Predictions of Space Weather Influences on Aircraft Radiation Exposure

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Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS)

Space/Earth System Models

Radiation Dose Rates:

HZETRN (physics-based)

Near-Earth Space Environment

•Badhwar/O'Neill GCR Model

•Semi-Physics Cutoff Rigidity

(IGRF+TS05)

•Physics-based Cutoff Rigidity

(LFM/CMIT+SEP-trajectory)

Space/Earth Observations

Near-Earth Space Environment

NASA/ACE

NASA/HEAO-3

NOAA/GOES

Assimilated Atmospheric

Atmospheric Depth (NCEP/GFS)

Ground-Based

Neutron Count Monitors

Predictions/Forecasts

Ionizing Radiation Nowcast

4-D Effective Dose

4-D Ambient Dose Equiv.

4-D Differential Flux

NAIRAS Distributed Network System

High-Performance Computer Systems

Server Interface

Operational and Archival Databases

Differential Particle Flux

HZE Particles (A=5-56)

Light-Ions (A=1-4)

Neutrons

Pions and Muons

Electromagnetic Cascasde Particles

Observations, Parameters & Products

Decision Support Systems, Assessments, Management Actions

NAIRAS decision support tool for NOAA/SWPC space weather forecasts, warnings, and advisories

NAIRAS available at public website & NOAA/ADD experimental aviation-related weather forecasts, observations, and analysis

Specific analyses to support the decision making

Predict real-time radiation exposure at airline altitudes (includes background GCR and SEP events)

Provide accumulated radiation exposures for representative set of domestic, international, and polar routes

Specific Decisions / Actions

Limit aircrew flight hours to within recommended annual and career limits

Alter route and/or altitude during SEP events

Value & Benefits to Society

Improvements in the decision-making, decisions, and actions

First-ever, data-driven, real-time prediction of biologically harmful radiation exposure levels at airline altitudes

Quantitative and qualitative benefits from the improved decisions

Comprehensive database of radiation exposure rates to formulate recommended annual and career limits to ionizing radiation exposure

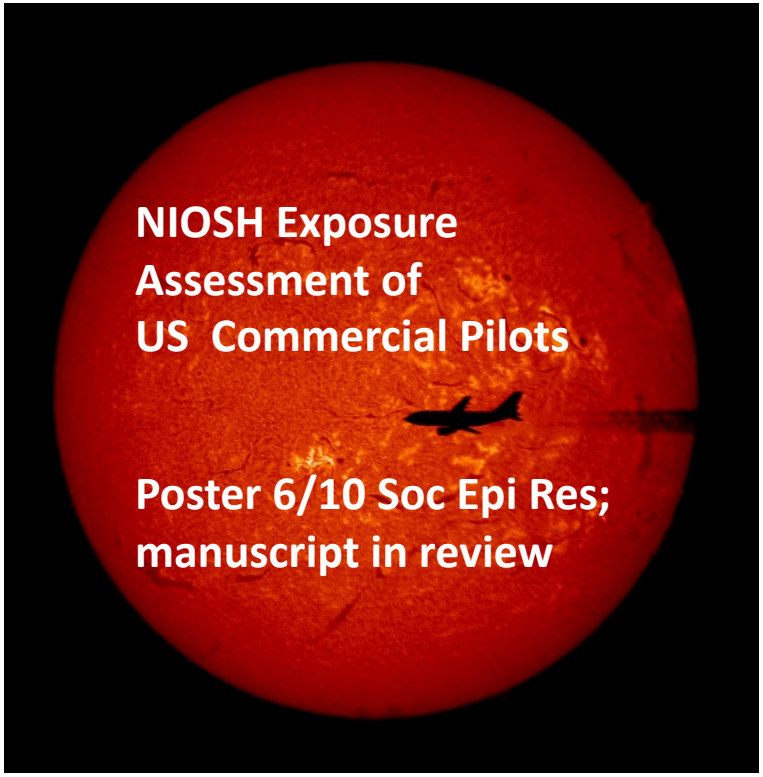
Comprehensive database of radiation exposure rates for airlines to assess cost/risk of polar routes

Real-time prediction of radiation exposure levels to enable optimal balance between airline cost and air traveler health risk during solar storm (SEP) events

Improve understanding of biological effects of atmospheric ionizing radiation on aircrew and passengers through collaboration of epidemiological studies by NIOSH

NAIRAS Team

- Chris Mertens (PI), NASA Langley Research Center, Hampton, VA
  - Cosmic ray transport; integration of NAIRAS models and data; V&V
- Kent Tobiska (Co-I; ARMAS PI), Space Environment Technologies, Inc, Pacific Palisades, CA
  - Distributed data nerve center and conduit for input data – models – output data
- Brian Kress (Co-I), Dartmouth College, Hanover, NH
  - Real-time magnetospheric transport / geomagnetic shielding model
- Mike Wiltberger and Stan Solomon (Co-I), NCAR/HAO, Boulder, CO
  - Benchmark MHD magnetospheric magnetic fields
- Brad Gersey (ARMAS Co-I), CRESSE, Prairie View A& M, Prairie View, TX
  - Radiation measurements and instrumentation
- Joe Kunches (Collaborator), NOAA/Space Environment Center, Boulder, CO
  - Guidance on research-to-operations; interaction with commercial aviation industry
- Barbara Grajewski (Collaborator), CDC/NIOSH, Cincinnati, OH
  - Aircraft radiation measurement data for V&V; epidemiological studies
- Steve Blattnig (Collaborator), NASA Langley Research Center, Hampton, VA
  - Cosmic ray nuclear interactions; transport physics
- Bill Atwell (ARMAS Collaborator), Boeing, Houston, TX
  - Radiation measurement data analysis
- Xiaojing Xu (Collaborator), SSAI, Hampton, VA
  - Scientific programming and data visualization tools
- Ryan Norman (Post-Doc Fellow), NASA Langley Research Center, Hampton, VA
  - Cosmic ray nuclear interactions; transport physics



FIRST STUDY OF

- **US commercial pilot career exposure profile from individual flight segments:**
  - **Cosmic radiation**
  - **Solar energetic particle events**
  - **Chronic circadian disruption**

FINDINGS

- **A median pilot incurred**
  - **34.4 mSv GCR and flew through 6 SEPs in 28 y flying**
  - **1.92 mSv in the last study year**
- **Exposure metrics increased markedly 1990+**

IMPLICATIONS

- **No dose limits for US crew**
- **Median pilot would trigger EU radiation monitoring (>1mSv/y)**
- **A pregnant female pilot could exceed ICRP guidelines for pregnant radiation workers**
- **High-exposed pilots at increased risk**

Image courtesy of Kanzelhöhe Observatory

Outline

- NAIRAS Model Overview
- NAIRAS Real-Time Products
- NAIRAS Radiation Storm Studies
- Space Weather: Needed Improvements
- Summary Remarks

Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) Model

Real-time Neutron Monitor Data (e.g., IZMIRAN and LOMNICKY)

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Fit to Climax HP

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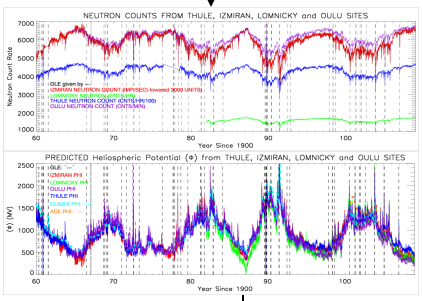

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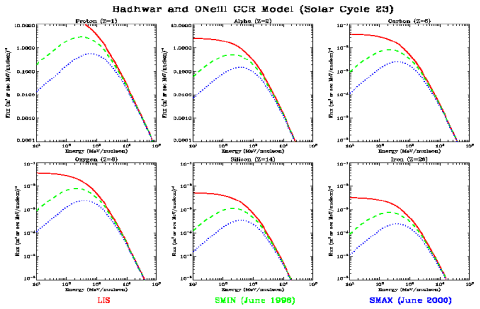
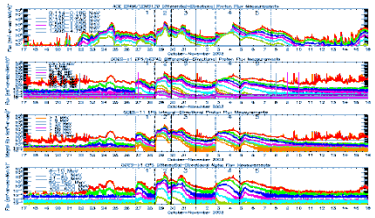
Badhwar+O'Neill GCR Model



NOAA/GOES +NASA/ACE Data



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Spectral Fitting

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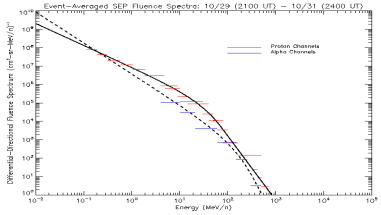

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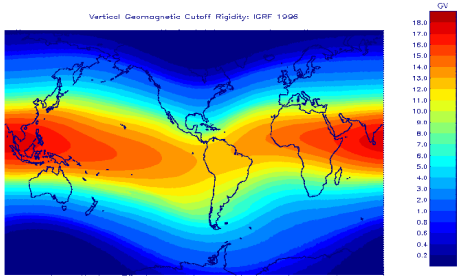
Cutoff Rigidity (IGRF)



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Magnetospheric Magnetic Field (e.g., T05) Effects on Cutoff Rigidity

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NASA/ACE Solar Wind and IMF Data

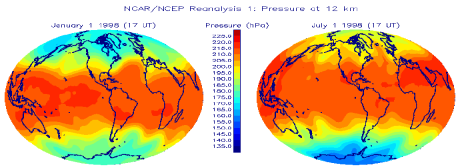
↓

HZETRN + Dosimetry

↓

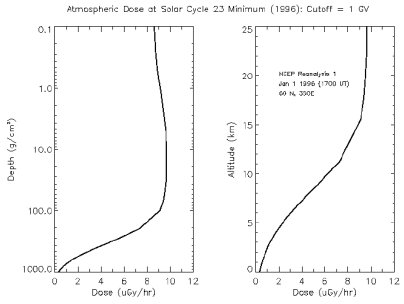
Atmospheric Density

↓



NCEP/GFS

→



Atmospheric Dose and Dose Equivalent

NAIRAS Real-Time Tabular/Graphics Products

Streaming Live Since April 2011!

