SPACE WEATHER INTRODUCTORY COURSE

SWIC

Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

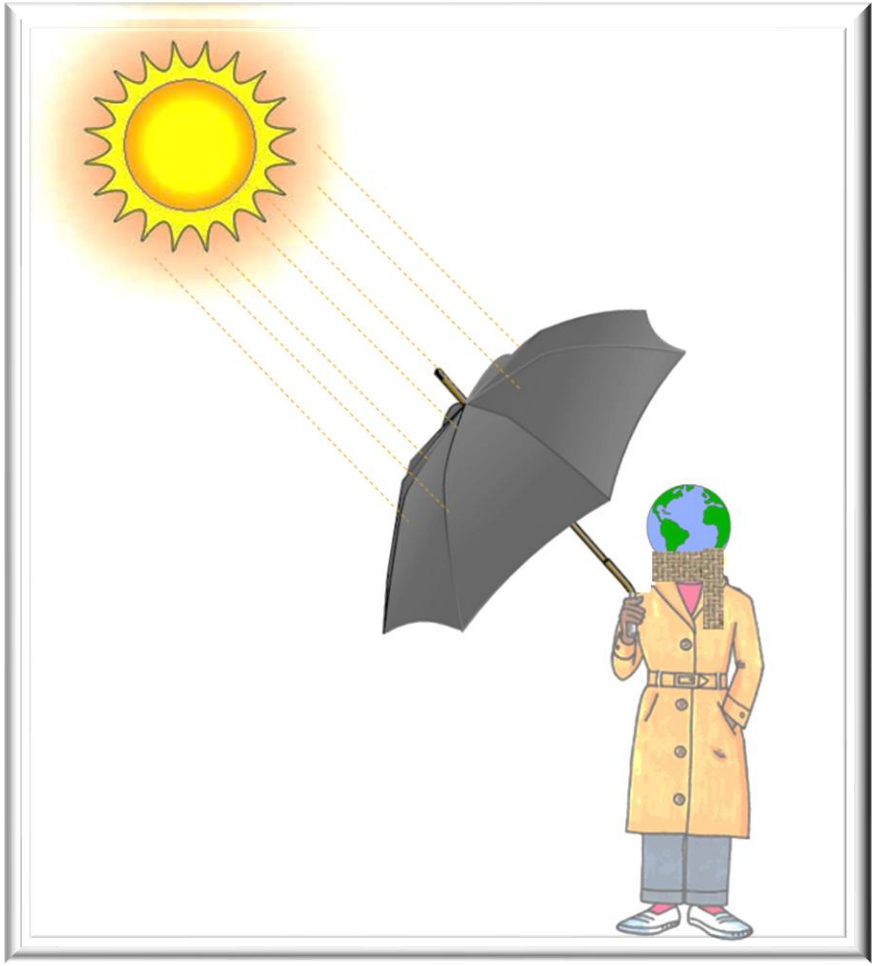
SWEC
Space Weather Education Center

Space weather impacts

Jan Janssens

Space Weather impacts (SWx impacts)

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

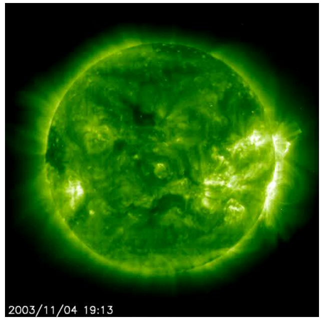


Drivers of disturbed SWx

Solar eruptions

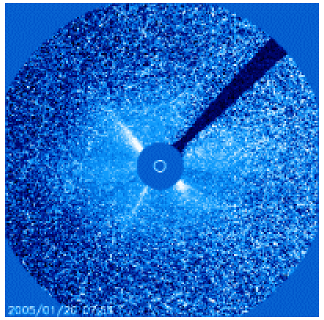
Electromagnetic Radiation

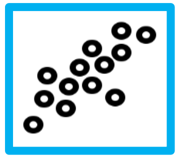
Solar flares



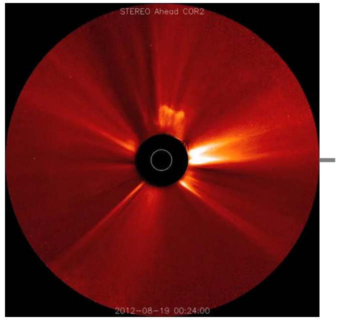
Particles

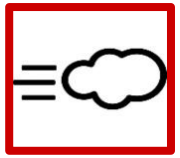
Proton events



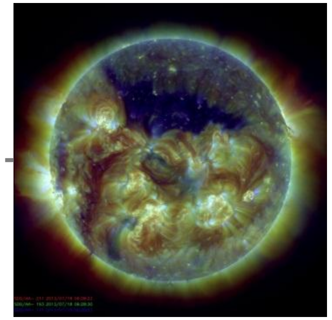


Coronal Mass Ejections

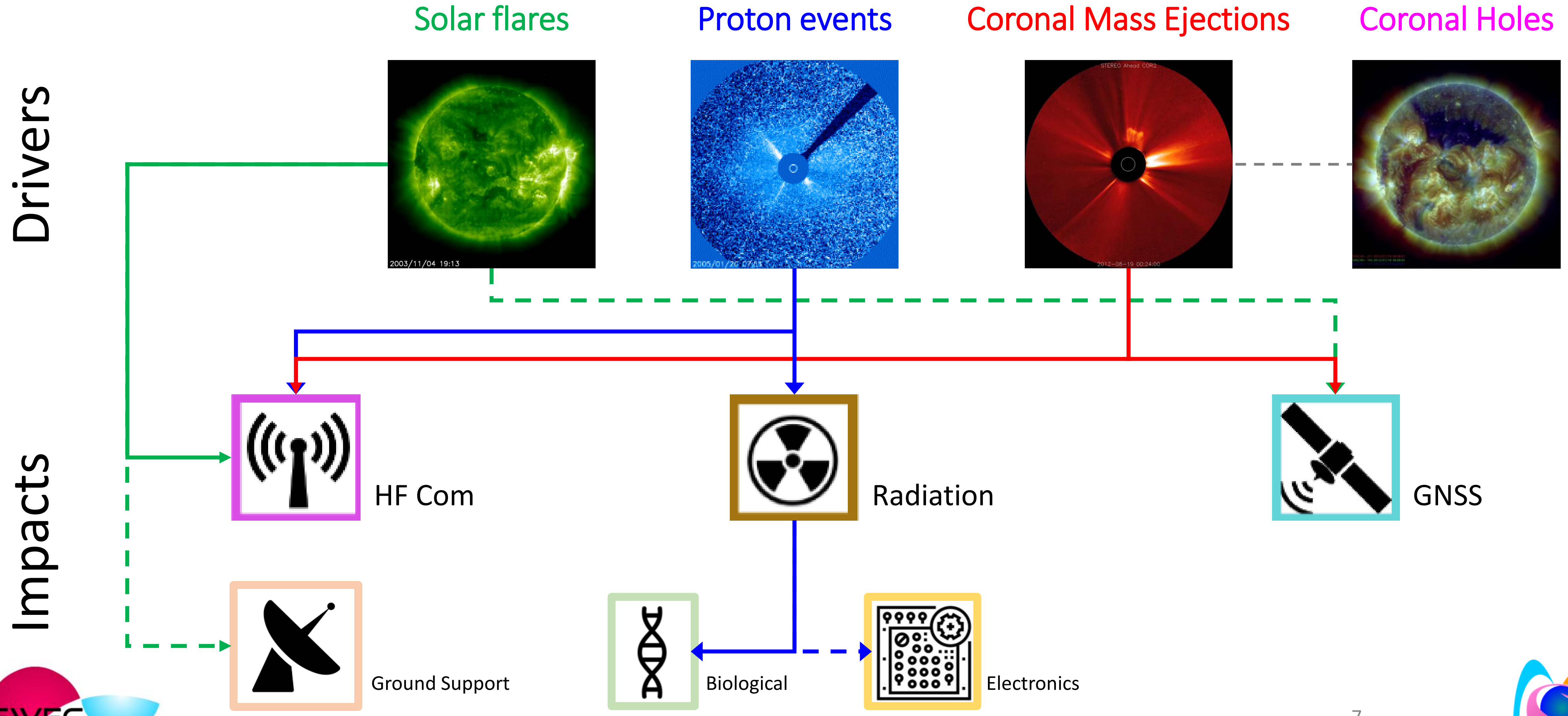




Coronal Holes



SWx impacts on aviation

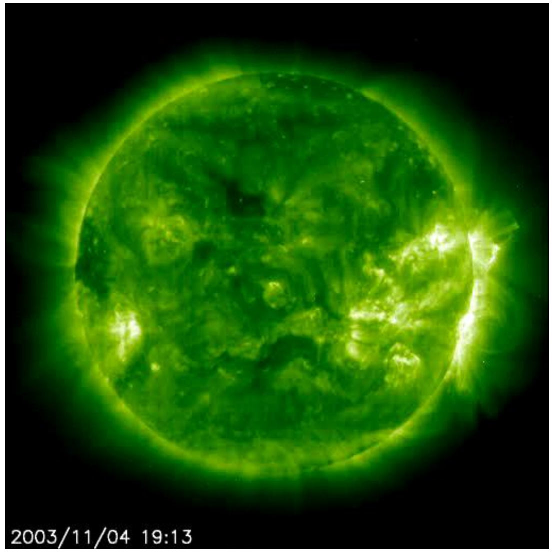


HF Com: High Frequency Communications (3-30 MHz) ; GNSS: Global Navigation Satellite Systems (GPS, Galileo,,…) — — — **Currently NOT covered by SWx advisories for ICAO**

Space Weather impacts (SWx impacts)

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

Solar flares



NOAA SWx scales: a word of caution

- ***Key disadvantages include***:
  - ***Outdated and Confusing Thresholds***: *The scales were designed in 1999 and have not kept pace with historic events, such as the 2003 Halloween storms and the May 2024 Gannon event, making them confusing for the public.*
  - ***Oversimplification***: *Not all impacts occur with each event, and not always with the same intensity. Some impacts are missing.*
  - ***Saturation at the High End (G5+)***: *The G5 "Extreme" category is too broad, covering everything from the lowest G5 threshold up to a "Carrington-level" superstorm. Users have expressed the need for a higher classification level to differentiate between a standard G5 and a more intense event.*
  - ***Lack of Actionable Information***: *The scales do not consistently communicate the localized impacts on specific technologies in a way that allows for operational decision-making.*
  - ***Insufficient Geographic Specificity***: *Space weather events are global but experienced locally (e.g., specific power grid transformers or latitudes for auroras), while the scales often lack localized details.*
  - ***"One-Size-Fits-All" Approach***: *The scales are used by the general public, researchers, and satellite operators alike, making it difficult to provide specialized, high-quality detailed information for specific user communities.*
  - ***Overconfidence and False Alarms***: *Verification studies indicate that NOAA solar flare forecasts, particularly for high-stakes X-class flares, can be overconfident, with high false-alarm rates that erode trust in the forecasts.*
  - ***Poor Warning Time***: *The scales often rely on data that provide only 60 minutes of lead time for warnings, which is insufficient for many operators to implement protective measures.*
- ***But***:
  - *It's the best we have (for general use)!*
  - *The scales are under revision, with possibility of additional, more specific scales.*

SWx impacts from solar flares

Scale	Description	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)

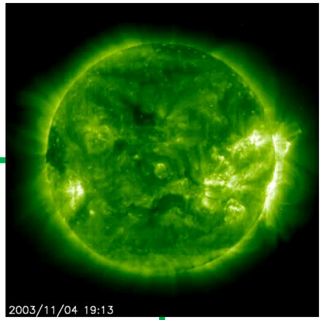
SWx impacts from solar flares

- 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

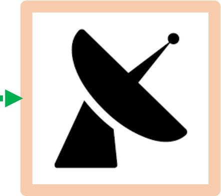
EUV: Extreme Ultraviolet ; GNSS: Global Navigation Satellite Systems ; VLF: Very Low frequency ; MF/HF: Medium/High Frequency
PECASUS: Pan-European Consortium for Aviation Space weather User Services

SWx impacts from solar flares on aviation

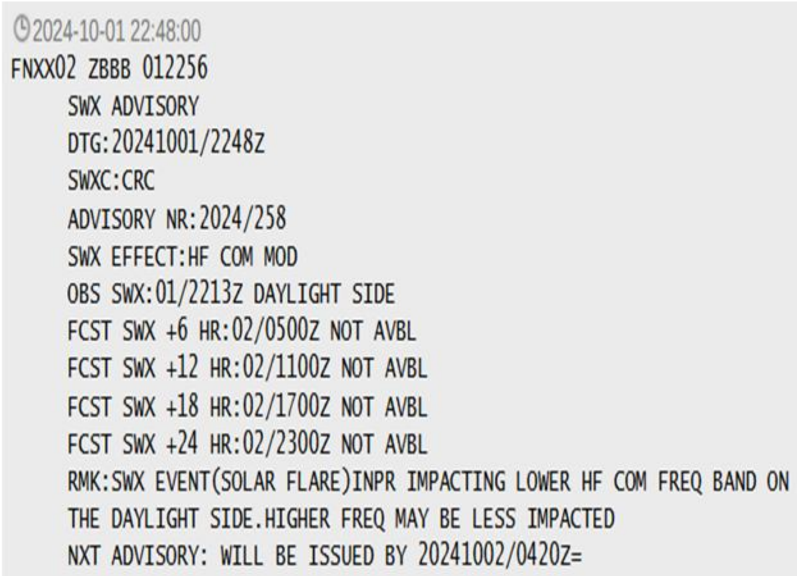
Solar flares



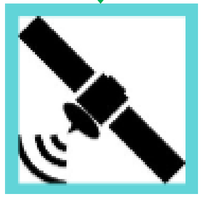
HF Com



Ground Support



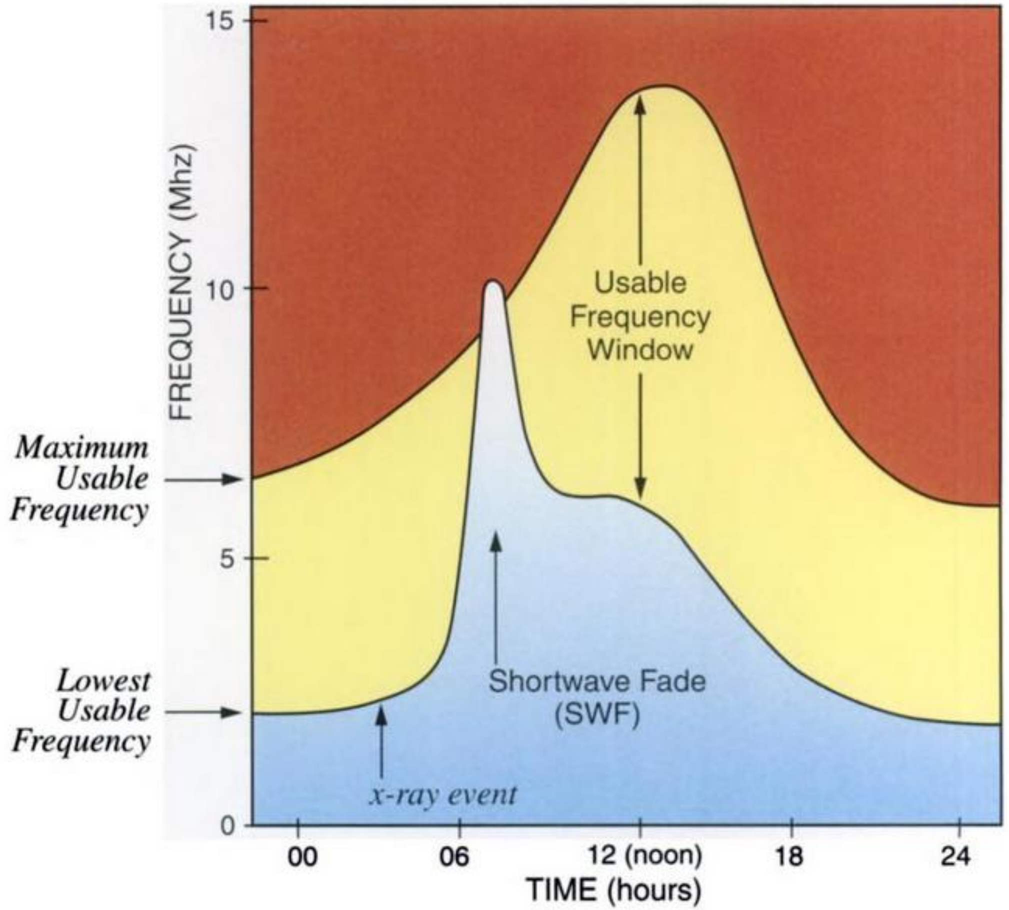
2024-10-01 22:48:00
FNXX02 ZBBB 012256
SWX ADVISORY
DTG:20241001/2248Z
SWXC:CRC
ADVISORY NR:2024/258
SWX EFFECT:HF COM MOD
OBS SWX:01/2213Z DAYLIGHT SIDE
FCST SWX +6 HR:02/0500Z NOT AVBL
FCST SWX +12 HR:02/1100Z NOT AVBL
FCST SWX +18 HR:02/1700Z NOT AVBL
FCST SWX +24 HR:02/2300Z NOT AVBL
RMK:SWX EVENT(SOLAR FLARE)INPR IMPACTING LOWER HF COM FREQ BAND ON
THE DAYLIGHT SIDE.HIGHER FREQ MAY BE LESS IMPACTED
NXT ADVISORY: WILL BE ISSUED BY 20241002/0420Z=



GNSS

HF Com: High Frequency Communications (3-30 MHz) ; GNSS: Global Navigation Satellite Systems (GPS, Galileo,,...) — — — **Currently NOT covered by SWx advisories for ICAO**

