NAIRAS Version 3.0

Atmospheric/Geospace Ionizing Radiation Environment Model

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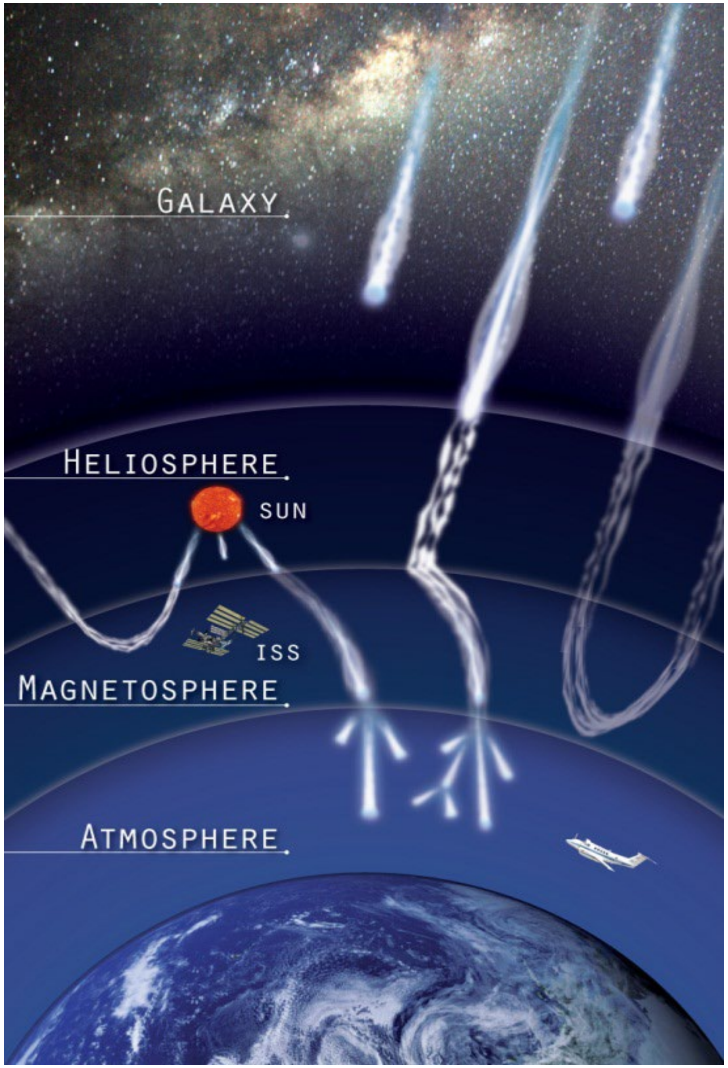
Projects/Team Members

1. **Improvements to Solar Energetic Particle (SEP) Dose Predictions (NASA Space Weather Science Applications Program)**
    - **NASA Langley Research Center (LaRC):** Chris Mertens, Guillaume Gronoff, Daniel Phoenix
    - **West Virginia University:** Piyush Mehta and Smriti Nandan Paul
    - **NASA Goddard Space Flight Center's Community Coordinated Modeling Center (CCMC):** Yihua Zheng
2. **Commercial Crew Program (CCP) Post-Flight Reference Radiation Environments (NESC)**
    - **NASA LaRC:** Chris Mertens, Guillaume Gronoff, Daniel Phoenix
    - **NASA Marshall Space Flight Center:** Joe Minow and Emily Willis
    - **NASA Kennedy Space Center:** Janessa Buhler
    - **Jet Propulsion Laboratory :** Insoo Jun
    - **CCMC:** Yihua Zheng

NAIRAS Model

- **Nowcast of Aerospace Ionizing RAdiation System (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 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 and forecast
  - Extend to low-Earth orbit (**LEO**) environment
  - Single-Event Effects (**SEE**) radiation risk assessment quantities
  - Run-on-Request (**RoR**) @ CCMC



