

SPACE WEATHER INTRODUCTORY COURSE



Collaboration of



Solar-Terrestrial Centre of Excellence



Koninklijke luchtmacht



Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu



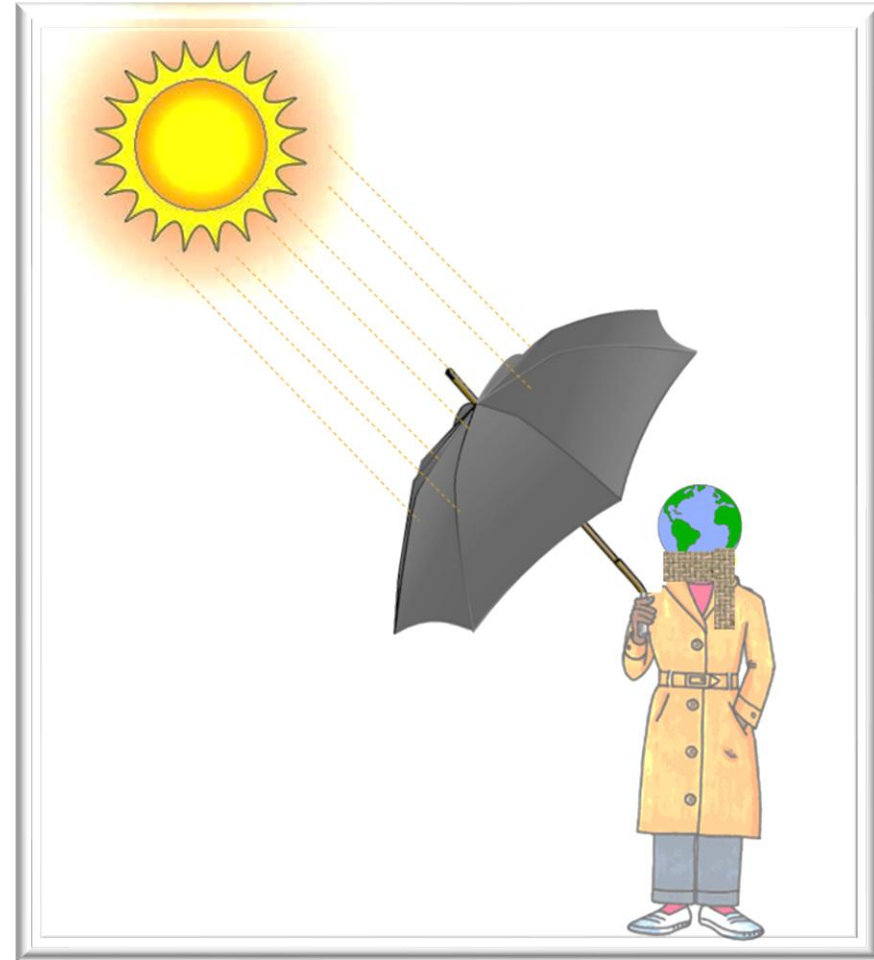
Space weather impacts

Jan Janssens



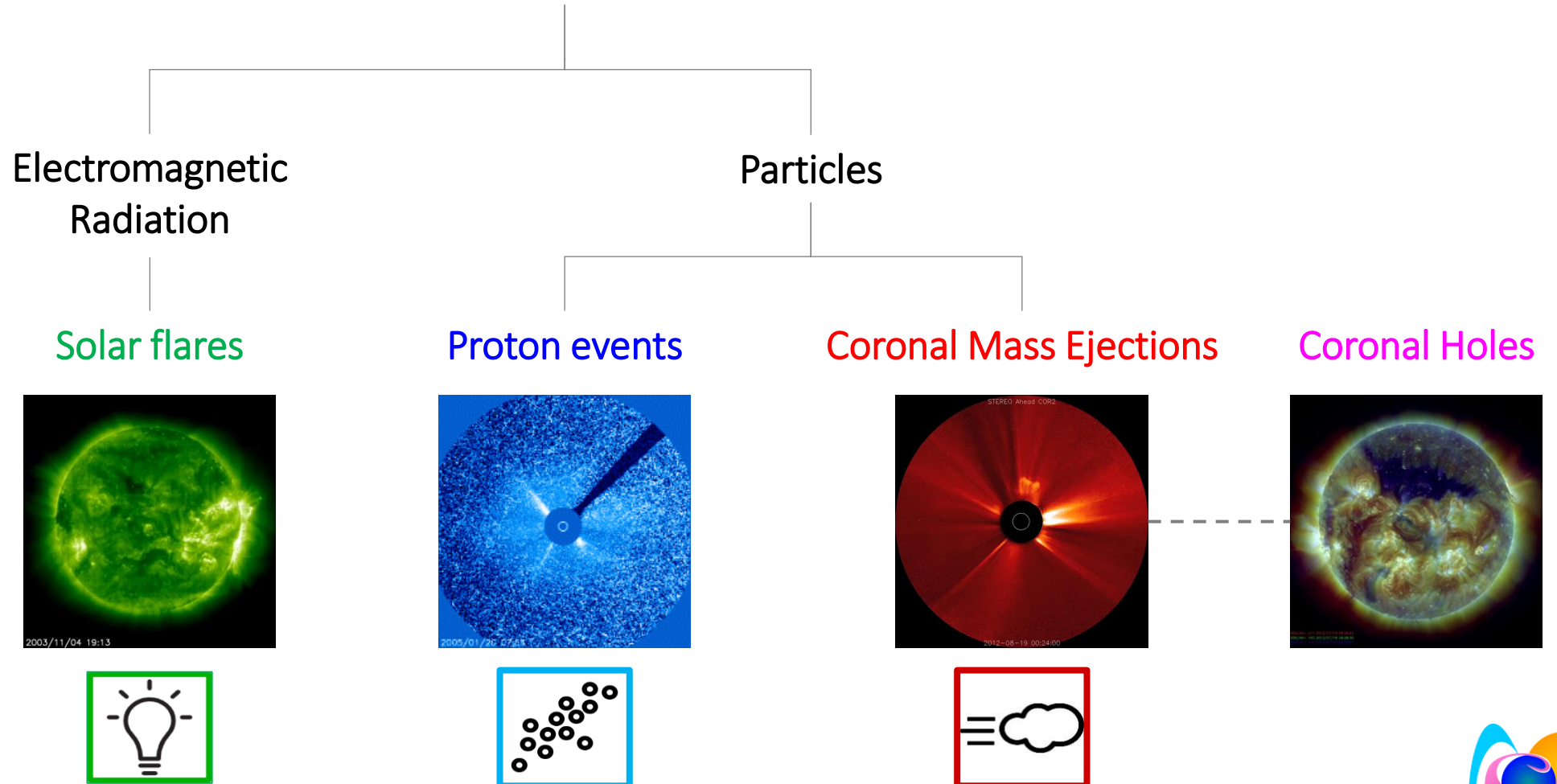
Space Weather impacts (SWx impacts)

- **Recap**
- *SWx impacts from*
 - *Solar flares*
 - *Proton events*
 - *ICMEs*
 - *Coronal holes*



Drivers of disturbed SWx

Solar eruptions

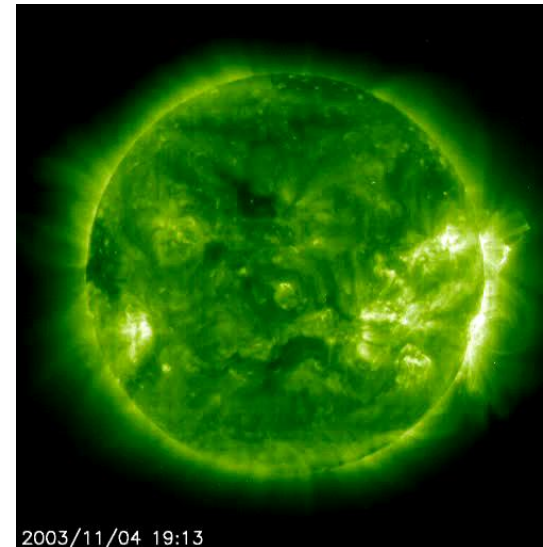




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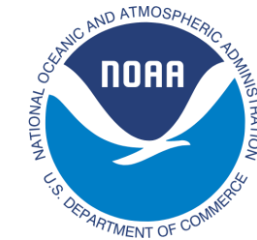
Solar flares





SWx impacts from solar flares

R: Radio blackout => SF: Solar Flare



Scale	Description (Physical)	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
R 5	Extreme	HF Radio: Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. Navigation: Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2×10^{-3})	Less than 1 per cycle
R 4	Severe	HF Radio: HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. Navigation: Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	HF Radio: Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. Navigation: Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	HF Radio: Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. Navigation: Degradation of low-frequency navigation signals for tens of minutes.	M5 (5×10^{-5})	350 per cycle (300 days per cycle)
R 1	Minor	HF Radio: Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. Navigation: Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

The scales are currently considered more as general measurement scales => for specific impacts: consult the experts





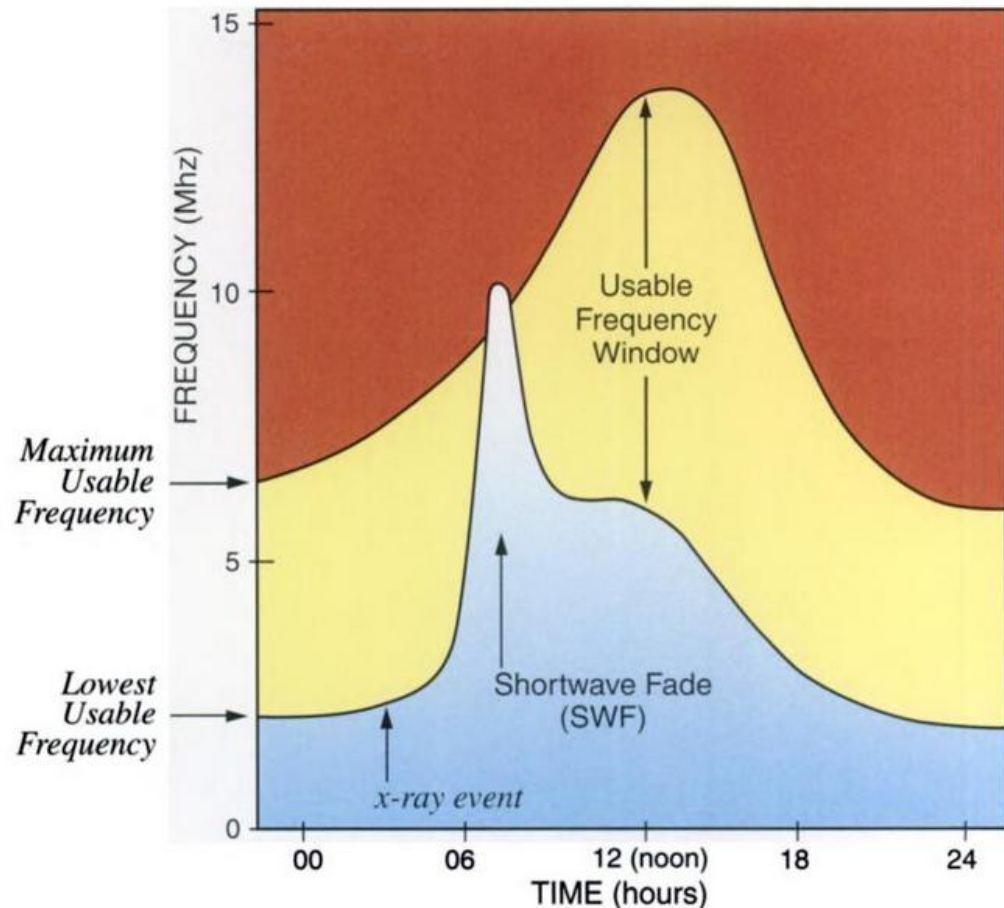
SWx impacts from solar flares

- From EUV & X-ray radiation
 - Solar flare effect (“magnetic crochet”)
 - => Effects from ICMEs
 - Shortwave fade (“Radio Blackout”)
 - => PECASUS
- From radio emission
 - GNSS disturbances
 - Radar disturbances





SWx impacts from solar flares on HFCom



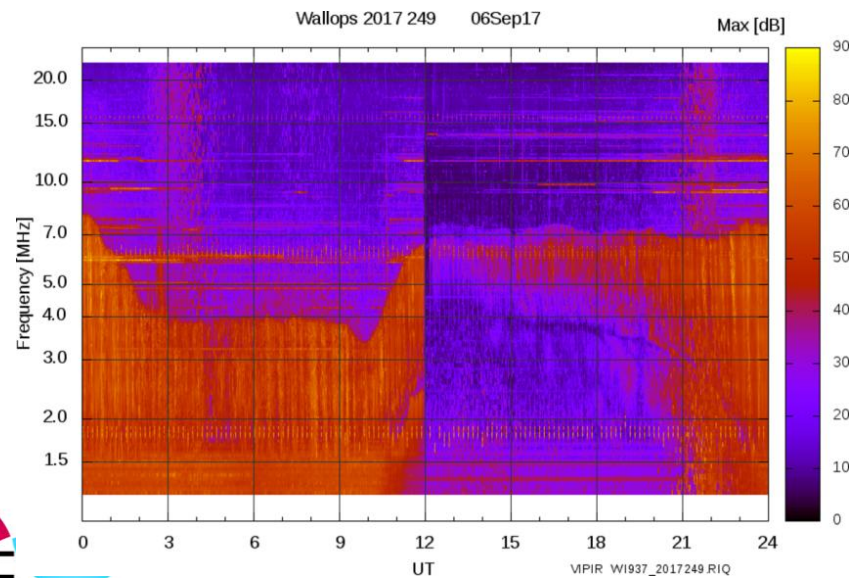
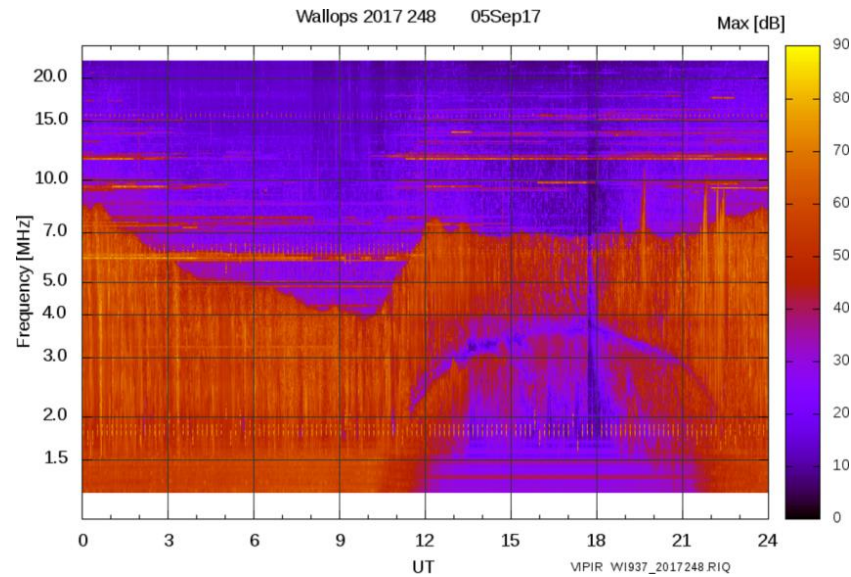
Credits: Poppe et al. (2006)

- Short-wave fade (SWF)
 - Aka “Radio blackout”
 - Misleading term
 - SXR from solar flare
 - Sunlit hemisphere of the Earth
 - Increase ionospheric plasma (D-region)
 - Increase in HF absorption
 - Affects lower frequencies most
 - => Backup systems (SATCom,...)
 - => Difficult to reach locations (polar zones,...) and disaster areas
- Duration depends on
 - Intensity/duration solar flare
 - Frequent, long duration X-class flares!
 - Solar zenith angle
- Advisories for aviation
 - X1/X10 (moderate/severe)



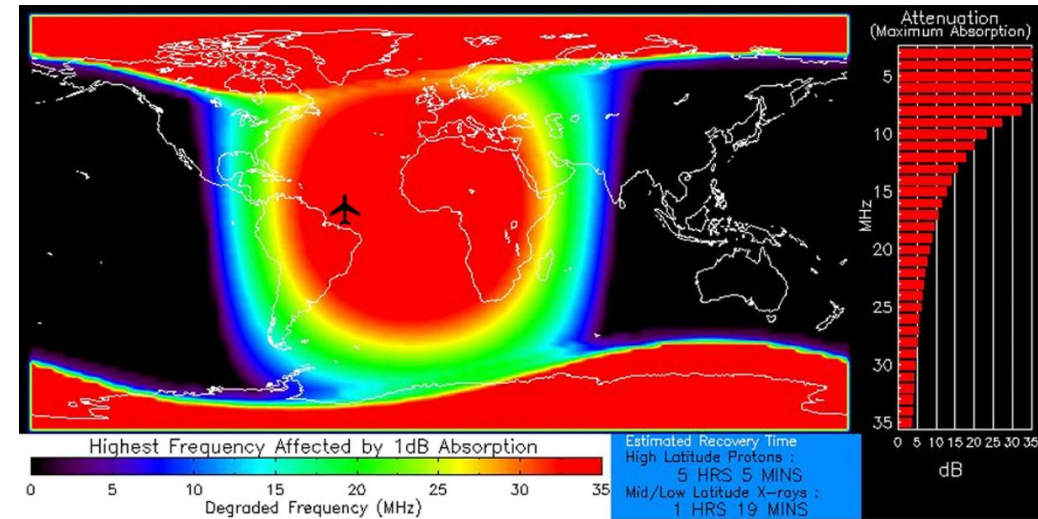


SWx impacts from solar flares on HFCom



Courtesy of CIRES, Terry Bullett

- Short-wave fade (SWF)
- September 2017
 - Several strong solar flares following hurricanes Irma and Jose in Caribbean
 - No HFCom for several hours
 - Contact with 1 cargo plane lost for 1.5h



Strong X-ray flux
Product Valid At : 2017-09-06 12:50 UTC

Minor Proton Flux
NOAA/SWPC Boulder, CO USA





SWx impacts from solar flares on GNSS



- From radio emission
 - 6 Dec 2006: X6.5
 - 1415 MHz: 10^6 sfu
 - Swamped GPS receivers on sunlit side
 - Loss-of-lock
 - GPS outages of several minutes
 - Positioning errors of 20 meters (H) and 60 meters (V)
 - Services impacted
 - WAAS, IGS, Surveying, offshore oil rig positioning, and precision agriculture.

