

Role of the ionosphere and space weather in military communications

8-10 September 2025



The background of the slide is a composite image of several satellites in orbit above Earth. The Earth's surface is visible as a blue and white horizon with clouds. The satellites have gold-colored bodies and large blue solar panel arrays. One satellite in the foreground is shown in a cutaway view, revealing internal components like a radiator and a camera lens.

EXTREME EVENTS and IMPACTS

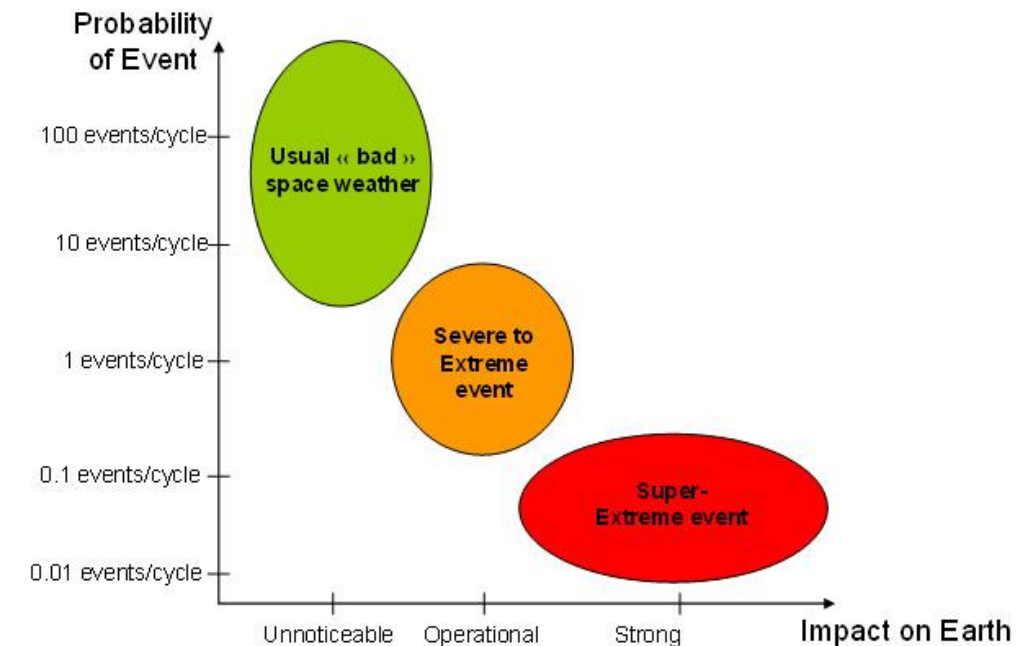
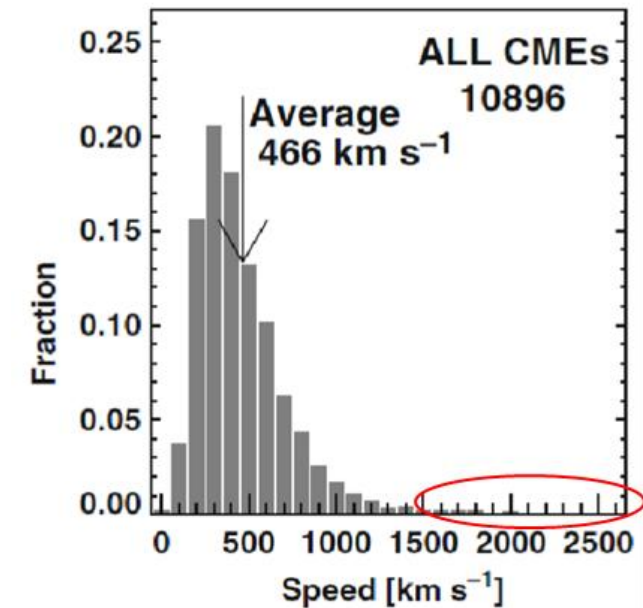
Focus on HF Com and SATCom

Contents

- What is an extreme event?
- SWx drivers & impacts: overview
- **HF Com** and **SATCom** 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...
 - 1 moderate and 1 weak solar cycle since the mid-1990s...



Nota: Solar cycle~11 years

Credits: Skybrary

What is an extreme event?

