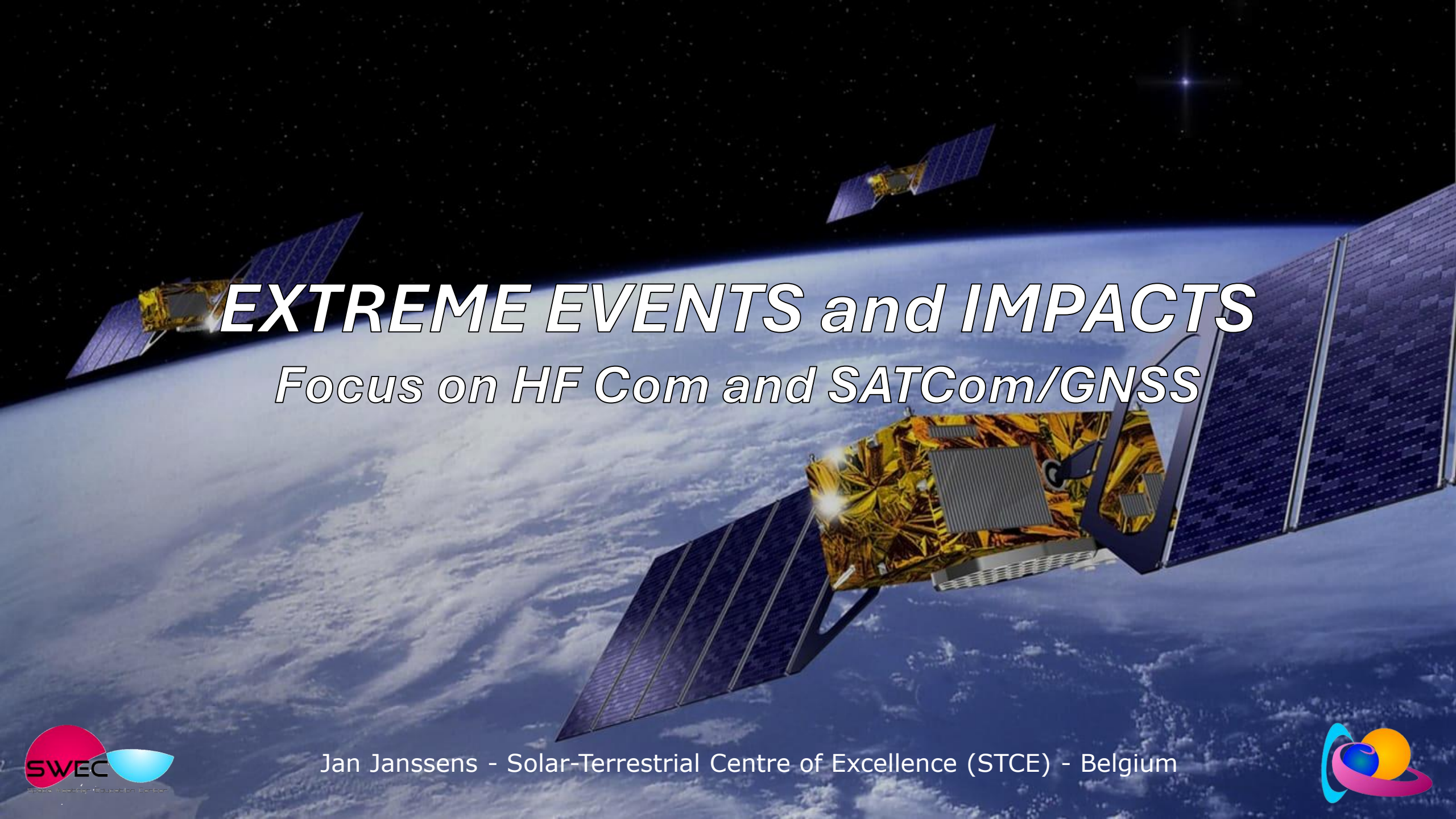
Role of the ionosphere and space weather in military communications

23-25 November 2026

Royal Observatory
of Belgium

Solar Influences
Data analysis Centre
www.sidc.be





EXTREME EVENTS and IMPACTS

Focus on HF Com and SATCom/GNSS

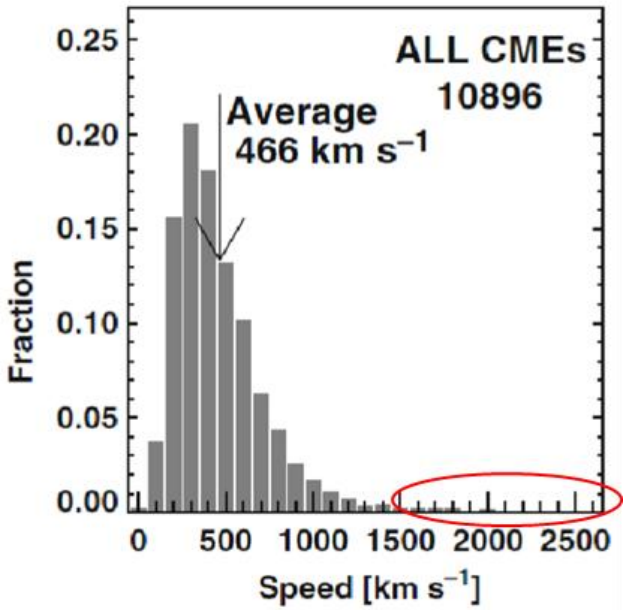
Jan Janssens - Solar-Terrestrial Centre of Excellence (STCE) - Belgium

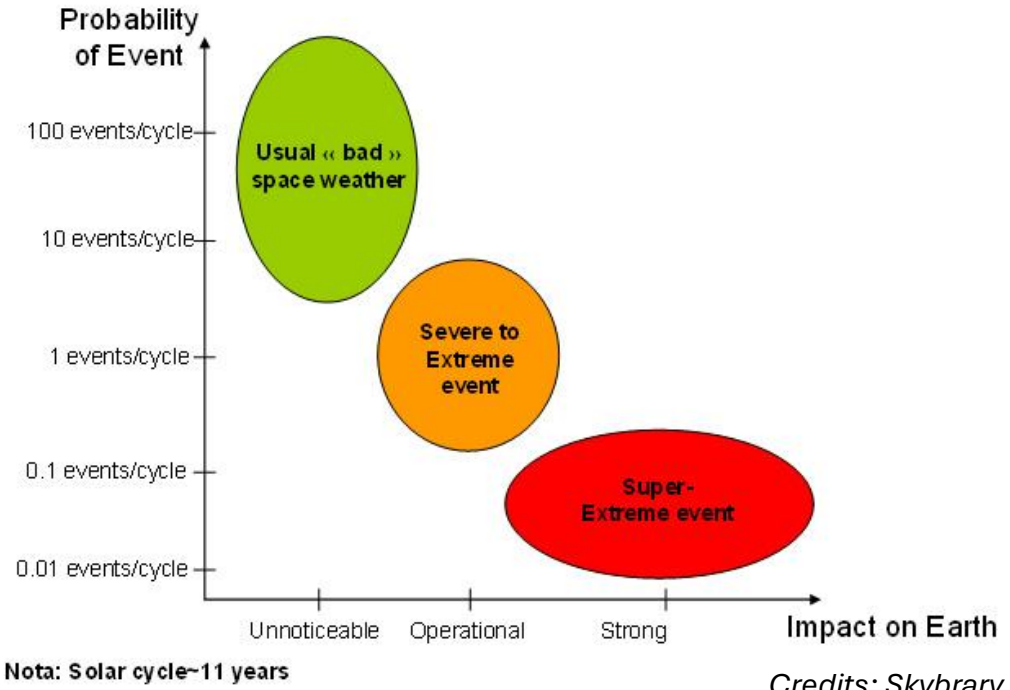
Contents

- What is an extreme event?
- SWx drivers & impacts: overview
- **HF Com** and **SATCom/GNSS** impacts from
  - Solar flares
  - Solar energetic particle events (SEP)
  - Interplanetary coronal mass ejections (ICME)
  - High speed streams from coronal holes (HSS/CH)

What is an extreme event?

- No very concrete definition:
  - Tail's end of a distribution
    - No one-on-one correlation between frequency and impact
      - E.g. July 2012 farside event
      - Boundary conditions
        - Day/night,…
  - Low probability, high impact event
    - Some high-tech systems and applications only have 10-25 years of data…
      - 2 moderate and 1 weak solar cycle since the mid-1990s…





Credits: Skybrary

What is an extreme event?

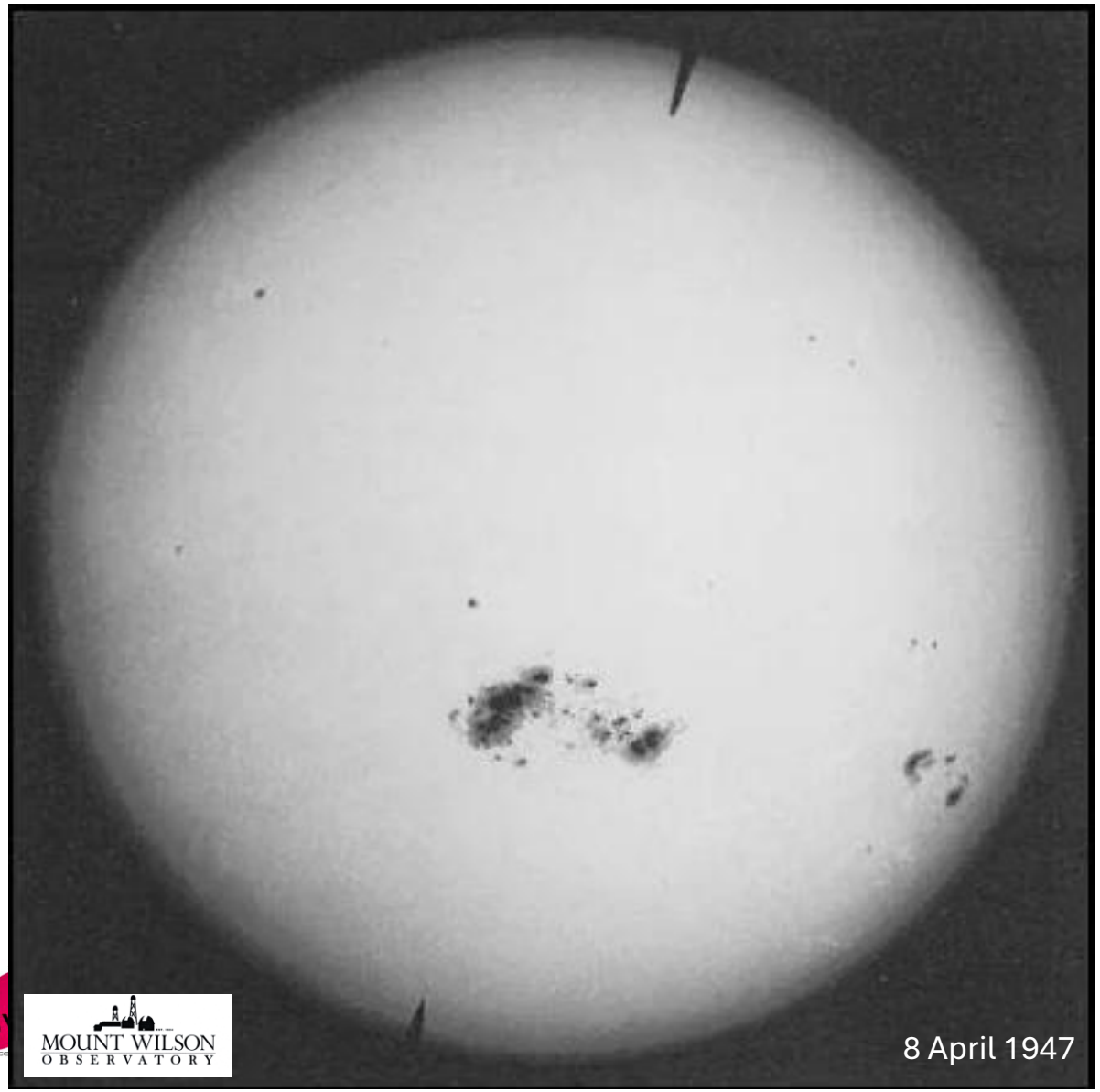
Observed, statistically expected, and modelled extreme solar and solar-terrestrial events

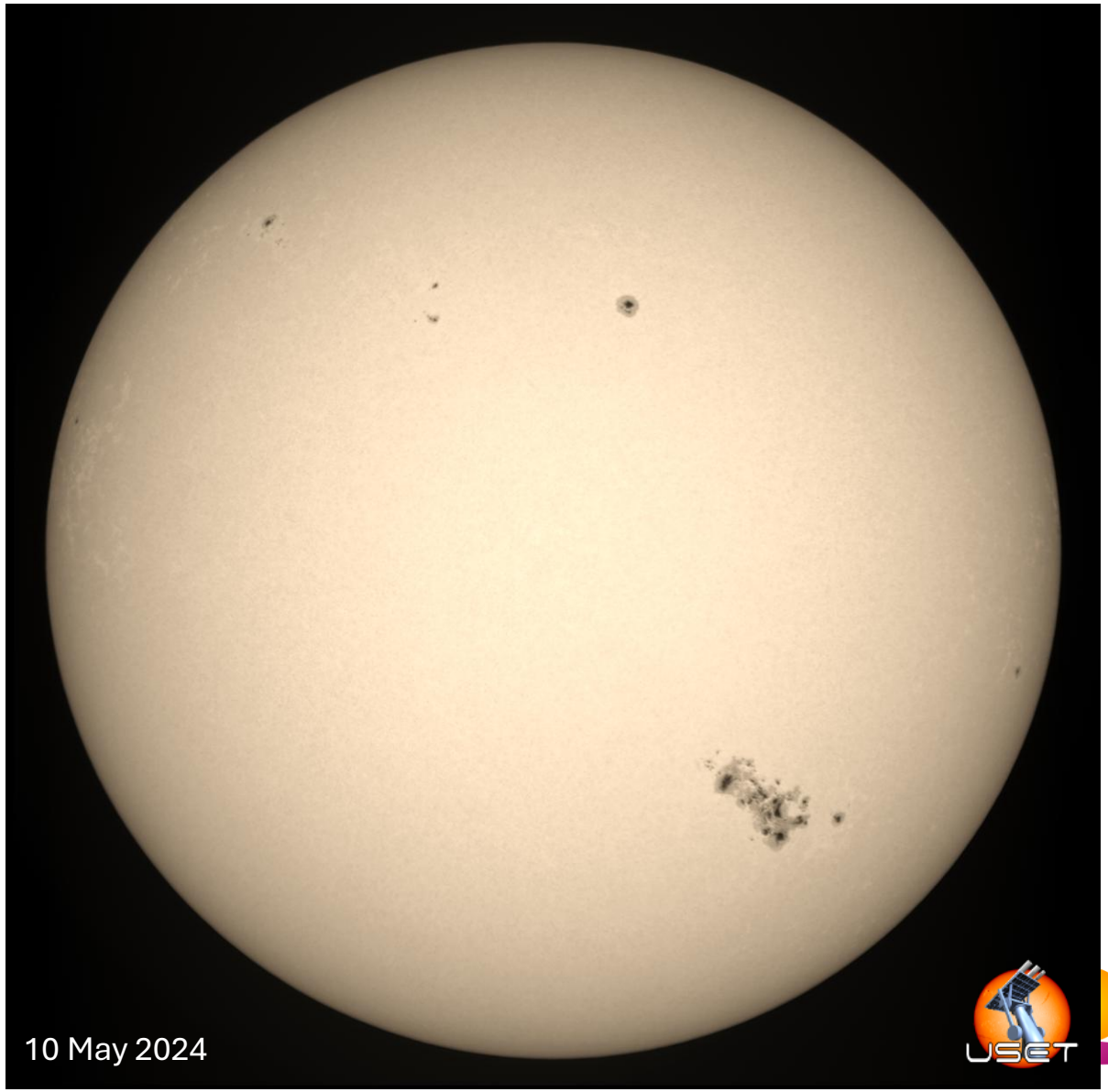
(based on Cliver et al. 2022 ; Gopalswamy 2018)