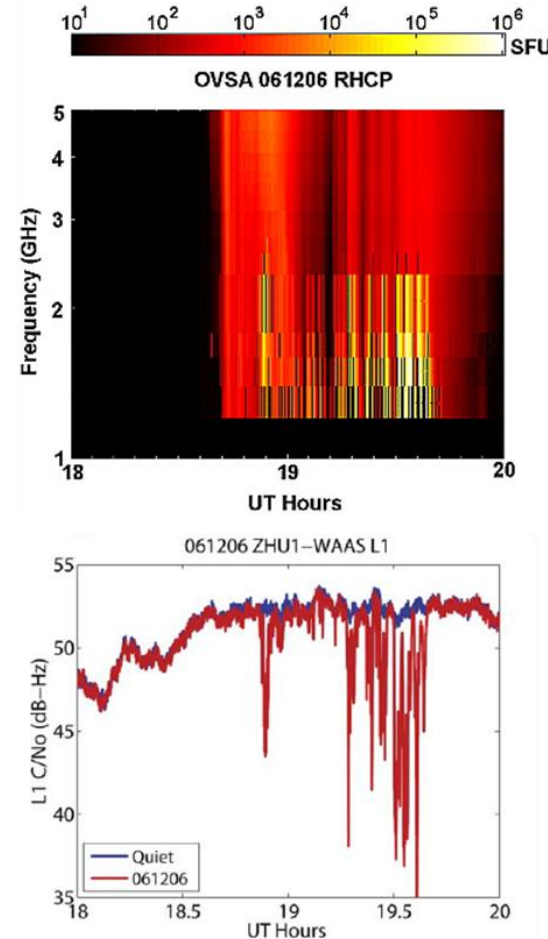


Figure 2. Response of a GPS receiver to the solar radio burst on 6 December 2006. The red line corresponds to C/N_0 on 6 December 2006, and the blue line corresponds to the previous sidereal day.

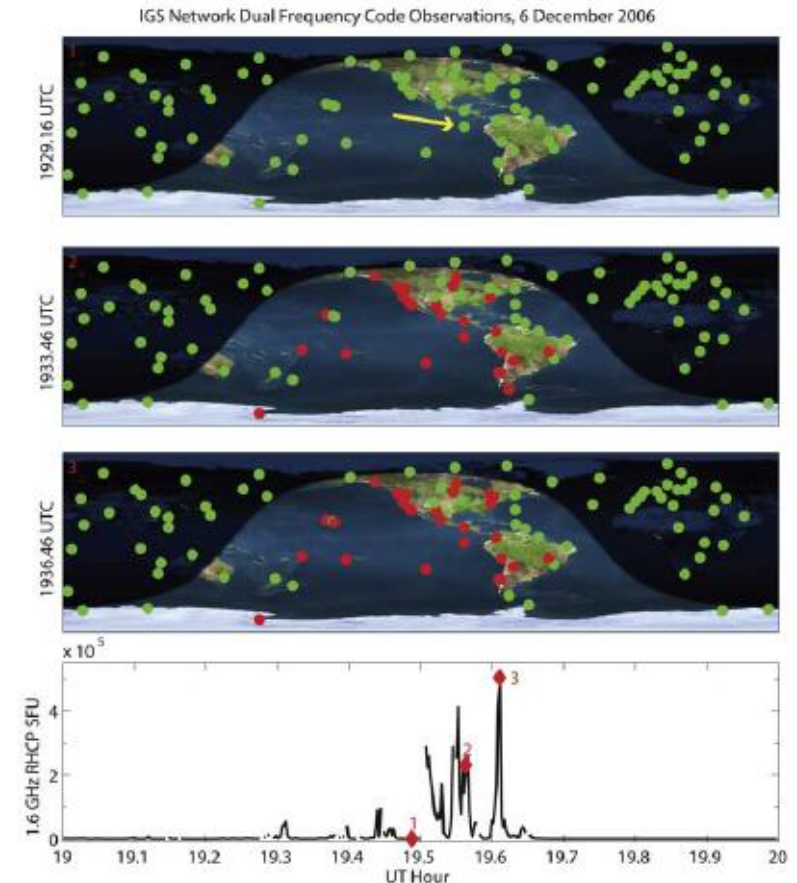


Figure 6. Receivers in the Global GPS Network that were analyzed during the solar radio burst. Green indicates the normal number of satellites being tracked. (fourth panel) During the burst (power at 1.6 GHz), several sunlit receivers tracked fewer than the four satellites needed for a full positioning solution (marked in red). (Image of Earth from the The Living Earth, 1996 and is used here by permission of the publisher. Day/night overlay created using Earth Viewer by J. Walker.)

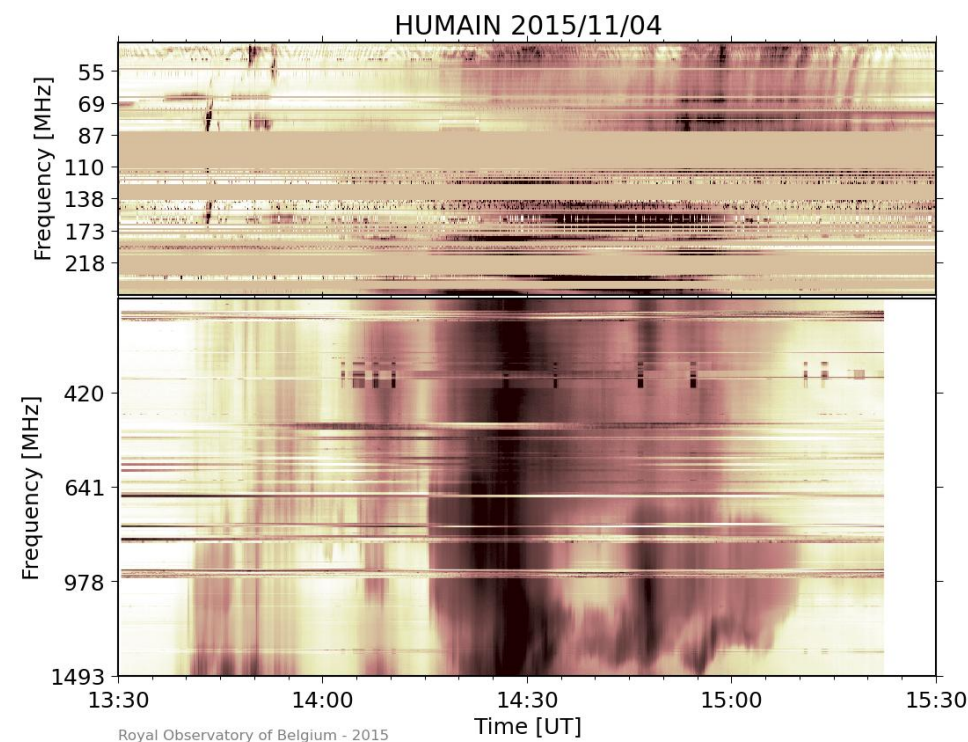
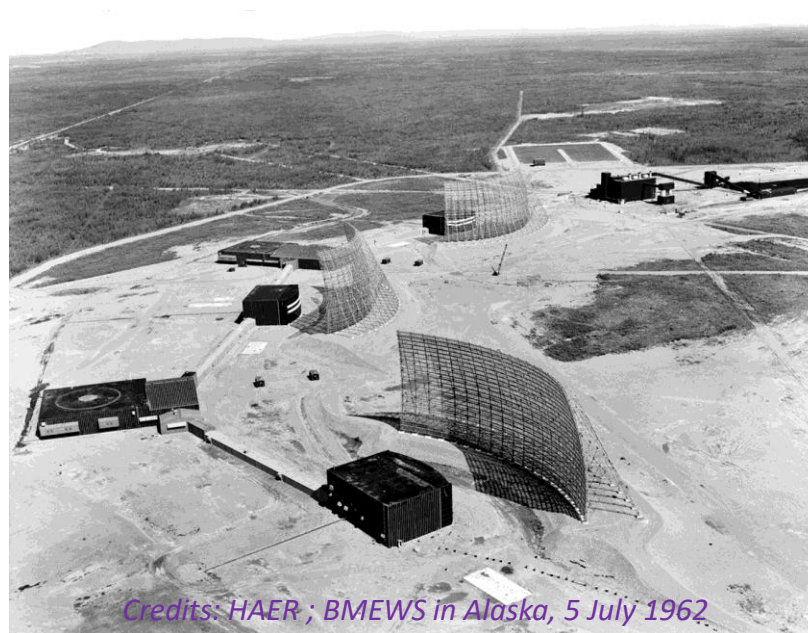
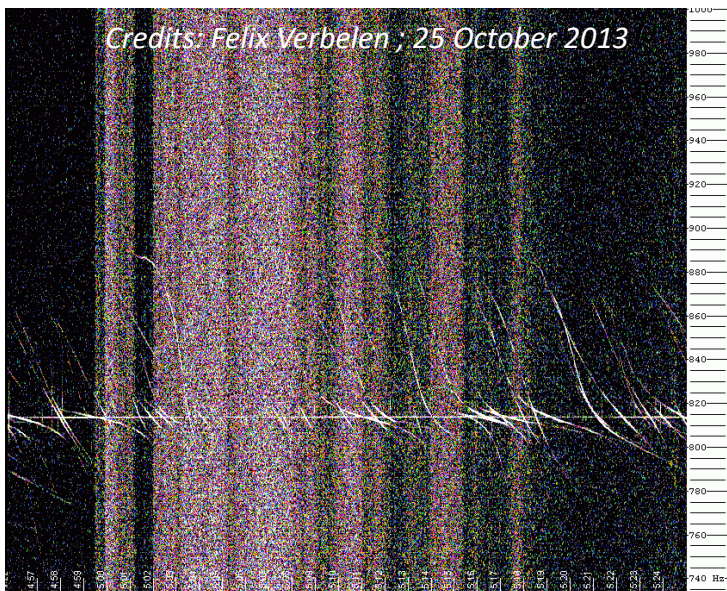
Credits: Cerruti et al. (2008)





SWx impacts from solar flares on Ground Supp

- Radar disturbance
 - 4 November 2015
 - M3 flare paralyzes Swedish air traffic
 - 23 May 1967
 - BMEWS disturbed
- Radio meteors

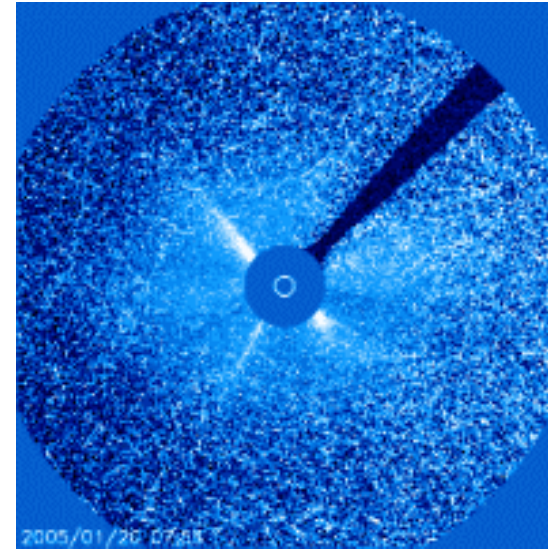




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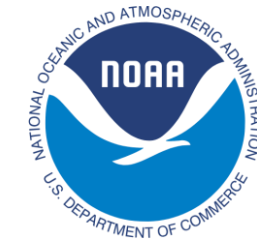
Proton events





SWx impacts from proton events

S: Solar radiation storm => P: Proton event



Scale	Description (Physical)	Effect	Physical measure (Flux level of ≥ 10 MeV particles)	Average Frequency (1 cycle = 11 years)
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	Fewer than 1 per cycle
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	3 per cycle
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	10 per cycle
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	25 per cycle
S 1	Minor	Biological: None. Satellite operations: None. Other systems: Minor impacts on HF radio in the polar regions.	10	50 per cycle

The scales are currently considered more as general measurement scales => for specific impacts: consult the experts





SWx impacts from proton events

- Polar Cap Absorption (PCA)
 - => PECASUS
- Radiation
 - Astronauts, Polar flights
 - => PECASUS
- Satellites
 - Star trackers
 - Solar arrays
 - Single Event Effects (SEE)
- Ground Level Enhancement (GLE)

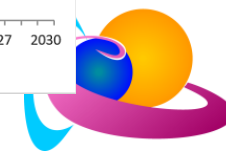
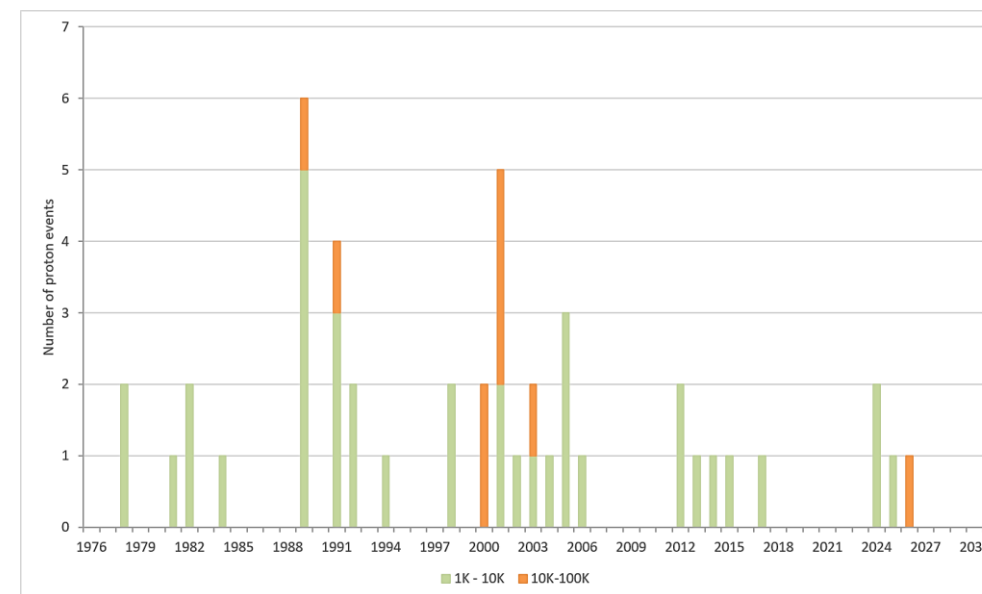
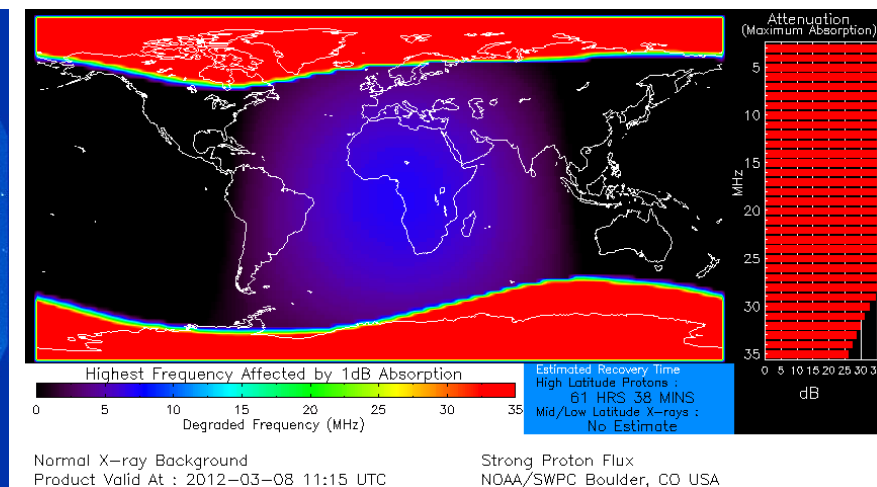
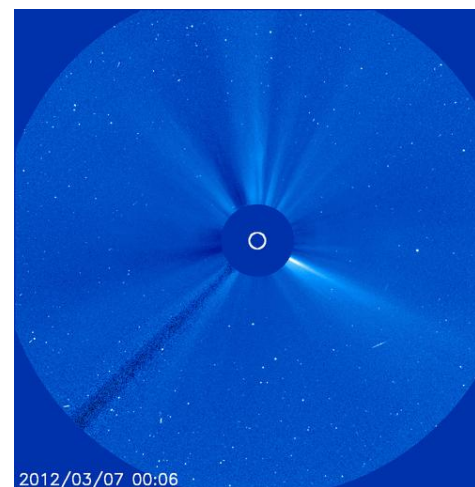




SWx impacts from proton events on HF Com



- Polar Cap Absorption (PCA)
 - From 10 MeV proton flux
 - Deviated by MF to poles
 - Affects lower ionosphere
 - Impacts HF Com at poles
 - Can last for days
- Polar flight detours
 - E.g. 7-8 March 2012
- Frequency
 - Proton events:
 - Strong: 8 per solar cycle
 - Severe: 2 per solar cycle





SWx impacts from proton events on HF Com



- The disappearance of the HMS Acheron (1956)

Amsterdam Evening Recorder
AND DAILY DEMOCRAT

Net Paid Circulation Over 18,350

Weather: Milder, Snow or Sleet

Vol. LXXVII, No. 158 Recorder Established 1893—Democrat Established 1870 Consolidated 1898 Amsterdam, N.Y., Friday, February 24, 1956 Full Associated-Press Report by Leased Wire Official City and County Paper 7 CENTS Per Single Copy 40c Weekly by Carrier

Critics Demand Dulles Explain Policy

WASHINGTON (AP)—The State Department today announced that Secretary of State George Marshall would go on the radio tonight to explain his most recent statement on the Russian satellite states.

Ousted Soviet Premier Draws Search Called Off

LONDON (AP)—The Admiralty today called off a search for the British submarine Acheron, sighted safe in gale-swept seas after being feared lost for nearly six hours.

Missing British Sub Feared Lost, Safe; Search Called Off

Acheron sighted in Gale-Swept Arctic Sea by Minesweeper; Failure of Communications System Made Contact With Admiralty Impossible; Was Unreported Since Wednesday When It Made Trial Dive

5 Die, 100 Hurt In Derailment Of P.R.R. Train

Seven Coaches Jump Rails With Train Speeding at 80 Miles Per Hour; Cause Of Accident Unknown

ODENTON, Md. (AP)—Seven cars of a Pennsylvania Railroad passenger train, racing at 80 m.p.h. through the flat countryside between Washington and Baltimore, jumped the track last night and three overturned down an embankment. Five persons were killed and more than 100 injured.