SWx impacts from solar flares on HFCom

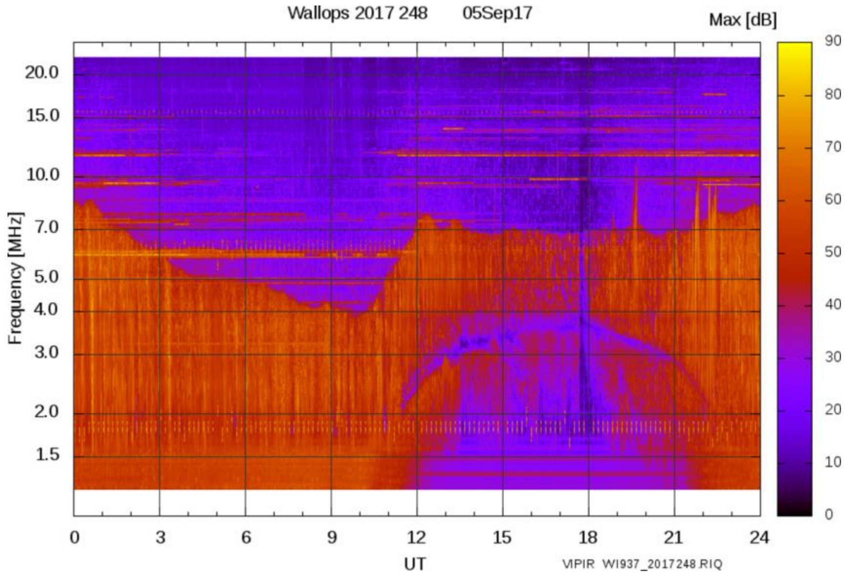


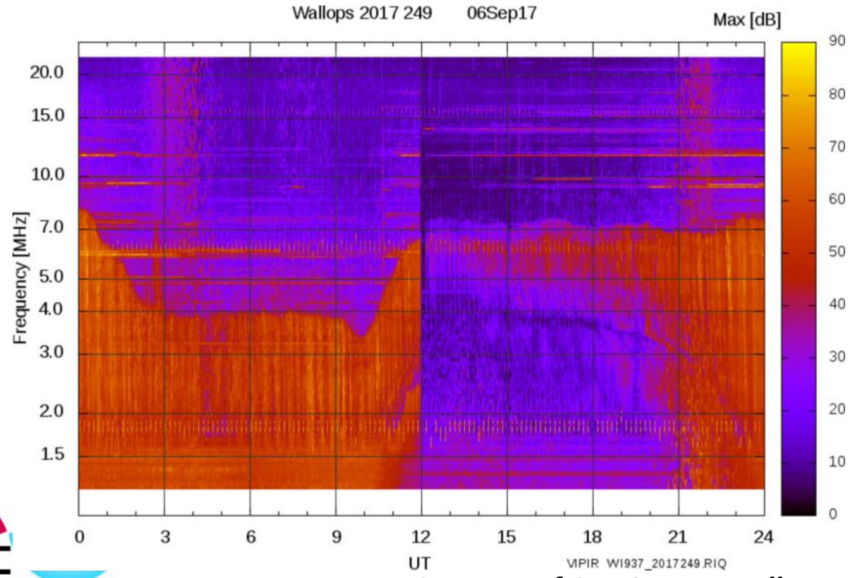
Credits: Poppe et al. (2006)

- 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)

HF Com: High Frequency Communications (3-30 MHz) ; SXR: soft x-rays ; SATCom: Satellite Communication ; MHz: megahertz

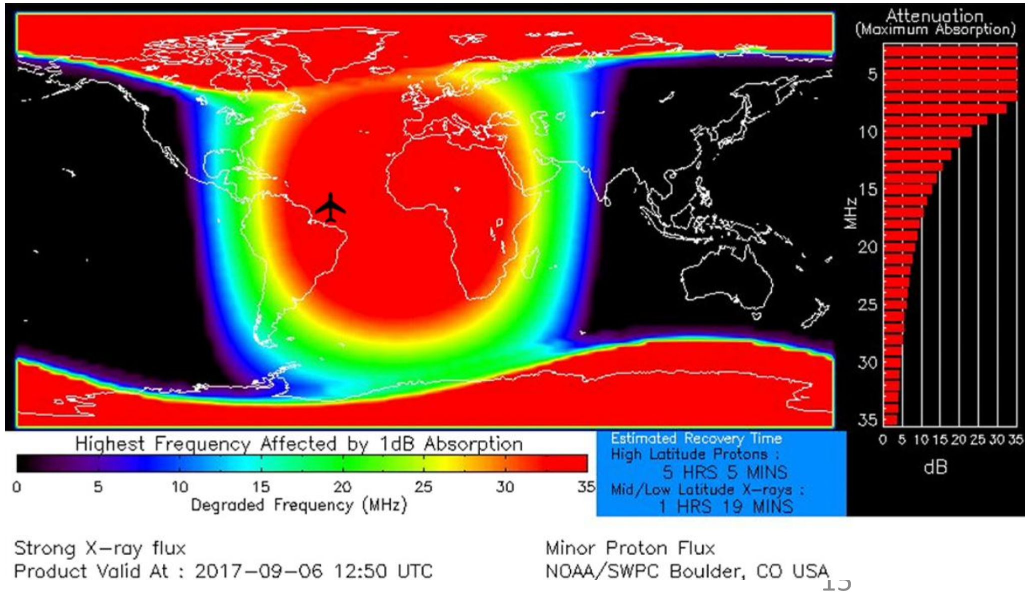
SWx impacts from solar flares on HFCom





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



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.

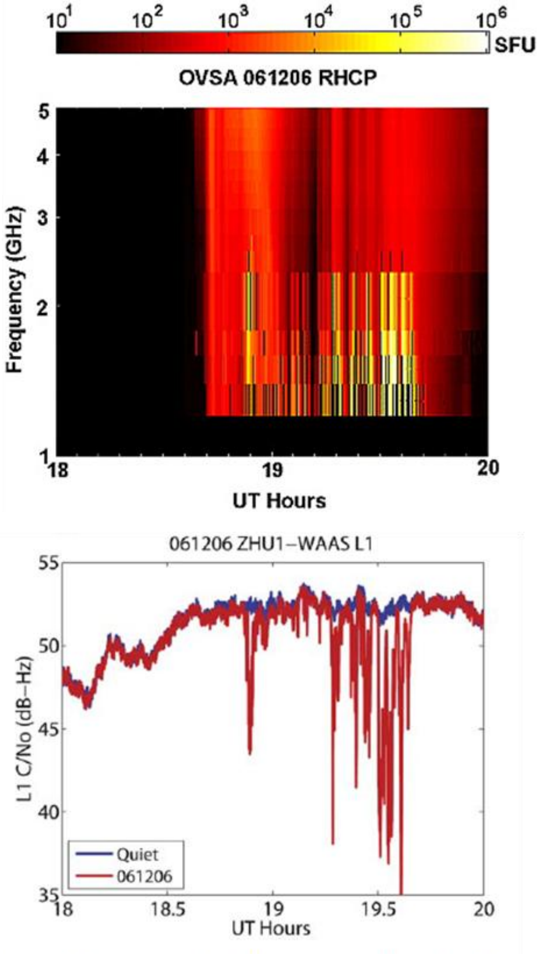


Figure 2. Response of a GPS receiver to the solar radio burst on 6 December 2006. The red line corresponds to C/N_0 on 6 December 2006, and the blue line corresponds to the previous sidereal day.

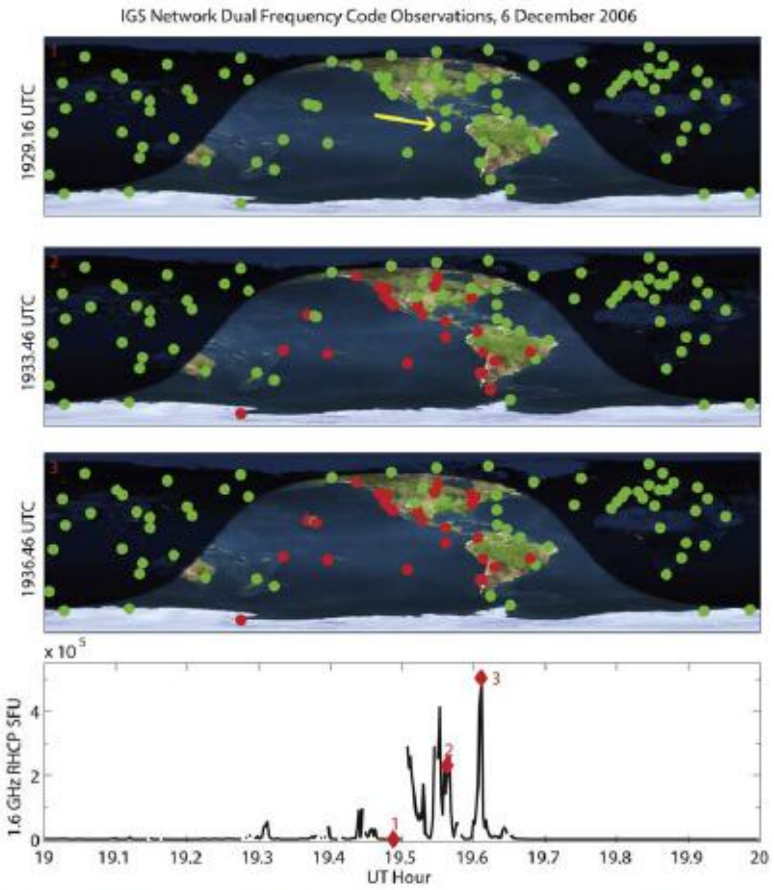


Figure 6. Receivers in the Global GPS Network that were analyzed during the solar radio burst. Green indicates the normal number of satellites being tracked. (fourth panel) During the burst (power at 1.6 GHz), several sunlit receivers tracked fewer than the four satellites needed for a full positioning 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.)

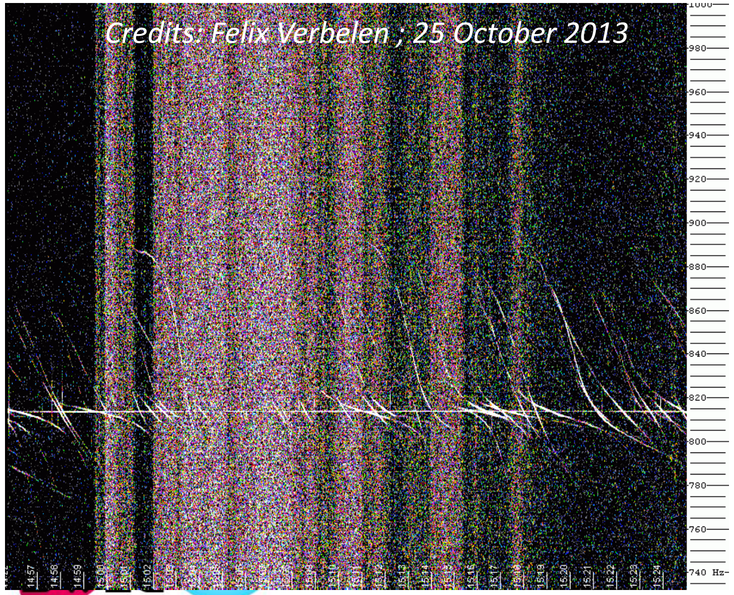
Credits: Cerruti et al. (2008)

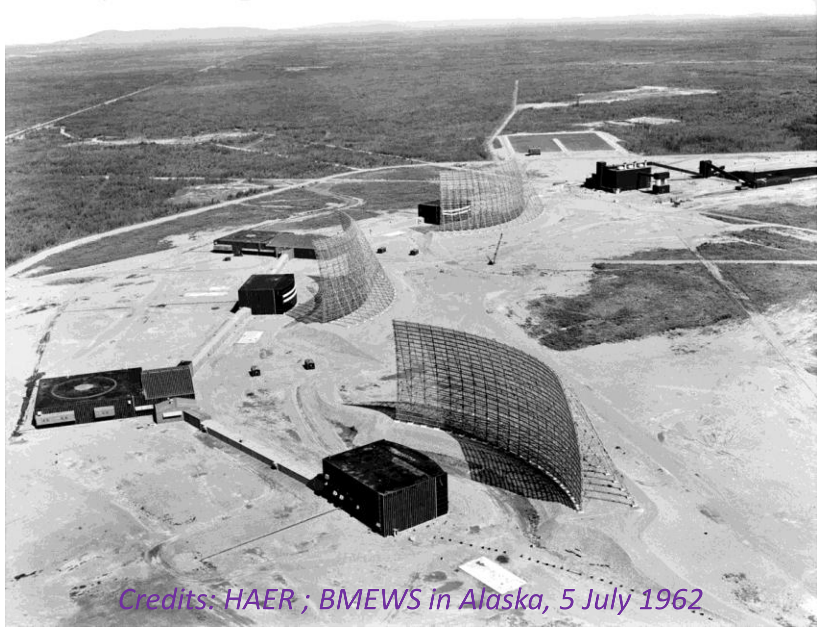
GNSS: Global Navigation Satellite Systems (GPS, Galileo,,…) ; sfu: solar flux units ; GHz: gigahertz ; IGS: International GNSS service

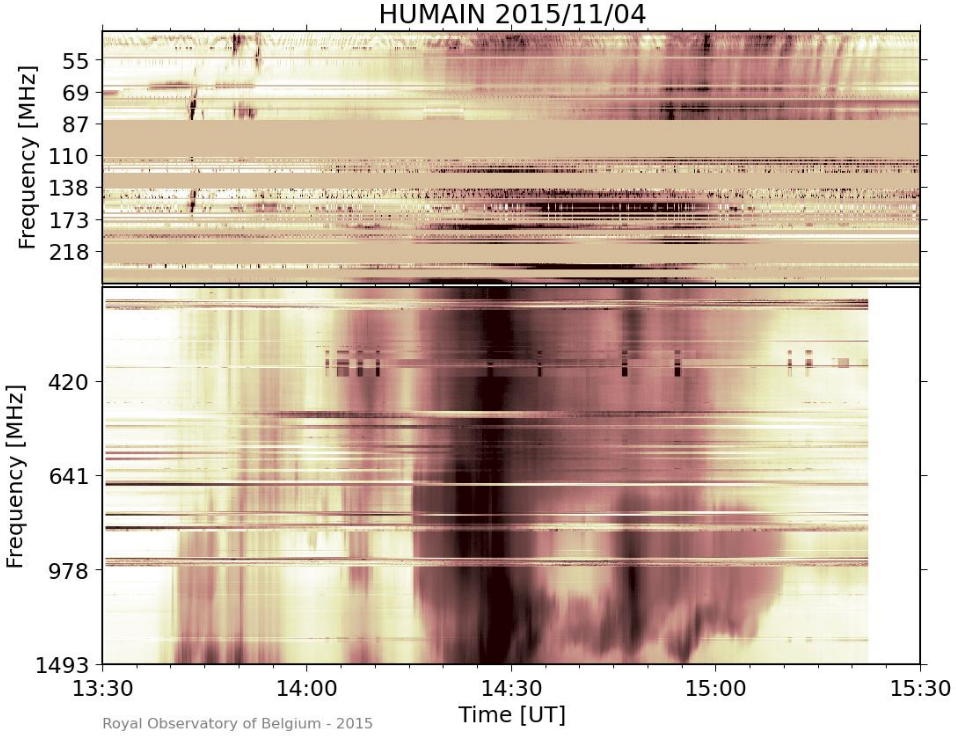
Currently NOT covered by SWx advisories for ICAO

SWx impacts from solar flares on Ground Suppo

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







Space Weather Education Center

Space Weather impacts (SWx impacts)

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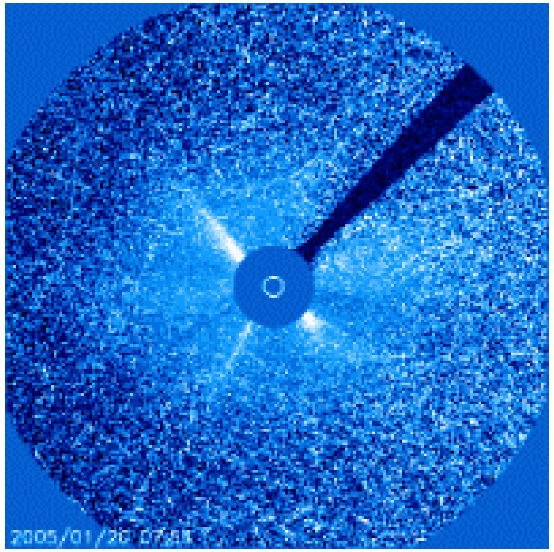
Proton events



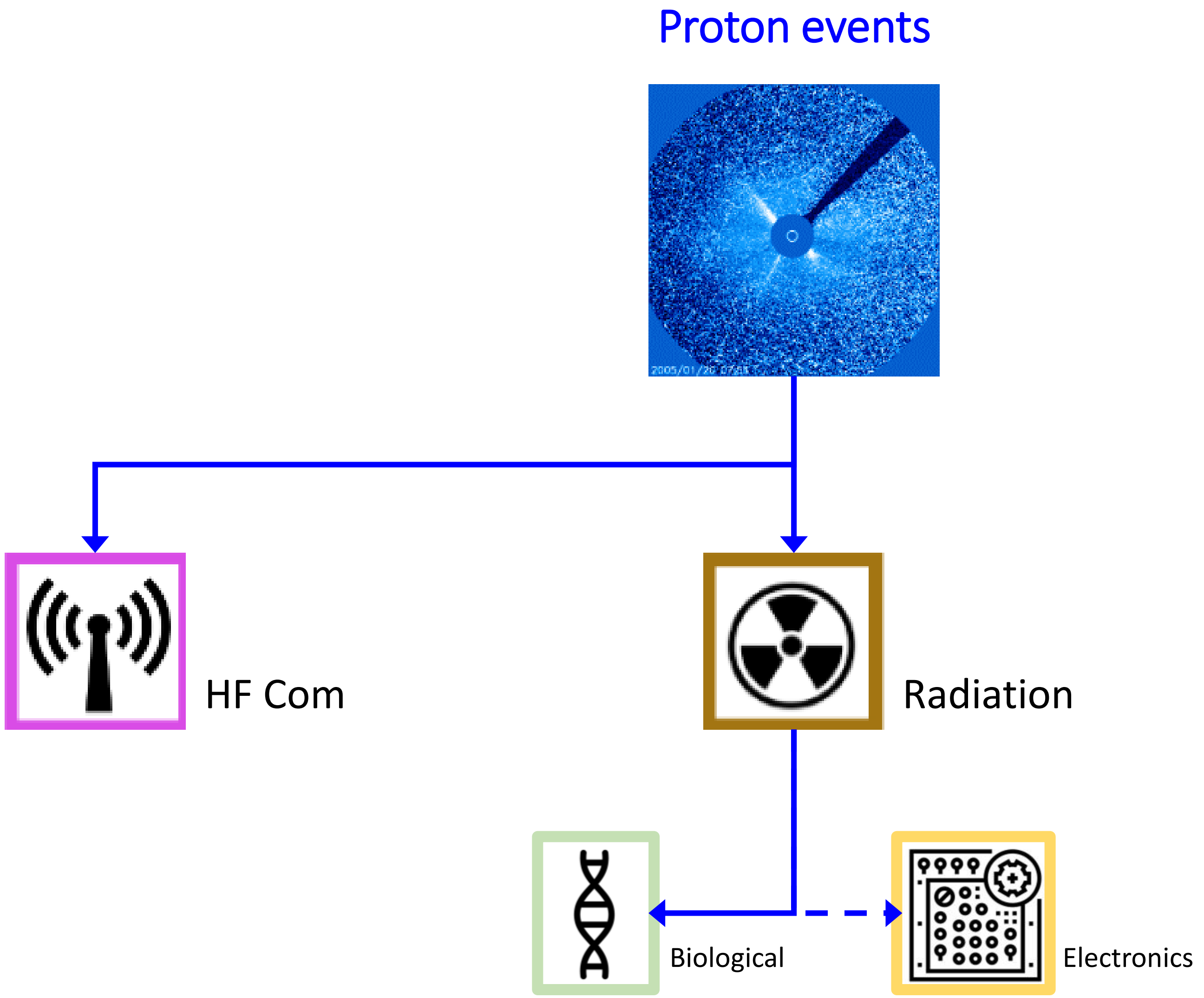
SWx impacts from proton events

Scale	Description	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

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)

