Aviation Exposure to Solar Energetic Particle Events

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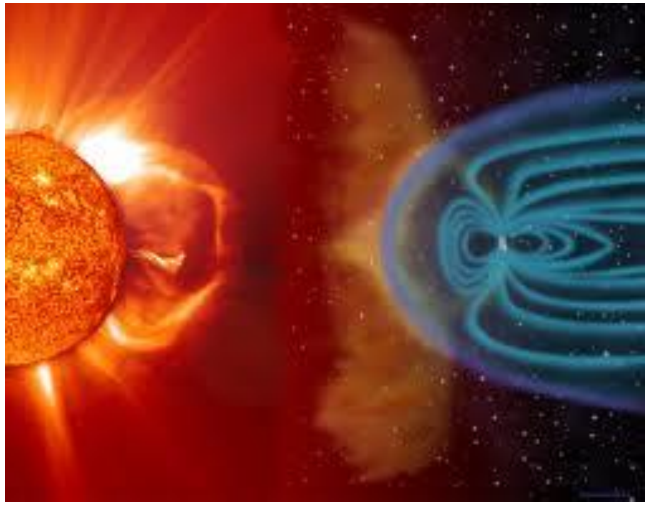

6th September 2017
SEESAW Conference
Boulder CO

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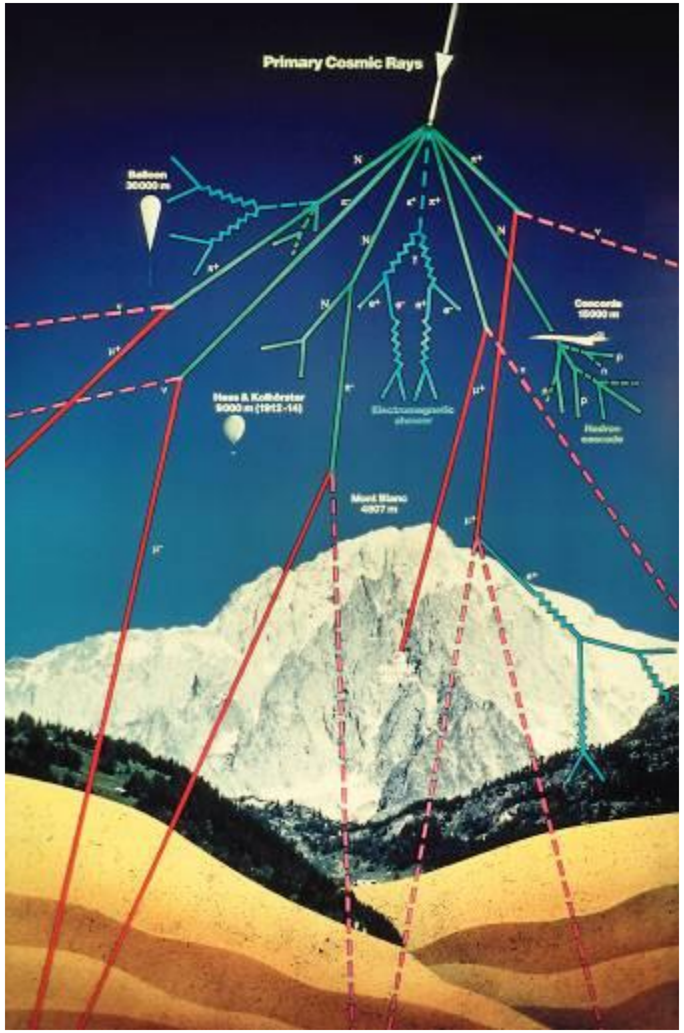
Atmospheric Radiation

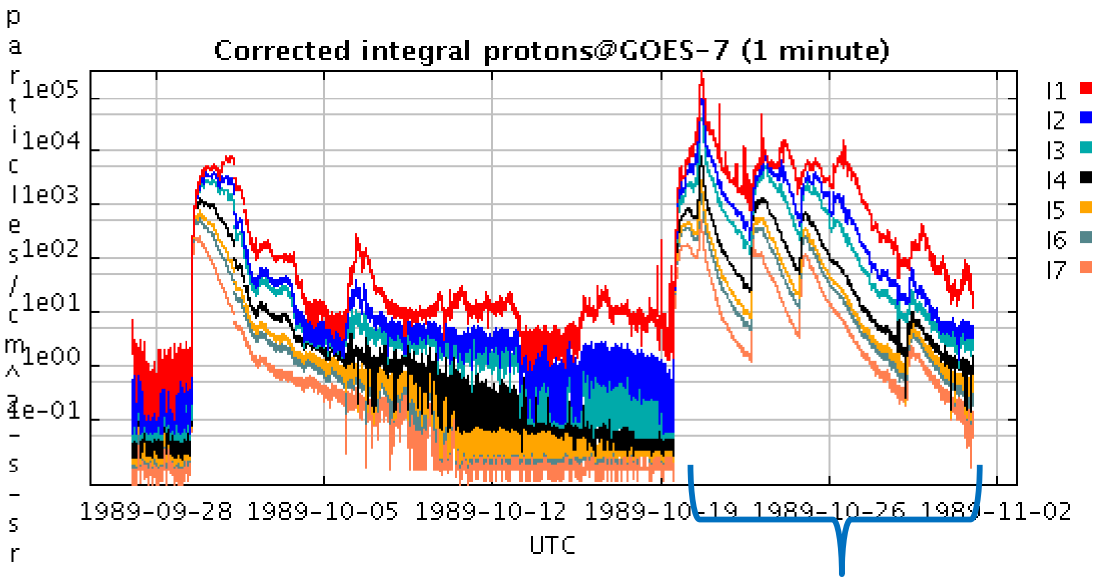
- Cosmic Rays consist primarily of protons and alpha particles with energies extending up to and beyond 10^{20} eV (c.f. LHC ~10^{13} eV)
- Interactions with the atmosphere produce various secondary particles including neutrons across a wide energy range
- Neutron flux builds up to a maximum at 60,000 feet but is reduced by two or three orders of magnitude at sea level
- Solar Energetic Particle Events (SEPEs) can result in several orders of magnitude enhancements, potentially causing radiobiological dose in excess of legal limits in a single flight
- Neutrons can deposit charge in sensitive volumes of semiconductors, leading to a variety of single event effects (SEE) in avionics systems
- Other effects on aviation exist (largely due to ionospheric disturbances – not discussed here)



SEPEs and GLEs

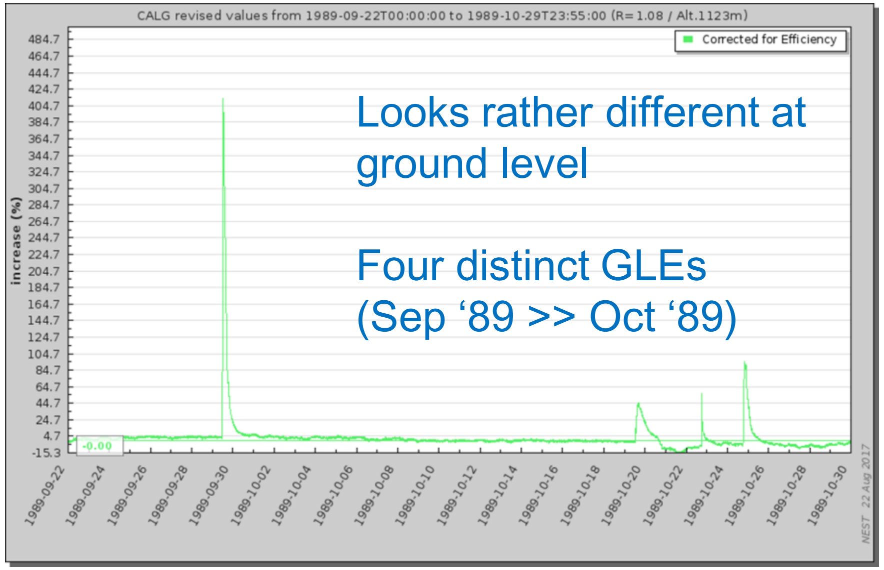
- Solar Energetic Particle Events (SEPEs) can produce large enhancements in incident high energy proton flux at the top of the atmosphere
- A “hard-spectrum” event can produce a Ground Level Enhancement (GLE) – potential hazard to aviation and ground-based systems (roughly one per year)

E.g. GOES data for September / October 1989:



Oct ‘89 often used as worst case for space

Cf. Calgary Neutron Monitor:

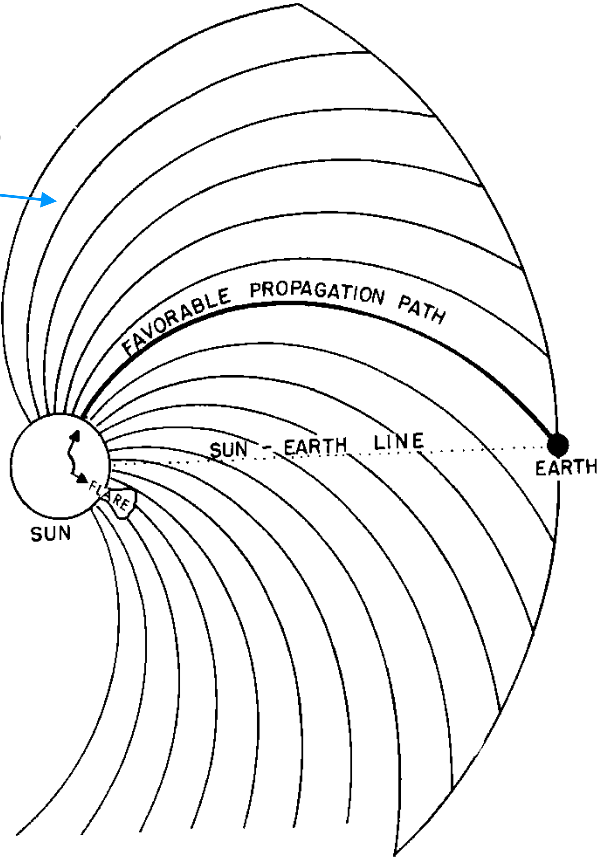


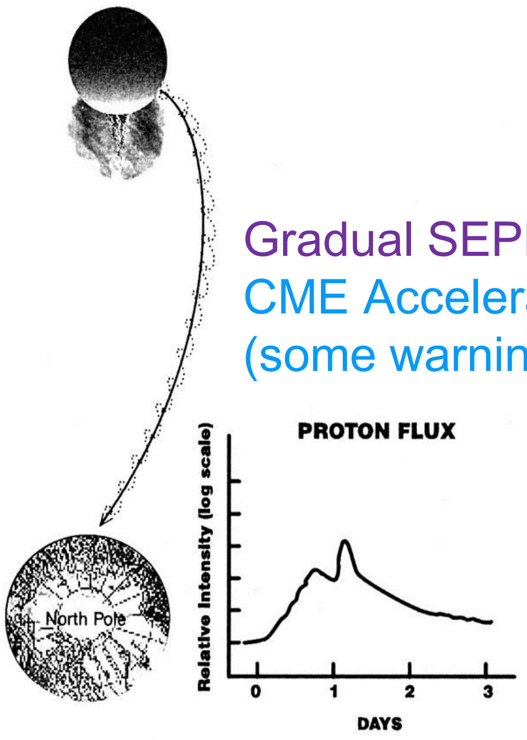
nmdb.eu

Canonical Types of SEPE

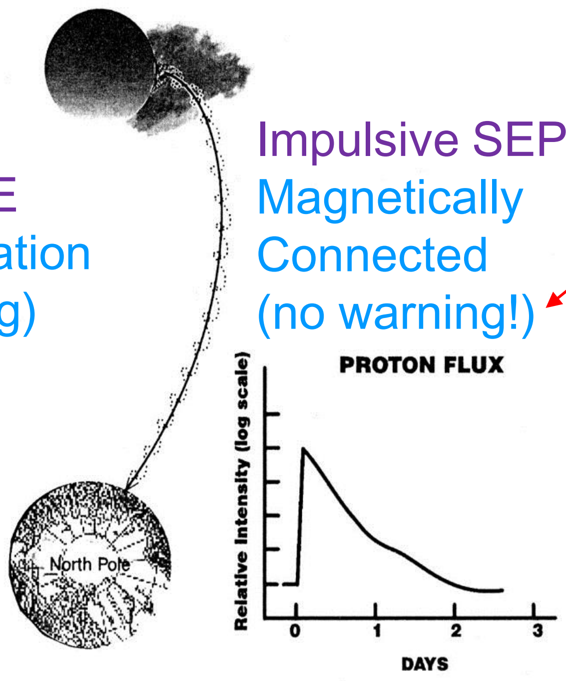
Particle Flux & Time Profile Depend On Event Location On Sun

Parker Spiral (magnetic field)





Gradual SEPE
CME Acceleration
(some warning)



Impulsive SEPE
Magnetically Connected
(no warning!)