3d Dixie Party Urged in Fight On Integration

SHREVEPORT, La. (AP)—Georgia Gov. Marvin Griffin called last night for an all-out war against both major political parties, charging they "are trying to keep the Negro out of the white man's house."

16 Aboard Safe

MIAMI, Fla. (AP)—The Coast Guard today announced that 16 persons were rescued from a sinking ship off the Florida coast.

State Agencies

WASHINGTON (AP)—Senate Democratic and Republican leaders disclosed today they were working on a bill to put more teeth in the Federal Bureau of Investigation.

Due to this, one million tons extra in conventional terms of fuel are consumed annually at high pressure electric stations alone.

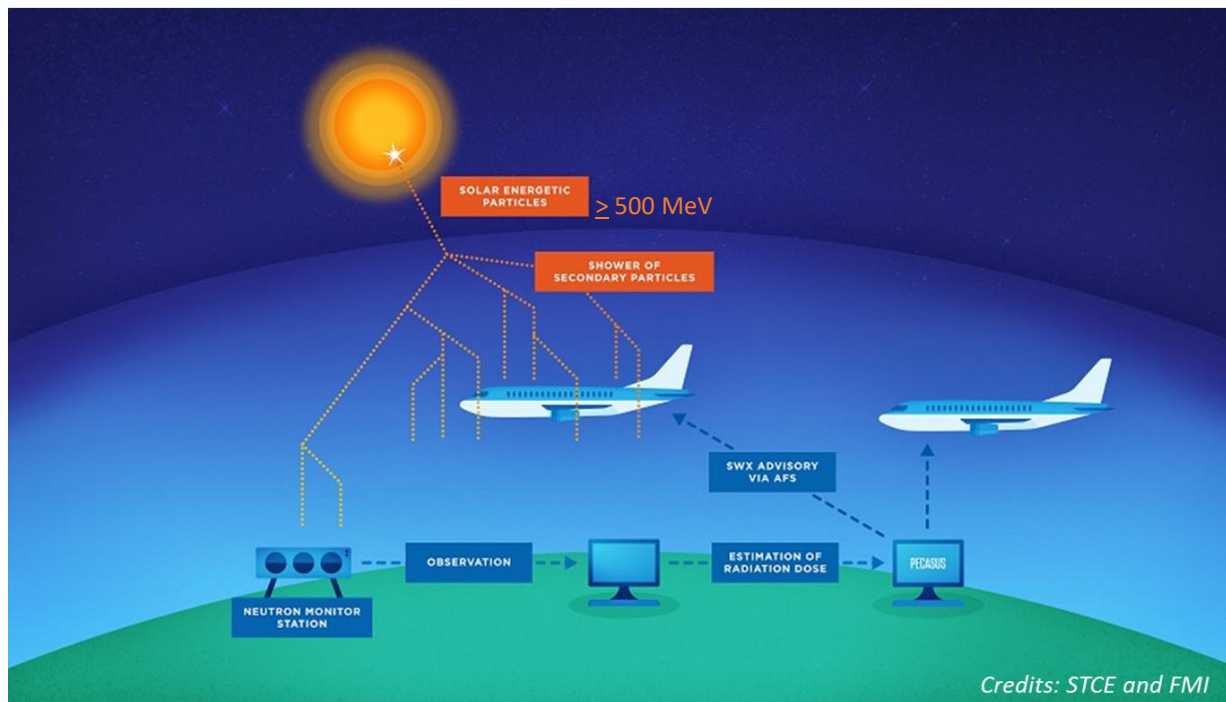




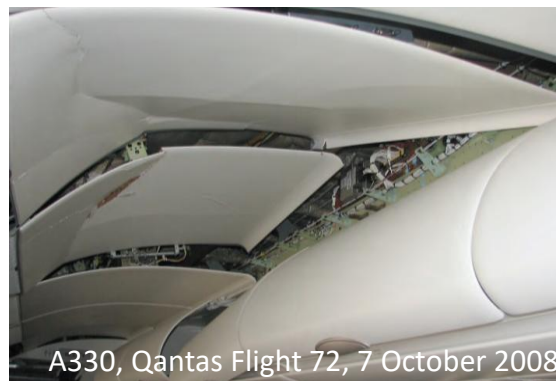
SWx impacts from proton events : Electronics



- Ground Level Enhancement (GLE)
 - Sharp increase #neutrons @ ground
 - Main source
 - Strong SEPs ~ 500 MeV per nucleon
 - $\Rightarrow$ RARE!! (about 1 per year)
 - Impacts
 - Computer glitches, servers,...
 - Pacemakers, defibrillators, and other medical devices,...
 - Difficult to prove connection!
 - Jetblue Airways Flight 1230 (A320) on 30 October 2025



<https://www.stce.be/news/797/welcome.html>



A330, Qantas Flight 72, 7 October 2008



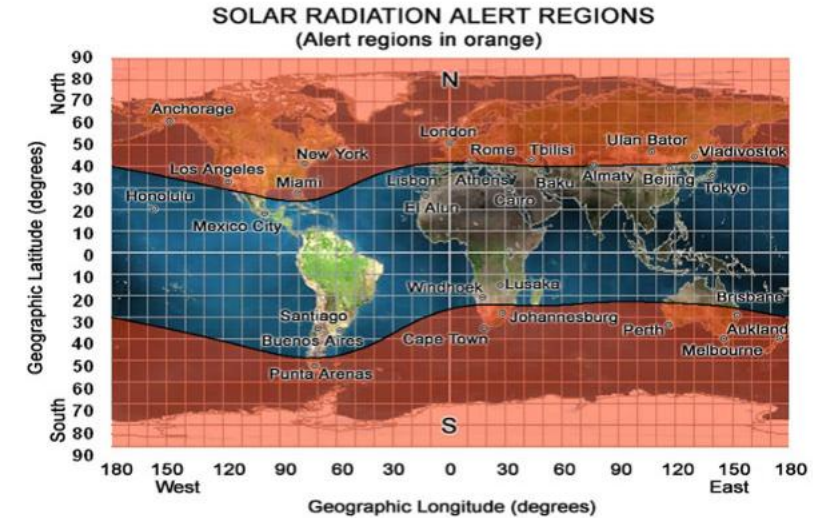
21 Credits: Don-vip



SWx impacts from proton events : Biological



- Energetic particles
 - Galactic Cosmic Rays (GCR)
 - South Atlantic Anomaly (SAA)
 - Solar Energetic Particles (SEP)
 - Can damage DNA and cause cancer & reproductive problems
- Radiation dose
 - $\mu\text{Sv/h}$, mSv/year
 - ICAO thresholds for civil aviation
- Mitigation polar flights
 - Halloween storms October 2003
 - Severe storm (29.500 pfu) + GLE (3!)
 - Decrease altitude
 - Reroute (away from poles)
- Mitigation astronauts
 - Oct 1989, Jul 2000, Oct 2003, Jan 2005,...
 - Shelter in more shielded parts of ISS
 - No space walks



Space Weather Message Code: ALTPAV Issue Time: 2003 Oct 28 2123 UTC
 ALERT: Solar Radiation Alert at Flight Altitudes
 Conditions Began: 2003 Oct 28 2113 UTC

Comment:
 Satellite measurements indicate unusually high levels of ionizing radiation, coming from the sun. This may lead to excessive radiation doses to air travelers at Corrected Geomagnetic (CGM) Latitudes above 35 degrees north, or south.

Avoiding excessive radiation exposure during pregnancy is particularly important.

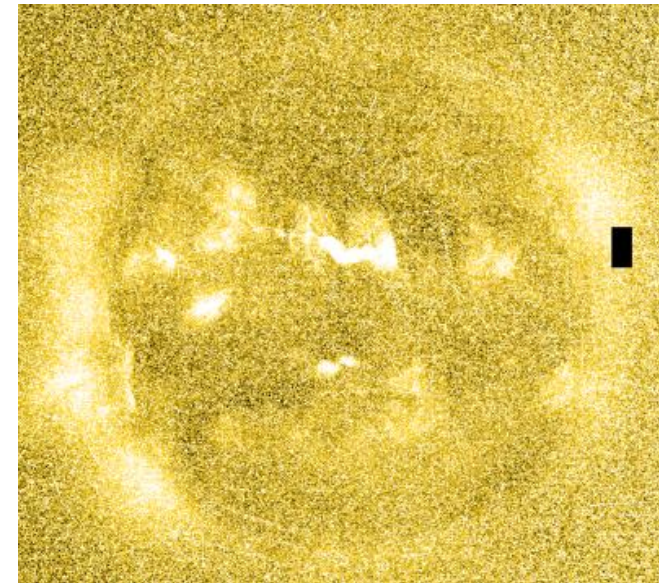
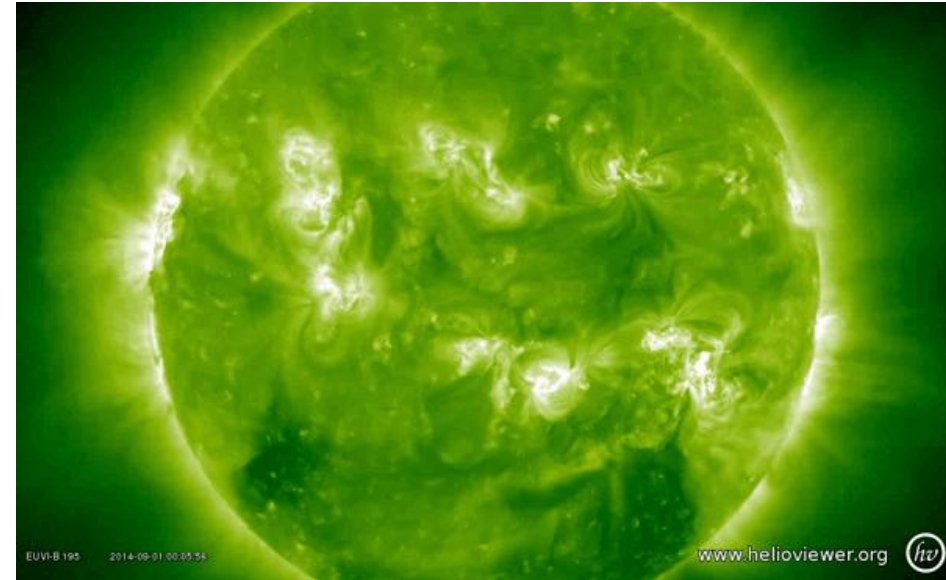
Reducing flight altitude may significantly reduce flight doses. Available data indicates that lowering flight altitude from 40,000 feet to 36,000 feet should result in about a 30 percent reduction in dose rate. A lowering of latitude may also reduce flight doses but the degree is uncertain. Any changes in flight plan should be preceded by appropriate clearance.





SWx impacts from **proton events** : Satellites

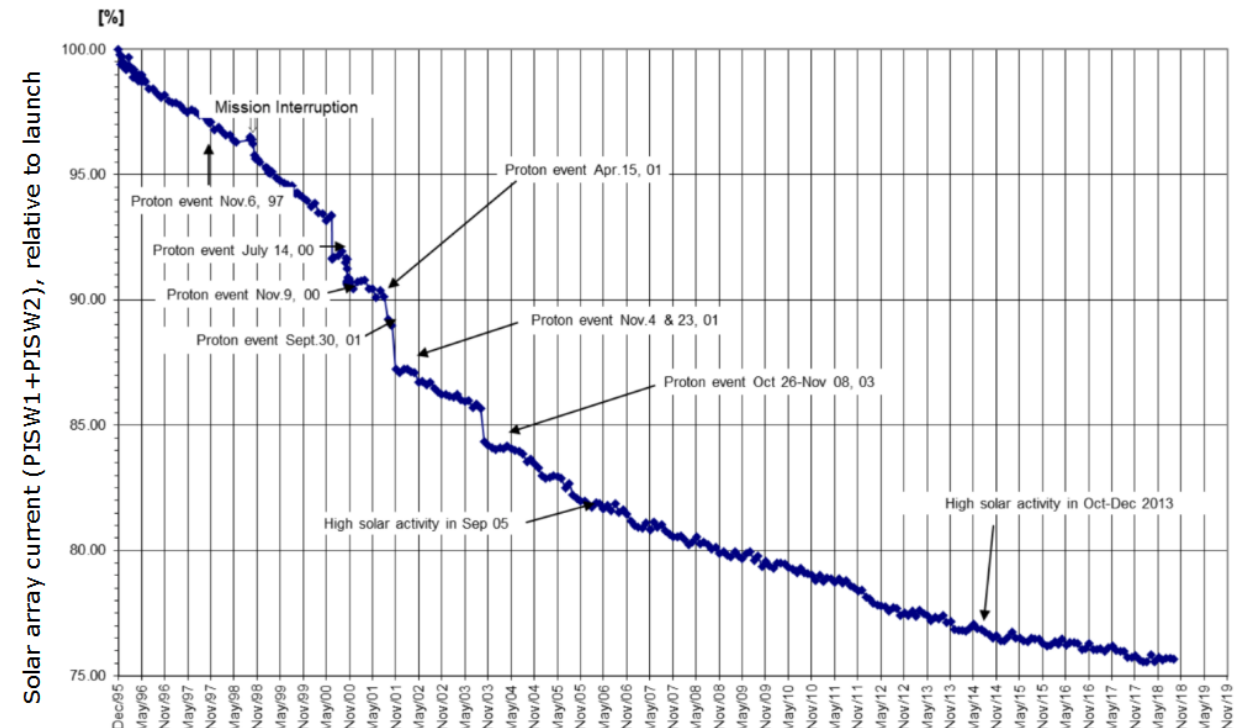
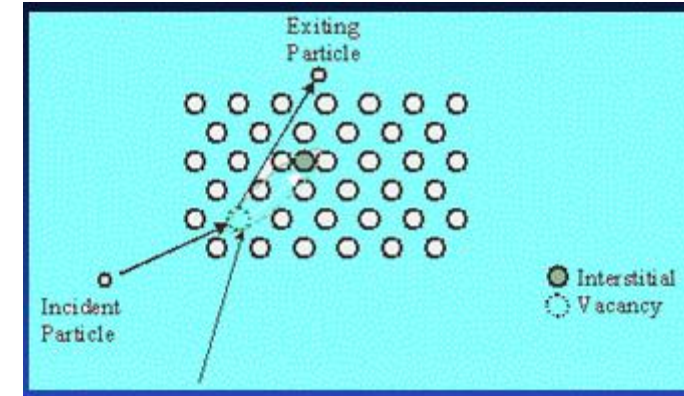
- Satellites
 - Star trackers
 - Spacecraft orientation
 - Photonics noise due to proton « impacts »
 - True stars?
 - Misorientation
 - Solar panels oriented away from the Sun
 - No energy
 - Science & Data loss
 - Gravity Probe-B
 - Coronagraphs





SWx impacts from proton events : Satellites

- Satellites
 - Solar Arrays
 - Displacement damage
 - Reduces efficiency in electricity production
 - Several % loss from one proton event is possible
 - 2% loss during Bastille Day event (14 July 00)
 - 5% loss during extreme 4 August 1972 event
 - Overall aging process of satellite and its instruments





SWx impacts from **proton events** : Satellites

- Satellites
 - Single Event Effect (SEE)
 - Direct hit of an electronic component by an energetic particle resulting in an anomaly
 - Several variations
 - SEU (bit flip), SEL, SEB,...
 - Sources
 - Galactic Cosmic Rays (GCR)
 - [DSCOVER](#)
 - Solar proton storms
 - Radiation belts