Aviation Radiation Avionic Effects

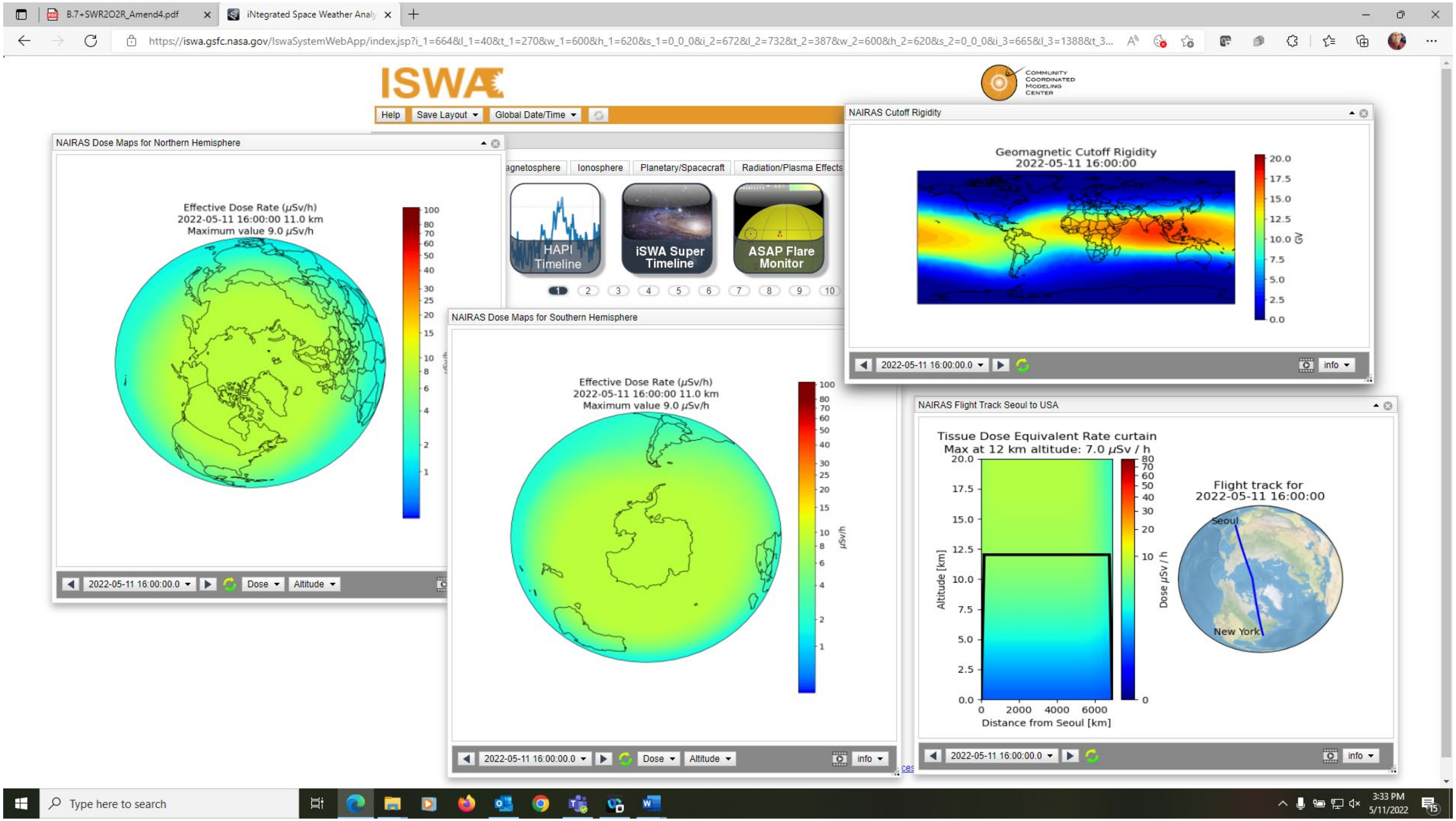
- Cosmic radiation effects on Avionics Systems
  - Interaction with semiconductor material, depositing charge causing single event effects (**SEE**) → change in logic state
  - Number of recorded instances of avionic **SEE** at GCR exposure levels (e.g., Normand et al., 1997, 2001; Olsen et al., 1993)
  - **SEE** in autopilot systems correlated with CR flux (altitude and latitude variation)
  - Avionics **SEE** occurrence rate (Royal Academy of Engineering, 2013)
    - **GCR: every 200 flight hours**
    - **Solar storm: > 1 per hour (scaled Feb 1956 event)**
  - **Near catastrophic event**: Qantas Airways flight 72, October 7, 2008 (pictured right)
    - SEE most probable explanation. All other environmental causes ruled out (ATSB, 2011)
    - Intermittent, incorrect inertial reference data initiated violent pitch-down command from flight control system
    - **110/303 passengers and 9/12 crew injured; 12 occupants seriously injured; 39 received hospital treatment**
- **For aircraft systems (as opposed to components) radiation standards and industry awareness less developed**
  - Guidance standards only
  - No regulatory standards

Outline

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

Real-Time NAIRAS @ CCMC

Integrated Space Weather Analysis (iSWA) System



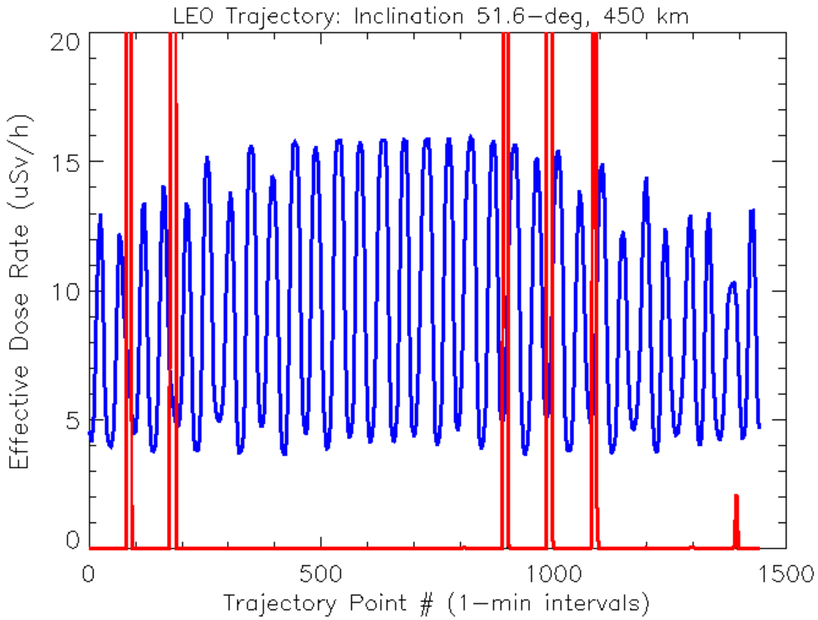
NAIRAS Model Improvements

- **LEO radiation environment (trapped protons)**
- **Extend GCR model to ultra-heavy nuclei (Z=29-92,A=64-238) for SEE assessment from high linear energy transfer (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 ground level enhancements (GLEs)
  - Overall algorithm robustness in real-time operation

NAIRAS Results for LEO Trajectory

- **NAIRAS Total Trajectory Effective Dose (per day)**
  - **GCR**: 215 uSv
  - **Trapped proton (TRP)**: 163 uSv
  - **Total**: 378 uSv
- **International Space Station (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