Parameter	*Observed Extremum*	100-year ev. Exp. Law	100-year ev. Power Law	1000-year ev. Exp. Law	1000-year ev. Power Law	Modelled Extremum	*SC25*
Sunspot group area (MH)	*6132*	5800	7100	8200	13600		*3360*
GOES flare SXR	*X40*	X44	X42	X100	X115	X180	*X9.0*
1.5 GHz radio emission (10^6 sfu)	*1*		3.2 - 12		61 - 200		*0.23*
> 30 MeV proton fluence (10^{10} cm^{-2})	*0.84*	1.6	2.1	5	16		*< 0.1*
> 200 MeV proton fluence (10^{10} cm^{-2})	*0.14*	0.6		3.5			
CME speed (km/s)	*3387*	3800	4500	4700	6600		*2427*
ICME transit time (h)	*14.6*					11.6	*25*
Dst (nT)	*~ -950*	-603	-774	-845	-1470	-2000 to -2500	*-406*

ev.: event ; **Exp. Law**: exponential law ; **MH**: Millionths of a solar hemisphere ; **GOES**: Geostationary Operational Environmental Satellite ; **SXR**: soft x-rays ; **GHz**: gigahertz ; **sfu**: solar flux units ; **MeV**: Mega electronvolt ; **pfu**: particle flux units ; **(I)CME**: (Interplanetary) Coronal Mass Ejection ; **Kp**: planetary K-index ; **Dst**: Disturbance storm time index ; **nT**: nano Tesla

Largest sunspot groups in SC18 and SC25





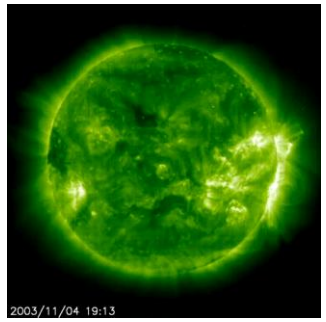
Drivers of disturbed space weather

Solar eruptions

Magnetic Reconnection

Radiation

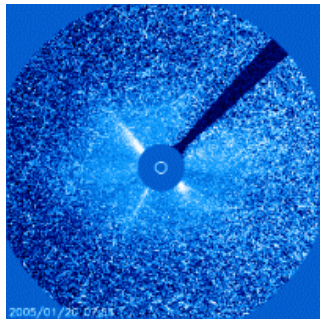
Solar flares





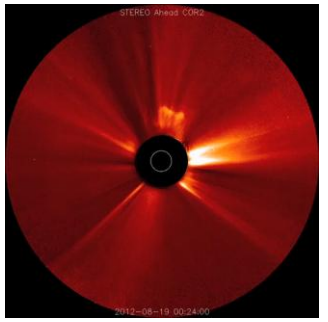
Particles

Proton events





Coronal Mass Ejections



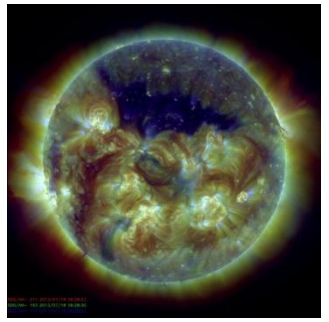


Solar corona

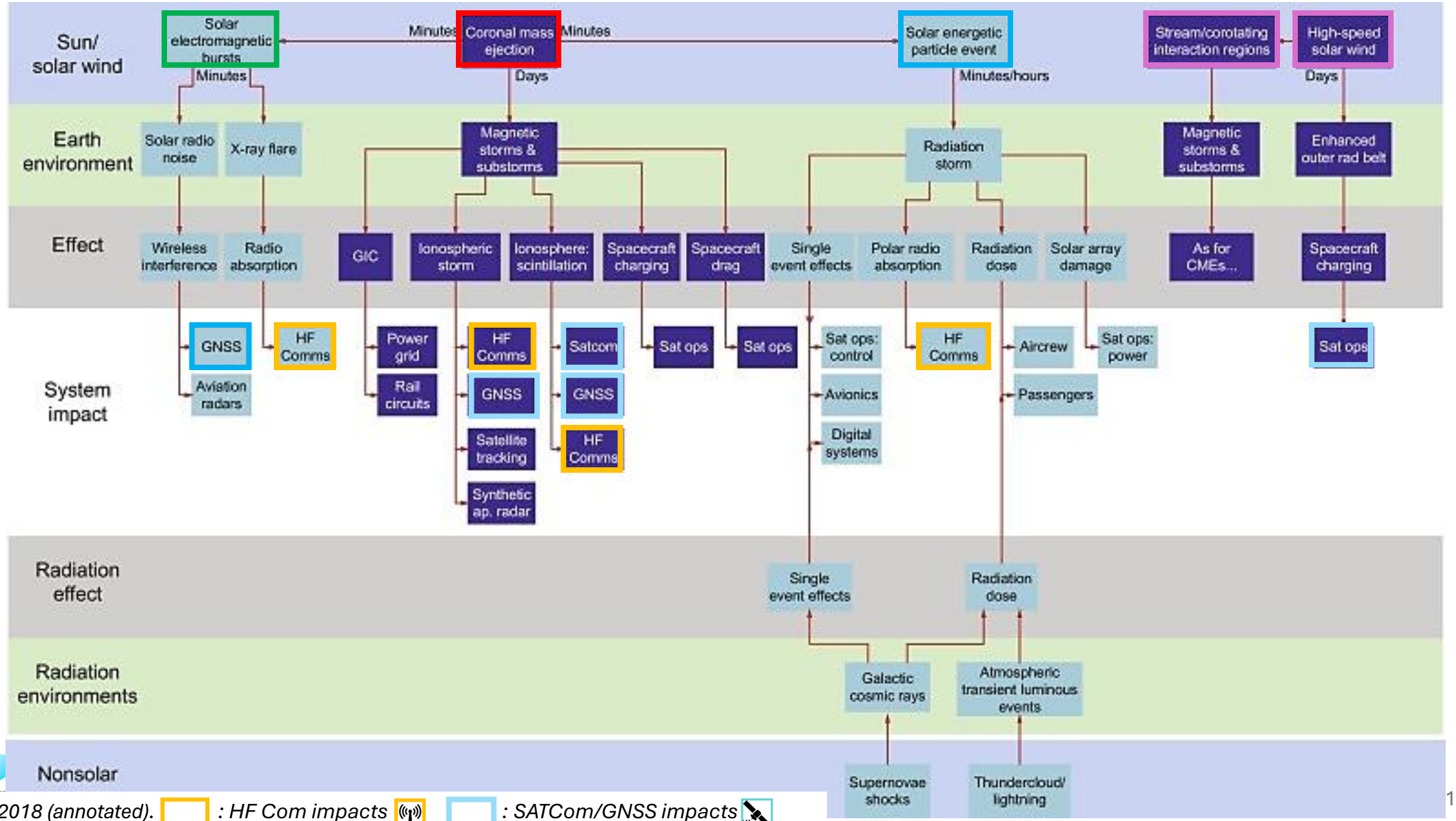
Solar wind

Particles

Coronal Holes

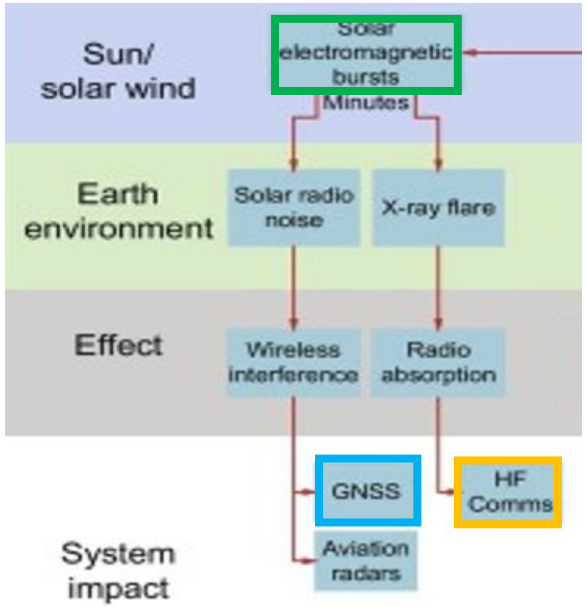


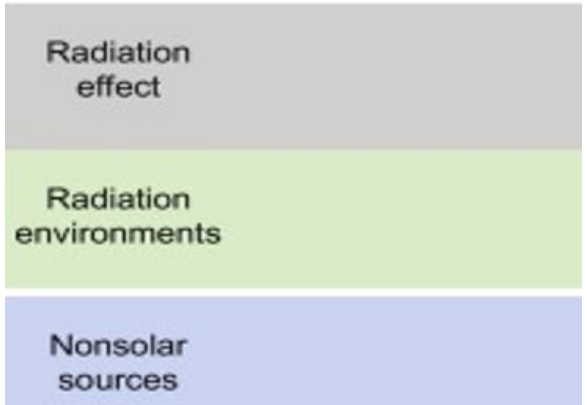
Impacts of disturbed SWx on HF Com and SATCom/GNSS



From Hapwood 2018 (annotated). : HF Com impacts : SATCom/GNSS impacts

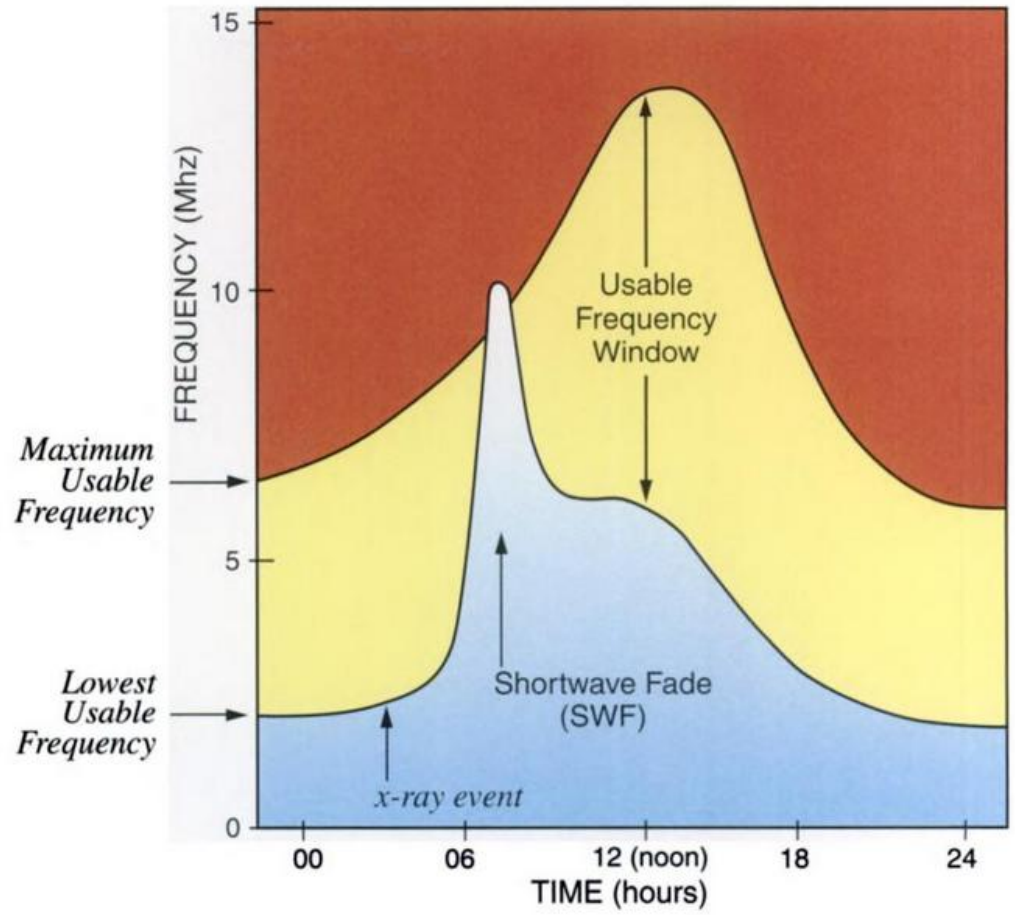
Impacts from solar flares





- From EUV & X-ray
  - Solar flare effect
    - *"magnetic crochet"*
    - Up to +/- 100 nT
  - Short-wave fade (SWF)
    - *"Radio Blackout"*
    - Impact on HF Com
- From radio emission
  - GNSS disturbances
  - Radar disturbances
  - Radio amateurs