Google NAIRAS

web\index.html

Space Environment Technologies

NAIRAS

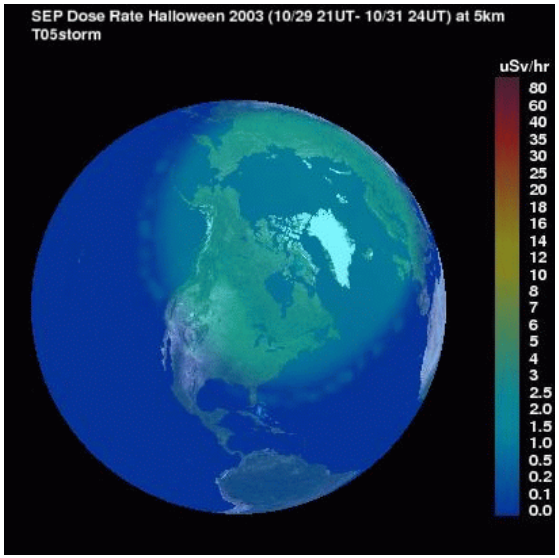
Nowcast of Atmospheric Ionizing Radiation System

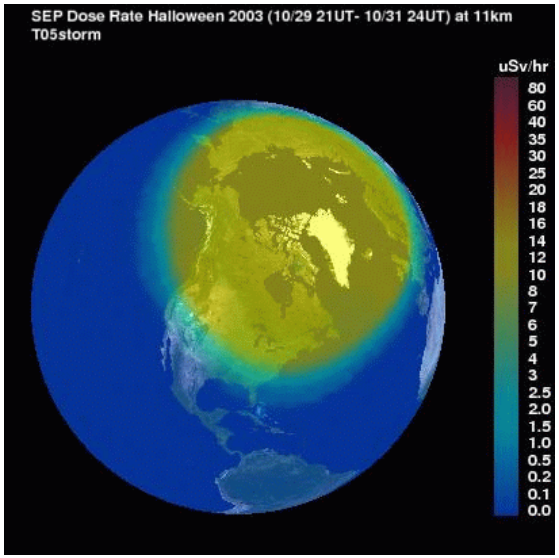
Halloween, 2003 10/29 UT21- 10/31 UT24

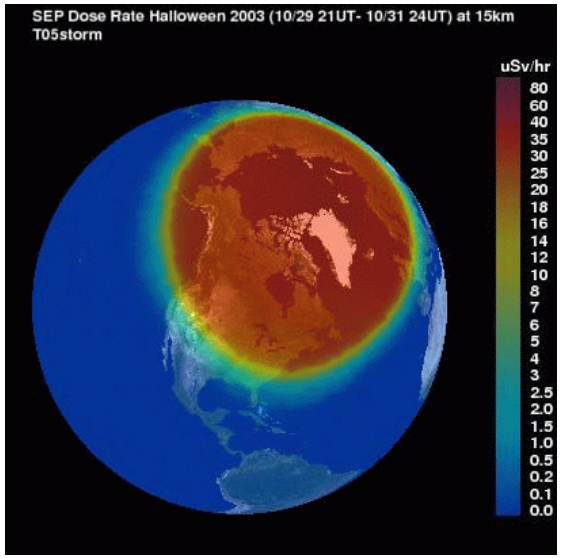
11km (35,000feet) SEP radiative Dose Rate(uSv/hr)

Latitude	60-90N	40-60N	20-40N	0-20N	0-20S	20-40S	40-60S	60-90S
average	10.80	4.87	0.25	<1e-2	<1e-2	0.49	6.14	11.78
maximum	11.57	11.06	8.26	0.01	<1e-2	8.68	11.86	13.67

Flight Name	Flight Time (hours)	Dose Rate (uSv/hr)	Dose (mSv)	Safety Signal 0.05<		>0.1
Chicago,IL-Beijing, China	13.50	9.133	0.123			
New York, NY - London, UK	5.75	9.198	0.053			
Chicago, IL - Stockholm, SW	8.42	10.302	0.087			
Chicago, IL - Munich, GE	8.75	9.085	0.079			
Nominal North Pole	10.00	11.570	0.116			







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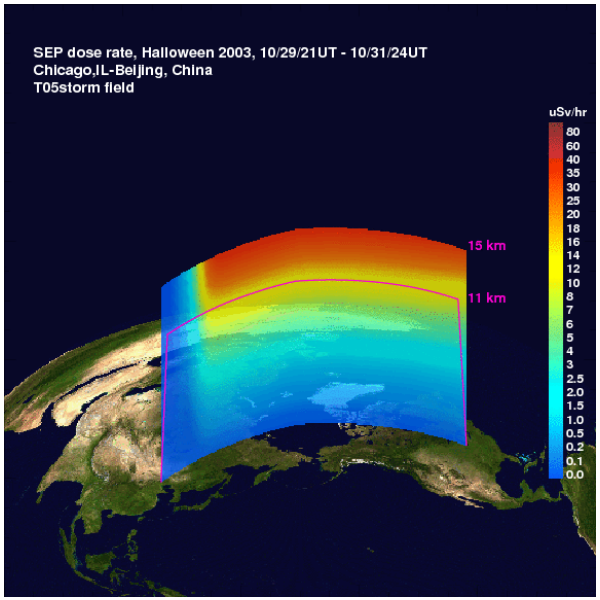

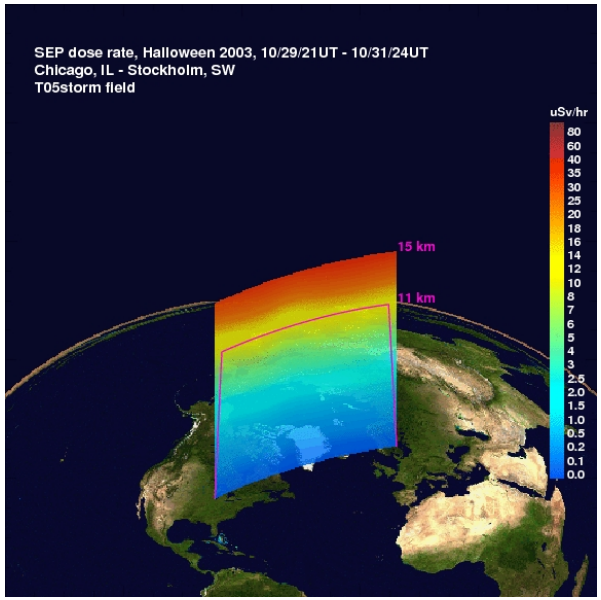

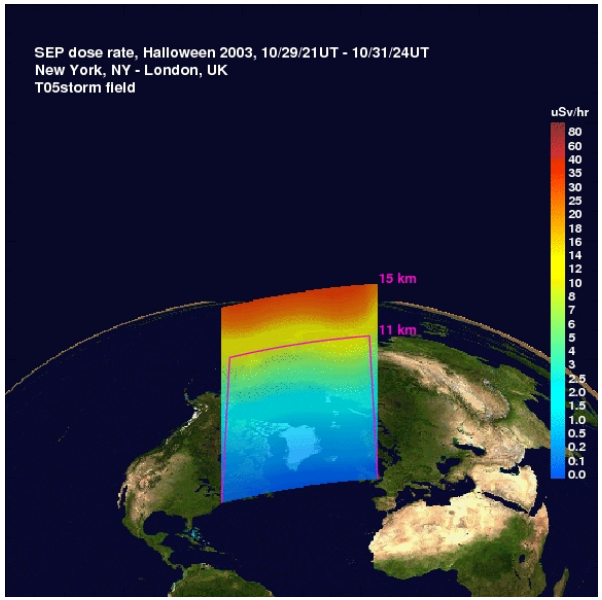

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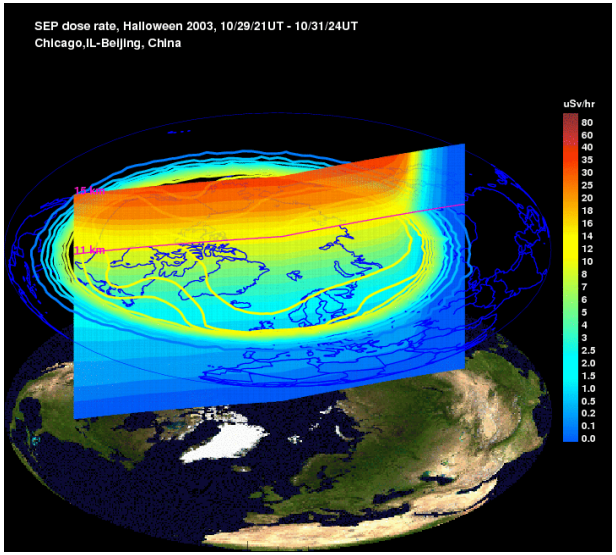
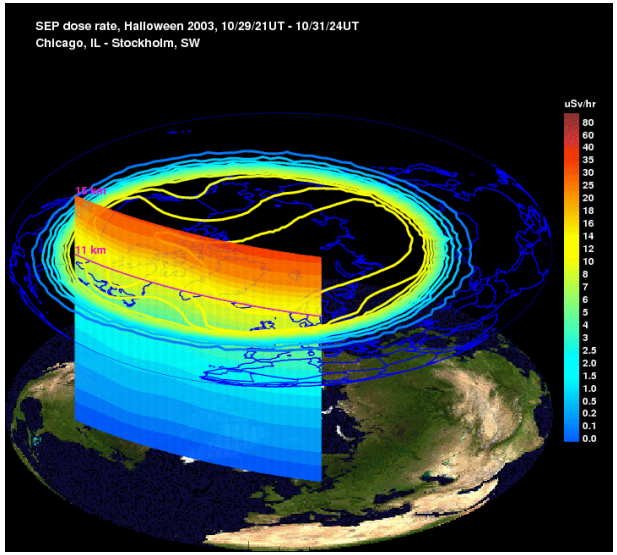
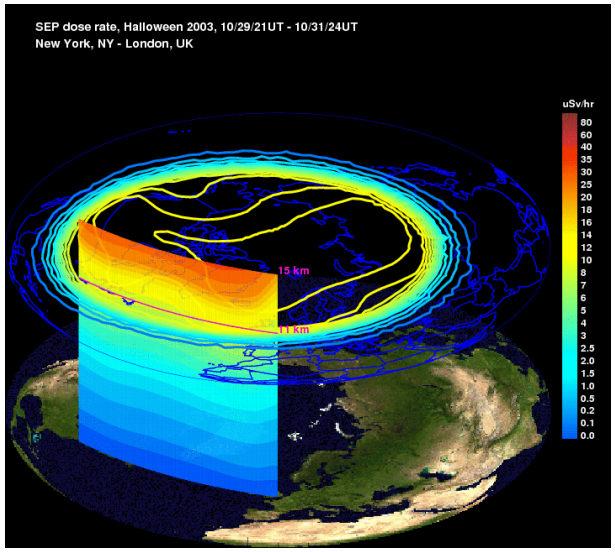
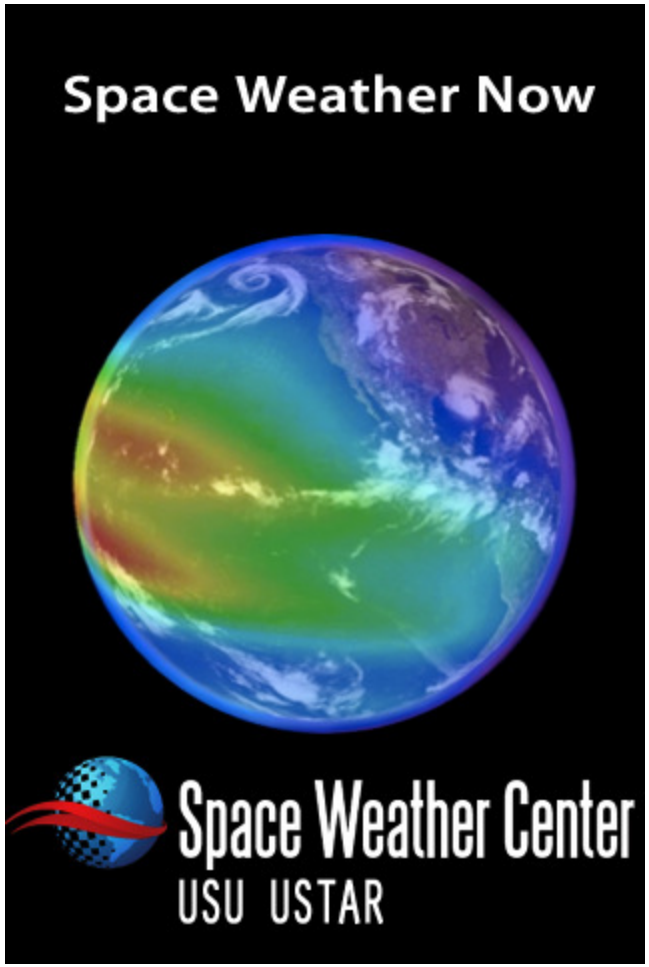