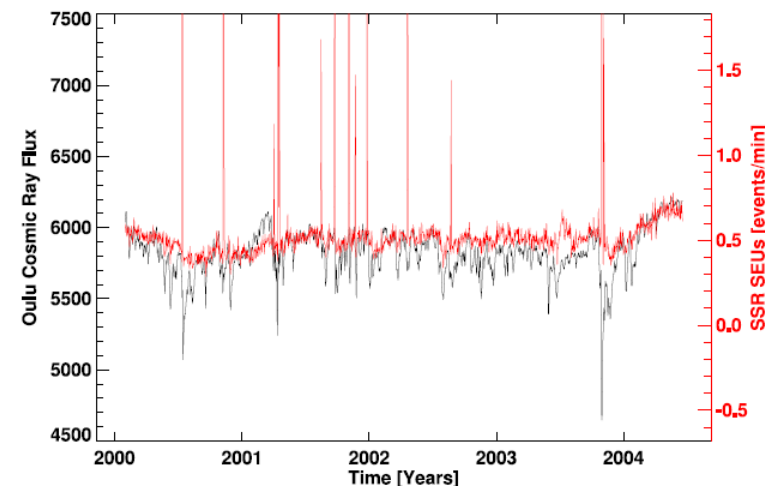
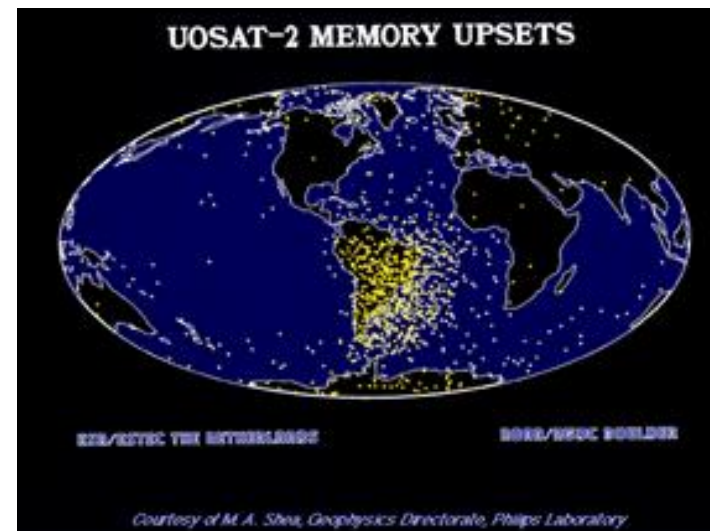
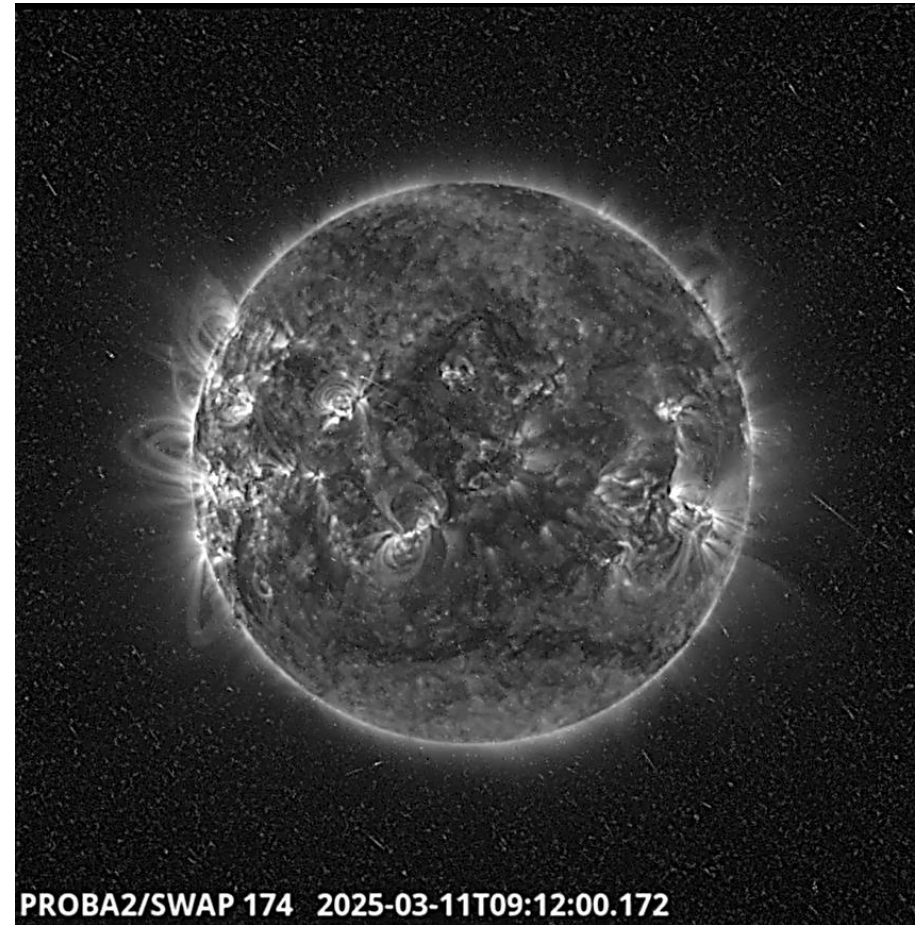
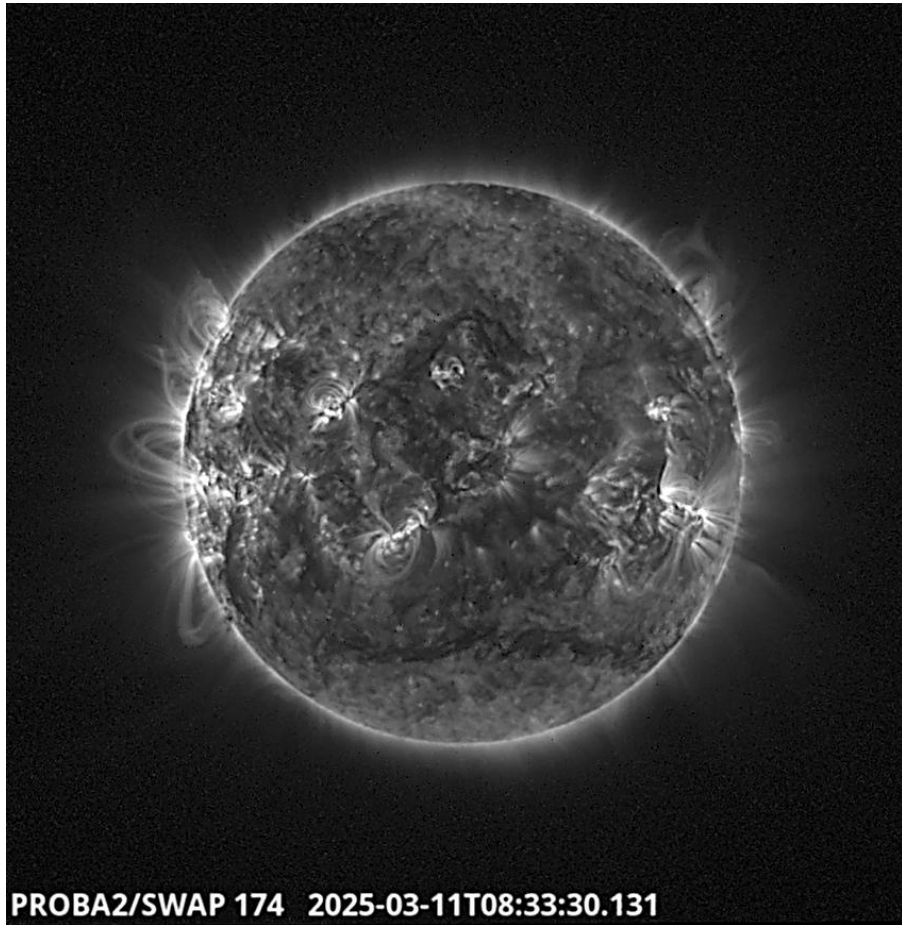
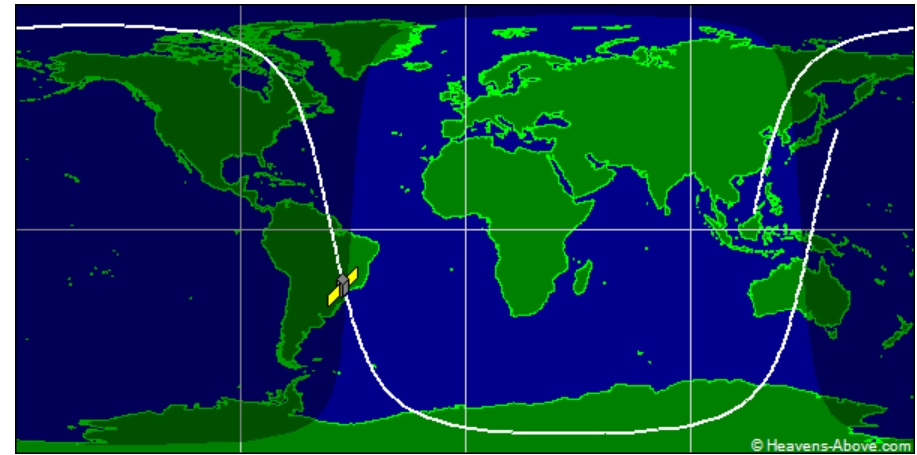
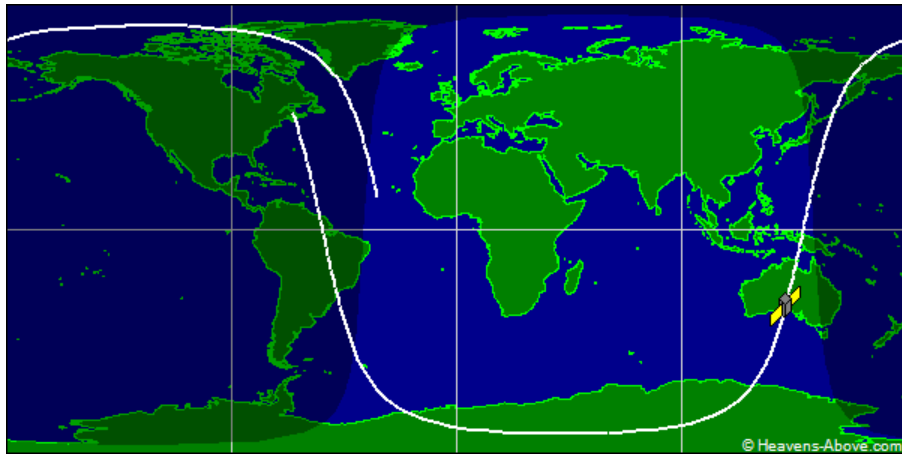


Figure 3: Subset of the data in Fig. 1 during solar maximum. The plot shows a dozen sharp spikes on top of the solar-cycle-modulated background of SSR SEUs triggered by cosmic ray hits. These spikes are caused by isolated strong SEP events. Most of them coincide with a CRF down spike.



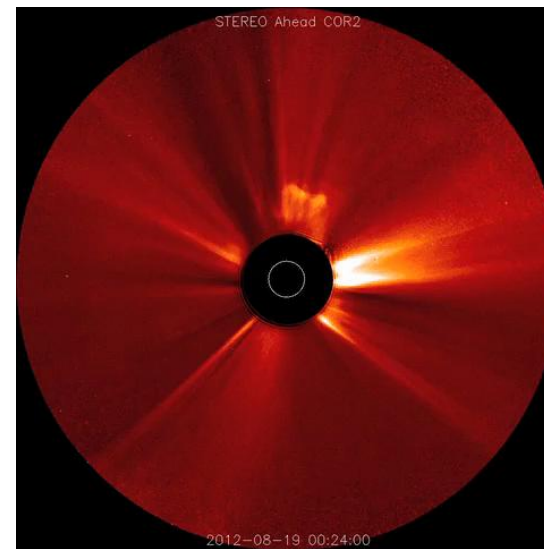




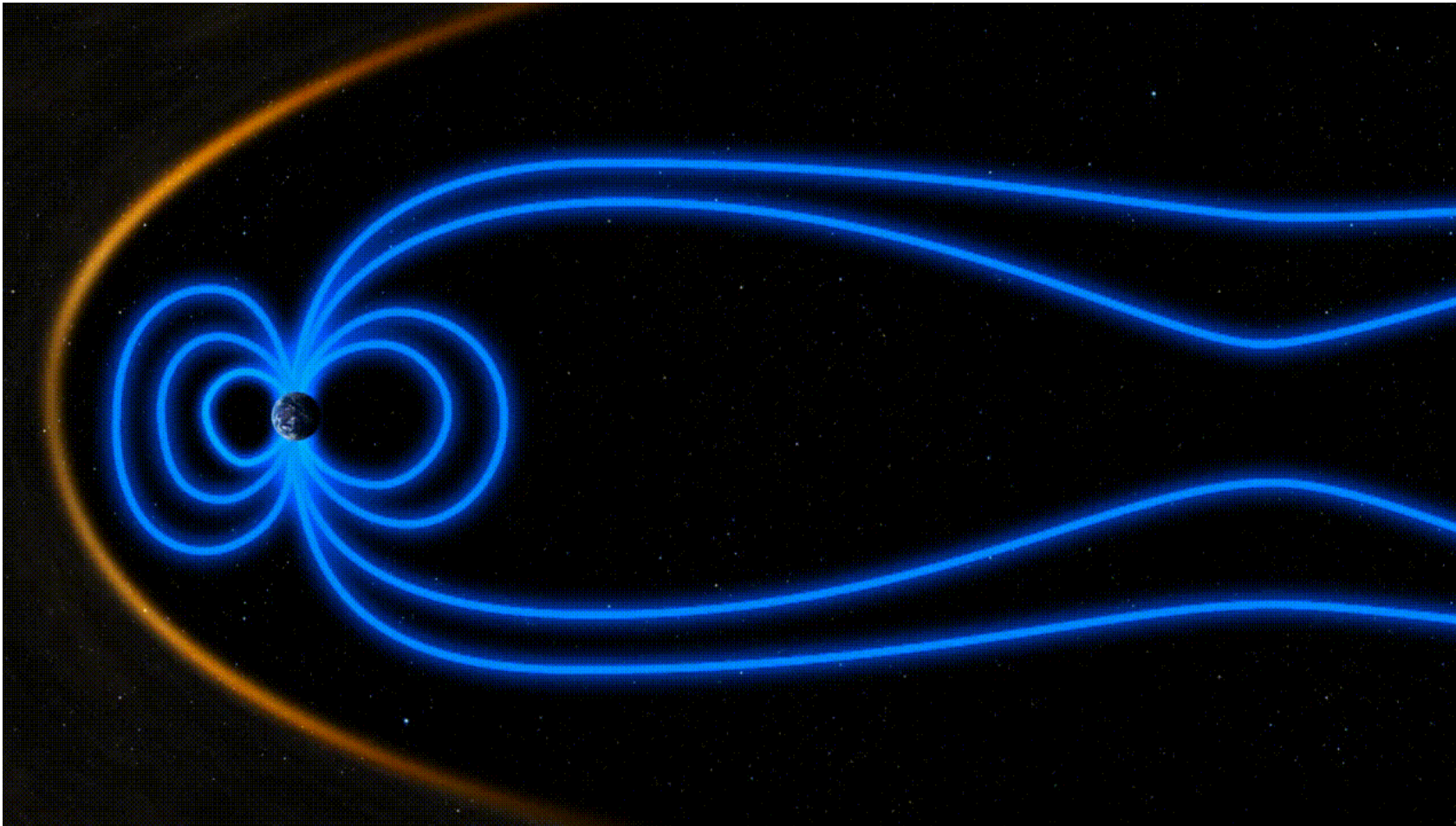
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Coronal Mass Ejections



SWx impacts from ICMEs



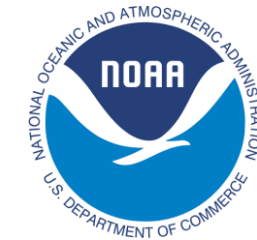
Credits: ESA





SWx impacts from ICMEs

G: Geomagnetic storm



Scale	Description (Physical)	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	Power systems: Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: May experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: Voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: Weak power grid fluctuations can occur. Spacecraft operations: Minor impact on satellite operations possible. Other systems: Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)



SWx impacts from ICMEs

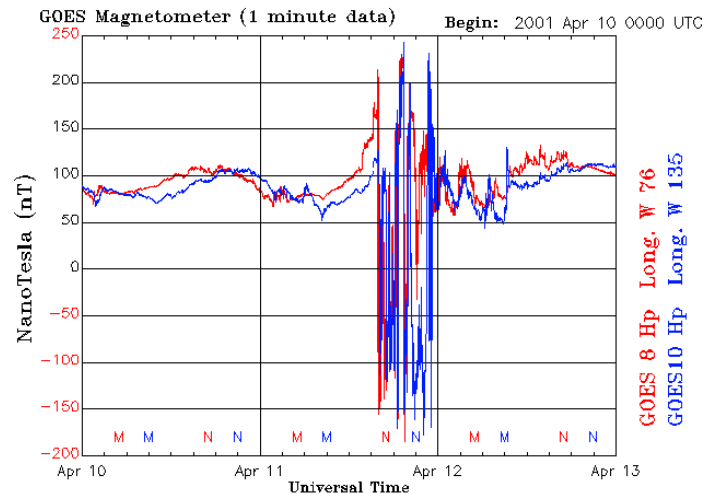
- From magnetic field
 - Satellites
 - Magnetopause crossings
 - High-Precision industry
 - GCR: Forbush decrease
- From particles
 - Aurora
 - Satellites
 - Drag
 - Charging effects
 - Satellite-based Comms/Nav applications (GNSS)
 - => PECASUS
 - HF Communication (aviation)
 - => PECASUS
 - Geomagnetically Induced Currents (GIC)



SWx impacts from ICMEs



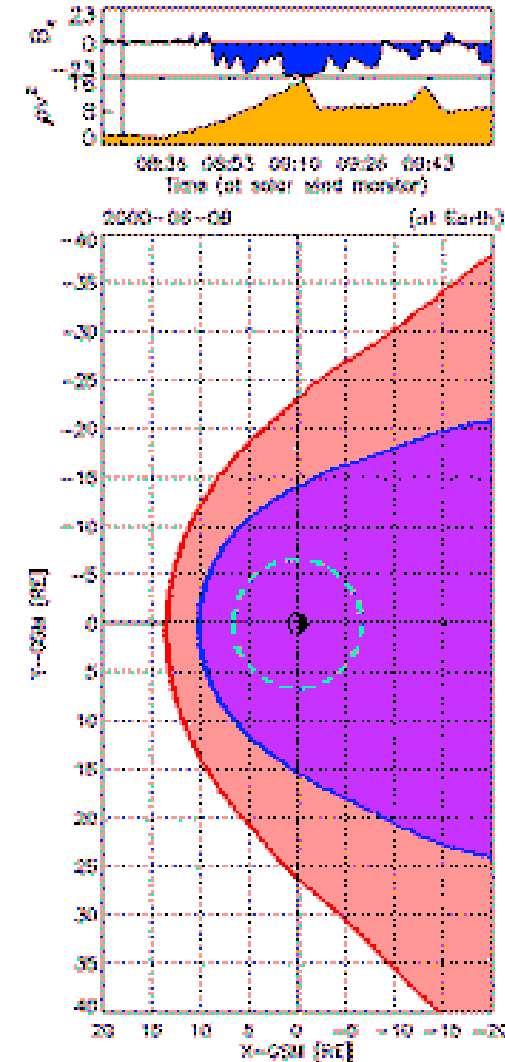
- Satellites
 - Magnetopause crossings
 - CME pushes magnetopause inside GEO
 - Satellites directly exposed to solar wind
 - Orientation problem



Updated 2001 Apr 12 23:59:04 UTC

NOAA/SEC Boulder, CO USA

GEO: geostationary (equatorial) orbit

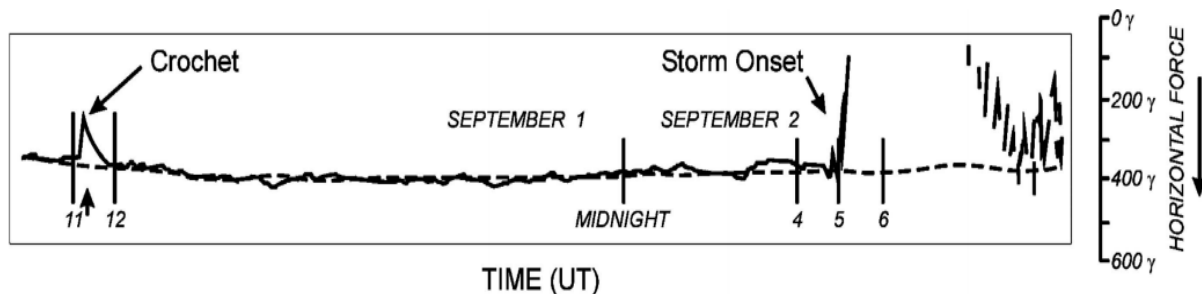


SWx impacts from ICMEs

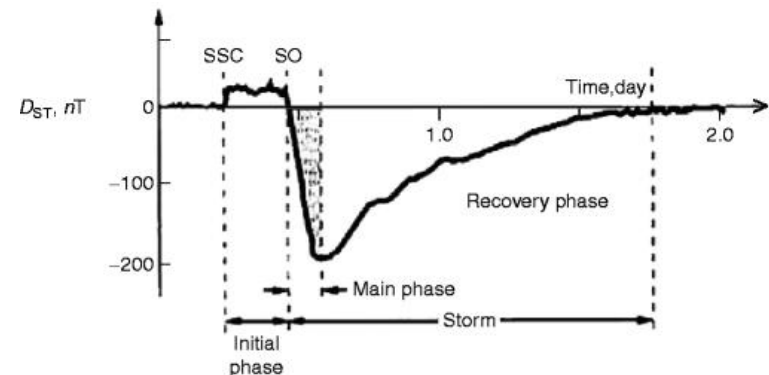
Rapid geomagnetic variations



- Solar flare effect (SFE)
 - Aka “magnetic crochet”
 - Source
 - Strong solar flare
 - H α : 2B (30%)
 - X-ray: X1 (50%)
 - f(local time & latitude)
 - Examples
 - 4 Nov 2003: + 115nT
 - 1 Sep 1859: + 110nT