Impacts from solar flares on HF Com

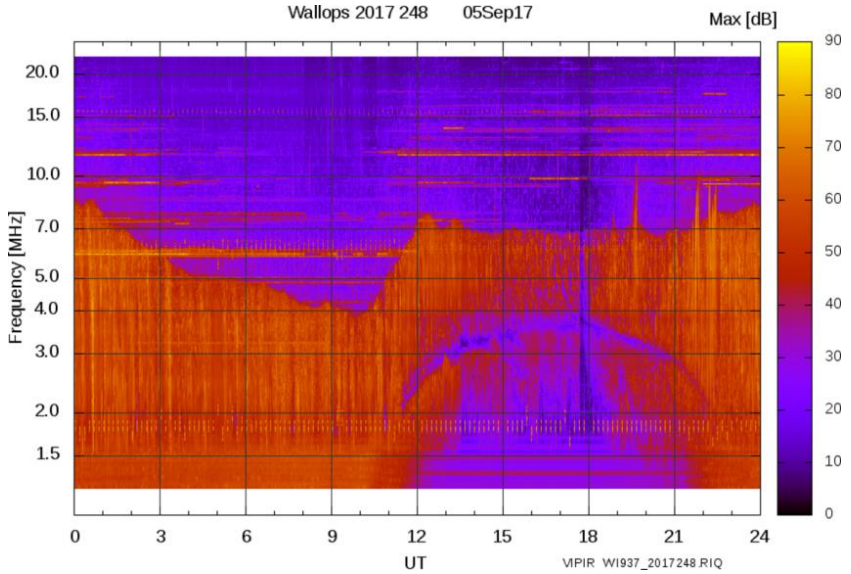


- Short-wave fade (SWF)
  - Aka “Radio blackout”
    - Misleading term
  - SXR from solar flare
    - Sunlit hemisphere of the Earth
    - Increase ionospheric plasma (D-region)
      - Increase in HF absorption
        - Affects lower frequencies most
        - => Backup systems (SATCom,…)
        -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

SWEC Space Weather Education Center

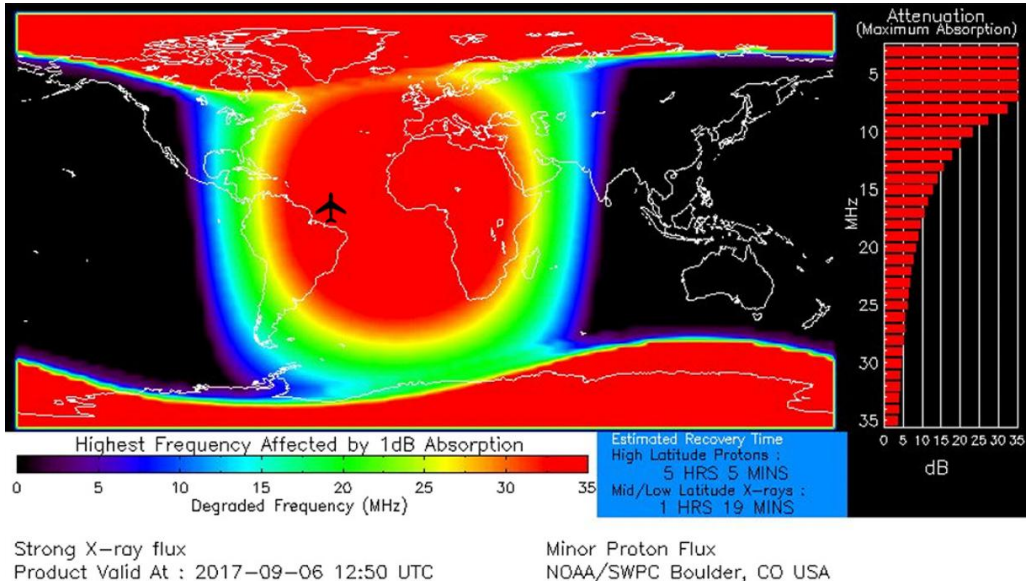
HF Com: High Frequency Communications (3-30 MHz) ; **SXR**: soft x-rays ; **SATCom**: Satellite Communication ; **MHz**: megahertz

Impacts from solar flares on HF Com

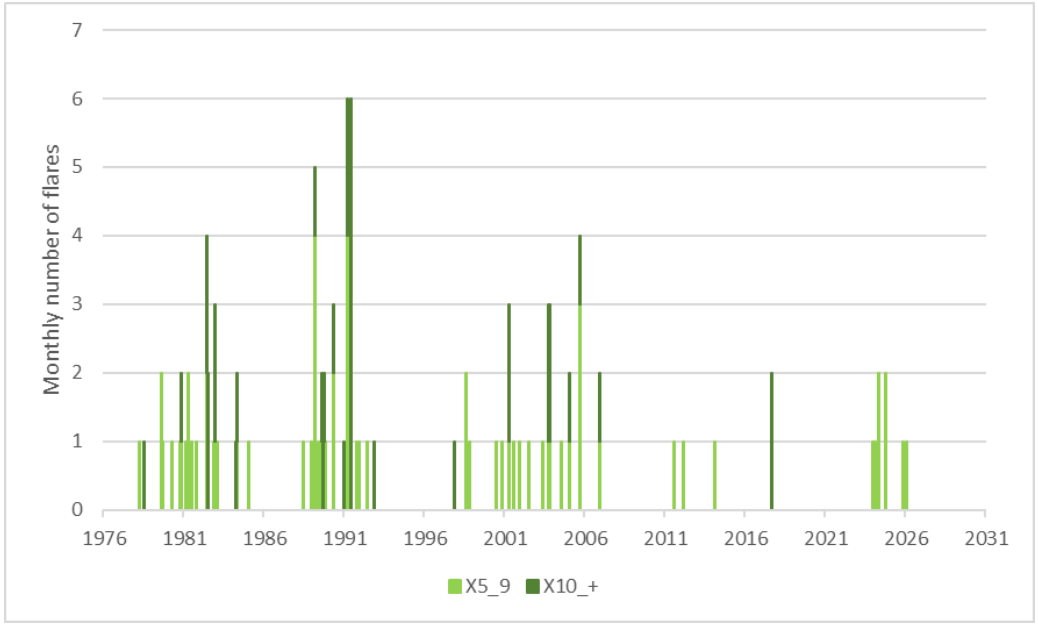


Courtesy of CIRES, Terry Bullett

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



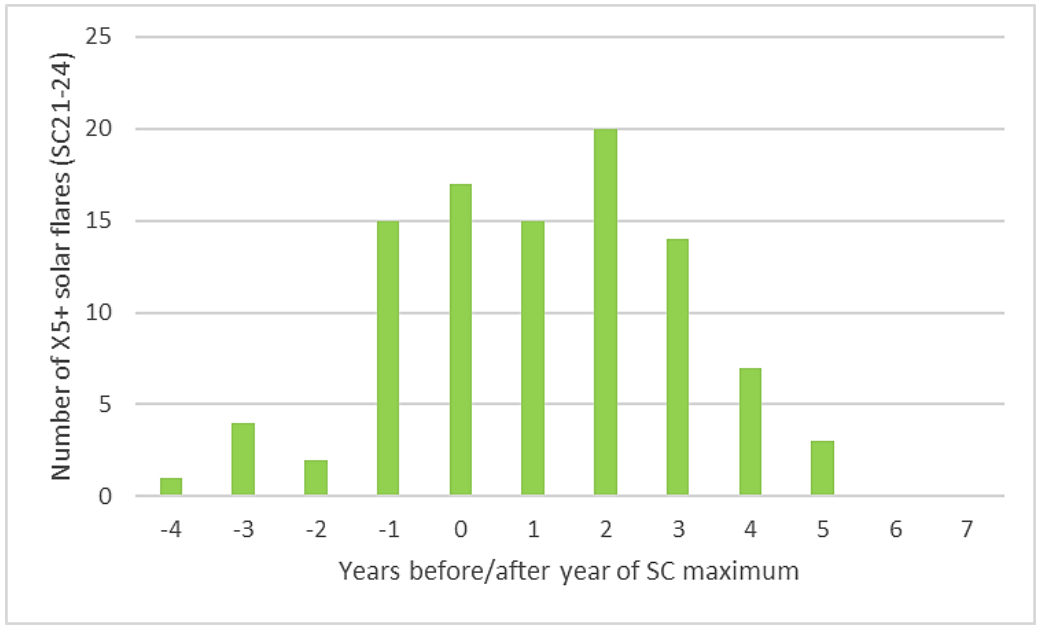
Impacts from solar flares on HF Com



- About 24 X5+ flares per SC
  - Large variability per SC!

SWF: Short-Wave Fade; **h**: hour; **dB**: decibel; **SZA**: Solar Zentih Angle; **MHz**: megahertz; **SC**: solar cycle; **HF Com**: High Frequency Communication

Impacts from solar flares on HF Com



1 (full) SWF event per	Duration (h) *(full SWF)*	Absorption (dB) *(SZA=0° ; f = 6.6MHz)*
1 year	0.63	71
10 years	1.8	130
100 years	4.0	210
1000 years	7.4	320

- About 24 X5+ flares per SC
  - Large variability per SC!
  - Up to 3-4 years after SC maximum!
  - Median duration of 1 hour
    - Extremes of several hours

Estimated extreme events for full SWF (Tao et al. 2020)

Tao et al. (2020): ***"... Frequent explosions of long-duration flares may provide long-duration SWFs. ..."***

SWF: Short-Wave Fade; **h**: hour; **dB**: decibel; **SZA**: Solar Zentih Angle; **MHz**: megahertz; **SC**: solar cycle; **HF Com**: High Frequency Communication

Impacts from solar flares on SatCom/GNSS

- From radio emission
  - 6 Dec 2006: X6.5
    - 1415 MHz: 10^6 sfu
    - NOAA/USAF reported only 13000 sfu!
      - Time resolution and analysis
      - Intensity of bursts (saturation) drove instruments into non-linearity
      - Post-event analysis and calibration (OVSA)

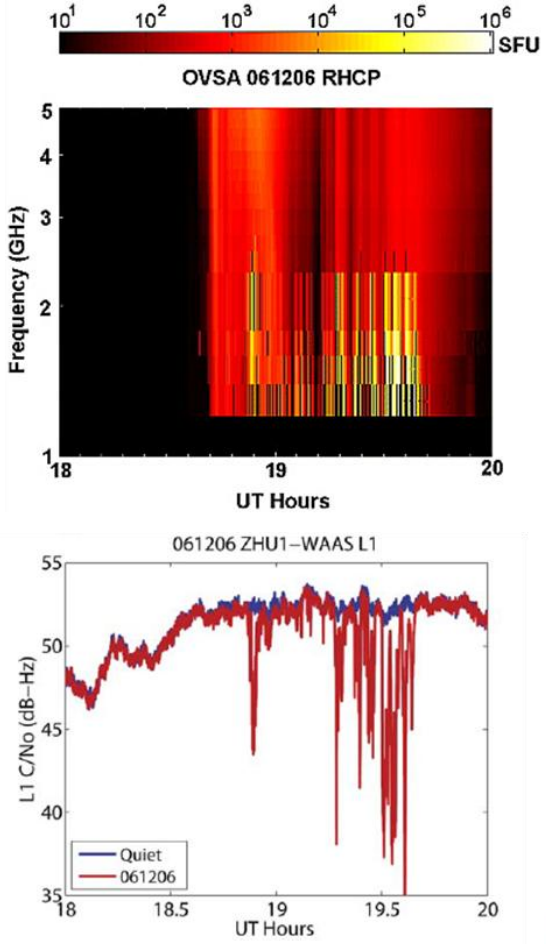


Figure 2. Response of a GPS receiver to the solar radio burst on 6 December 2006. The red line corresponds to C/N_0 on 6 December 2006, and the blue line corresponds to the previous sidereal day.

