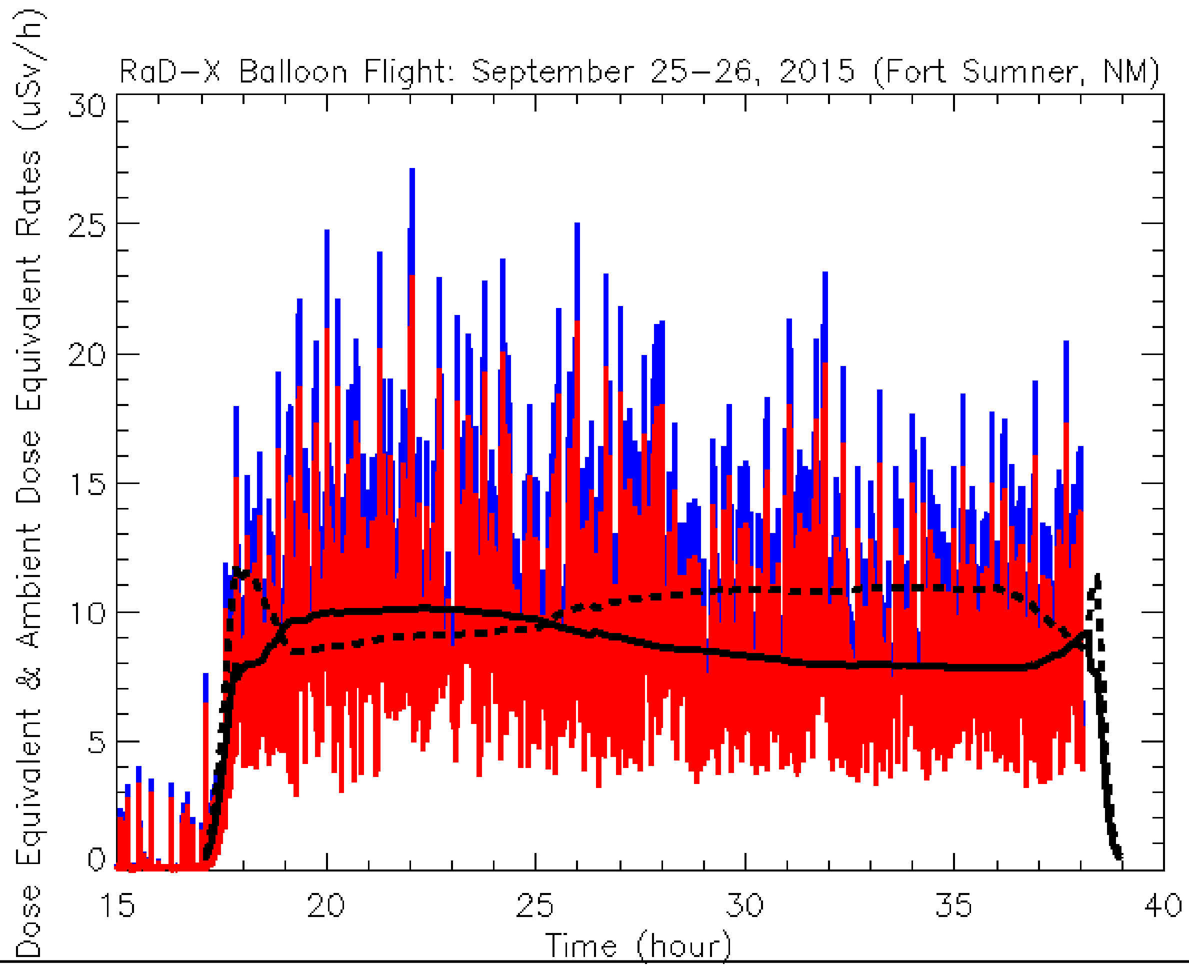
NASA RaD-X Balloon Flight



Liulin; TEPC; **NAIRAS Ti-Dose** (Dashed); **NAIRAS Si-Dose** (Solid)

Region A (Balt: 21-27 km) **Diff** = -0.2% **|** **Region B** (Balt: > 32.5 km) **Diff** = -8.4%