- Storm Sudden Commencement (SSC)
 - Sudden impulse (SI)
 - = no geomagnetic storm
 - Source
 - Dayside compression by strong ICME
 - Global, but f(local sit.)
 - Max. Amplitude: +/- 300 nT
 - 10-11 May 2024: 108 nT



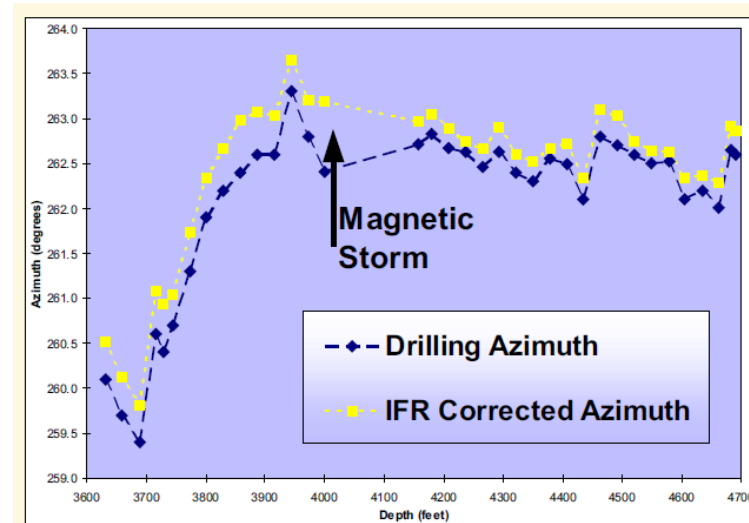


SWx impacts from ICMEs

Rapid geomagnetic variations

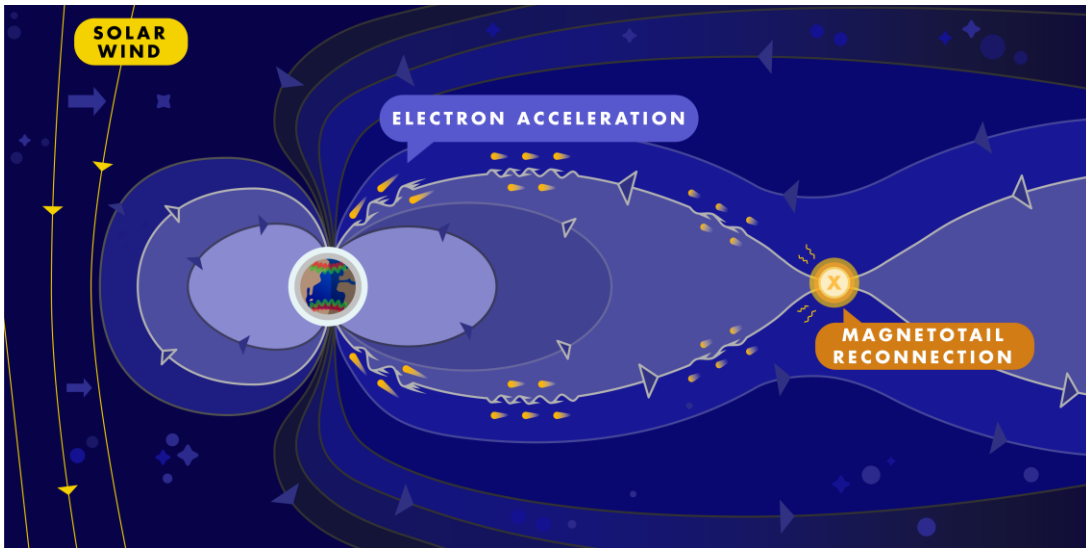


- High-precision industry
 - Industries depending on amplitude of magnetic field
 - magnetic anomaly surveys
 - directional wellbore drilling
- Performance degradation
 - Mitigation possible
- 4 August 1972
 - Vietnam: sea mine detonation
- 10-11 May 2024
 - ONC – Ocean Networks Canada
 - Deep-sea compasses activated

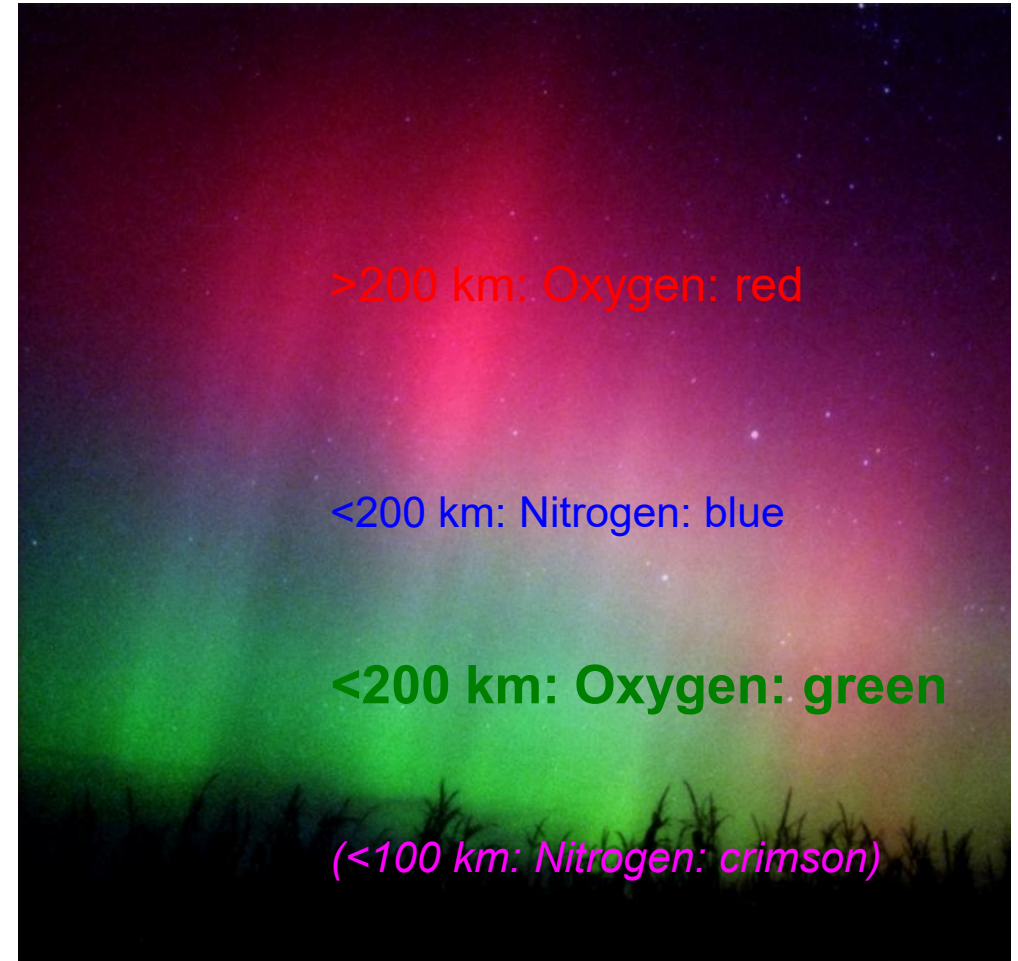


SWx impacts from ICMs

- Aurora



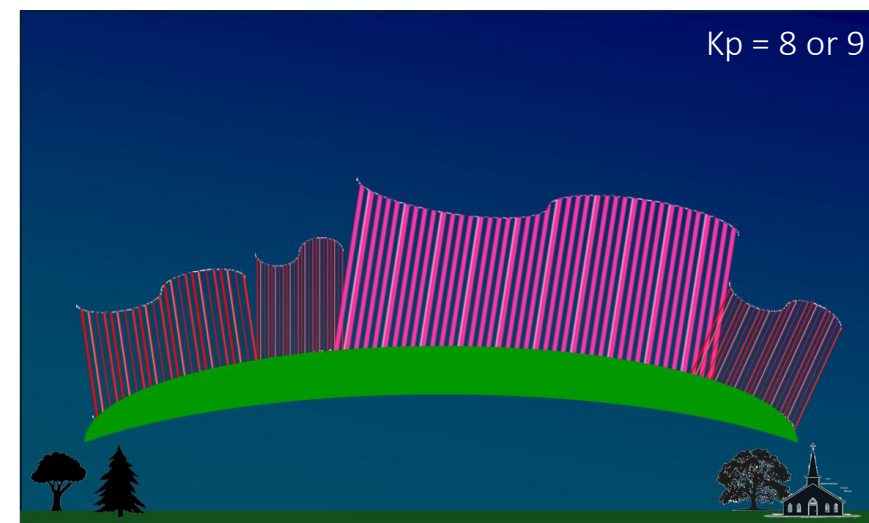
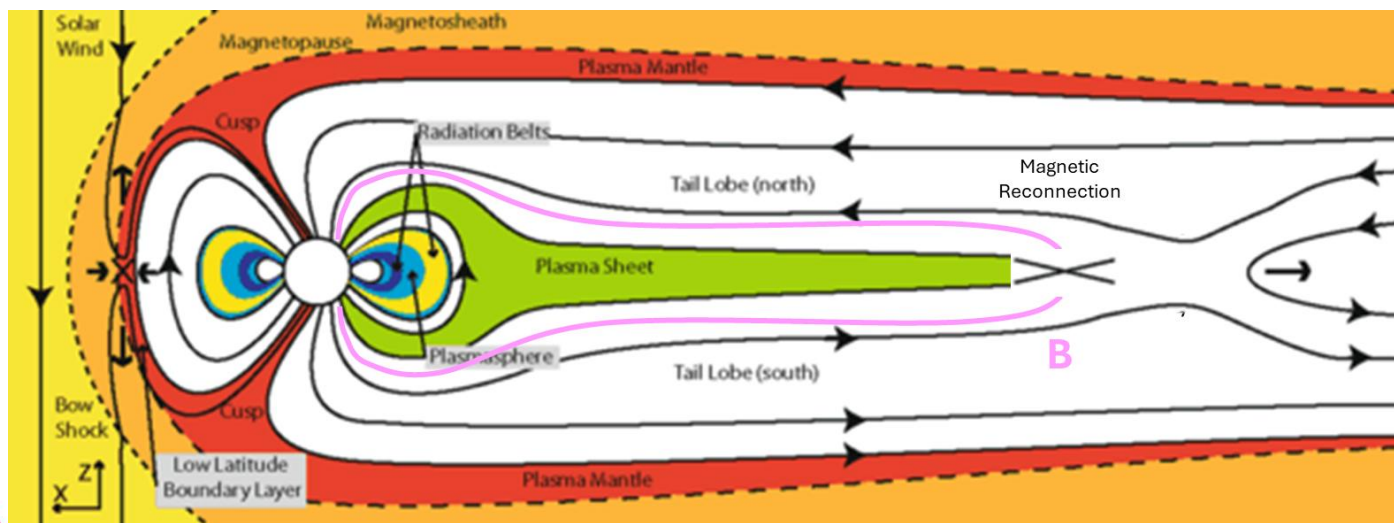
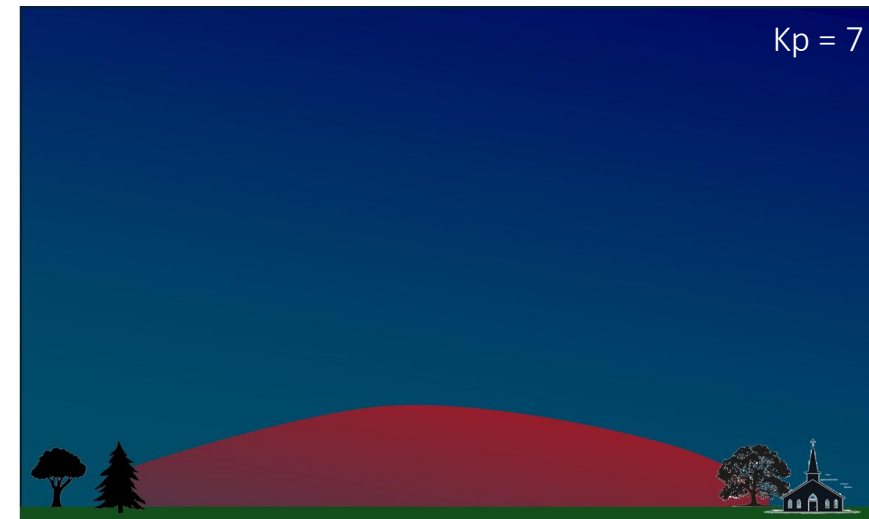
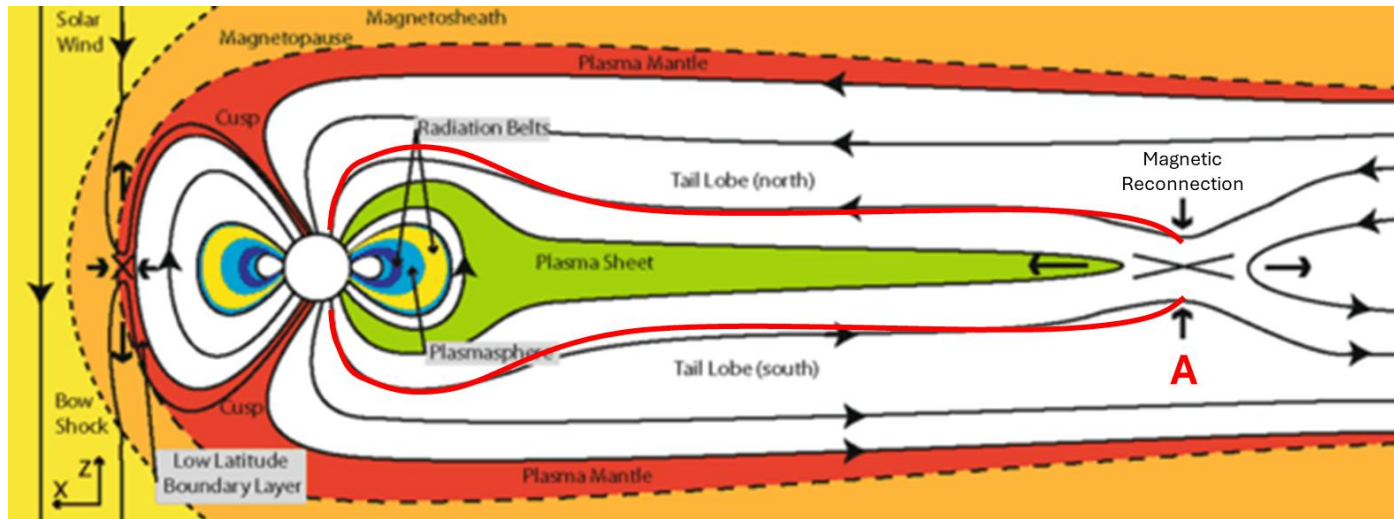
© G. G. Howes, University of Iowa, 2021



