Australian Government
Bureau of Meteorology

Radiation effects on spacecraft in Earth orbit

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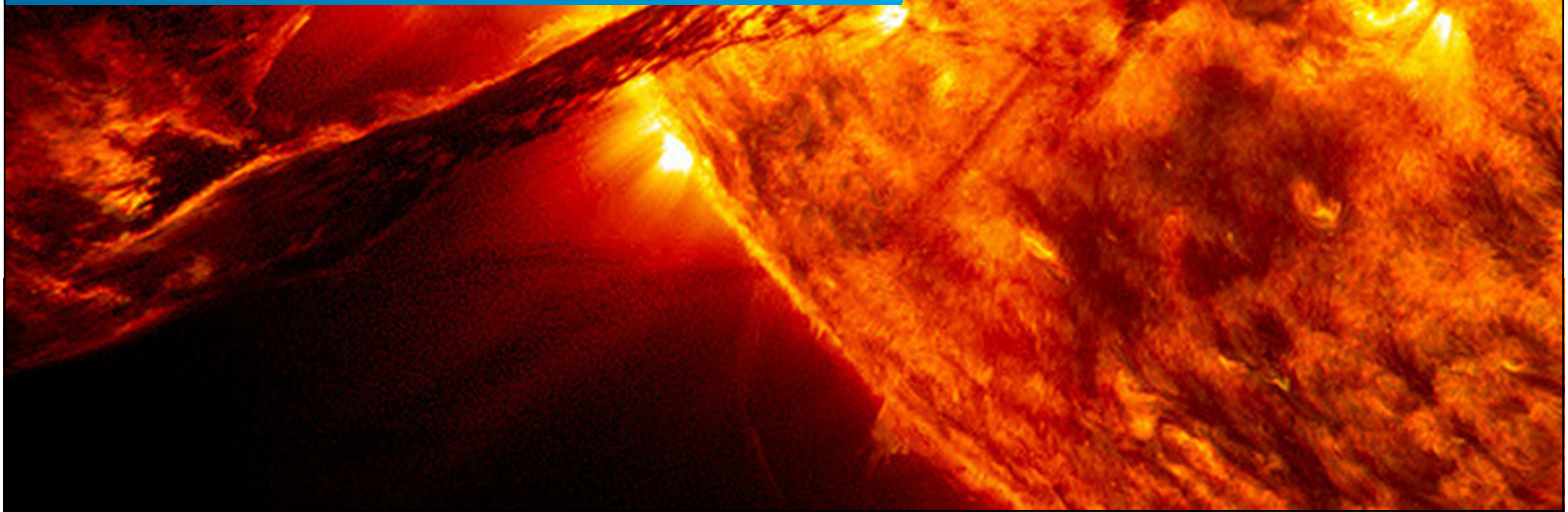


Overview

- Satellite communication may be degraded by the ionosphere
- Spacecraft operate in a variable radiation environment
- Spacecraft RADHAZ issues are diverse
- Effects depend heavily on the spacecraft design and location
- Space weather support services are still R&D

Satellite Communications and ionospheric scintillation

- SATCOM signals are mainly UHF (3-30GHz) and pass through the electrically charged plasmasphere and ionosphere with very small angular deviation.

- During disturbed ionosphere, radio ‘scintillation’ may occur. Rapid fluctuations in signal phase and amplitude.

- Increased bit error rates (BER) for digital systems and distortion for analogue. Less or no throughput, so more expensive to run the circuit.

- Standard scintillation index is S4
(square-root of the normalised variance of signal intensity over a given interval of time)

- Most significant at low (near equatorial) and high (polar) latitudes.

- Weak scintillation in most of solar cycle 24

- No reported problems from operators.
But do they know if they have suffered higher BER due to scintillation?

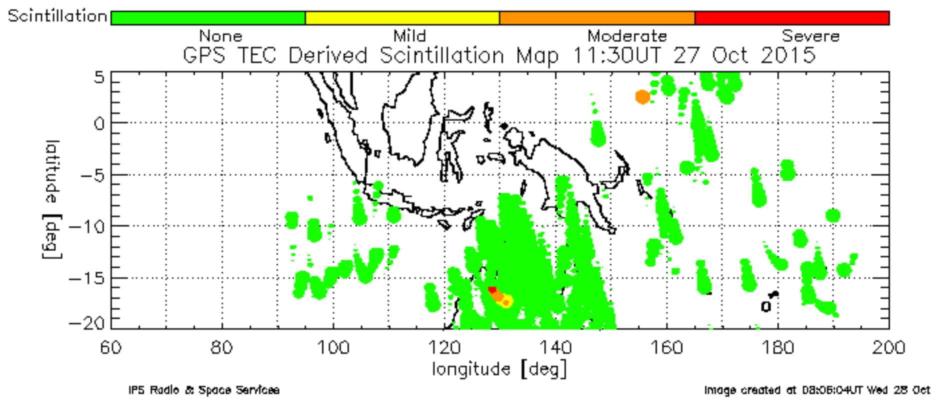
SWS SATCOM services

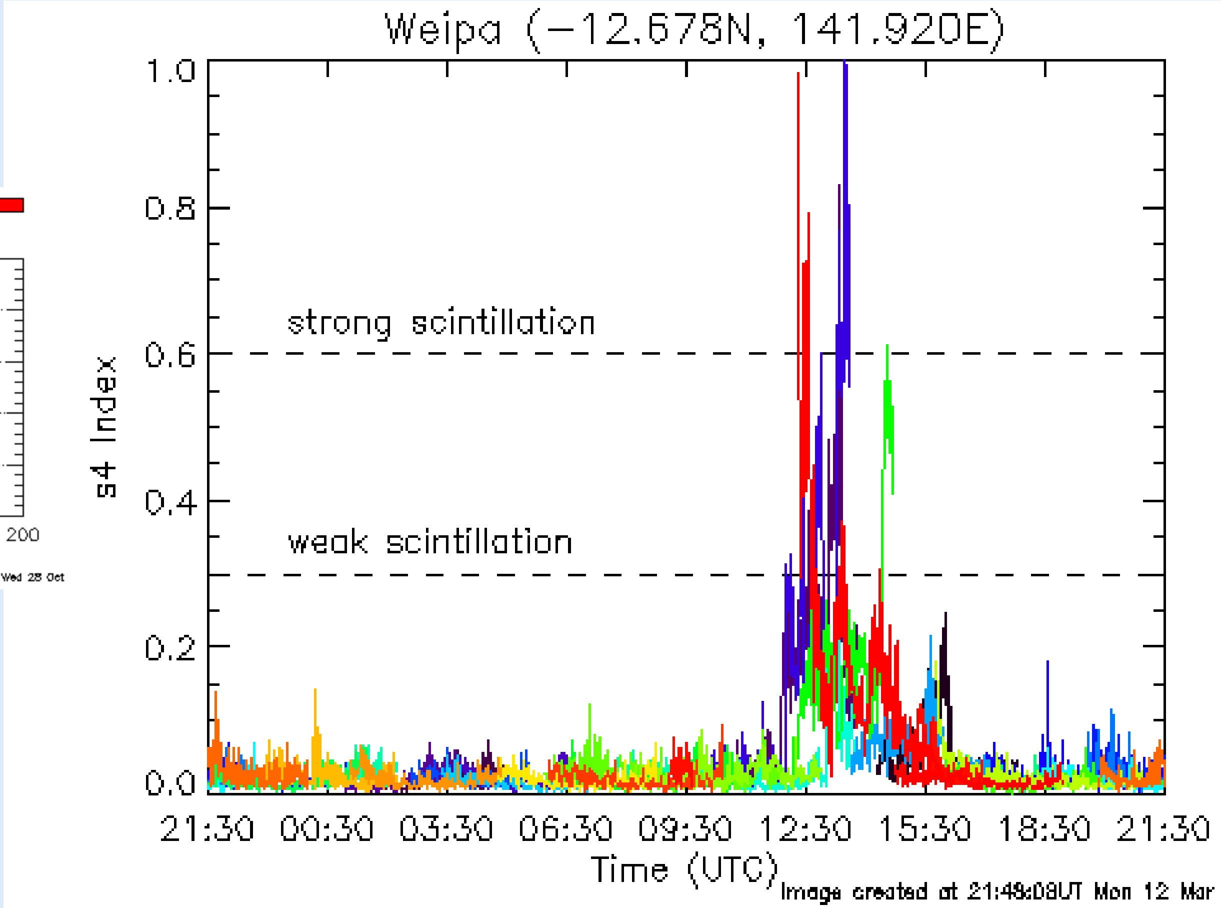
Email alerts

SUBJ: IPS SCINTILLATION ALERT ISSUED AT 07:38UT
07 Oct 2015 BY IPS RADIO AND SPACE SERVICES
AREA AFFECTED: NIUE

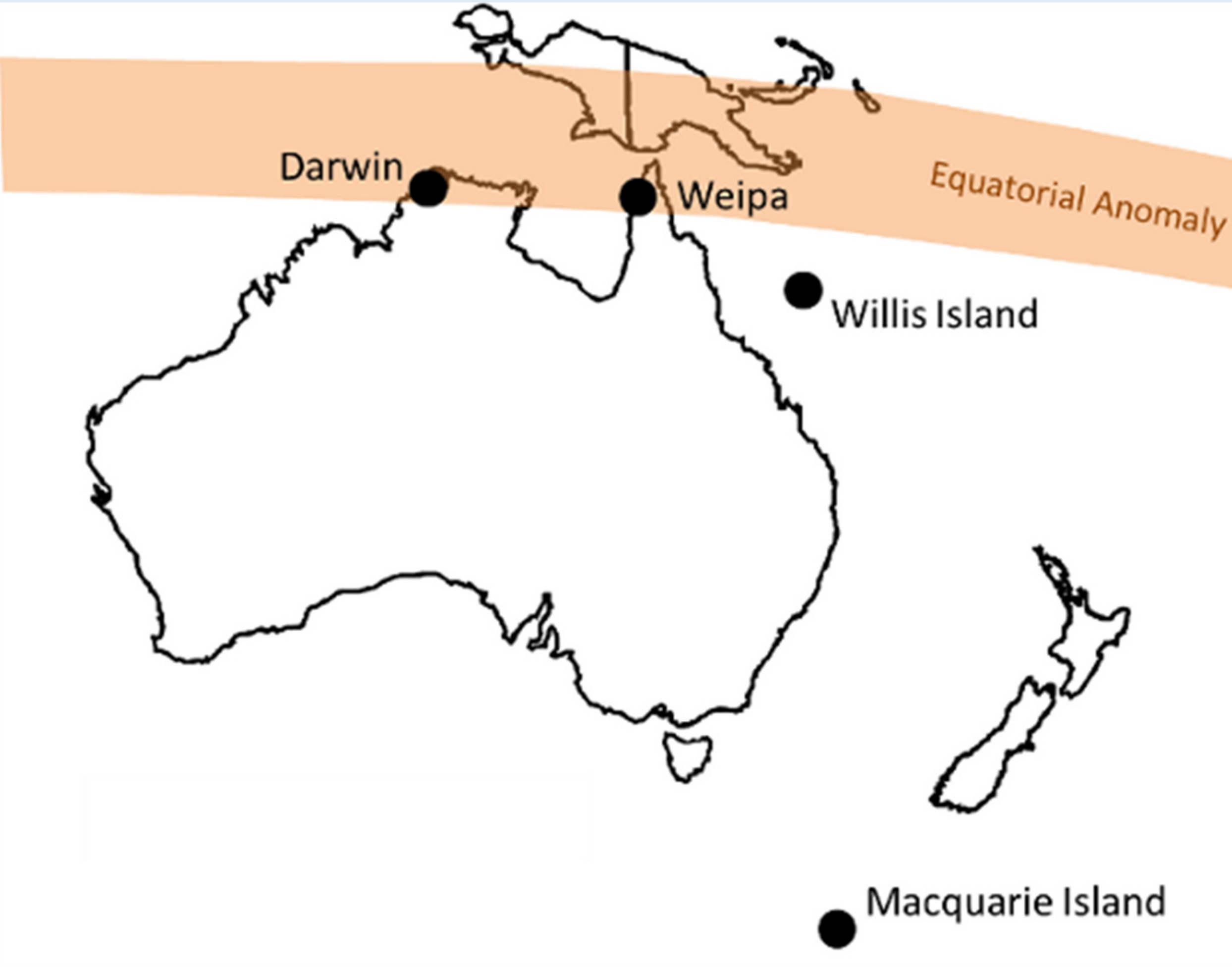
Approximate Peak of disturbance : 07:37UT 07 Oct 2015
Maximum S4 Index : 1.00000
Eightieth percentile of S4 during disturbance : 0.824997
Observed at Sites : Niue

