Safeguarding Society with Actionable Space Weather Information

Neutron Monitor Observations for Space Weather Forecasting

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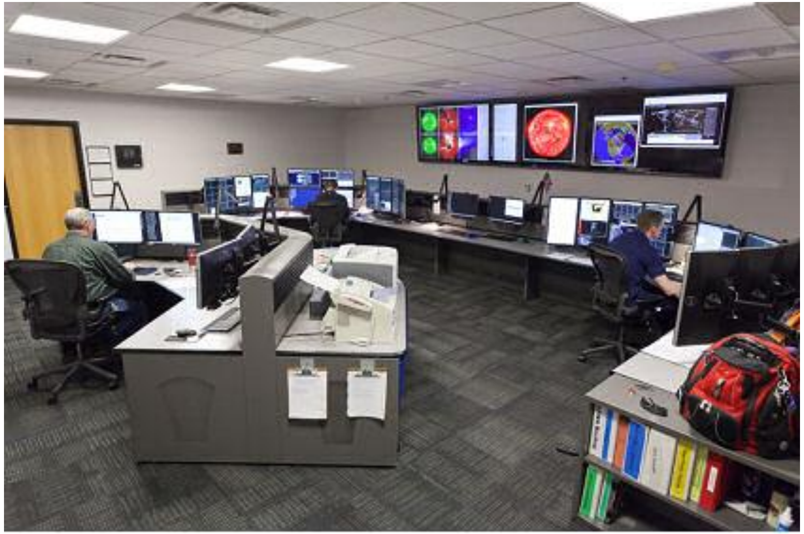
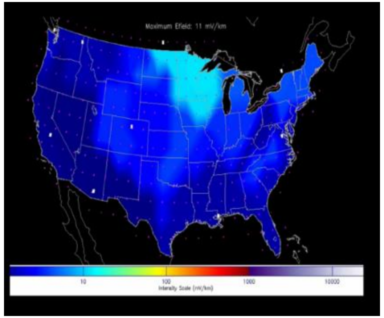
NOAA Space Weather Prediction Center

NOAA’s Space Weather Prediction Center (SWPC), in Boulder CO, serves as the nation’s official source for advance warning of Space Weather disturbances.

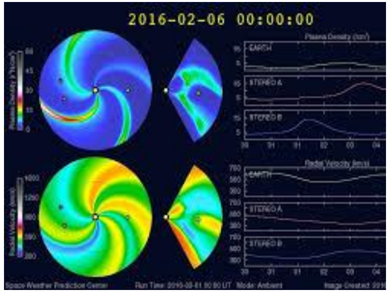
Forecasters at SWPC issue space weather warnings and alerts to customers who use these forecasts to safeguard their assets.





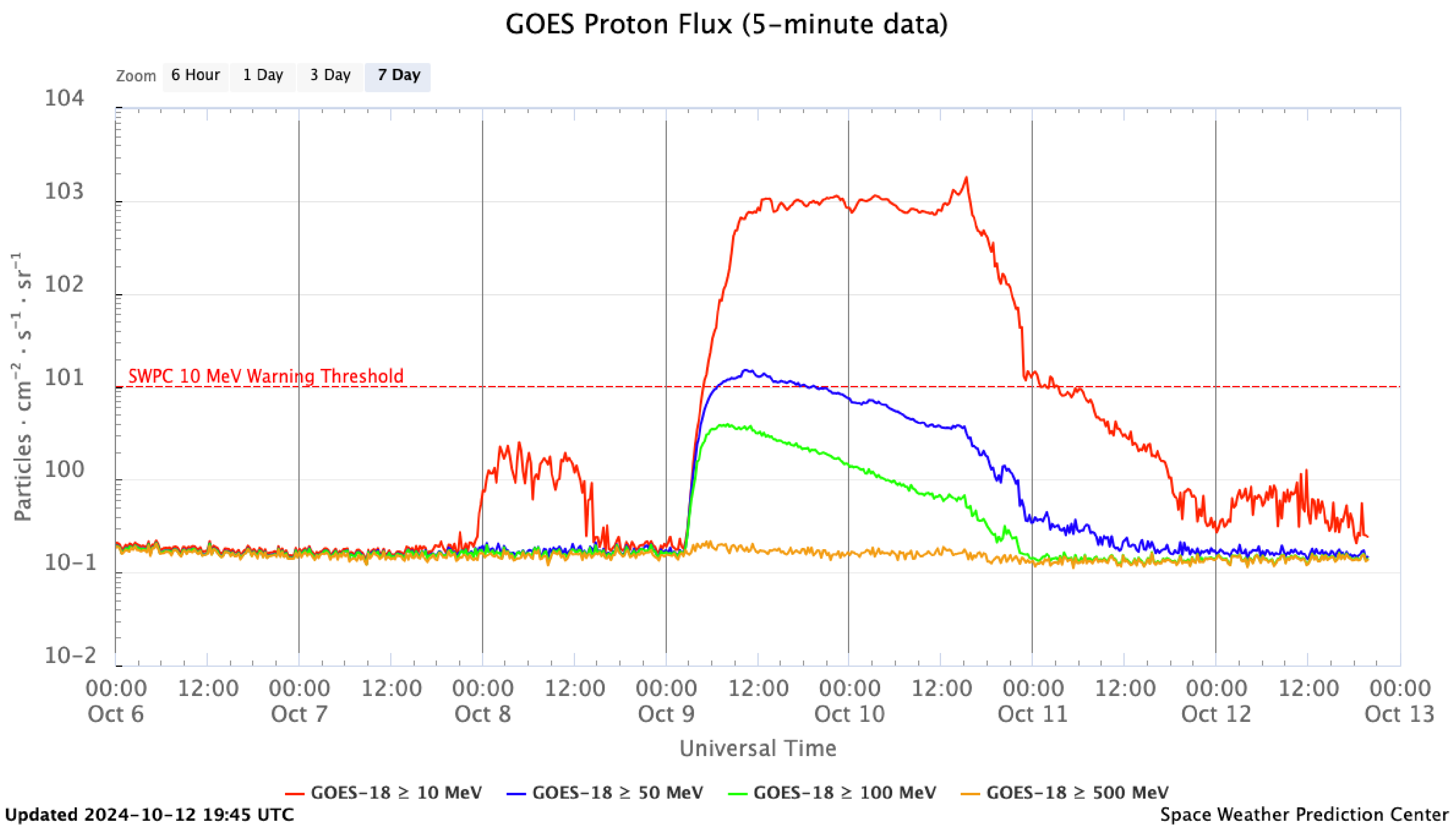

Maximum Efield: 11 mV/km
10
100
1000
10000
Intensity Scale (mV/km)