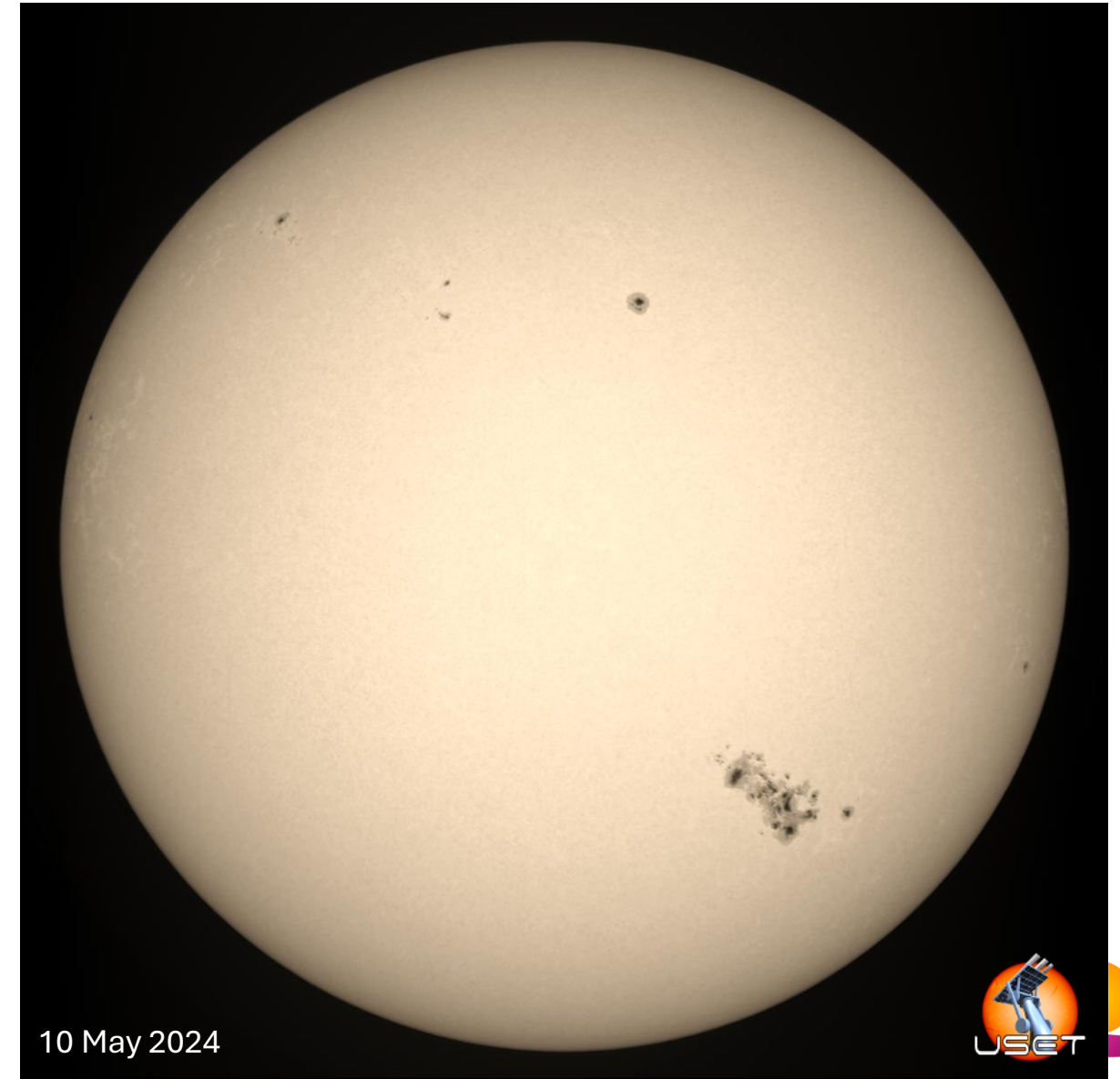
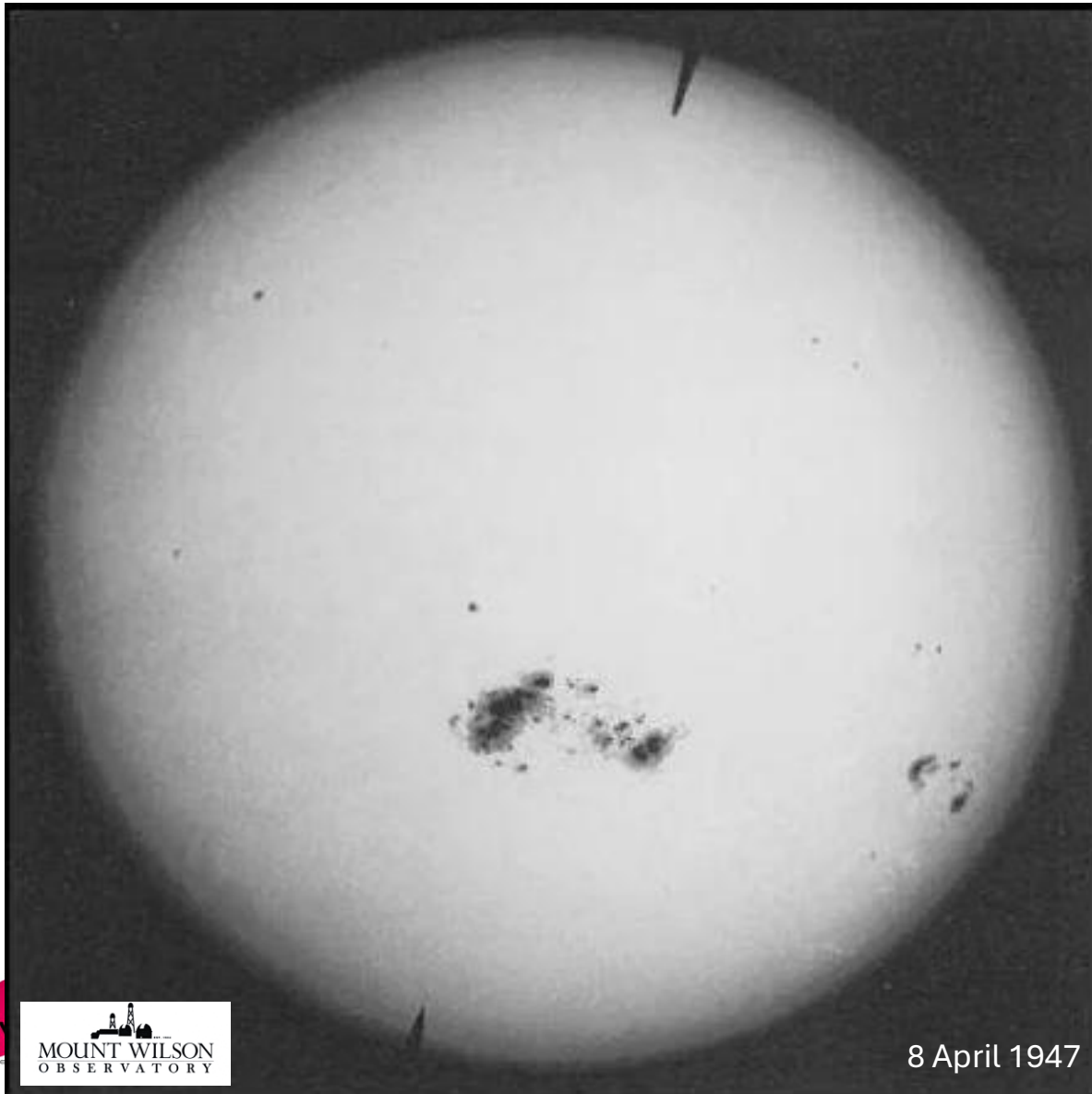
Observed, statistically expected, and modelled extreme solar and solar-terrestrial events