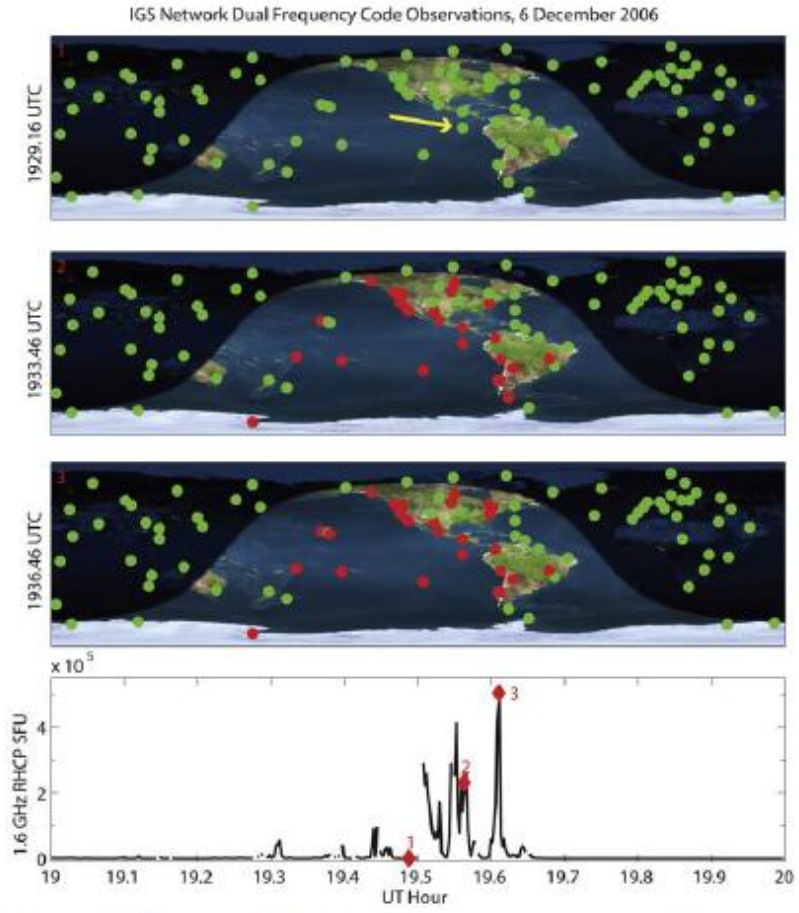


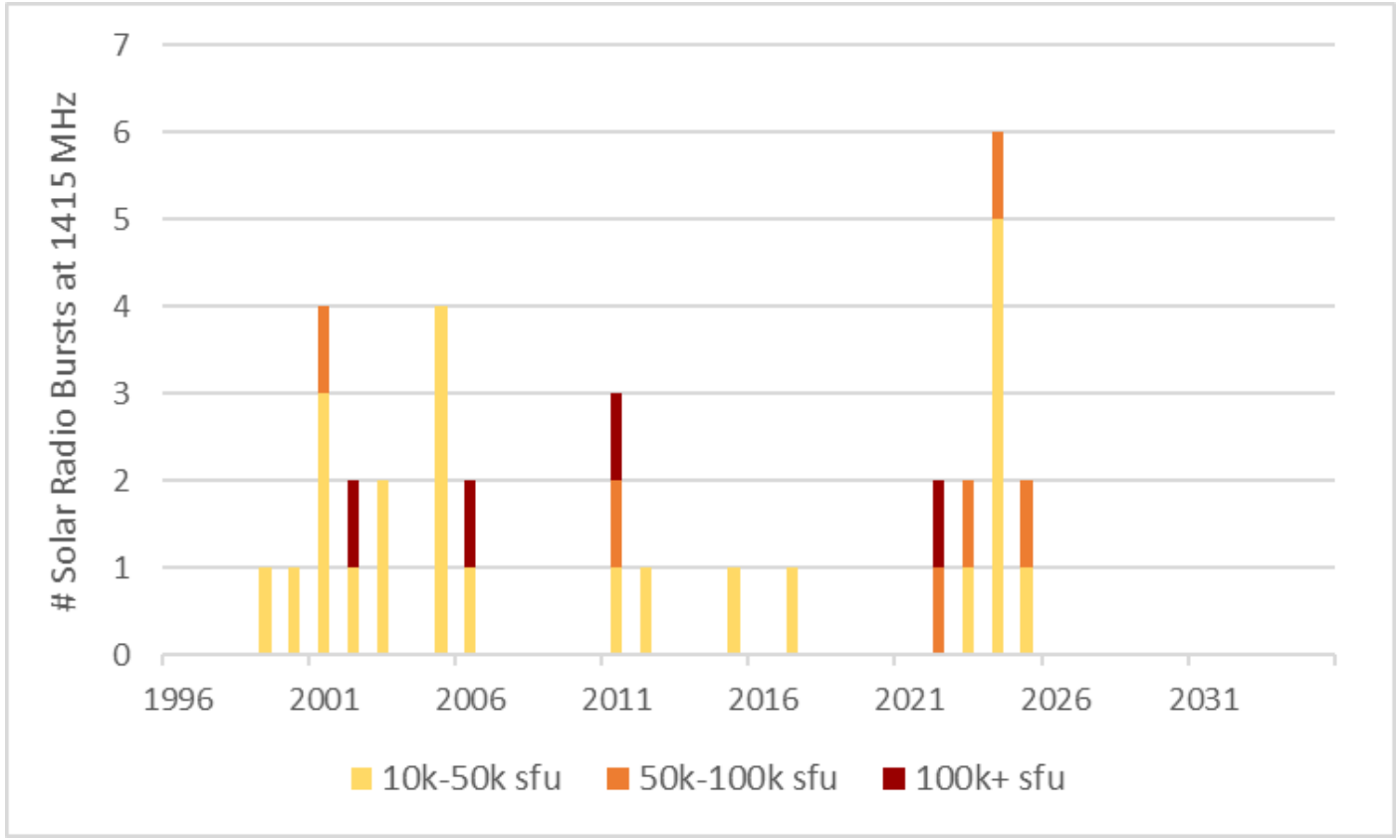
Figure 6. Receivers in the Global GPS Network that were analyzed during the solar radio burst. Green indicates the normal number of satellites being tracked. (fourth panel) During the burst (power at 1.6 GHz), several sunlit receivers tracked fewer than the four satellites needed for a full positioning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

MHz: megahertz ; **GHz**: gigahertz ; **sfu**: solar flux units ; **C/N$_0$**: Carrier-to-Noise ratio ; **L1** : GPS frequency (1575.42 MHz) ; **dB**: decibel (=10 log$_{10}$ (Power/Power$_{base}$)) ; **IGS**: International GNSS service ; **WAAS**: Wide Area Augmentation Service

Impacts from solar flares on SatCom/GNSS

- Impact threshold
  - 1000 – 10.000 sfu
    - Initially 10k-40k sfu
  - Not f(SXR intensity)!
    - Only sunlit side
    - Also SC minimum
- Frequency occurence
  - > 1000 sfu: ~ 7/year
  - > 10.000 sfu: ~ 11/SC
  - > 100.000 sfu: ~ 2/SC
  - Yue et al. (2003-2012)
    - ***Degrading eff.: ~ 9/SC***

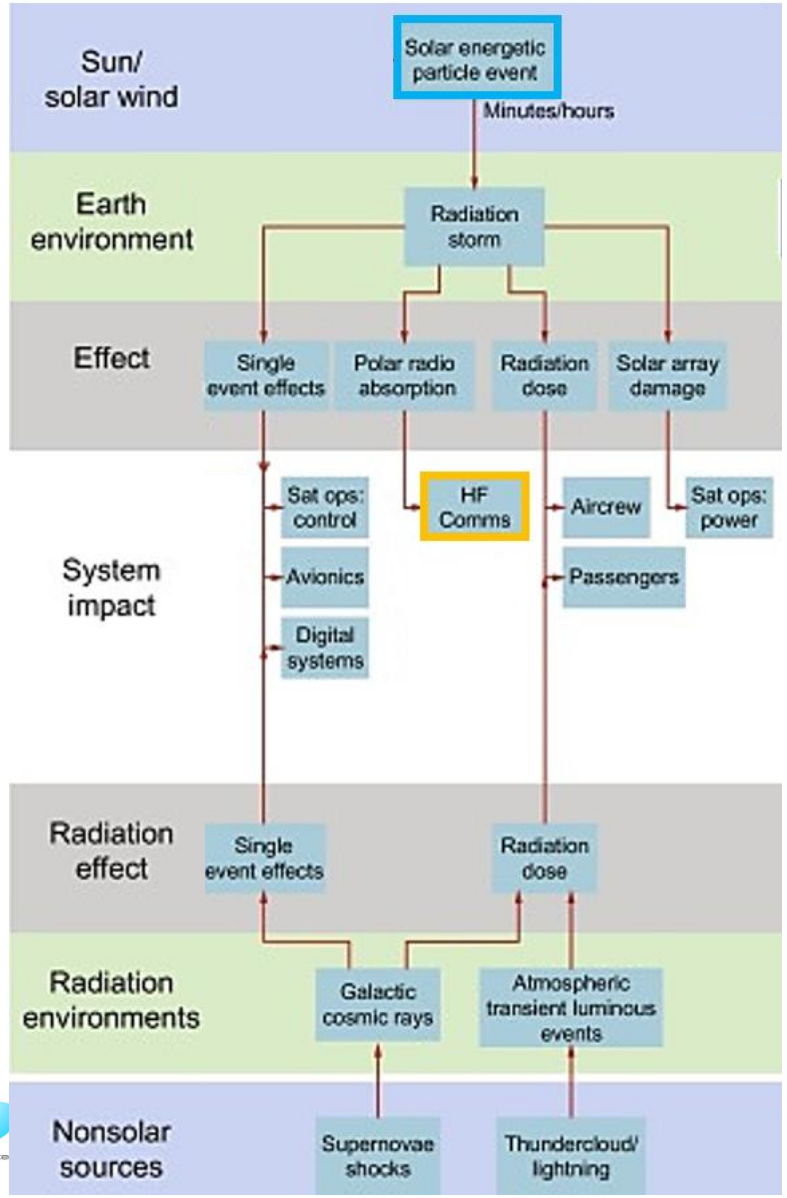


Based on reports from the NOAA/USAF network

https://www.stce.be/content/sc25-tracking#SRB

MHz: megahertz ; **GHz**: gigahertz ; **sfu**: solar flux units ; **C/N$_0$**: Carrier-to-Noise ratio ; **L1** : GPS frequency (1575.42 MHz) ; **dB**: decibel (=10 log$_{10}$ (Power/Power$_{base}$)) ; **IGS**: International GNSS service ; **WAAS**: Wide Area Augmentation Service

Impacts from SEP events

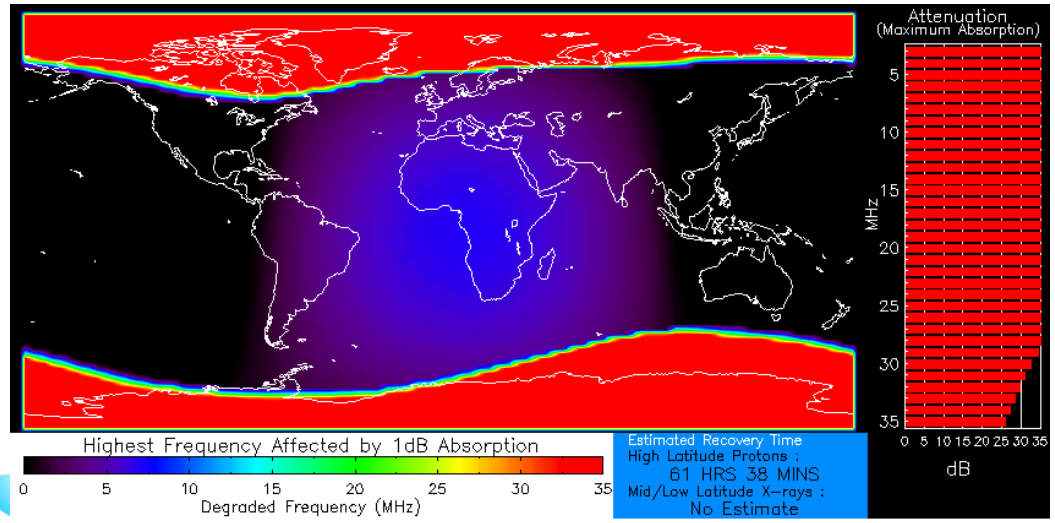


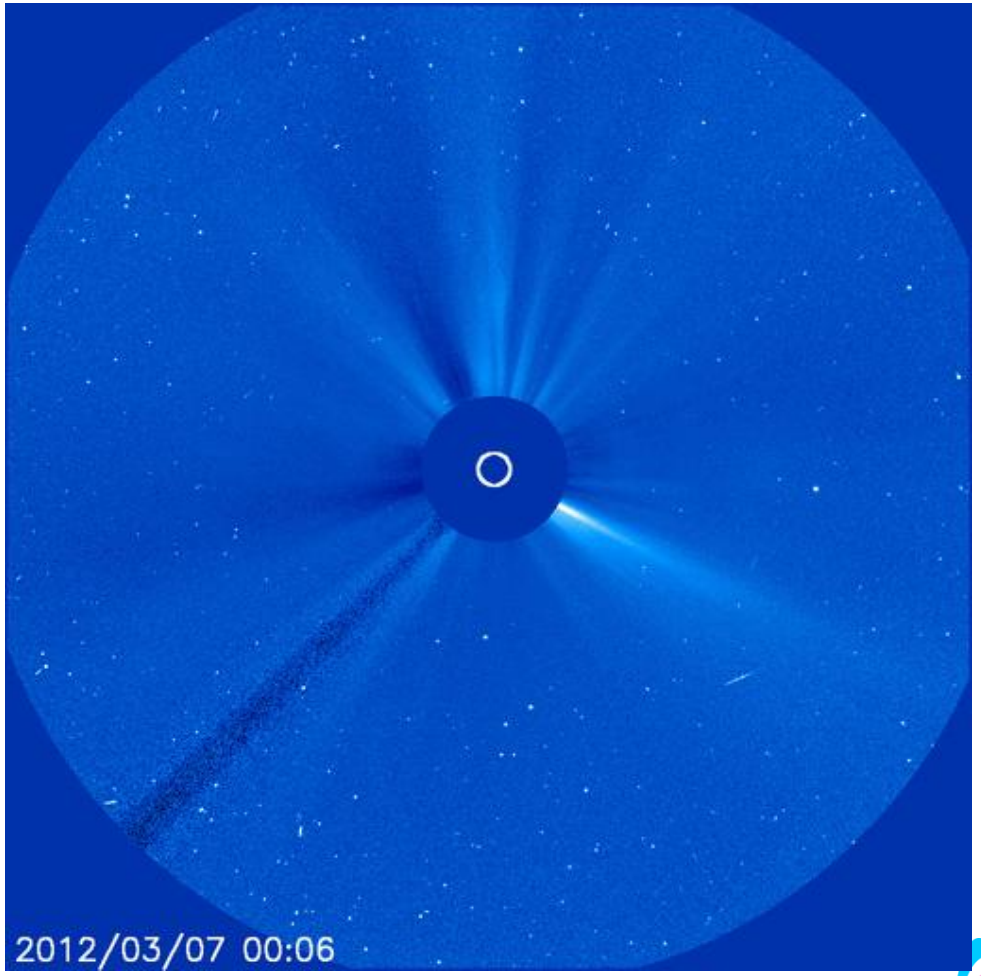
- From SEP events
  - Single event effects
    - Affect mainly avionics/electronics
    - Ground Level Enhancement (GLE)
  - Polar Cap Absorption (PCA)
    - Deviated by MF to poles
    - Affects D-region
    - Impacts HF Com at polar regions
  - Radiation
    - Biological component
  - Solar array damage
- Non-solar sources
  - Supernovae (GCR)
  - Thundercloud lightning (TLE)
  - South Atlantic Anomaly (LEO)

SEP: Solar Energetic Particles ; **GCR**: Galactic Cosmic Rays ; **GNSS**: Global Navigation Satellite Systems ; **TLE**: Transient Luminous Events ; **MF**: Magnetic field ; **LEO**: Low Earth Orbit ; **HF Com**: High Frequency Communication

Impacts from SEP events on HF Com

- Polar Cap Absorption (PCA)
  - From 10 MeV proton flux
    - Deviated by MF to poles
    - Affects lower ionosphere (D-region)
    - Impacts HF Com at poles
      - Can last for days
  - Polar flight
    - detours (HF Com)
    - lower altitude (radiation hazard)