FEMA


2016-02-06 00:00:00
EARTH
STEREO A
STEREO B
Space Weather Prediction Center



SIEMENS



GOES Proton Flux (5-minute data)
Zoom 6 Hour 1 Day 3 Day 7 Day
SWPC 10 MeV Warning Threshold
Particles · cm-2 · s-1 · sr-1
104
103
102
101
100
10−1
10−2
00:00 Oct 6
12:00
00:00 Oct 7
12:00
00:00 Oct 8
12:00
00:00 Oct 9
12:00
00:00 Oct 10
12:00
00:00 Oct 11
12:00
00:00 Oct 12
12:00
00:00 Oct 13
Universal Time
GOES-18 ≥ 10 MeV
GOES-18 ≥ 50 MeV
GOES-18 ≥ 100 MeV
GOES-18 ≥ 500 MeV
Updated 2024-10-12 19:45 UTC
Space Weather Prediction Center

Solar Radiation Storm Scale (S-scale)

Scale	Description	Effect	Physical measure (Flux level of >= 10 MeV particles)
S 5	Extreme	**Biological:** Unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** Complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5
S 4	Severe	**Biological:** Unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** May experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** Blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4
S 3	Strong	**Biological:** Radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** Degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3
S 2	Moderate	**Biological:** Passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk. **Satellite operations:** Infrequent single-event upsets possible. **Other systems:** Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2
S 1	Minor	**Biological:** None. **Satellite operations:** None. **Other systems:** Minor impacts on HF radio in the polar regions.	10

Radiation Impacts to Aviation

Health of crew and passengers:

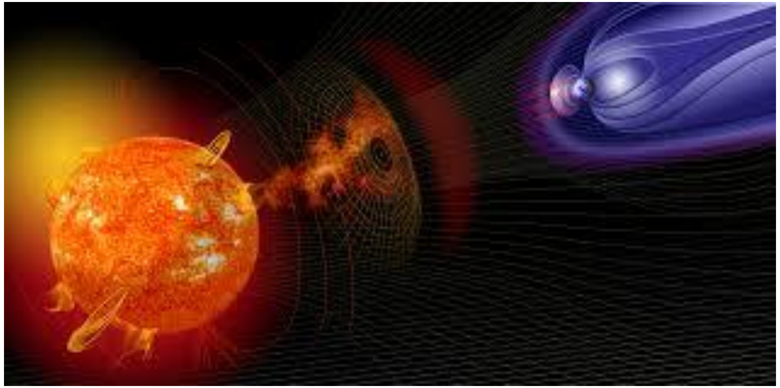
- Elevated radiation dose rates at flight altitudes during solar radiation storms

On-board electronics:

- Reboots and anomalies resulting from e.g. single event upsets (SEEs)

Polar Cap Absorption (PCA):

- Energetic protons precipitating in the D-region of the atmosphere can impact High Frequency (HF) communications

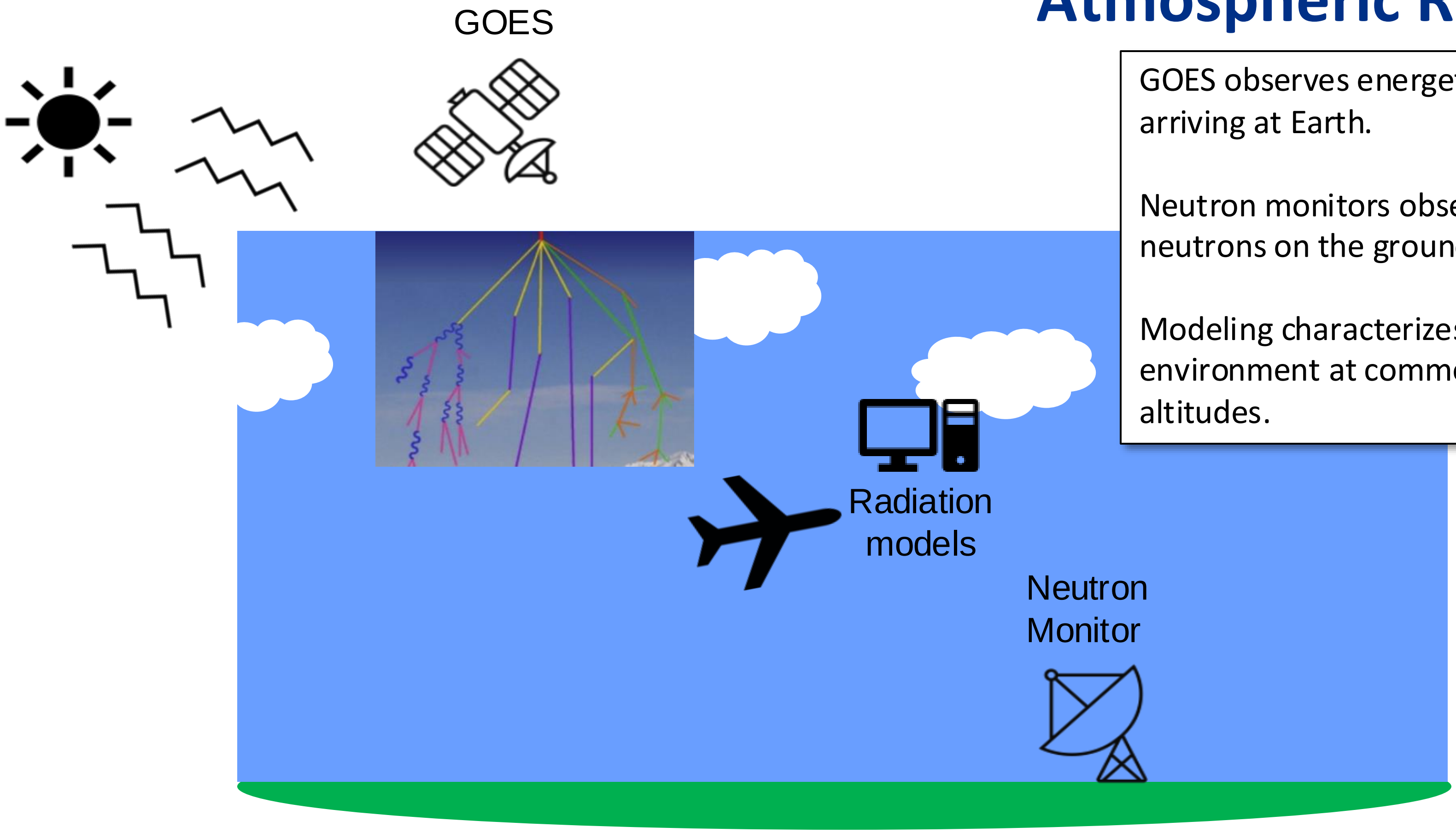


Atmospheric Radiation

GOES observes energetic particles arriving at Earth.