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

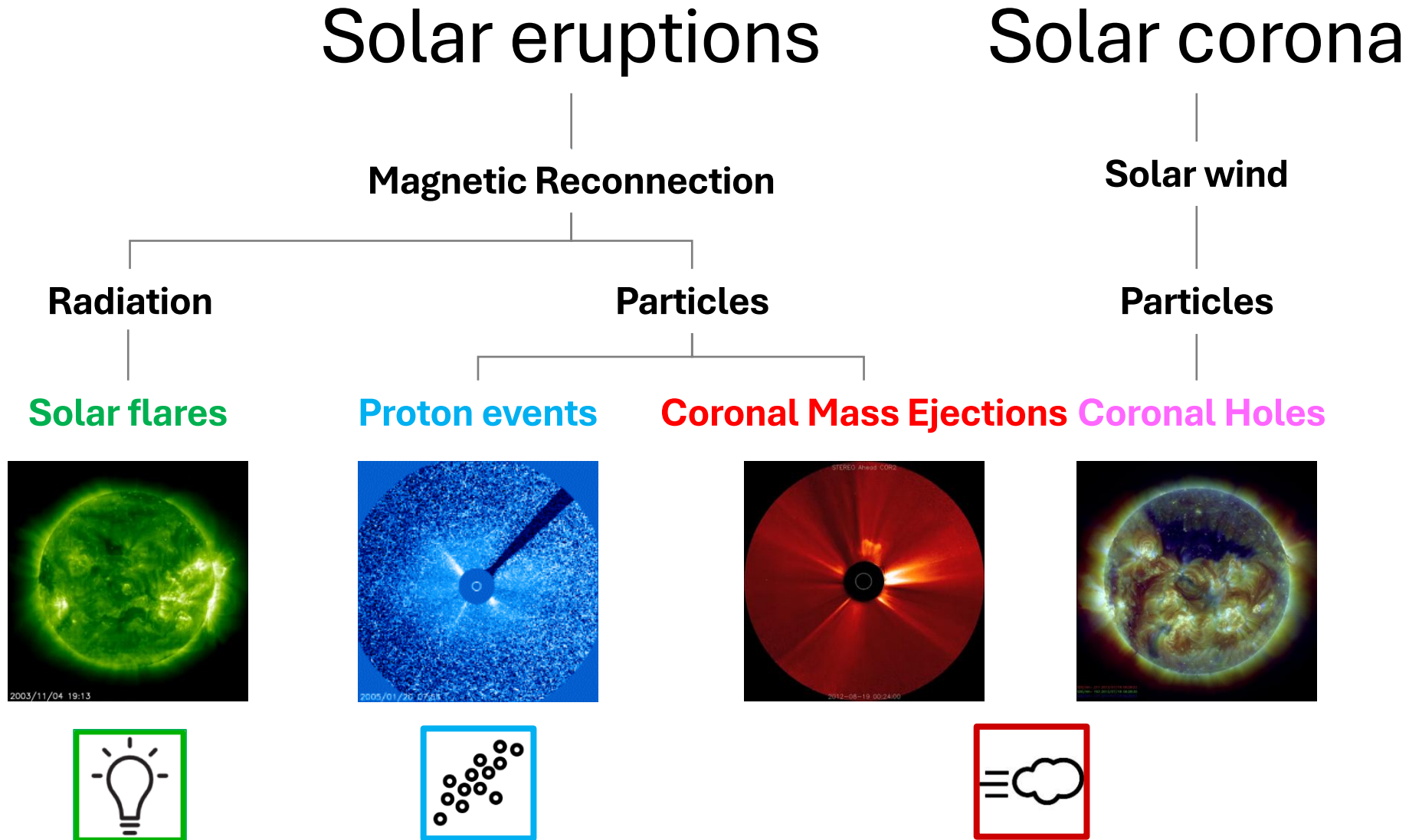
<i>Parameter</i>	Observed Extremum	100-year ev. Exp. Law	100-year ev. Power Law	1000-year ev. Exp. Law	1000-year ev. Power Law	Modelled Extremum
<i>Sunspot group area (MH)</i>	6132	5800	7100	8200	13600	
<i>GOES flare SXR</i>	X40	X44	X42	X100	X115	X180
<i>1.5 GHz radio emission (10^6 sfu)</i>	1		3.2 -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