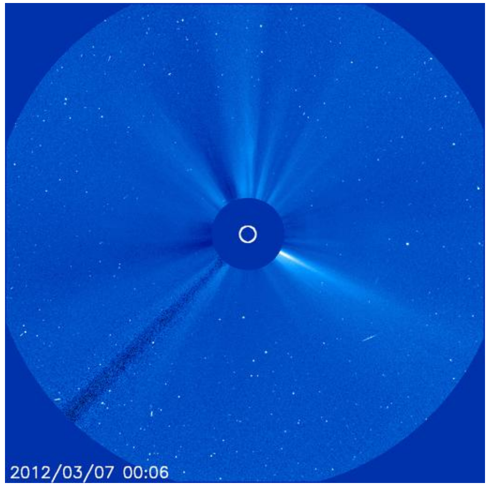
SWx impacts from proton events on aviation

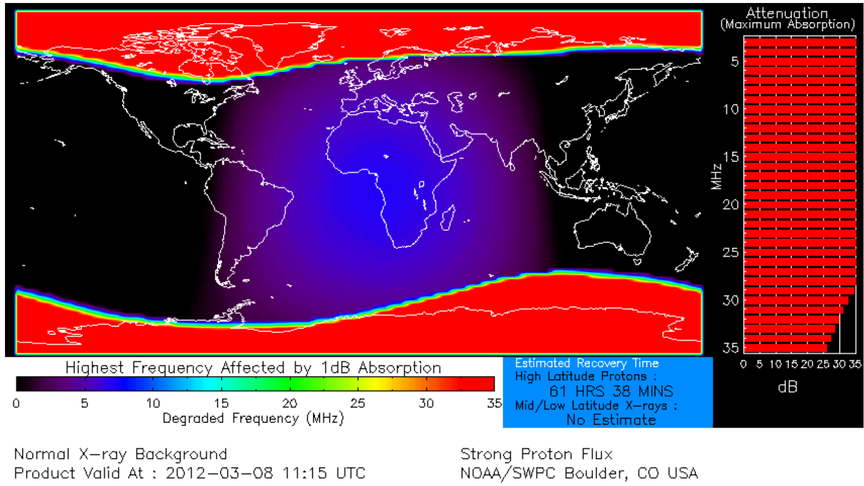


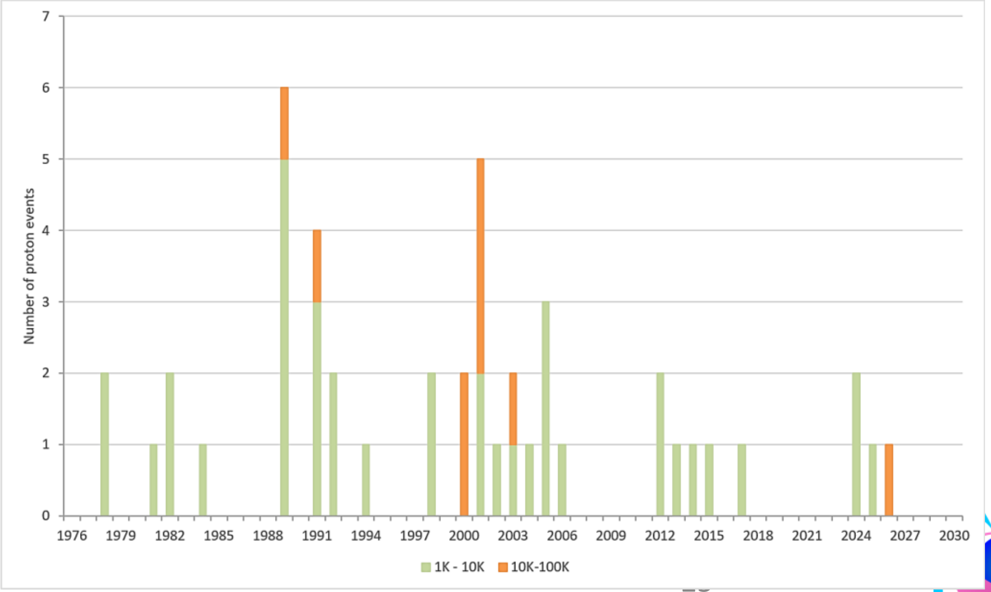
HF Com: High Frequency Communications (3-30 MHz) - - - - **Currently NOT covered by SWx advisories for ICAO**

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







MeV: megaelectronvolt ; MF: magnetic field ; HF Com: High Frequency Communications (3-30 MHz) ; pfu: proton flux units ; dB: decibel

SWx impacts from proton events on HF Com

- The disappearance of the HMS Acheron (1956)

Net Paid Circulation Over 18,350

Amsterdam Evening Recorder
AND DAILY DEMOCRAT

Weather: Milder, Snow or Sleet

Vol. LXXVII., No. 158 — Recorder Established 1833—Democrat Established 1870, Consolidated 1858 — 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 Poli…

Ousted Soviet Premier Draws…

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

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.

The British minesweeper Coquette radioed three hours after the Admiralty reported the Acheron overdue that she had made "visual contact" with the sub.

The Coquette also reported the Acheron, carrying 65 men, said her communications system was out of order. The Acheron then proceeded to Iceland.

The search started after the Acheron failed to make her routine radio report this morning.

Six hours later the Admiralty said: "The Acheron has now succeeded in passing her routine check signal and as a result the search for her has been canceled."

The 1,123-ton Acheron is a sister ship of the Affray, which sank in the English Channel in April 1951 with 75 dead.

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…

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.

Of 90 persons taken to six Maryland hospitals, 59 remained hospitalized today. Scores of others were treated at the scene by dozens of doctors and nurses.

By mid-morning, investigators still had not determined what caused the wreck of the New York-bound Embassy. A Pennsylvania Railroad spokesman said the possibility of faulty air brakes had been ruled out. The engineer said earlier the brakes had appeared to grab suddenly.

The worst mangled car was the diner. Apparently it tipped over just as it started to pass one of the heavy steel girders supporting the overhead electric cables that provide power to the engines.

16 Aboard Safe

MIAMI, Fla. (AP)—The Coast…

State Agencies

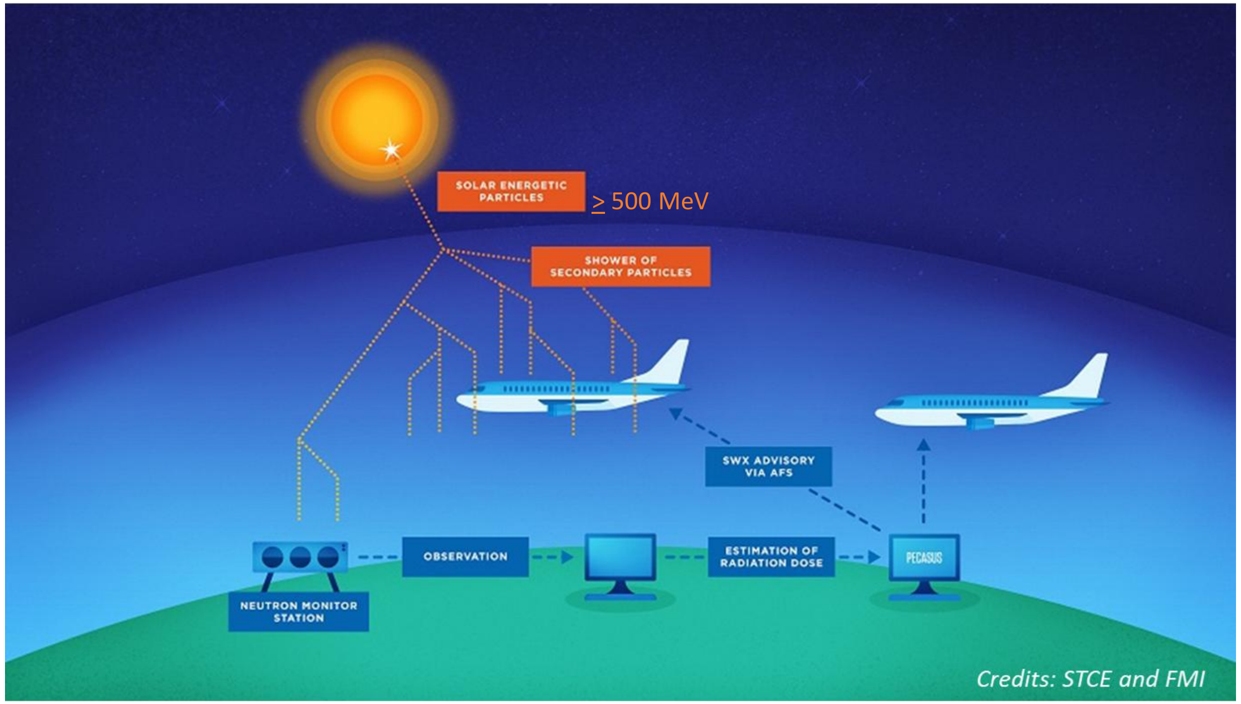
WASHINGTON (AP)—Senate Democratic and Republican leaders disclosed today they were working on a bill to put more teeth in the…

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

George … said he thought the session "will help get a return of a greater measure of bipartisan consultation." He added, "I think it would tend in that direction."

SWx impacts from proton events : Electronics

- Ground Level Enhancement (GLE)
  - Sharp increase #neutrons @ ground
  - Main source
    - Strong SEPs ~500 MeV per nucleon
      - => 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

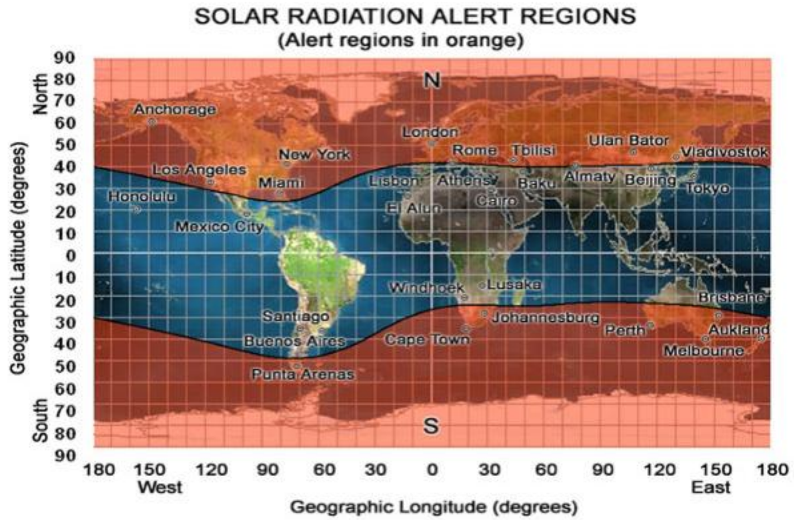
A330, Qantas Flight 72, 7 October 2008

SEP: Solar Energetic Particles ; GCR: Galactic Cosmic Rays ; MeV: megaelectronvolt
SEU: Single Event Upset ; SEL: Single Event Latchup ; SEB: Single Event Burnout

- - - - Currently NOT covered by SWx advisories for ICAO

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
  - µSv/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.

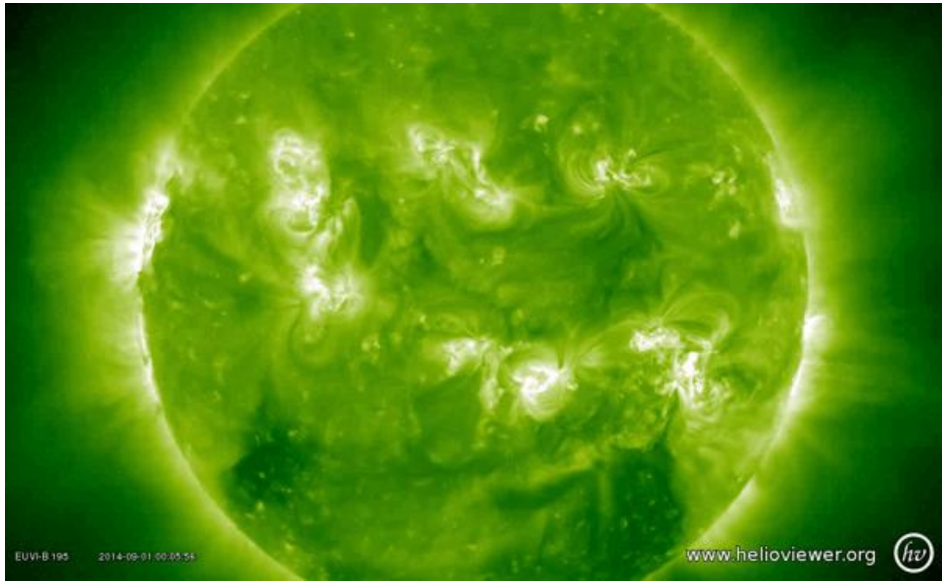
Avoiding excessive radiation exposure during pregnancy is particularly important.

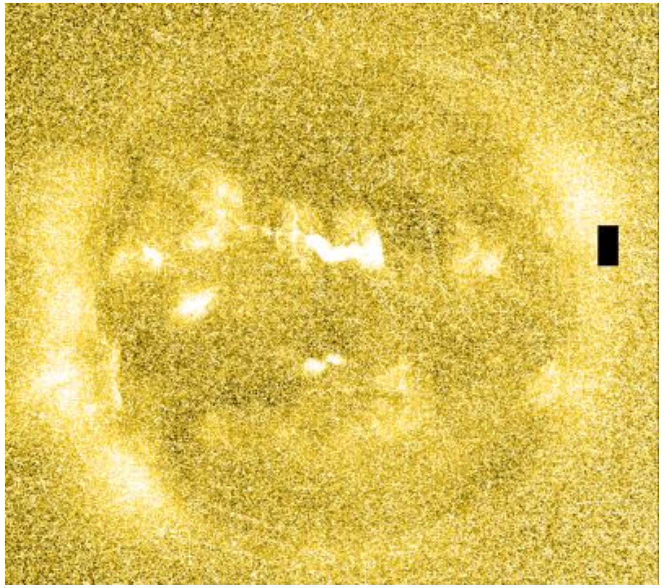
Reducing flight altitude may significantly reduce flight doses. Available data indicates that lowering flight altitude from 40,000 feet to 36,000 feet should result in about a 30 percent reduction in dose rate. A lowering of latitude may also reduce flight doses but the degree is uncertain. Any changes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

ICAO: International Civil Aviation Organization ; ISS: International Space Station ; GLE: Ground Level Enhancement ; µSv/h: microsievert per hour ; mSv: millisievert ; FL: Flight Level (100 feet) ; pfu: proton flux units

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

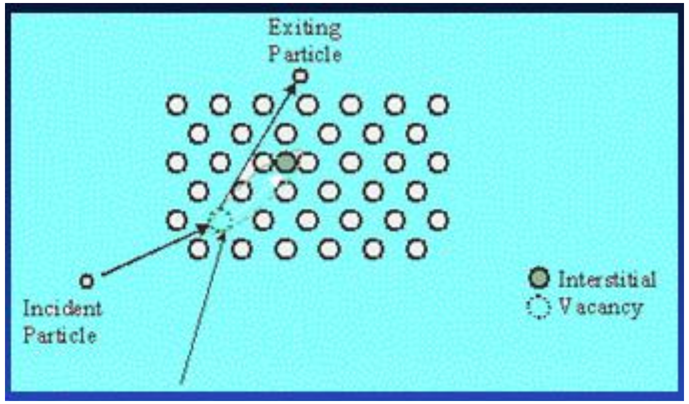


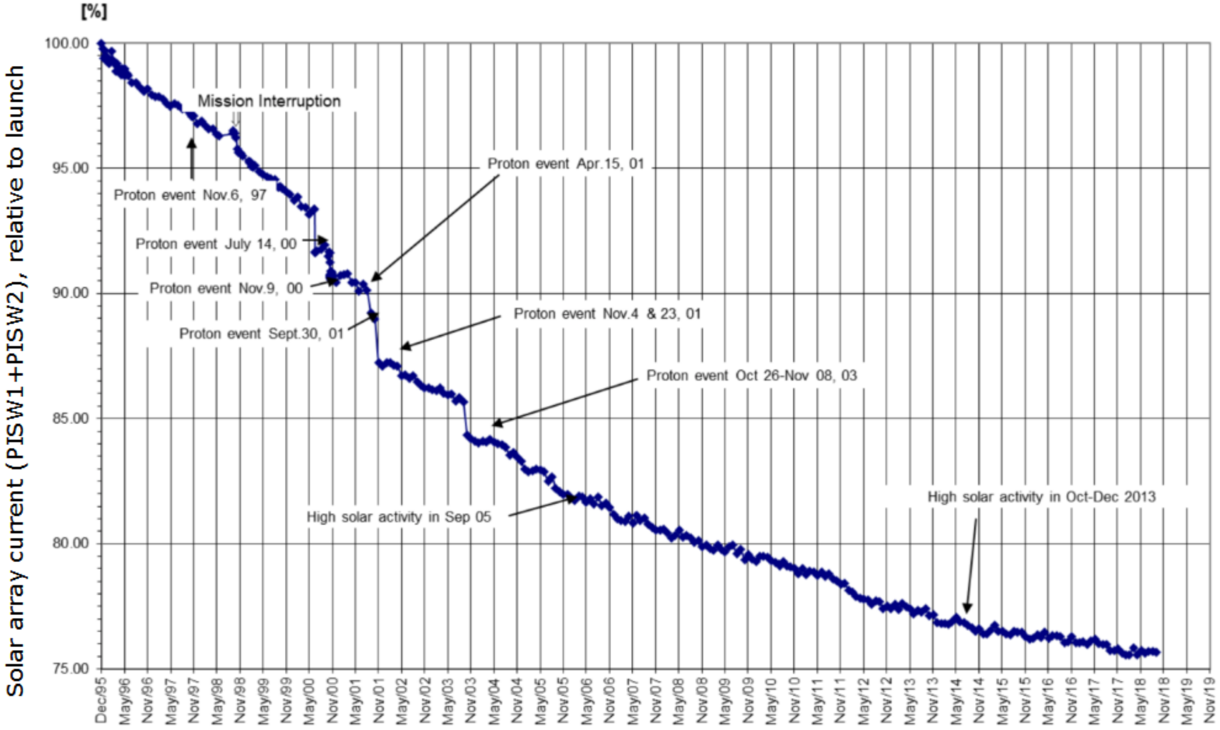


SWEC
Space Weather Education Center

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





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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)
        - DSCOVR
      - Solar proton storms
      - Radiation belts