Neutron monitors observe secondary neutrons on the ground during GLEs.

Modeling characterizes the radiation environment at commercial aviation altitudes.

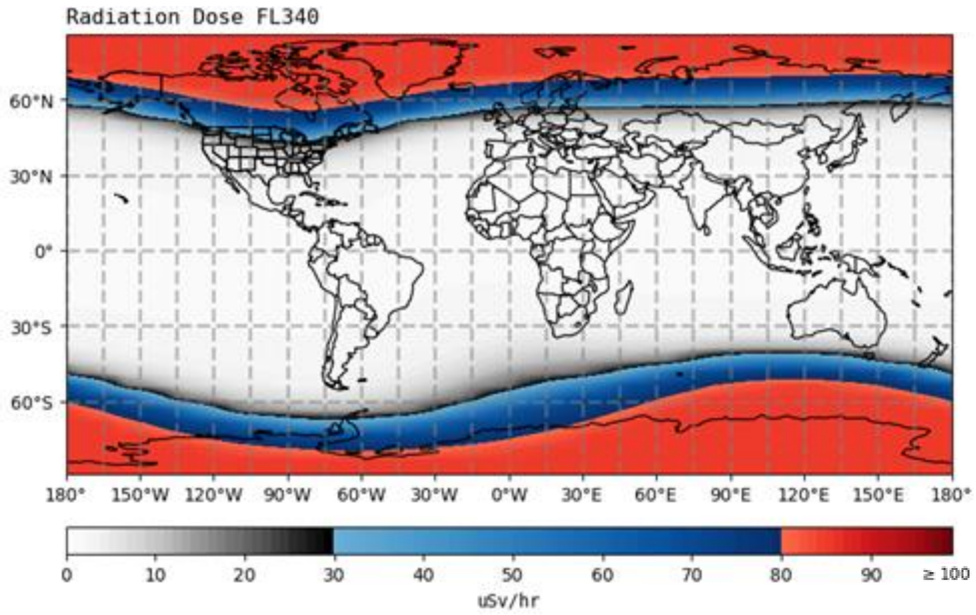


CARI-7 Model

NOAA SWPC radiation advisories are guided by the FAA CARI-7a (Copeland 2008, 2017, 2021).

Model determines the radiation effective dose rate at aviation flight levels:

- Galactic Cosmic Radiation (GCR) modulation
- Solar energetic particle (SEP) event
- Geomagnetic and atmospheric responses

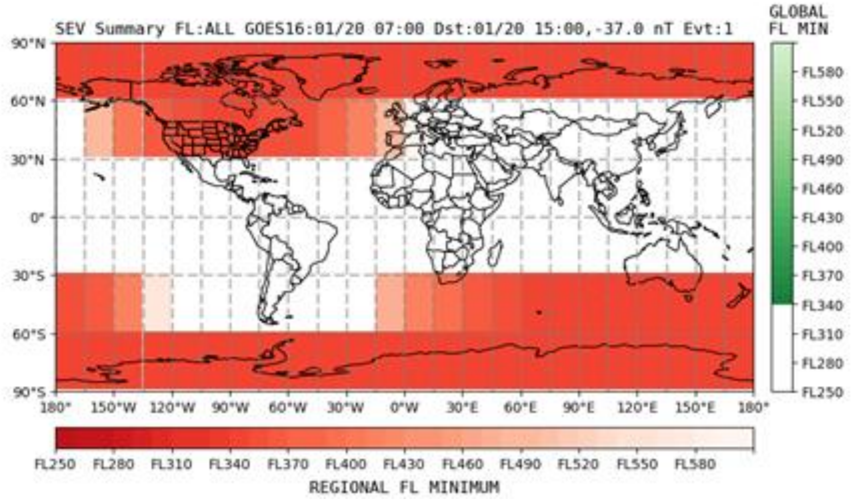


ICAO Radiation Advisory

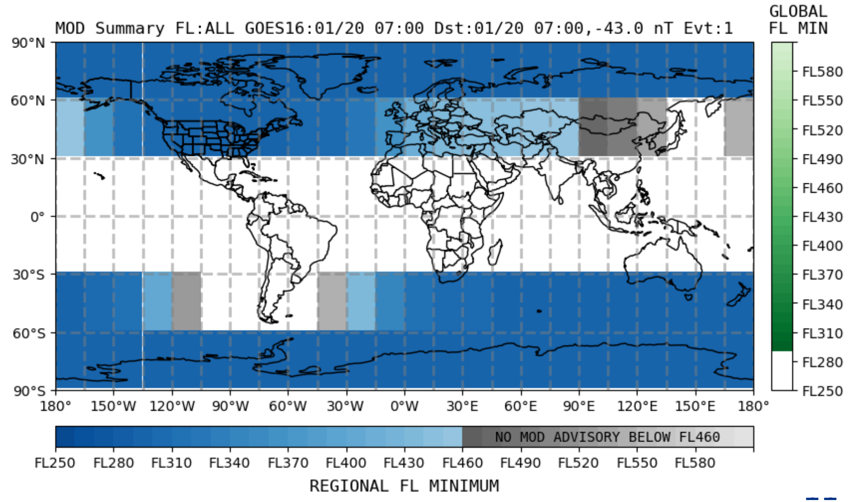
Regional advisory issued when effective dose rates exceed 30 μSv/hr (moderate) and 80 μSv/hr (severe) between 25,000 ft and 60,000 ft.