Web pages





Important latitudes for scintillation effects



Only 4 events since 7 Oct 2015

Approximate Peak of disturbance : 12:02UT 23 Sep 2016
Maximum S4 Index : 1.00000
Eightieth percentile of S4 during disturbance : 0.871900
Observed at Sites : Weipa

Approximate Peak of disturbance : 14:07UT 26 Oct 2015
Maximum S4 Index : 0.870600
Eightieth percentile of S4 during disturbance : 0.809840
Observed at Sites : Weipa

Approximate Peak of disturbance : 12:28UT 24 Oct 2015
Maximum S4 Index : 1.00000
Eightieth percentile of S4 during disturbance : 1.00000
Observed at Sites : Darwin

Approximate Peak of disturbance : 14:34UT 19 Oct 2015
Maximum S4 Index : 1.00000
Eightieth percentile of S4 during disturbance : 0.865320
Observed at Sites : Darwin

Space Weather Impact on Satellites

(RAE, 2013)

Date	Event	Satellite	Orbit	Cause (probable)	Effects seen
8 March 1985		Anik D2	GEO	ESD	Outage
October 1989	CME-driven storm	TDRS-1	GEO	SEE	Outage
July 1991		ERS-1	LEO	SEE	Instrument failure
20 January 1994	Fast solar wind stream	Anik E1	GEO	ESD – note: all three satellites were of same basic design	Temporary outage (hours)
		Anik E2	GEO		6 months outage, partial loss
		Intelsat K	GEO		Temporary outage (hours)
11 January 1997	Fast solar wind stream	Telstar 401	GEO	ESD	Total loss
19 May 1998	Fast solar wind stream	Galaxy 4	GEO	ESD	Total loss
15 July 2000	CME-driven storm	Astro-D (ASCA)	LEO	Atmospheric drag	Total loss
6 Nov 2001	CME-driven storm	MAP	Interplanetary L2	SEE	Temporary outage
24 October 2003	CME-driven storm	ADEOS/MIDORI 2	LEO	ESD (solar array)	Total loss
26 October 2003		SMART-1	HEO	SEE	Engine switch-offs and star tracker noise
28 October 2003		DRTS/Kodama	GEO	ESD	Outage (2 weeks)
14 January 2005		Intelsat 804	GEO	ESD	Total loss
15 October 2006	Fast solar wind stream	Sicral 1	GEO	ESD	Outage (weeks)
5 April 2010	Fast solar wind stream	Galaxy 15	GEO	ESD	Outage (8 months)
13 March 2012	CME-driven storm	Spaceway 3	GEO	SEE?	Outage (hours)
7 March 2012		SkyTerra 1	GEO	SEE/ESD?	Outage (1 day)
22 March 2012		GOES15	GEO	ESD?	Outage (days)

$70M

$150M

2003: 450 Spacecraft

- 1 total loss
- 10 operational loss
- 47 outages
- 11 Skynet-4 anomalous events in 48 hours

2015: >1000 spacecraft

- 10% outages
- Rapid ageing
- $30bn cost

Spacecraft Environment

• GEO (geostationary – 36,000km), MEO (medium earth orbit – low 20,000km) and LEO (low earth orbit <2000km) are different *radiation* environments

• GEO = communications, weather;   MEO = navigation; LEO = cubesats, weather, earth-obs, recon

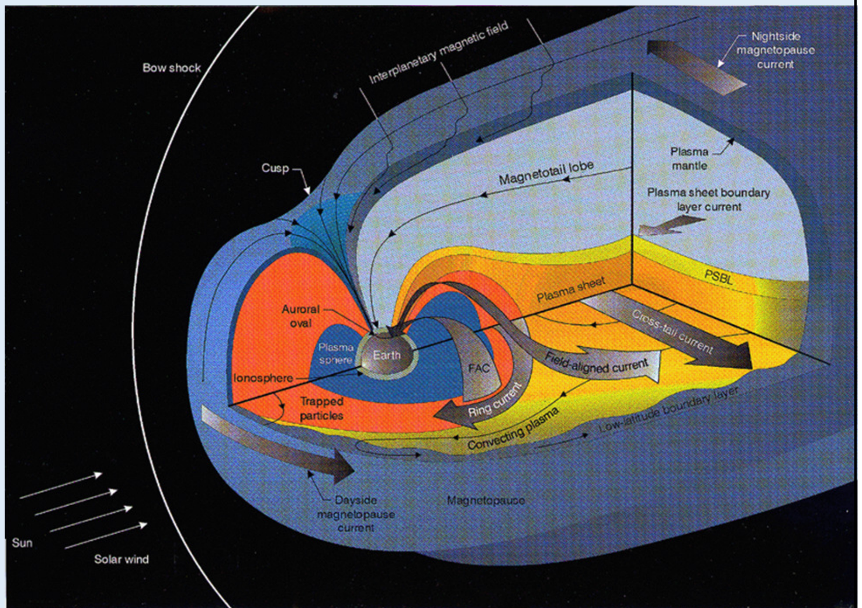
• GEO and MEO in the radiation belts. Active during geomagnetic storms. Both protons and electrons a problem.

• LEO polar orbit passes through auroral 'field-aligned-currents'

• LEO susceptible to 'South Atlantic anomaly' enhanced radiation due to magnetic field offset

• Solar Proton Events (>10MeV) –> SEU

• High energy electrons (>2MeV) -> DDD, ESD

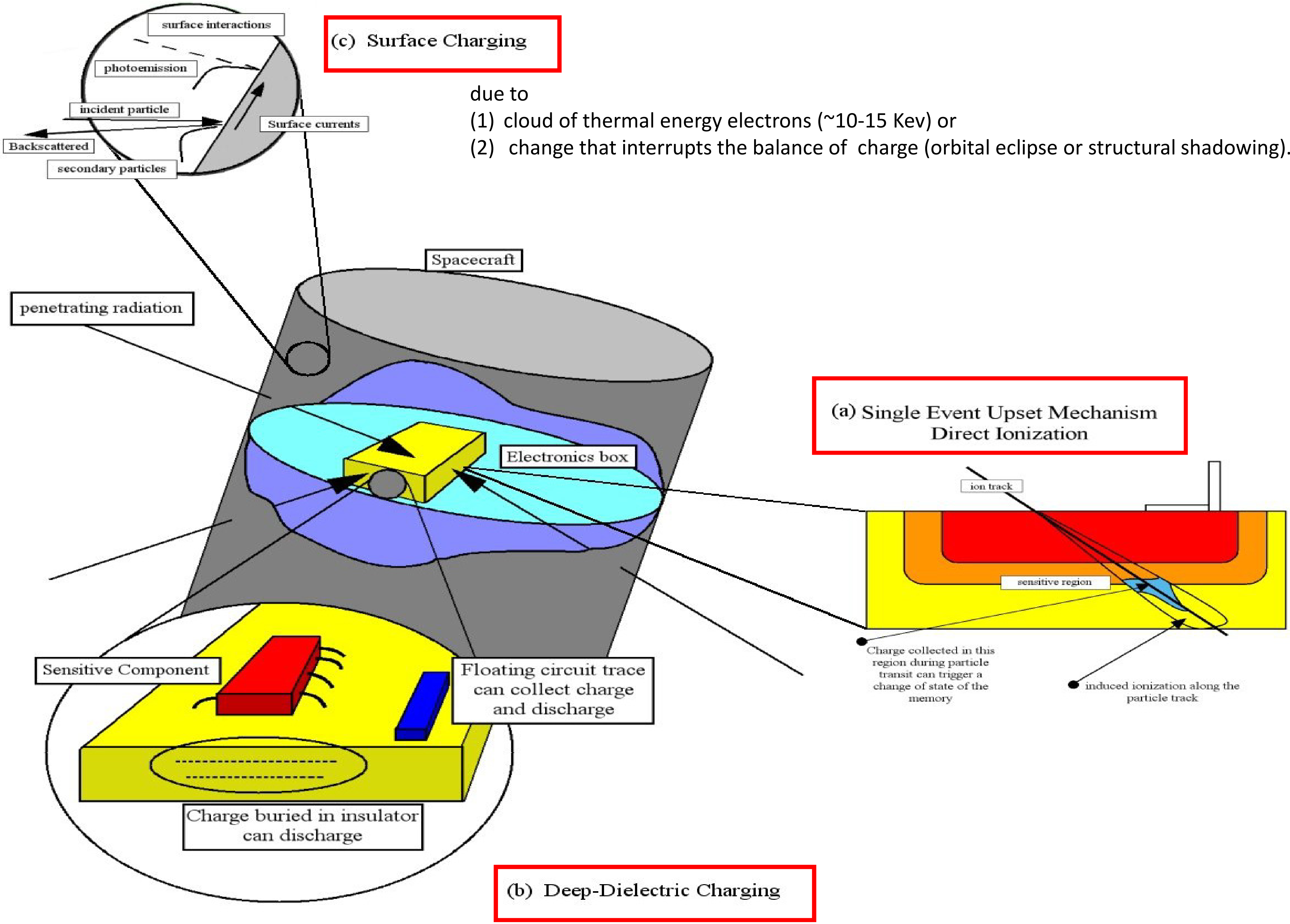


(c) Surface Charging

due to

(1) cloud of thermal energy electrons (~10-15 Kev) or

(2) change that interrupts the balance of charge (orbital eclipse or structural shadowing).



Primary Spacecraft Effects

(a) Single Event Upset (SEU)

Direct electronic circuit penetration by high energy (>10MeV) protons or heavier ions.

Solar Energetic Particles' (SEPs) reach Earth in 1-4 hours and can penetrate deep into the geomagnetic field, affecting at least GEO/MEO and sometimes LEO.

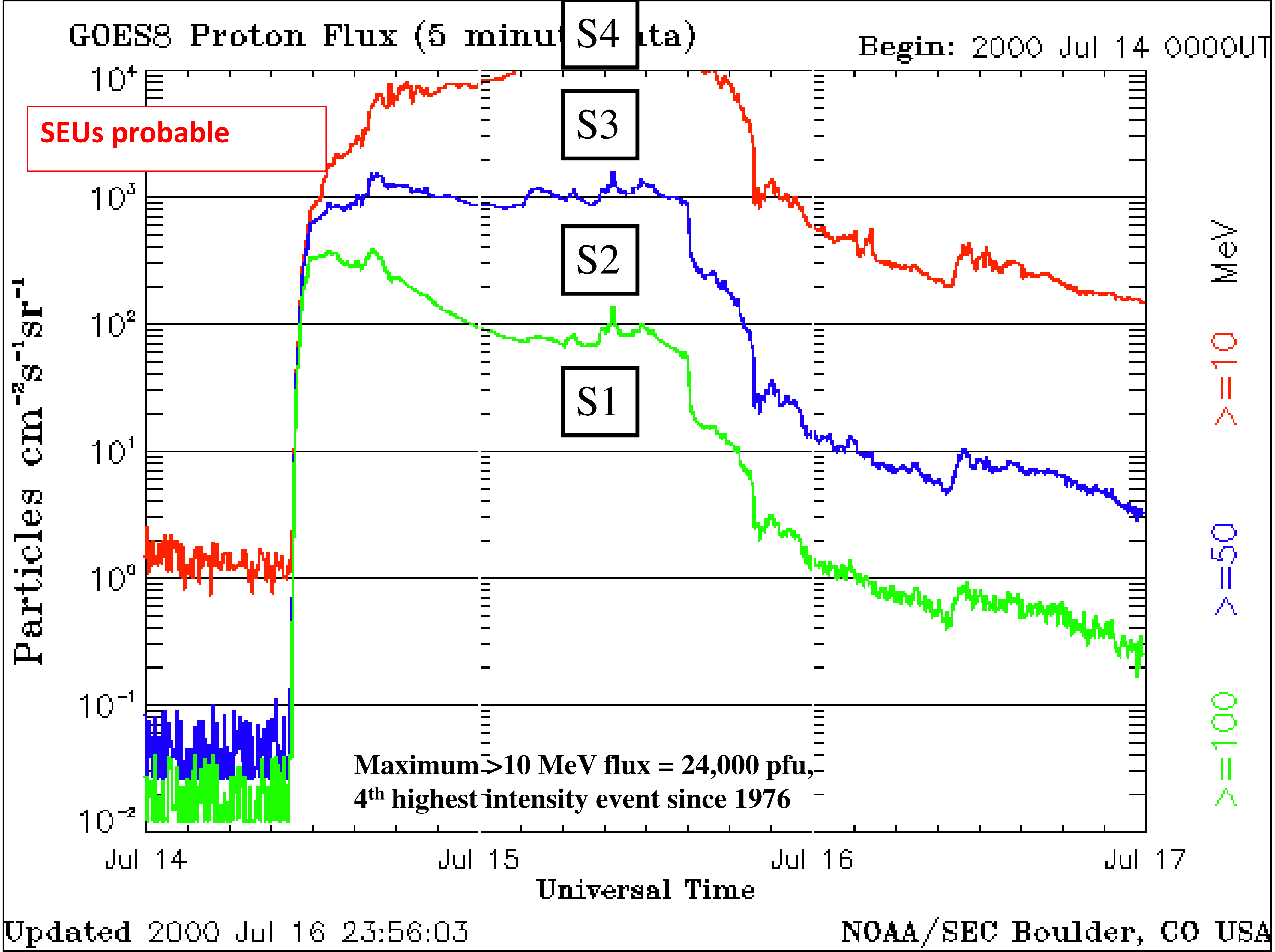
(b) Deep Dielectric Discharge (DDD)

Relativistic electrons ($\geq$ 2 MeV) penetrate and accumulate in dielectrics either outside the satellite (cables, thermal blankets, or power panel structure) or inside (circuit boards), and discharge (DDD) with destructive effect. (e.g. Equator-S)

(c) Surface Charging & Electrostatic Discharge (ESD)

Differential voltages on satellite outer surface

Changes in reference voltages that trigger circuits (Phantom Commands), or generate destructive electrostatic discharges.