© G. Gonzales, Iowa State University, Oct 2003



SWx impacts from ICMEs





SWx impacts from ICMEs

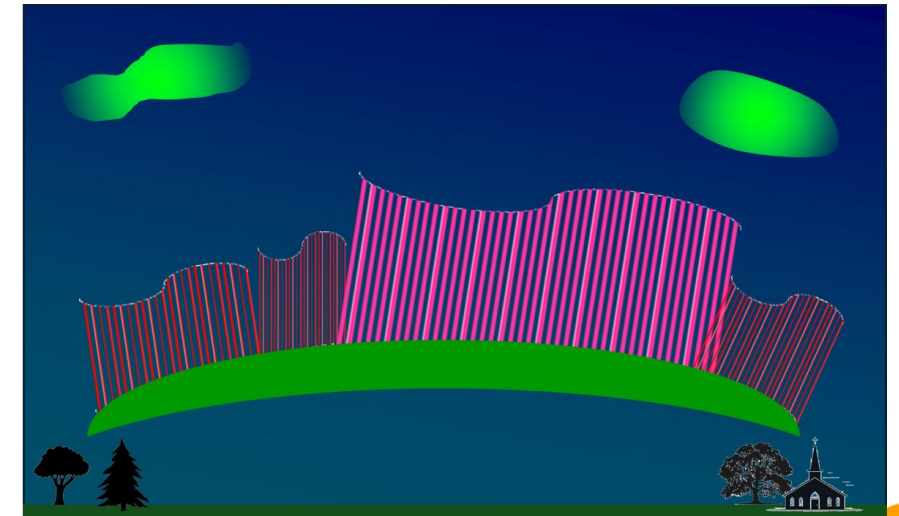
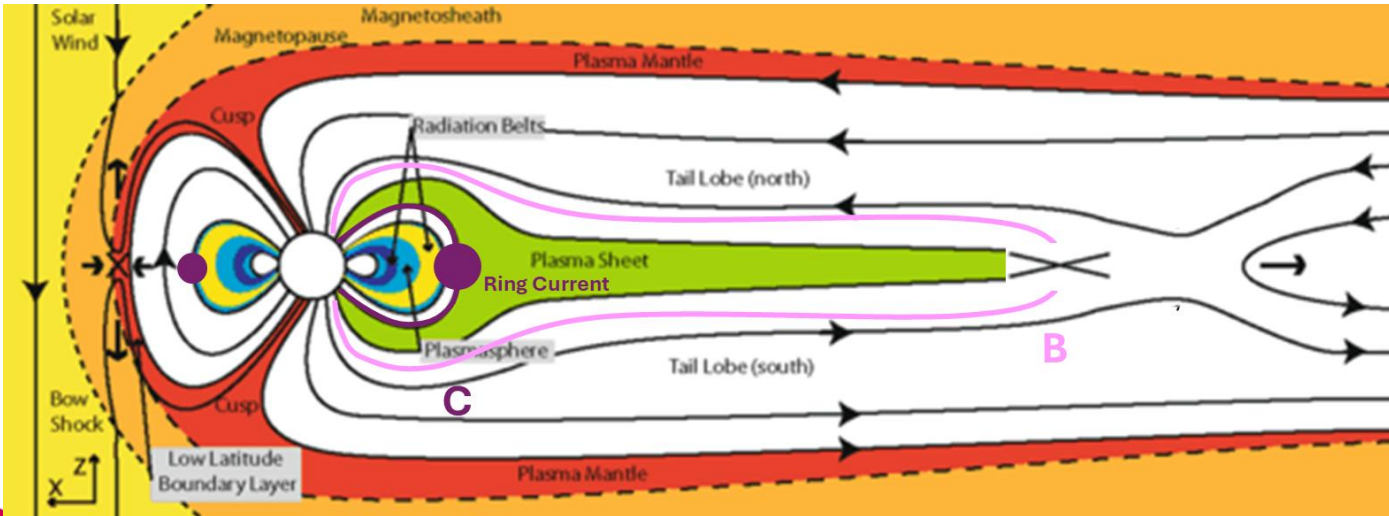
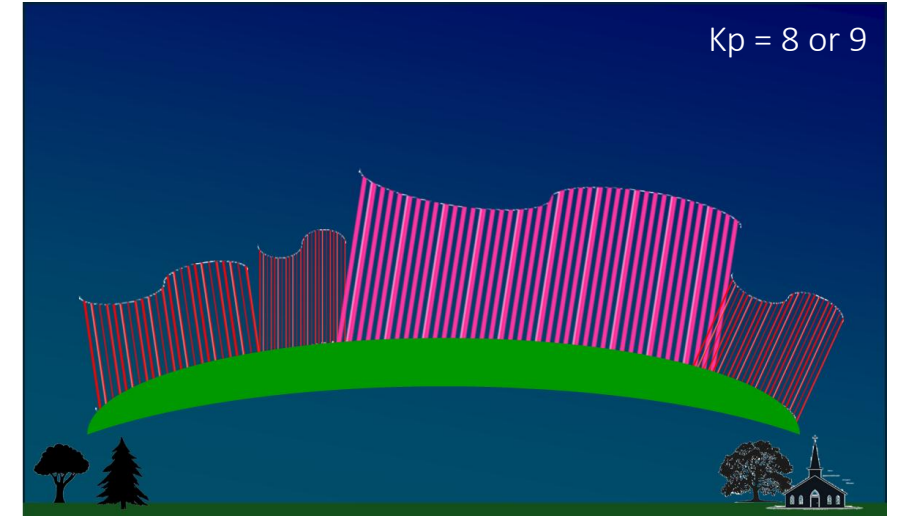
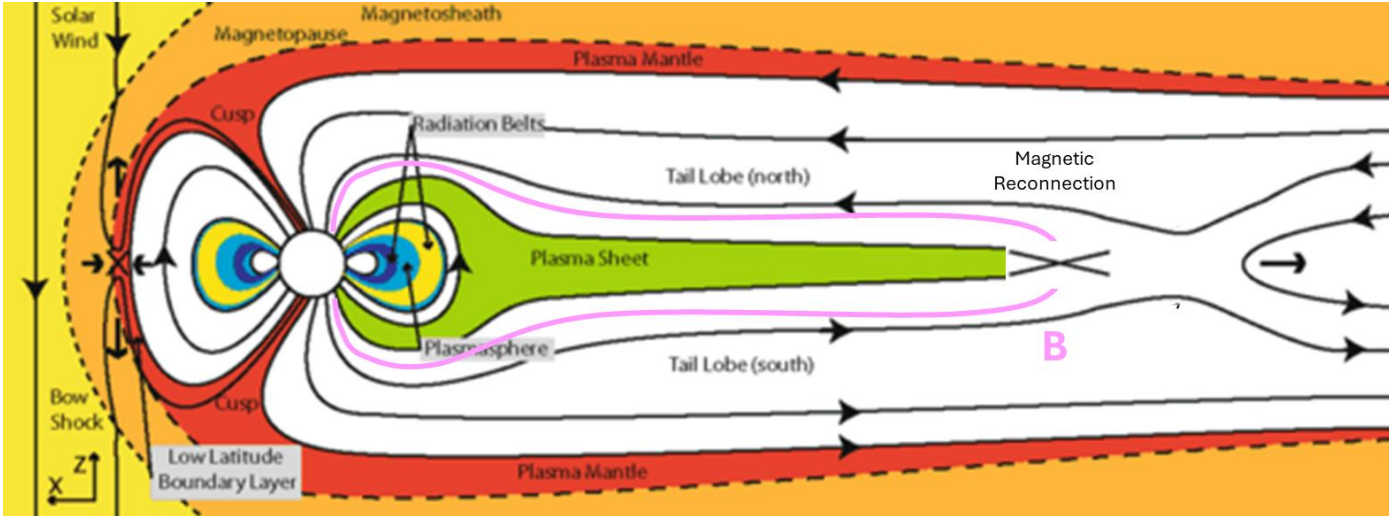
Aurora on 19-20 January 2026



Credits: Jonas Piontek - <https://www.youtube.com/watch?v=MxM-h5pU9mE> ; STCE newsitem: <https://www.stce.be/news/802/welcome.html>

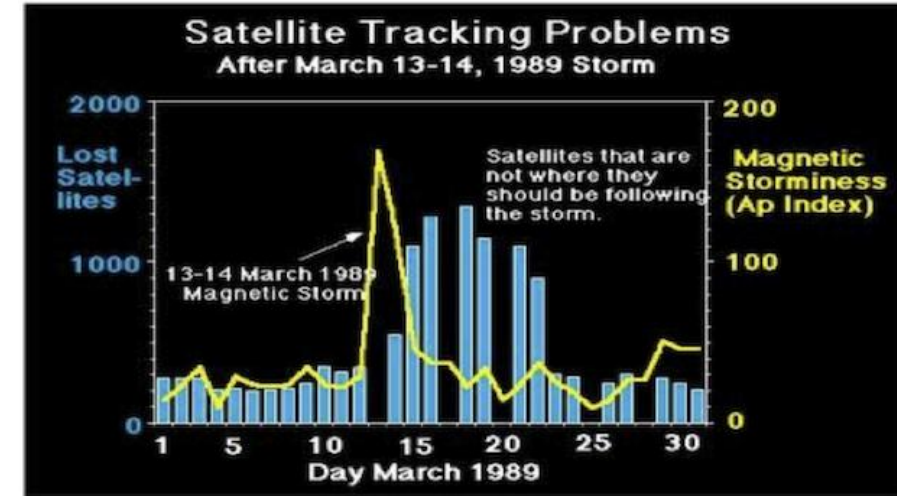


SWx impacts from ICMEs

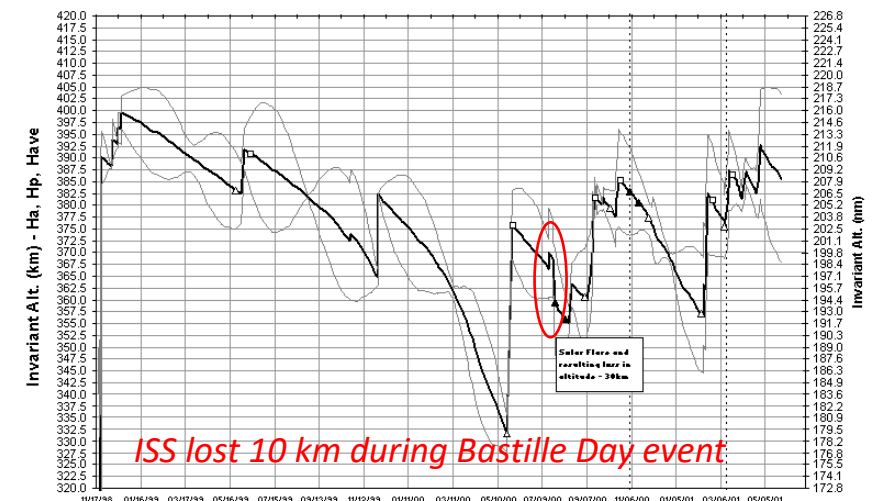


SWx impacts from ICMs

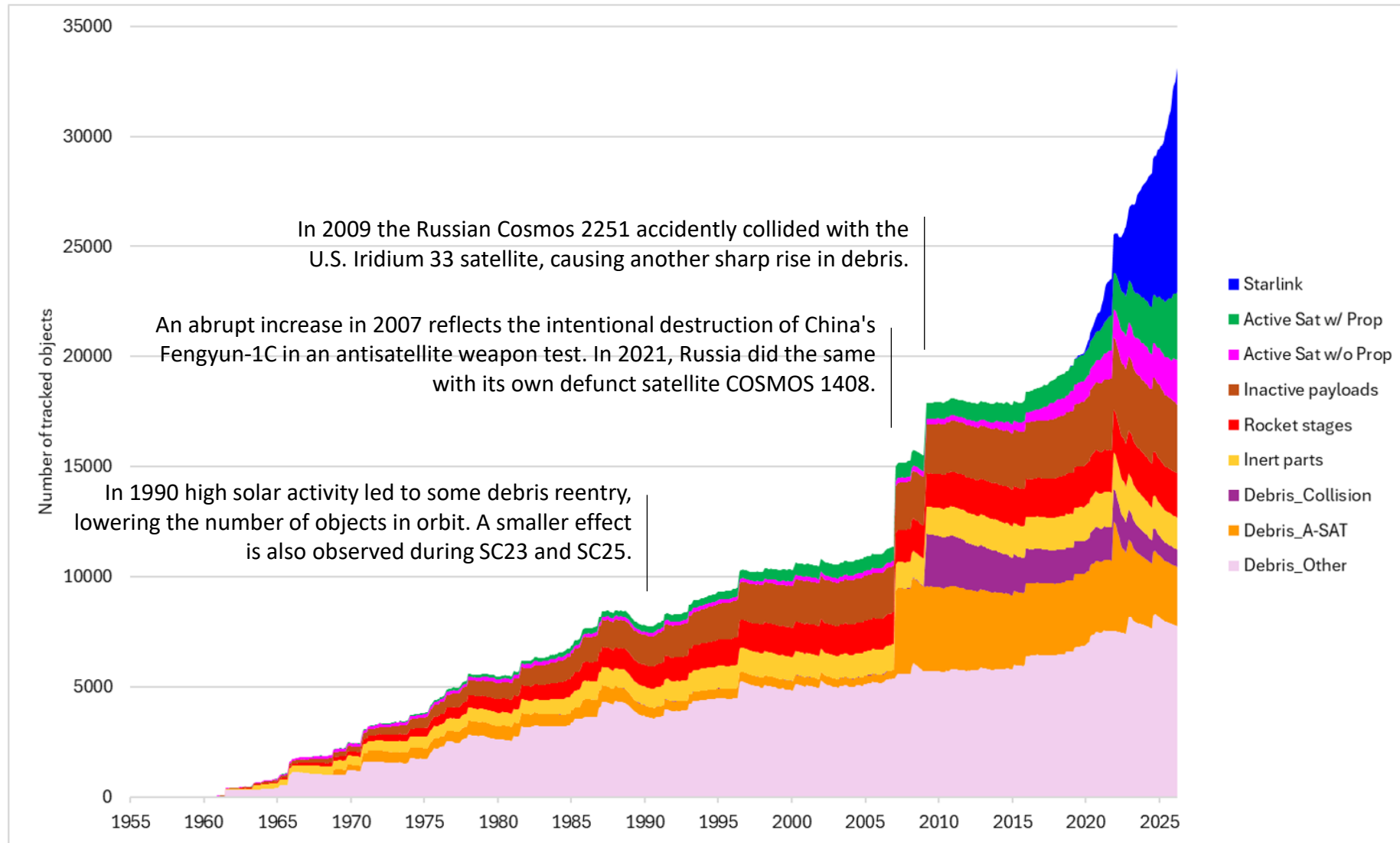
- Satellites
 - Atmospheric drag
 - Low Earth Orbit (LEO)
 - Sources
 - Shortterm: ICME
 - NOAA: $K_p > 6$
 - Longterm: Solar EUV radiation (solar cycle)
 - NOAA: $F_{10.7} > 250$ sfu
 - Slows down satellite
 - Burns up in atmosphere
 - Examples
 - March 1989
 - 1000 satellites off-track
 - Premature mission end
 - Solar Max, Skylab, Starlink
 - 10-11 May 2024: ISS lost 0.5 km
 - Space debris
 - Cleaned up by high solar activity
 - SpaceX Dragon crew capsule trunk
 - Early re-entry (27 April 2023)



International Space Station As Flown Altitude Profile
(Based on MCC-MUUSP Tracked SV Data)



SWx impacts from ICMEs

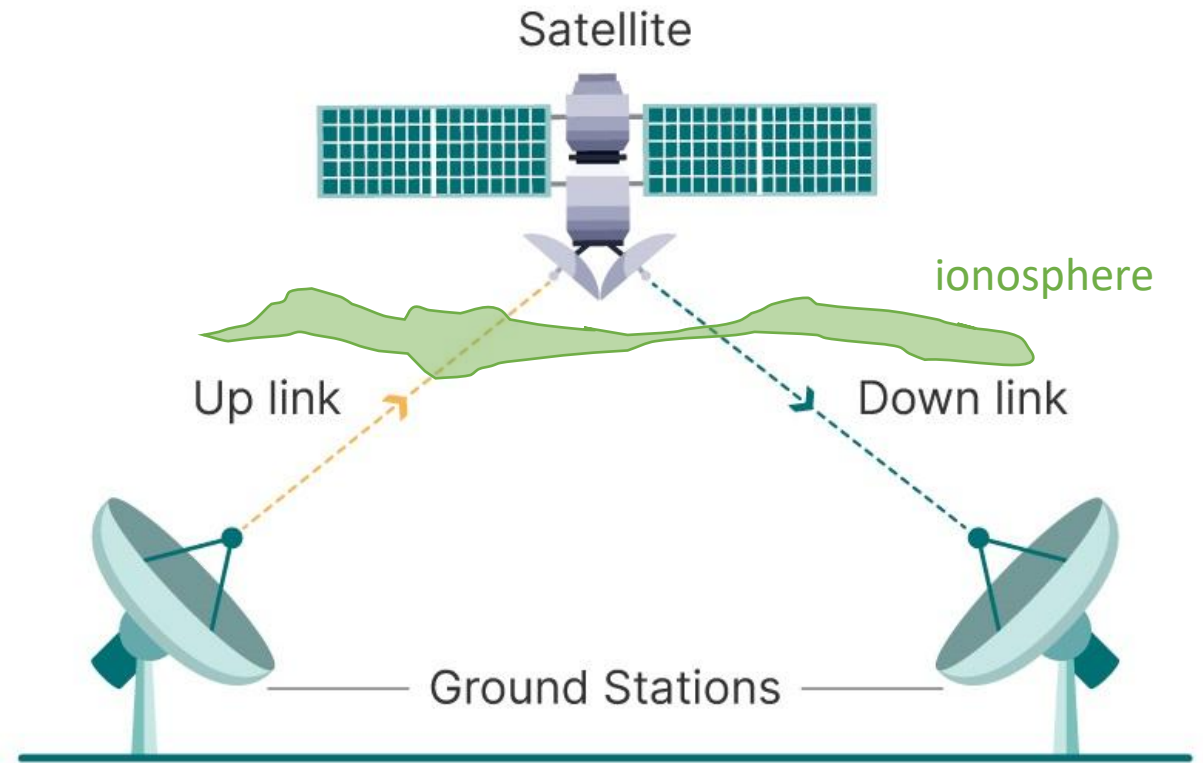




SWx impacts from ICMEs on SATCom/GNSS



- Satellite Communication (SATCom)
 - Media, Meteo, Military, Internet,...
 - Wide frequency range
 - usually UHF/SHF
 - Applications such as WAAS, EGNOS,...
 - Signals travel through ionosphere...





SWx impacts from ICMEs on SATCom/GNSS



- Satellite Communication (SATCom)
 - Media, Meteo, Military, Internet,...
 - Wide frequency range
 - usually UHF/SHF
 - Applications such as WAAS, EGNOS,...
 - Signals travel through ionosphere...
 - Ionospheric scintillation
 - Small scale irregularities in e^- density
 - May develop in large structures
 - Rapid fluctuations in satellite signal
 - Phase and intensity
 - May result in signal loss

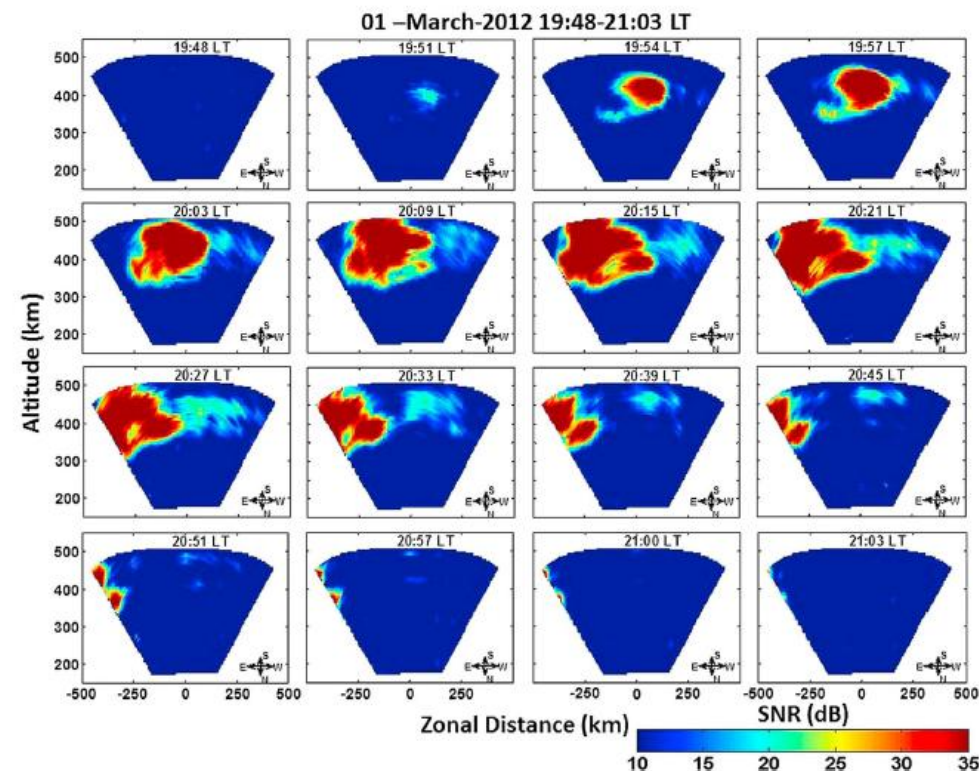


Figure 1. An example showing the genesis and successive development of EPB (evolving-type) over Kototabang observed from the fan sector maps of EAR on 1 March 2012.