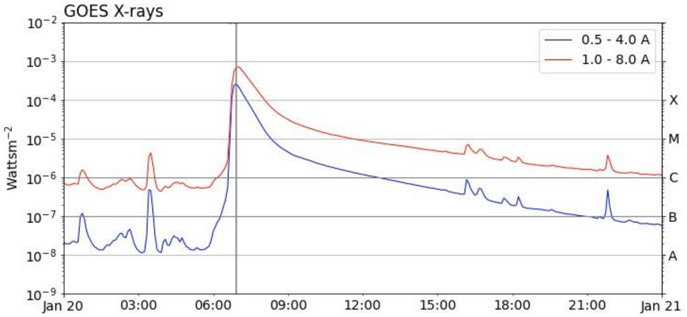
Advisory issued for six 30^{o} latitude bands.

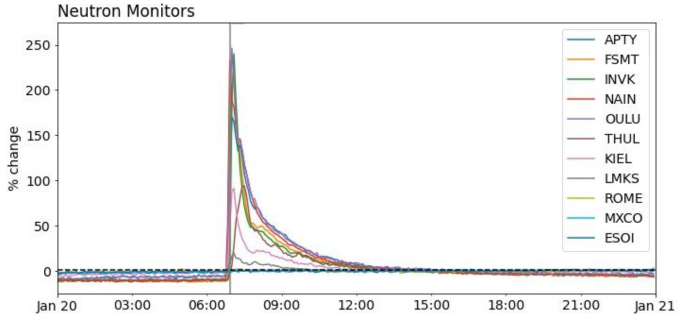
SEV

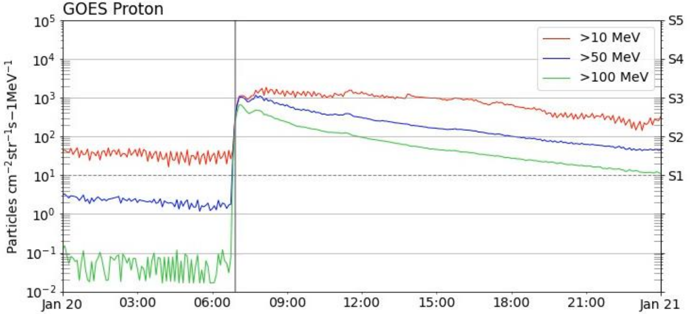


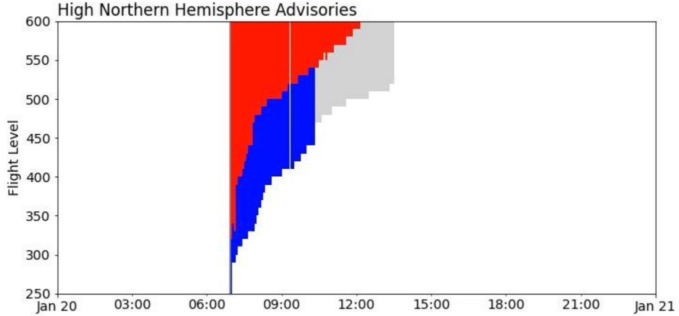
MOD

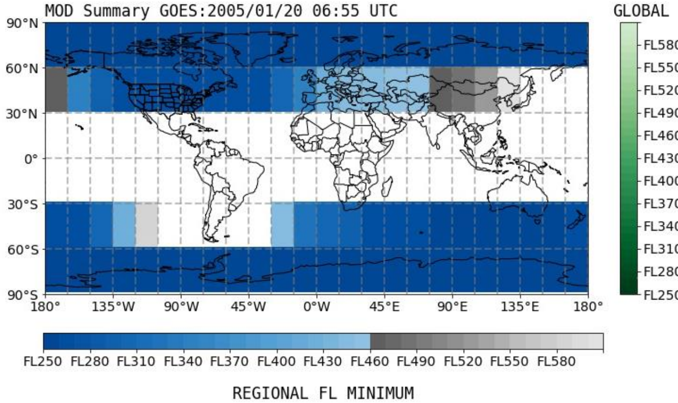


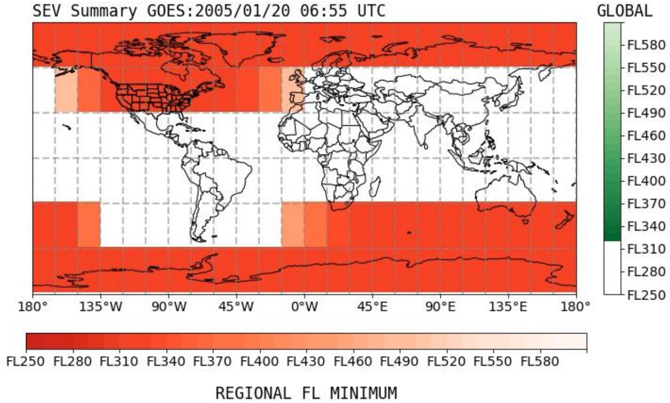

GOES X-rays
0.5 - 4.0 A
1.0 - 8.0 A
Wattsm^{-2}
X
M
C
B
A
Jan 20
03:00
06:00
09:00
12:00
15:00
18:00
21:00
Jan 21


Neutron Monitors
% change
APTY
FSMT
INVK
NAIN
OULU
THUL
KIEL
LMKS
ROME
MXCO
ESOI
Jan 20
03:00
06:00
09:00
12:00
15:00
18:00
21:00
Jan 21


GOES Proton
Particles cm^{-2}str^{-1}s-1MeV^{-1}
>10 MeV
>50 MeV
>100 MeV
S5
S4
S3
S2
S1
Jan 20
03:00
06:00
09:00
12:00
15:00
18:00
21:00
Jan 21


High Northern Hemisphere Advisories
Flight Level
Jan 20
03:00
06:00
09:00
12:00
15:00
18:00
21:00
Jan 21


MOD Summary GOES:2005/01/20 06:55 UTC
GLOBAL
FL580
FL550
FL520
FL490
FL460
FL430
FL400
FL370
FL340
FL310
FL280
FL250
90°N
60°N
30°N
0°
30°S
60°S
90°S
180°
135°W
90°W
45°W
0°W
45°E
90°E
135°E
180°
REGIONAL FL MINIMUM


SEV Summary GOES:2005/01/20 06:55 UTC
GLOBAL
FL580
FL550
FL520
FL490
FL460
FL430
FL400
FL370
FL340
FL310
FL280
FL250
180°
135°W
90°W
45°W
0°W
45°E
90°E
135°E
180°
REGIONAL FL MINIMUM