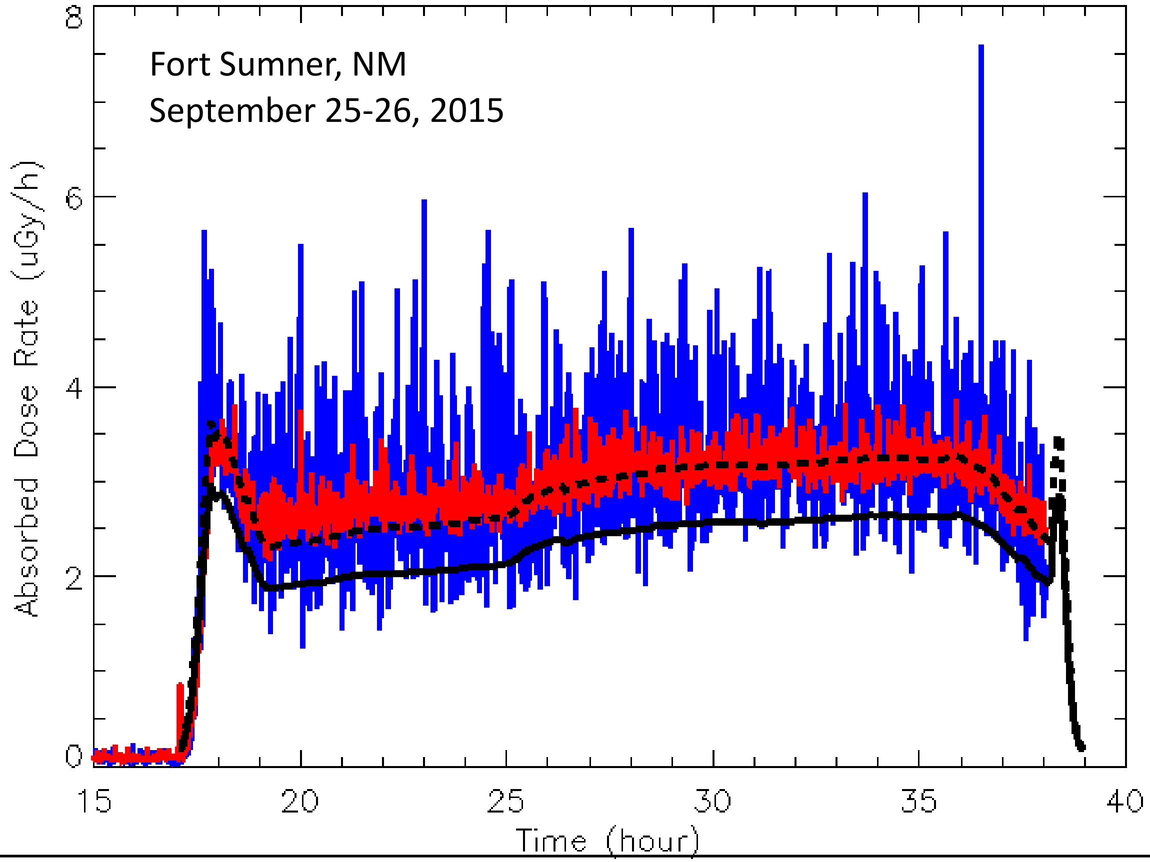
Blue: GCR effective dose rate

Red: TRP effective dose rate

Al Shielding: 50 g/cm²

NASA RaD-X Balloon Flight

Time Series of Dose Rates Measured on RaD-X Balloon



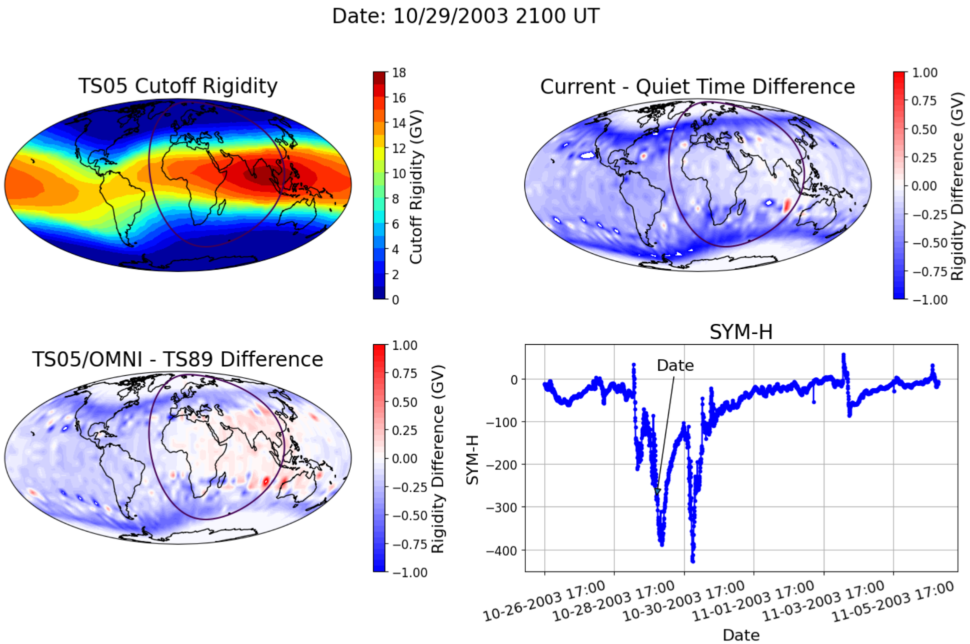
Liulin; **TEPC**; **NAIRAS Ti-Dose** (Dashed); **NAIRAS Si-Dose** (Solid)