Important (and often ignored) contrast to other SW threats

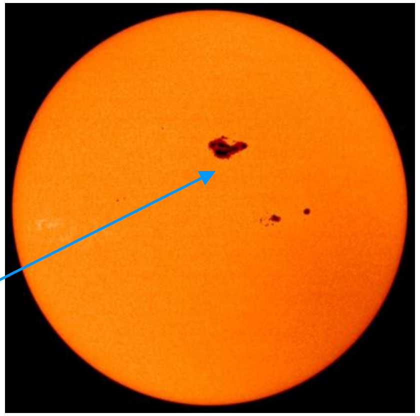
(from Shea & Smart)

January 2005 Events

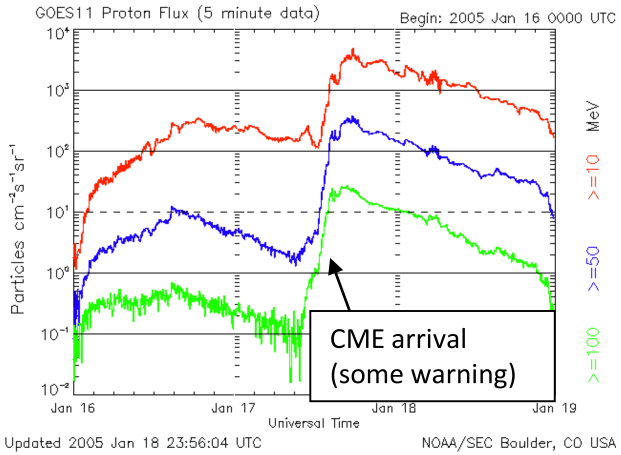
Good case study – gradual and impulsive SPEs (also last major GLE)

16th/17th Jan

Sunspot 720 near central meridian



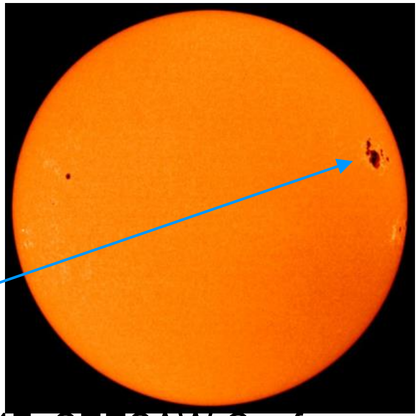
Compare GOES proton flux

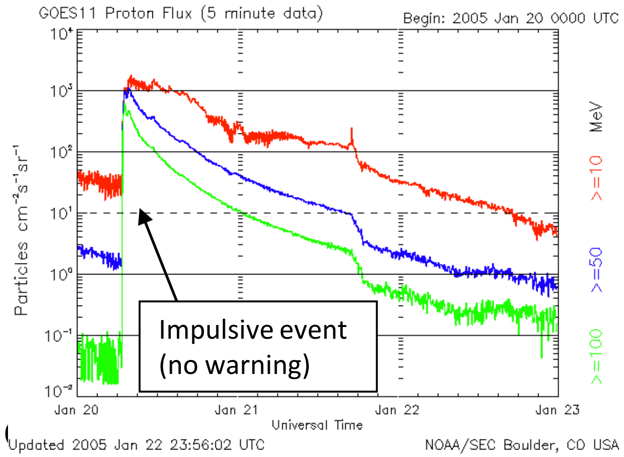


Soft spectrum → no GLE

20th Jan

Sunspot 720 near Western limb





Hard spectrum → GLE

Progressive change vs Shock & Awe ?

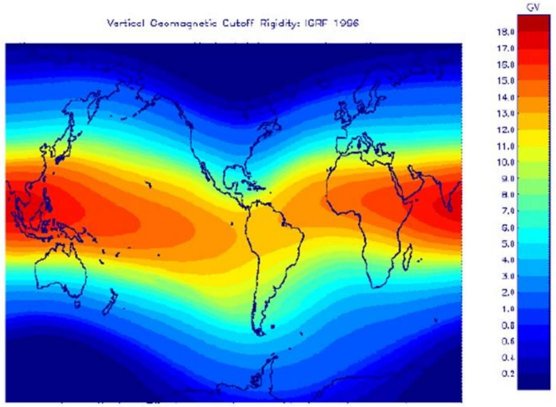
17th Jan = MLK Day

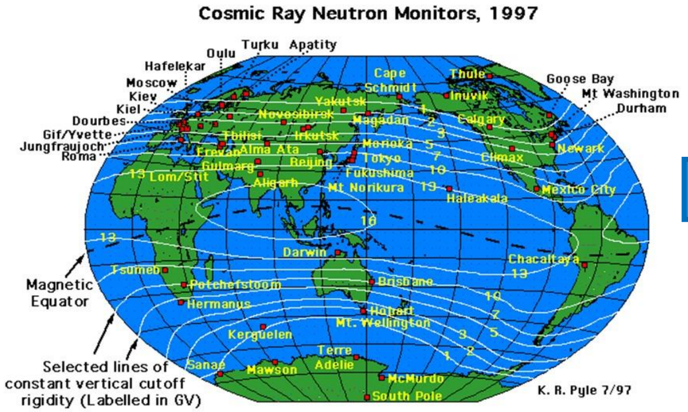
20th Jan = 2nd term inauguration of George W. Bush

Takeaway Point: For GLEs nowcasting is the only game in town

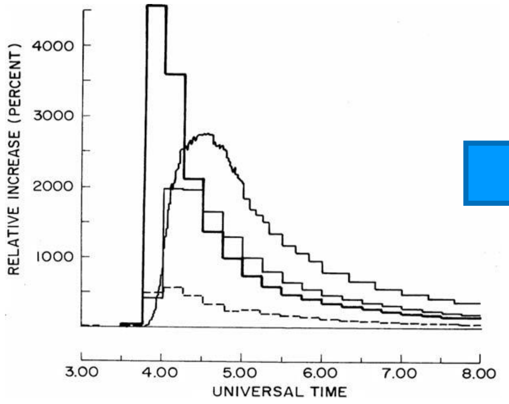
- We cannot (yet) predict which active regions will produce impulsive SEPEs leading to GLEs (long-term goal for forecasting)
- Need real-time *in situ* measurements to feed nowcasting of atmospheric radiation environment (no systematic measurements currently in place)
- Best proxy we have today: ground-level neutron monitors – can be used for alerts as signal appears <u>before</u> space-based proton data

Earth's magnetic field acts like a spectrometer:

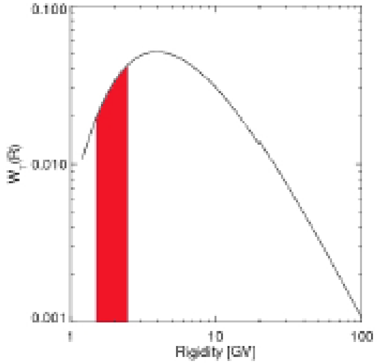




NM data



Primary spectrum



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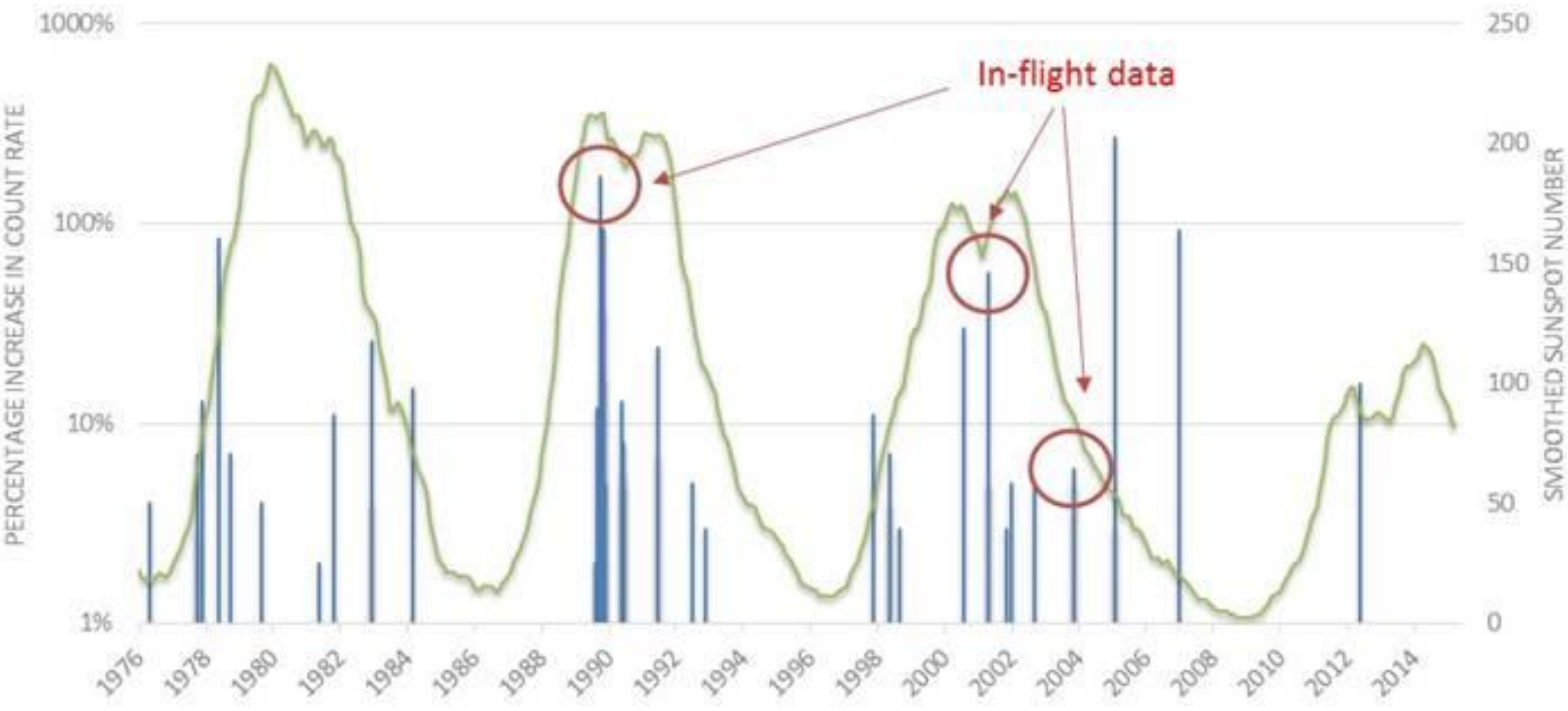
A Brief History of In-flight measurements

Very few GLEs have been observed with on-board active radiation detectors



http://cosmicrays.oulu.fi/GLE.html

Sep / Oct 1989:
GLEs 42, 43, 44 & 45 (large increase in dose rate observed on Concorde during GLE42)

April 2001:
GLE60 (small increase in dose rate observed independently on two flights)

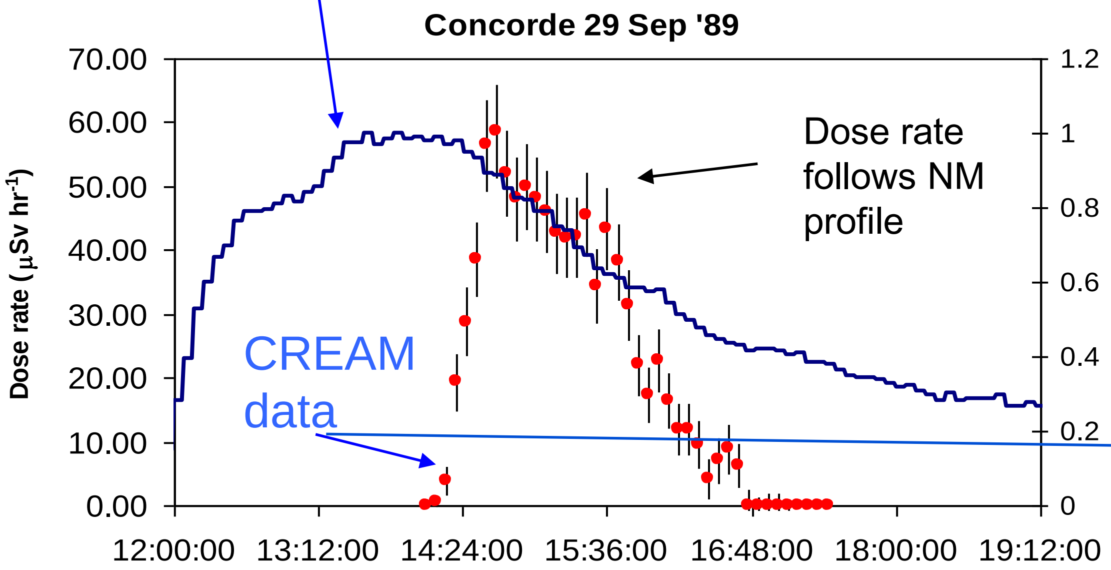
October 2003:
GLE65 (small increase in dose rate)
GLE66 (small increase coincident with altitude rise)

(a handful of null measurements exist, e.g. March 2012)