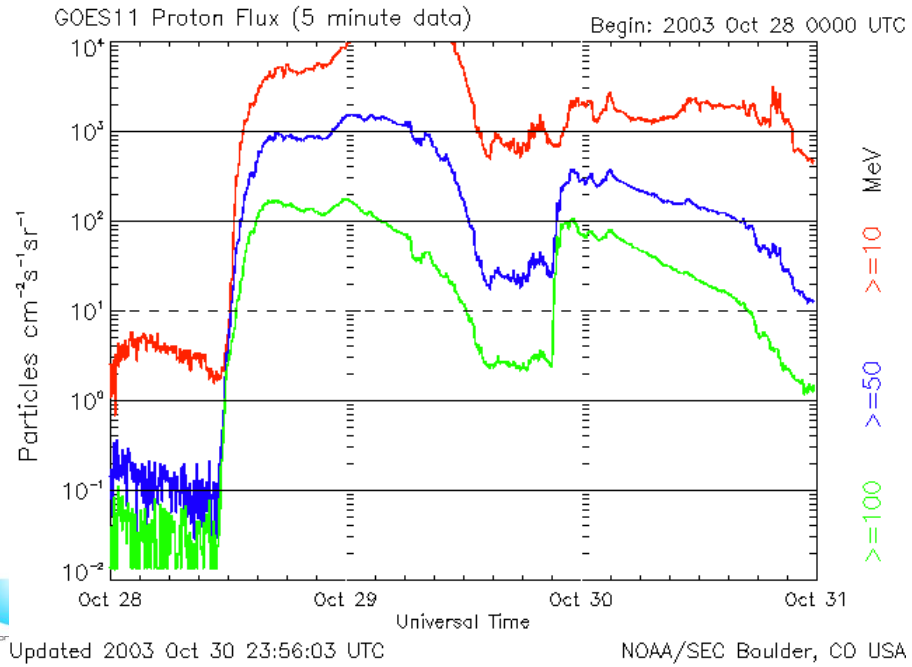




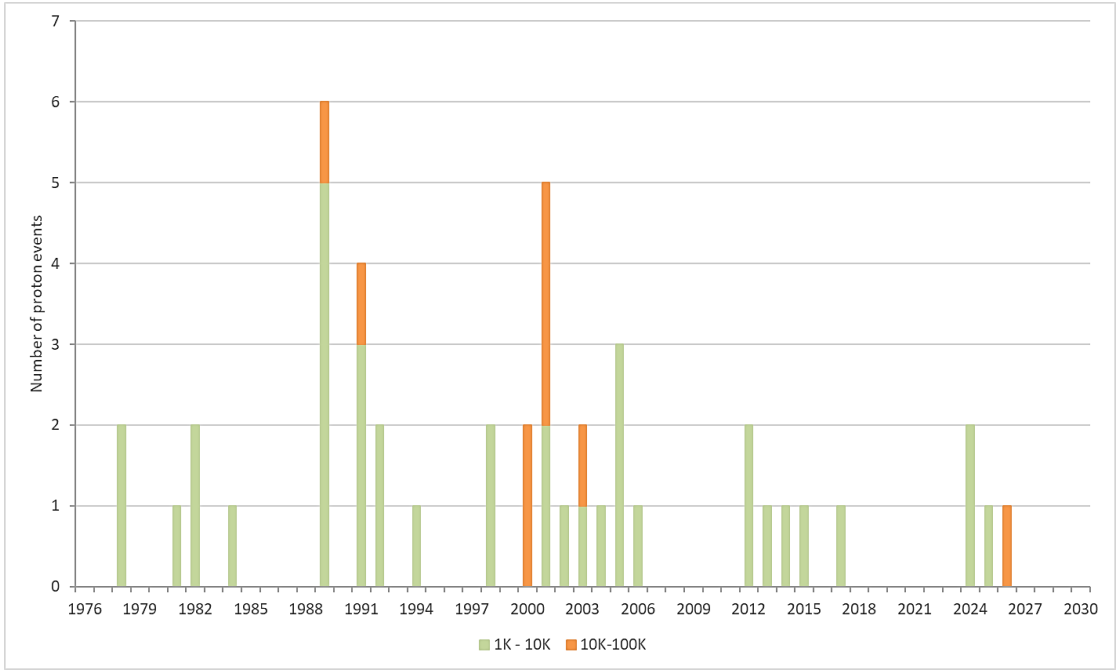
SEP: Solar Energetic Particles ; **MF**: Magnetic field ; **HF Com**: High Frequency Communication; **MeV**: mega electronvolt

Impacts from SEP events on HF Com

- Alert thresholds
  - 10 MeV protons: 10 pfu
  - 100 MeV protons: 1 pfu



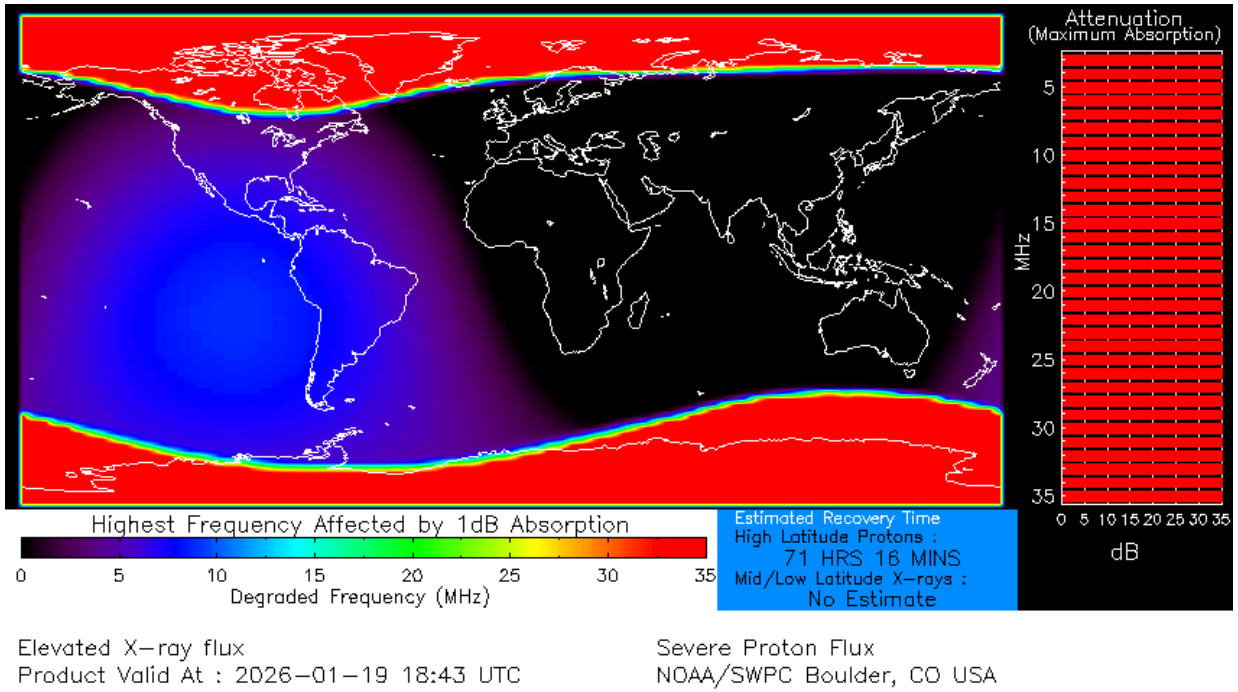
- Frequency
  - Proton events:
    - Strong: 8 per solar cycle
    - Severe: 2 per solar cycle

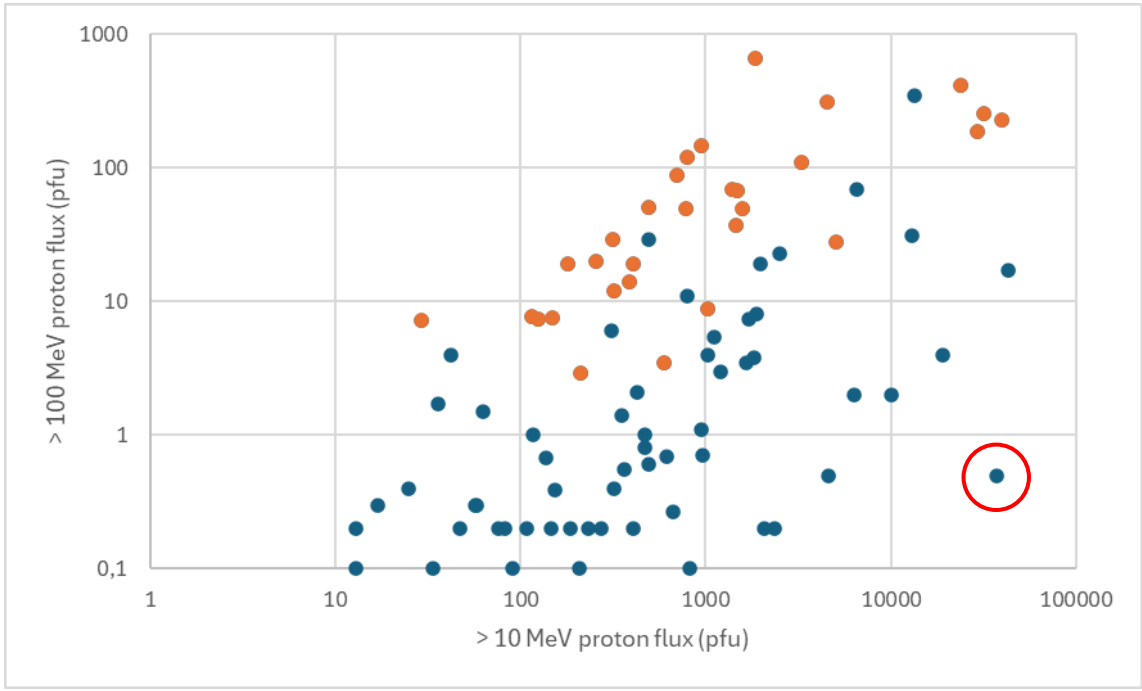


MeV: megaelectronvolt ; **pfu**: proton flux unit

Impacts from SEP events on HF Com

- A word on the "severe" proton event of 19 January 2026
  - 10MeV flux: 37.000 pfu , **BUT** 100 & 500 MeV flux: Background level





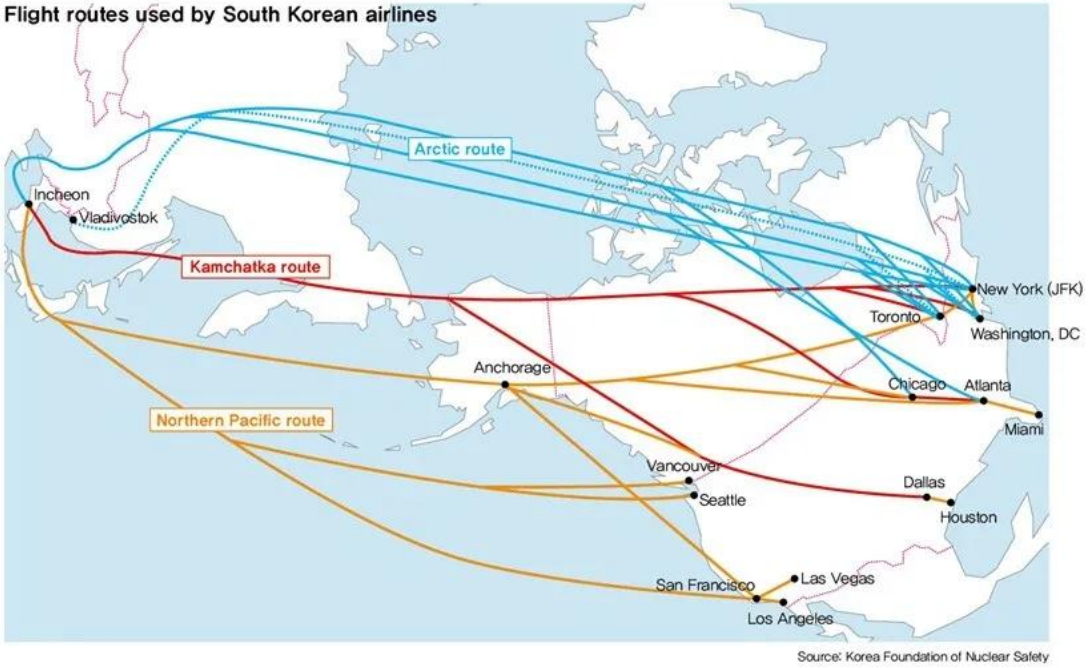
https://www.swpc.noaa.gov/products/d-region-absorption-predictions-d-rap

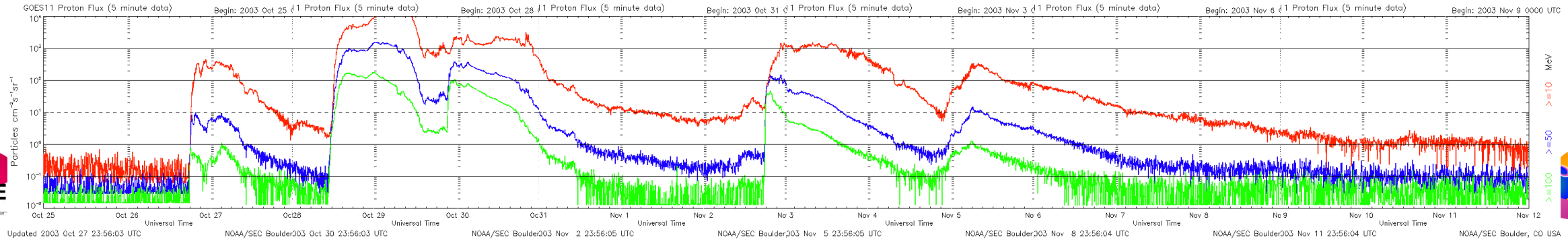
GLE: Ground Level Enhancement

MeV: megaelectronvolt ; **pfu**: proton flux unit

Impacts from SEP events on HF Com

- Halloween events (Oct-Nov 2003)
  - One major airline rerouted 6 polar flights to non-polar routes
  - Antarctic/McMurdo station
    - 130 hours of HF communication blackout
      - Combines solar flares and SEP events





Impacts from SEP 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 1878 — 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

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WASHI of State D his most at a put George (would ge on the rig

Dulles Senate Fo tee for q istration sion-ridde ways to c nomic, p moves.

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"I am pearing George t it is advis

George sion "will help get a return of a greater measure of bipartisan consultation." He added, "I think it would tend in that direction."



Ousted Soviet Premier Draws

der

r De- s Ad- Power ul

Soviet direct electric Prem- ised of eech to Soviet d in the e plan- y prime ov. ed the 955, he been in- tly ex- n.

Malen- o doubt nt was Malen- n.

c power is pro- ith the of new stations.

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

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

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.