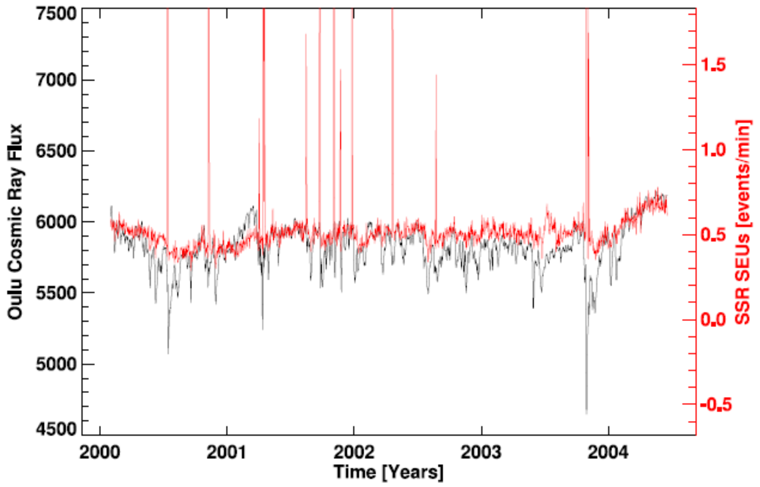
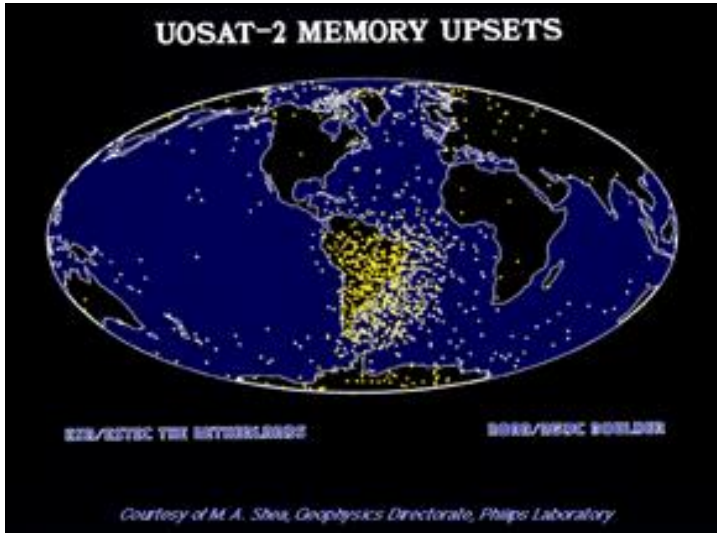
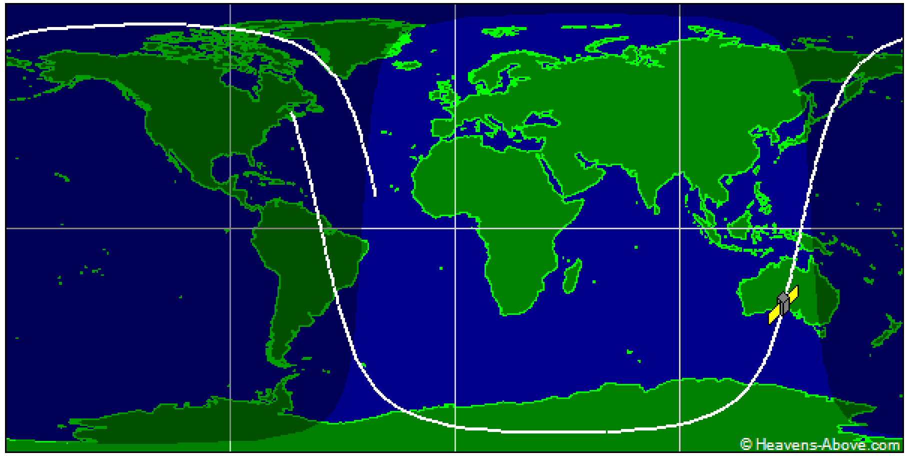
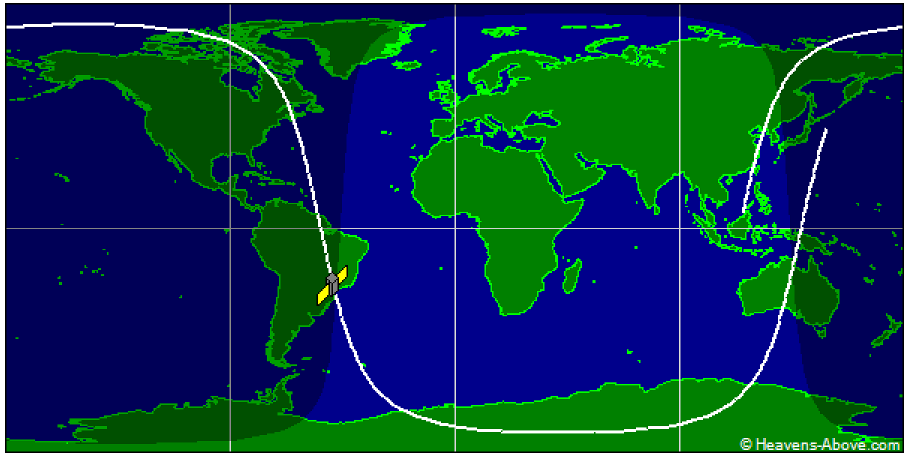


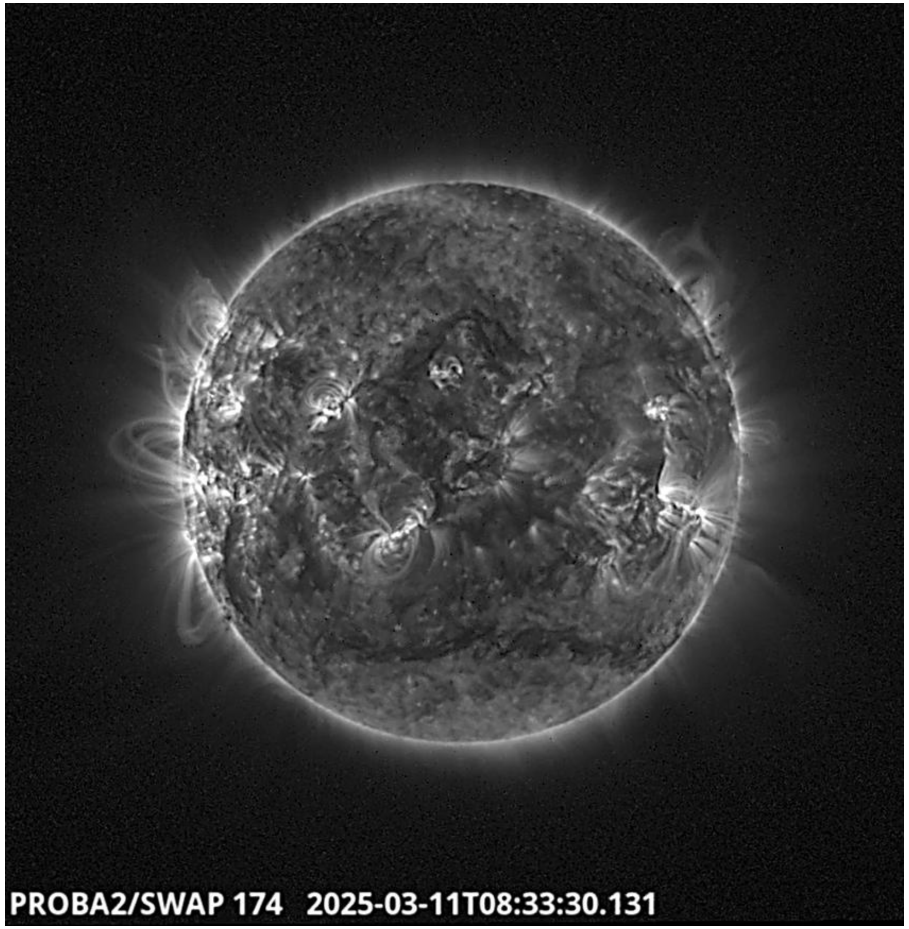
Figure 3: Subset of the data in Fig. 1 during solar maximum. The plot shows a dozen sharp spikes on top of the solar-cycle-modulated background of SSR SEUs triggered by cosmic ray hits. These spikes are caused by isolated strong SEP events. Most of them coincide with a CRF down spike.

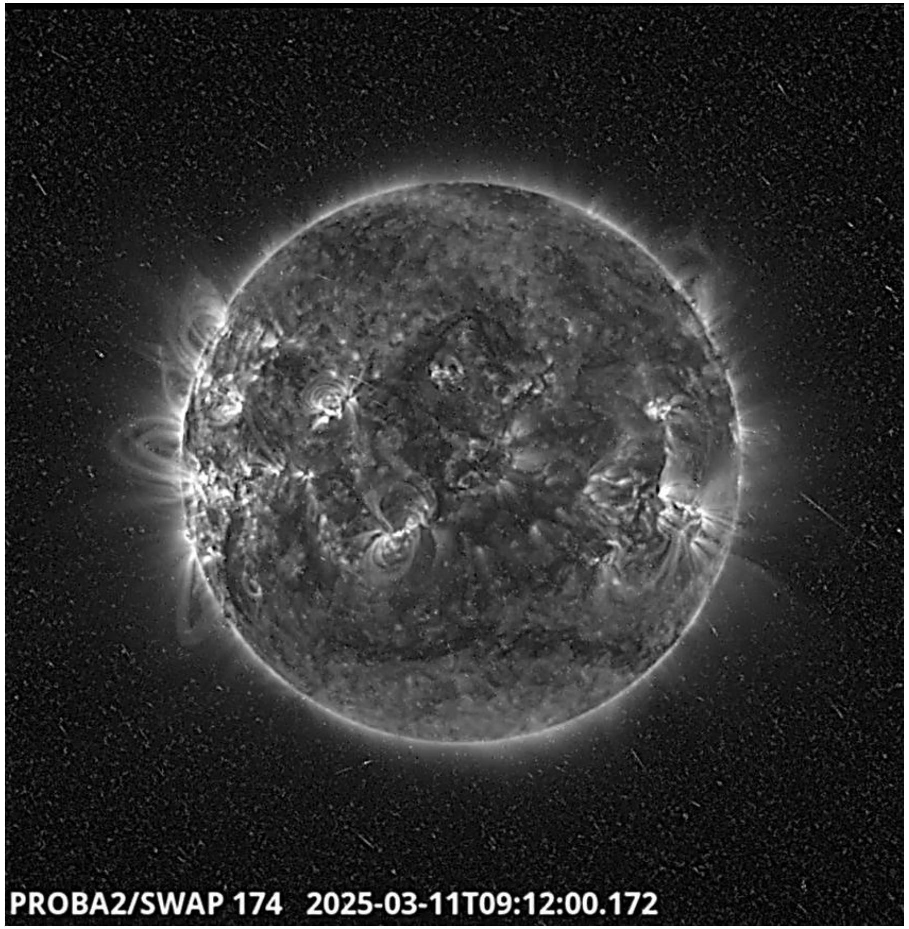


SEU: Single Event Upset ; SEL: Single Event Latchup
SEB: Single Event Burnout ; DSCOVR: Deep Space Climate Observatory









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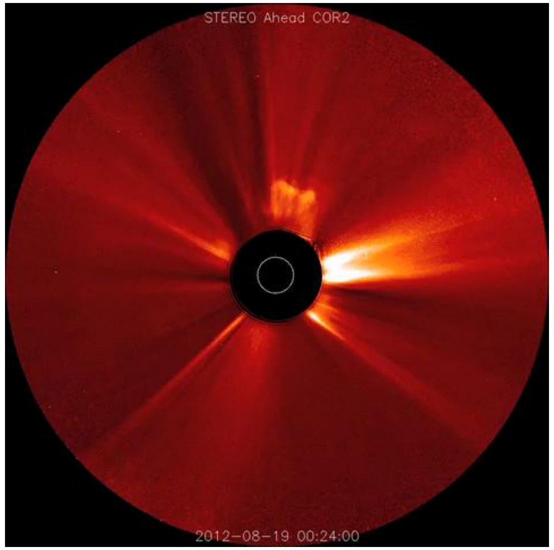
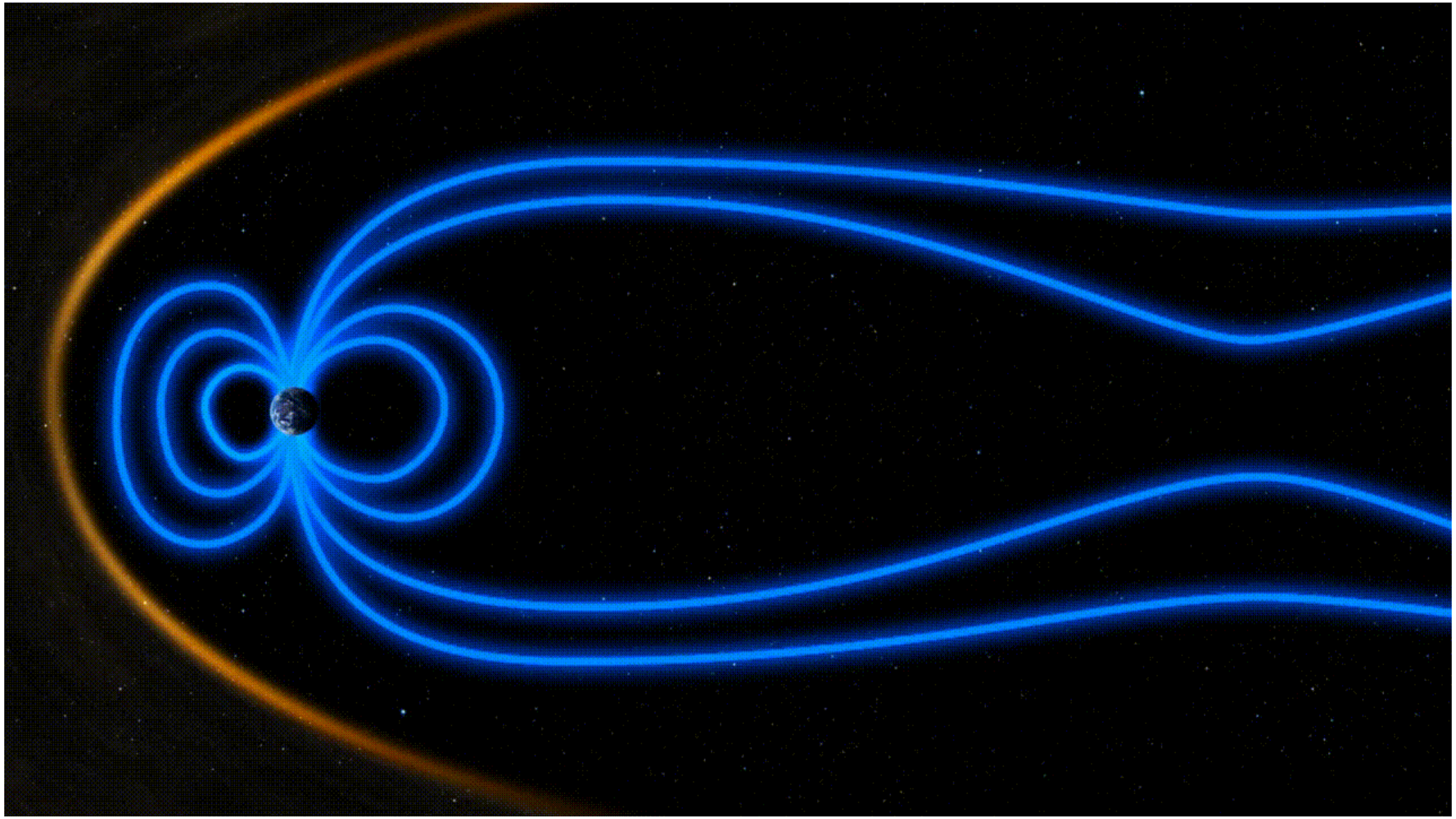
Space Weather impacts (SWx impacts)

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

Coronal Mass Ejections



SWx impacts from ICMEs



Credits: ESA

SWx impacts from ICMEs

Scale	Description	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)