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

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

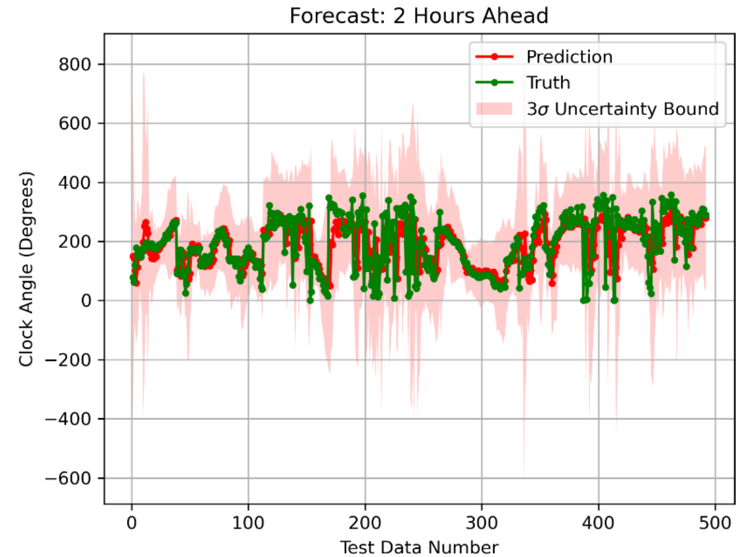


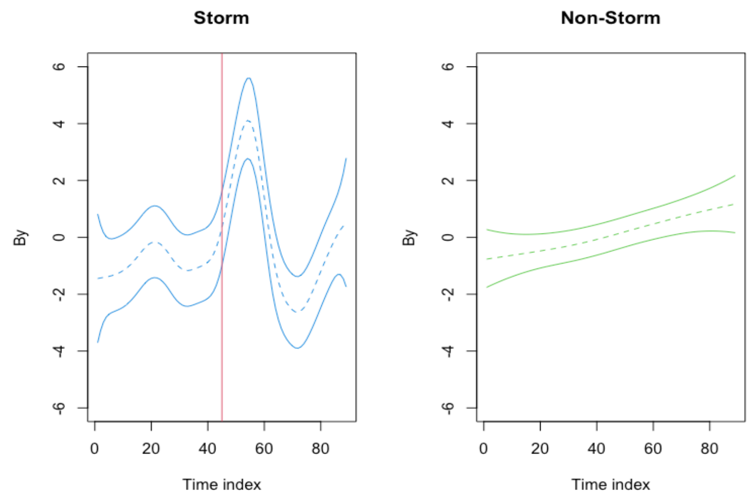
Top Right: Largest suppression of cutoff (~1 GV) (open-closed field boundary) occurs in dusk sector due to max build-up of partial ring current in TS05 (IMF Bz dependent)

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, performance not adequate
  - Improved performance sought using Functional Data Analysis (FDA) methods (bottom right)

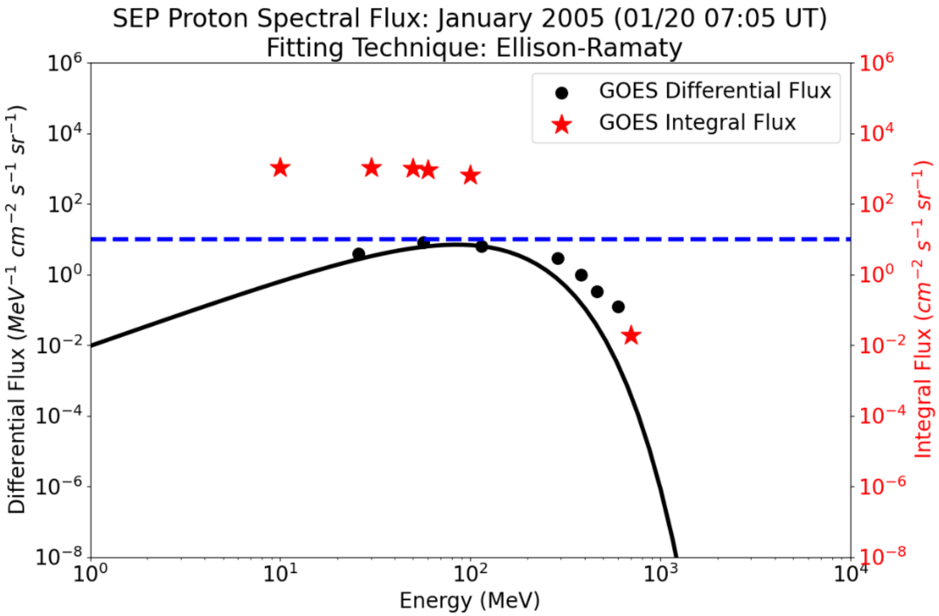




Functional means with 95% uncertainty bands.
Vertical line marks storm onset

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



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.

New SEP Spectral Fitting Algorithm

SEP proton spectral fitting problematics

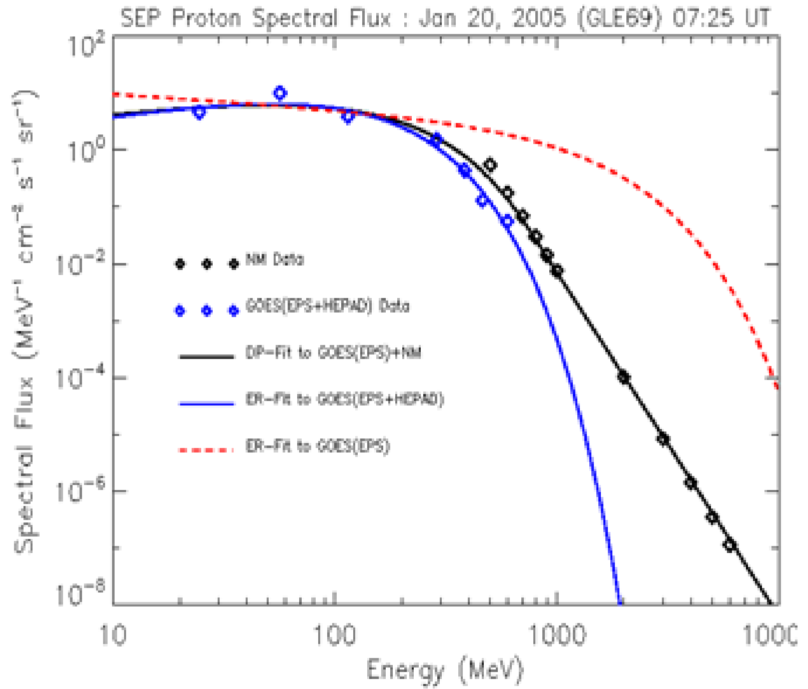


Figure 1: GOES (EPS+HEPAD) differential proton flux measurements and NM-inferred differential proton flux for January 20, 2005 SEP/GLE. Double power-law (DP-Fit) and Ellison-Ramaty (ER-Fit) functional fits to the observations.