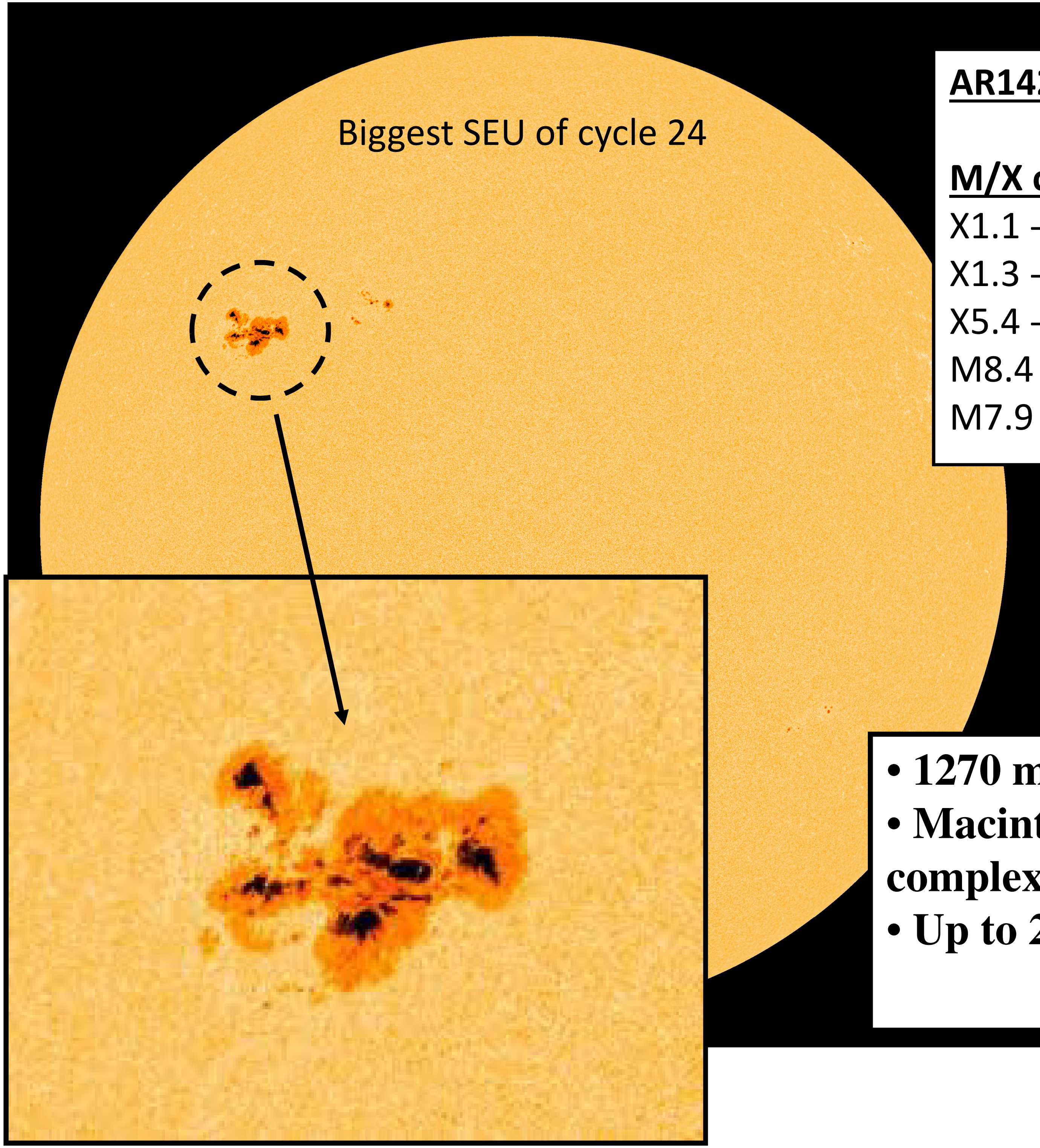


GOES8 Proton Flux (5 minut ta)
Begin: 2000 Jul 14 0000UT
S4
S3
S2
S1
SEUs probable
Particles cm-2s-1sr-1
10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
Maximum >10 MeV flux = 24,000 pfu,
4th highest intensity event since 1976
Jul 14
Jul 15
Jul 16
Jul 17
Universal Time
>=10 MeV
>=50
>=100
Updated 2000 Jul 16 23:56:03
NOAA/SEC Boulder, CO USA

Satellite Anomalies: 14-16 July 2000
Proton Event & Geomagnetic Storm

- **GEO** – orientation problems during magnetopause crossing
- **GEO** Satellites lost ~0.1 amp output from solar arrays
- **LEO** Satellites affected – deep penetration into geomagnetic field.
- **ASCA** (Advanced Satellite for Cosmology and Astrophysics) – lost attitude fix resulting in solar array
- misalignment and power loss, satellite probably lost
- **GOES-8 & -10** – SEM Electron sensor problems, power panels
- **ACE** (Advanced Composition Explorer) – Temporary SW and other sensor problems
- **WIND** – Permanent (25%) loss of primary transmitter power & Temporary loss of Sun and star sensors
- **SOHO** (also **YOHKOH** & **TRACE**) – High energy protons obscure solar imagery

Many anomalies caused by SEUs

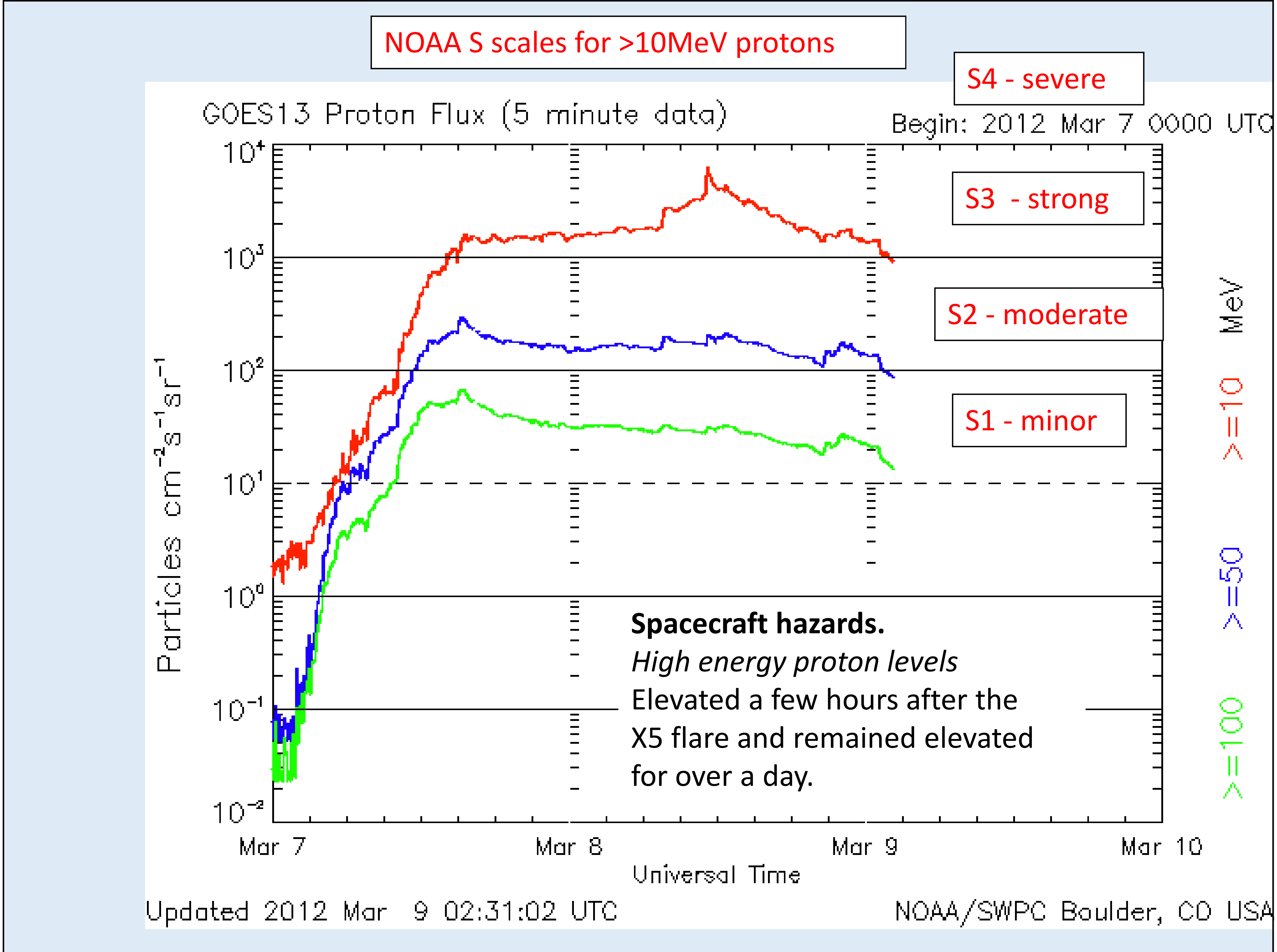


AR1429 – March 2012

M/X class flares

X1.1 - March 5 2012
X1.3 - March 6 2012
X5.4 - March 7 2012 (S3)
M8.4 - March 9 2012
M7.9 - March 13 2012 (S2)

- **1270 millionths of the solar disc**
- **Macintosh magnetic complexity class Ekc**
- **Up to 28 spots.**



NOAA S scales for >10MeV protons
S4 - severe
GOES13 Proton Flux (5 minute data)
Begin: 2012 Mar 7 0000 UTC
S3 - strong
S2 - moderate
S1 - minor
Particles cm^{-2}s^{-1}sr^{-1}
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
>=10 MeV
>=50
>=100
Spacecraft hazards.
High energy proton levels
Elevated a few hours after the
X5 flare and remained elevated
for over a day.
Mar 7
Mar 8
Mar 9
Mar 10
Universal Time
Updated 2012 Mar 9 02:31:02 UTC
NOAA/SWPC Boulder, CO USA

SWS Severe Event Service

- Predicts when a flare occurs, if an associated CME is likely to cause a severe geomagnetic storm (Dst < -250 nT).