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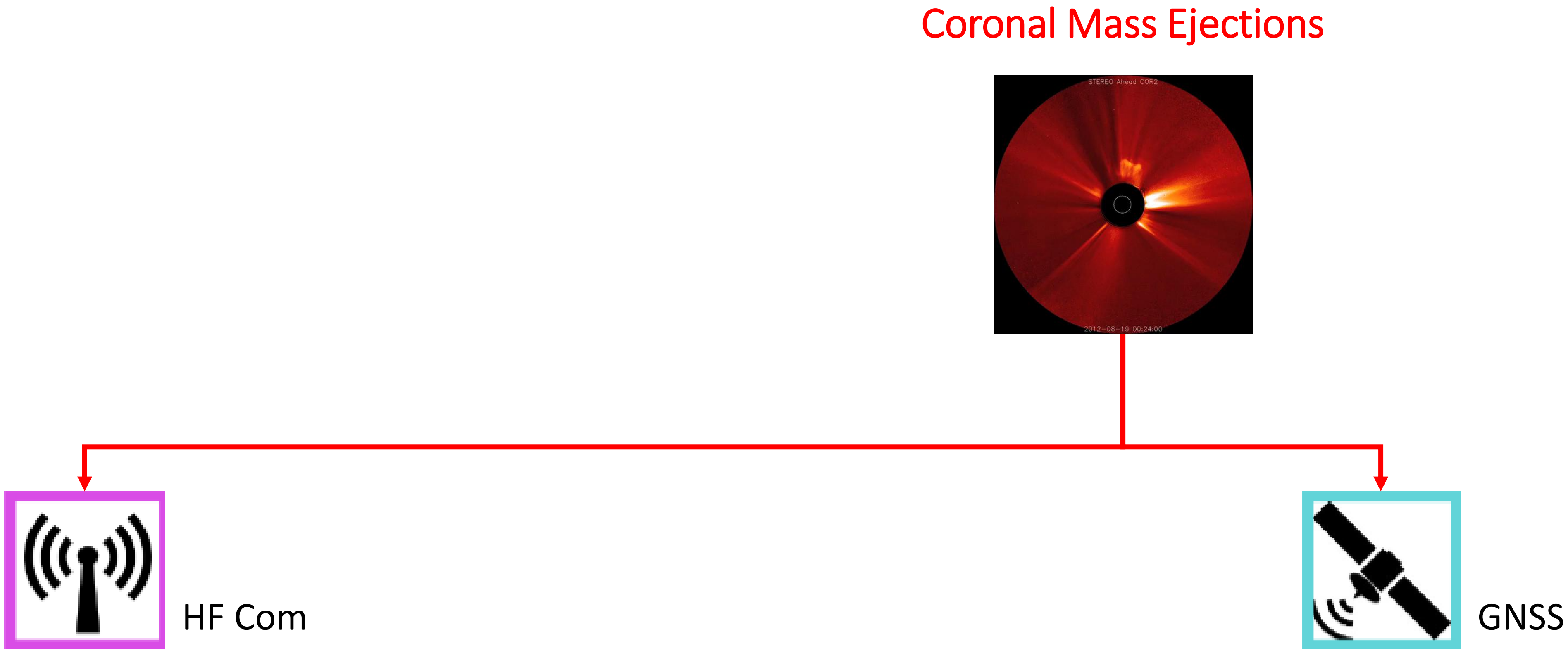
SWx impacts from ICMEs

- 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)

GCR: Galactic Cosmic Rays ; GNSS: Global Navigation Satellite Systems ; Comms/Nav: Communications/Navigation
PECASUS: Pan-European Consortium for Aviation Space weather User Services ; HF: High Frequency

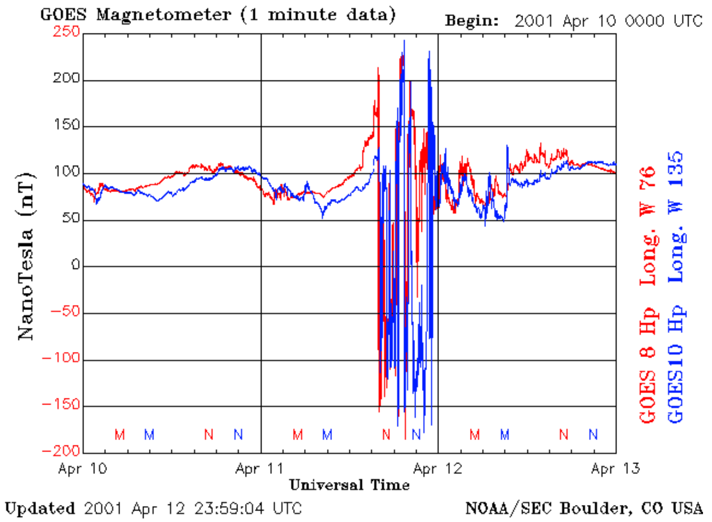
SWx impacts from ICMEs on aviation

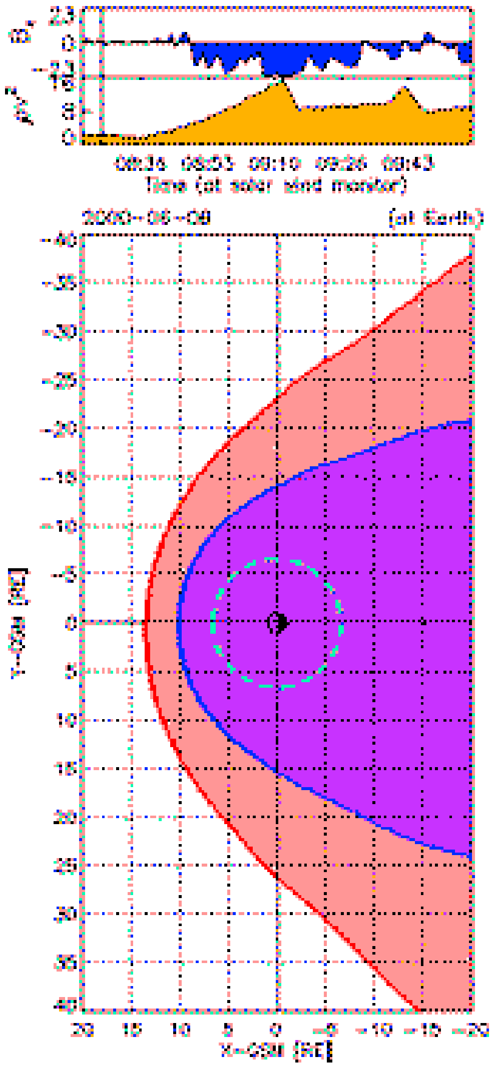


HF Com: High Frequency Communications (3-30 MHz) ; GNSS: Global Navigation Satellite Systems (GPS, Galileo,,…)

SWx impacts from ICMEs

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



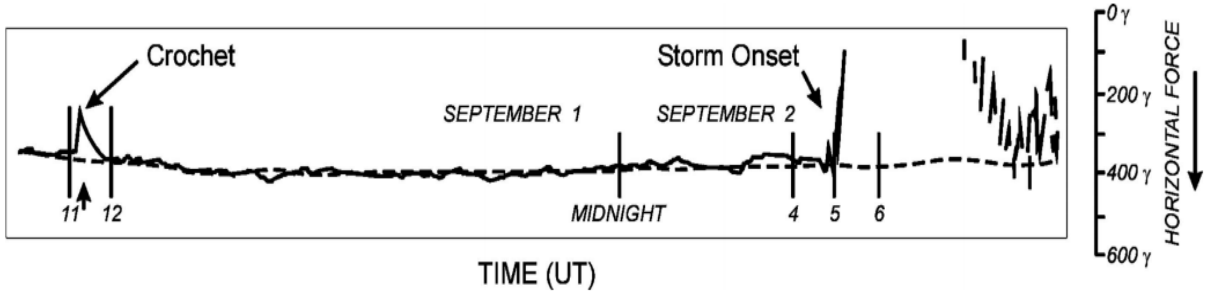


GEO: geostationary (equatorial) orbit

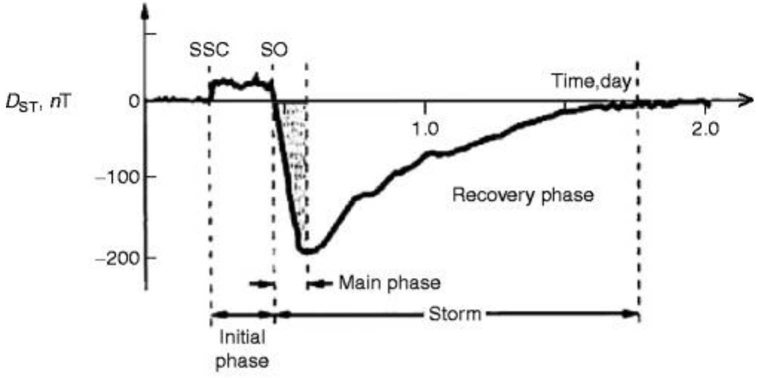
SWx impacts from ICMEs

Rapid geomagnetic variations

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



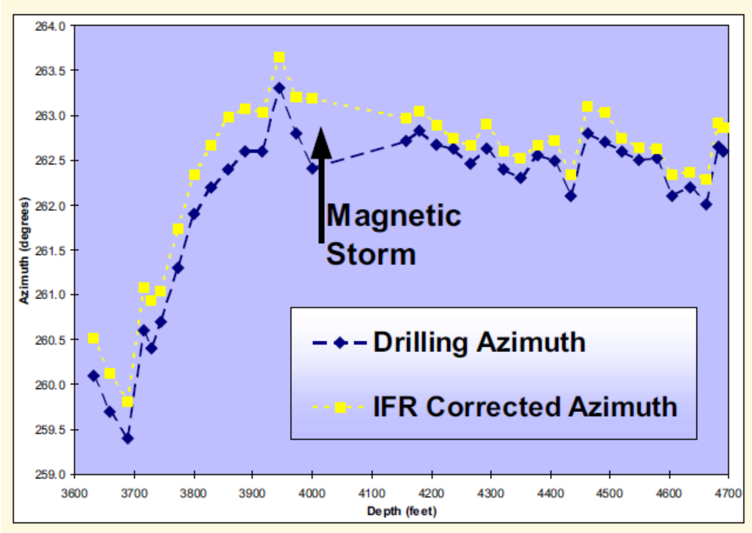
- Storm Sudden Commencement (SSC)
  - Sudden impulse (SI)
    - = no geomagnetic storm
  - Source
    - Dayside compression by strong ICME
    - Global, but f(local sit.)
  - Max. Amplitude: +/- 300 nT
    - 10-11 May 2024: 108 nT



SWx impacts from ICMEs

Rapid geomagnetic variations

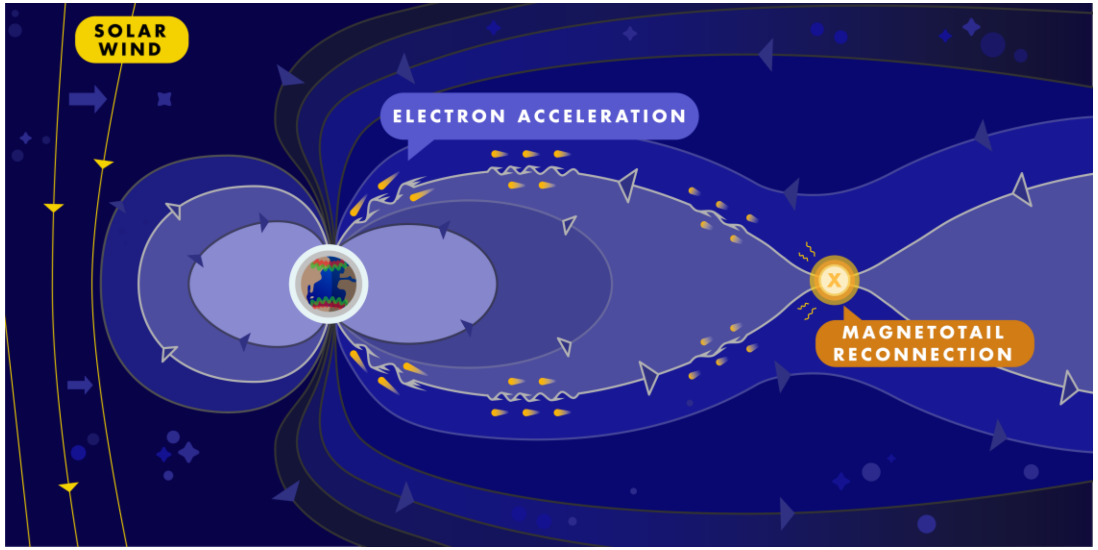
- High-precision industry
  - Industries depending on amplitude of magnetic field
    - magnetic anomaly surveys
    - directional wellbore drilling
  - Performance degradation
    - Mitigation possible
  - 4 August 1972
    - Vietnam: sea mine detonation
  - 10-11 May 2024
    - ONC – Ocean Networks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



IIFR: Interpolated In-Field Referencing

SWx impacts from ICMEs

- Aurora



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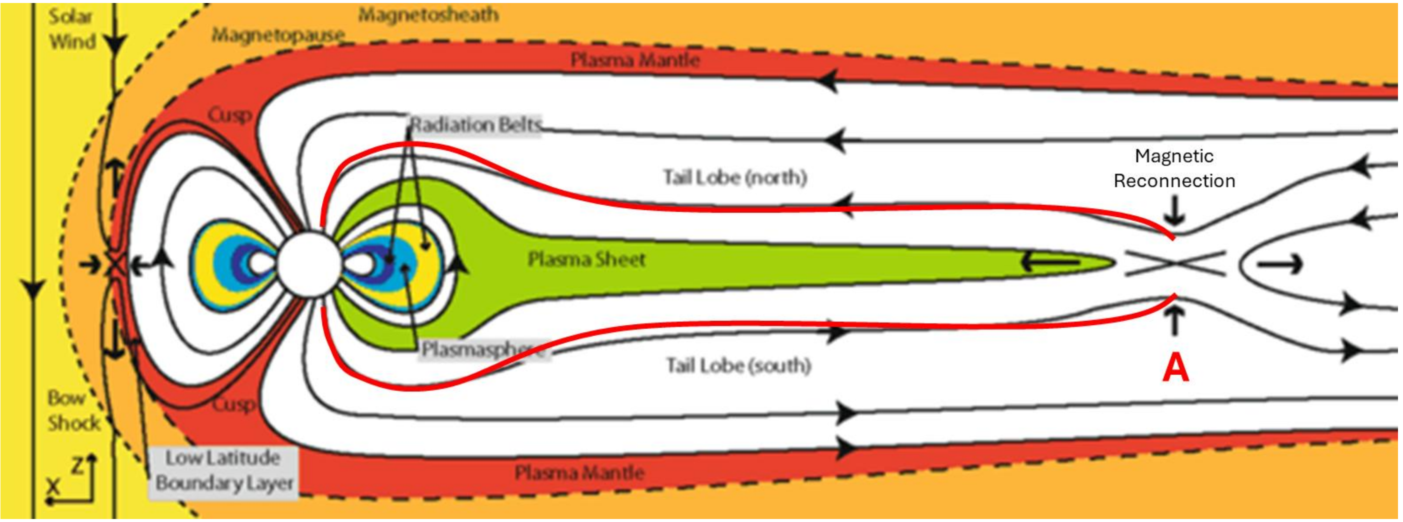
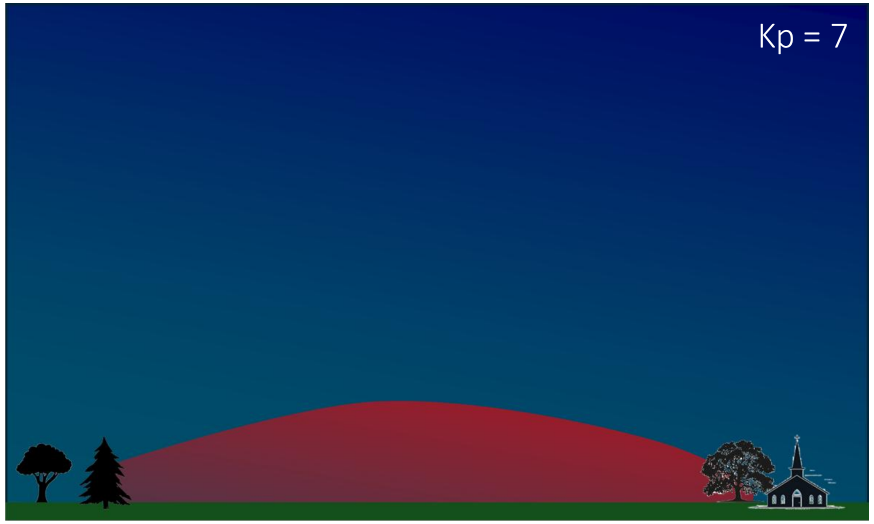
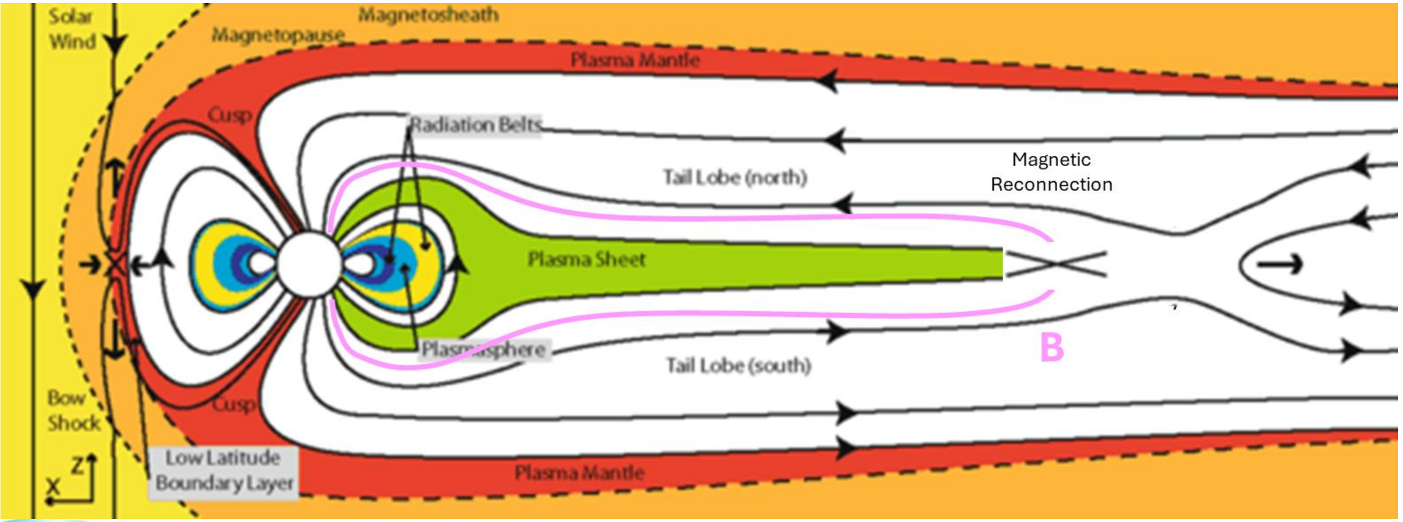
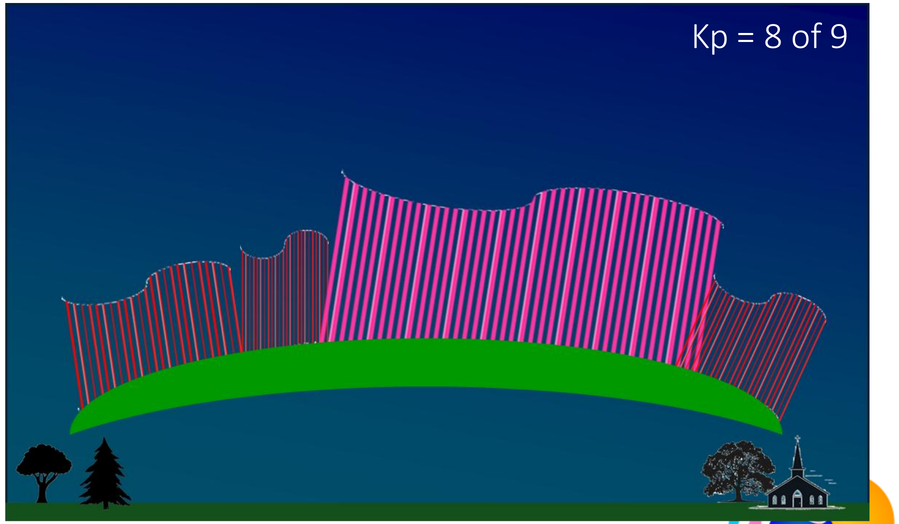
SWx impacts from ICMEs