New approach using GOES integral flux

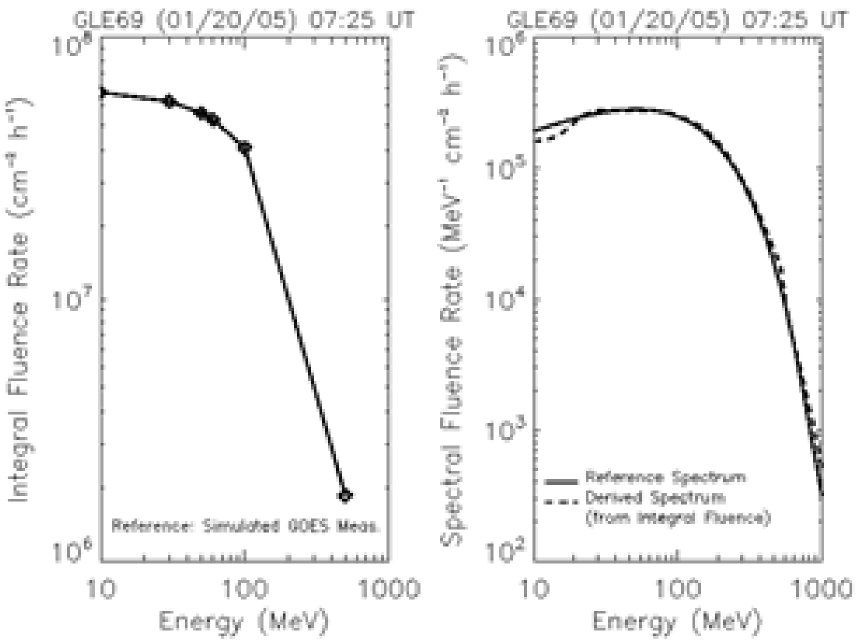


Figure 1: (left) Simulated GOES integral flux measurements (diamonds). (right) Results of new spectral flitting algorithm (dashed) compared to reference spectrum (solid) in previous figure.

Summary and Conclusions

- **Major NAIRAS Code Deliverables to CCMC/iSWA**
  - **NAIRAS Real-Time Global Dosimetric Quantities (Publicly Available Now)**
  - **NAIRAS RoR Capability (Publicly Accessible in August 2022)**
  - **NAIRAS Improved SEP Proton Spectral Fitting Algorithm (Operational in Fall 2022)**
- **Significant Improvements to NAIRAS Model: Developed, Implemented and Tested**
- **NAIRAS predicts both dosimetric quantities to assess human radiation exposure and differential/flux quantities to assess SEEs in avionic system**
- **SEP Dose Forecast Development**
  - **Geomagnetic Cutoff Rigidity Forecast Model (Under Development)**
  - **SEP Proton Spectrum Forecast (Begin soon!)**