- email warning from **[Ips-esws-general] Severe space weather WATCH**

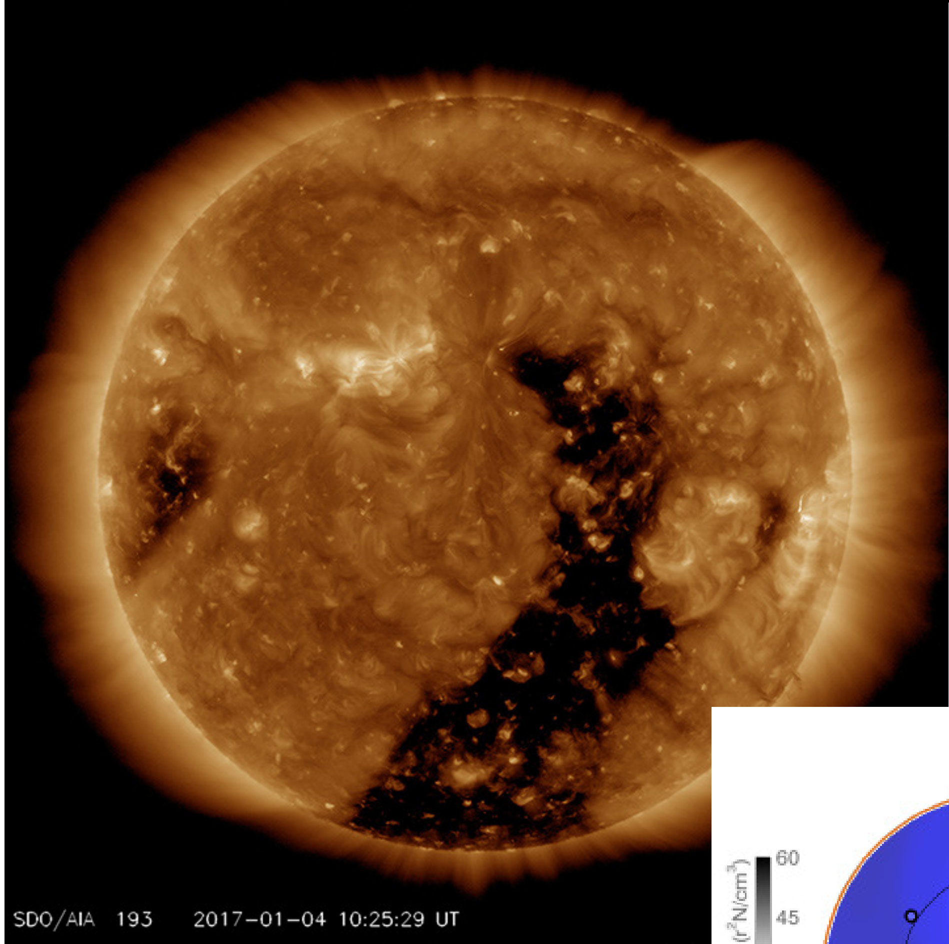
- Associated Solar Energetic Particles?

- Radiation belt energisation?

> Severe space weather WATCH Issued at 0438 UT on 22 Jun 2015 by IPS Radio and Space Services from the Australian Space Forecast Centre
>
> *A recent Coronal Mass Ejection associated with a solar flare is anticipated to impact the Earth within the next 48 hours. The effects are expected to be significant. Increased awareness of critical infrastructure is advised.*

Solar Energetic Particle (SEP) Prediction

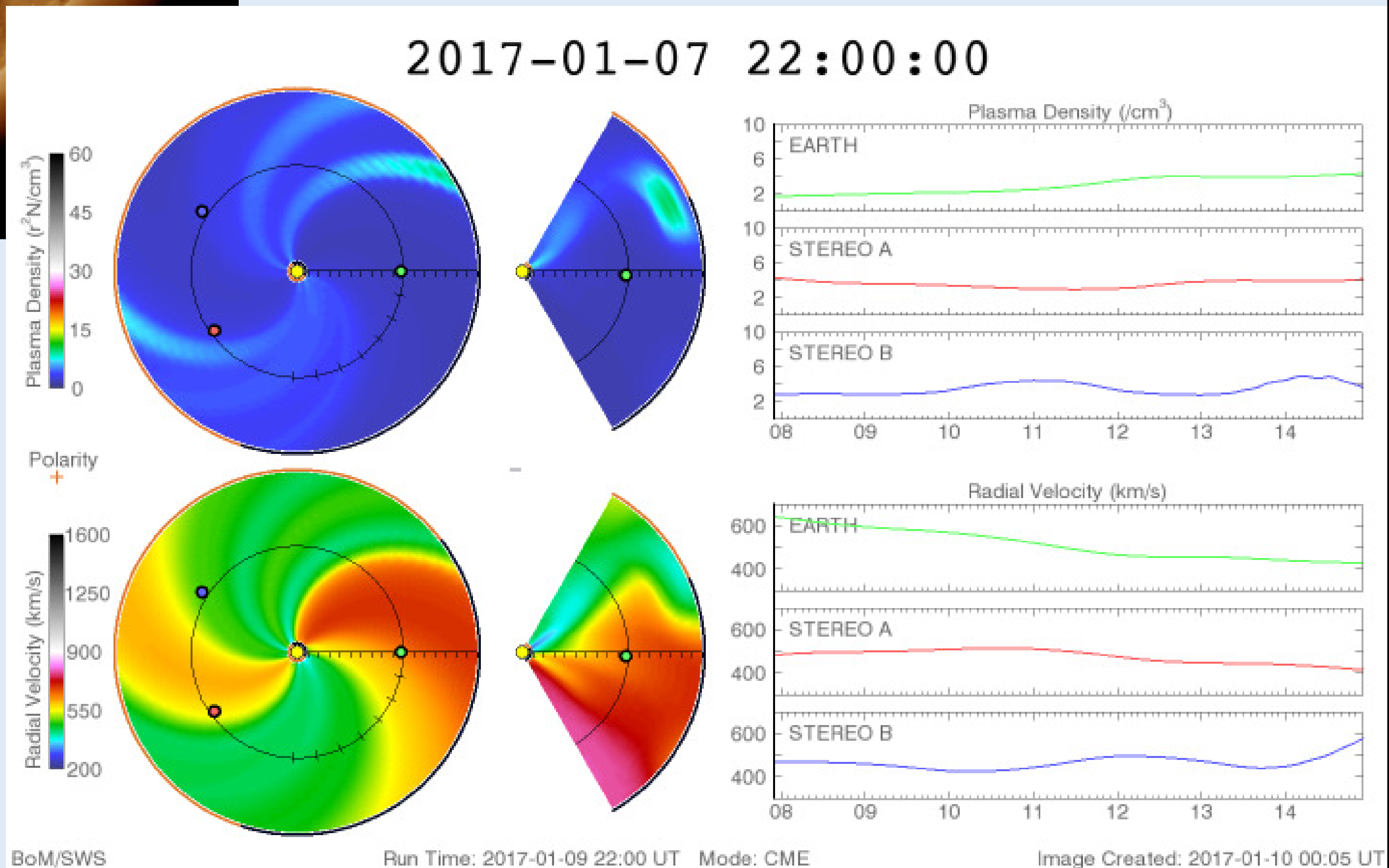
- ARC Linkage Grant with University of Sydney Solar Physics
- Magnetic mapping technique between the Earth and Sun allows us to more accurately predict the occurrence and properties of SEP events at Earth.



Deep Di-electric Discharge (DDD)

High speed solar wind streams (HSSWS) from coronal holes carry high-energy electrons that enter radiation belts and are further energised to > 2MeV.

27 days rotational recurrence for larger coronal holes



Deep Dielectric Discharge (DDD)

• Enhanced velocity 'high-speed solar-wind streams' (HSSWS) emerge from ‘coronal hole’ regions and spread outward from Sun in the “Parker Spiral” pattern.

• As the streams sweep past Earth, they inject a greater volume of higher-speed electrons.

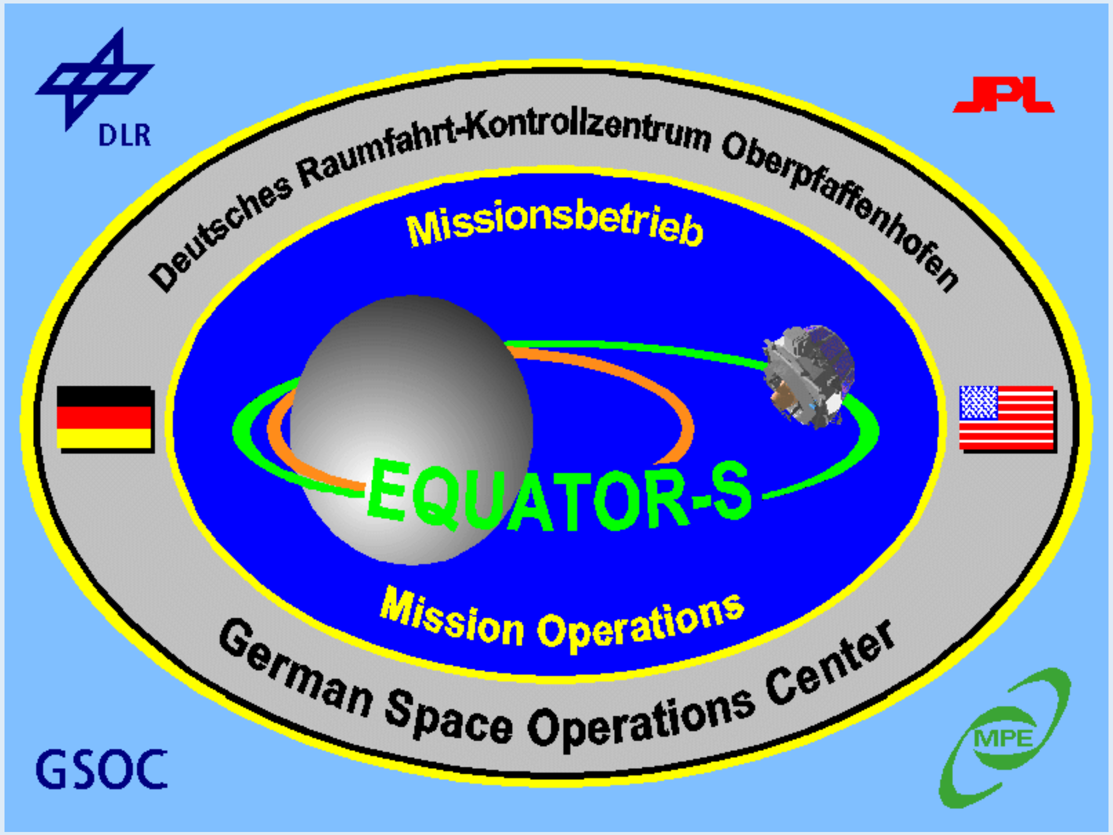
• Most often seen during years of low or declining sunspot number.

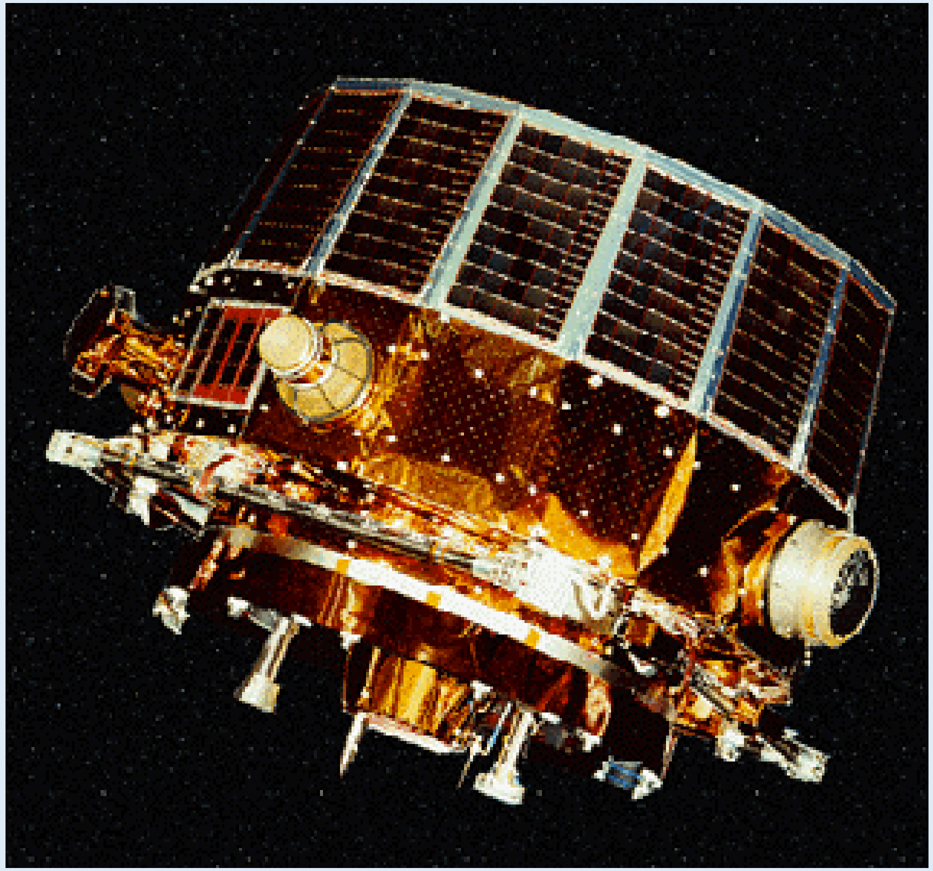
• During first 24-hours of recurrent HSSWS geomagnetic storm, MeV electrons at GEO **drop** to minimum background levels.
Then sudden **increase** in electrons at energies greater than 2 MeV by 100 or 1000 times.