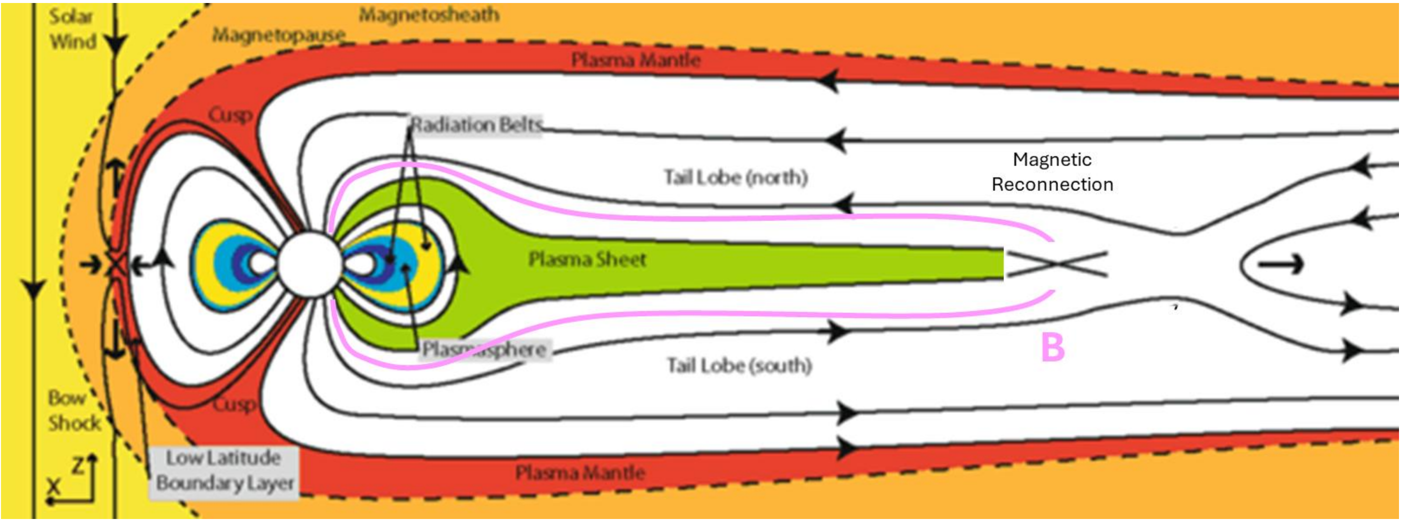
https://www.stce.be/news/802/welcome.html

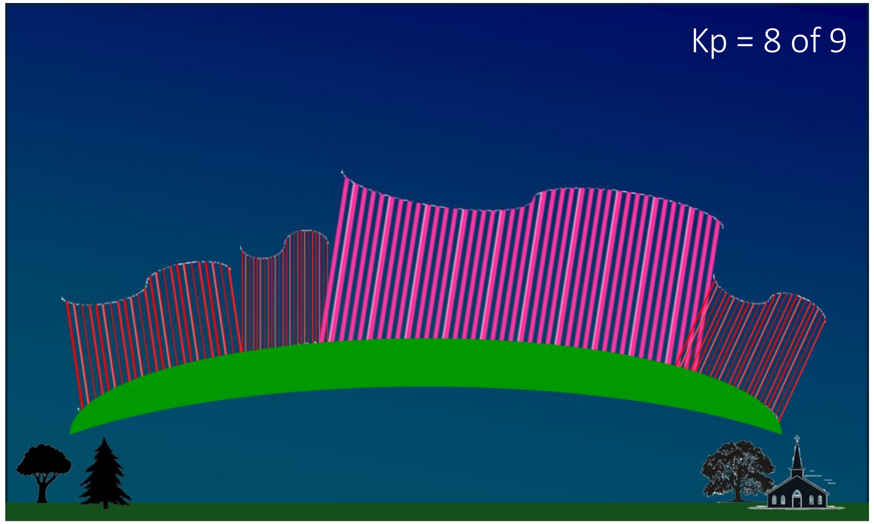
SWx impacts from ICMEs

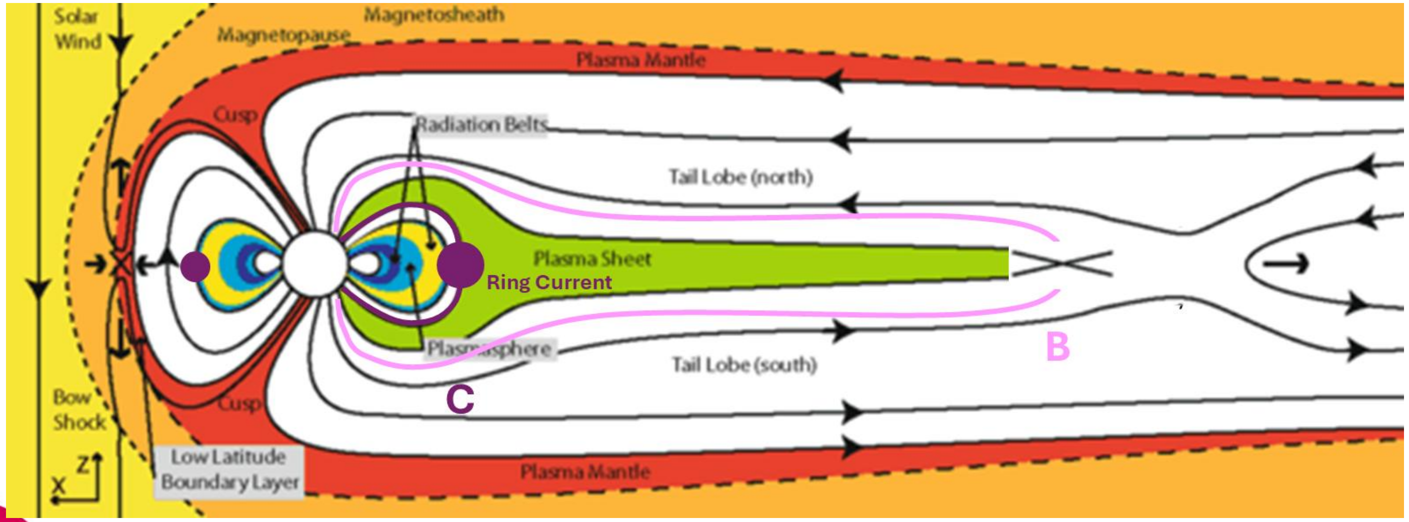
Aurora on 19-20 January 2026

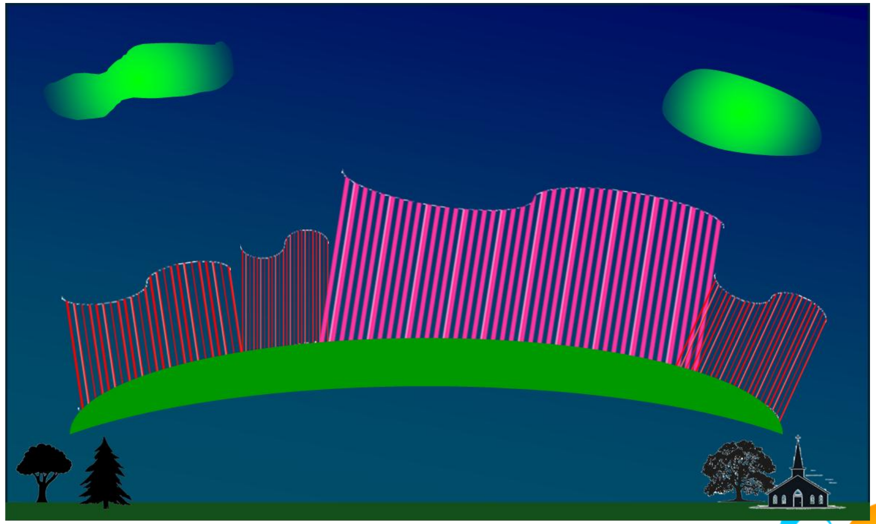
Credits: Jonas Piontek - https://www.youtube.com/watch?v=MxM-h5pU9mE ; STCE newsitem: https://www.stce.be/news/802/welcome.html

SWx impacts from ICMEs









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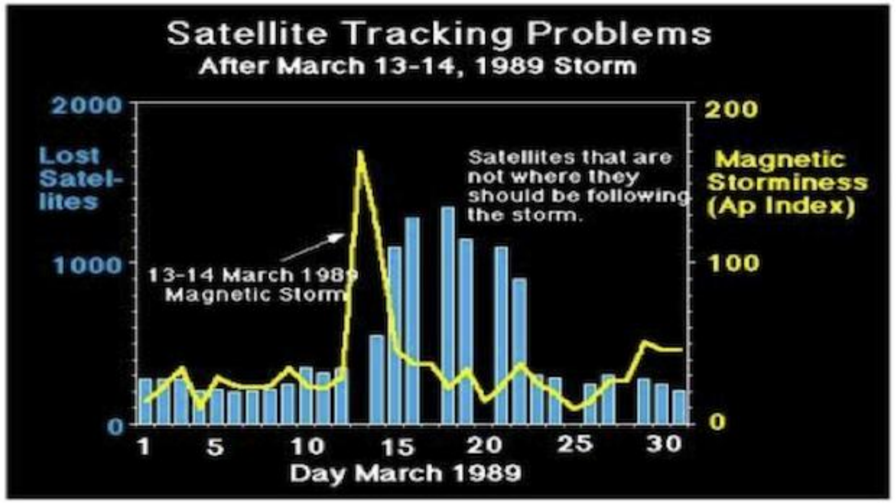
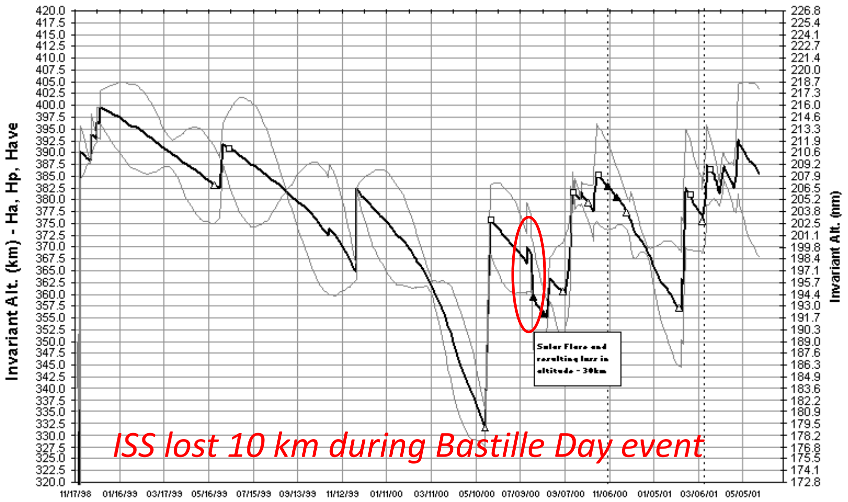
https://www.stce.be/news/802/welcome.html

SWx impacts from ICMEs

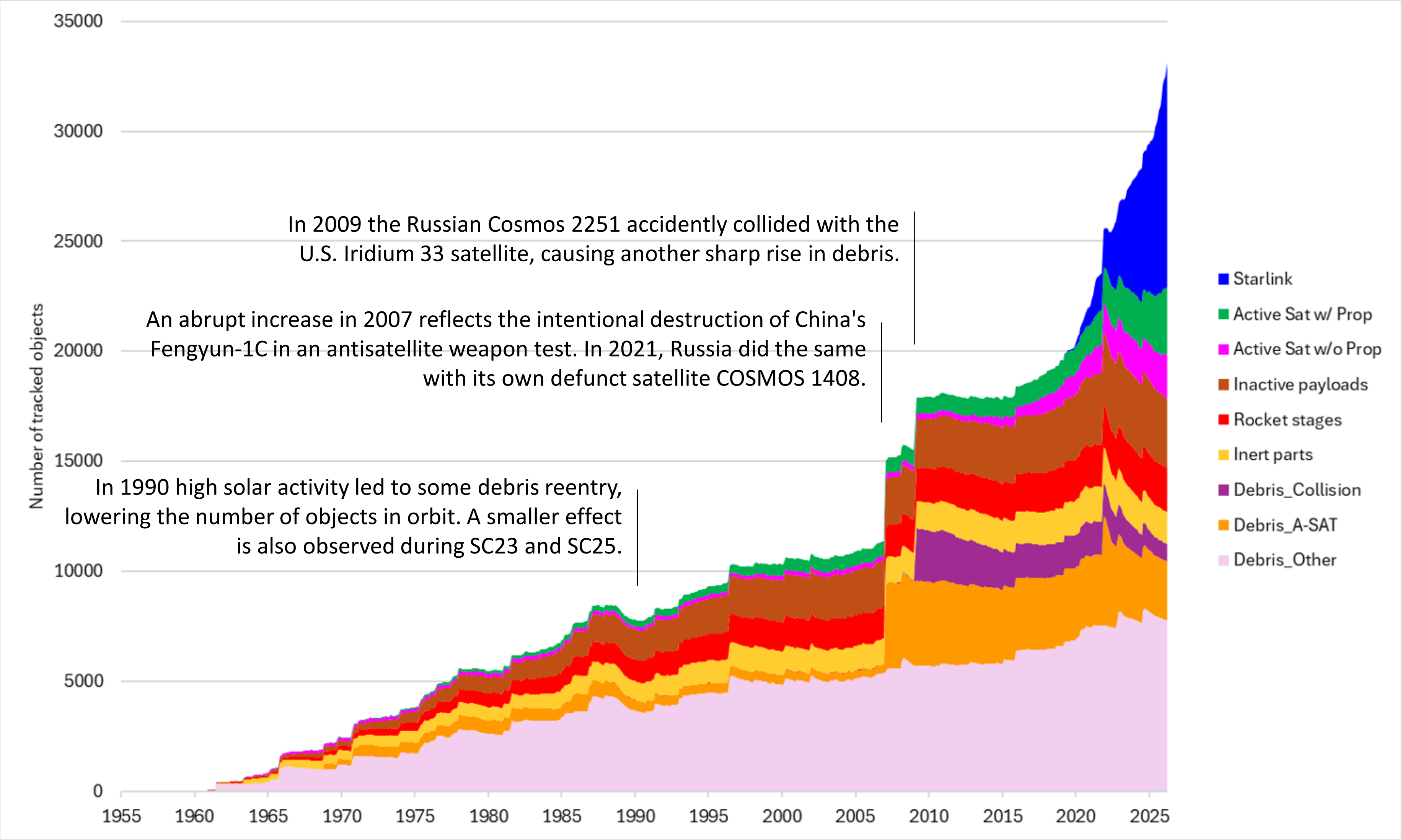
- Satellites
  - Atmospheric drag
    - Low Earth Orbit (LEO)
    - Sources
      - Shortterm: ICME
        - NOAA: Kp > 6
      - Longterm: Solar EUV radiation (solar cycle)
        - NOAA: F10.7 > 250 sfu
    - Slows down satellite
      - Burns up in atmosphere
    - Examples
      - March 1989
        - 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-M/USSP Tracked SV Data)



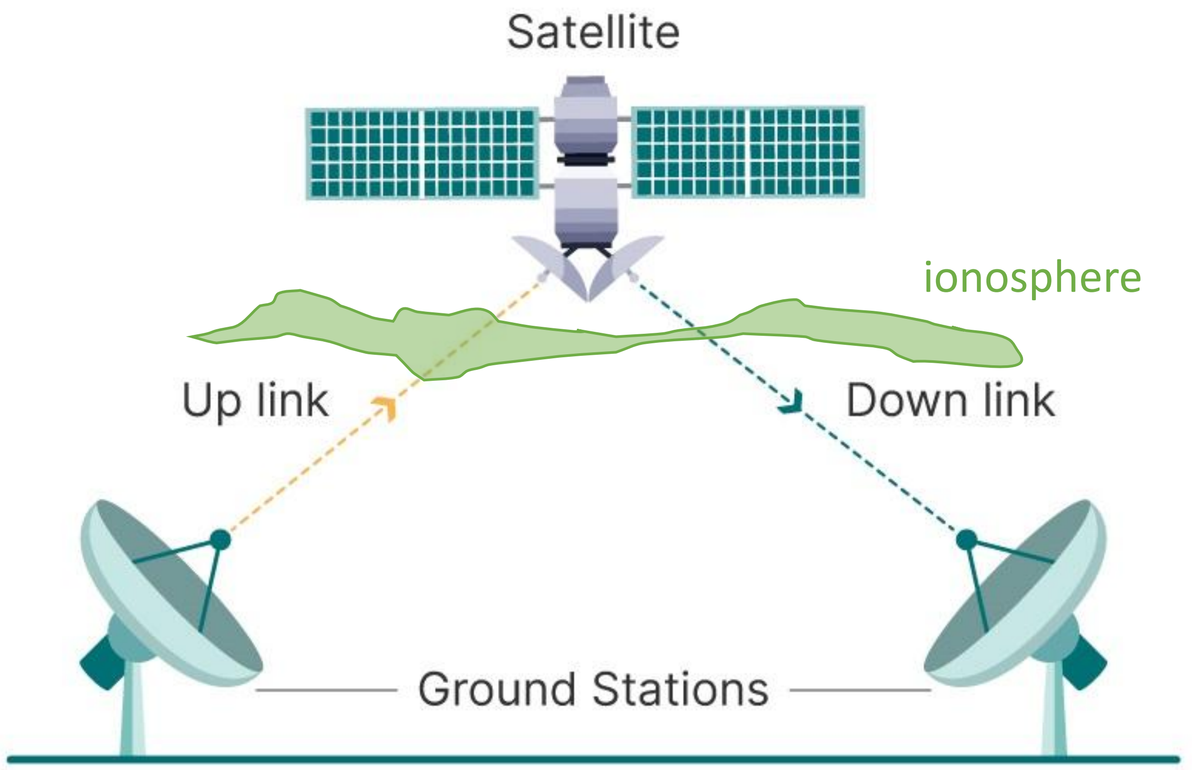
SWx impacts from ICMEs



https://www.stce.be/news/816/welcome.html

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…



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 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