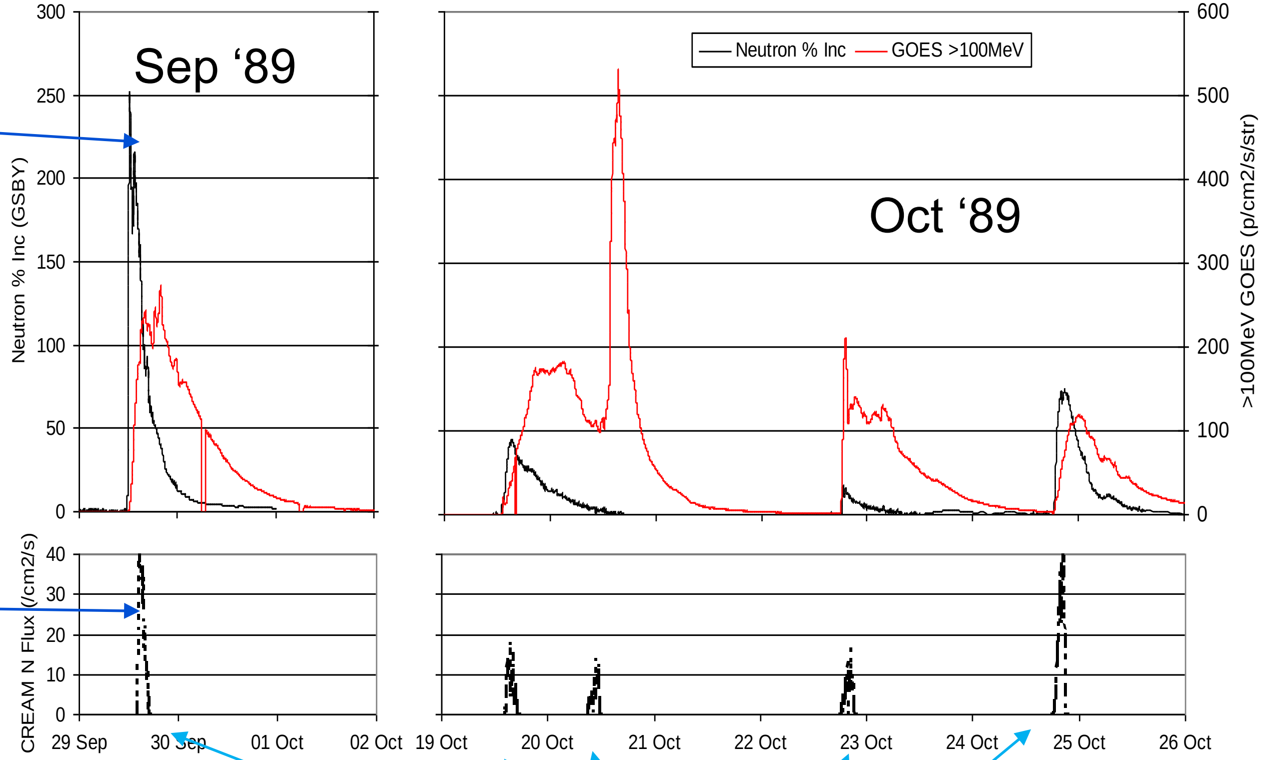
Concorde Measurements

- Solid-state CREAM detector flown on trans-Atlantic routes (~1000 hours of observation)
- 4 GLEs observed in 1989

Neutron monitor count rates



http://cosmicrays.oulu.fi/GLE.html



These are the highest dose rates measured in flight (so far!)

Concorde flights

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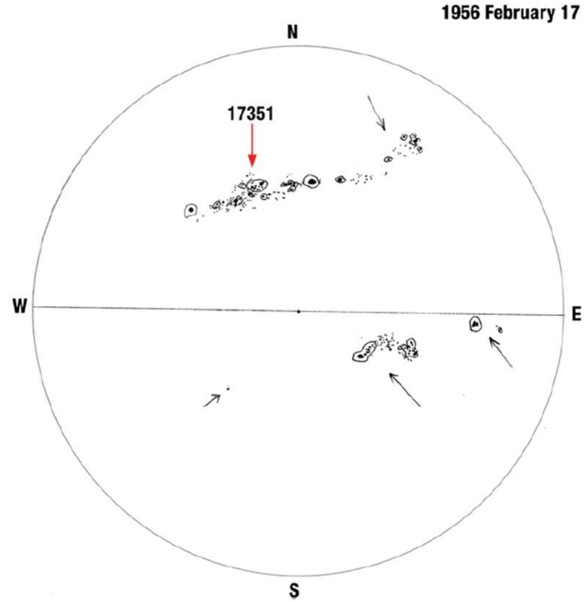
Worst Recorded Event (on the ground) – Feb '56

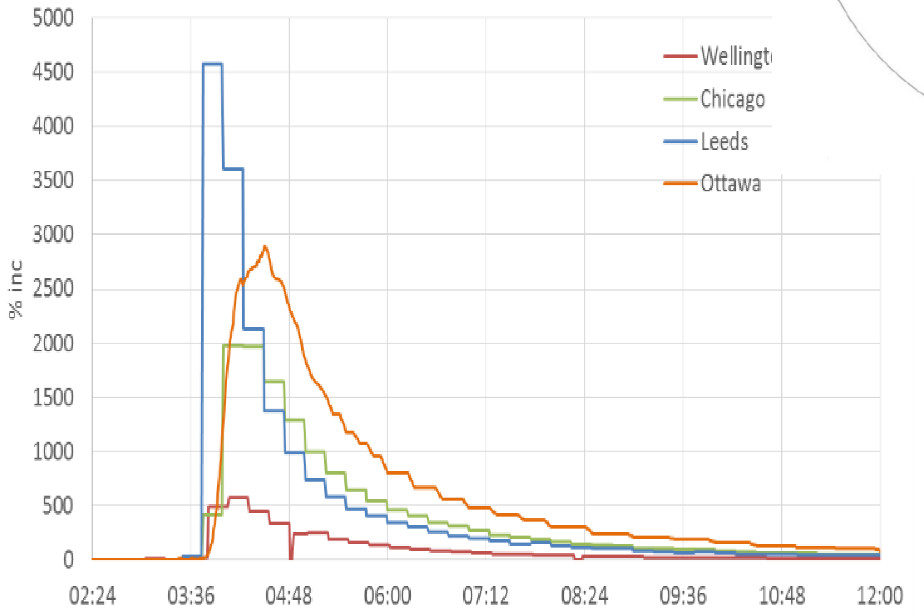
Sun spots ~ 1 week before:



- 23rd February 1956 is the most severe directly measured GLE
- >4500% increase at Leeds NM, UK
- Highly anisotropic in early phase
- Increases at Mexico and Peru indicated

  (particle energies of >14 GeV)
- Impulsive limb event (no warning)
- Lantos & Fuller estimate high latitude in-flight dose at ~6 mSv (some other estimates are significantly higher)
- Recent analysis of ionisation chamber data shows peak flux potentially ~double previous estimates (McCracken et al.)

Neutron Monitors



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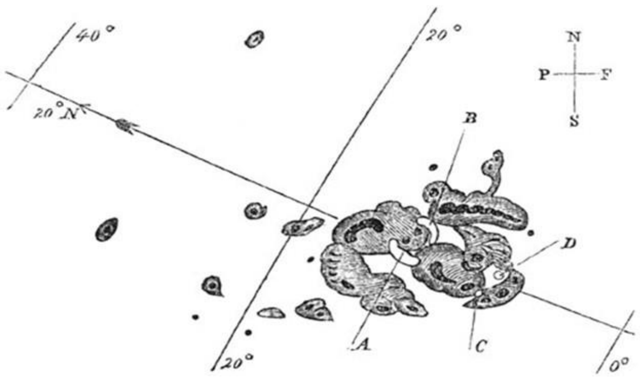
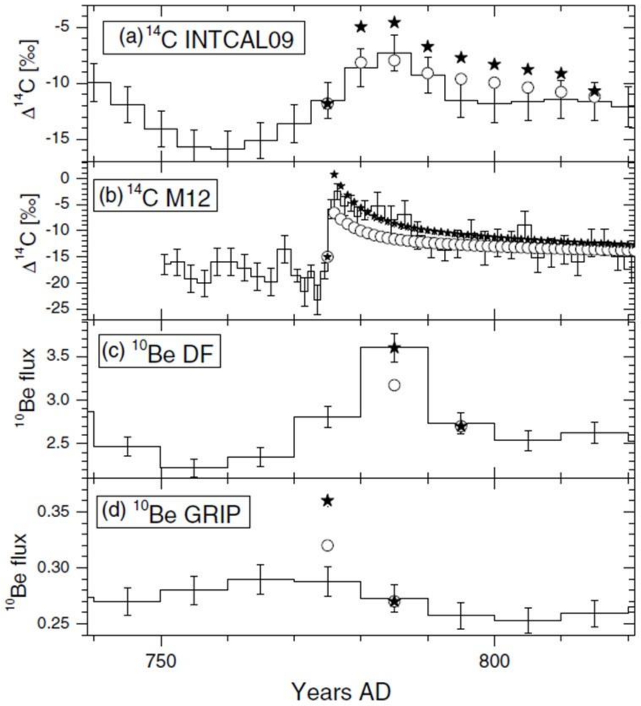
Historical Large Events

- Most famous general case – Carrington Event:
  - Was part of a sequence of events from an active region which was at 12º W on 1 Sept 1859. (non-optimum position for GLE)
  - There was a preceding storm with aurora observed in Hawaii !
  - Travel time to earth of Coronal Mass Ejection (CME) was a record breaking 17 hours.
  - Estimates for proton fluence based on nitrates in Antarctic ice cores – now discredited (we have no idea how large a SEPE this was!)
- AD774 Event:
  - Historical proton event fluences (not flux) can be inferred by modelling isotope production rates (Beryllium-10 in ice cores, Carbon-14 in tree rings)
  - Estimated 25 – 50 x Feb '56 fluence (!!)
  - Time resolution of data inherently poor - flux depends on light curve assumption (impulsive event? CME driven? Series of events?)
  - Analysis of C-14 records over >10,000 years implies this type of event occurs approximately once every 1000 years

Carrington's sketch of active region:



Cosmogenic data:



Usoskin (2012)

Single Event Effects (SEE)

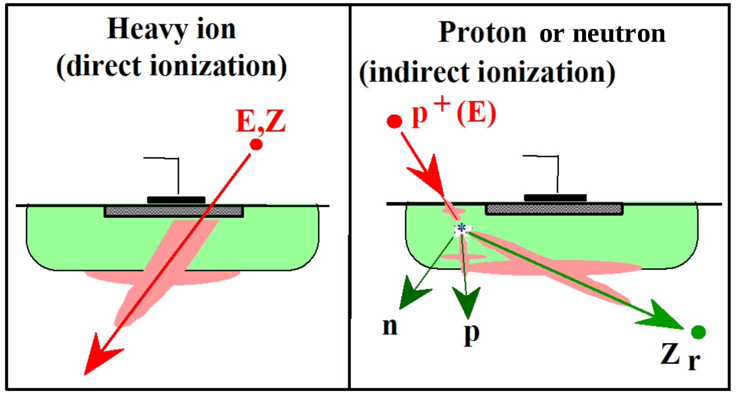
Dose to humans on flights often gets most attention, but threat to avionics is arguably more significant

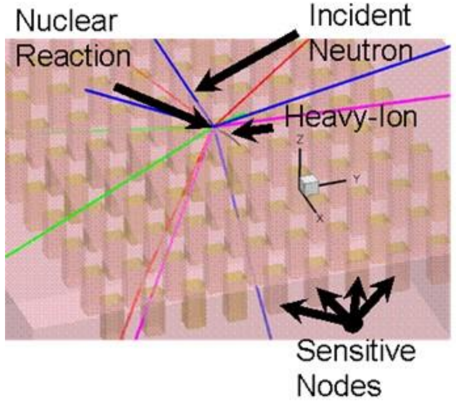
Single particles can deposit charge in sensitive volumes of semiconductors, leading to a variety of single event effects:

- Single Event Upset (SEU)
- Single Event Latchup (SEL)
- Single Event Gate Rupture (SEGR)
- Single Event Burnout (SEB)
- And an increasing variety of others

NB SEE rates would increase dramatically during a major GLE

SEE basic mechanisms:





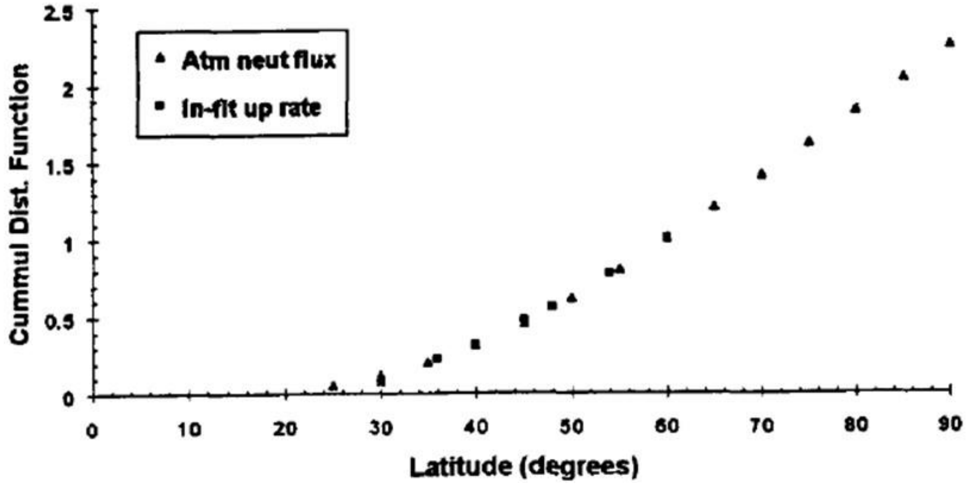
Dominant in Space

Dominant for aviation (particularly neutrons)

Flight Experience of SEE

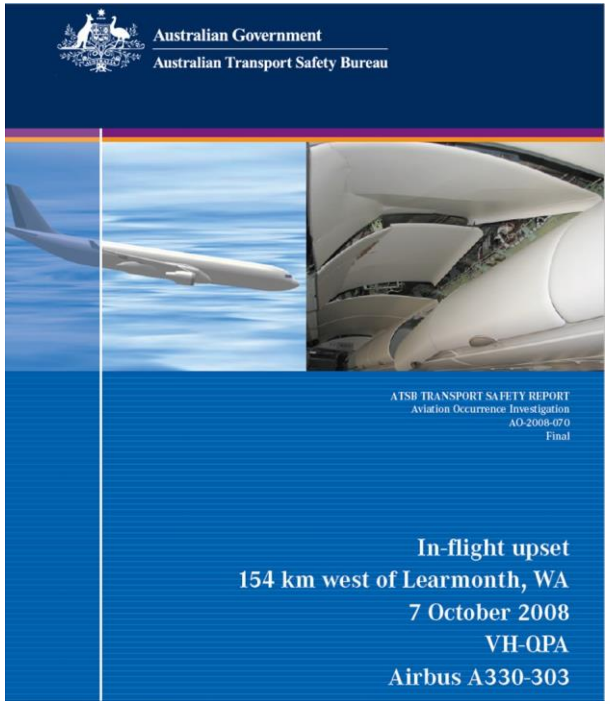
- PERFORM computer withdrawn for tests in 1991 following accumulation of errors in SRAM memory.
- More than one upset per flight in 280 64K SRAMs on Boeing E-3 AWACS and NASA ER-2.
- Autopilot design altered after faults (every 200 flight hours) shown to correlate with altitude and latitude.
- Saab CUTE experiment in 1996 showed upset every 200 flight hours in 4 Mbit SRAM. 2% are multiple-bit upsets.
- At least 3 major types of equipment with latch-up problem (including burn out) - probable cause of an emergency landing due to smoke in cockpit.