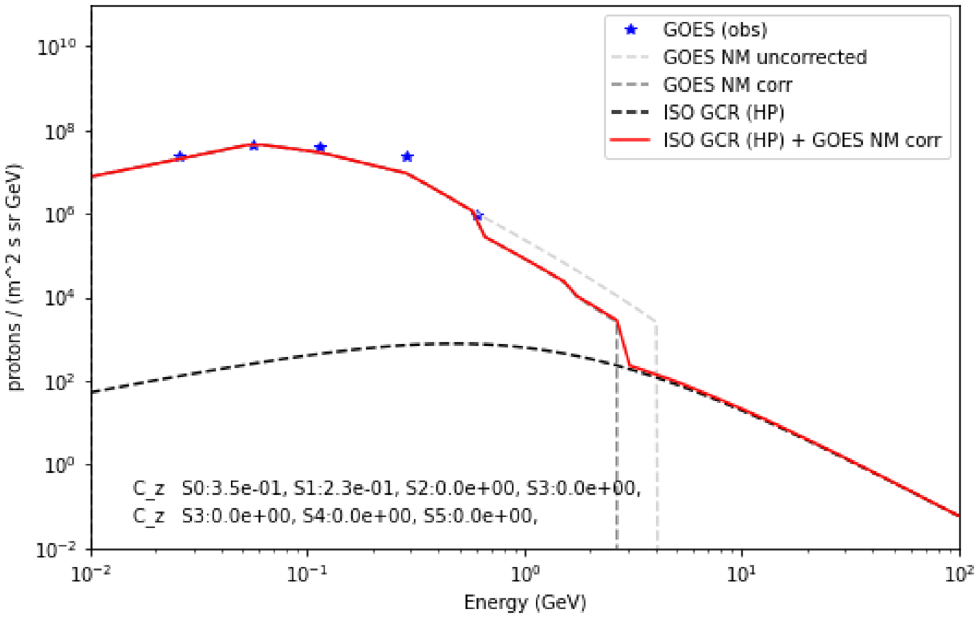
Incident SEP Proton Spectra

NM measurements from range of geomagnetic locations used to infer the spectral shape of the SEP proton spectra (Matthiä, 2018, Hands 2022, Copeland 2008)

Neutron counts are used to correct the highest rigidity portion (>1200 MV) of the spectrum.

High rigidity portion of the spectrum is divided into *n* zones, corresponding to neutron monitors in *n* cutoff rigidity zones, spanning low to high geomagnetic latitudes (based on the availability of RT monitors).

Initial spectral slope estimated from GOES then correction factors applied for each rigidity zone



Incident SEP Proton Spectra

Percent increase ($\pi_{sim(j)}$) between the pre-event GCR and SEP neutron count rate is simulated for each station (j).

$$\pi_{sim(j)} = 100\frac{C_{SEP(j)}}{C_{GCR(j)}}$$

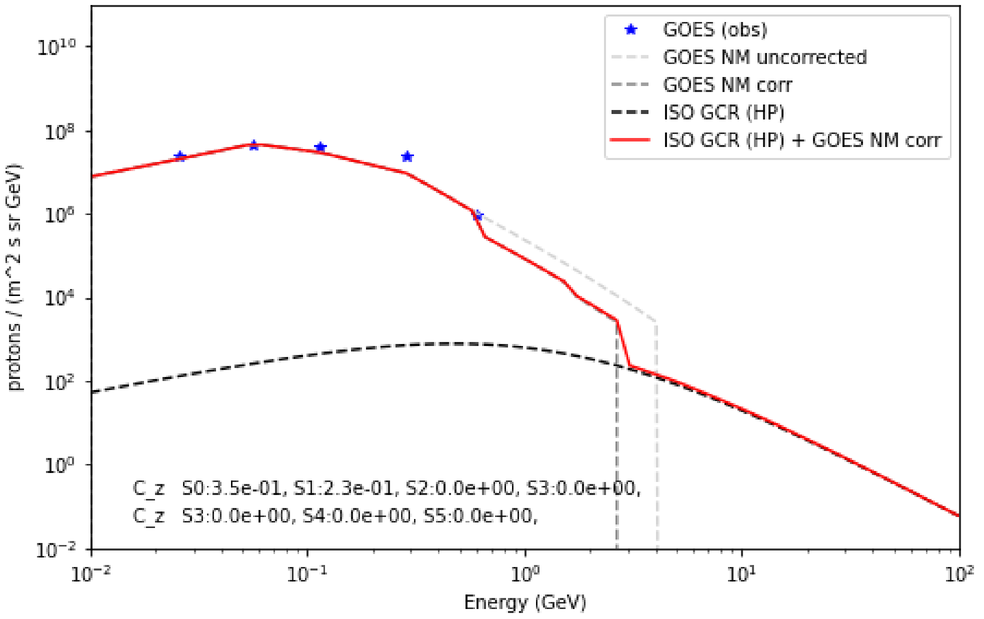
The simulated percent increase is compared with that observed by each station ($\pi_{obs(j)}$)

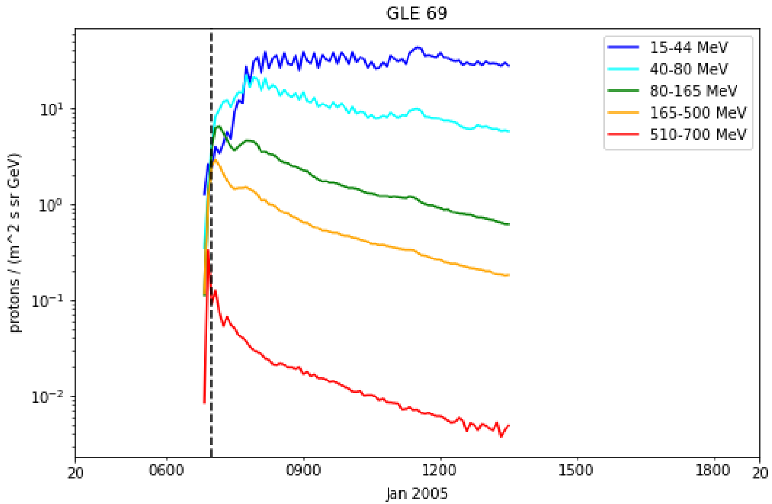
Starting with the highest rigidity zone, a correction factor, Cz(j), is calculated for each zone