Acronyms: **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

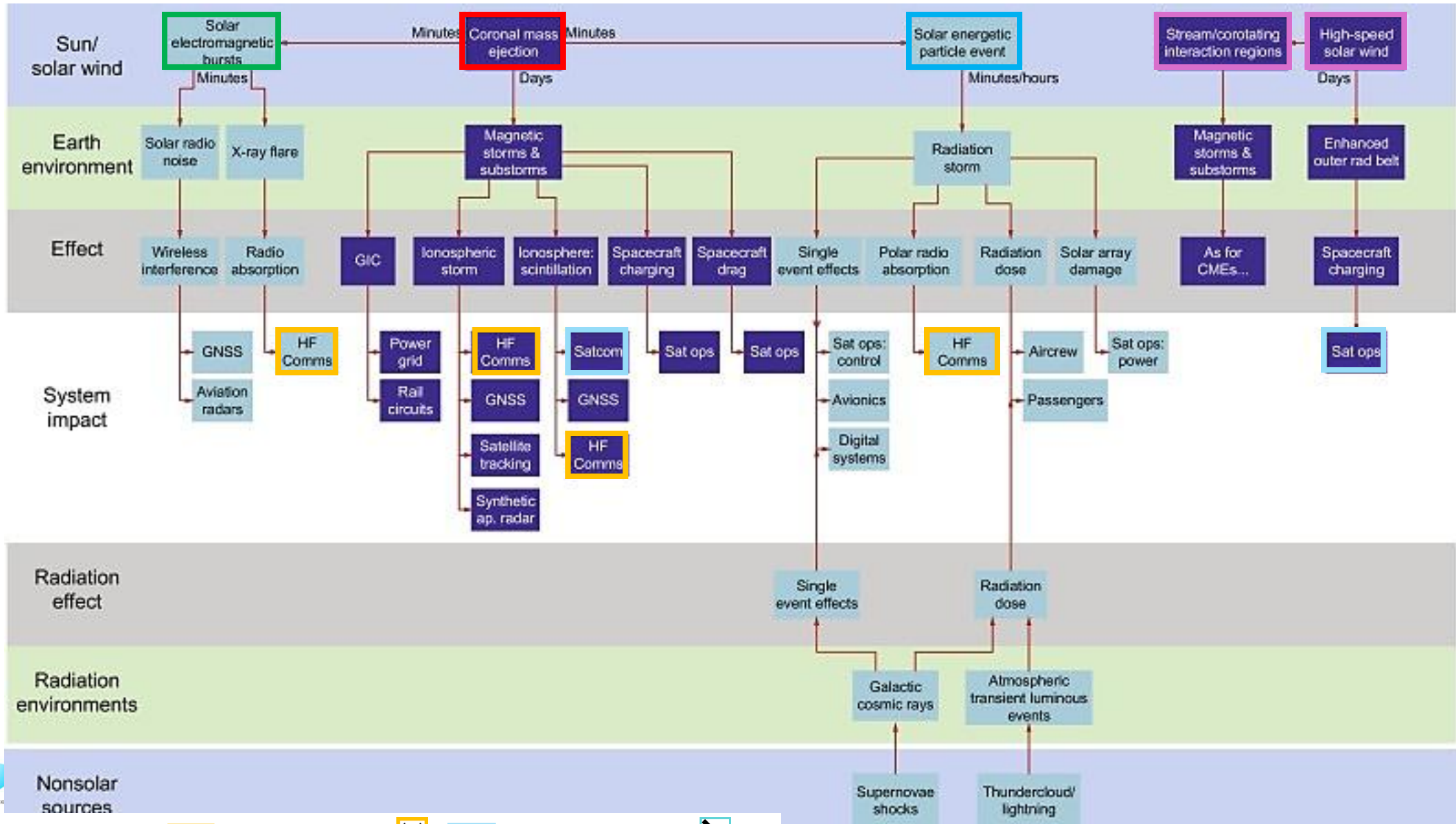
Largest sunspot groups in SC18 and SC25

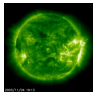


Drivers of disturbed space weather

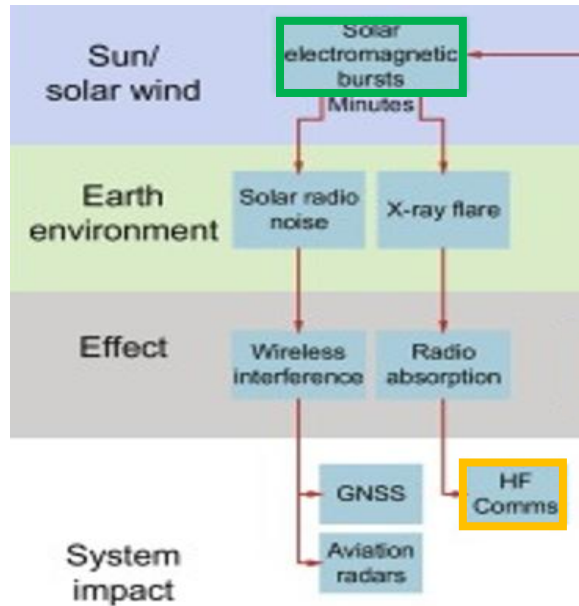


Impacts of disturbed SWx

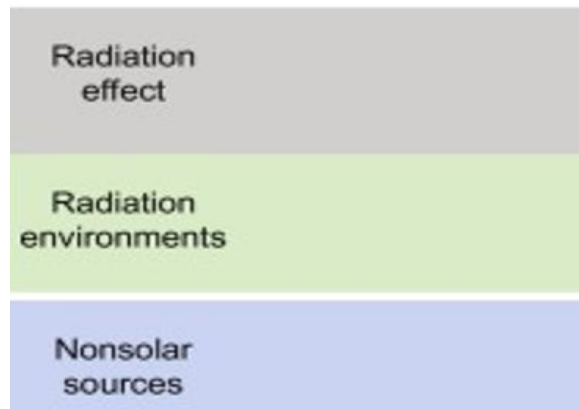


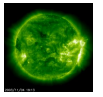


Impacts from solar flares