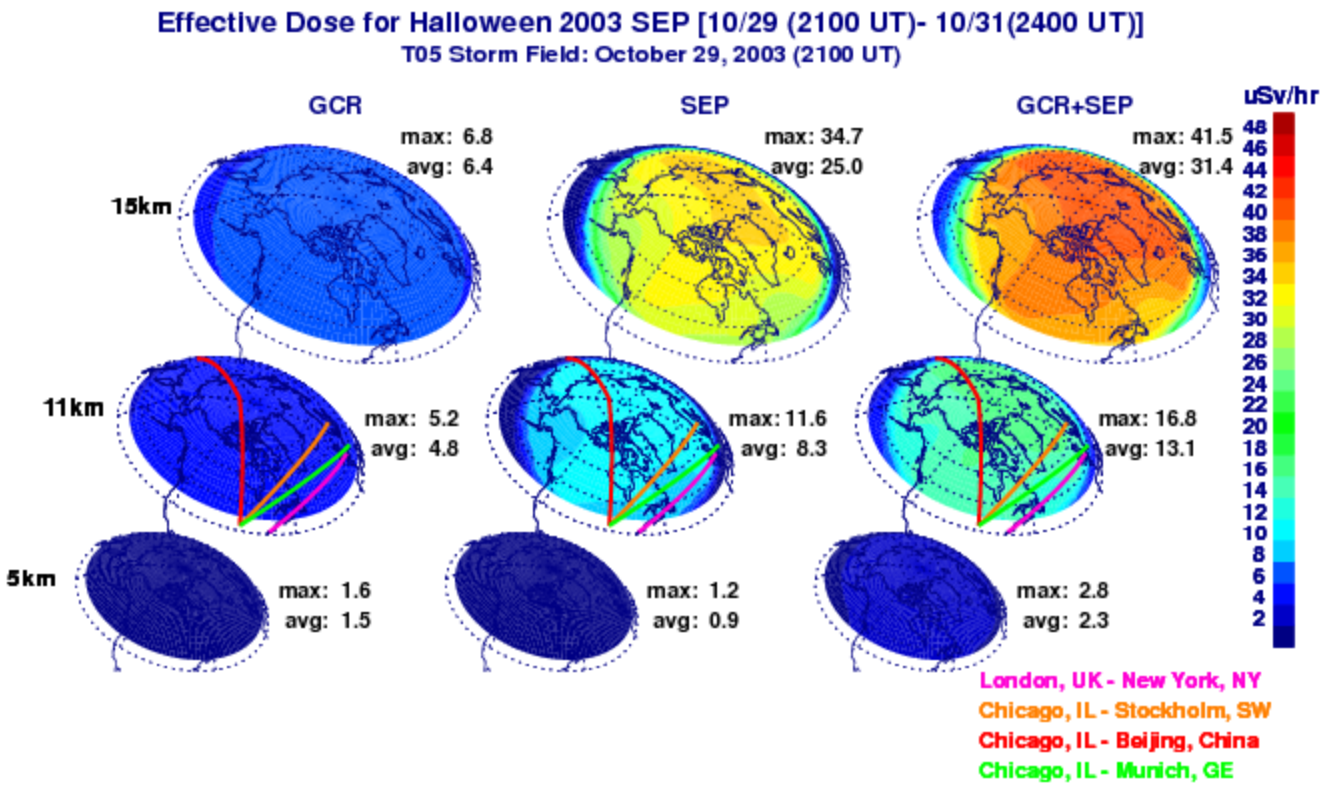


NAIRAS Real-Time Predictions Available on iPhone app

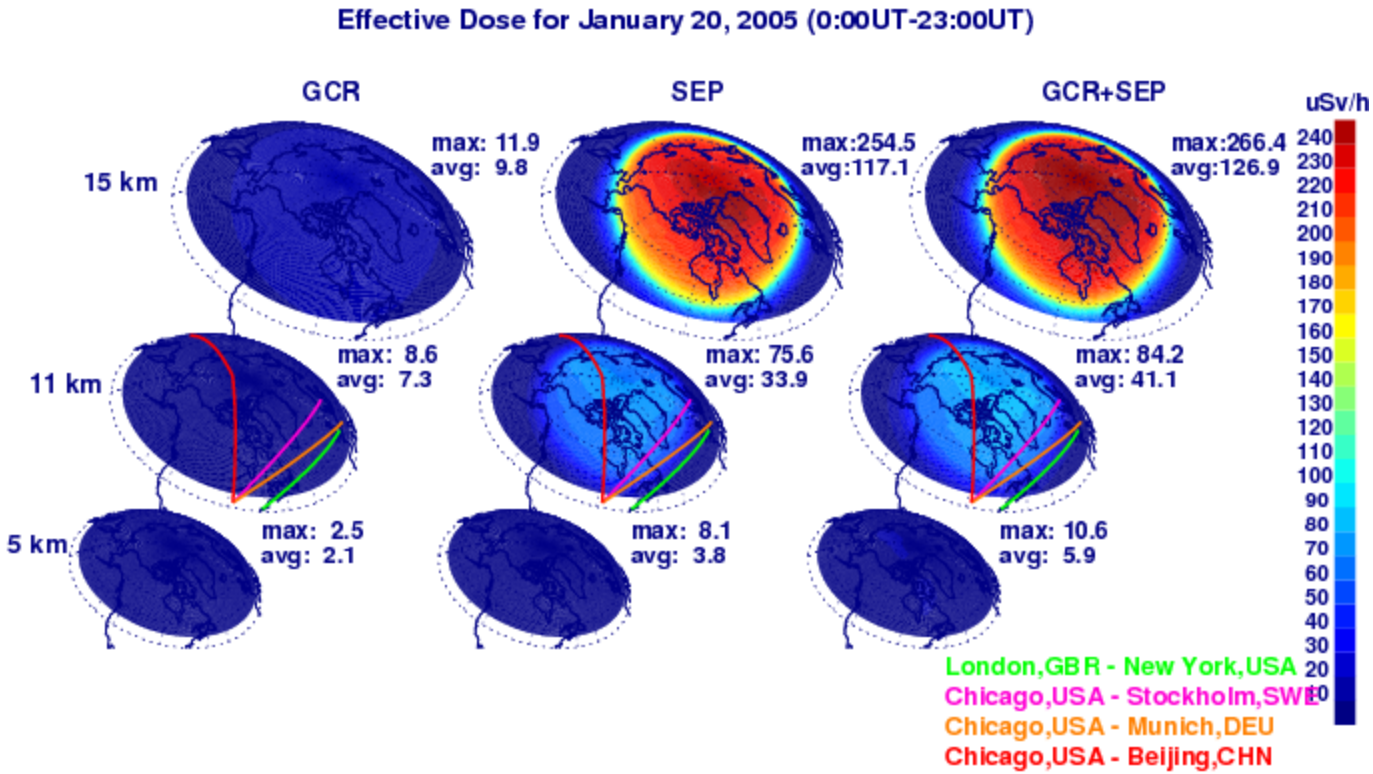
Search "SpaceWx"



Halloween 2003



January 2005



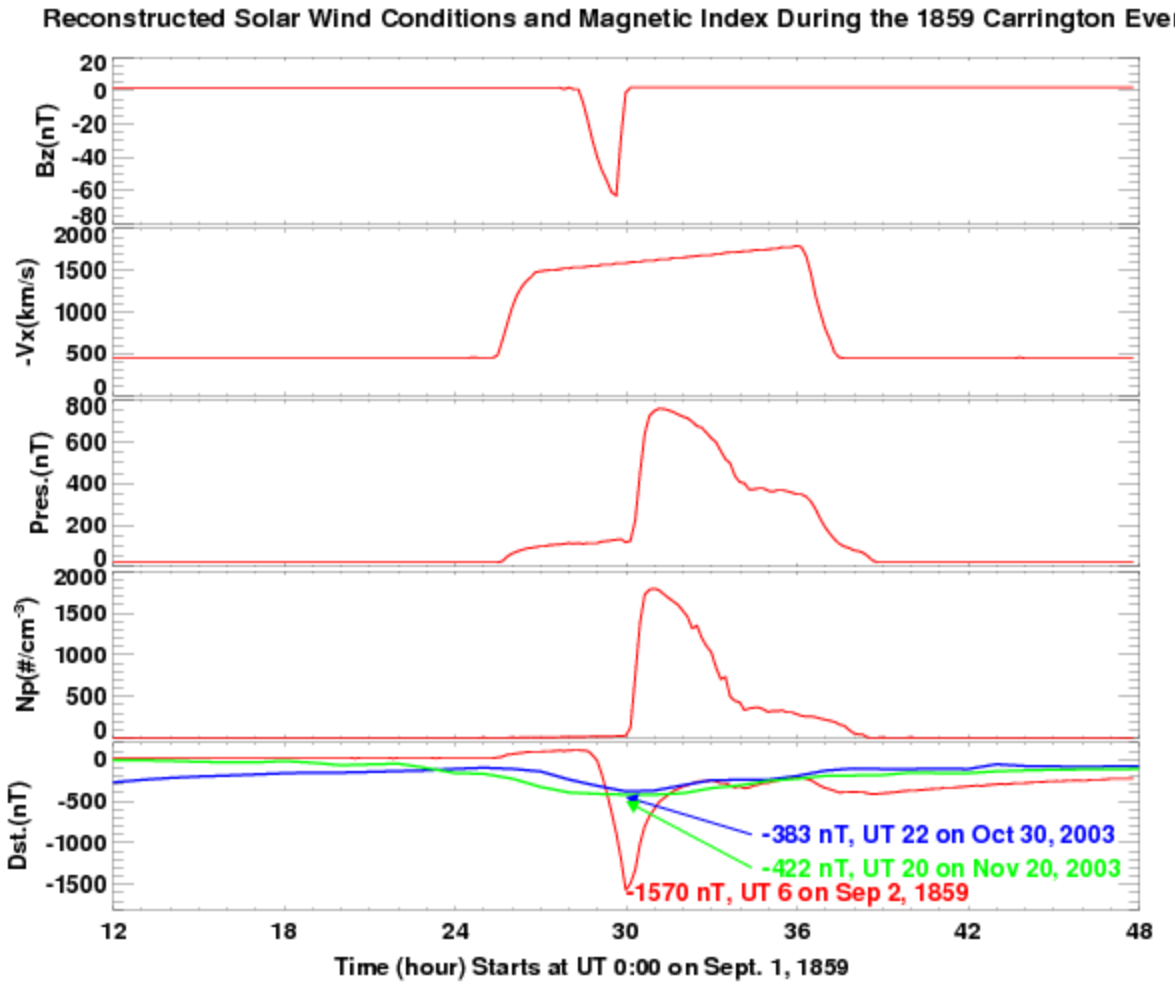
Carrington Event

- **SEP Spectral Fluence [Smart et al., 2006; Townsend et al., 2006]**
  - **Five measured spectral shapes considered**
    - **August 1972 (soft)**
    - **September 1989 (hard)**
  - **Spectral shapes normalized to >30 MeV proton fluence determined by impulsive NOy deposition in polar ice cores [McCracken et al. 2001]**
  - **Lack of detectable increase in annual ^{10}Be deposition in polar ice favors a soft spectrum**