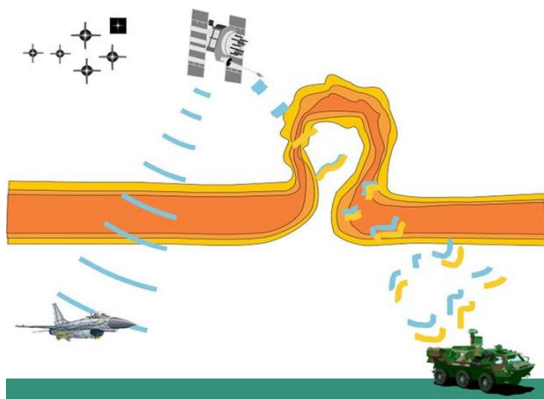




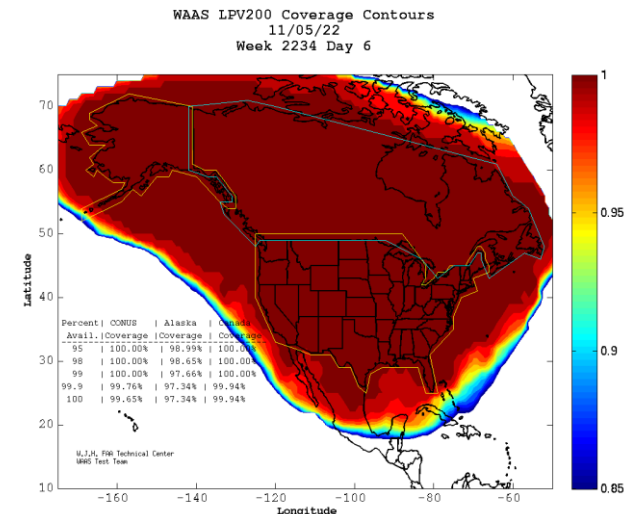
SWx impacts from ICMEs on SATCom/GNSS



- Battle of Takur Ghar
 - 4 March 2002
 - Ionospheric disturbance contributed to SATCom outage during Mil operation
 - Despite active to unsettled geomagnetic conditions
 - Can occur anytime!
- GNSS applications such as WAAS & EGNOS
 - 7 November 2022
 - 10-11 May & 10-11 October 2024
 - Complete loss of GNSS applications for several hours



Credits: US Air Force Research Laboratory



GHz: gigahertz ; (I)CME: (Interplanetary) Coronal Mass Ejection ; WAAS: Wide Area Augmentation System ; EGNOS: European Geostationary Navigation Overlay Service ; UHF: ultra high frequency ; SHF: super high frequency

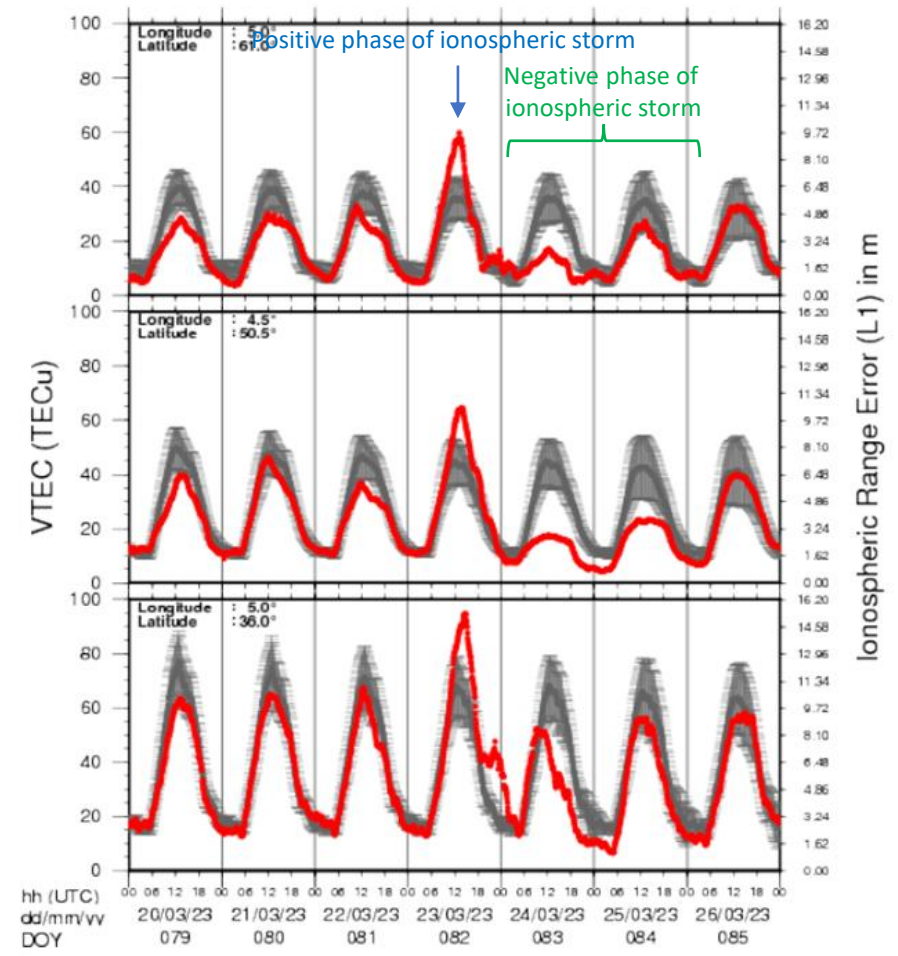
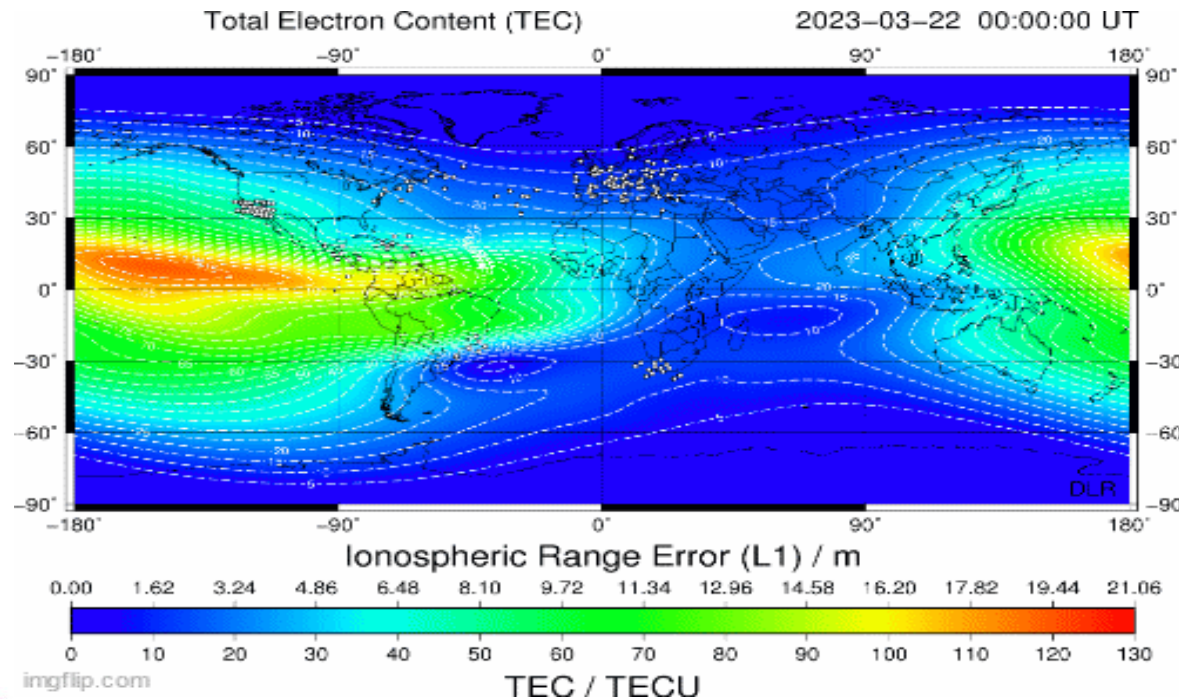




SWx impacts from ICMEs on HF Com



- Ionospheric storm
 - Example: 23-24 March 2023
 - Kp = 80 ; Dst = -163 nT



Credits: ROB/GNSS



Credits images: PECASUS & DLR/IMPC

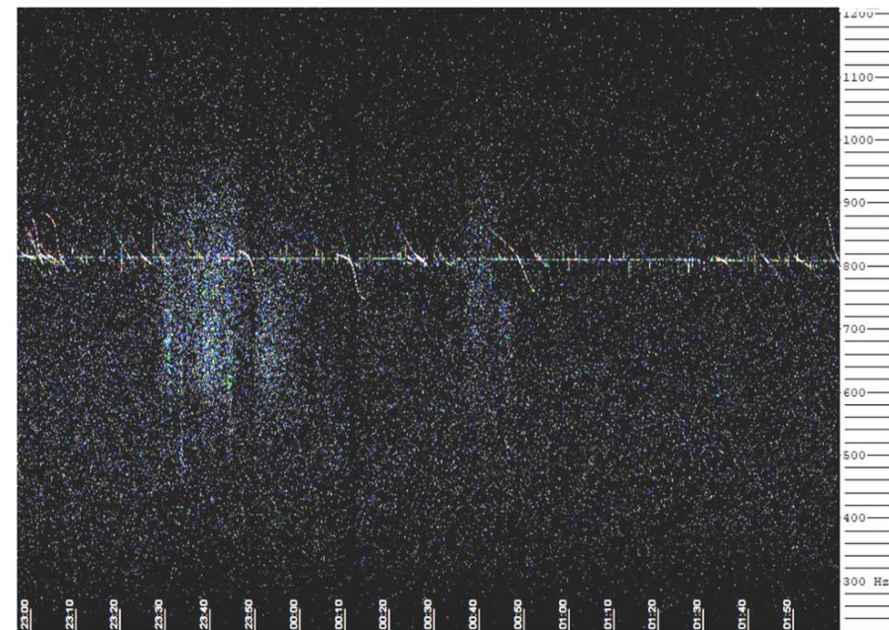
HF: High Frequency ; (I)CME: (Interplanetary) Coronal Mass Ejection ; Kp: planetary K index ; Dst: Disturbance storm-time index ; nT nano tesla ; (V)TEC: (Vertical) Total Electron Content ; TECU: TEC unit



SWx impacts from ICMEs on HF Com

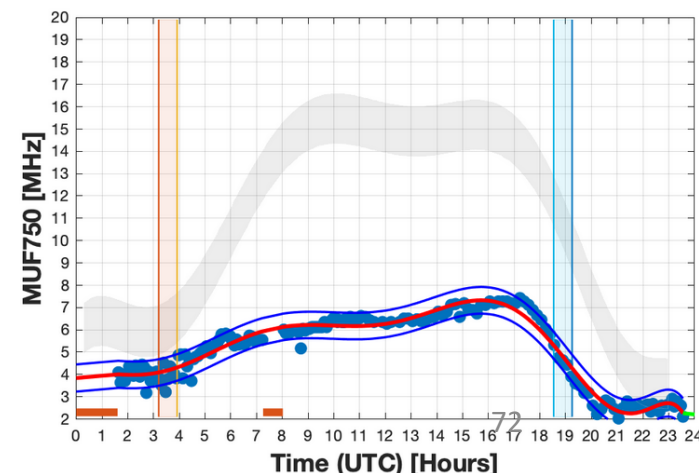


- Auroral Absorption (AA)
 - HF Com due to aurora affecting lower ionosphere
 - 18-19 Sep 1941
 - Kp=9- for 24 hours (!)
 - Radio broadcast disturbed
 - Bombing raids under light of aurora
- Post-Storm Depression (PSD)
 - Negative phase of ionospheric storm
 - => strong reduction electron content ionosphere
 - = Reduce HF higher frequencies
 - 25-26 May 1967
 - Most negative phase in TEC ever recorded



Credits: Felix Verbelen (BRAMS)
10-11 October 2024

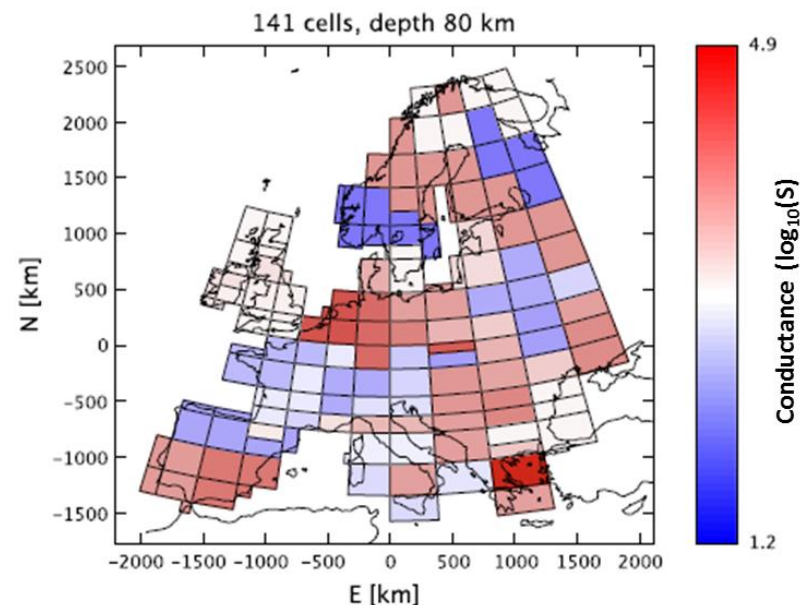
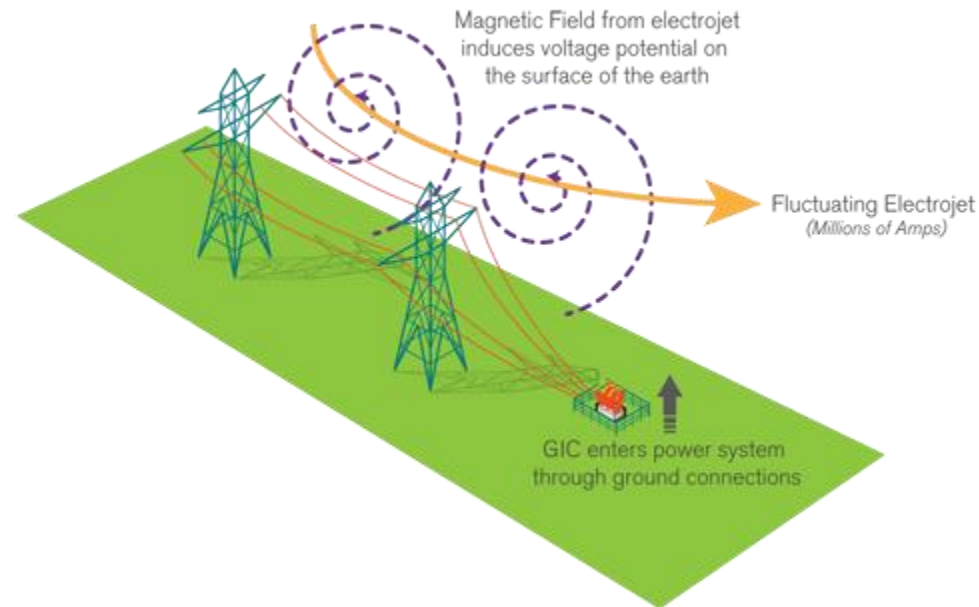
Ionosphere Maximum Usable Frequency (MUF750)
Date : 2023-03-24 Day Number : 083
Time : 23:33:16 [UTC]



Credits: IMPC – 24 March 2023

SWx impacts from ICMEs

- Geomagnetically Induced Currents (GIC)
 - Electrons from magnetotail => ionospheric currents => Magnetic field => currents in crust surface
 - Affects all long conductors
 - Enters via ground connections
 - GIC depends on
 - Strength ICME
 - Geomagnetic latitude
 - Eq. Latitudes too!
 - Local conductance
 - Network details



SWx impacts from ICMEs

- GICs
 - Power grids
 - Distortions voltage pattern
 - Transformer damage
 - South-Africa, Oct 2003
 - Grid collapse
 - Québec, March 1989
 - Malmö, Sweden, 2003
 - 10-11 May 2024
 - No major impacts on grids
 - Longterm effects of power loss!