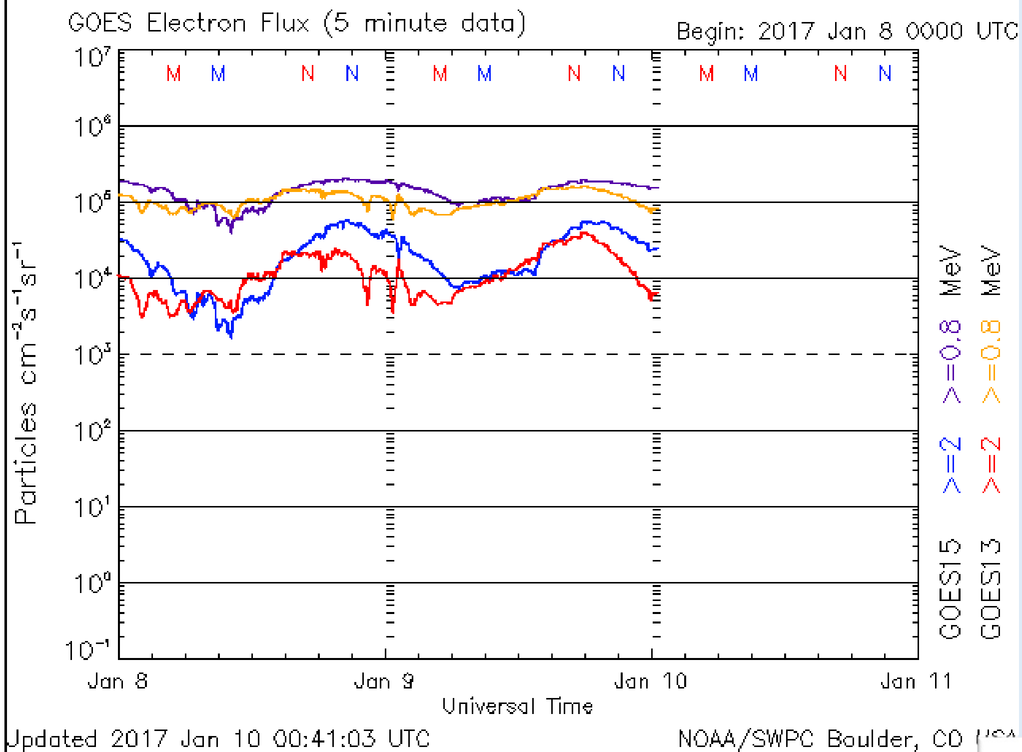
• These are the energetic particles that cause DDD events and have been called “Killer Electrons”. Accelerated within the radiation belts by plasma waves.

DDD example – Equator-S 1998

- Orbit apogee at magnetopause
- 5 months after launch in planned 2 year mission
- CPU latchup
- Comms still active, carrier wave received
- After several days of high-speed solar wind
- Tried for eclipse re-boots

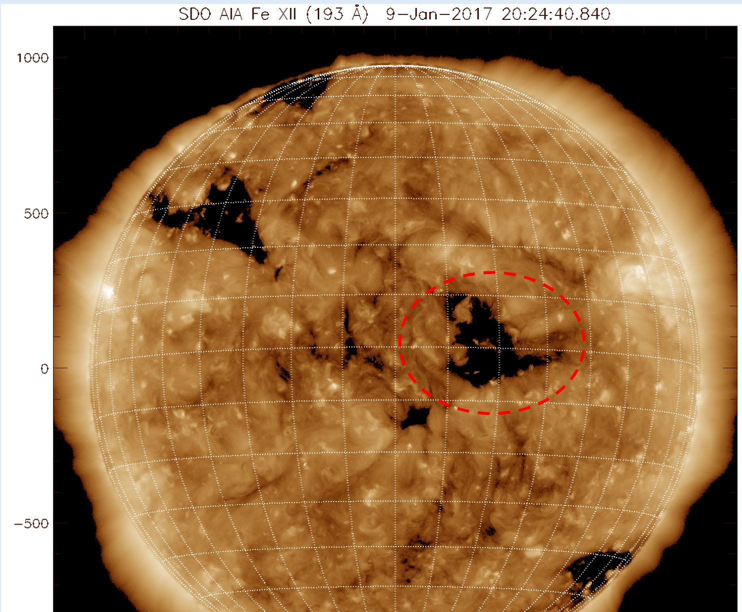




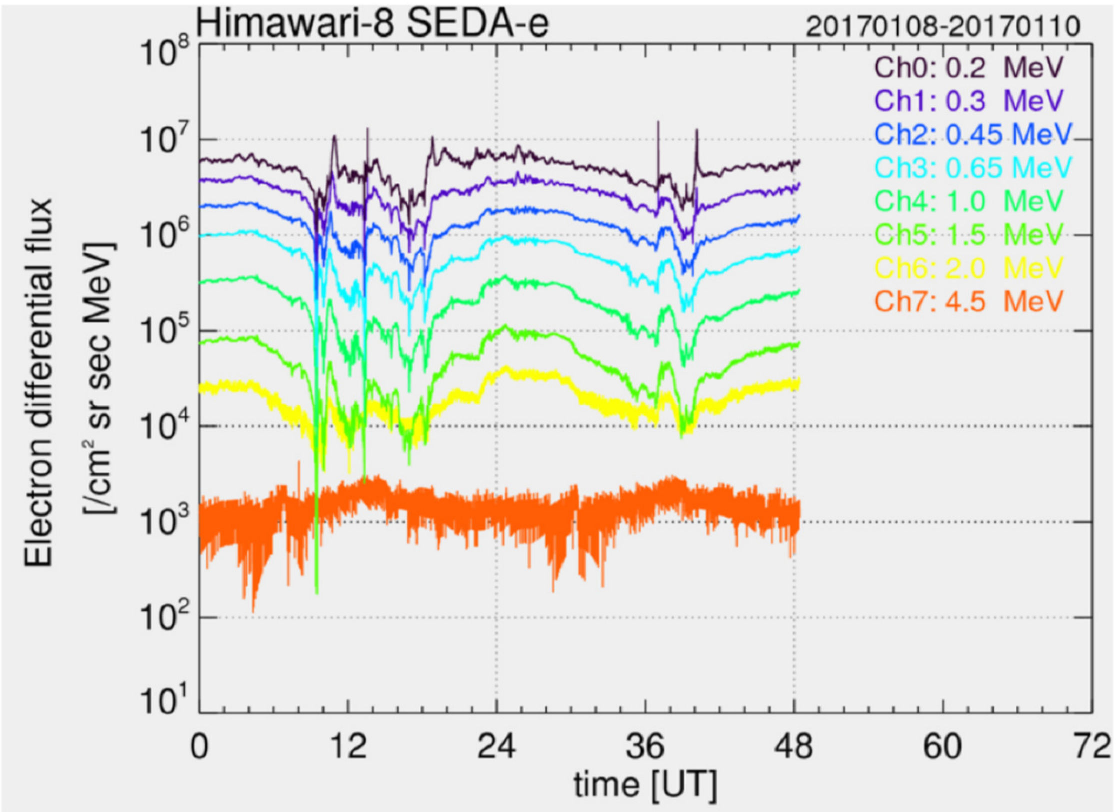


SWS Daily Report 9/1/17

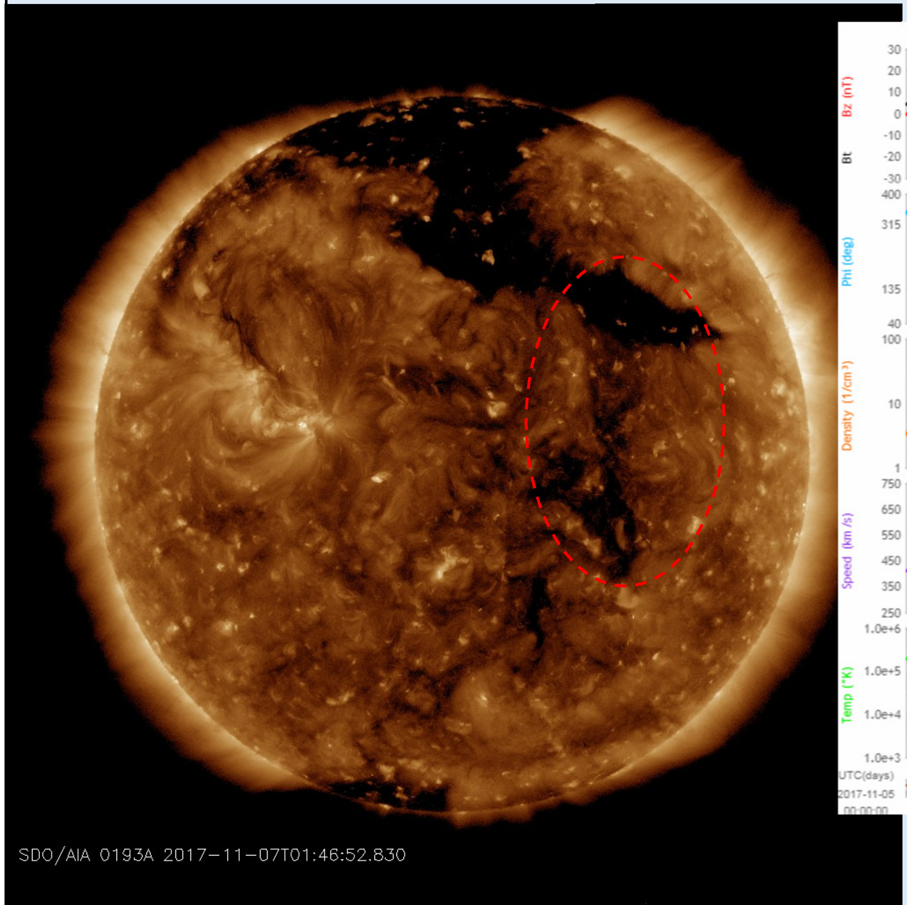
SPACE ENVIRONMENT SUMMARY
GOES satellite data for 08 Jan
Daily Electron Fluence >2 MeV: 9.90E+08
(high fluence)
Daily Deep Dielectric Discharge Probability: **30%**