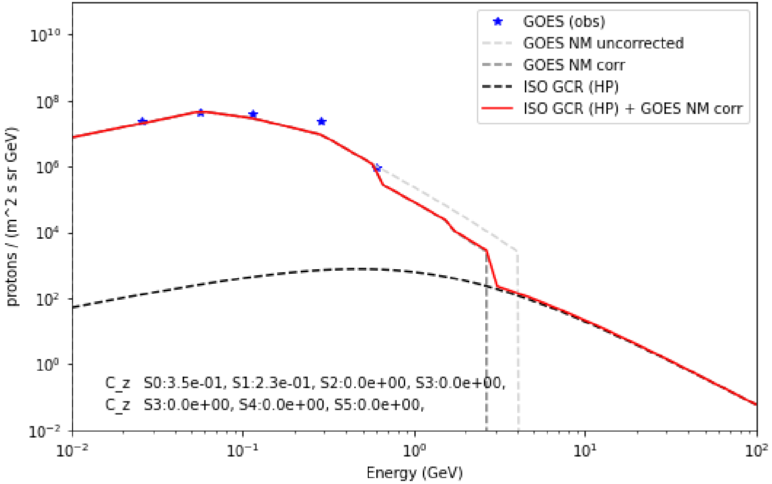
$$\pi_{C(j)} = 100\sum_{k=j+1}^{n}\frac{C_{z(k)}C_{SEP(k)}}{C_{GCR(j)}}$$

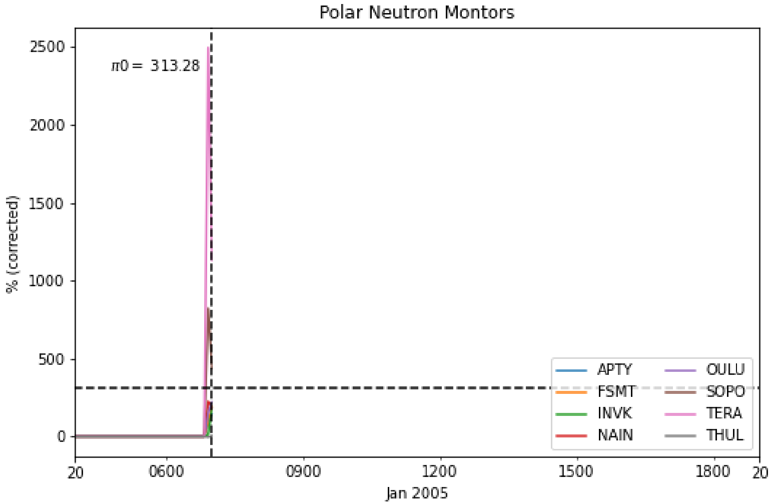
$$C_{z(j)} = \frac{\pi_{obs(j)} - \pi_{C(j)}}{\pi_{sim(j)}}$$

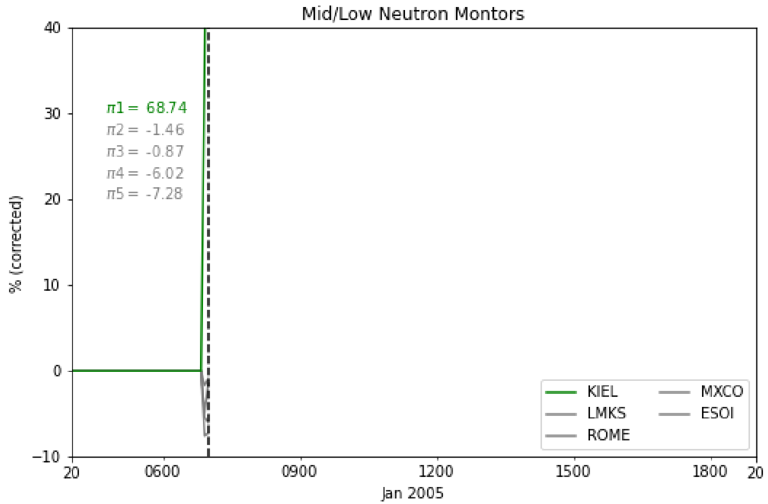
$\pi_{C(j)}$ is the percent increase at station j resulting from flux in higher rigidity zones