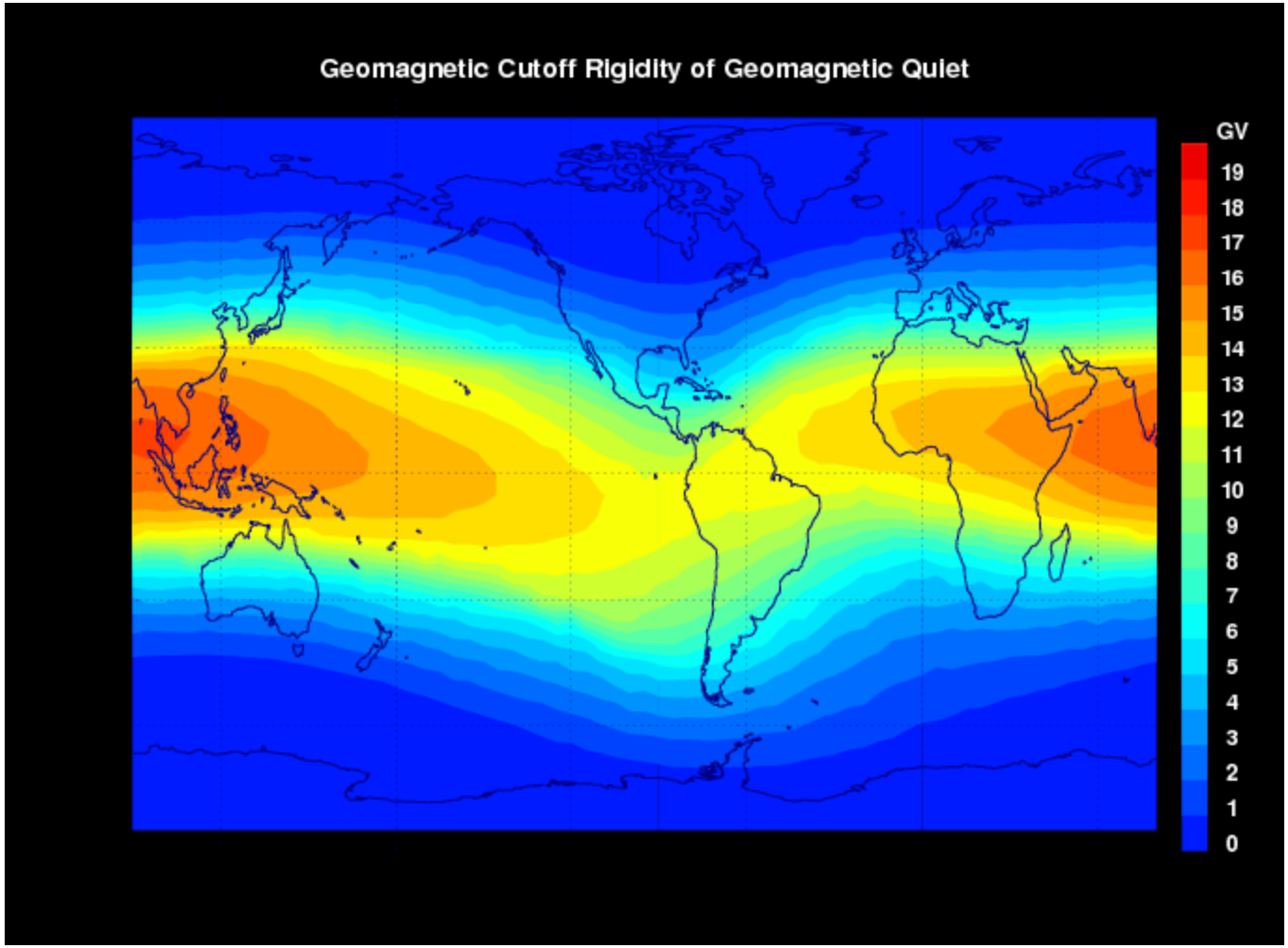
Carrington Event

- **Geomagnetic Storm [Li et al., 2006]**
  - **H-component depression measured in India and taken as Dst**
  - **Solar wind shock velocity: determined from time between flare and magnetic disturbance**
  - **Temerin and Li [2002] Dst model fits measured H-component depression**
    - **Interplanetary Ey = VxBz determine maximum Dst depression**
    - **Large solar wind density (to calculate dynamic pressure) needed to reproduce rapid recovery**