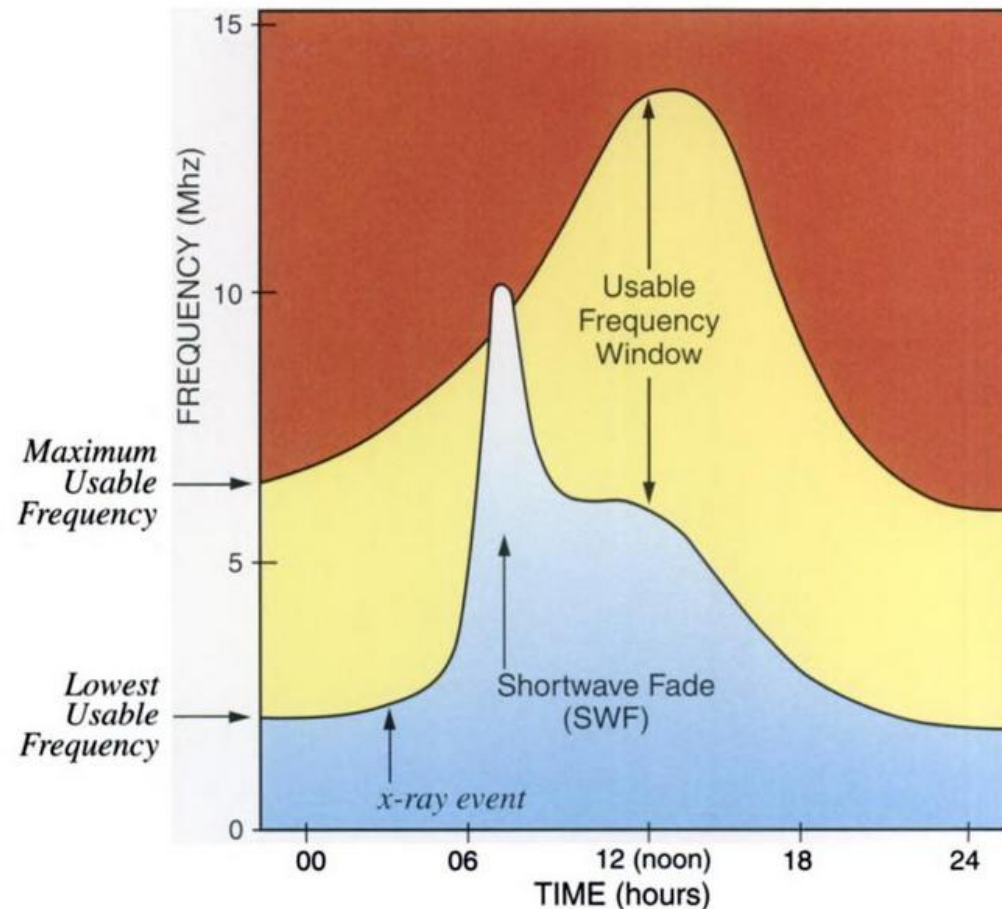


- From EUV & X-ray
 - Solar flare effect
 - “magnetic crochet”
 - Up to +/- 100 nT
 - Short-wave fade (SWF)
 - “Radio Blackout”
 - Impact on HF Com
- From radio emission
 - GNSS disturbances
 - Radar disturbances
 - Radio amateurs

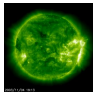




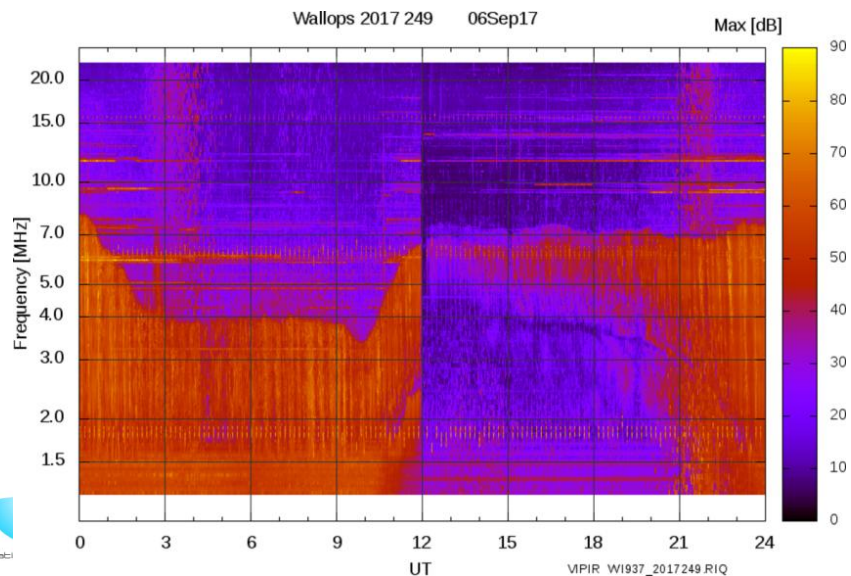
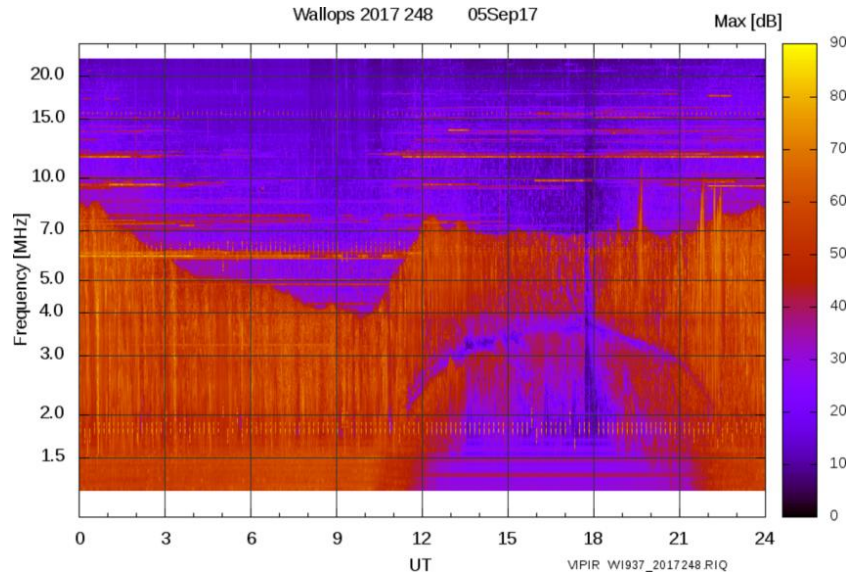
Impacts from solar flares on HF Com