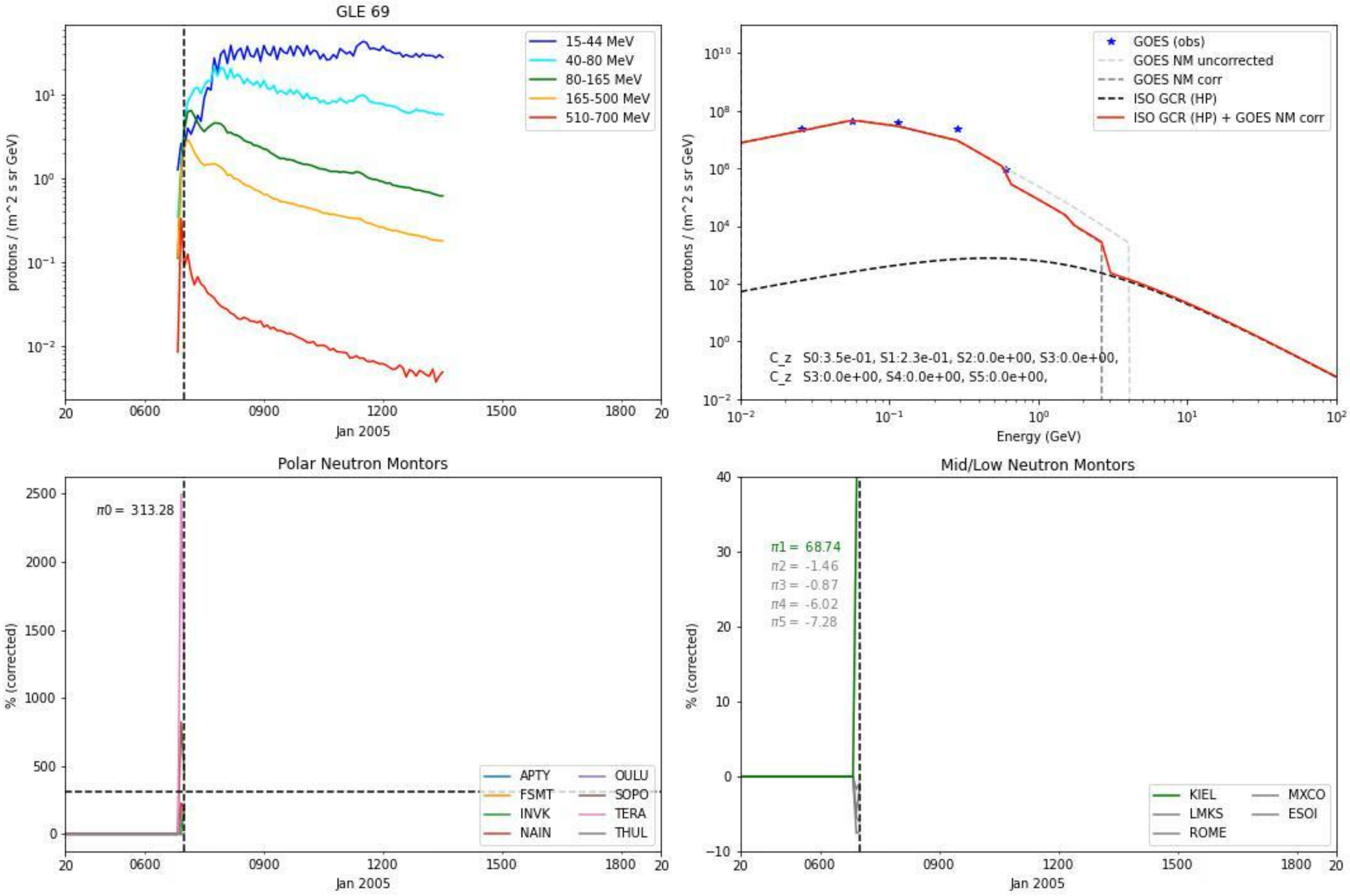



GLE 69
15-44 MeV
40-80 MeV
80-165 MeV
165-500 MeV
510-700 MeV
protons / (m^2 s sr GeV)
20
0600
0900
1200
1500
1800
20
Jan 2005


GOES (obs)
GOES NM uncorrected
GOES NM corr
ISO GCR (HP)
ISO GCR (HP) + GOES NM corr
C_z S0:3.5e-01, S1:2.3e-01, S2:0.0e+00, S3:0.0e+00,
C_z S3:0.0e+00, S4:0.0e+00, S5:0.0e+00,
protons / (m^2 s sr GeV)
Energy (GeV)

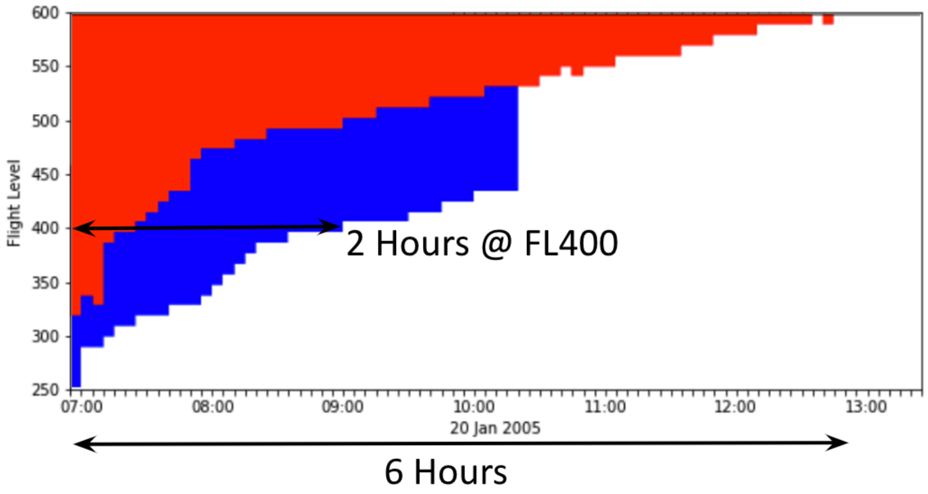

Polar Neutron Montors
π0 = 313.28
APTY
FSMT
INVK
NAIN
OULU
SOPO
TERA
THUL
% (corrected)
20
0600
0900
1200
1500
1800
20
Jan 2005

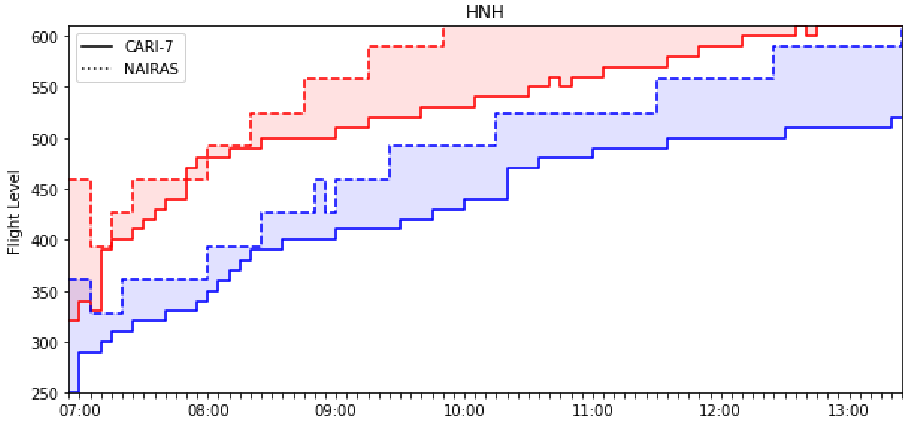

Mid/Low Neutron Montors
π1 = 68.74
π2 = -1.46
π3 = -0.87
π4 = -6.02
π5 = -7.28
KIEL
LMKS
ROME
MXCO
ESOI
% (corrected)
20
0600
0900
1200
1500
1800
20
Jan 2005


GLE 69
15-44 MeV
40-80 MeV
80-165 MeV
165-500 MeV
510-700 MeV
protons / (m^2 s sr GeV)
20
0600
0900
1200
1500
1800
20
Jan 2005
GOES (obs)
GOES NM uncorrected
GOES NM corr
ISO GCR (HP)
ISO GCR (HP) + GOES NM corr
C_z S0:3.5e-01, S1:2.3e-01, S2:0.0e+00, S3:0.0e+00,
C_z S3:0.0e+00, S4:0.0e+00, S5:0.0e+00,
Energy (GeV)
Polar Neutron Montors
π0 = 313.28
% (corrected)
APTY
FSMT
INVK
NAIN
OULU
SOPO
TERA
THUL
Mid/Low Neutron Montors
π1 = 68.74
π2 = -1.46
π3 = -0.87
π4 = -6.02
π5 = -7.28
KIEL
LMKS
ROME
MXCO
ESOI

Flight Level Uncertainties

Comparisons between aviation radiation model results during large SEPs indicate inconsistencies in moderate and severe flight level boundaries.