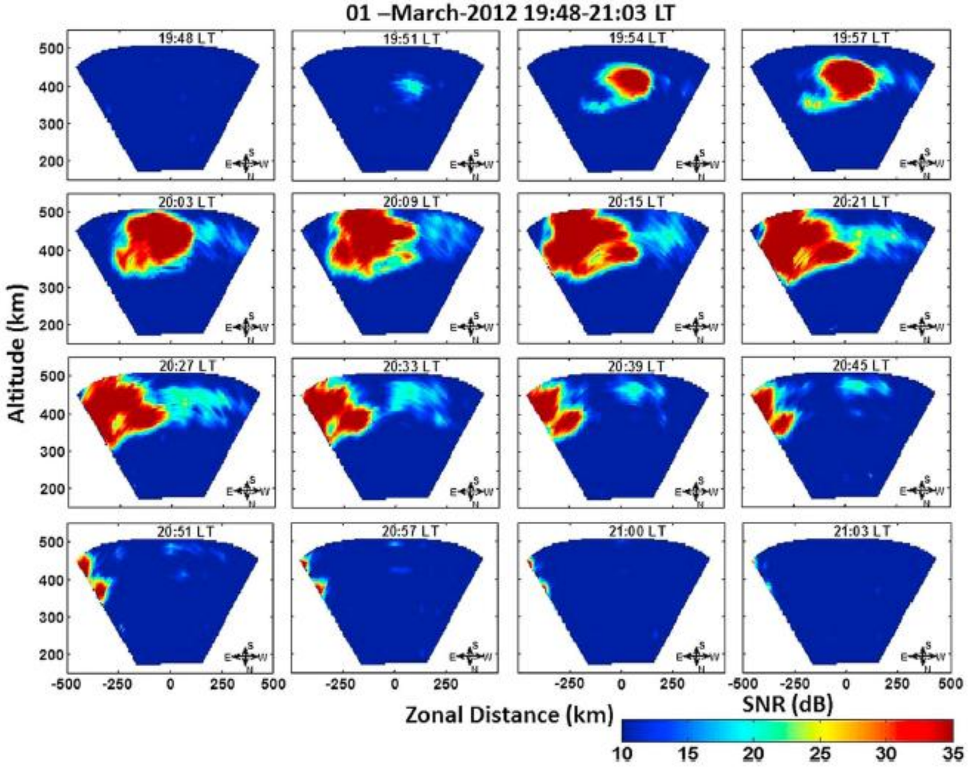
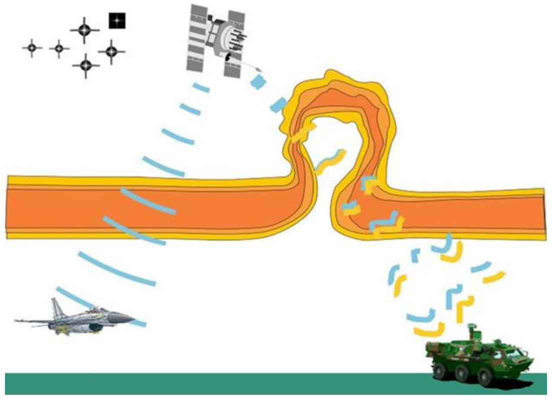


Figure 1. An example showing the genesis and successive development of EPB (evolving-type) over Kototabang observed from the fan sector maps of EAR on 1 March 2012.

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

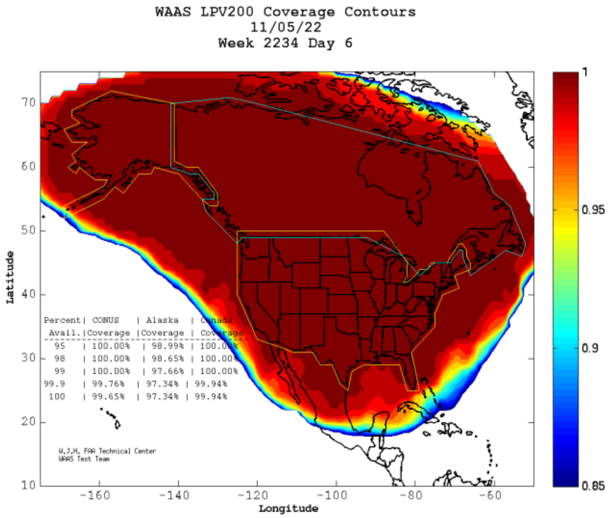
SWx impacts from ICMEs on SATCom/GNSS

- 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!



Credits: US Air Force Research Laboratory

- GNSS applications such as WAAS & EGNOS
  - 7 November 2022
  - 10-11 May & 10-11 October 2024
    - Complete loss of GNSS applications for several hours



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

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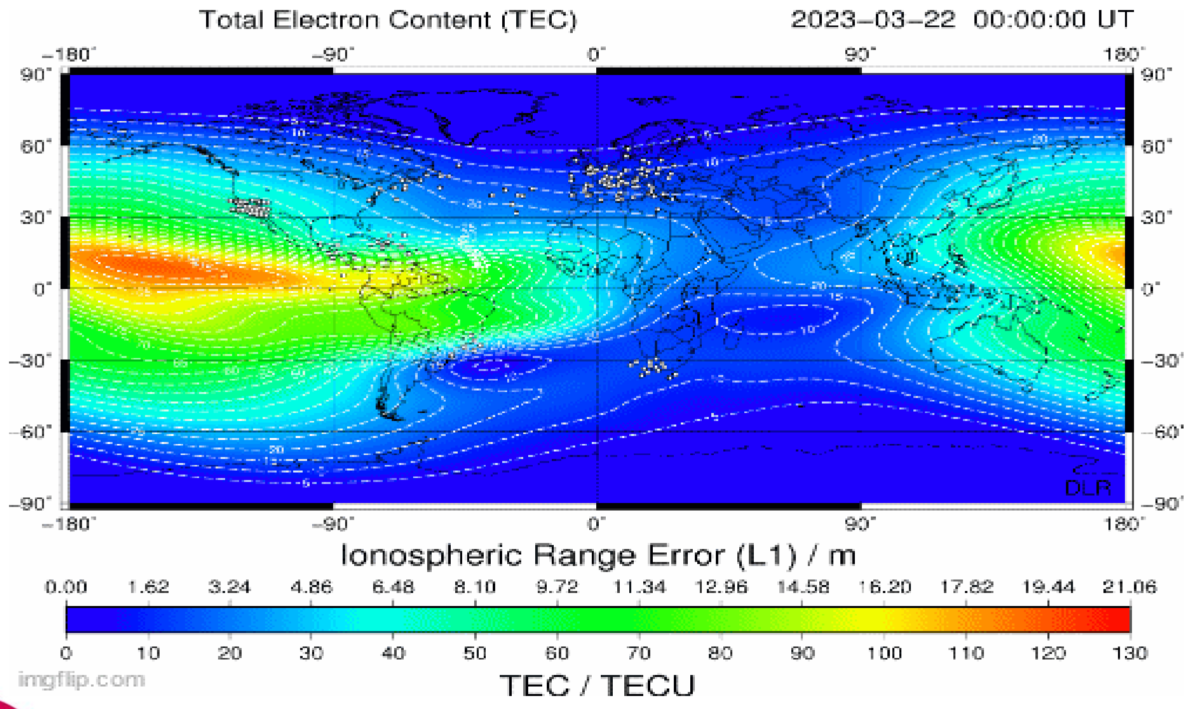
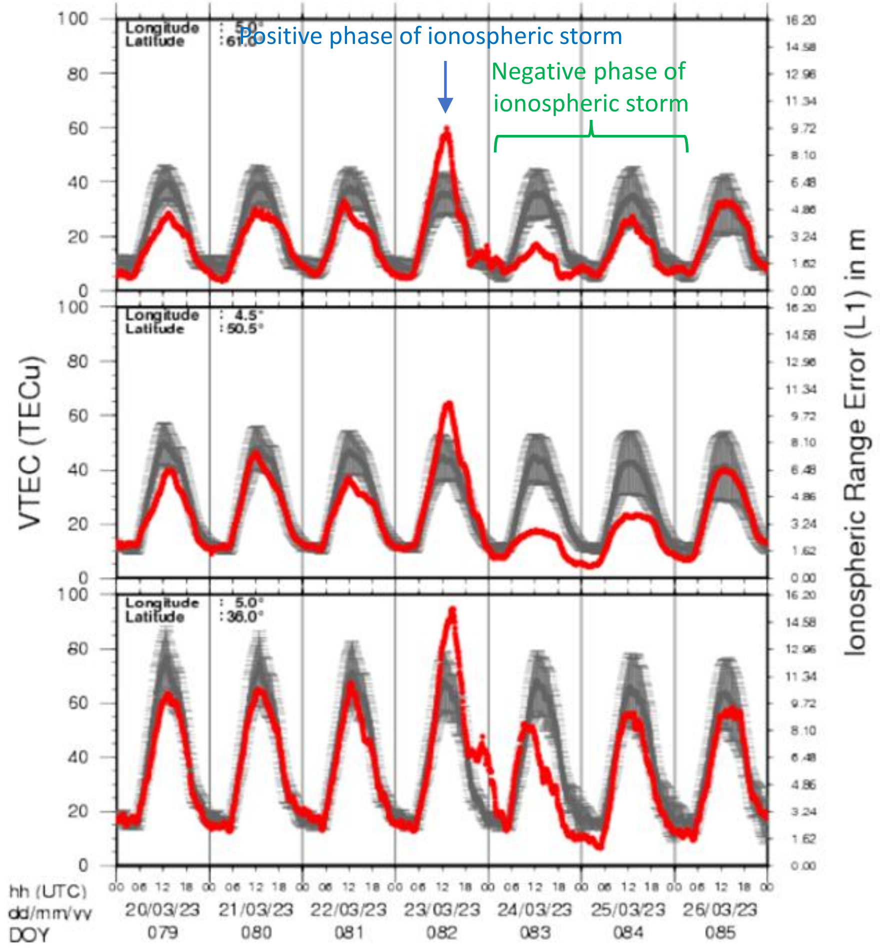
SWx impacts from ICMEs on HF Com

- Ionospheric storm
  - Example: 23-24 March 2023
  - Kp = 8o ; Dst = -163 nT



Credits images: PECASUS & DLR/IMPC



Credits: ROB/GNSS

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

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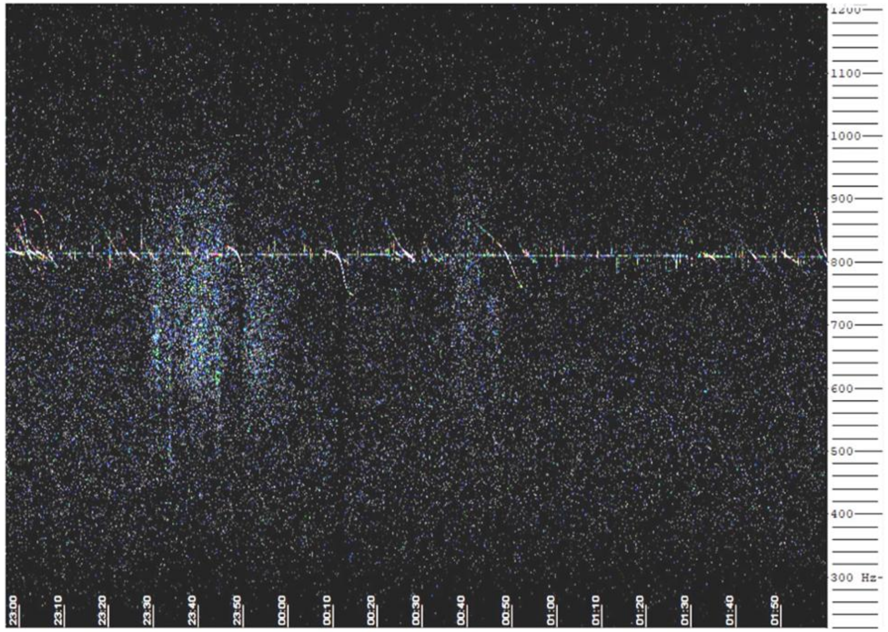
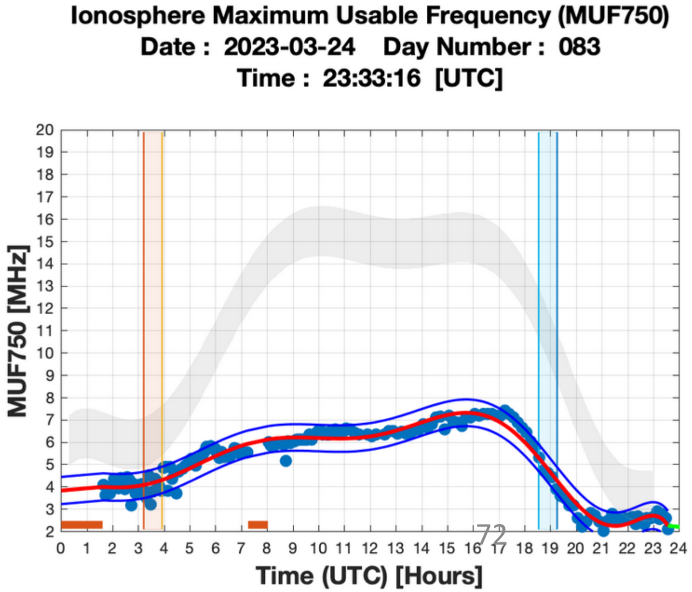
SWx impacts from ICMEs on HF Com

- 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

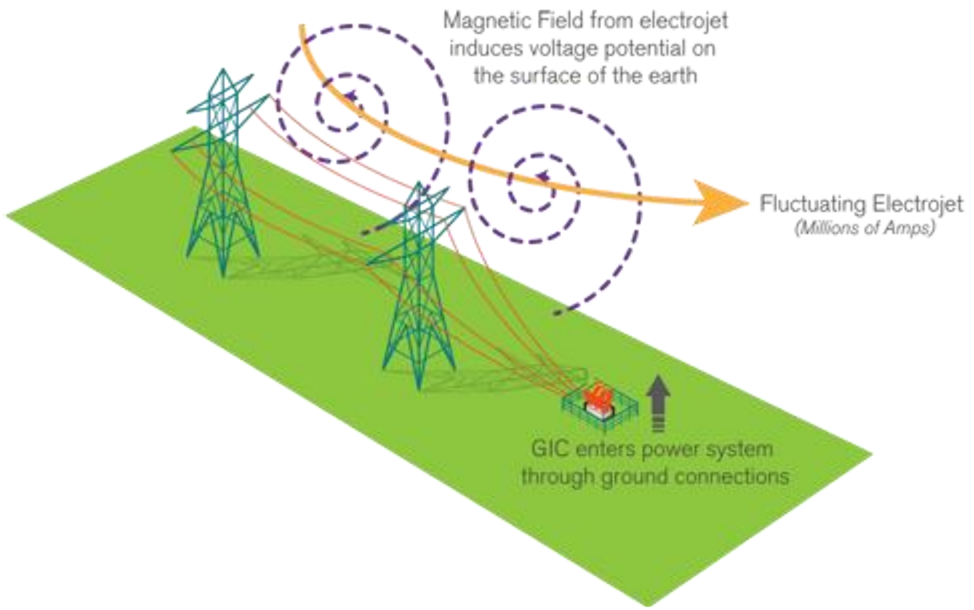


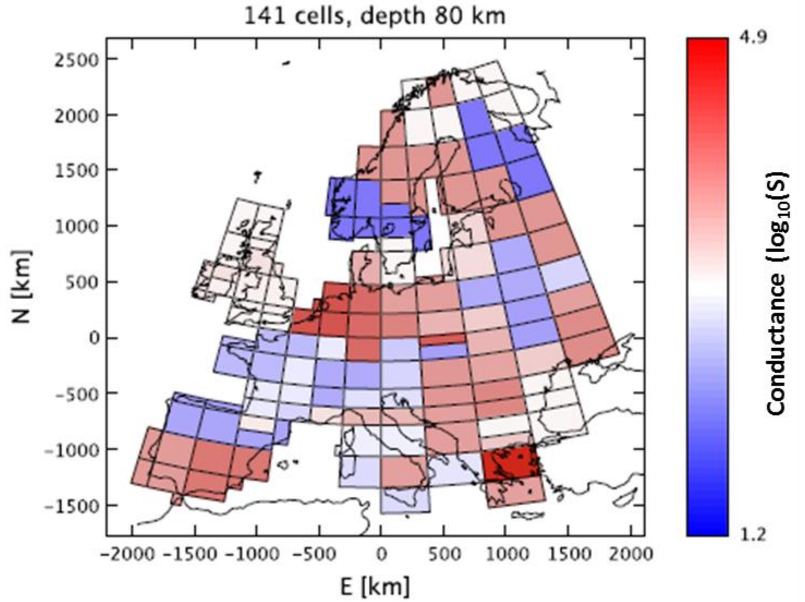
Credits: IMPC – 24 March 2023

HF Com: High Frequency Communications (3-30 MHz) ; ICME: Interplanetary coronal mass ejection ; TEC: Total Electron Content

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





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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!