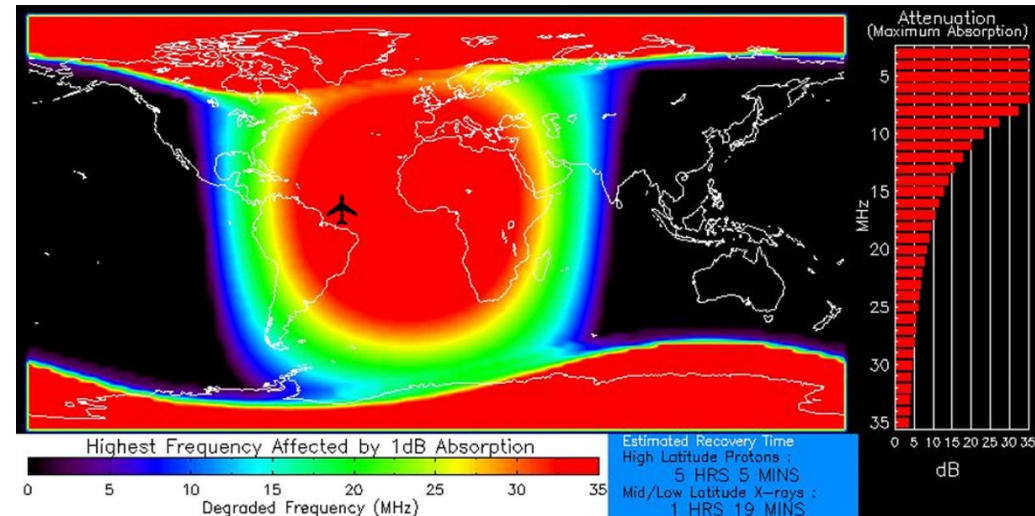
- Short-wave fade (SWF)
 - Aka “Radio blackout”
 - Misleading term
 - SXR from solar flare
 - Sunlit hemisphere of the Earth
 - Increase ionospheric plasma (D-region)
 - Increase in HF absorption
 - Affects lower frequencies most
 - => Backup systems (SATCom,...)
 - => Difficult to reach locations (polar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



Impacts from solar flares on HF Com



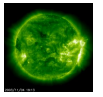
- Short-wave fade (SWF)
- September 2017
 - Several strong solar flares following hurricanes Irma and Jose in Caribbean
 - No HF Com for several hours
 - Contact with 1 cargo plane lost for 1.5h



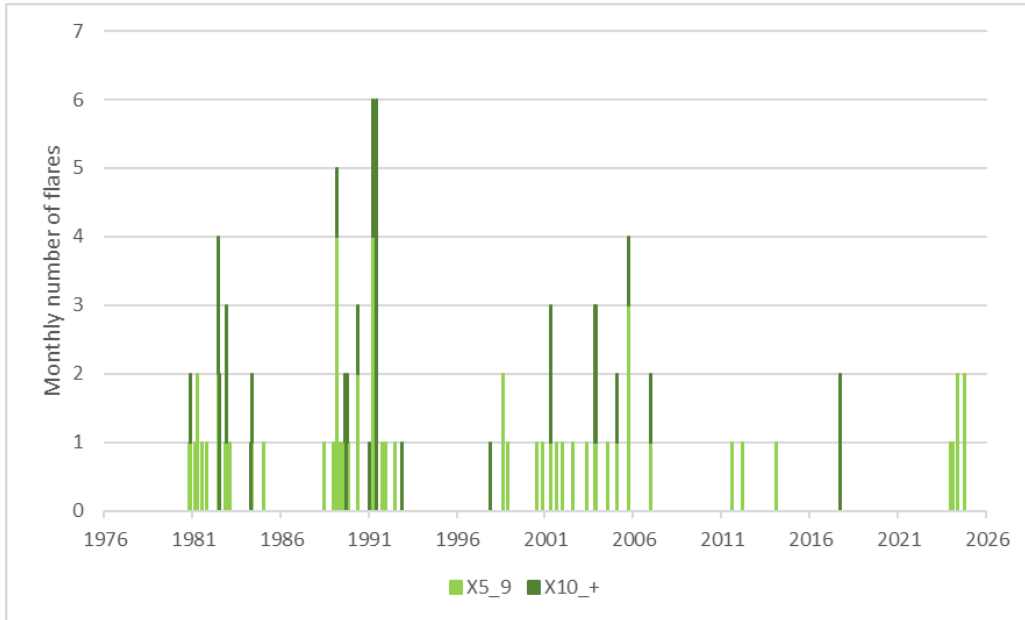
Strong X-ray flux
Product Valid At : 2017-09-06 12:50 UTC