Normand & Baker (1993) observed correlation between SEU rates and neutron flux (latitude)



Example: Qantas Flight 72

- 7th October 2008 QF72 experienced several anomalies in AoA data supplied electronically to the flight computer, leading to pitching manoeuvres that caused serious injuries
- Single event effect identified as plausible cause by process of elimination (but not confirmed)
- Not an ESW-related event, however…
- Investigation revealed neutron-induced susceptibility of air data inertial reference unit (ADIRU)
- “No reference to SEU” during certification of A330/A340 aircraft (SEE in avionics only became apparent in 1990s)
- Airbus amended its standard in 2007 (mentions SEE and references IEC)


Australian Government
Australian Transport Safety Bureau

ATSB TRANSPORT SAFETY REPORT
Aviation Occurrence Investigation
AO-2008-070
Final

In-flight upset
154 km west of Learmonth, WA
7 October 2008
VH-QPA
Airbus A330-303

International Electronical Commission (IEC) Standard

- Atmospheric Radiation Environment Standard for SEE in Avionics: IEC 62396
- Focus is on background (GCR) environment, with several parts aimed at different aspects of effects in aircraft electronics (component testing, high voltage parts, thermal neutrons etc.)
- New Technical Report (Part 6) on Extreme Space Weather suggests the following scenarios for worst case environments:

I.e. 3 orders of magnitude increase in dose and SEE rates

ESW Level 1: A February '56 scale event:

Enhancement Factor (cf. GCR): 1000

Peak neutron flux: 6×10^{6} n cm^{-2} h^{-1} (>10 MeV at 12 km, high latitude)

ESW Level 2: 1 in 1000 year event:

Enhancement Factor (cf. GCR): 30,000

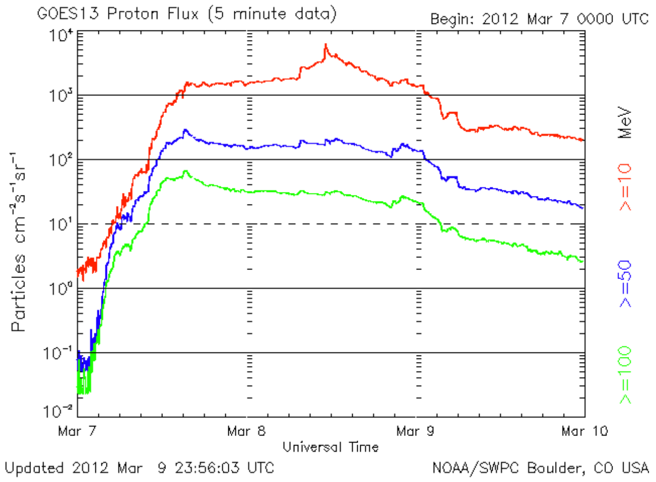
Peak neutron flux: 2×10^{8} n cm^{-2} h^{-1} (>10 MeV at 12 km, high latitude)

IEC 62396 Part 6 TR published July 2017

Mitigation

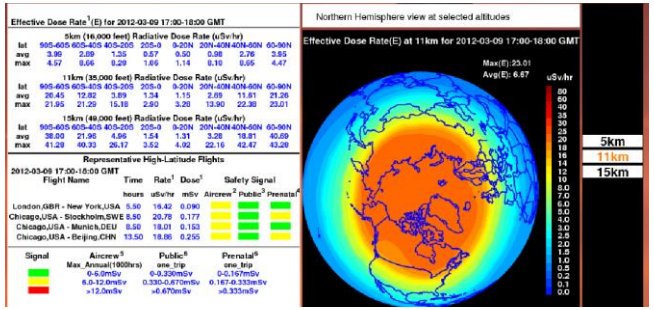
- Current status: we are <u>unprepared</u> for a major SEPE/GLE
- Some airlines use NOAA-SWPC radiation alerts based on GOES >10 MeV proton data
- This leads to multiple false alarms, e.g.:

March 2012

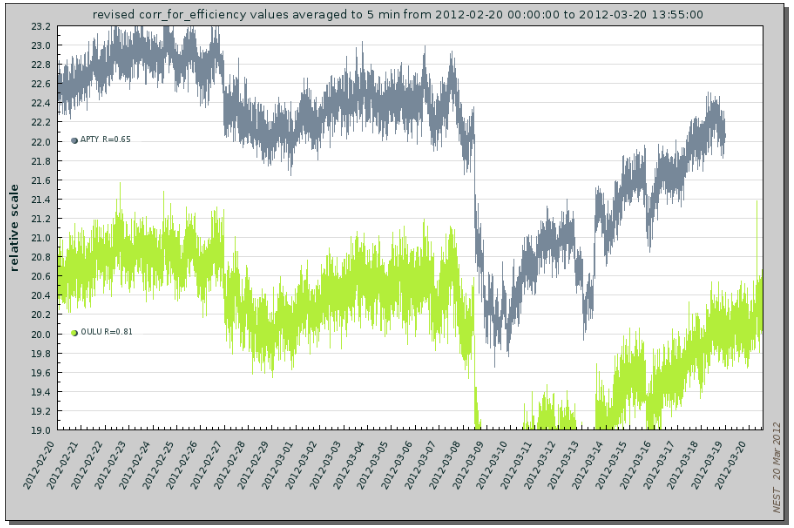


S3 event

(NASA NAIRAS model predicts high dose rates)

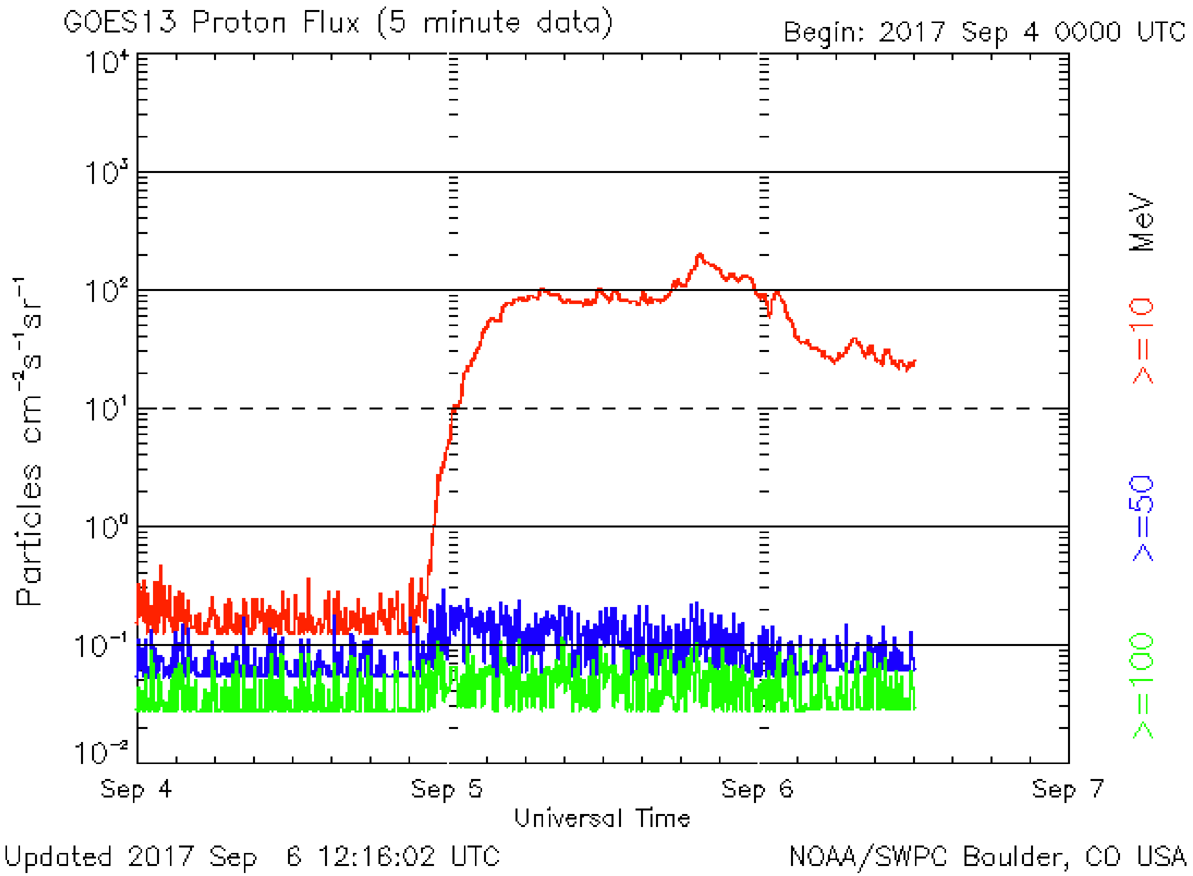


However… NM data show "Forbush decrease" (dose rates *lower* than normal!)



NB Protons require approx. >300 MeV to produce secondary neutron cascades

Another example - Today

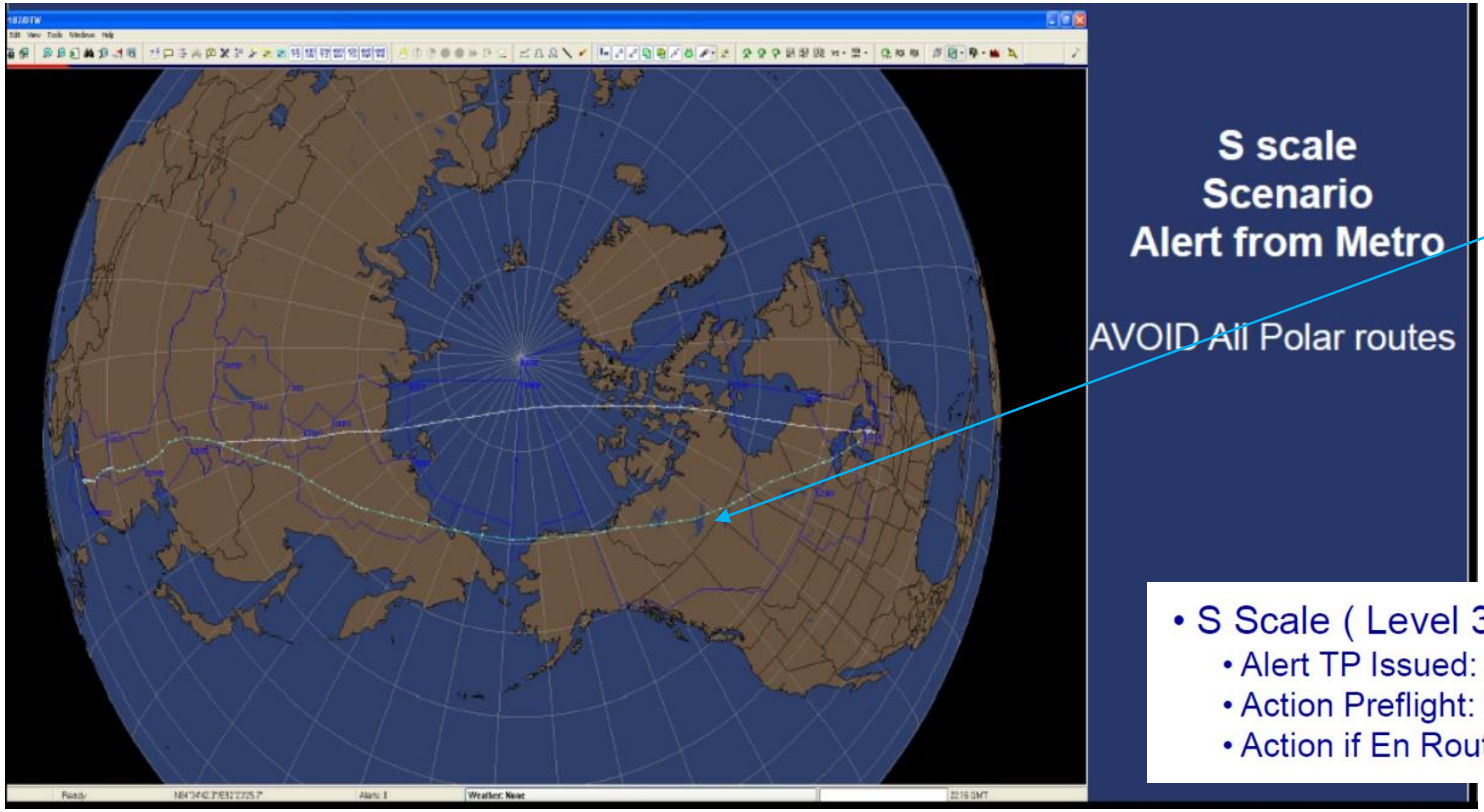


S2 alerts sent

(no need to panic!)