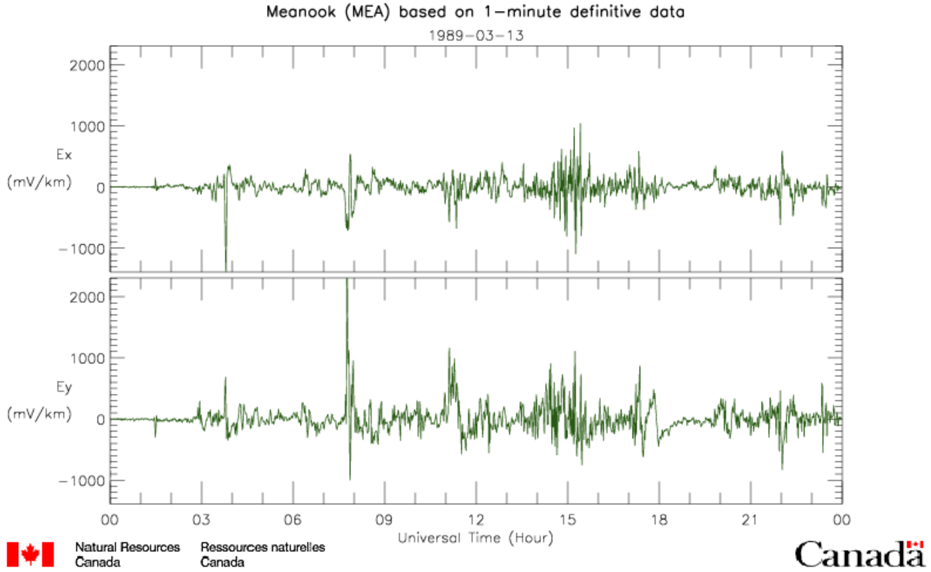

Table 3 Parameters for the GIC emergency alert model. The criterion for each alert level is shown in the second column, and the following columns show the expected extreme dB/dt values for RC-, AE-, and SC-type GICs

		dB/dt of GICs		
Alert level	Criterion	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

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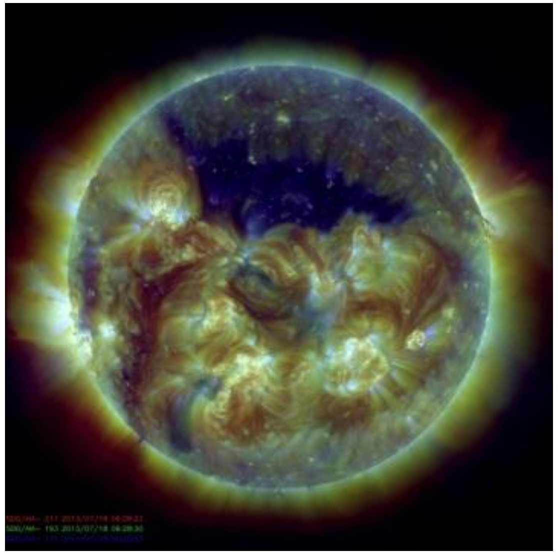
Effects from ICMEs

- 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



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SWx impacts from CHs

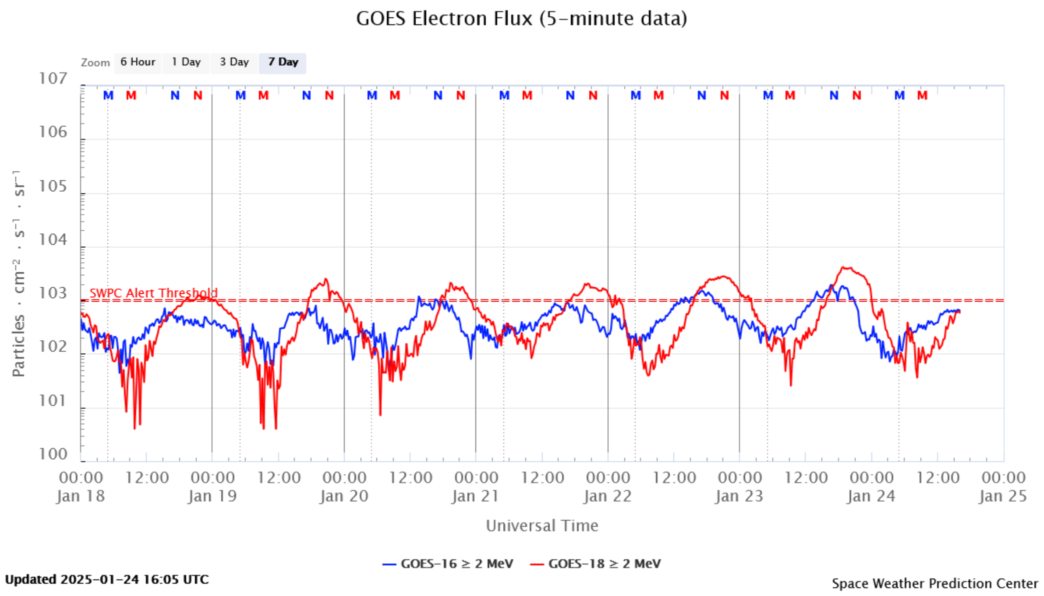
Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft 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**

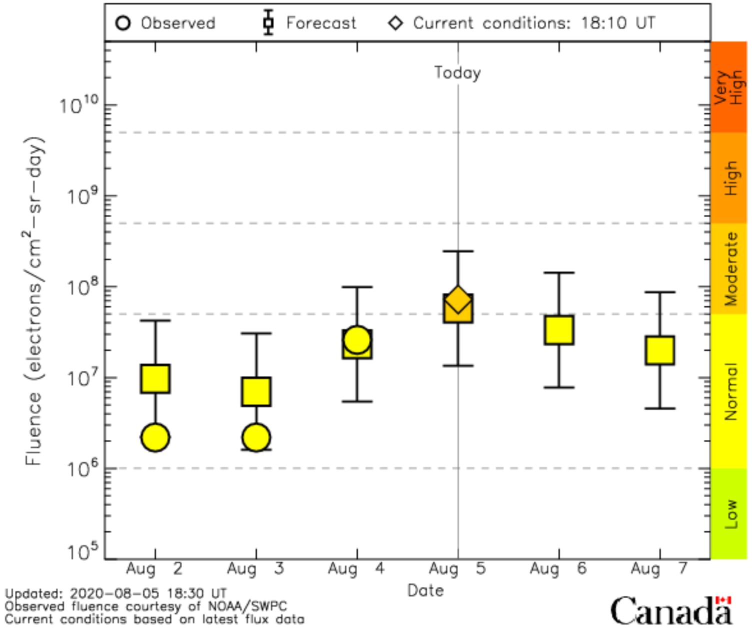
SWx impacts from CHs on satellites

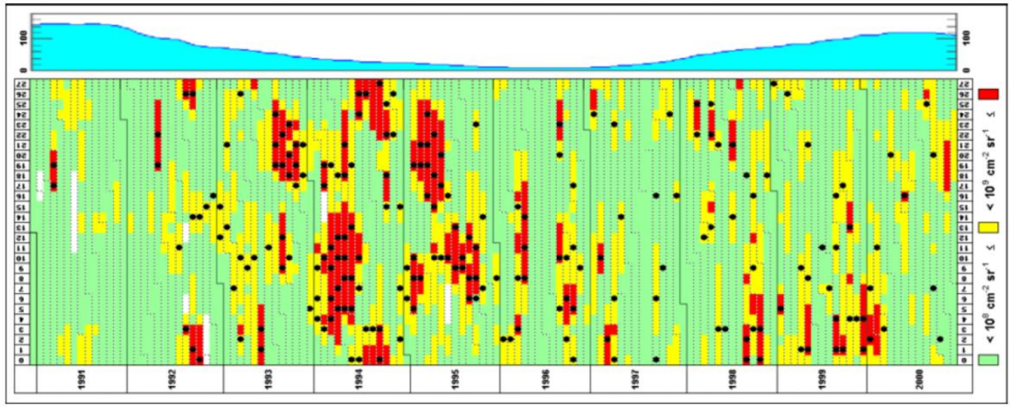
- High-Speed Stream (HSS)
  - Satellite charging
    - Deep di-electric charging
      - About 1 to a few MeV e-
      - Deeply penetrate spacecraft (S/C)
    - Fluxes > 2 MeV e-
      - Accumulation effect within S/C (ESD: electrostatic discharge)
    - Dayside effect



SWx impacts from CHs on satellites

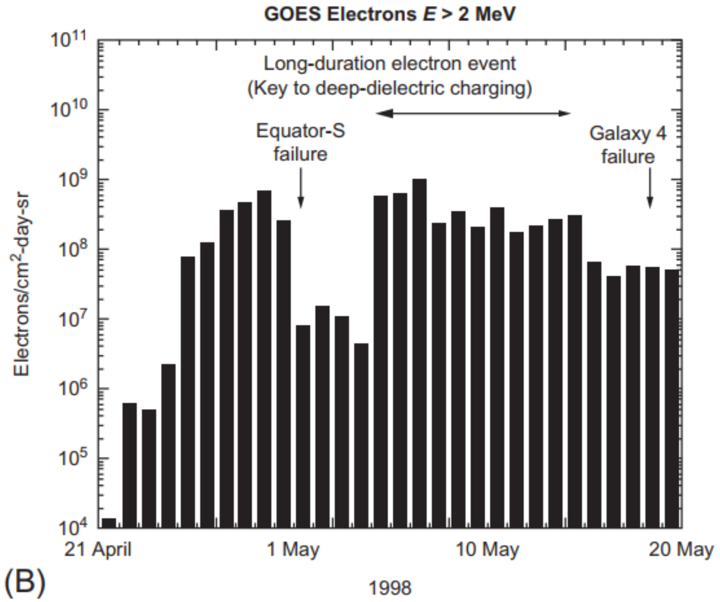
- High-Speed Stream (HSS)
  - Satellite charging
    - Deep di-electric charging
      - About 1 to a few MeV e-
      - Deeply penetrate spacecraft (S/C)
    - Fluxes > 2 MeV e-
      - Accumulation effect within S/C (ESD: electrostatic discharge)
    - Dayside effect
      - Fluence (24h)
    - Declining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



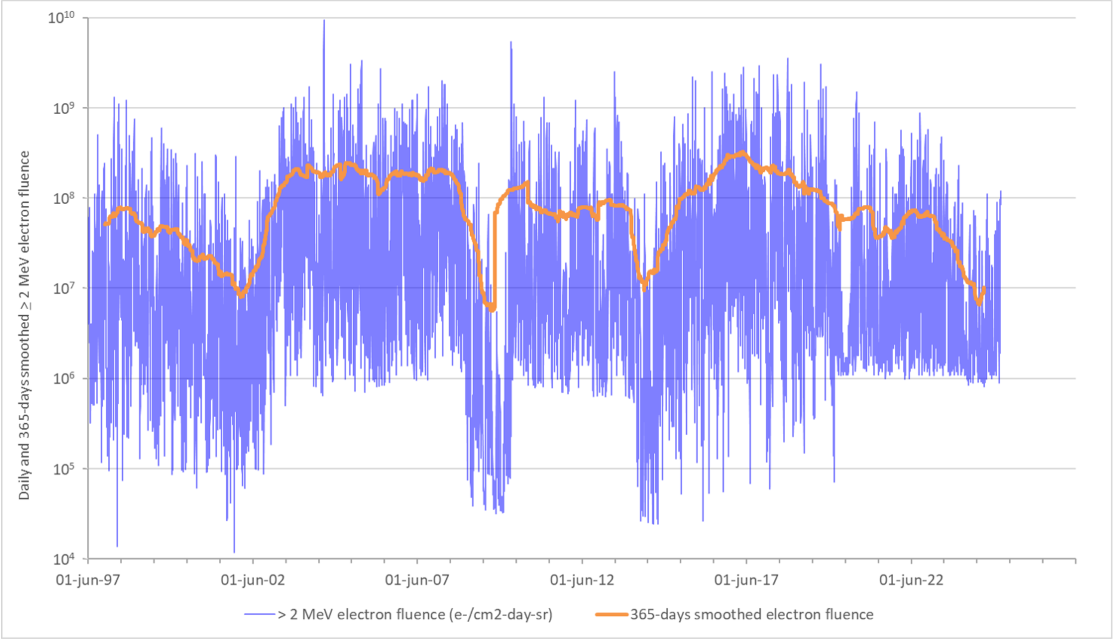


Credits: Wrenn et al. (2002)

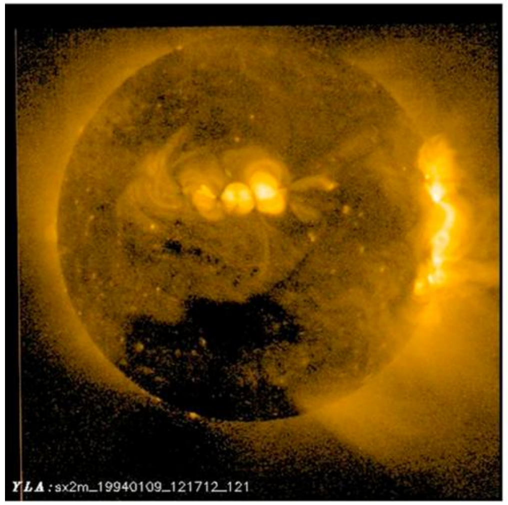
SWx impacts from CHs on satellites

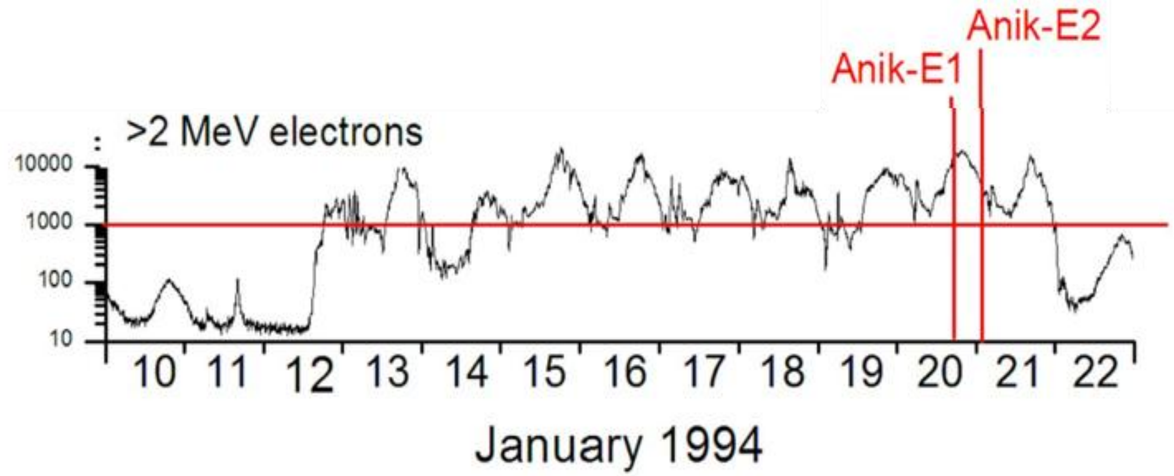


Credits: Lai et al. 2018



Frequency High fluence: ~18 days / year





Credits: Lam et al. 2012

SWEC
Space Weather Education Center

: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

Finding your way in the URSIgram

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.

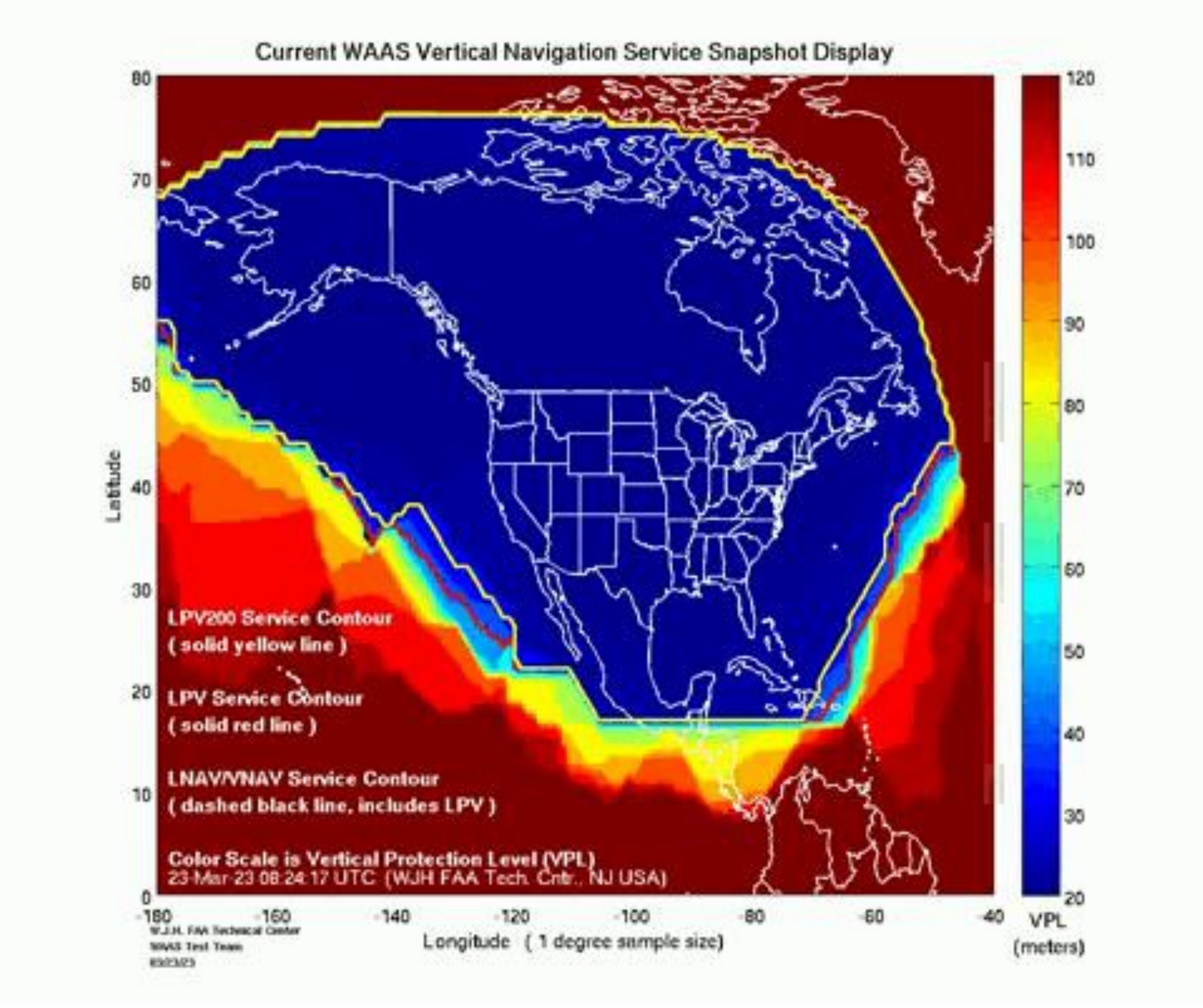
TODAY'S ESTIMATED ISN : 074, BASED ON 10 STATIONS.

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.

≥ 2MeV 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?



Current WAAS Vertical Navigation Service Snapshot Display
Latitude
Longitude (1 degree sample size)
LPV200 Service Contour
(solid yellow line)
LPV Service Contour
(solid red line)
LNAV/VNAV Service Contour
(dashed black line, includes LPV)
Color Scale is Vertical Protection Level (VPL)
23-Mar-23 08:24:17 UTC (WJH FAA Tech. Cntr., NJ USA)
VPL
(meters)
W.J.H. FAA Technical Center
WAAS Test Team