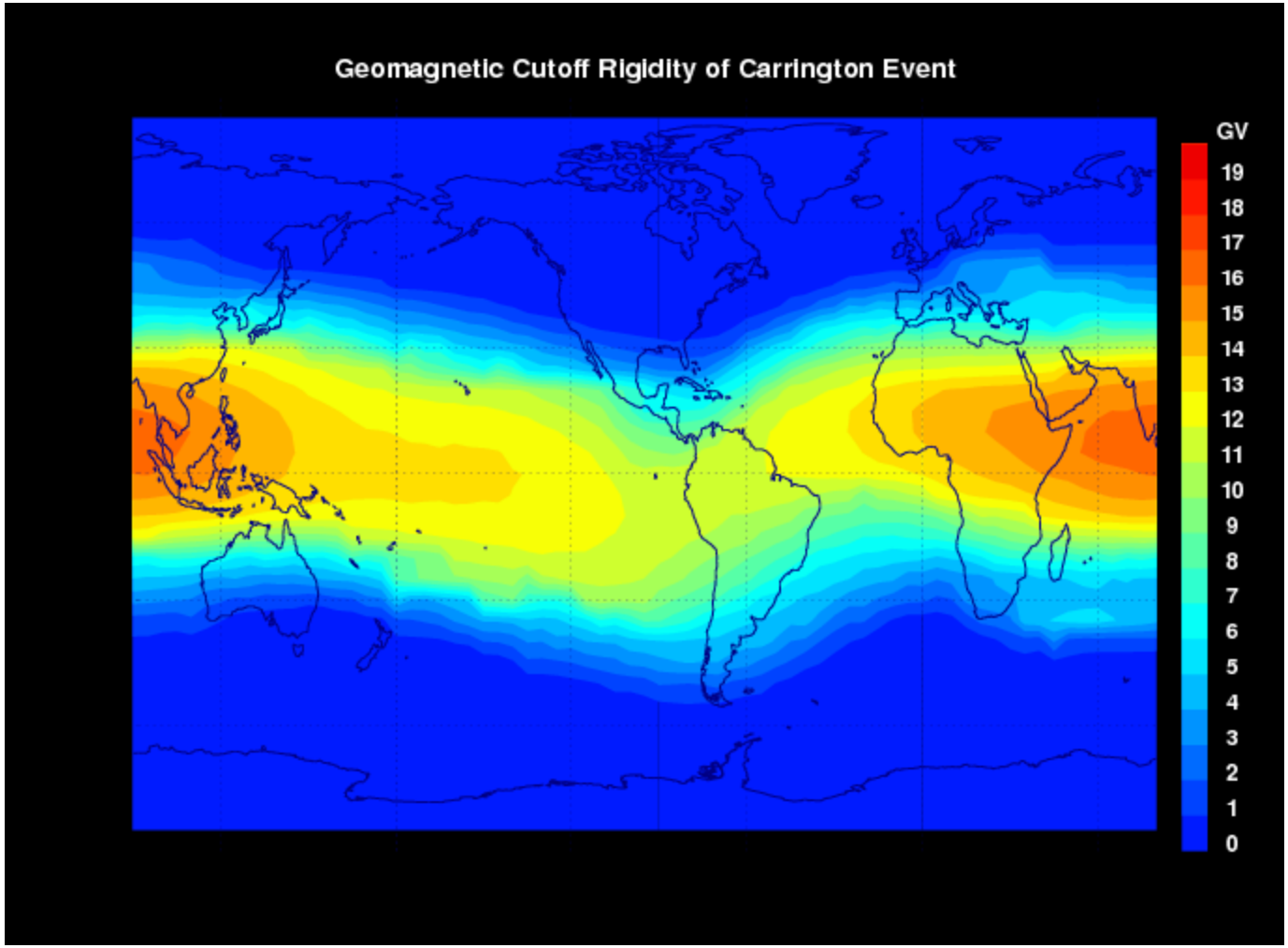
Carrington 1859



Carrington 1859



Carrington 1859



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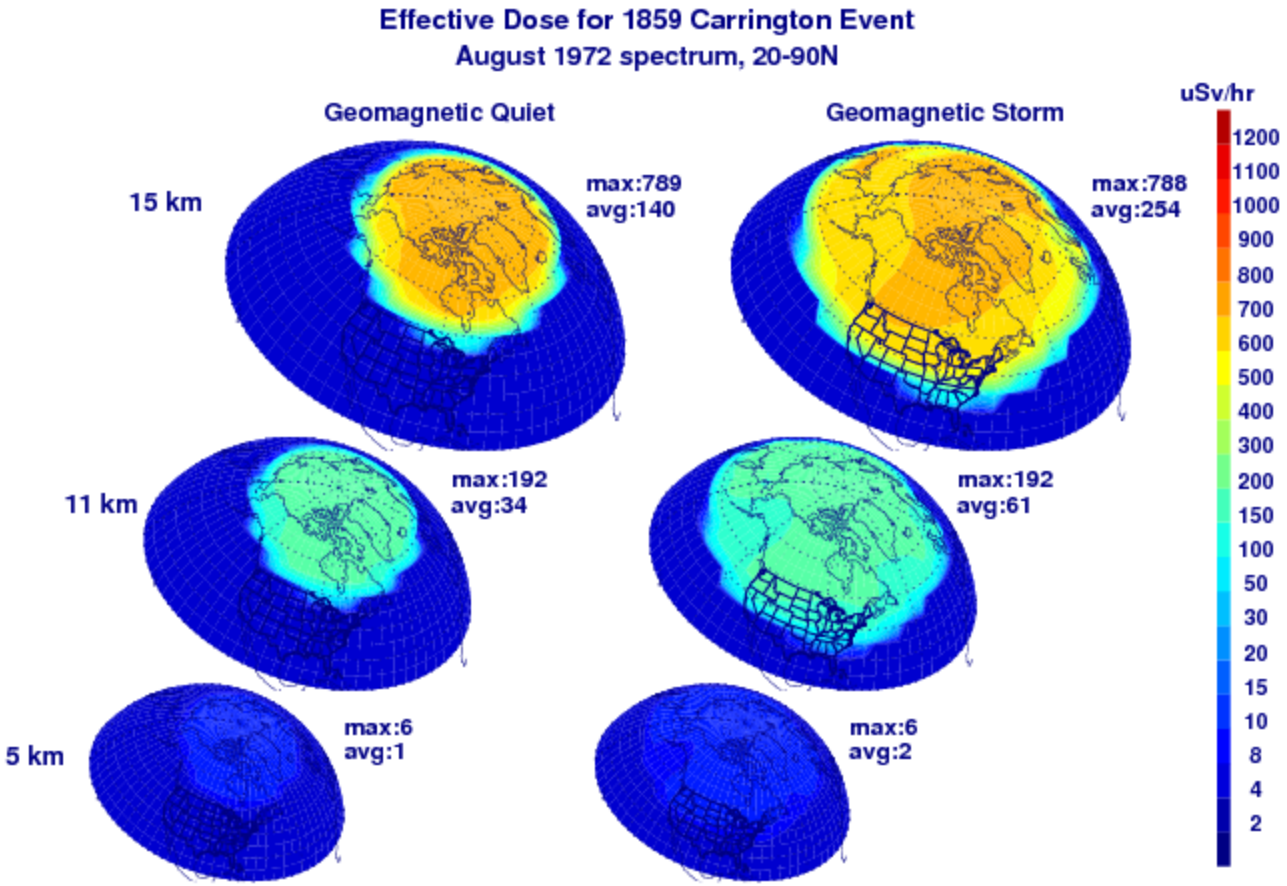
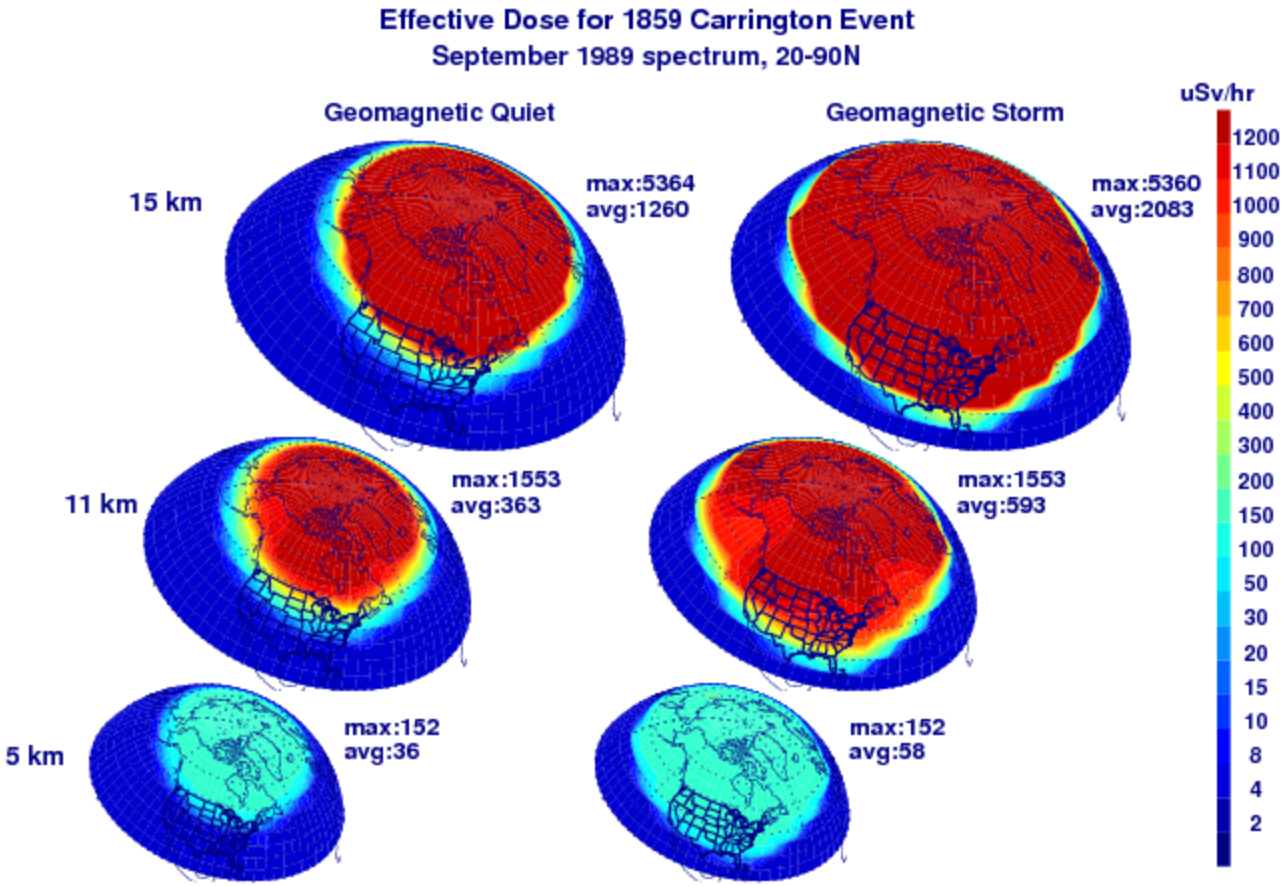
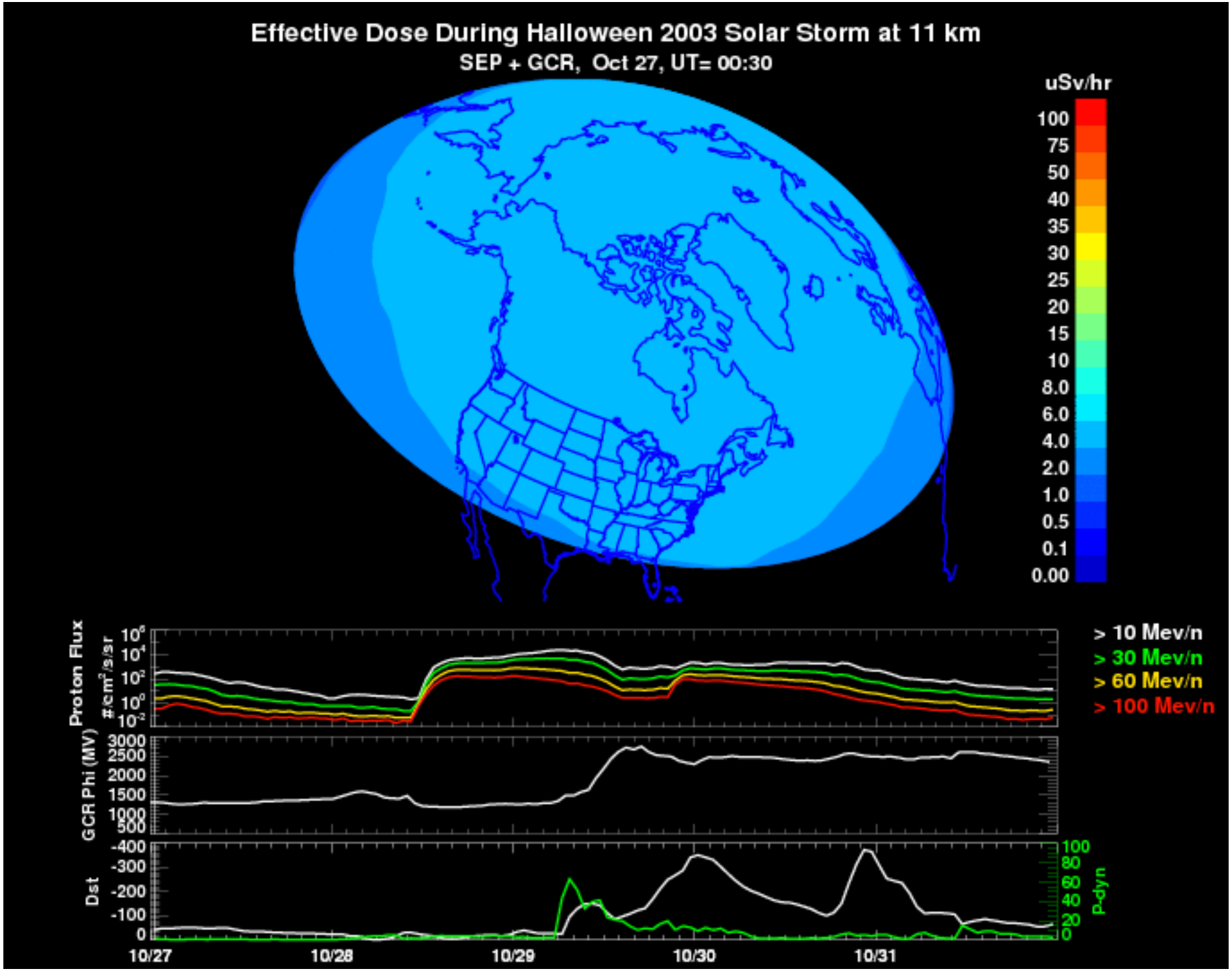
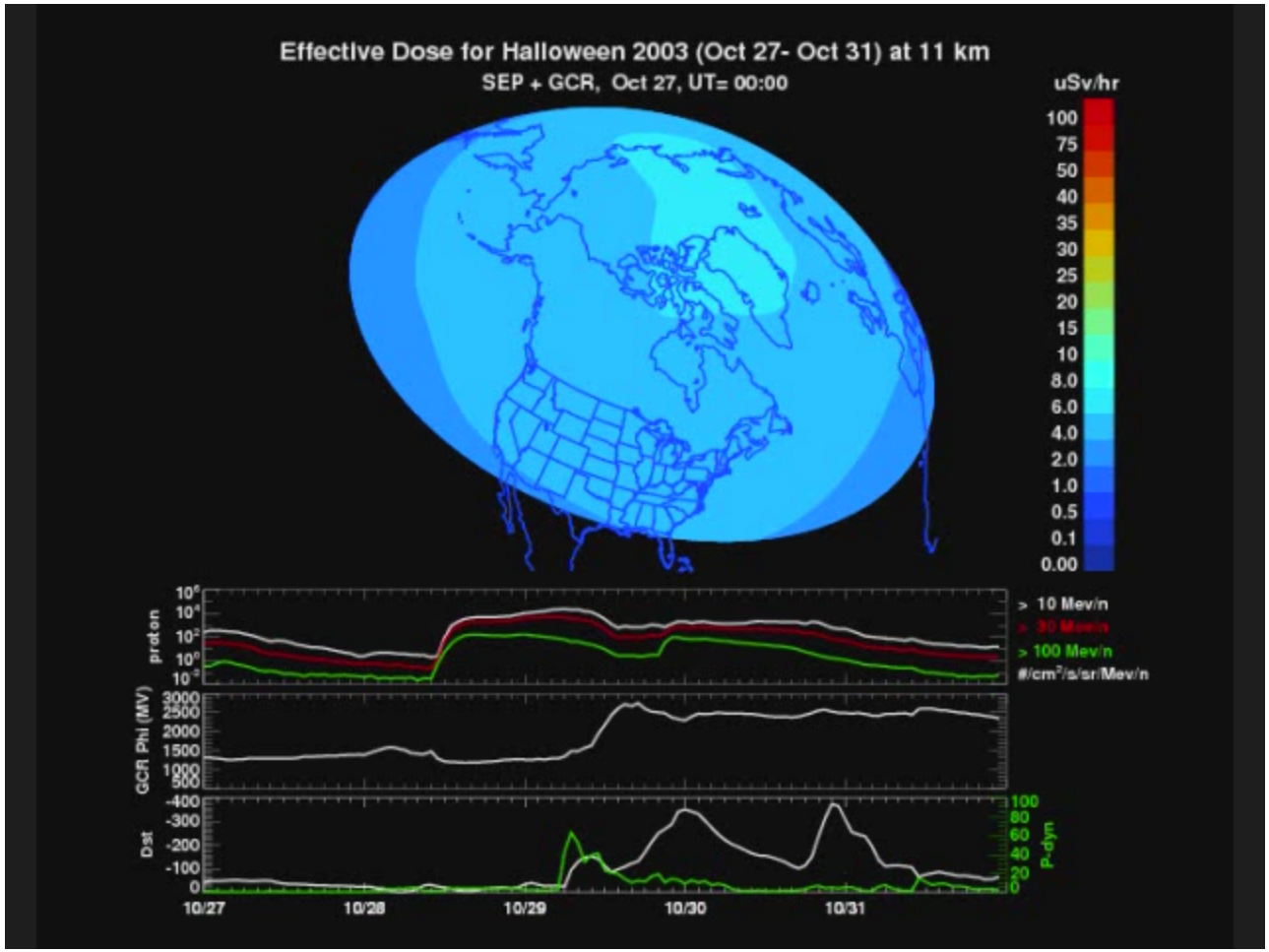
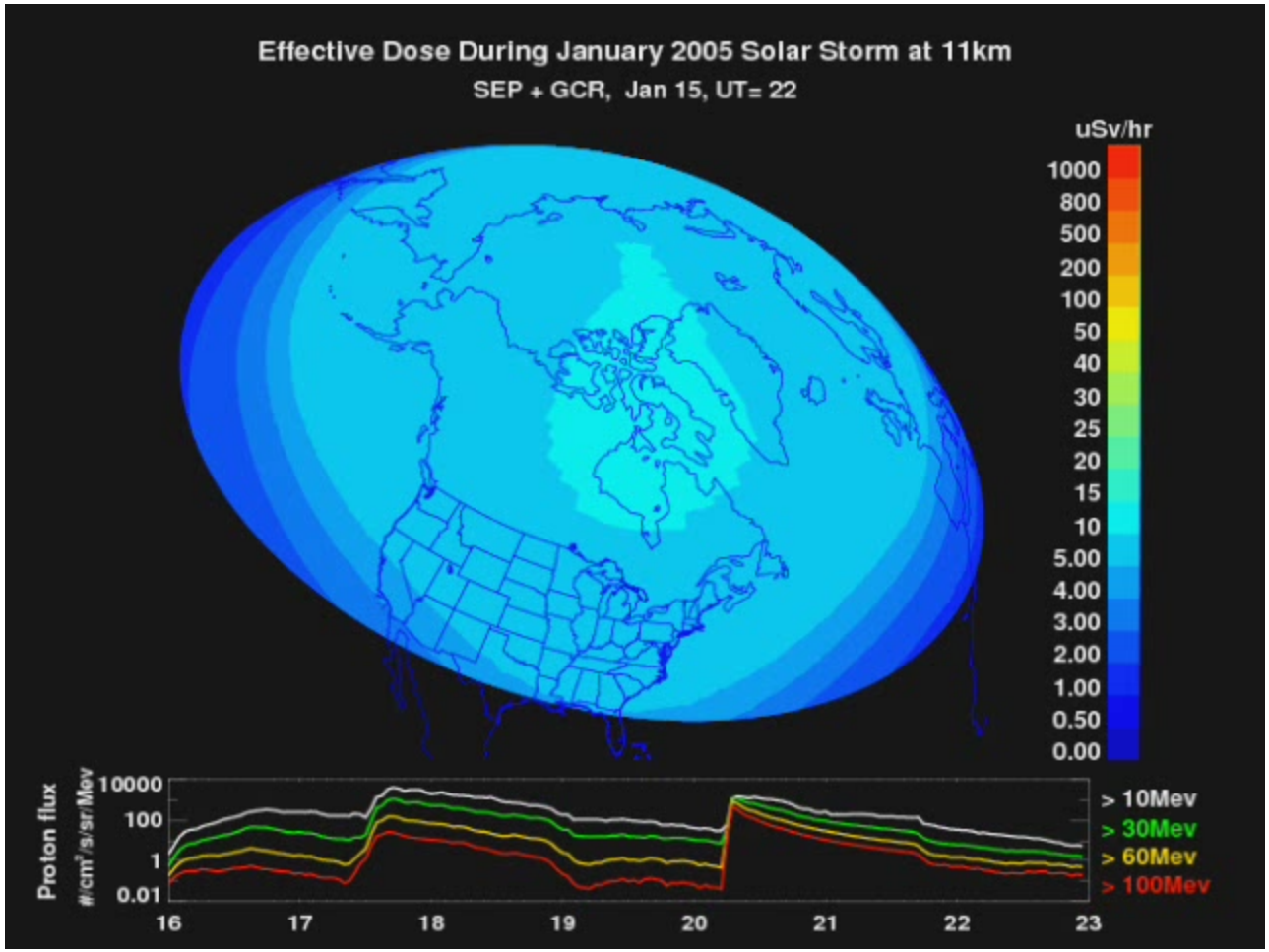