NASA RaD-X Balloon Flight



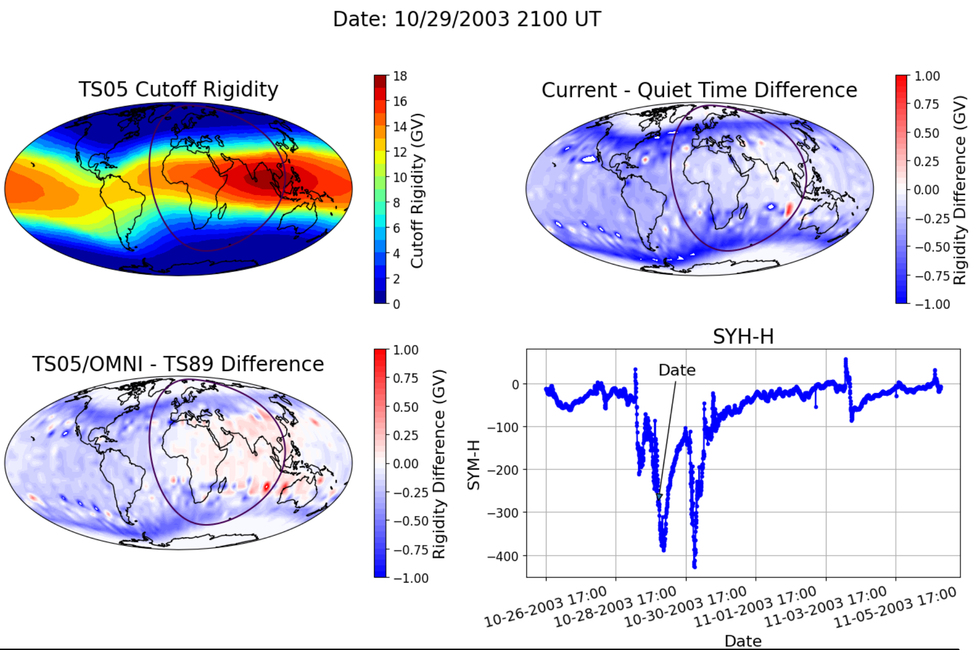
TEPC H*(10); TEPC DoseEq; **NAIRAS H*(10)** (Dashed); **NAIRAS DoseEq** (Solid)

Region A (Balt: 21-27 km) **DEq Diff** = 3.9% | **Region B** (Balt: > 32.5 km) **DEq Diff** = 5.2%

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, IMF, SYM-H/Dst, and other derivative solar wind quantities
  - **T89 →** parameterized by 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

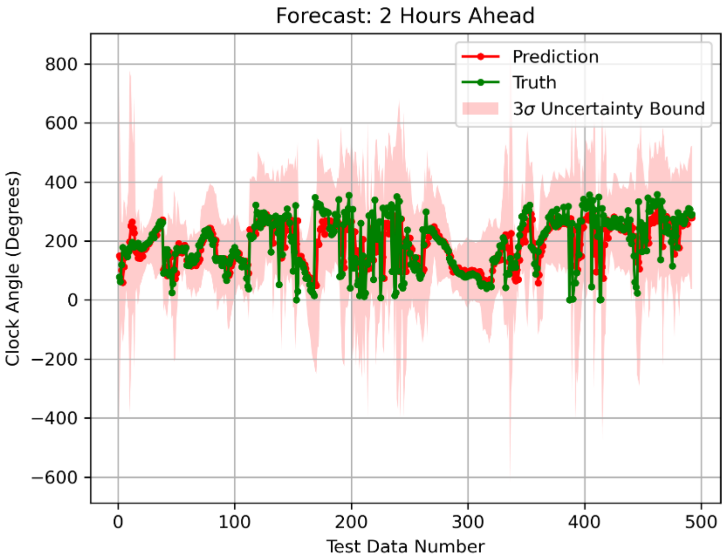


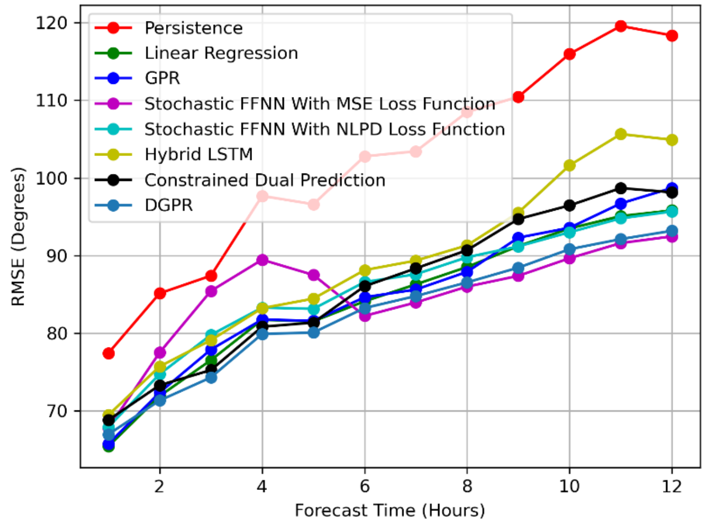
Top Right: Largest suppression of cutoff (~1 GV) (open-closed field boundary) occurs in dusk sector due to max build-up of partial ring current in TS05 (IMF Bz dependent)