Operational Considerations

Operationally supported neutron measurements are crucial for space weather forecasting applications.

Maintain and upgrade the current U.S. funded stations to ensure robust provision data to space weather operational centers.

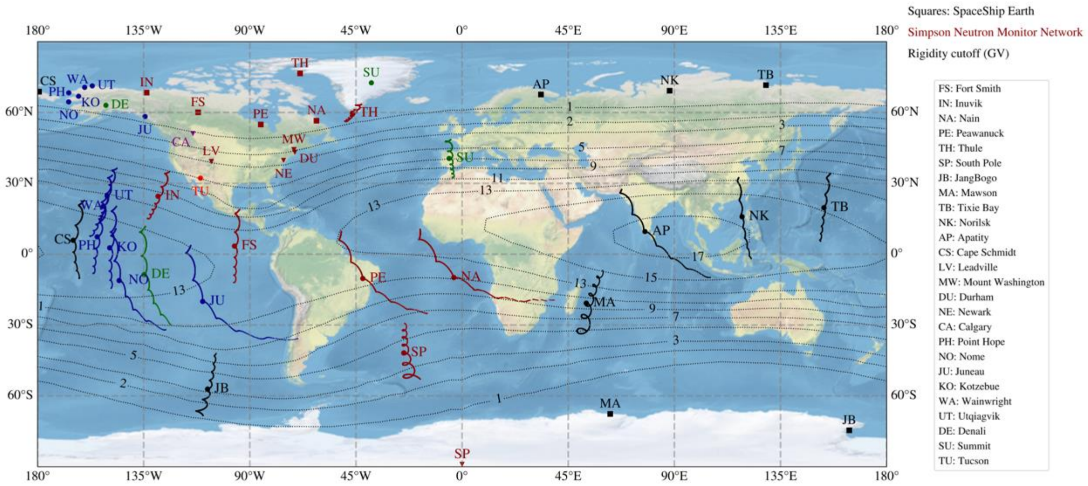
- Computational reliability through redundancy, typically required for operational assets.

Ensure delivery of data in near real-time.

- Provide 1 minute pressure corrected data
- Maximum 5 minute latency, with a goal of 1 minute latency (similar to GOES)

Invest in modern, cost-effective detector designs and alternative approaches.

Perform studies to determine the optimal distribution of stations to support space weather operations.

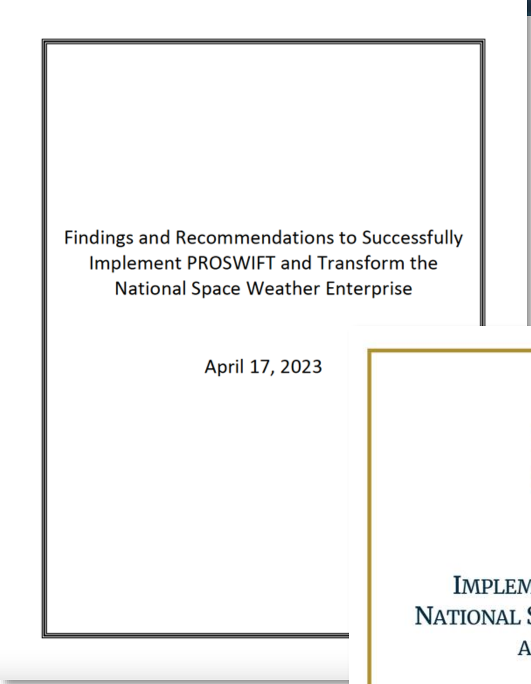


Findings and Recommendations to Successfully Implement PROSWIFT and Transform the National Space Weather Enterprise 2023

Ground-based…networks provide cost-effective and reliable data for space weather operations…Sensors such as…neutron monitors...can provide reliable data streams. However, because of the fundamental research nature of most sensor networks, there has not been a viable path for these instruments to be supported, maintained, and funded for long-term operational applications. Additionally, consideration should be given to determine the optimal location…of these sensors and networks.

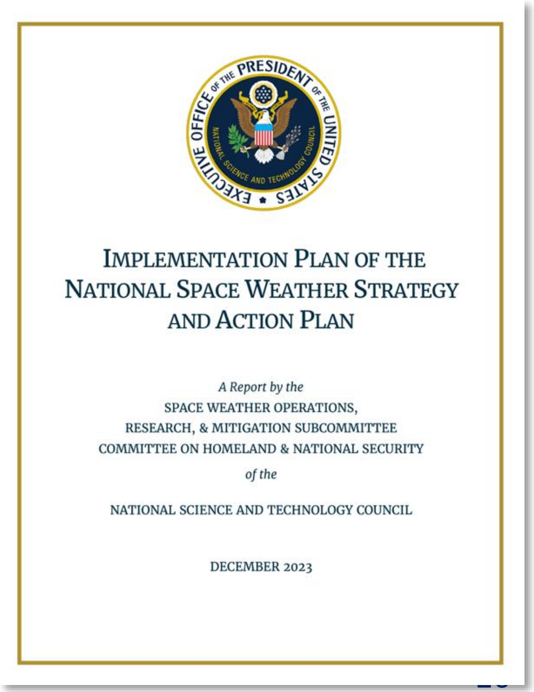
Implementation Plan of the National Space Weather Strategy and Action Plan 2023

2.2.10 Update a collaborative Research-to Operations plan for the implementation of a global network of ground-based neutron monitors meeting scientific and operational forecast needs that includes delivery of real-time data to operational space weather forecast centers. [DOC, DOD, NSF]



Findings and Recommendations to Successfully Implement PROSWIFT and Transform the National Space Weather Enterprise

April 17, 2023



IMPLEMENTATION PLAN OF THE NATIONAL SPACE WEATHER STRATEGY AND ACTION PLAN

A Report by the
SPACE WEATHER OPERATIONS, RESEARCH, & MITIGATION SUBCOMMITTEE
COMMITTEE ON HOMELAND & NATIONAL SECURITY
of the
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

DECEMBER 2023

Summary

Neutron monitors provide crucial observational inputs for space weather operations (GLE Alerts and inputs to models).

Neutron monitors are required to accurately characterize the high energy SEP particles which are most impactful to the radiation environment at aviation flight levels.

A network of neutron measurements needs to be operationally supported (funded for RT O&M)

Studies should be carried out to identify optimal neutron monitor locations which can support space weather models and address user needs.

Studies are required to investigate cost-effective, modern approaches.