Carrington 1859



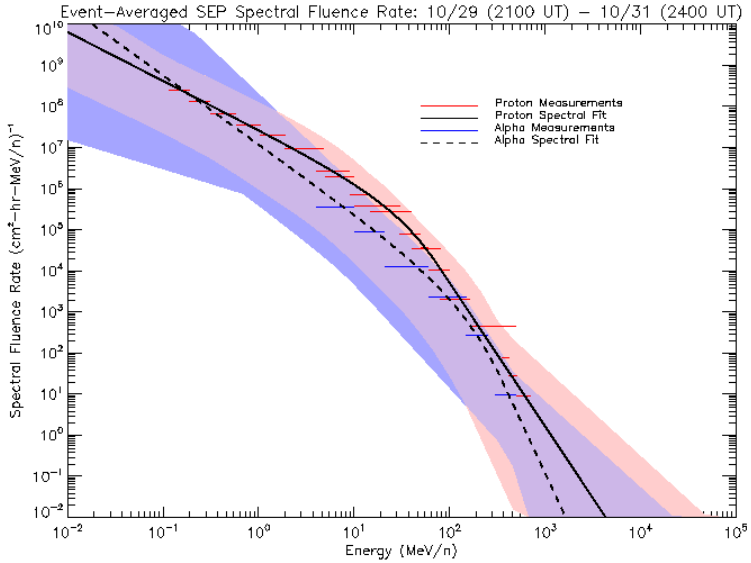

Effective Dose During Halloween 2003 Solar Storm at 11 km
SEP + GCR, Oct 27, UT= 00:30
uSv/hr
100
75
50
40
35
30
25
20
15
10
8.0
6.0
4.0
2.0
1.0
0.5
0.1
0.00
Proton Flux
#/cm²/s/sr
> 10 Mev/n
> 30 Mev/n
> 60 Mev/n
> 100 Mev/n
GCR Phi (MV)
Dst
P-dyn
10/27
10/28
10/29
10/30
10/31


Effective Dose for Halloween 2003 (Oct 27- Oct 31) at 11 km
SEP + GCR, Oct 27, UT= 00:00
uSv/hr
100
75
50
40
35
30
25
20
15
10
8.0
6.0
4.0
2.0
1.0
0.5
0.1
0.00
proton
> 10 Mev/n
> 30 Mev/n
> 100 Mev/n
#/cm²/s/sr/Mev/n
GCR Phi (MV)
Dst
P-dyn
10/27
10/28
10/29
10/30
10/31


Effective Dose During January 2005 Solar Storm at 11km
SEP + GCR, Jan 15, UT= 22
uSv/hr
1000
800
500
200
100
50
40
30
25
20
15
10
5.00
4.00
3.00
2.00
1.00
0.50
0.00
Proton flux
#/cm²/s/sr/Mev
10000
100
1
0.01
16
17
18
19
20
21
22
23
> 10Mev
> 30Mev
> 60Mev
> 100Mev

SEP Ion Flux High-Energy Tail Emerging Science Questions

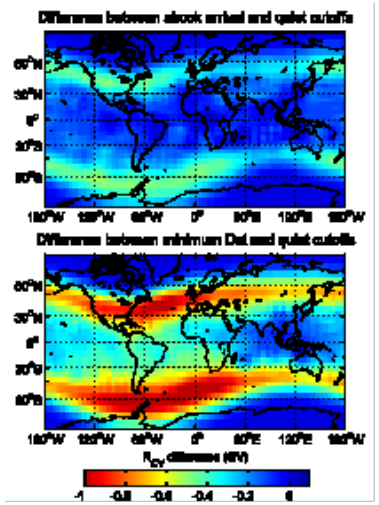
- SEP ion spectral fluence rates unconstrained by measurements > ~ 500 MeV/n
- This implies large uncertainties in atmospheric dose rates
- Retrospective SEP dose calculations differ by order of magnitude **[Dyer et al., 2009]**
- Need ~ 1 GeV detectors on satellite
- Can available world-wide network of real-time neutron monitor data be used to constrain high-energy tail for robust, real-time applications?
  - Are neutron monitor yield functions sufficiently accurate?
  - Initially compare with neutron monitor count rates not used in the fit
  - Need future onboard radiation measurements for definitive V&V



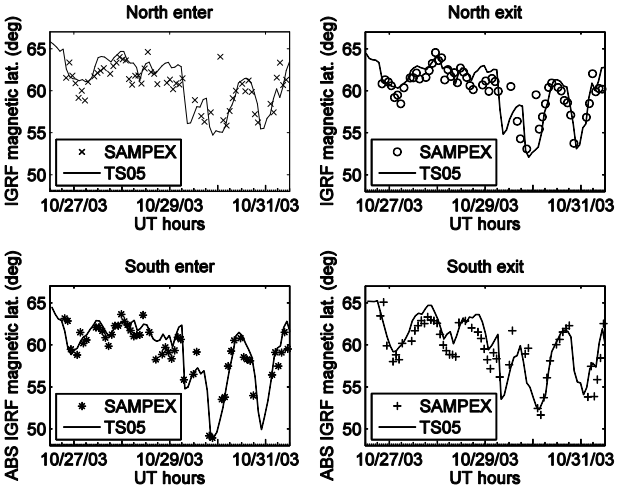
Potential improvement in spectral fits by combining satellite ion flux measurements with neutron monitor data:

- **Protons: ~ 100 keV to ~ 10 GeV**
- **Alphas: ~ 1 MeV to ~ 5 GeV**

Halloween 2003 Geomagnetic Storm

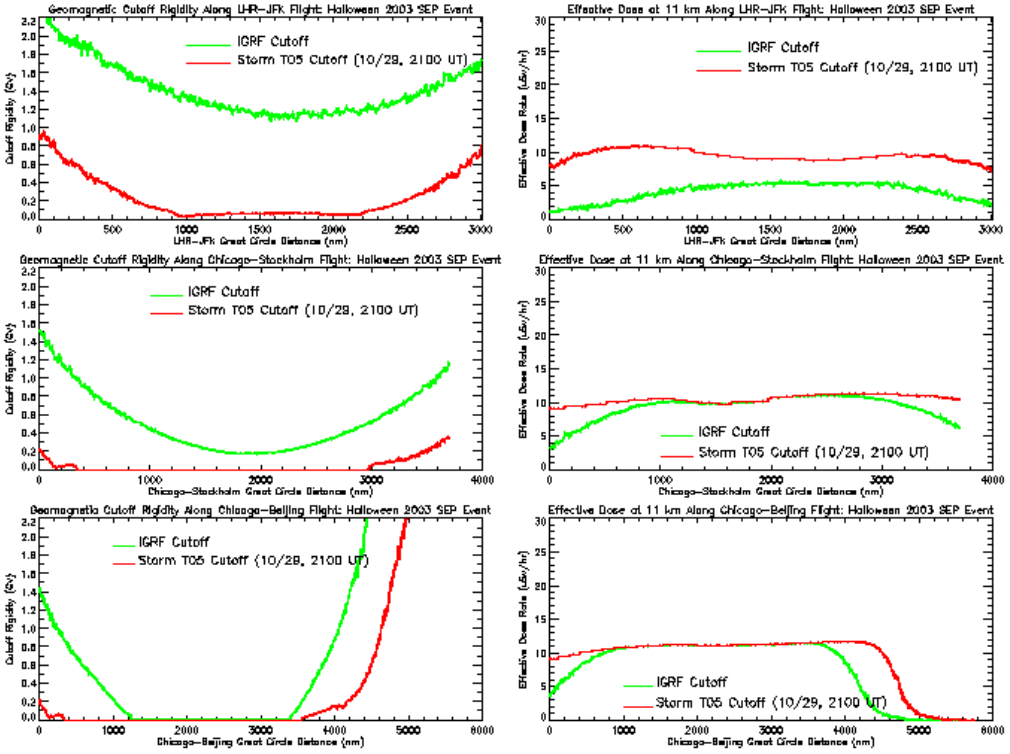


Cutoff Latitude of ~ 20 MeV protons



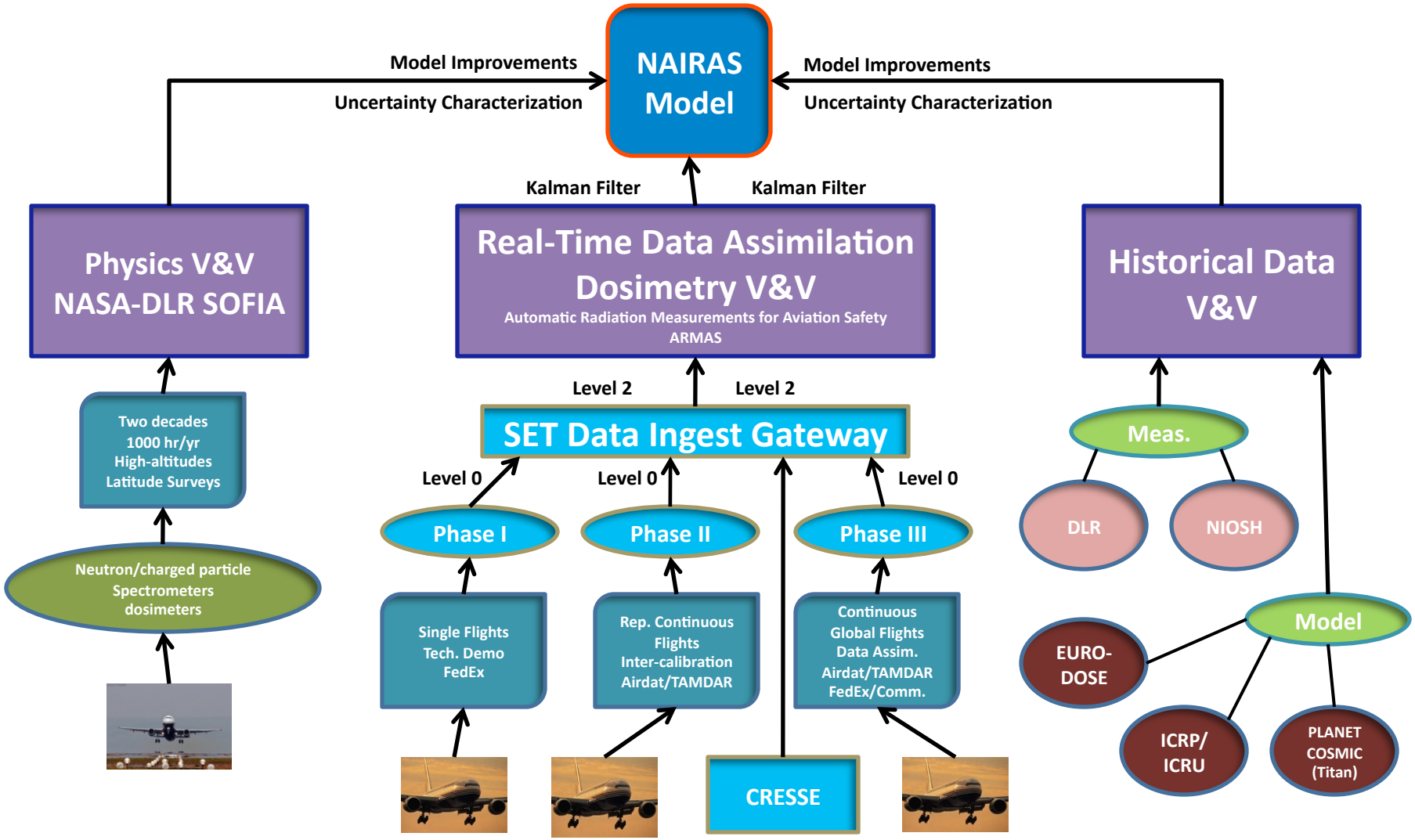
- TS05 cutoff latitude accuracy: ~ 2-degrees
- TS05 cutoff accuracy significantly better LFM/MHD code
- 2-degree cutoff uncertainty in latitude can translate into factor ~2 or greater aircraft dose uncertainty

Flight Path Comparison
Geomagnetic Effects



- **LHR-JFK flight path**
  - Significant differences because flight comes near to or crosses the open/closed field line boundary
  - Geomagnetic effects introduce a factor ~ 2 or greater variation in dose
- **ORD-PEK flight path**
  - Limited differences since both models include passage into polar cap
  - Significant dosage is seen in both cases

NAIRAS V&V and Data Assimilation Plan



ARMAS Program

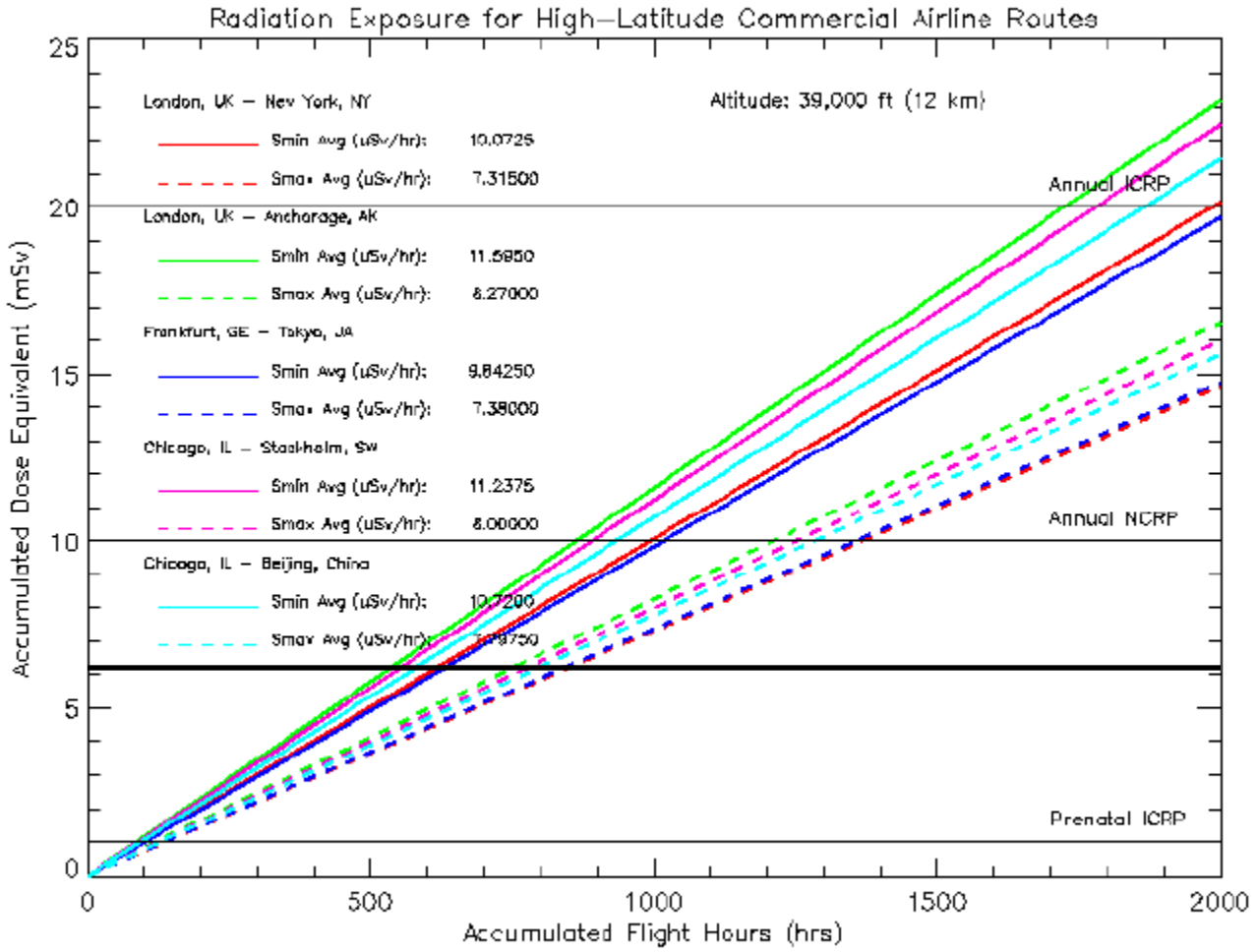
- ARMAS
  - Automated Radiation Measurements for Aviation Safety
- NASA/SBIR project lead by Space Environment Technologies
  - Phase I selected for funding to address Phase I of NAIRAS Decadal Roadmap for V&V and Data Assimilation of Radiation Measurements
- ARMAS Team
  - Kent Tobiska (PI), Space Environment Technologies
  - Brad Gersey (Co-I), CRESSE, Prairie View A &M
  - Bill Atwell (Collaborator), Boeing
  - Chris Mertens (Collaborator/Customer), NASA LaRC

Summary Remarks

- **Main Summary**
  - NAIRAS is now streaming live from our public website and available as an iPhone app!
  - NIOSH statistical study shows median US pilot would trigger monitoring in EU States
  - ICRP prenatal and annual public limits can be exceeded during high-latitude SEP events
  - A Carrington-like event can result in ICRP prenatal and annual limits exceeded on nearly all US flights – domestic and international

Backup Slides

GCR Exposure



EU Action Level

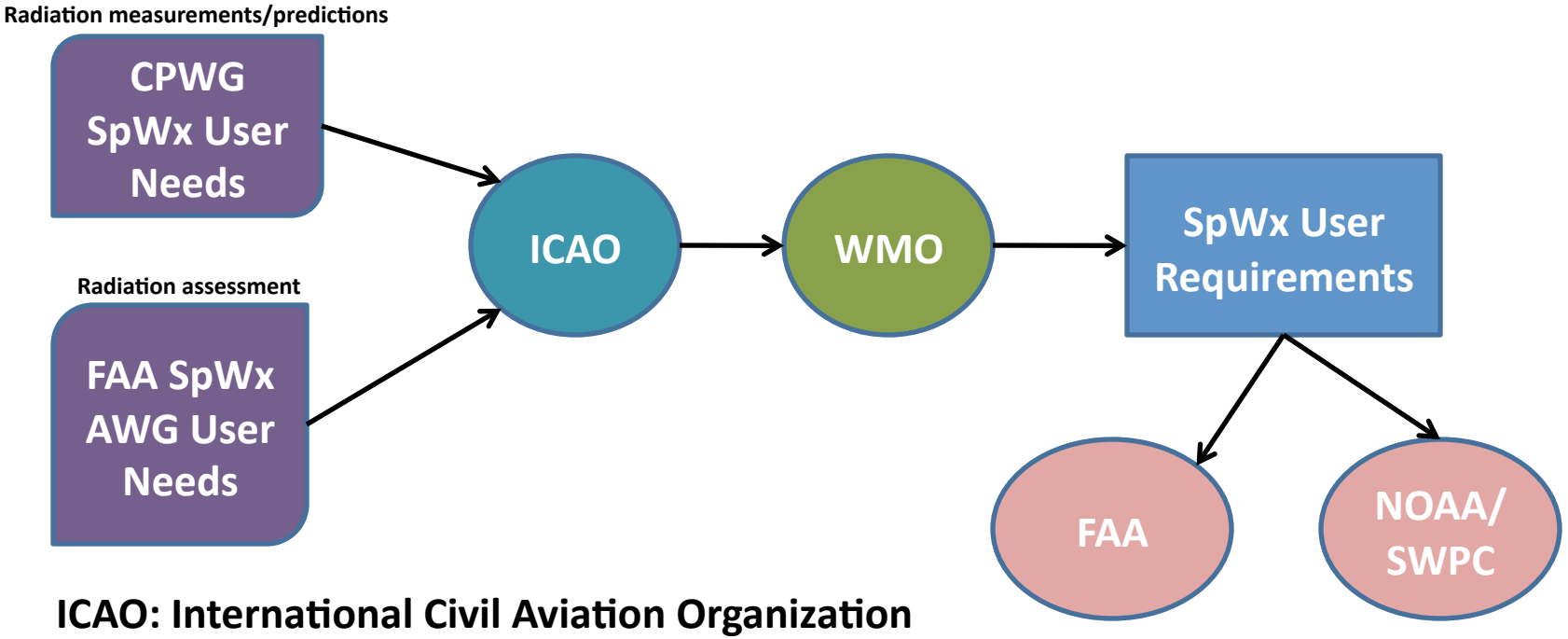
ICRP Public/Prenatal

Aircraft Radiation Exposure Medical Research

- Cosmic rays can directly break DNA strands in biological tissue, or produce chemically active radicals in tissue that alter the cell function [Wilson et al., 2005, 2003]
  - Both can lead to cancer
- Other adverse health effects include, but are not limited to, reproductive disorder and prenatal injury [Lauria et al., 2006; Waters et al., 2000; Aspholm et al., 1999]
- Because aircrew total career dose is received is low doses per flight, and accumulated slowly over the length of a flying career, the direct evidence that a person can develop cancer as a result of cosmic radiation is inconclusive
  - Other lifestyle risk factors exist over a flying career
- However, radiation protection community accepts the Linear No Threshold (LNT) theory
  - Every radiation exposure will have an effect on human health