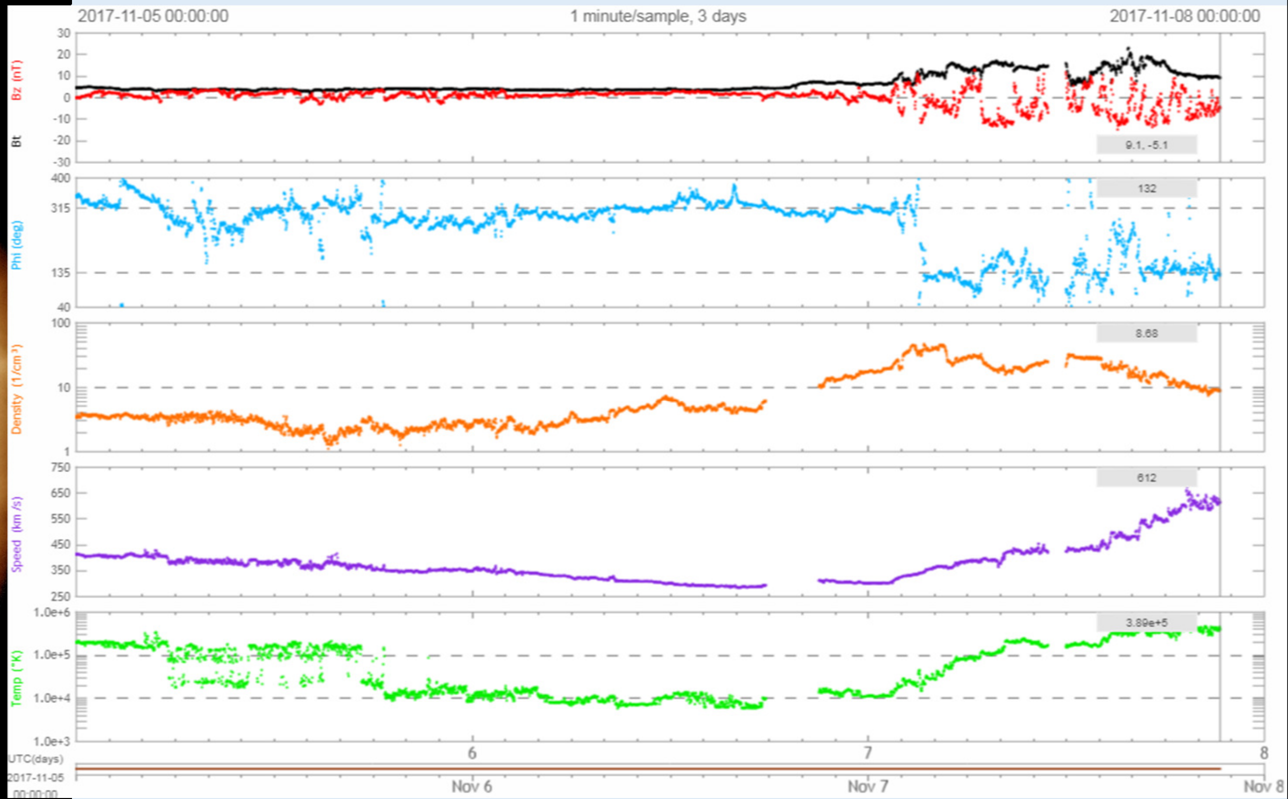


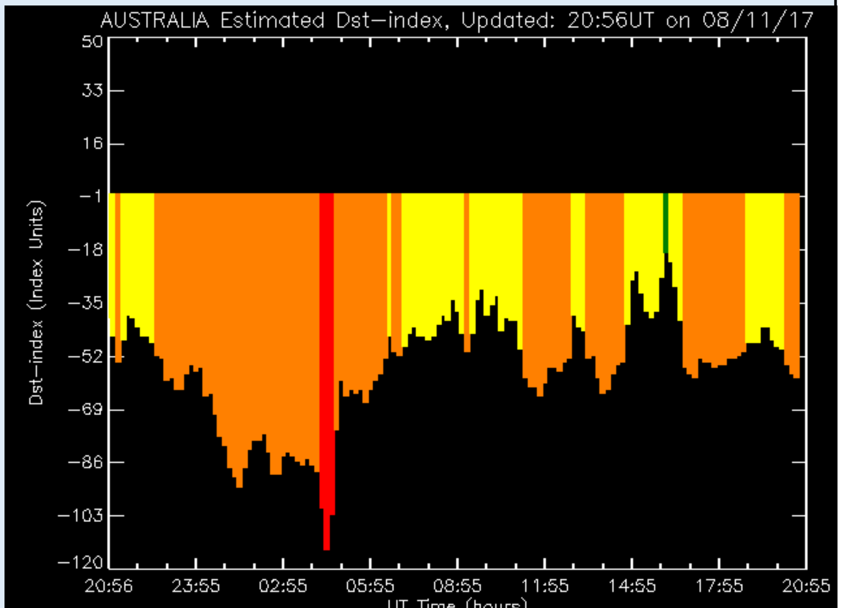
DDD related anomaly observed on a COMSAT ~23UT 6th January, approximately half-way through the stream)

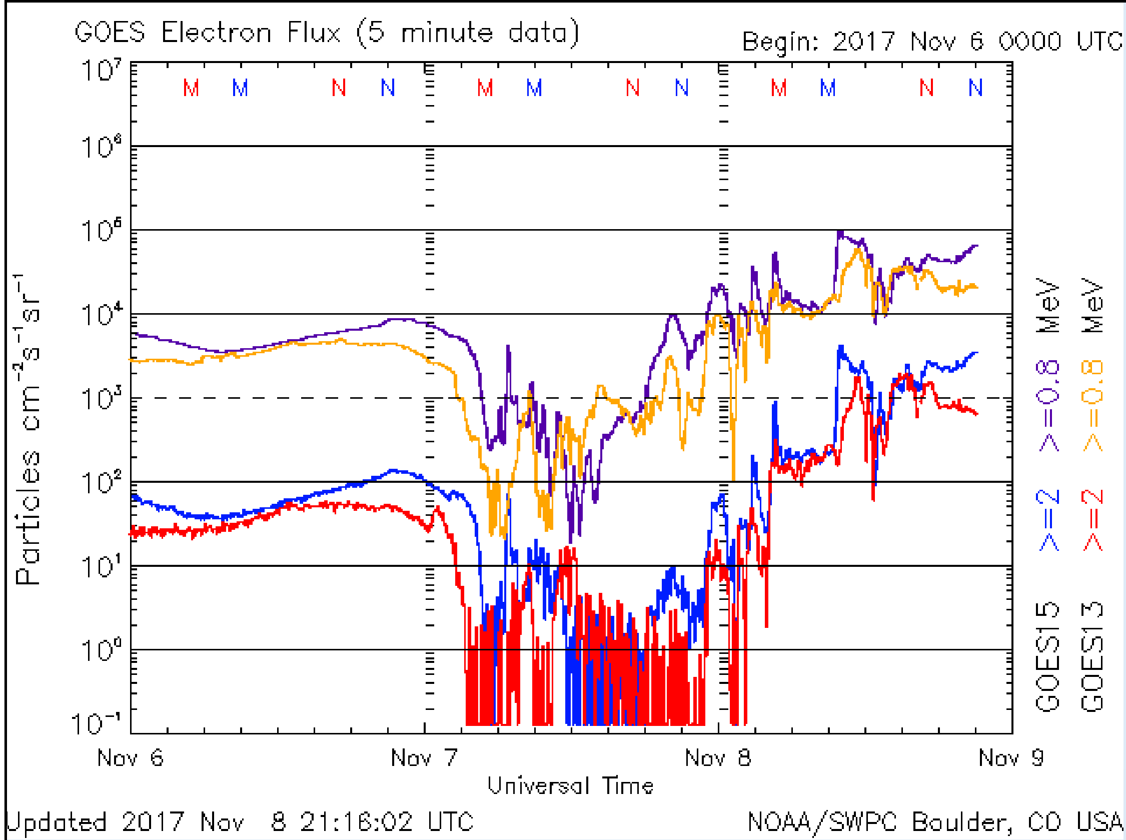


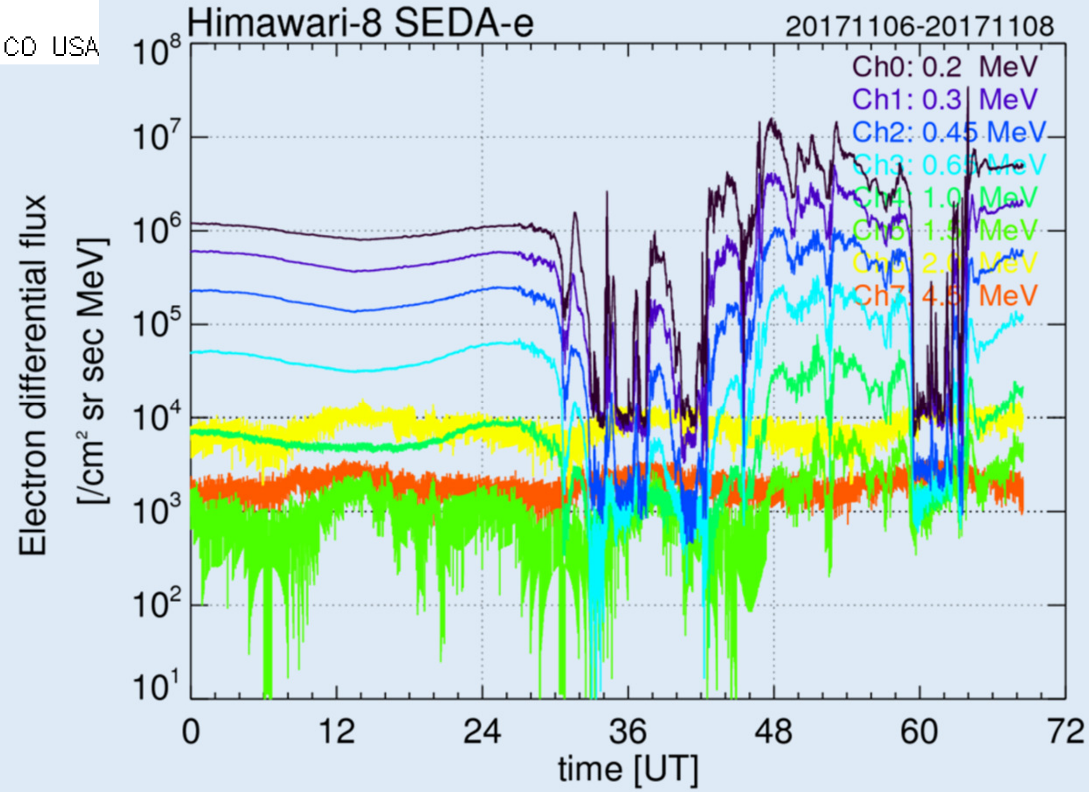
Recent HSSWS event – onset last week 7th Oct








GOES Electron Flux (5 minute data)
Begin: 2017 Nov 6 0000 UTC
Particles cm^{-2}s^{-1}sr^{-1}
Nov 6
Nov 7
Nov 8
Nov 9
Universal Time
GOES15 >=2 >=0.8 MeV
GOES13 >=2 >=0.8 MeV
Updated 2017 Nov 8 21:16:02 UTC
NOAA/SWPC Boulder, CO USA

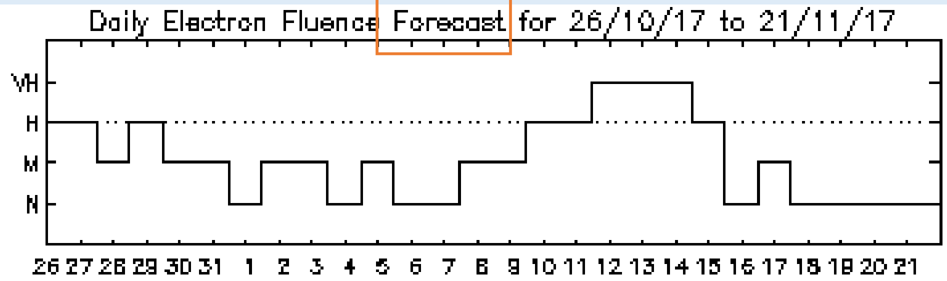

Himawari-8 SEDA-e
20171106-20171108
Electron differential flux
[/cm^2 sr sec MeV]
Ch0: 0.2 MeV
Ch1: 0.3 MeV
Ch2: 0.45 MeV
time [UT]

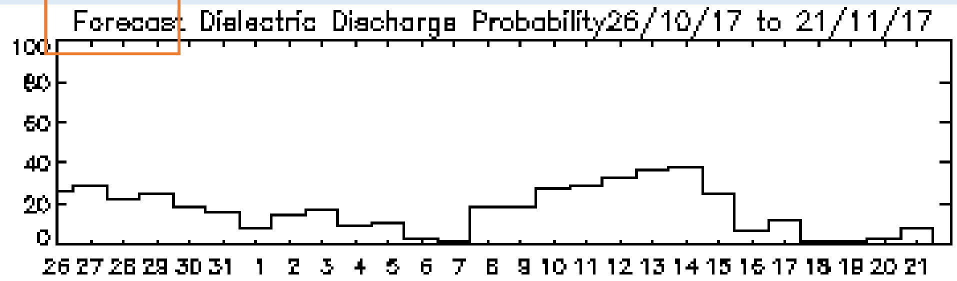
SWS web service - Deep Di-electric Discharge (DDD)

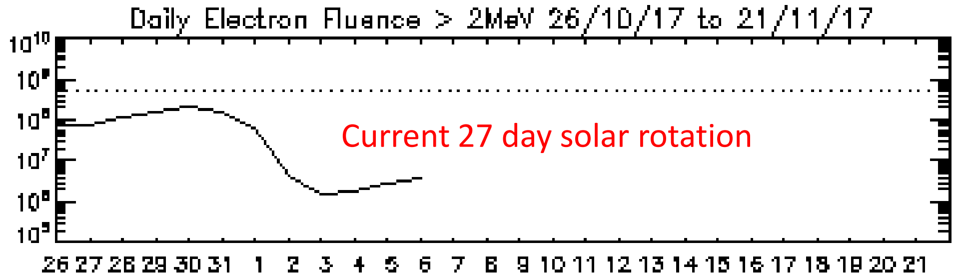
Algorithm by J. Kennewell,
website by G. Paterson