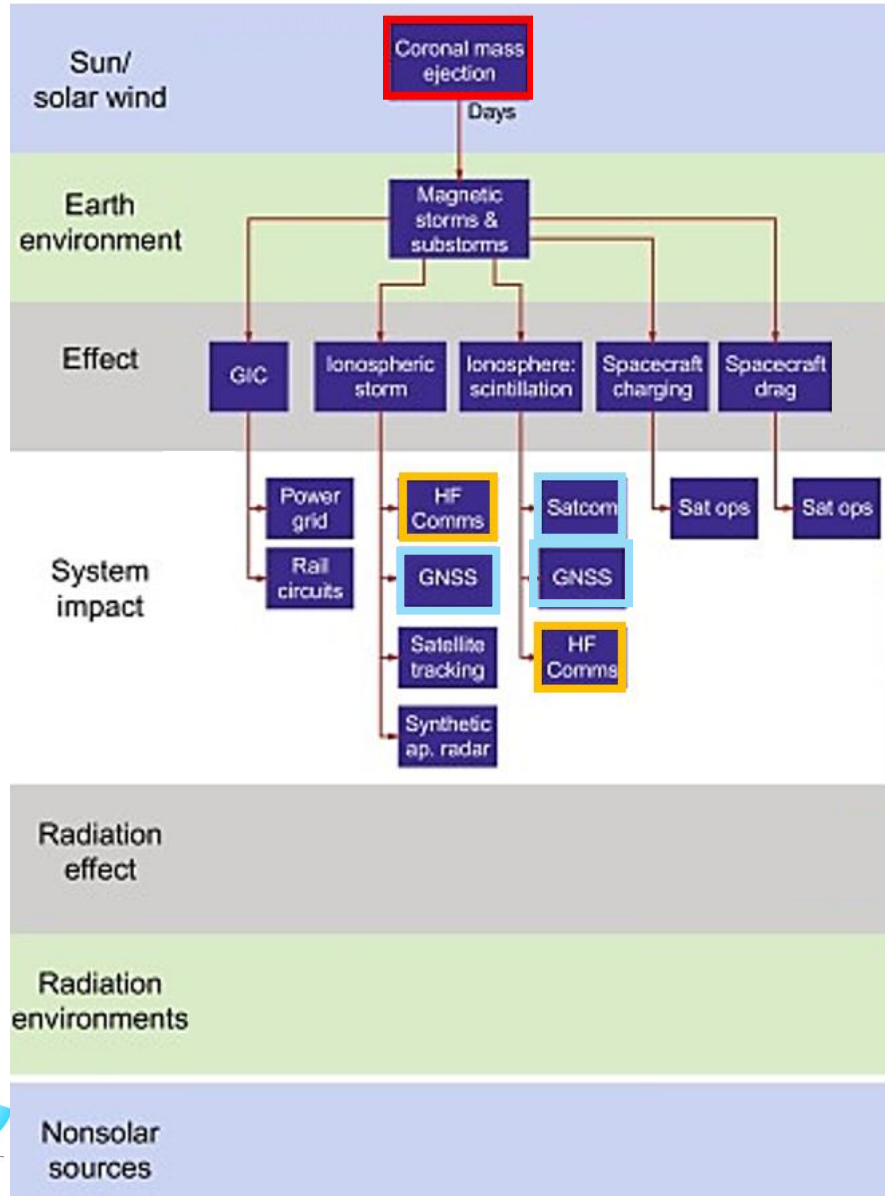
Of 90 persons taken to six Maryland hospitals, 59 remained hospitalized today. Scores of others were treated at the scene by dozens of doctors and nurses.

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.

SWEC Space Weather Education Center

Impact from ICMEs

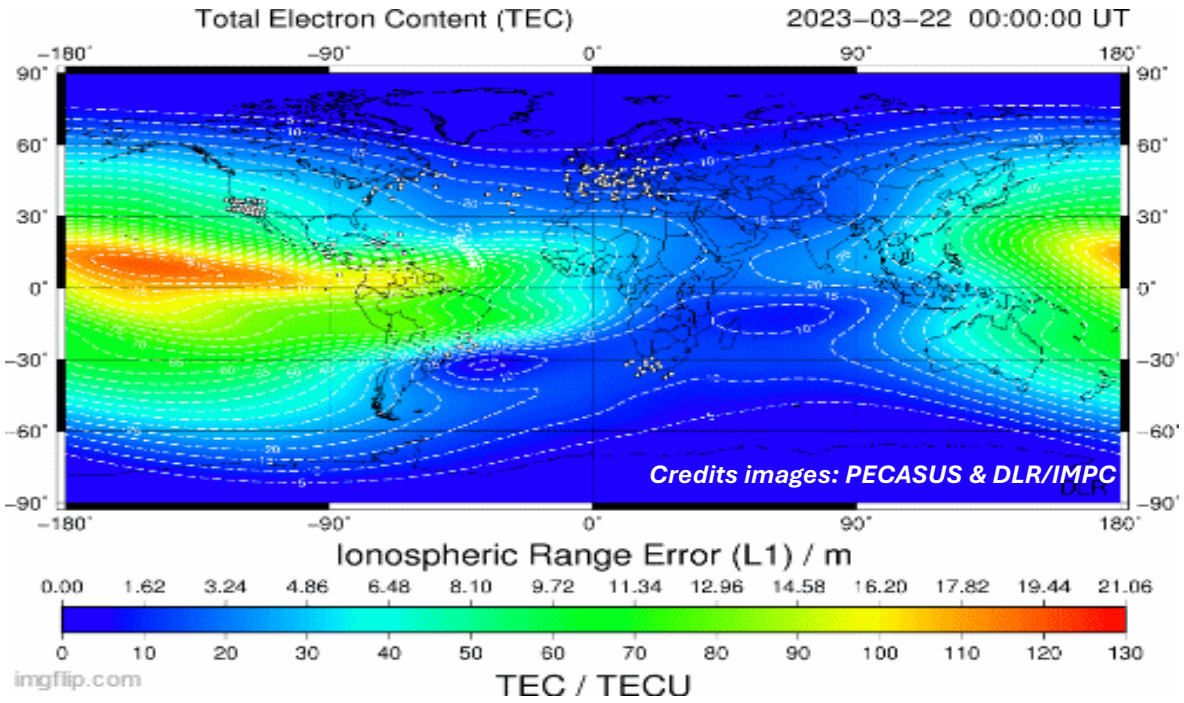


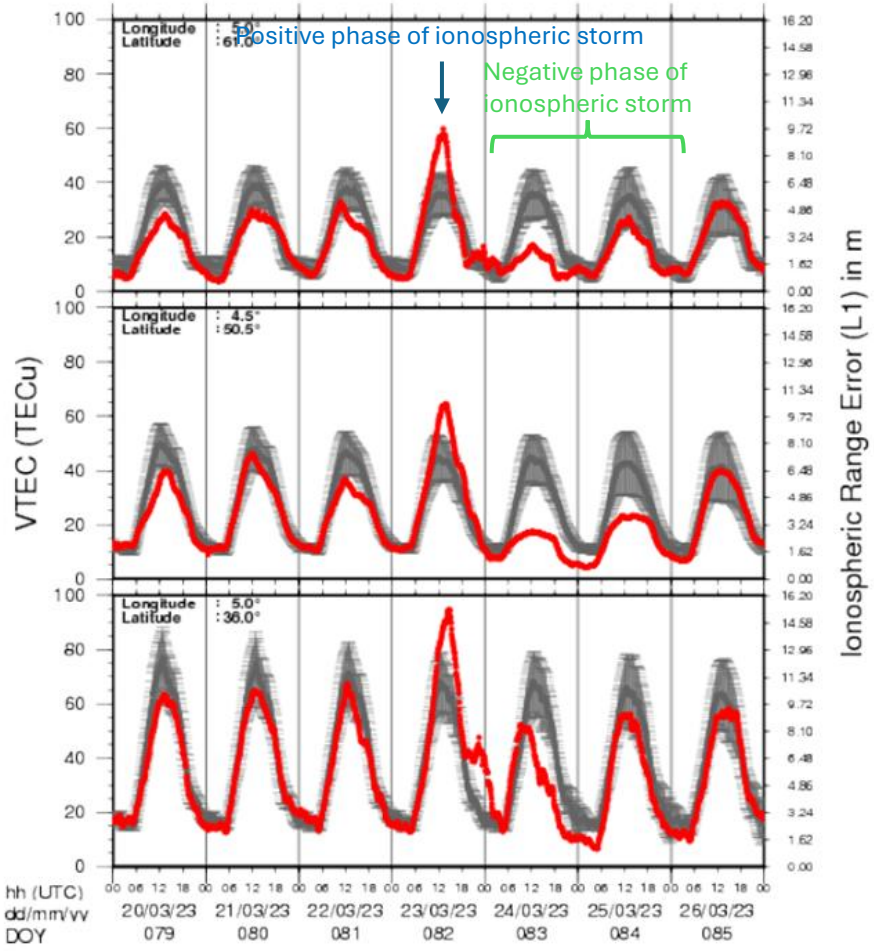
- From magnetic field
  - Satellites
    - Magnetopause crossings
  - High-Precision industry
  - GCR: Forbush decrease
- From particles (ionospheric)
  - Aurora
  - Geomagnetically Induced Currents (GIC)
  - HF Communication
  - Satellites
    - Drag
    - Charging effects
  - Satellite-based Comms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

GCR: Galactic Cosmic Rays ; **Comms/Nav**: Communications/Navigation ; **PECASUS**: Pan-European Consortium for Aviation Space weather User Services ; **HF**: High Frequency ; **(I)CME**: (Interplanetary) Coronal Mass Ejection

Impact from ICMEs on HF Com

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



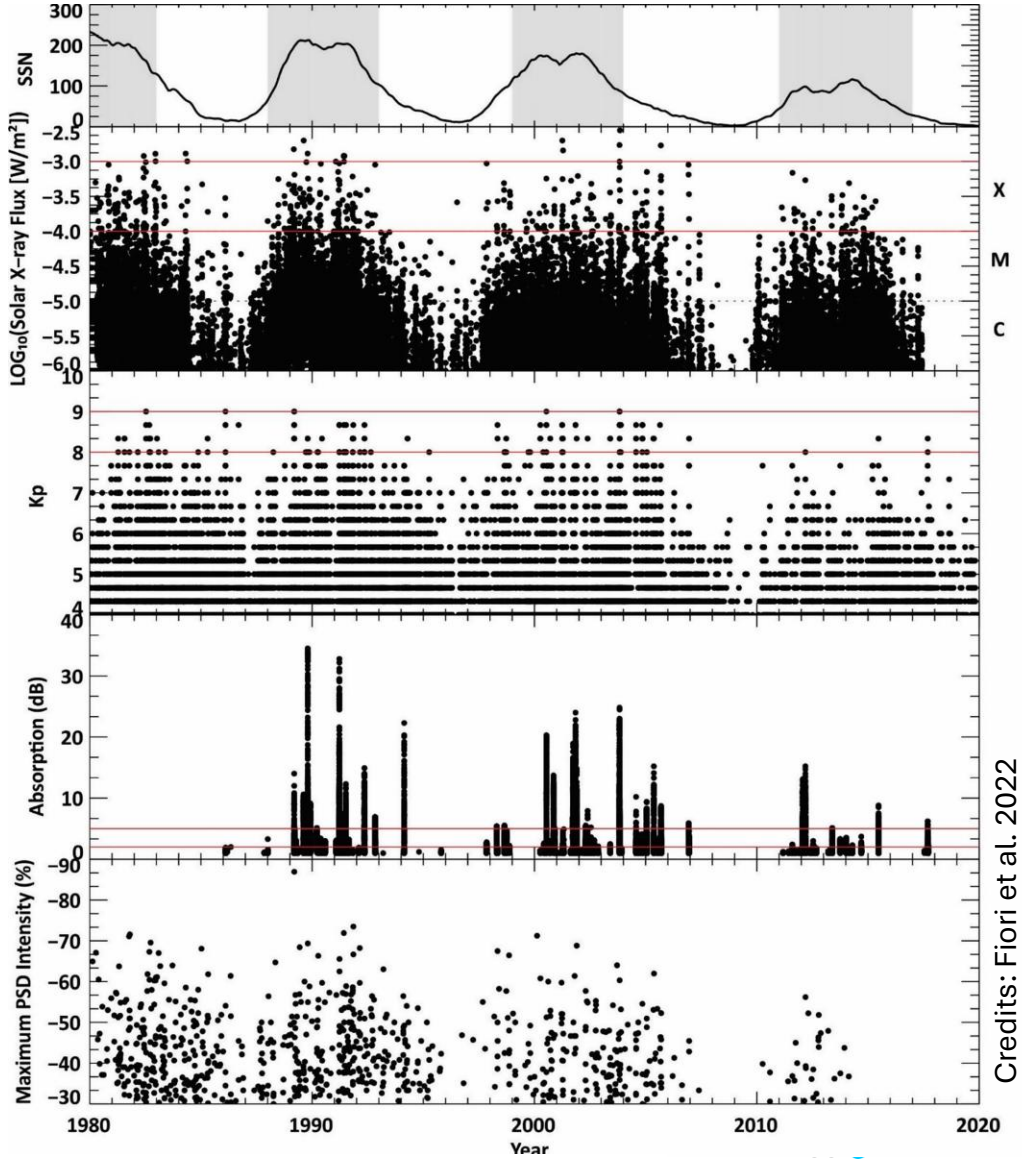


Credits: ROB/GNSS

(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 ; **PECASUS**: Pan-European Consortium for Aviation Space weather User Services ; **DLR**: German Aerospace Centre; **IMPC**: Ionosphere Monitoring and Prediction Center; **GNSS**: Global Navigation Satellite Systems (GPS, Galileo,,...); **DOY**: Day Of Year

Impact from ICMEs on HF Com

- Auroral Absorption (AA)
  - HF Com degradation due to aurora affecting lower ionosphere
  - 18-19 September 1941
    - Kp ≥ 9- for 24 hours (!)
    - Radio broadcast disturbed
    - Bombing raids under light of aurora



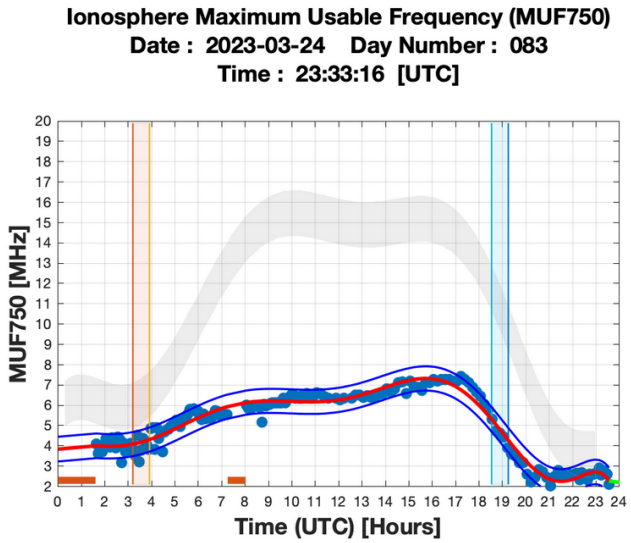
Credits: Fiori et al. 2022

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

Impact from ICMEs on HF Com

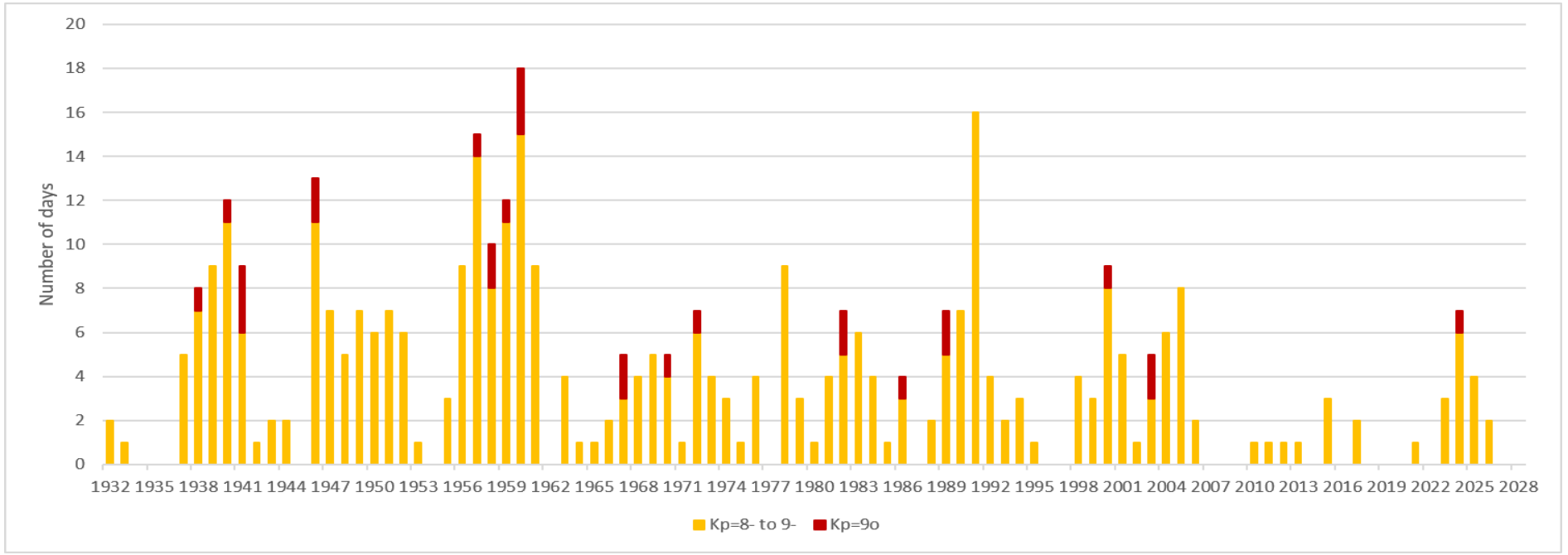
- Post-Storm Depression (PSD)
  - Negative phase of ionospheric storm
    - => strong reduction electron content ionosphere
    - = Reduction higher portion HF band
  - 25-26 May 1967
    - Most negative phase in TEC ever recorded