Mitigation – Case Study

Delta Airlines S-Scale scenario (SW workshop, April 2012):



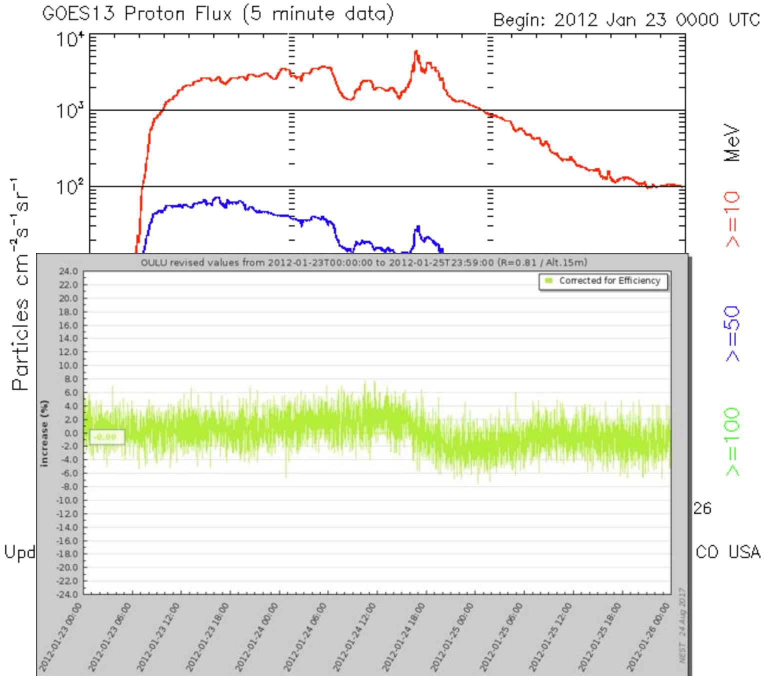
Route change DTW – HKG based on dose concerns (estimated cost $4507)

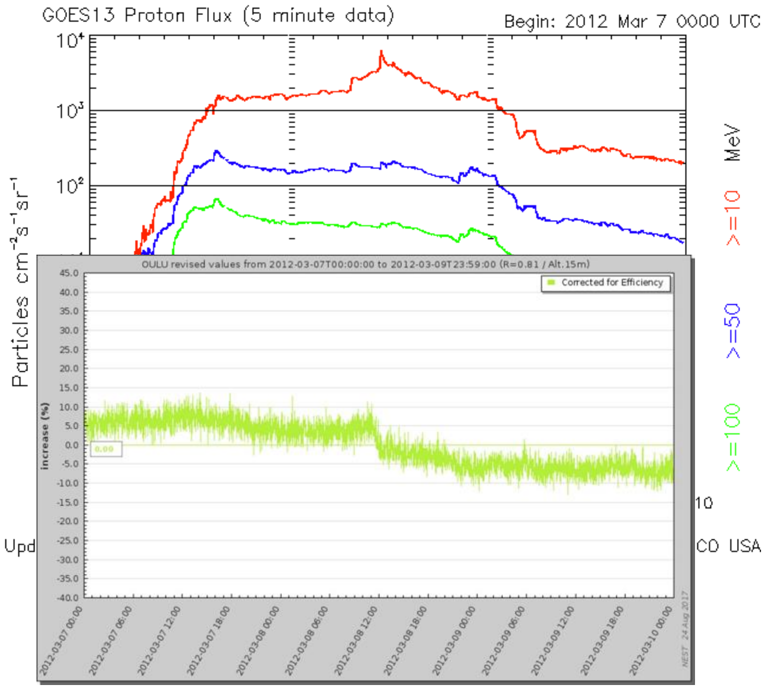
Flight latitudes restricted to <78N

- S Scale (Level 3, 4 or 5)
  - Alert TP Issued: As "Forecast" or "Observed"
  - Action Preflight: No Polar Routes (78N to Pole).
  - Action if En Route: Reroute or reducing altitude to FL310.

Mitigation – Case Study

Triggered during January and March 2012 S3 events (~8 flights diverted)

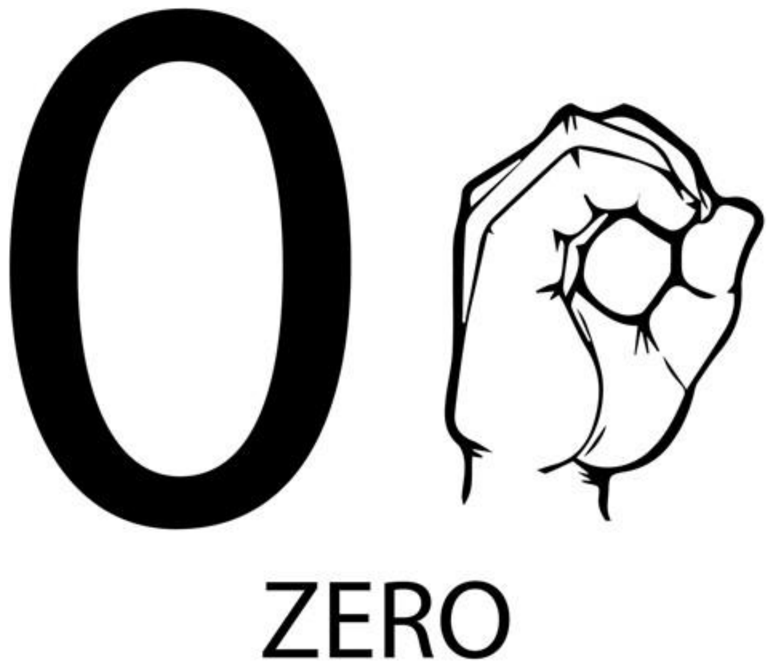




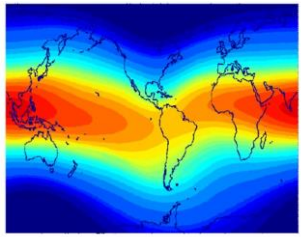
However…
Ground level neutron monitors were not frightened !
(soft proton spectra meant that aircraft dose rates would not have increased)

Mitigation – Case Study

- What about during a Feb ‘56 type event?
- The effect (on neutron flux) of re-routing to 78N to avoid poles would be…

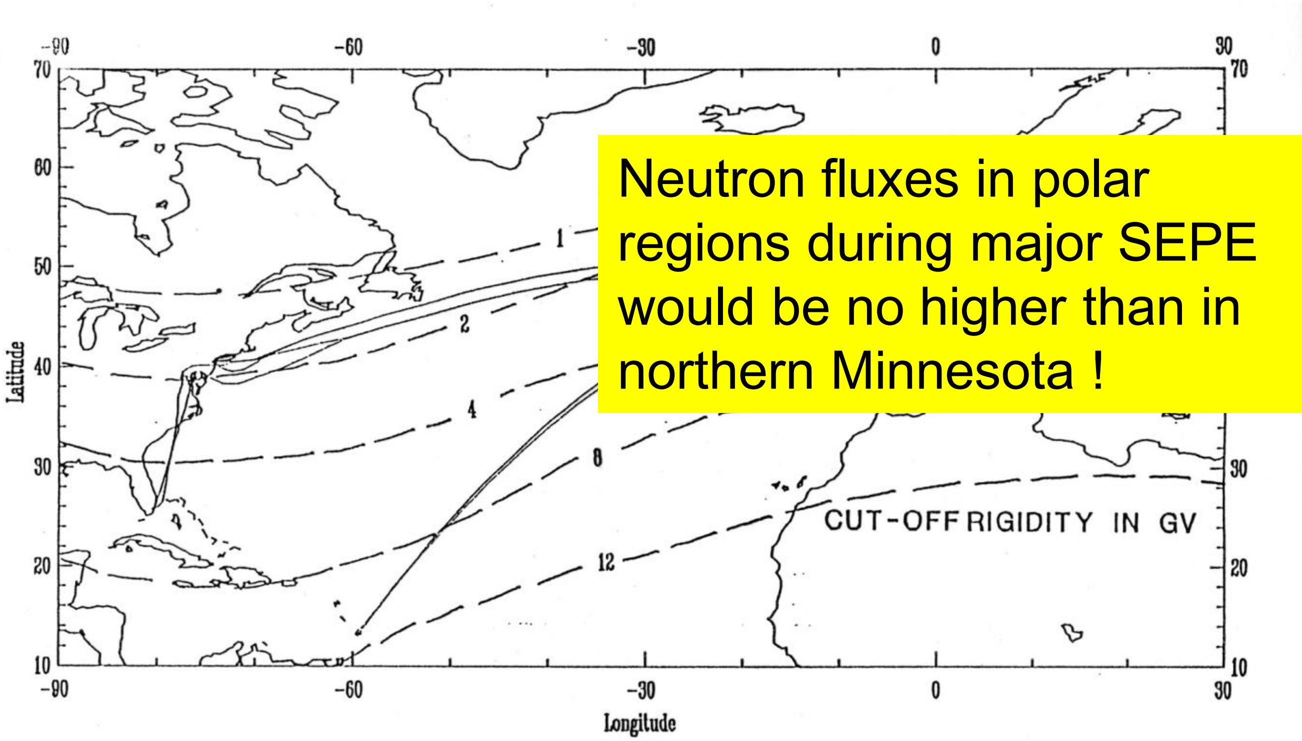


Mitigation – Case Study

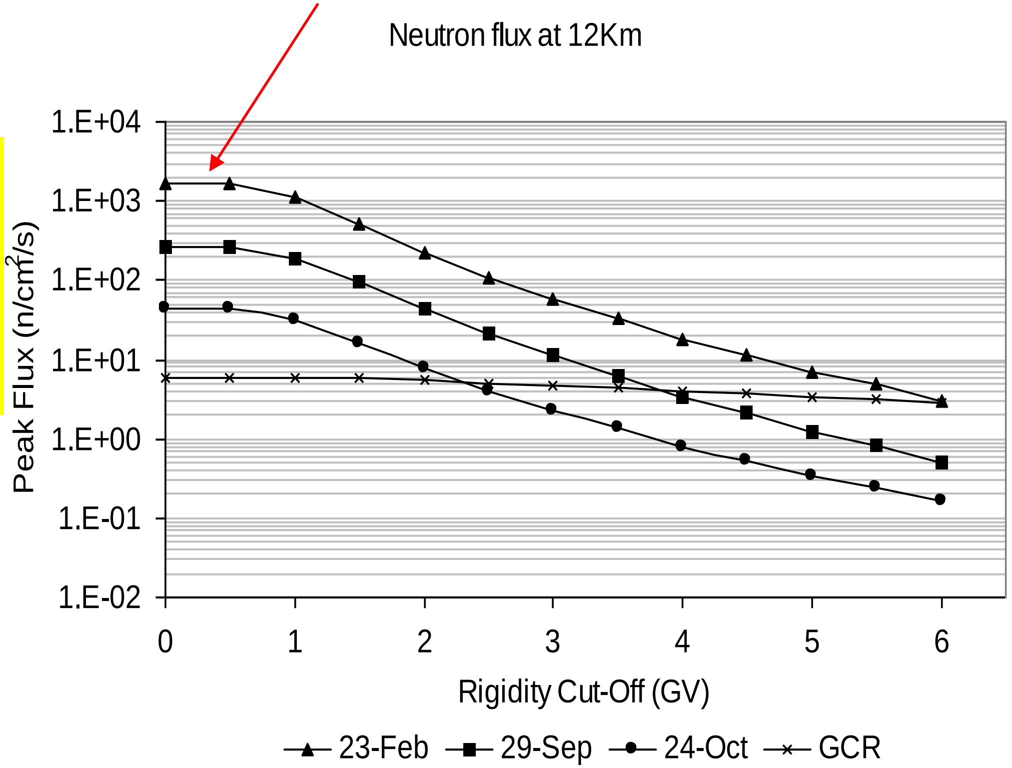


- The intensity of the radiation environment depends on geomagnetic cut-off rigidity (R)
- 300 MeV energy threshold for secondary neutron cascade corresponds to ~800 MV rigidity (0.8 GV)
- Corresponding latitude range ~49 – 62 N depending on longitude

(no further reduction at higher lats)



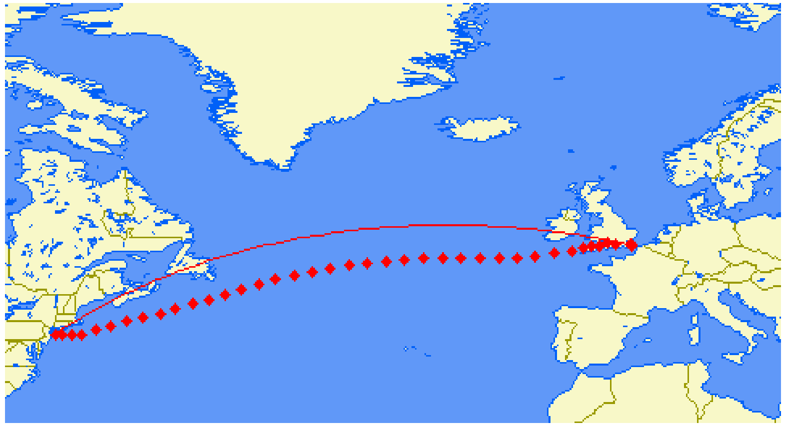
Neutron fluxes in polar regions during major SEPE would be no higher than in northern Minnesota !