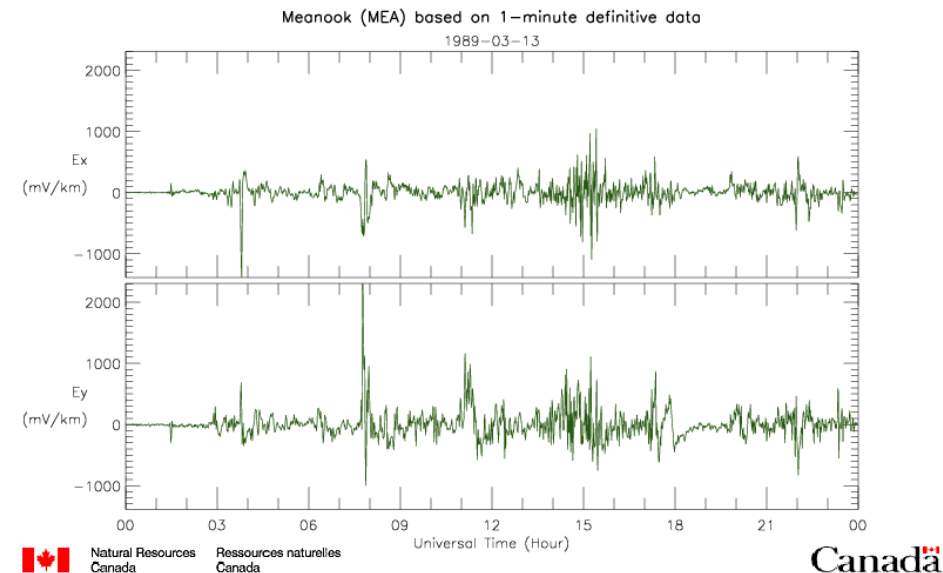


Table 3 Parameters for the GIC emergency alert model. The criterion for each alert level is shown in the second column, and the following columns show the expected extreme dB/dt values for RC-, AE-, and SC-type GICs

Alert level	Criterion	dB/dt of GICs		
		RC (nT/h)	AE (nT/min)	SC (nT/s)
Caution	$Dst < -300$ nT	100-150	2000	40-110
Warning	$Dst < -600$ nT	150-400	4000	40-110
Emergency	$Dst < -900$ nT	400-1250	6000	40-110
Transient alert	High SEP flux			40-110



Credits: Metatech



Effects from ICMEs

- GICs
 - Railways
 - New York (USA), 14-15 May 1921
 - Sweden, 13-14 July 1982
 - China, 17 March & 23 June 2015
 - Pipelines
 - Corrosion => Oil leaks
 - Telephone/Telegraph
 - Carrington event (1859),...
 - Transcontinental cables
 - 4 August 1972
 - Transatlantic cables
 - Copper to optical fiber
 - But « optical repeaters »!
 - March 1989 event
 - High-precision industry
 - Wellbore drilling
 - Manitoba, Canada, 27 February 2023

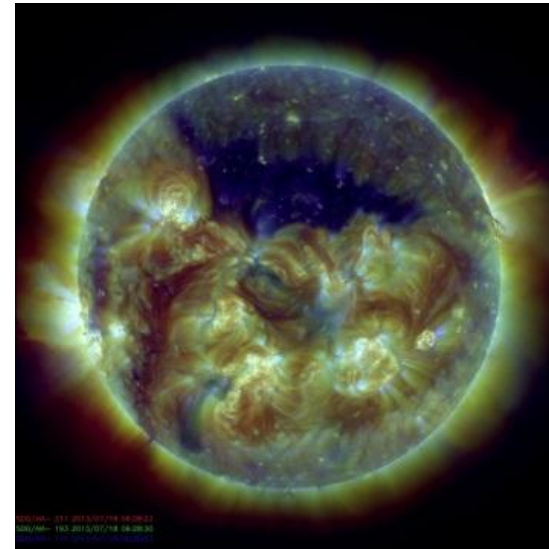




Space Weather impacts (SWx impacts)

- *Recap*
- *SWx impacts from*
 - *Solar flares*
 - *Proton events*
 - *ICMEs*
 - ***Coronal holes***

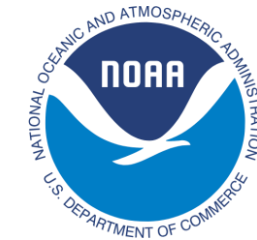
Coronal Holes





SWx impacts from CHs

G: Geomagnetic storm



Scale	Description (Physical)	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	Power systems: Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: May experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: Voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: Weak power grid fluctuations can occur. Spacecraft operations: Minor impact on satellite operations possible. Other systems: Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)





SWx impacts from CHs

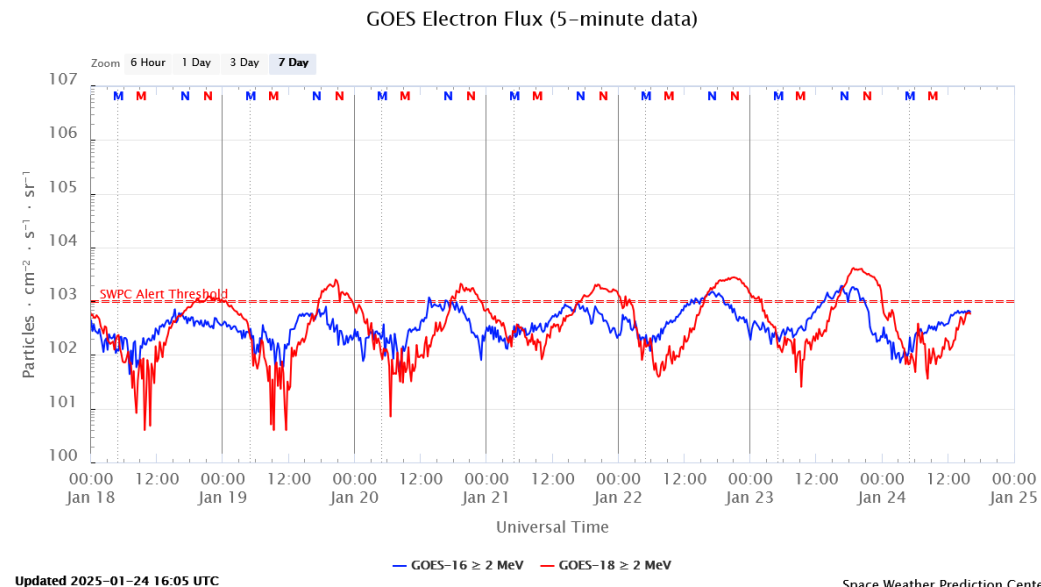
- Similar to effects from ICMEs but less intense
- except...
- From particles
 - Satellites
 - **Deep di-electric charging**





SWx impacts from CHs on satellites

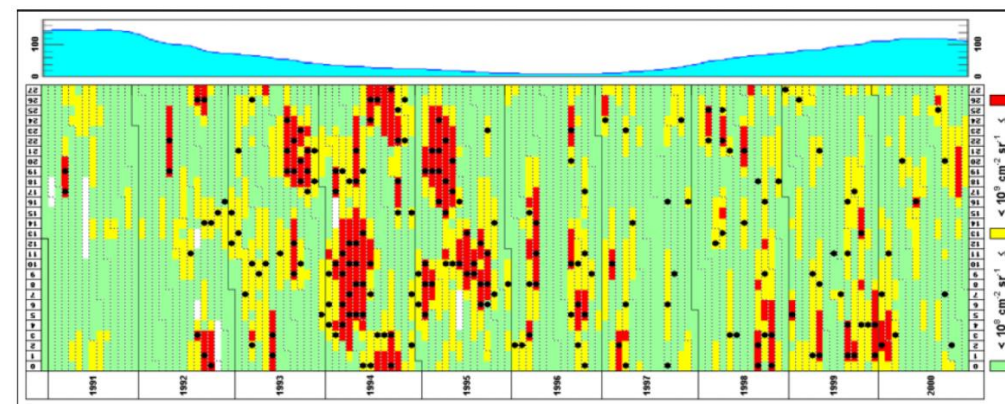
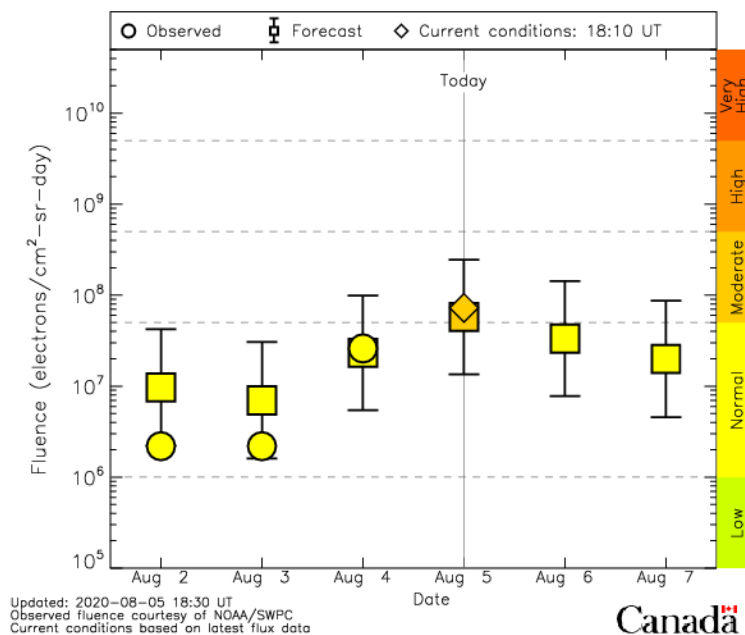
- High-Speed Stream (HSS)
 - Satellite charging
 - Deep di-electric charging
 - About 1 to a few MeV e-
 - Deeply penetrate spacecraft (S/C)
 - Fluxes > 2 MeV e-
 - Accumulation effect within S/C (ESD: electrostatic discharge)
 - Dayside effect





SWx impacts from CHs on satellites

- High-Speed Stream (HSS)
 - Satellite charging
 - Deep di-electric charging
 - About 1 to a few MeV e⁻
 - Deeply penetrate spacecraft (S/C)
 - Fluxes > 2 MeV e⁻
 - Accumulation effect within S/C (ESD: electrostatic discharge)
 - Dayside effect
 - Fluence (24h)
 - Declining phase solar cycle (coronal holes)
 - ~ 20 ESD/yr/GEO sat
 - Also strong ICME, e.g. 3-4 Nov 2021

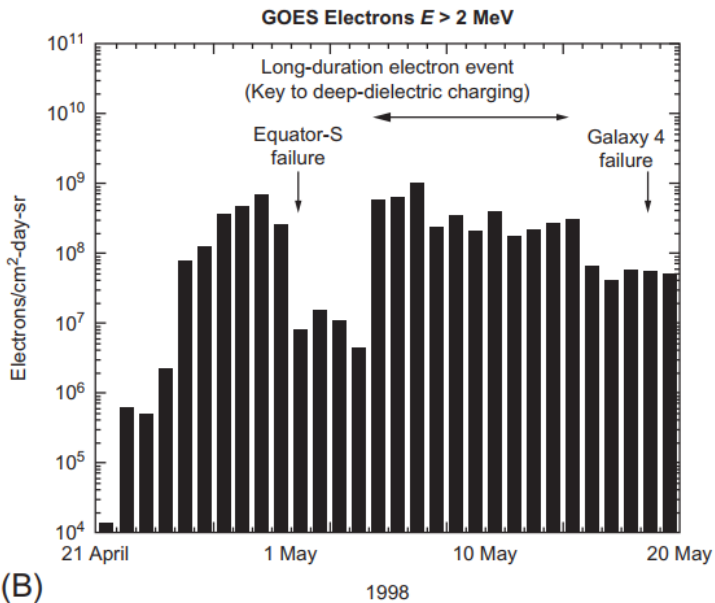


Credits: Wrenn et al. (2002)

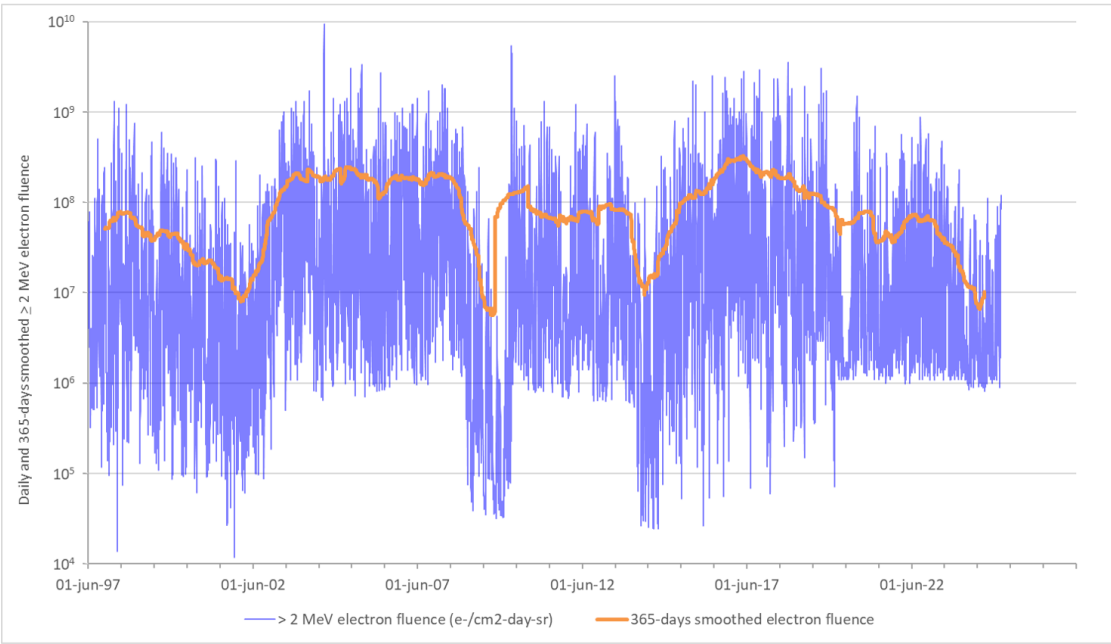




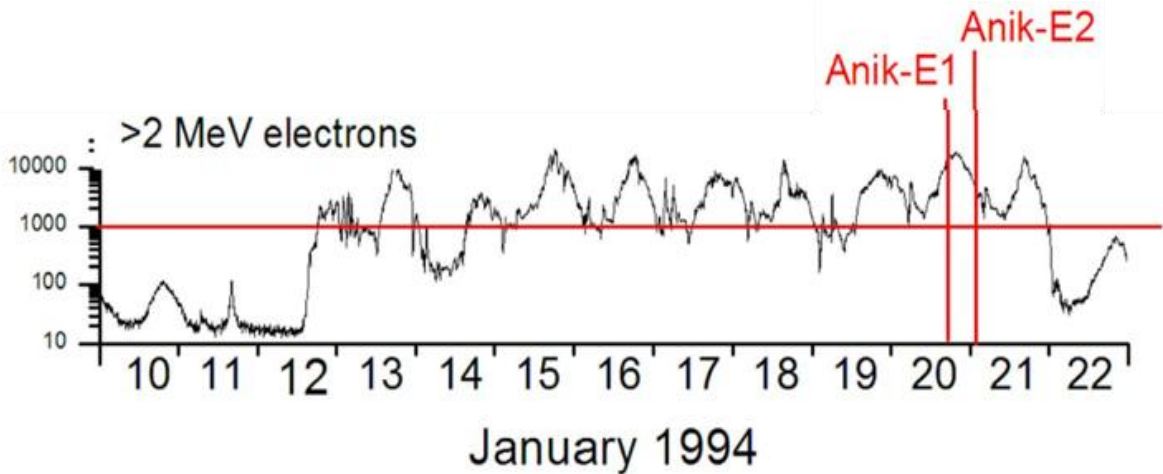
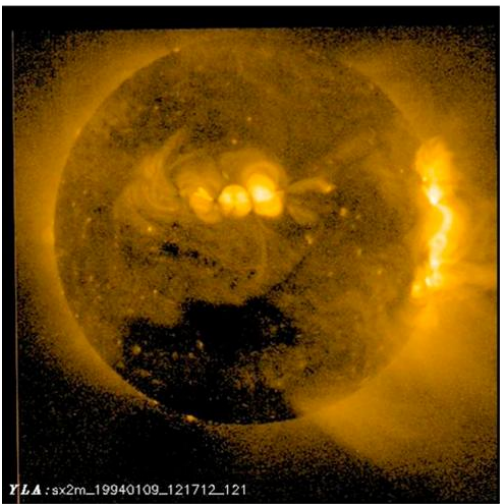
SWx impacts from CHs on satellites



Credits: Lai et al. 2018



Frequency High fluence: ~18 days / year



Credits: Lam et al. 2012





:Issued: 2024 Mar 17 1231 UTC
:Product: documentation at <http://www.sidc.be/products/tot>

#-----#
DAILY BULLETIN ON SOLAR AND GEOMAGNETIC ACTIVITY from the SIDC #
#-----#

SIDC URSIGRAM 40317
SIDC SOLAR BULLETIN 17 Mar 2024, 1231UT
SIDC FORECAST
SOLAR FLARES : M-class flares expected (probability >=50%)
GEOMAGNETISM : Quiet (A<20 and K<4)
SOLAR PROTONS : Quiet
PREDICTIONS FOR 17 Mar 2024 10CM FLUX: 144 / AP: 007
PREDICTIONS FOR 18 Mar 2024 10CM FLUX: 146 / AP: 007
PREDICTIONS FOR 19 Mar 2024 10CM FLUX: 148 / AP: 007



Solar Active Regions and flaring: There are five active regions visible on the solar disk. They all have simple beta or alpha magnetic field configuration and produced minor C-class flaring. The main activity in the last 24 hours has been observed from active regions behind the east limb, that will rotate into view in the next hours. The strongest was an M3.5 flare peaking at 16:35 UTC on 16 March, from a region not yet visible, located behind the east limb. As these regions rotate into view, we expect more M-class and possible X-class flares in the next 24 hours.

Coronal mass ejections: There was a partial halo CME (angular width about 180 degrees) directed towards the south, first seen at 03:24 UTC by LASCO C2. This CME originates from a filament eruption in the southern hemisphere. Since the filament was located close to the disk center, an ICME may arrive to the Earth on 20-21 March (a better estimation will be given when more data become available).

Solar wind: The Earth is inside slow solar wind, with speeds close to 350 km/s and an interplanetary magnetic field around 5 nT. Similar conditions are expected for the next 24 hrs.

Geomagnetism: Geomagnetic conditions were quiet both global and locally (NOAA_Kp up to 1 and K_BEL up to 1). Similar conditions can be expected for the next 24 hours.

Proton flux levels: The 10 MeV proton flux (measured by GOES-18) has come below the 10 pfu threshold, but remains elevated. It is expected that it will go back to low levels in the next 24 hrs.

Electron fluxes at GEO: The greater than 2 MeV electron flux from GOES 16 was below the threshold level in the last 24 hours. It is expected to remain below the threshold during the next 24 hours. The 24h electron fluence was at normal level and is expected to remain so.

TODAY'S ESTIMATED ISN : 074, BASED ON 10 STATIONS.

SOLAR INDICES FOR 16 Mar 2024
WOLF NUMBER CATANIA : ///
10CM SOLAR FLUX : 144
AK CHAMBON LA FORET : 005
AK WINGST : 002
ESTIMATED AP : 002
ESTIMATED ISN : 058, BASED ON 23 STATIONS.

$\geq 2 \text{ MeV}$ electron flux & fluence

NOTICEABLE EVENTS SUMMARY
DAY BEGIN MAX END LOC XRAY OP 10CM Catania/NOAA RADIO_BURST_TYPES
16 1622 1635 1644 // M3.5 //
16 2127 2155 2211 // M1.1 //
END



Questions?