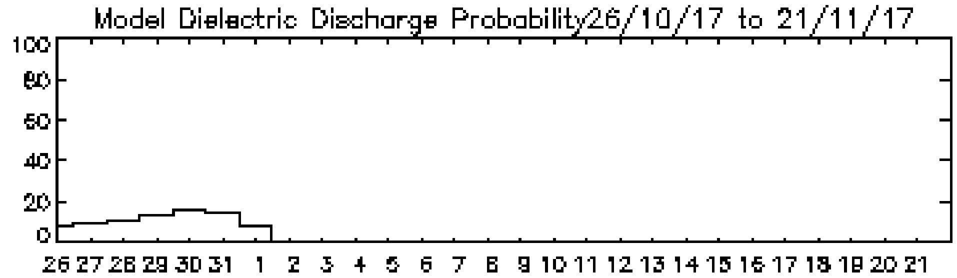
Electron Fluence and DDD Forecast

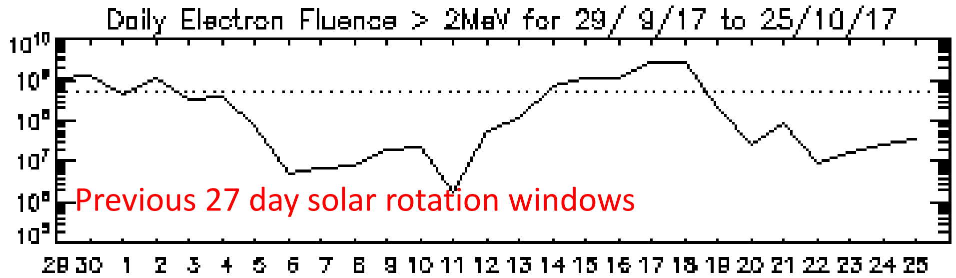
N	Normal Background Fluence	Less than 10e8
M	Moderate Fluence	Greater than 10e8, less than 5x10e8
H	High Fluence	Greater than 5x10e8, less than 10e9
VF	Very High Fluence	Greater than 10e9

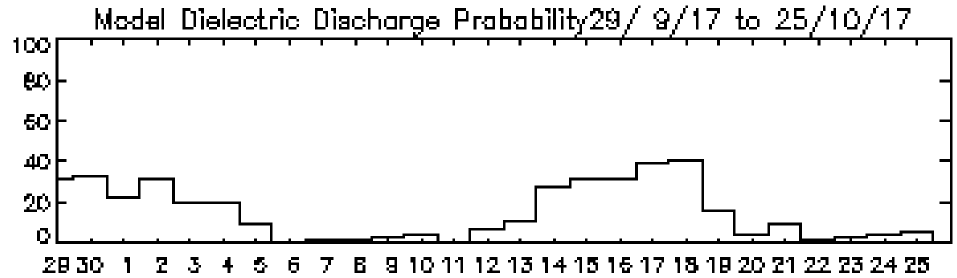




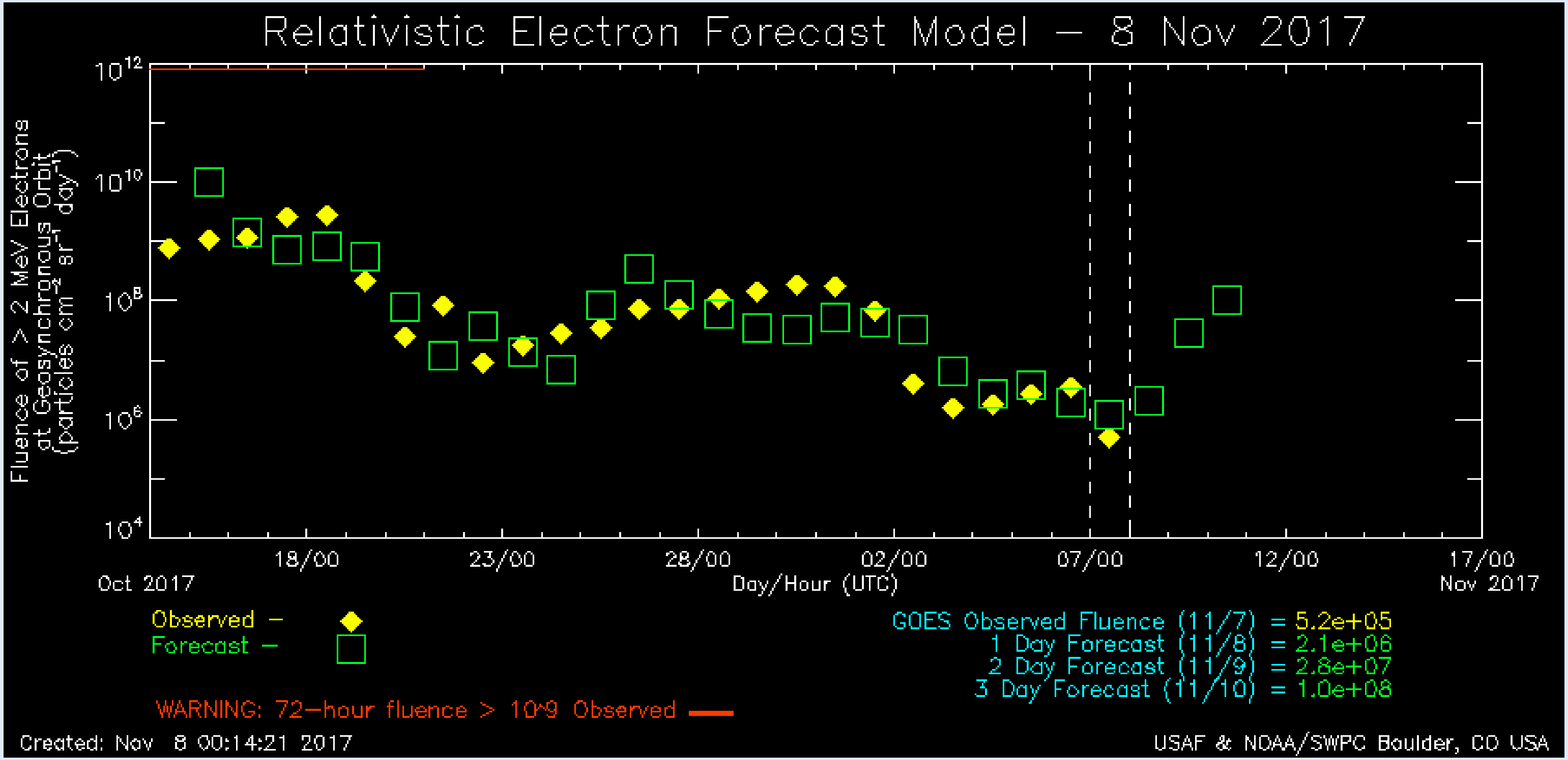






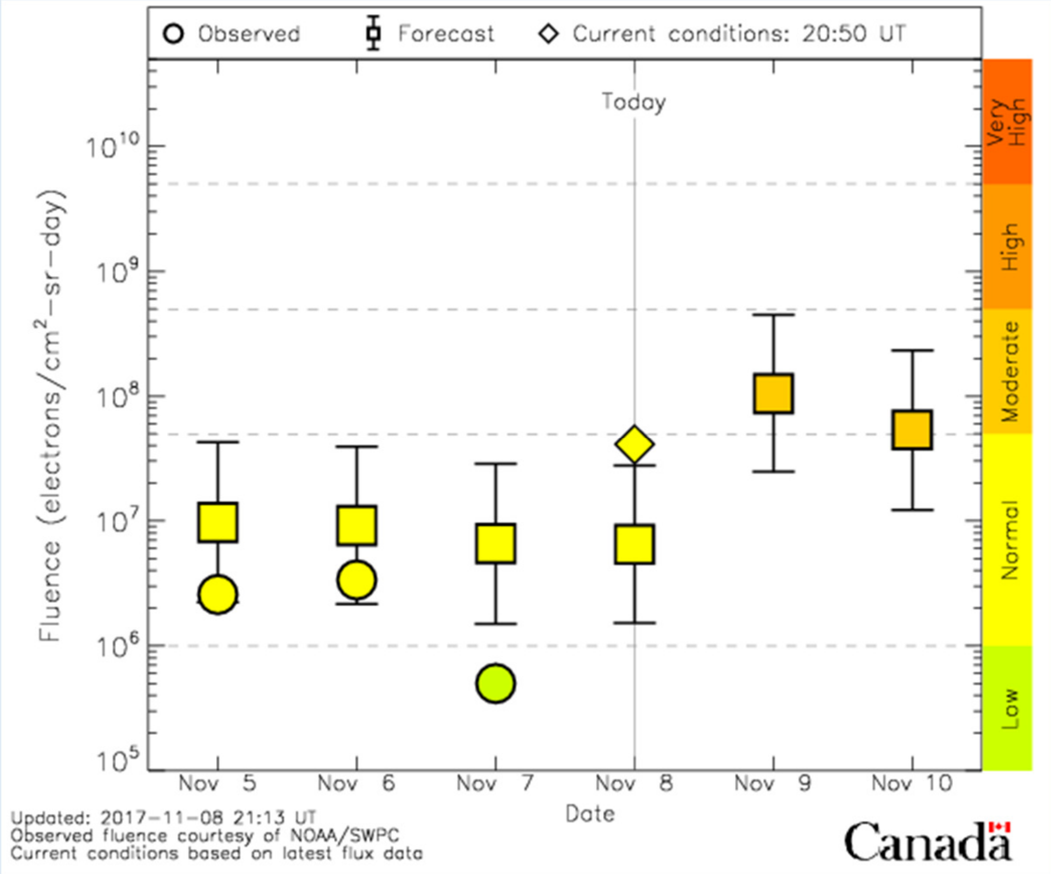


NOAA SWPC Relativistic Electron Forecast Model (REFM)

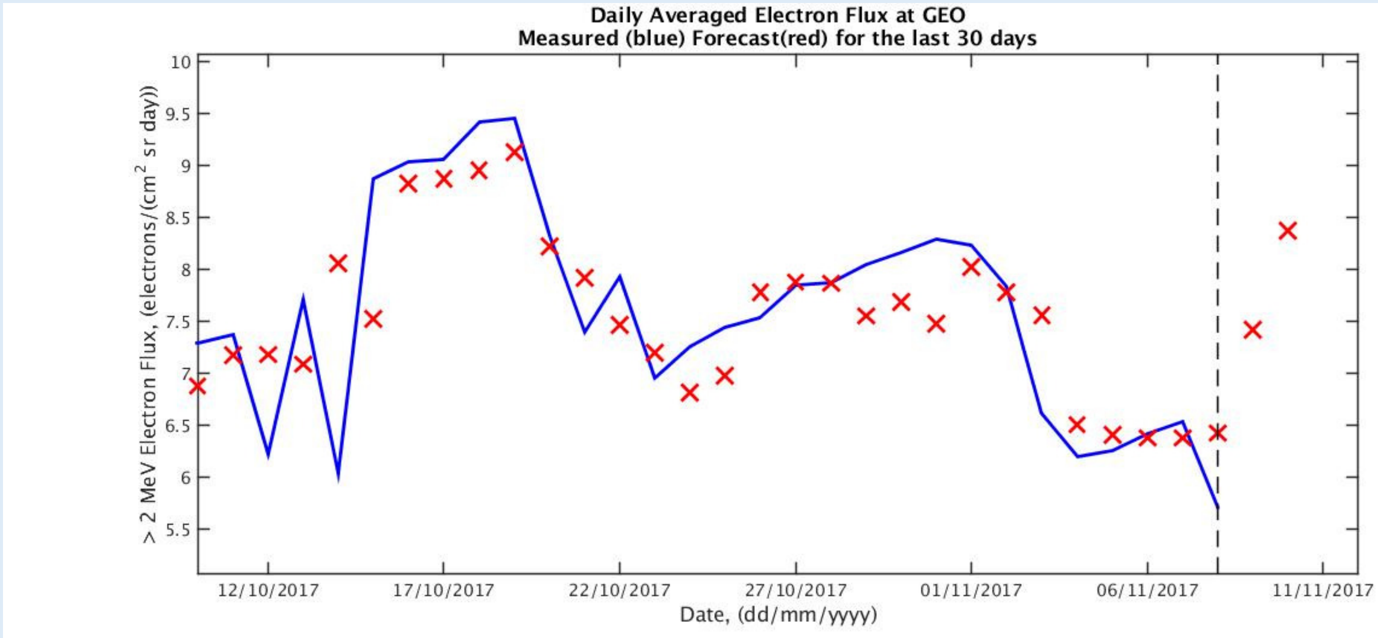


REFM predicts the occurrence of high energy electrons at GEO.