Impact from ICMEs on HF Com

- Frequency geomagnetic storms
  - Kp *(planetary K-index)*
    - ~ 40 severe storm days / SC
    - ~ 3 extreme storm days / SC

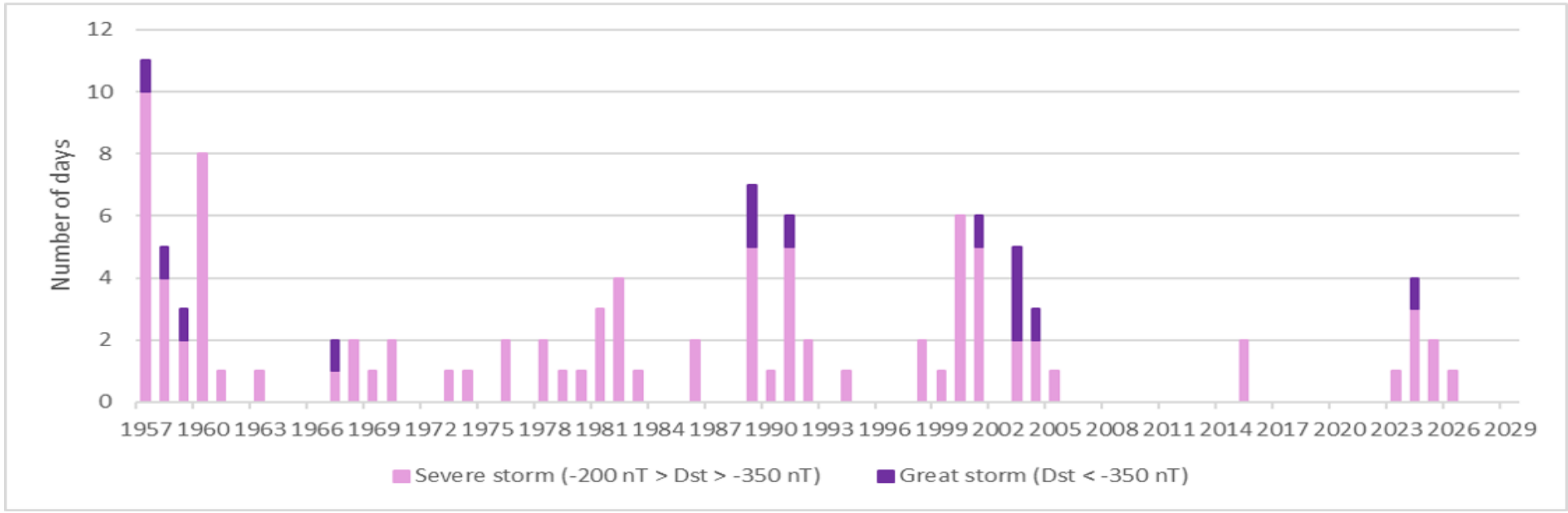


HF Com: High Frequency Communications (3-30 MHz) ; **ICME**: Interplanetary coronal mass ejection ; **SC**: solar cycle

Impact from ICMEs on HF Com

- Frequency geomagnetic storms
  - Kp *(planetary K-index)*
    - ~ 40 severe storm days / SC
    - ~ 3 extreme storm days / SC

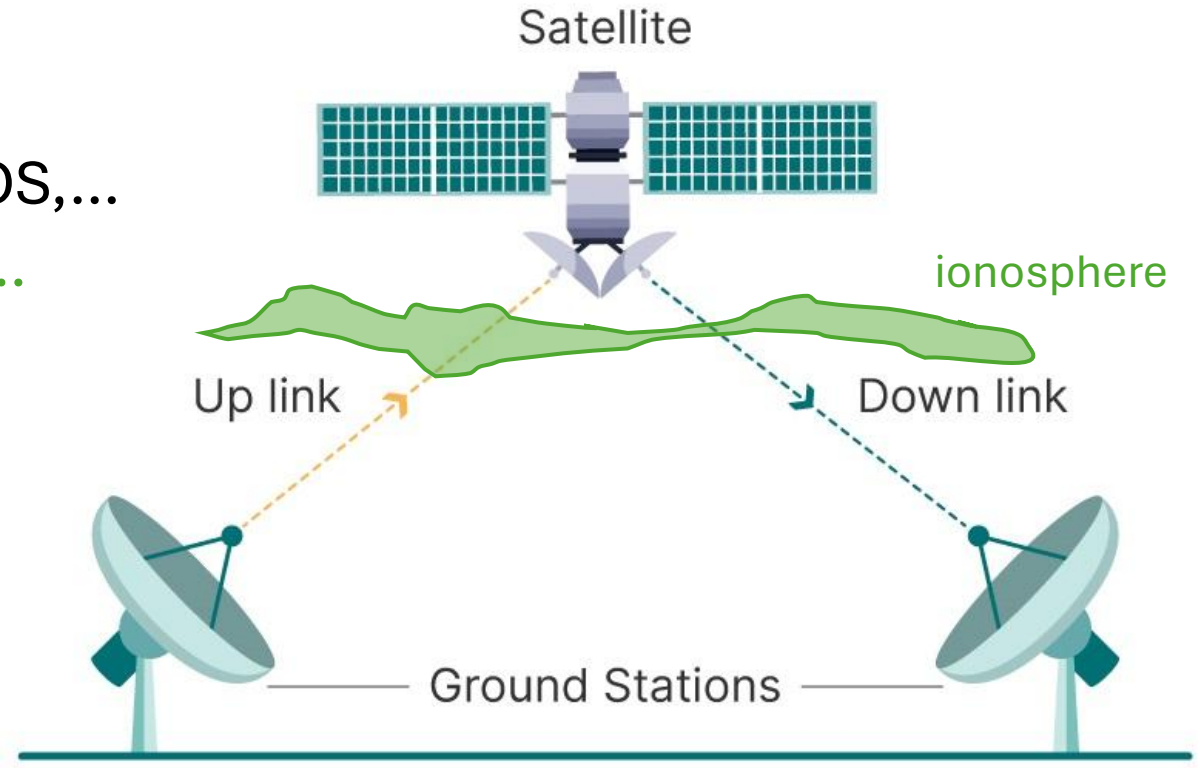
- Frequency geomagnetic storms
  - Dst *(Disturbance storm-time index)*
    - ~ 14 severe storm days / SC
    - ~ 2 extreme storm days / SC



HF Com: High Frequency Communications (3-30 MHz) ; **ICME**: Interplanetary coronal mass ejection ; **SC**: solar cycle

Impact 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 (300 MHz-3 GHz ; **SHF**: super high frequency (3-30 GHz)

Impact from ICMEs on SATCom/GNSS

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  - Applications such as WAAS, EGNOS,…
  - Signals travel through ionosphere…
    - Ionospheric scintillation
      - Plasma bubbles
      - = small scale irregularities in e^- density
        - May develop in large structures
      - Rapid fluctuations in satellite signal
        - Phase and intensity
        - May result in signal loss

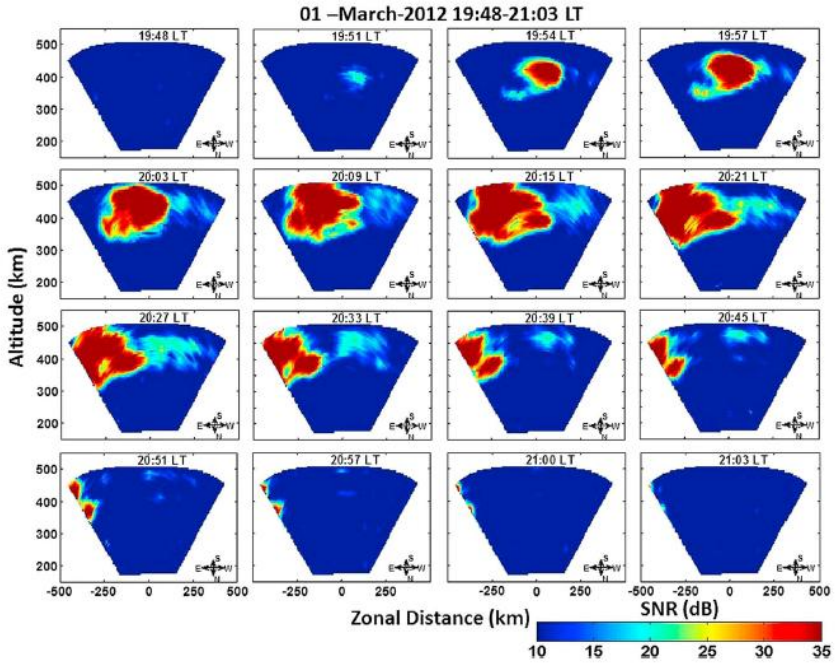


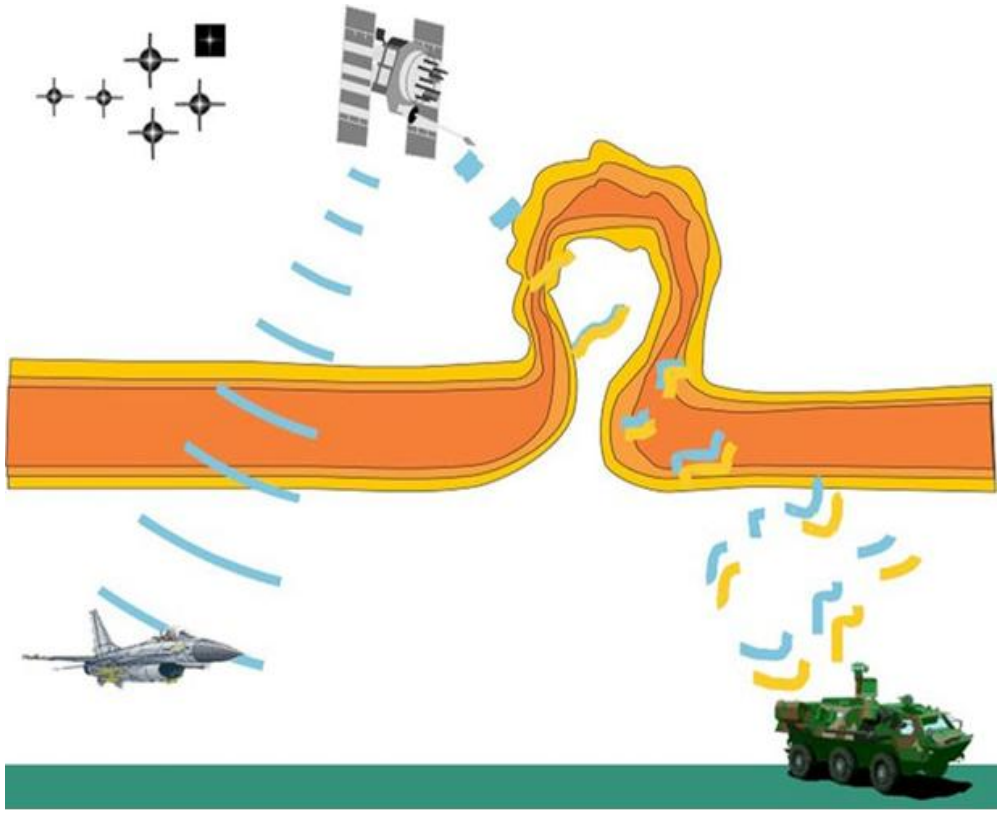
Figure 1. An example showing the genesis and successive development of EPB (evolving-type) over Kototabang observed from the fan sector maps of EAR on 1 March 2012.

Credits: Ajith et al. (2015)

GHz: gigahertz ; **(I)CME**: (Interplanetary) Coronal Mass Ejection ; **WAAS**: Wide Area Augmentation System ; **EGNOS**: European Geostationary Navigation Overlay Service ; **UHF**: ultra high frequency (300 MHz-3 GHz ; **SHF**: super high frequency (3-30 GHz)

Impact 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!