Backup Slides

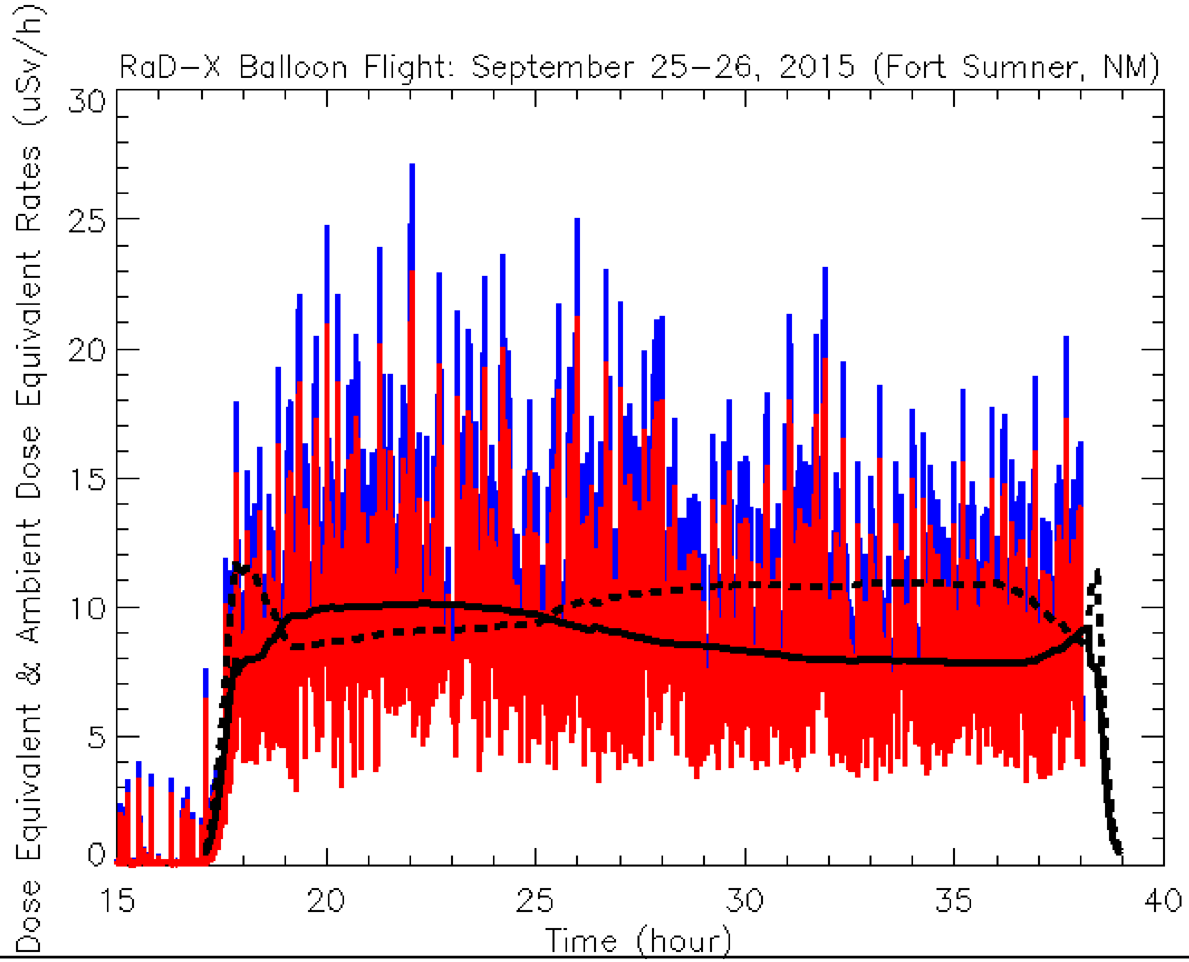
NAIRAS RoR Output Products

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

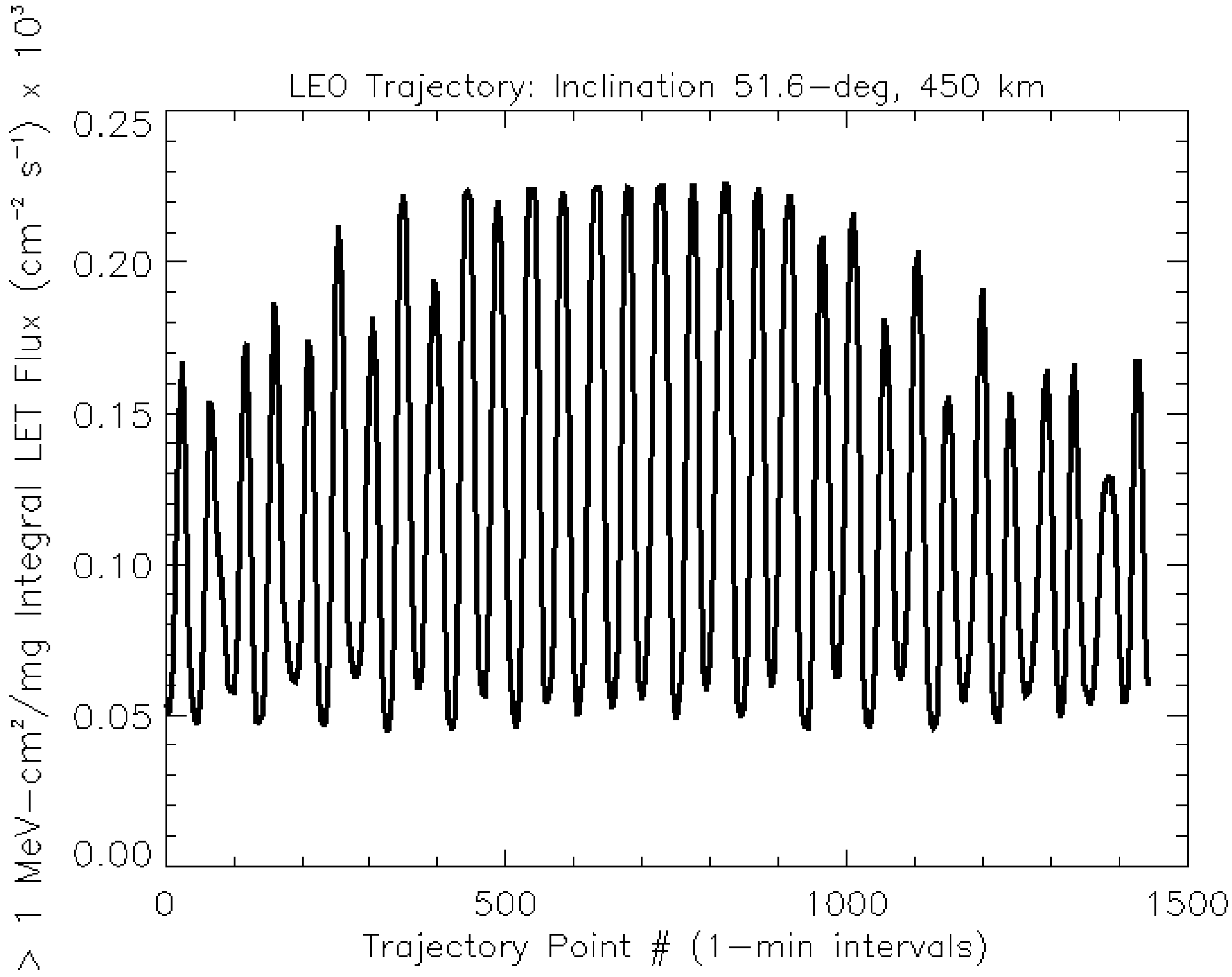