Trans-Atlantic routes on the other hand…

Great Circle vs. actual flight path

JFK-LHR 29 September 1989



Concorde route during event of 29 September 1989 (Kp = 2). Data from CREAM JFK-LHR

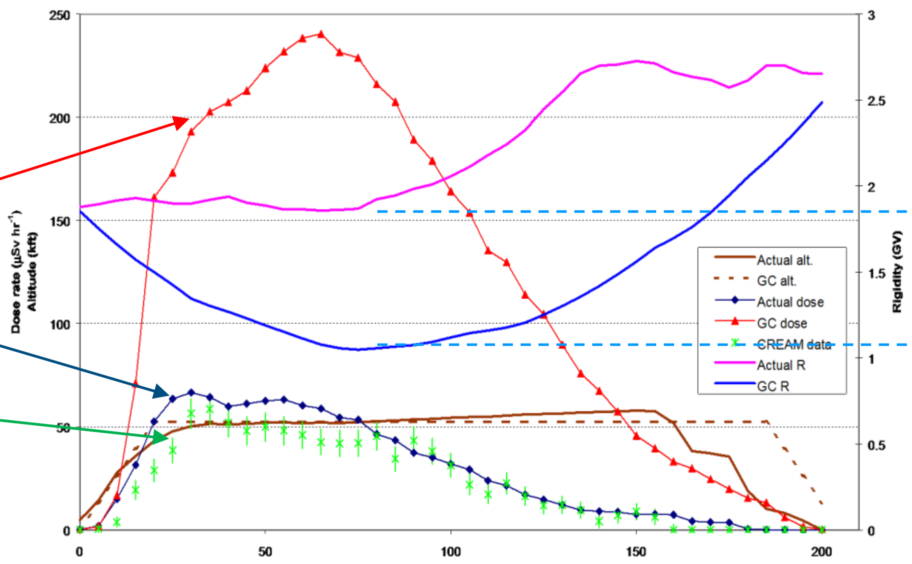
Peak dose rate on great circle route (solid line) would have been factor 5 higher cf. actual route (dotted).

Modelled dose rates:

Great Circle

Actual Path

Measured



Relatively small change in geomagnetic cut-off rigidity makes big difference to dose

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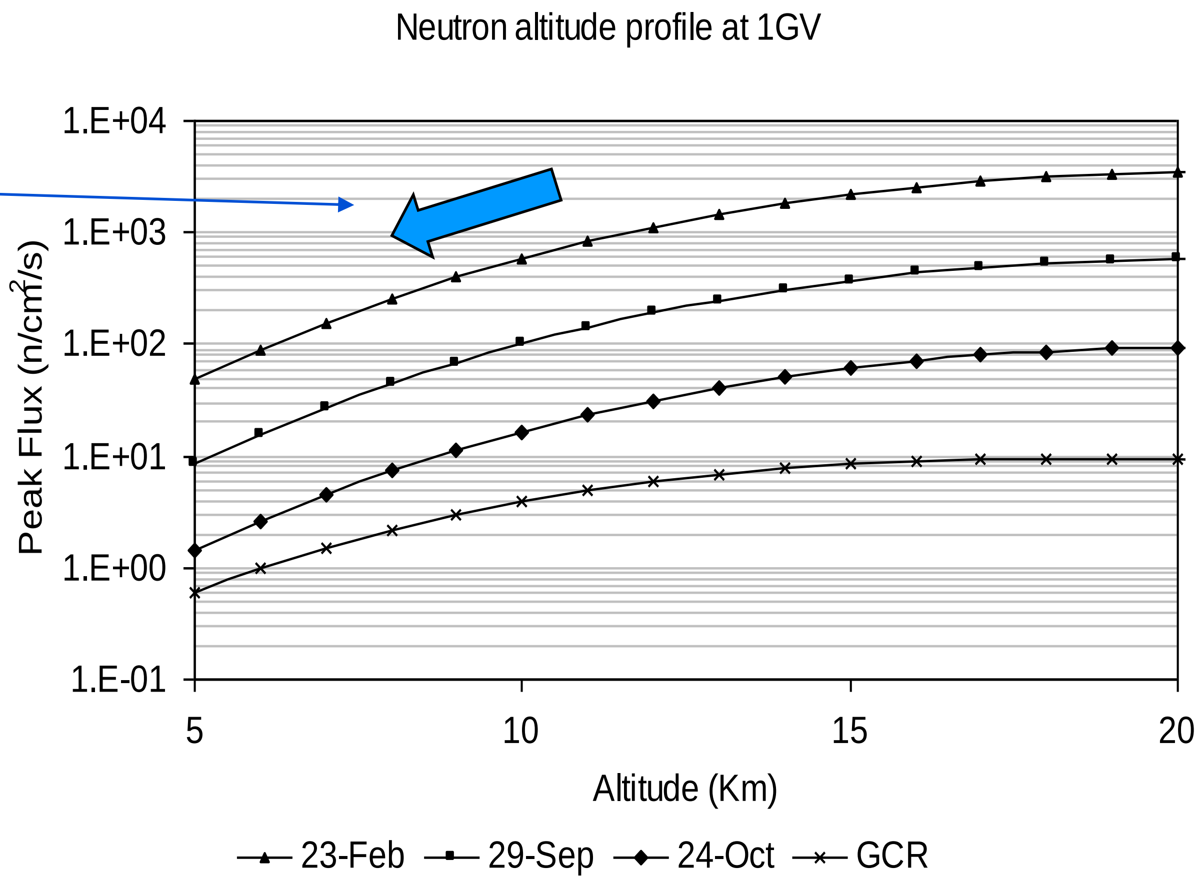
And Of Course

- Reducing altitude has an immediate impact

Steep gradient w.r.t. altitude (~30% per km)



Conclusions

- High-latitude commercial flight routes are very exposed to energetic solar protons
- Impulsive events produce ground level enhancements without warning
- Space-based measurements are inadequate on their own – e.g. NOAA-SWPC S-scale not relevant to dose or SEE rates (though >500 MeV channel on GOES-R is)
- Neutron monitor data are a better proxy though still imperfect
- Feb '56 event increased atmospheric radiation levels by three orders of magnitude – high dose rates and (as yet) unquantified effect on avionics
- Few in-flight GLE measurements exist
- Recommended approach:

1. Systematic in-flight monitoring for accurate measurement of *in situ* environment
2. Link data to models for real-time picture of global radiation map
3. Qualification testing (at system level) of avionics equipment to survive worst case environment

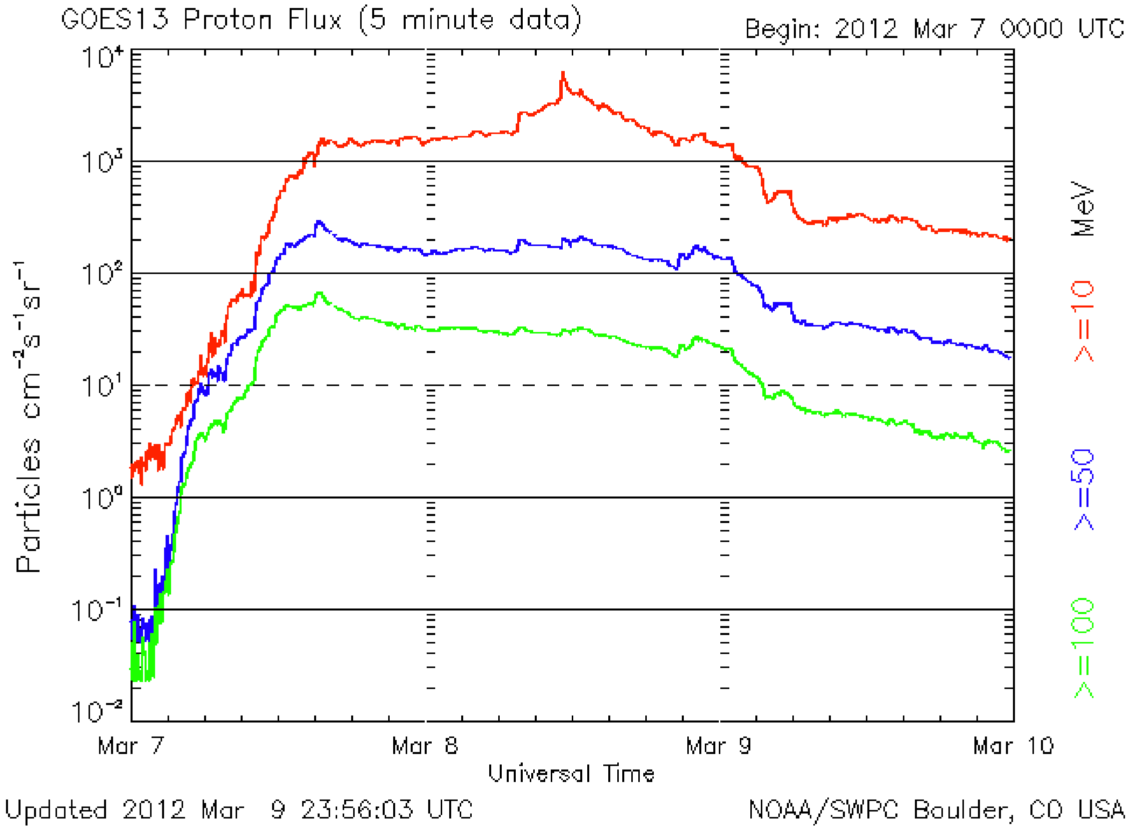
THANK YOU

Photo by Bruno Boni de Oliveira of Manhattan,
New York (Spaceweather.com 11 July 2017)

Spare Slides

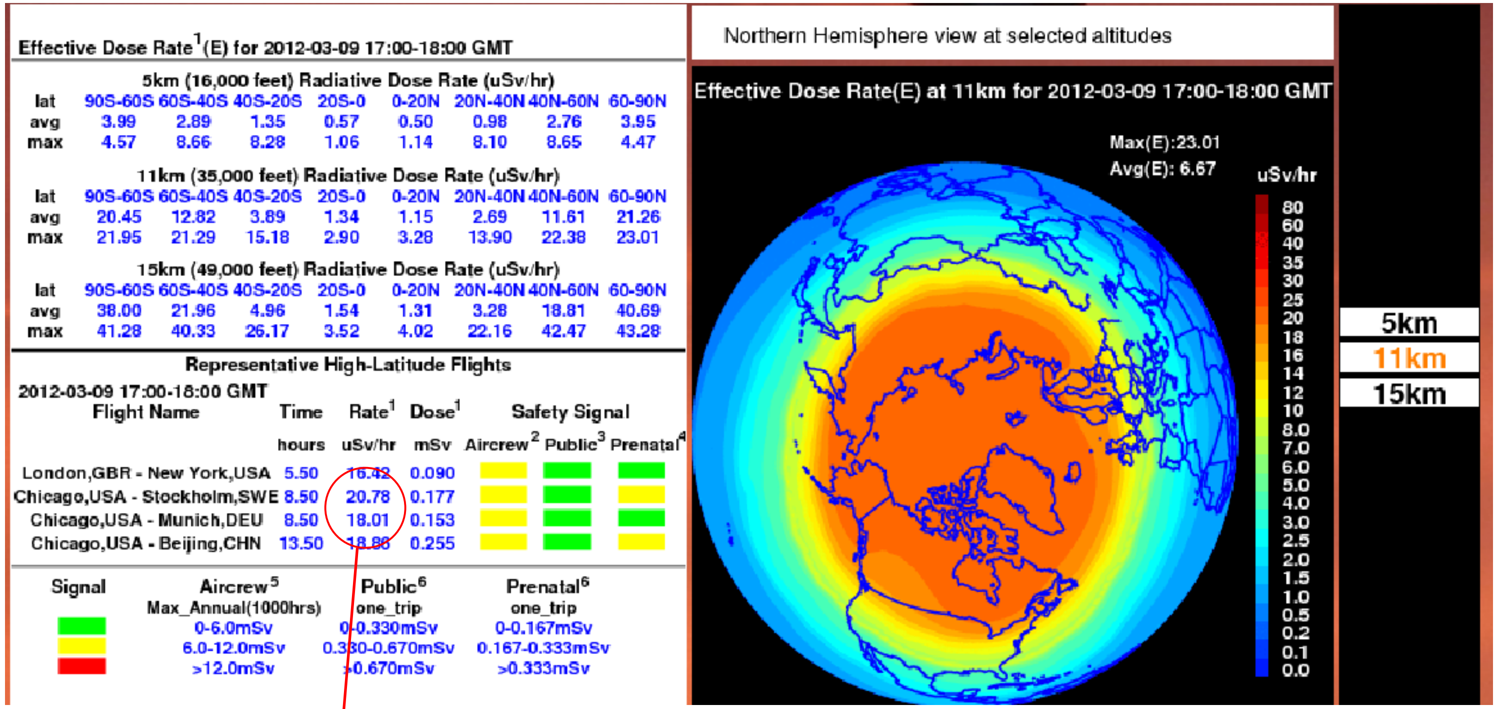
Cautionary Tales

- Very easy to overestimate effect on aviation during “small” events
- E.g. March 2012
  - Mid-longitude solar active region
  - S3 on NOAA scale (nearly S4)
  - Largest since 2003 “Halloween” event
  - Large increase in >100 MeV proton flux