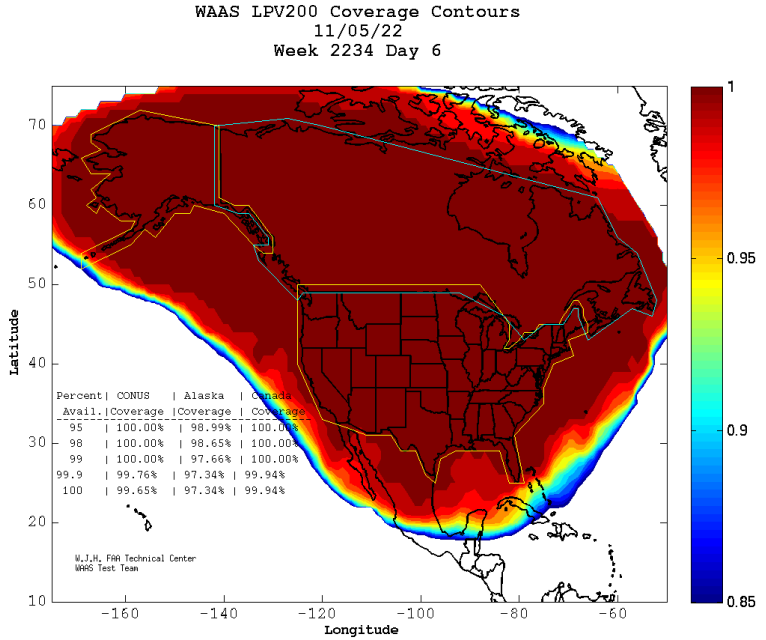


Credits: US Air Force Research Laboratory

Impact from ICMEs on SATCom/GNSS

- Satellite Communication (SATCom)
  - GNSS applications such as WAAS / EGNOS

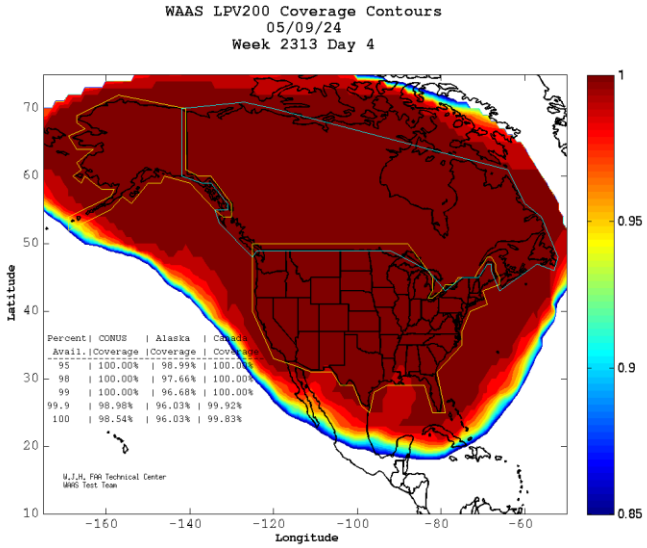


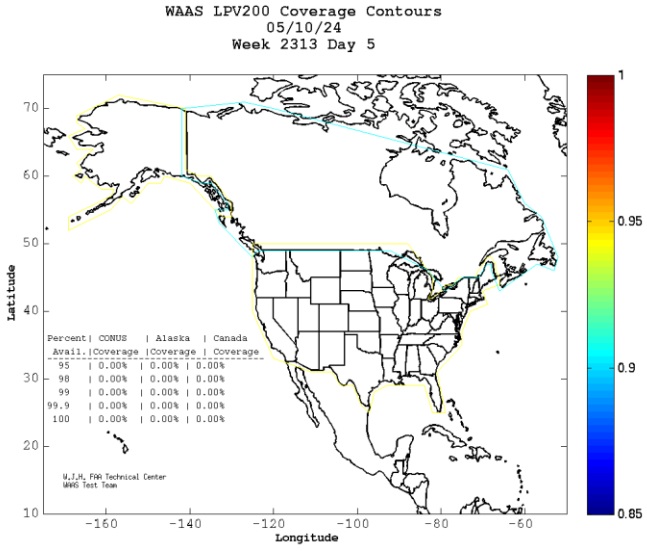


GNSS: Global Navigation Satellite Systems (GPS, Galileo,,...) ; **ICME**: Interplanetary coronal mass ejection ; **nT**: nanotesla ; **Dst**: Disturbance storm time ; **dB**: decibel ; **WAAS**: Wide Area Augmentation System (WAAS) ; **LPV**: Localizer Performance with Vertical Guidance ; **PECASUS**: Pan-European Consortium for Aviation Space weather User Services ; **EGNOS**: European Geostationary Navigation Overlay Service ; **NOTAM**: Notice to Airmen

Impact from ICMEs on SATCom/GNSS

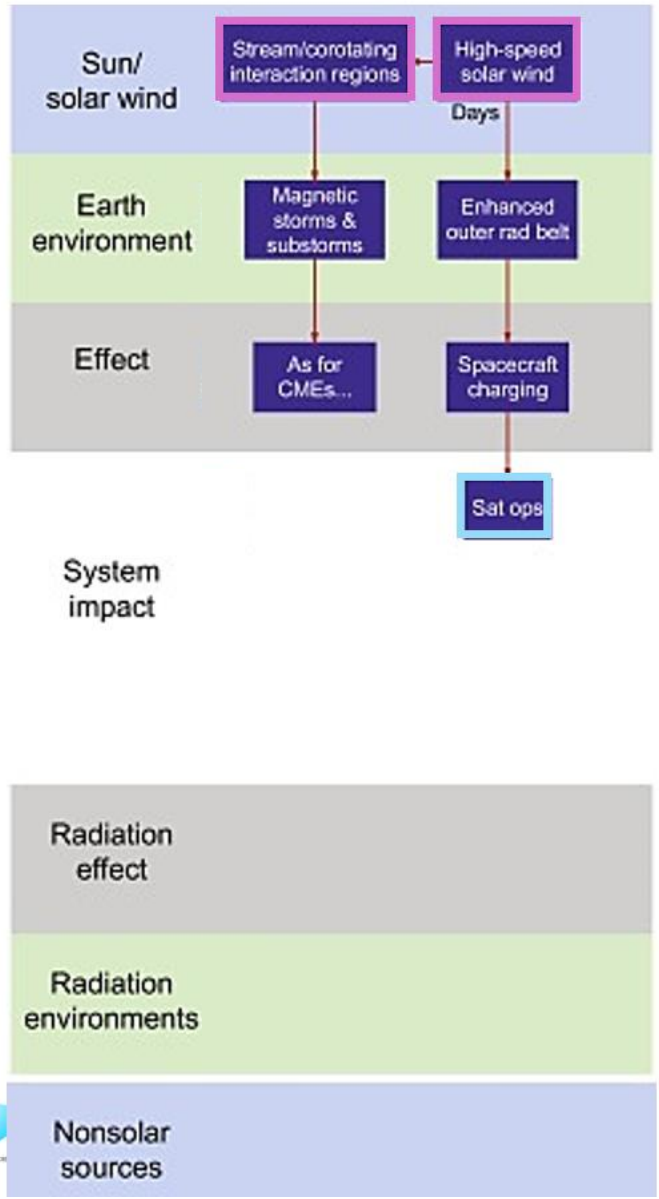
- Satellite Communication (SATCom)
  - GNSS applications such as WAAS / EGNOS
    - 10-11 May 2024 *(Kp = 9o)*
      - WAAS Extreme storm detector (ESD) tripped for the first time since its inception in 2007 causing an extended loss of LPV/LPV200 over entire WAAS coverage volume
        - NOTAMs issued advising on navigational disruptions
          - EGNOS limited over Europe
        - ESD tripped again during the 10-11 Oct 2024 storm…





GNSS: Global Navigation Satellite Systems (GPS, Galileo,,…) ; **ICME**: Interplanetary coronal mass ejection ; **nT**: nanotesla ; **Dst**: Disturbance storm time ; **dB**: decibel ; **WAAS**: Wide Area Augmentation System (WAAS) ; **LPV**: Localizer Performance with Vertical Guidance ; **PECASUS**: Pan-European Consortium for Aviation Space weather User Services ; **EGNOS**: European Geostationary Navigation Overlay Service ; **NOTAM**: Notice to Airmen

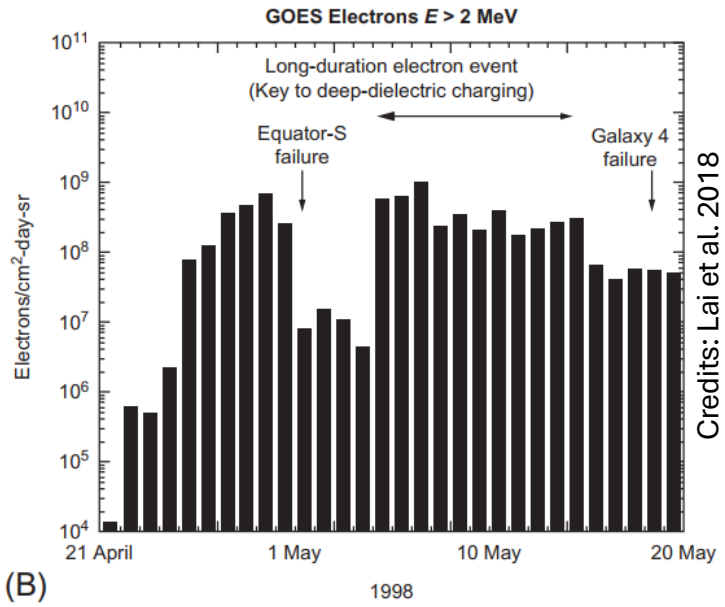
Impact from CH HSS on SATCom



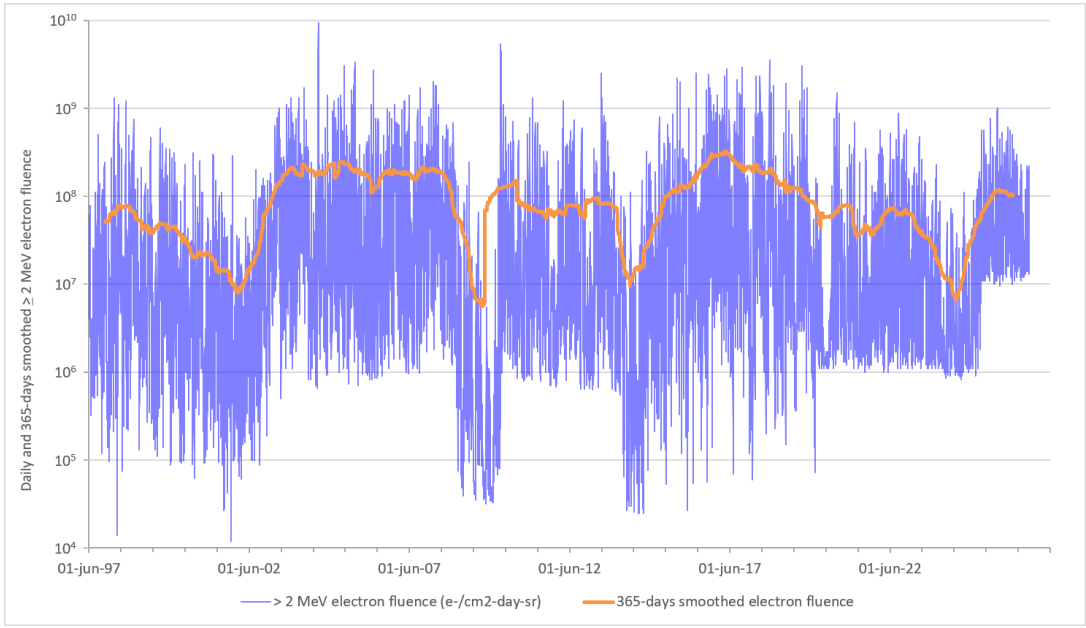
- Similar to effects from ICMEs but less intense
- except…

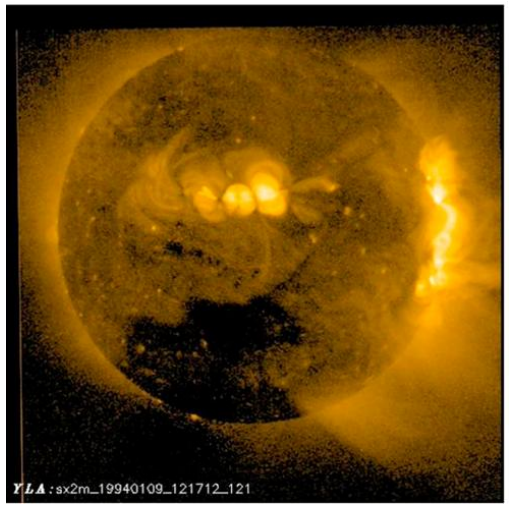
- From particles
  - Satellites
    - Deep di-electric charging
      - *NOT ionosphere related*

Impact from CH HSS on SATCom

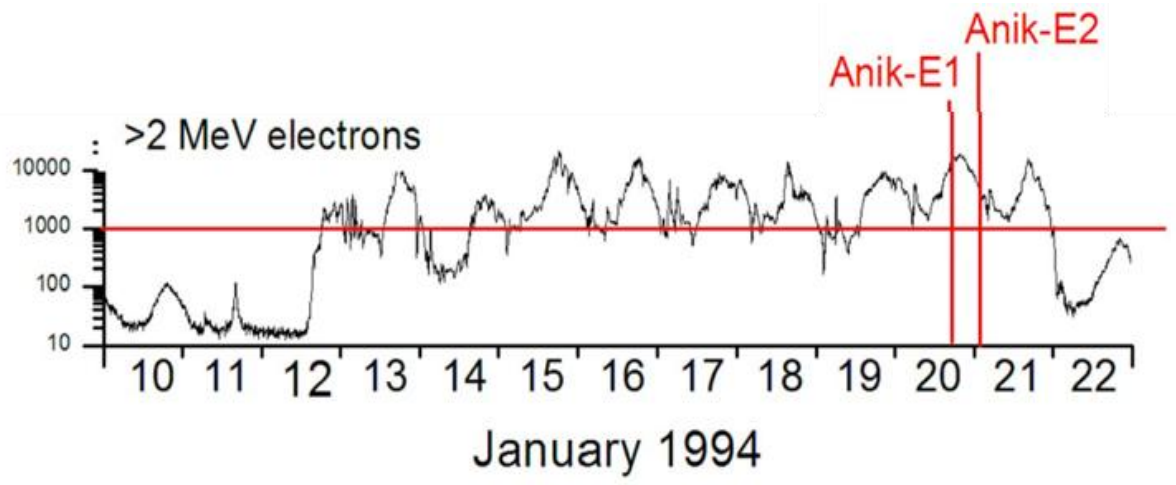


Credits: Lai et al. 2018



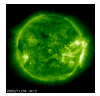
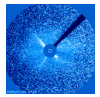
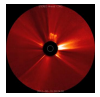
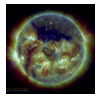


Frequency High fluence: ~17 days / year



Credits: Lam et al. 2012

Summary

	HF Com	SATCom/GNSS
 Solar flares	Short-Wave Fade (SWF)	Radio bursts
 Solar energetic particle events (SEP)	Polar Cap Absorption (PCA)	
 Interplanetary coronal mass ejections (ICME)	Auroral Absorption (AA) Post-Storm Depression (PSD)	Ionospheric scintillation
 High speed streams from coronal holes (HSS/CH)		Deep di-electric charging