NASA RaD-X Balloon Flight



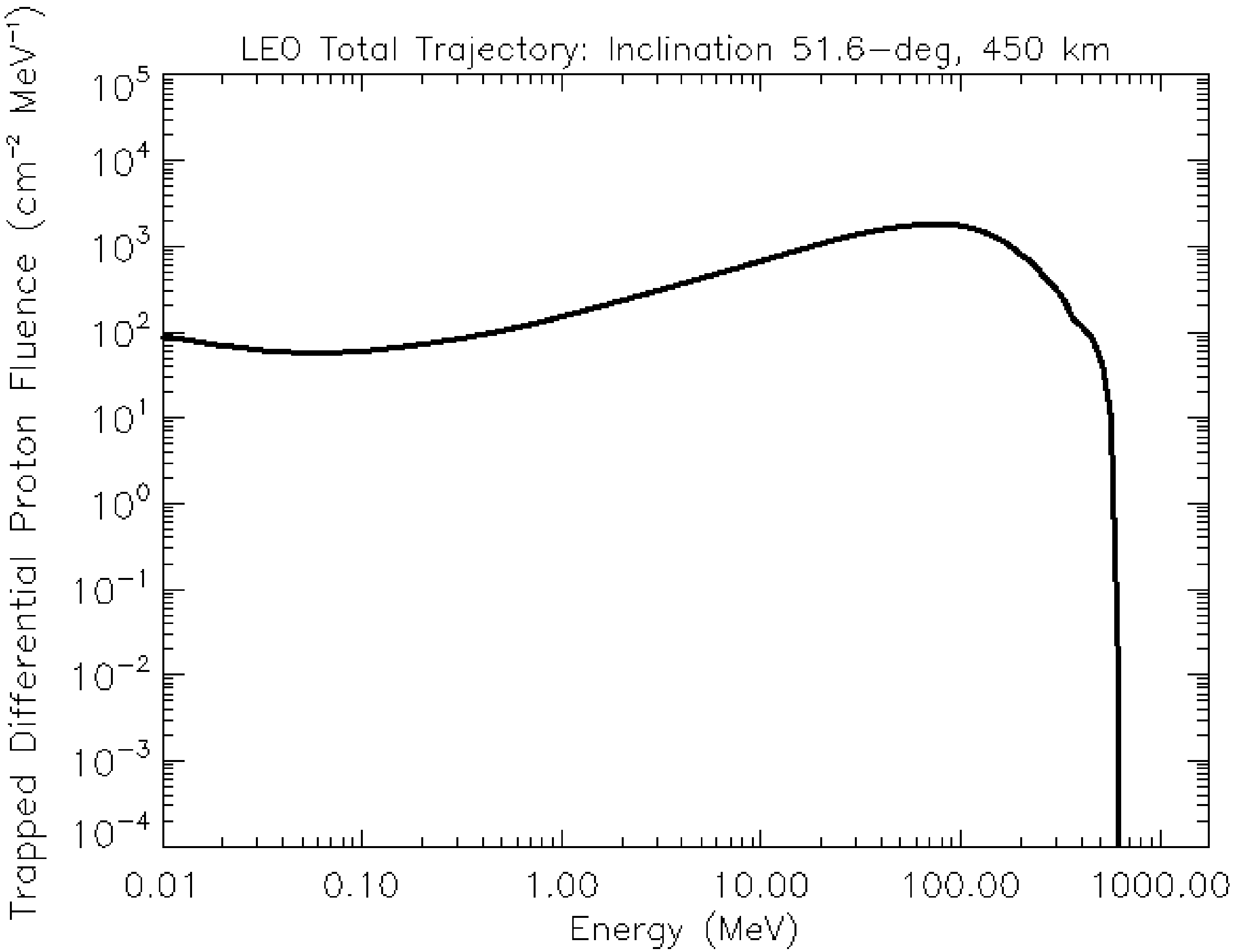
TEPC H*(10); **TEPC DoseEq**; **NAIRAS H*(10)** (Dashed); **NAIRAS DoseEq** (Solid)