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 and total IMF B-field and 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 CME structure
- **Machine Learning IMF Clock Angle**
  - Trained on 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 substantial improvement over current operational Kp/Dst models at CCMC
  - The stochastic models developed provide mean predictions and reliable uncertainty quantification
  - The models improve upon existing techniques and can be confidently used for at least 6 hours in advance or for longer/shorter hours at the discretion of the user





Real-Time SEP Spectral Fitting

- **Current Approach**
  - Fit four functional forms to GOES differential proton flux
  - Choose solution with minimum chi-square
  - **Issue**: solution can be unreliable/unphysical during weak events and event onset
- **Improvements**
  - Option to fit functional forms to either differential or integral GOES proton flux
  - Interpolated/extrapolate on differential GOES proton flux based on absolute chi-square criterion
  - **New:** promising technique that uses >500 MeV proton flux from GOES-R+ series without the use of functional forms (**next slide**)
- **SEP/GLE relativistic proton spectrum and pitch-angle distribution fitting algorithm for benchmarking real-time model**
  - Inferred from neutron monitor data (Mishev et al., 2013, 2014)
  - Testing and validating nowcast/forecast SEP spectral fitting approaches

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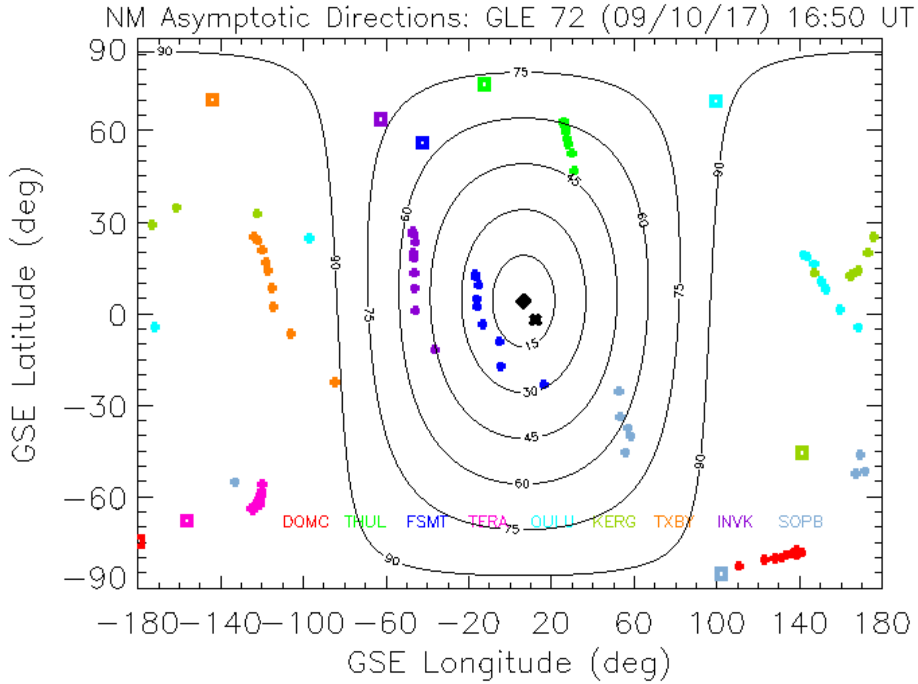

Legend:
- **Color Squares: NM Locations**
- **Color Plus: NM Asym Dir (1-5 GV)**
- **Black Diamond: SEP Proton Asymmetry Direction**
- **Black Asterisk: IMF Direction**
- **Contour: Proton Pitch-Angle (deg)**