March 2012 Event: Dose Predictions / Now-casting

- NASA's NAIRAS model provided dose predictions during event



Effective Dose Rate[1](E) for 2012-03-09 17:00-18:00 GMT

5km (16,000 feet) Radiative Dose Rate (uSv/hr)

lat	90S-60S	60S-40S	40S-20S	20S-0	0-20N	20N-40N	40N-60N	60-90N
avg	3.99	2.89	1.35	0.57	0.50	0.98	2.76	3.95
max	4.57	8.66	8.28	1.06	1.14	8.10	8.65	4.47

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

lat	90S-60S	60S-40S	40S-20S	20S-0	0-20N	20N-40N	40N-60N	60-90N
avg	20.45	12.82	3.89	1.34	1.15	2.69	11.61	21.26
max	21.95	21.29	15.18	2.90	3.28	13.90	22.38	23.01

15km (49,000 feet) Radiative Dose Rate (uSv/hr)

lat	90S-60S	60S-40S	40S-20S	20S-0	0-20N	20N-40N	40N-60N	60-90N
avg	38.00	21.96	4.96	1.54	1.31	3.28	18.81	40.69
max	41.28	40.33	26.17	3.52	4.02	22.16	42.47	43.28

Representative High-Latitude Flights

2012-03-09 17:00-18:00 GMT

Flight Name	Time	Rate[1]	Dose[1]	Safety Signal		
	hours	uSv/hr	mSv	Aircrew[2]	Public[3]	Prenatal[4]
London,GBR - New York,USA	5.50	16.42	0.090			
Chicago,USA - Stockholm,SWE	8.50	20.78	0.177			
Chicago,USA - Munich,DEU	8.50	18.01	0.153			
Chicago,USA - Beijing,CHN	13.50	18.88	0.255			

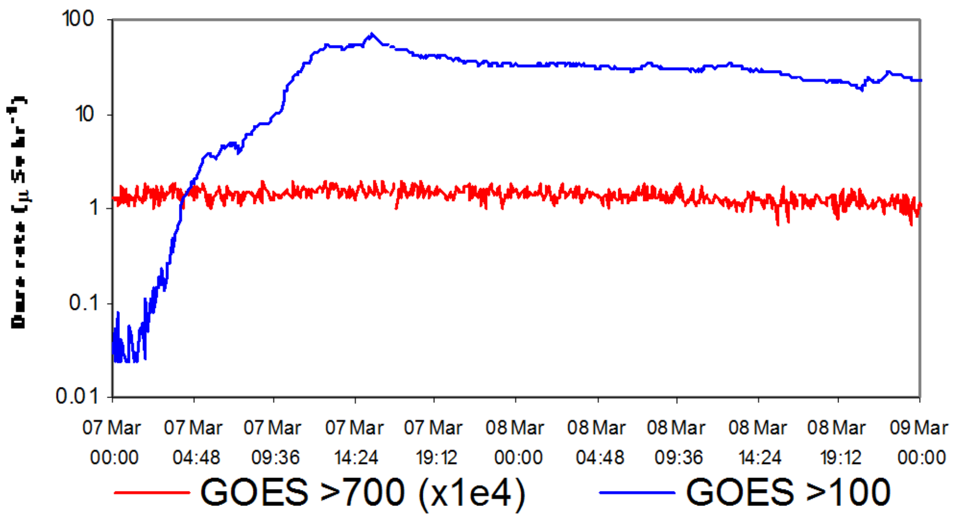
Signal	Aircrew[5] Max_Annual(1000hrs)	Public[6] one_trip	Prenatal[6] one_trip
	0-6.0mSv	0-0.330mSv	0-0.167mSv
	6.0-12.0mSv	0.330-0.670mSv	0.167-0.333mSv
	>12.0mSv	>0.670mSv	>0.333mSv

Doses of >20 uSv/hr predicted at high latitude
(2 or 3 times background dose rates)

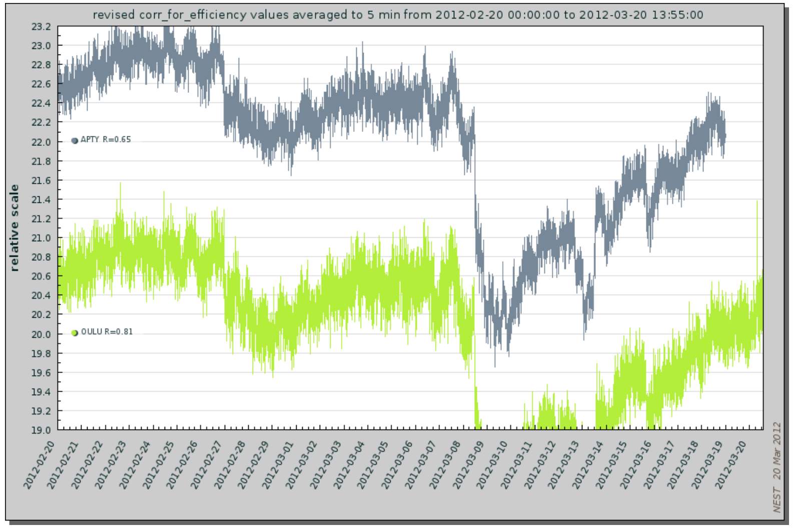
March 2012 Event

- However… little change in GOES >700 MeV proton flux

  (hence no enhancement anticipated at aircraft altitude)

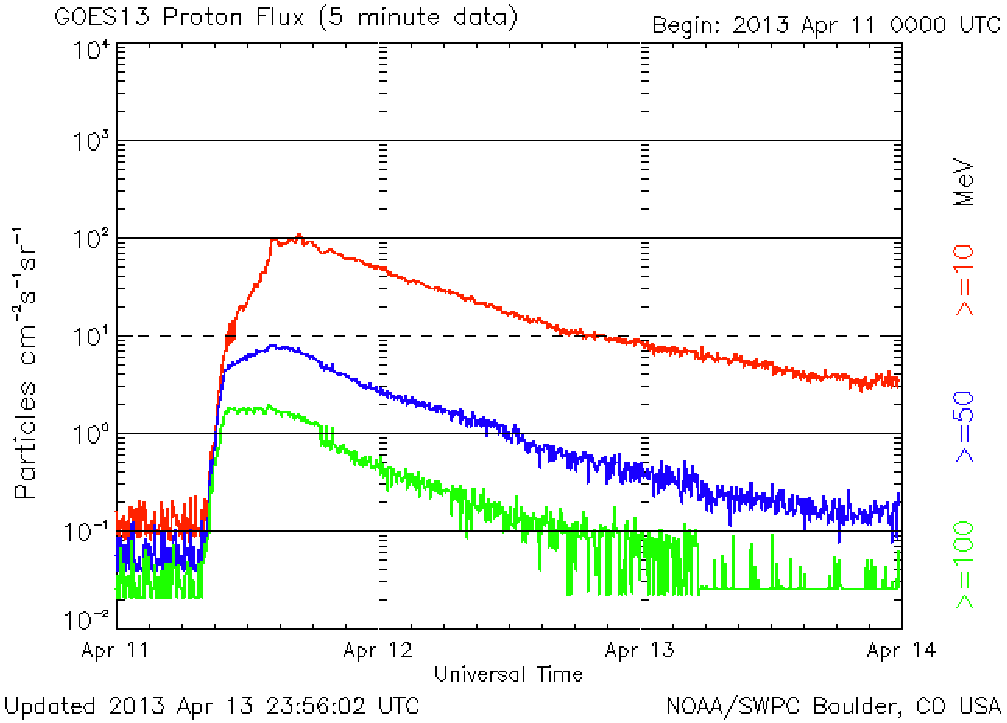


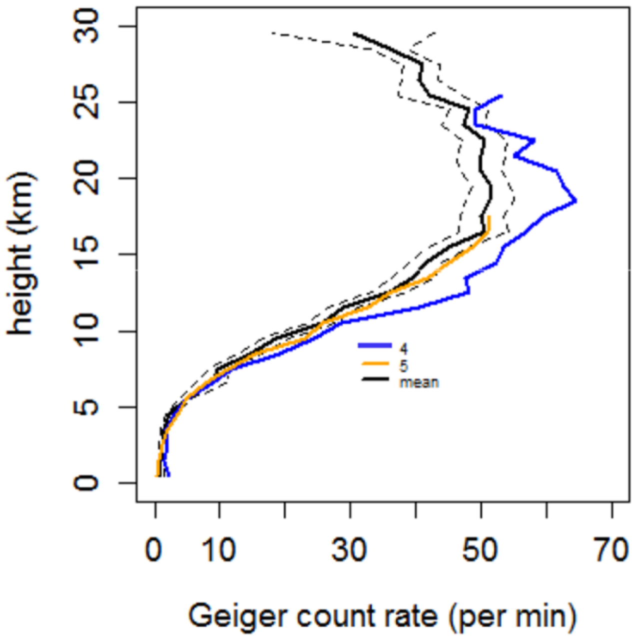
- And…Forbush decrease apparent in ground level neutron monitor data (hence could expect *decrease* in dose rate)
- Trans-polar flight data mid event (8^{th} March) measured dose lower than average



2. April 2013 Event

- Small S2 event on 11th April 2013
- Higher than average dose rates measured with Geiger counter on balloon flight over UK





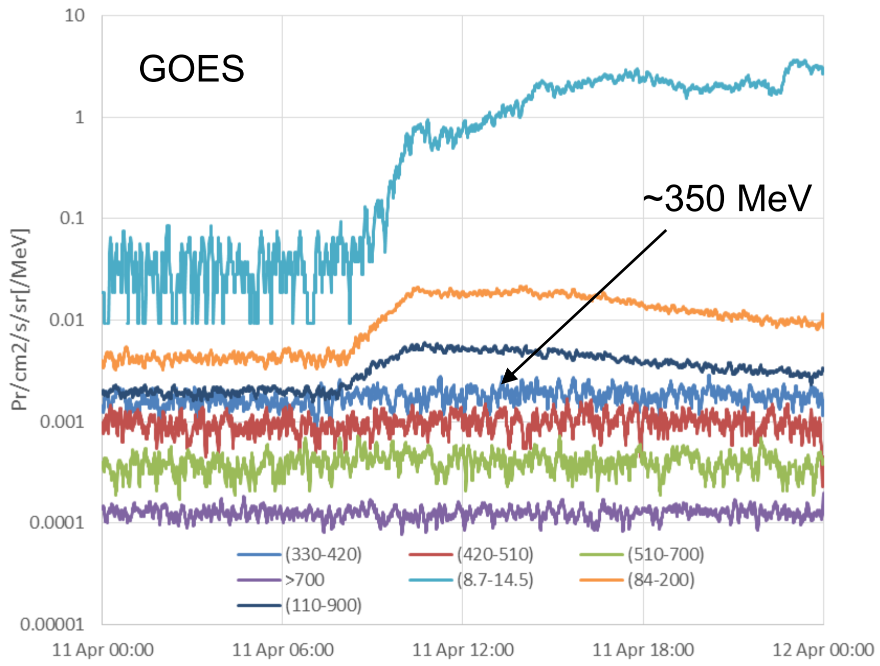
Nicoll et al. (2014)

However…

April 2013 Event

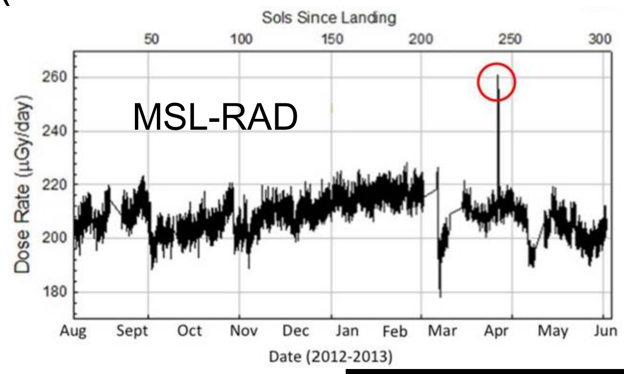
…relatively soft spectrum -> no enhancement in higher energy GOES channels:

(and no increase in GLNM count rates)

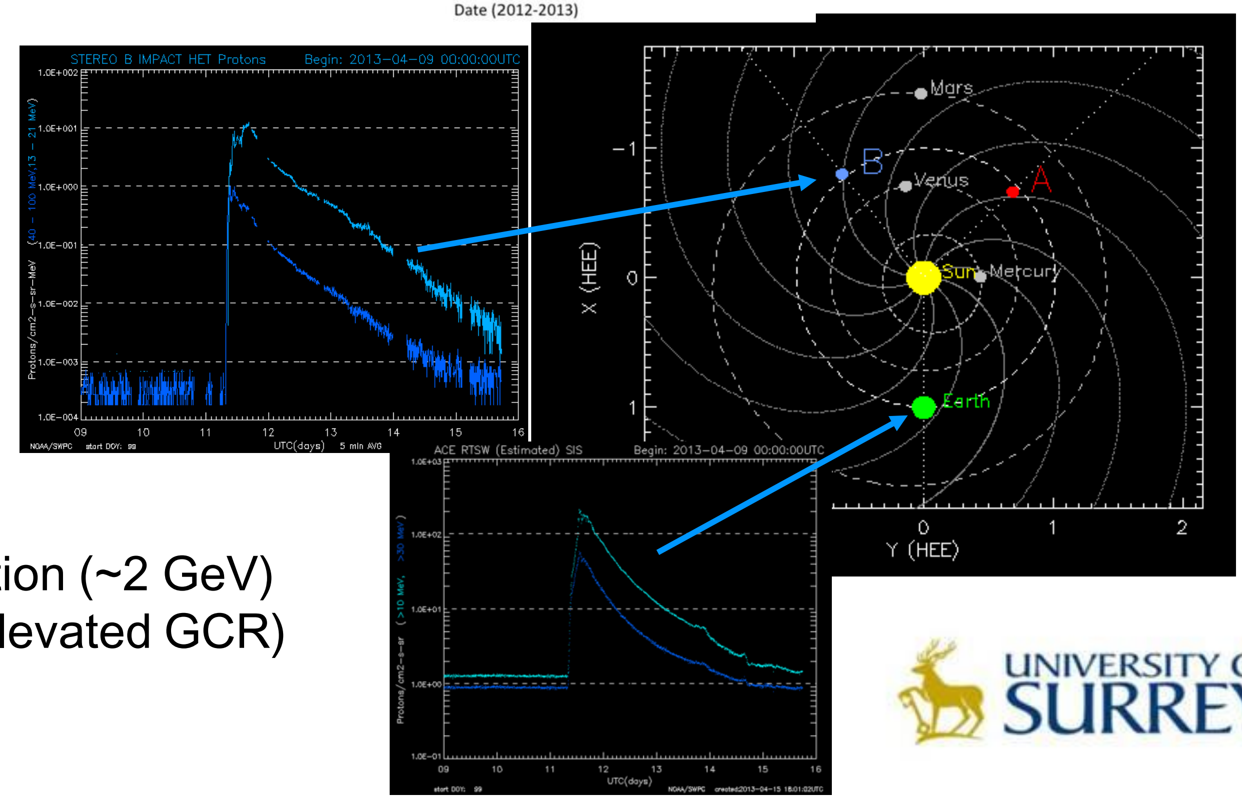


But it was observed on Mars!...