Plots and data are updated daily at 0010 UT. Dashed vertical lines indicate the last vertical value.



Observed
Forecast
Current conditions: 20:50 UT
Today
Very High
High
Moderate
Normal
Low
Fluence (electrons/cm^2–sr–day)
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
Nov 5
Nov 6
Nov 7
Nov 8
Nov 9
Nov 10
Date
Updated: 2017–11–08 21:13 UT
Observed fluence courtesy of NOAA/SWPC
Current conditions based on latest flux data
Canada

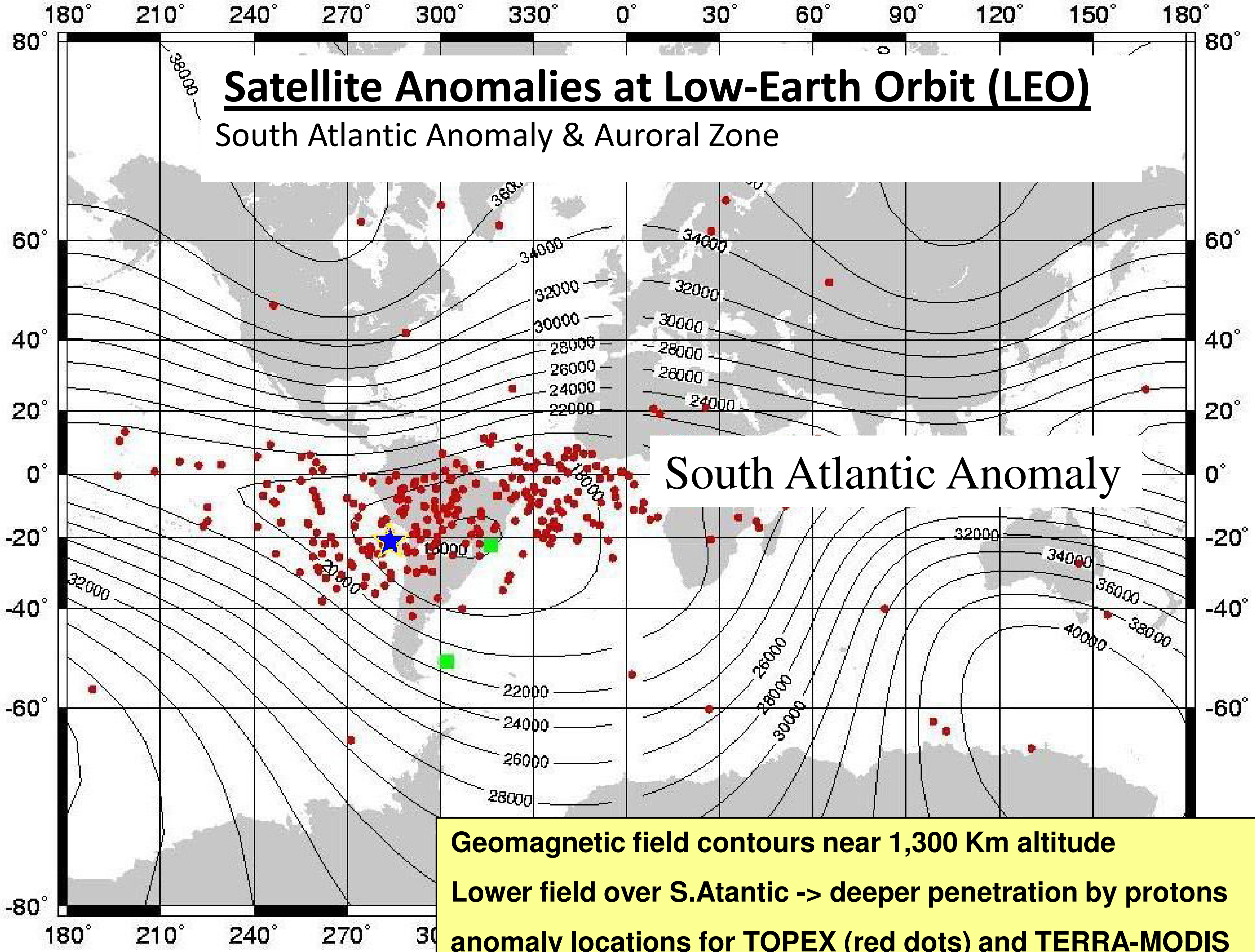


Daily Averaged Electron Flux at GEO
Measured (blue) Forecast(red) for the last 30 days
> 2 MeV Electron Flux, (electrons/(cm^2 sr day))
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
12/10/2017
17/10/2017
22/10/2017
27/10/2017
01/11/2017
06/11/2017
11/11/2017
Date, (dd/mm/yyyy)

TOPEX – 1992-1998 and TERRA-MODIS 2001

Satellite Anomalies at Low-Earth Orbit (LEO)

South Atlantic Anomaly & Auroral Zone



Geomagnetic field contours near 1,300 Km altitude

Lower field over S.Atantic -> deeper penetration by protons

anomaly locations for TOPEX (red dots) and TERRA-MODIS temporary failure location in June 2001.

Satellite Anomalies at Low-Earth Orbit (LEO)

South Atlantic Anomaly & Auroral Zone

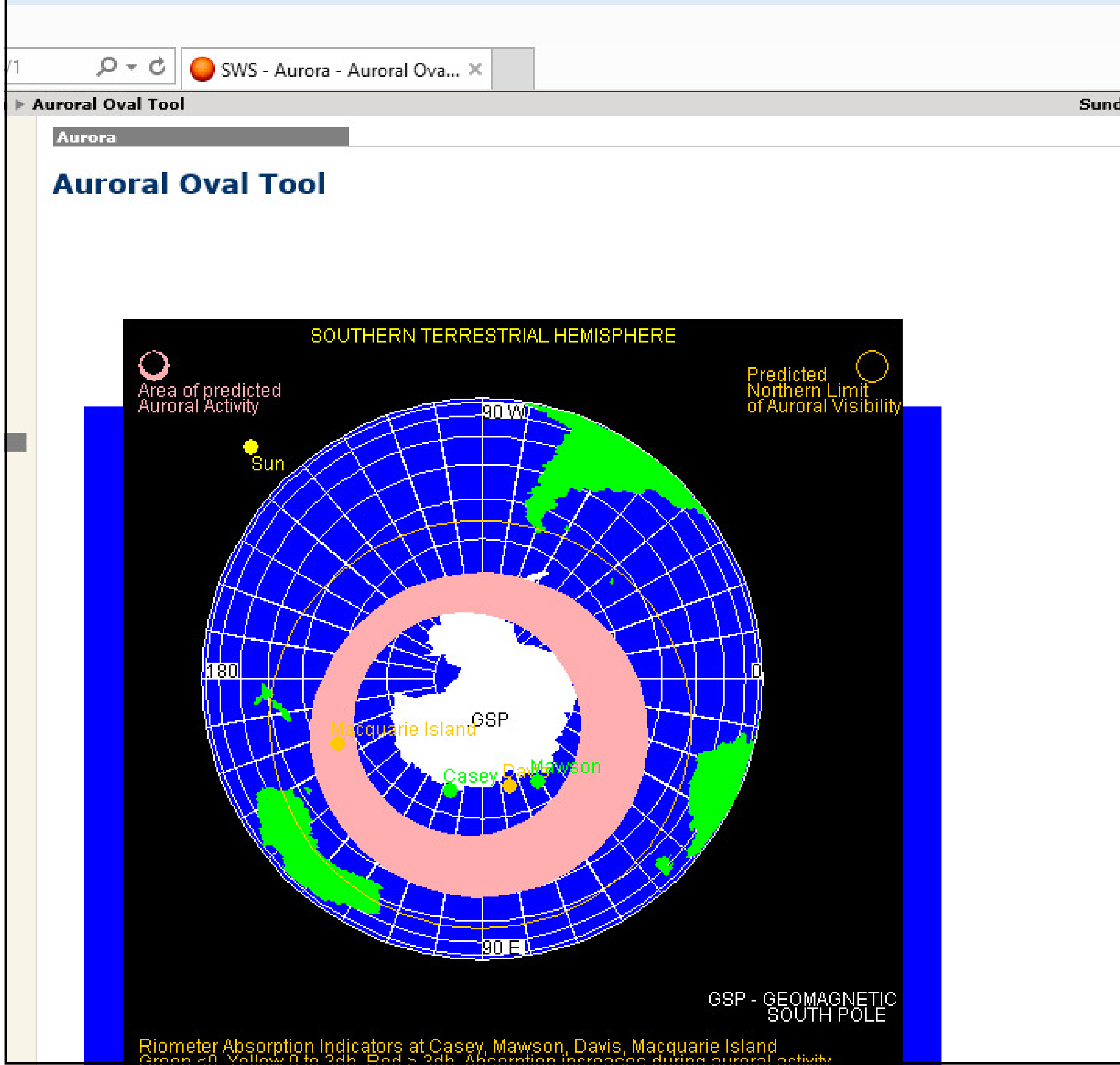
Anomalies in the following spacecraft at LEO – solar cycles 22 & 23

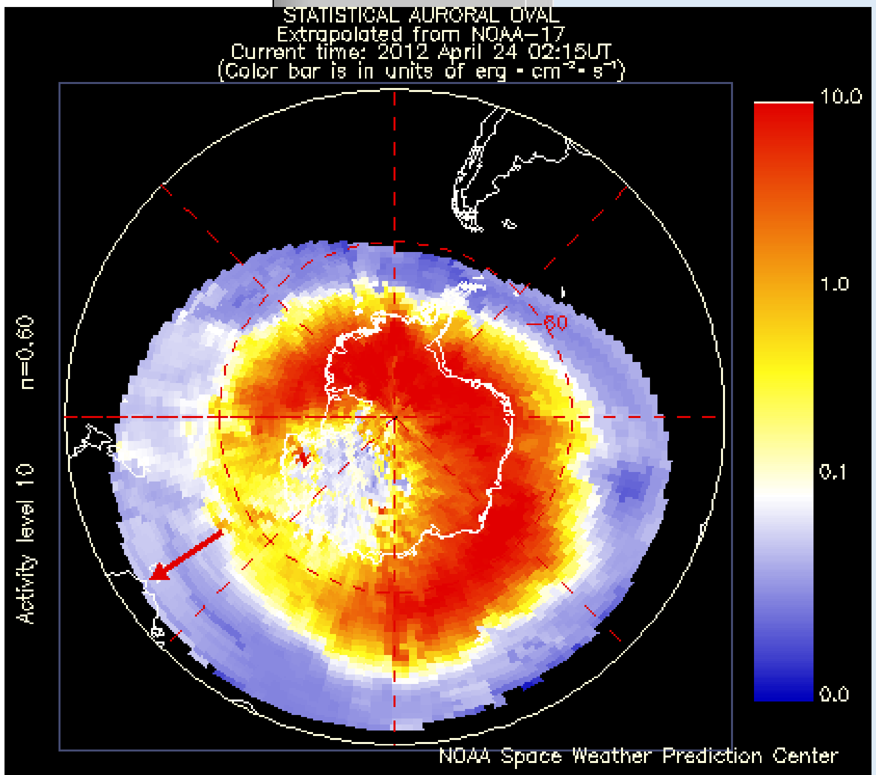
• TERRA-MISR	3-16 Feb 2000
• TERRA-SFE off	26 Oct 2000
• TERRA-MODIS	15 June 2001, 03:56 UT
• TOPEX	1992-1998
• NOAA-11	Sept 1988 - Aug 1990
• Shuttle STS-37, 39, 43, & 44	1991

Polar orbiting LEO satellites affected by enhanced Field-Aligned-Currents

- Limited in-situ current measurements as spacecraft rapidly pass through currents
- Can partially monitor current activity with ground based sensors such as magnetometers and riometers (on Antarctic stations).

- Most LEO weather satellites have retrograde polar orbits (98 degrees) for sun-synchronous





Summary

- Spacecraft operate in a variable radiation environment
- Spacecraft RADHAZ issues are diverse
- Effects depend heavily on the spacecraft design and location
- Space weather support services are still R&D

Australian Government
Bureau of Meteorology

Thank you

Contact details

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