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

Trajectory Integral LET Flux

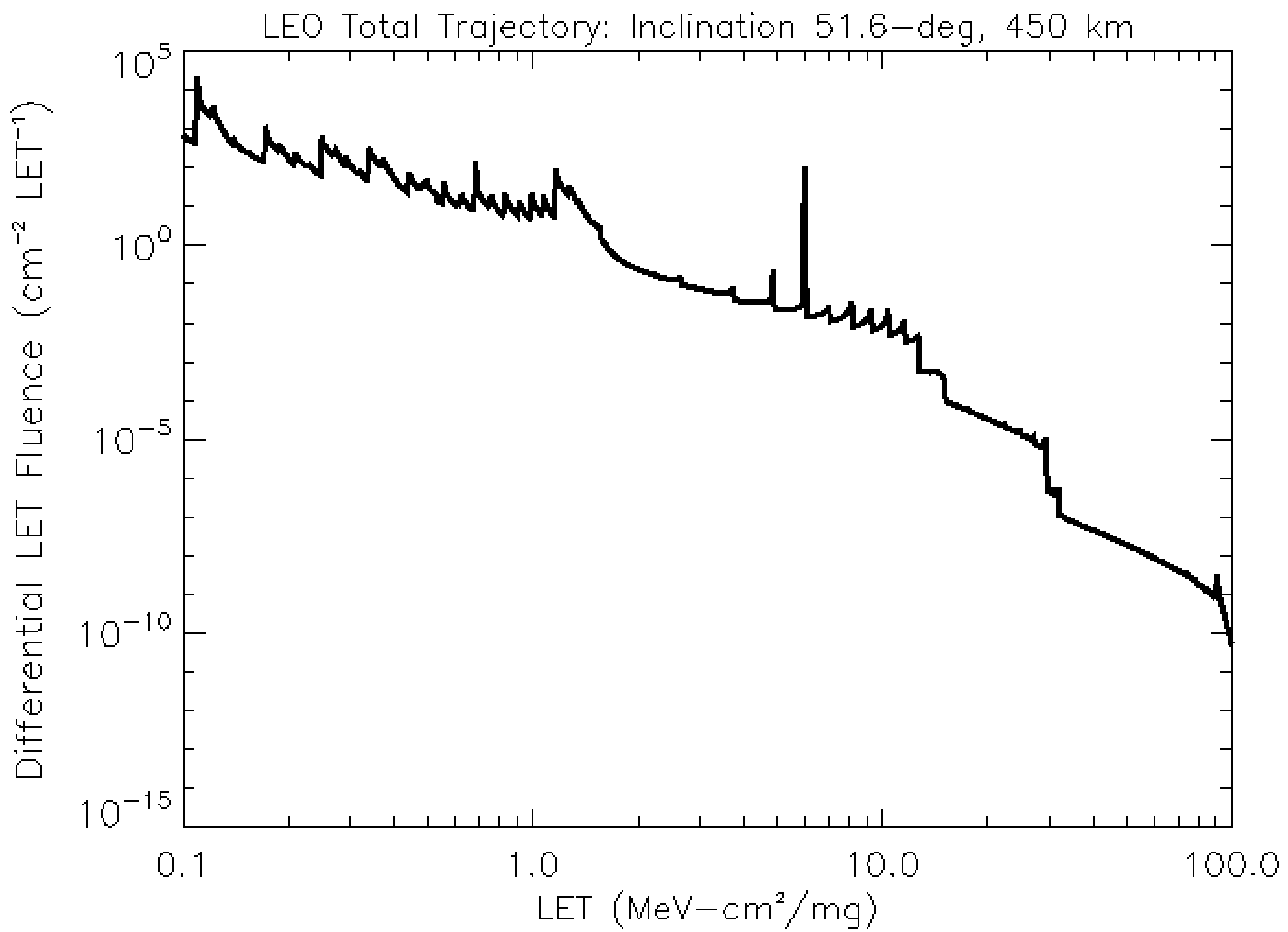


Trajectory Trapped Proton Fluence



Shielding: 4 g/cm² Al-Eq

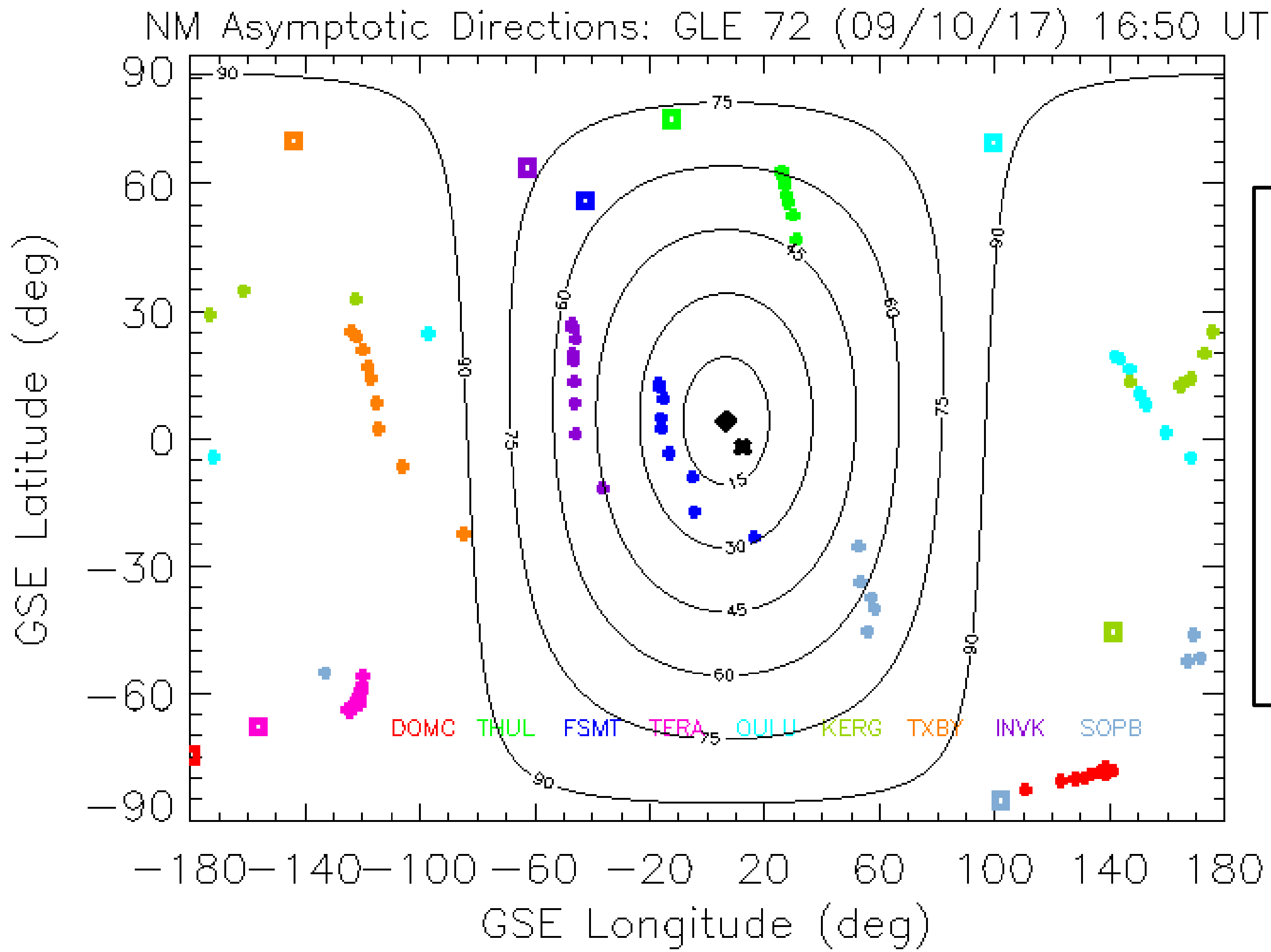
Trajectory Differential LET Fluence



Shielding: 4 g/cm² Al-Eq

Neutron Monitor (NM) Analysis

Asymptotic Directions and Pitch-Angle Distribution



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)**