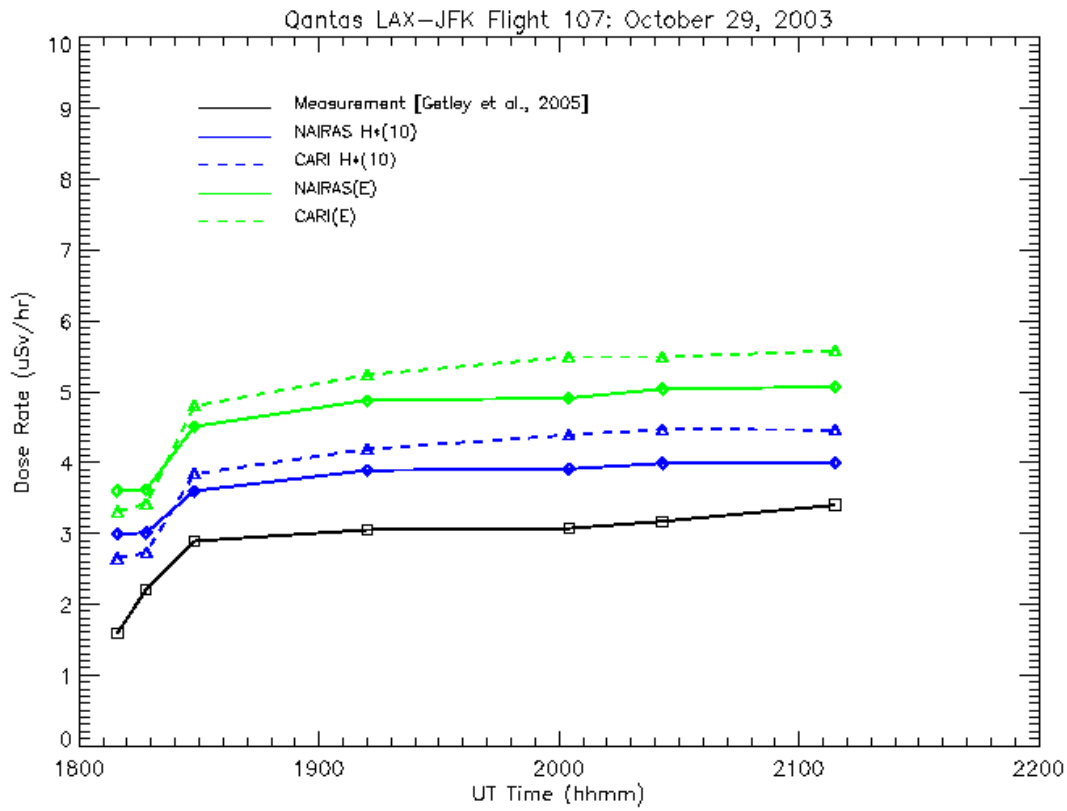
Aircraft Radiation Exposure Recommendations and Actions

- **USA**
  - **ICRP recommendations for occupational exposures** (< 20 mSv/yr, < 1 mSv during pregnancy)
  - **ICRP recommendation during pregnancy** (< 0.5 mSv in any month)
  - **ICRP recommendation for public** (< 1 mSv)
- **Current development of SpWx/aircraft radiation requirements**

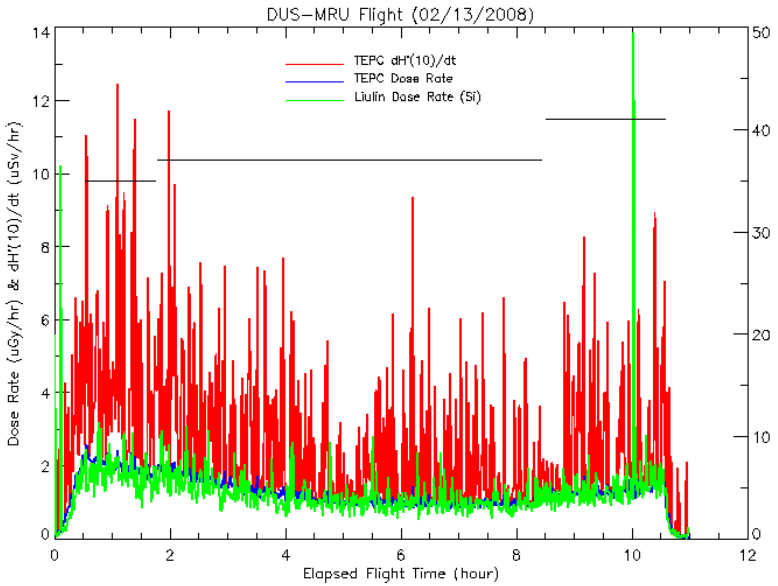


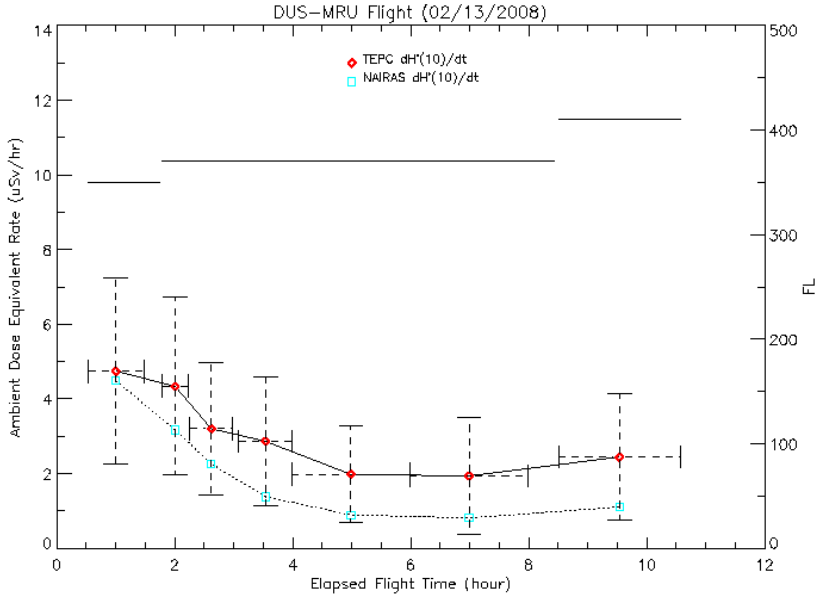
ICAO: International Civil Aviation Organization

NAIRAS/Qantas-TEPC Comparison



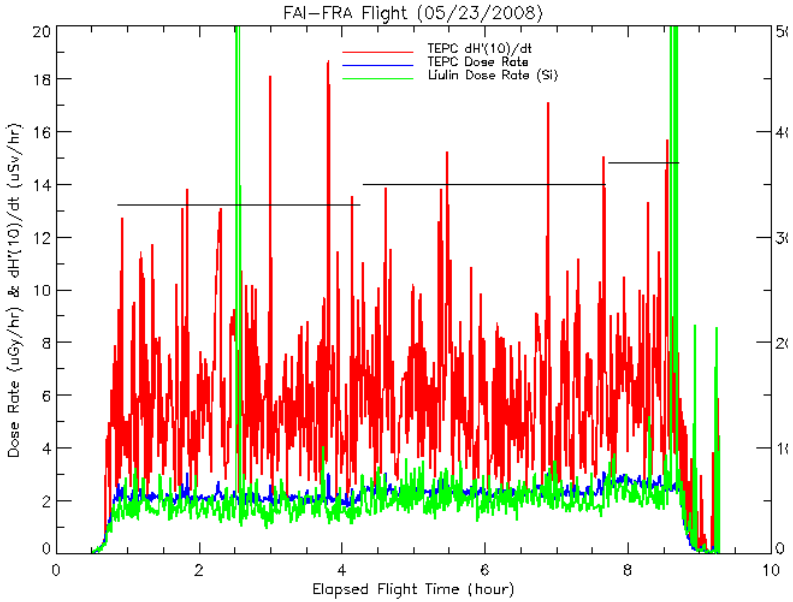
NAIRAS/DLR-TEPC Comparisons

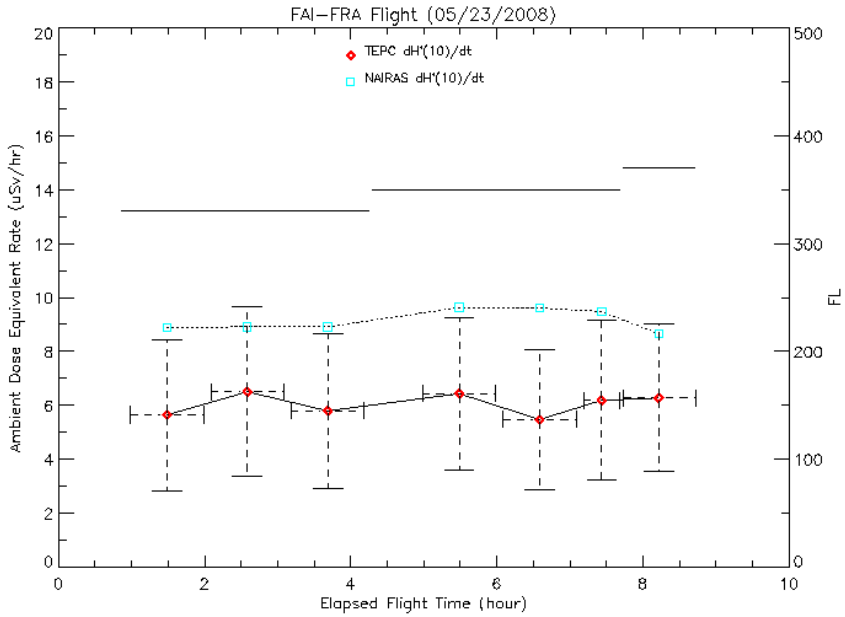




TEPC data courtesy of Matthias Meier

NAIRAS/DLR-TEPC Comparisons





TEPC data courtesy of Matthias Meier