New SEP Spectral Fitting Algorithm

SEP proton spectral fitting problematics

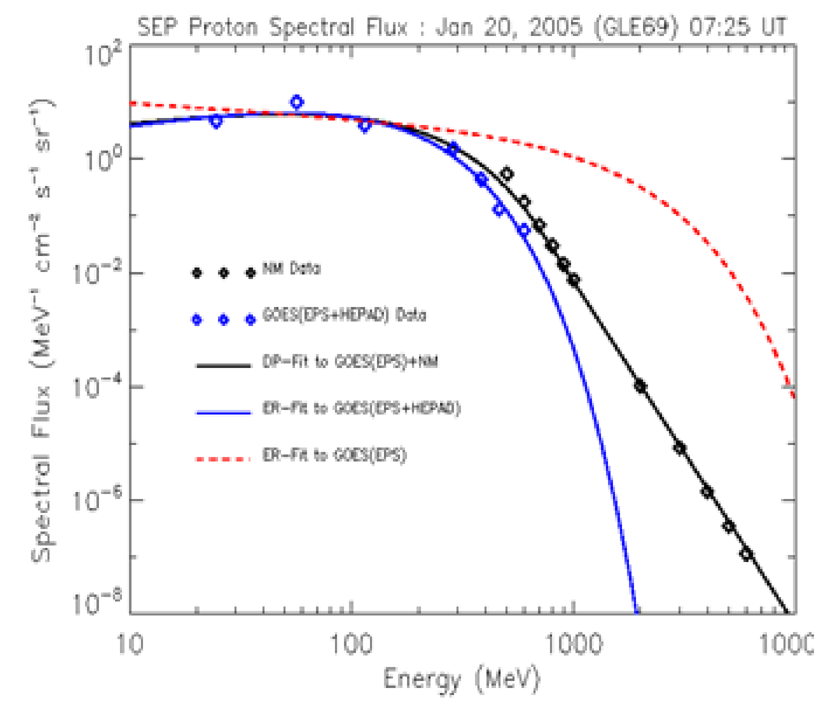

Figure 1: GOES (EPS+HEPAD) differential proton flux measurements and NM-inferred differential proton flux for January 20, 2005 SEP/GLE. Double power-law (DP-Fit) and Ellison-Ramatv (ER-Fit) functional fits to the observations.

New approach using GOES >500 MeV channel

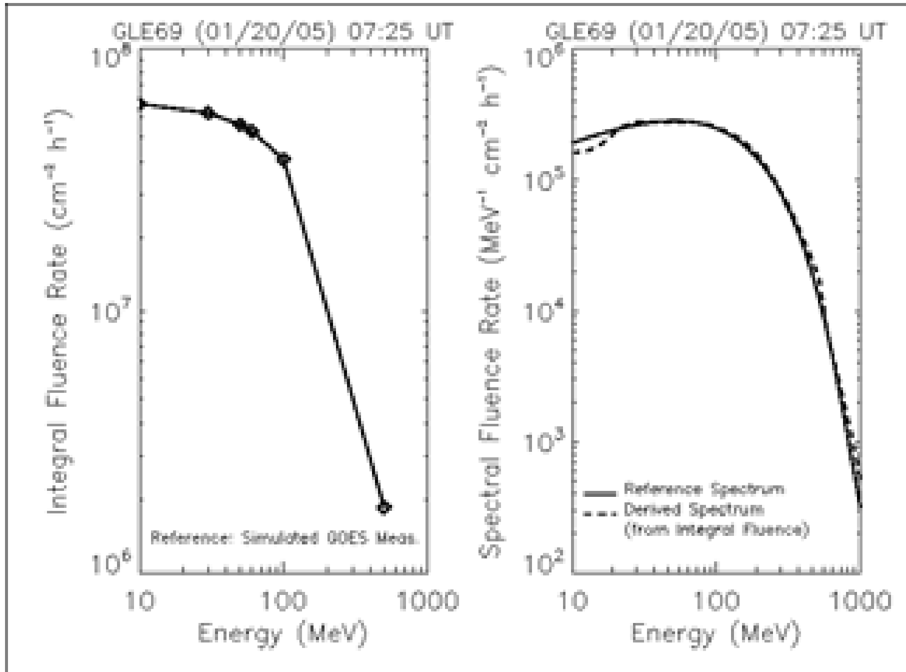

Figure 1: (left) Simulated GOES integral flux measurements (diamonds). (right) Results of new spectral flitting algorithm (dashed) compared to reference spectrum (solid) in previous figure.

Summary & Conclusions

- **Major NAIRAS Code Deliverables to CCMC/iSWA**
  - **NAIRAS Real-Time Global Dosimetric Quantities (Publicly Available Now)**
  - **NAIRAS RoR Capability (Publicly Accessible in Spring 2022)**
  - **NAIRAS Improved SEP Proton Spectral Fitting Algorithm (Operational in Fall 2022)**
- **Significant Improvements to NAIRAS Model Developed, Implemented and Tested**
- **SEP Dose Forecast Development**
  - **Geomagnetic Cutoff Rigidity Forecast Model (Under Development)**
  - **SEP Proton Spectrum Forecast (Begin this Year)**
- **NAIRAS Transition to CCMC and Example Output**
  - **See Gronoff et al. Session 11.5 on Wednesday**

Acknowledgements

- **NASA SMD Space Weather Operations to Research (ROSES Solicitation NNH19ZDA001N-SWO2R)**
  - SEP dose nowcast improvements and forecast development
- **NASA Engineering and Safety Center (NESC) Commercial Crew Program Post-Flight Reference Radiation Environments**
  - RoR capability and model improvements and development for SEE radiation risk assessment