(better connection with event and zero cut-off rigidity)



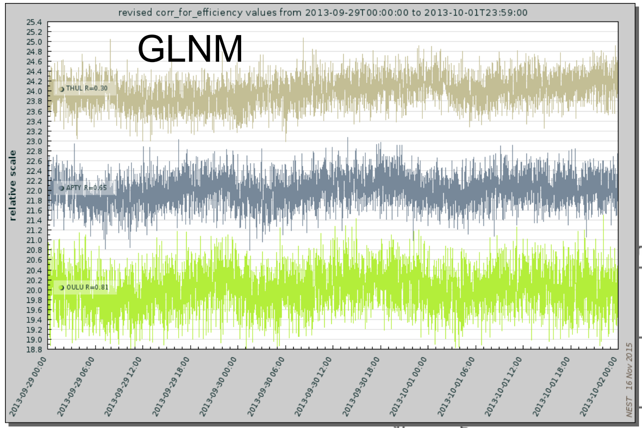
Hassler et al. (2014)

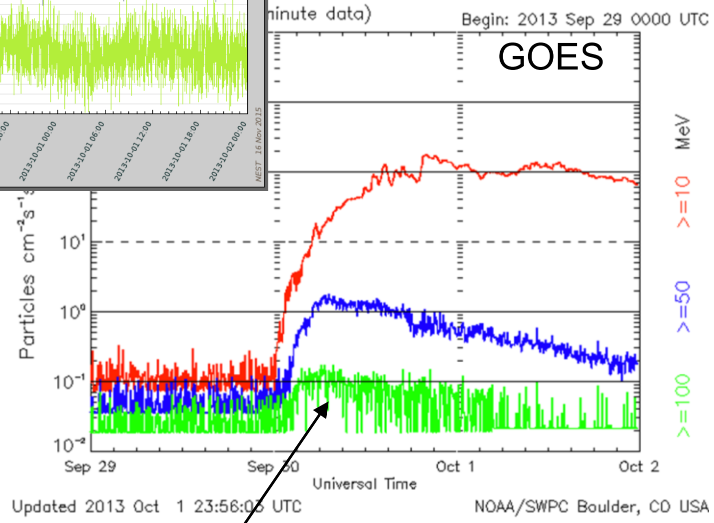


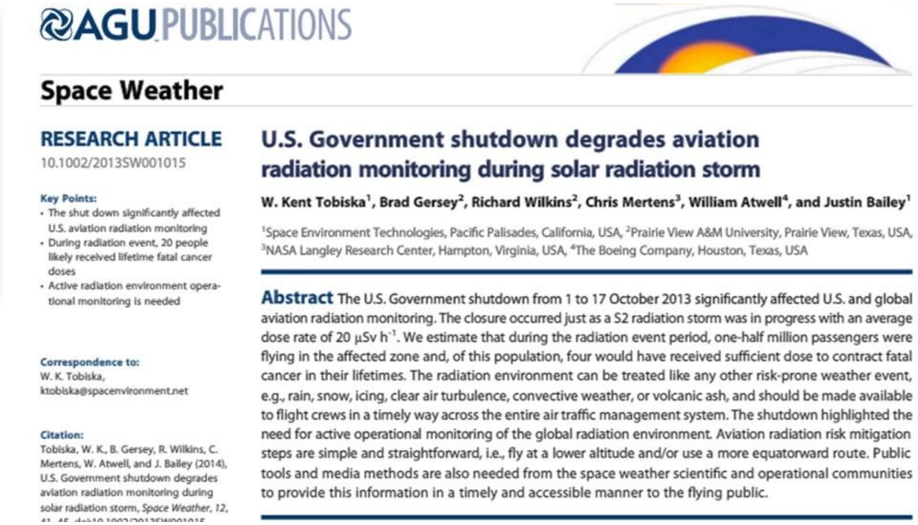
Cf. geomagnetic cut-off energy of measurement location (~2 GeV) -> dose rates cannot have been due to SPE (rather elevated GCR)

3. September/October 2013 Event

- S2 event on 30th September 2013
- So-called "Government Shutdown event"
- Tobiska et al. (2013) claimed additional dose from event might cause several deaths due to increased exposure for flyers and subsequent cancer risk :






AGU PUBLICATIONS

Space Weather

RESEARCH ARTICLE
10.1002/2013SW001015

U.S. Government shutdown degrades aviation radiation monitoring during solar radiation storm

W. Kent Tobiska[1], Brad Gersey[2], Richard Wilkins[2], Chris Mertens[3], William Atwell[4], and Justin Bailey[1]

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Key Points:
- The shut down significantly affected U.S. aviation radiation monitoring
- During radiation event, 20 people likely received lifetime fatal cancer doses
- Active radiation environment operational monitoring is needed

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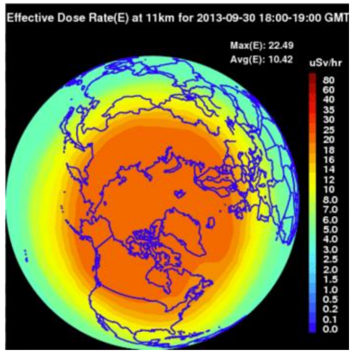
Citation:
Tobiska, W. K., B. Gersey, R. Wilkins, C. Mertens, W. Atwell, and J. Bailey (2014), U.S. Government shutdown degrades aviation radiation monitoring during solar radiation storm, *Space Weather*, 12,

Abstract The U.S. Government shutdown from 1 to 17 October 2013 significantly affected U.S. and global aviation radiation monitoring. The closure occurred just as a S2 radiation storm was in progress with an average dose rate of 20 μSv h⁻¹. We estimate that during the radiation event period, one-half million passengers were flying in the affected zone and, of this population, four would have received sufficient dose to contract fatal cancer in their lifetimes. The radiation environment can be treated like any other risk-prone weather event, e.g., rain, snow, icing, clear air turbulence, convective weather, or volcanic ash, and should be made available to flight crews in a timely way across the entire air traffic management system. The shutdown highlighted the need for active operational monitoring of the global radiation environment. Aviation radiation risk mitigation steps are simple and straightforward, i.e., fly at a lower altitude and/or use a more equatorward route. Public tools and media methods are also needed from the space weather scientific and operational communities to provide this information in a timely and accessible manner to the flying public.

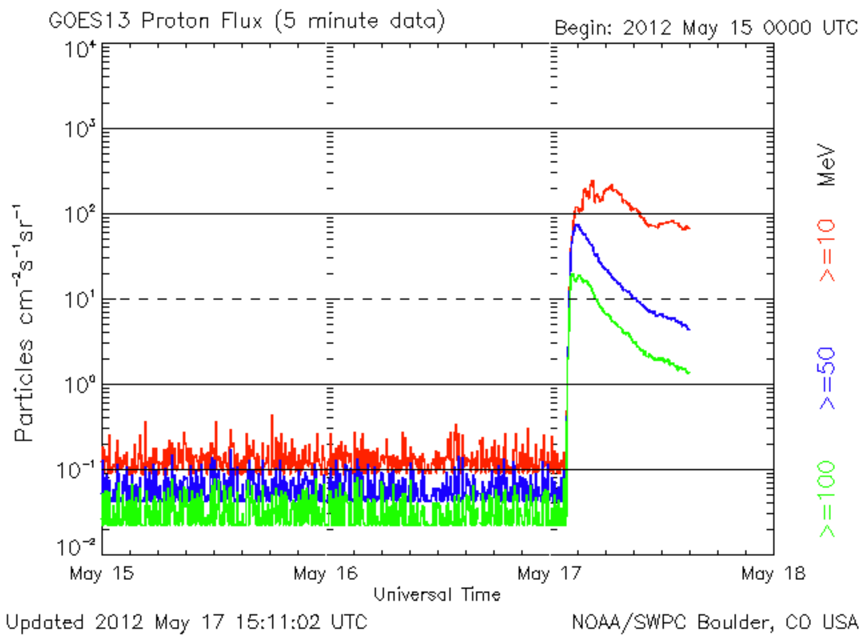
NAIRAS predicted >20 μSv/hr:

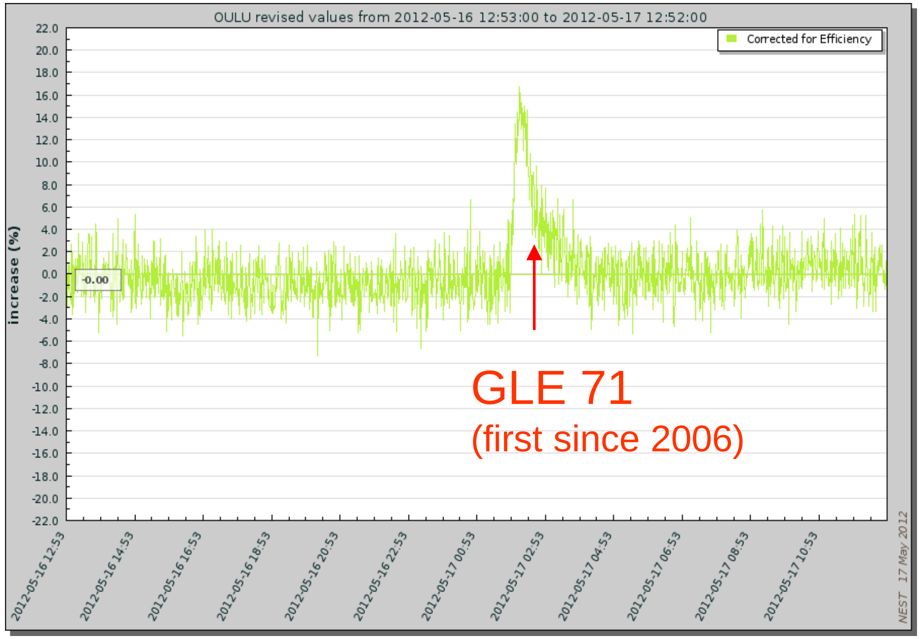


However… no significant enhancement in high E protons or GLNM count rates (therefore zero additional dose)

Whereas… May 2012 Event

- ‘Smaller’ than March event in >10 MeV proton flux (SWPC S2 cf. S3)
- Limb event – fast rising, well connected, harder spectrum
- Resulted in only GLE in the last decade
- Unfortunately, no in-flight data





Standards

- Various International Standards / Working Groups cover single event effects:
- USA:
  - JEDEC JESD89A "Measurement and reporting of Alpha Particle and Terrestrial Cosmic Ray-Induced Soft errors in Semiconductor Devices "
  - AVSI72 "Mitigating Radiation Effects on Current & future Avionics Systems"
  - SAE ARP4761 "Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment"
  - SAE AIR6219 "Incorporation of Atmospheric Neutron Single Event Effects Analysis into Safety Assessment"
- Other:
  - IEC TC107 "Process Management for Avionics"

Only one (yet) to cover ESW

- Also relevant:
  - EASA Proposed CM-AS-004 "Single Event Effects (SEE) Caused by Atmospheric Radiation"

Consequences of an Extreme Event

- Two categories – biological dose and SEE in avionics
- Total route dose to air crew and passengers more easily constrained
  - Feb 56 event: 6 – 10 milli Sieverts (mSv) at 0 GV & 40,000 feet
  - 4 x Feb '56 (Carrington-like recurrence rate 1 in 150 years [Dyer et al.]) : 24 – 40 mSv
  - AD774 event (1 in 1000 year): 200 – 300 mSv

[Cf. UK regulatory limits on annual dose: 20 mSv / yr (maximum), 6 mSv / yr (recommended ceiling), 1 mSv (limit for pregnant air crew)]

- Consequences of SEE in avionics are much harder to predict
  - Can estimate individual component failure rates (e.g. 2500 SEU / hr / Gbyte & 0.01 SEL / hr /chip for Feb '56 [Dyer et al.])
  - Effect at system level is complicated (multiple simultaneous effects can override in-built redundancies)
  - System-level testing rarely done and almost never published
  - Given poor qualification requirements, we have very little knowledge of what systems will be affected and how badly