Minor Proton Flux
NOAA/SWPC Boulder, CO USA

Courtesy of CIRES, Terry Bullett



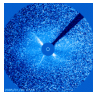
Impacts from solar flares on HF Com



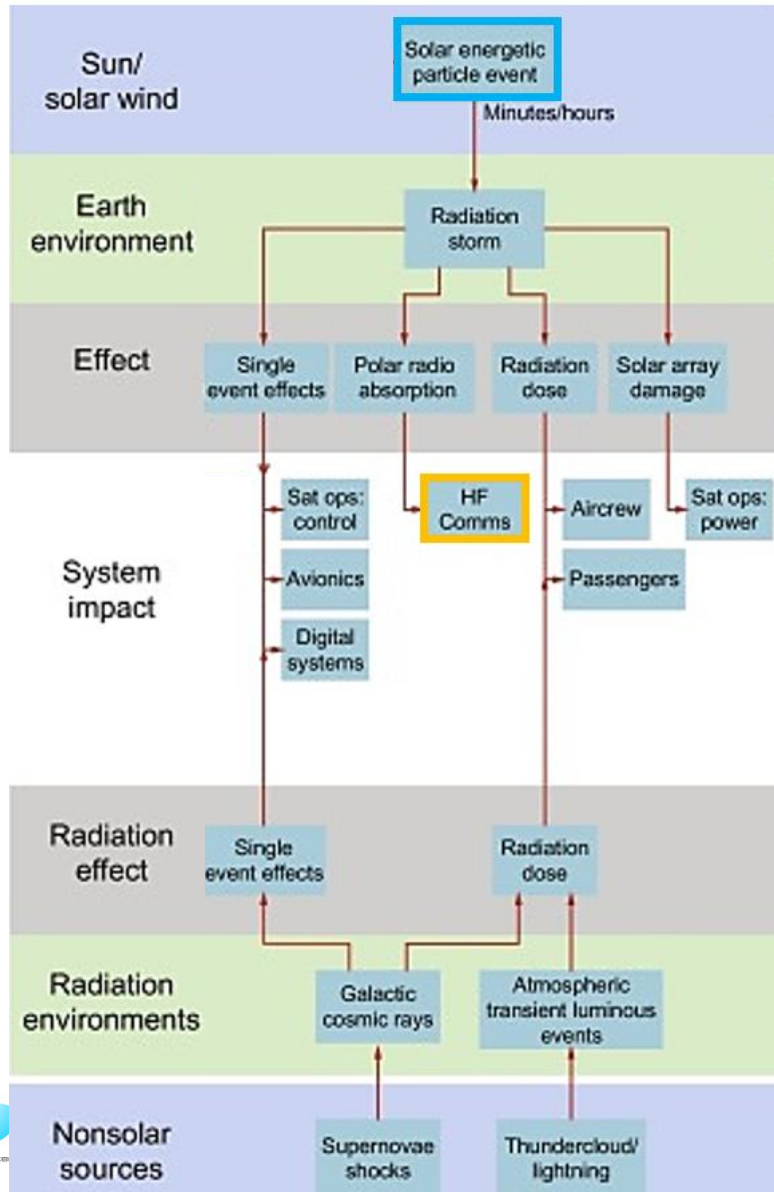
- About 9 X5+ flares per SC
 - Large variability per SC!
 - Median duration of 1 hour
 - Extremes from 5 up to 10 hours

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

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



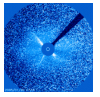
Impacts from SEP events



• 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)

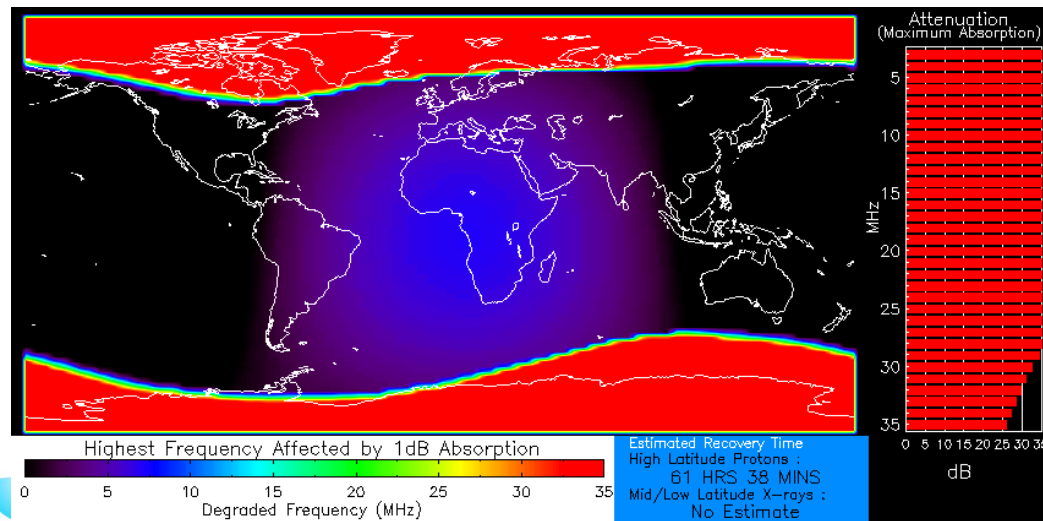
SEP: Solar Energetic Particles ; GCR: Galactic Cosmic Rays ; GNSS: Global Navigation Satellite Systems ; TLE: Transient Luminous Events ; MF: Magnetic field ; LEO: Low Earth Orbit ; HF Com: High Frequency Communication



Impacts from SEP events on HF Com

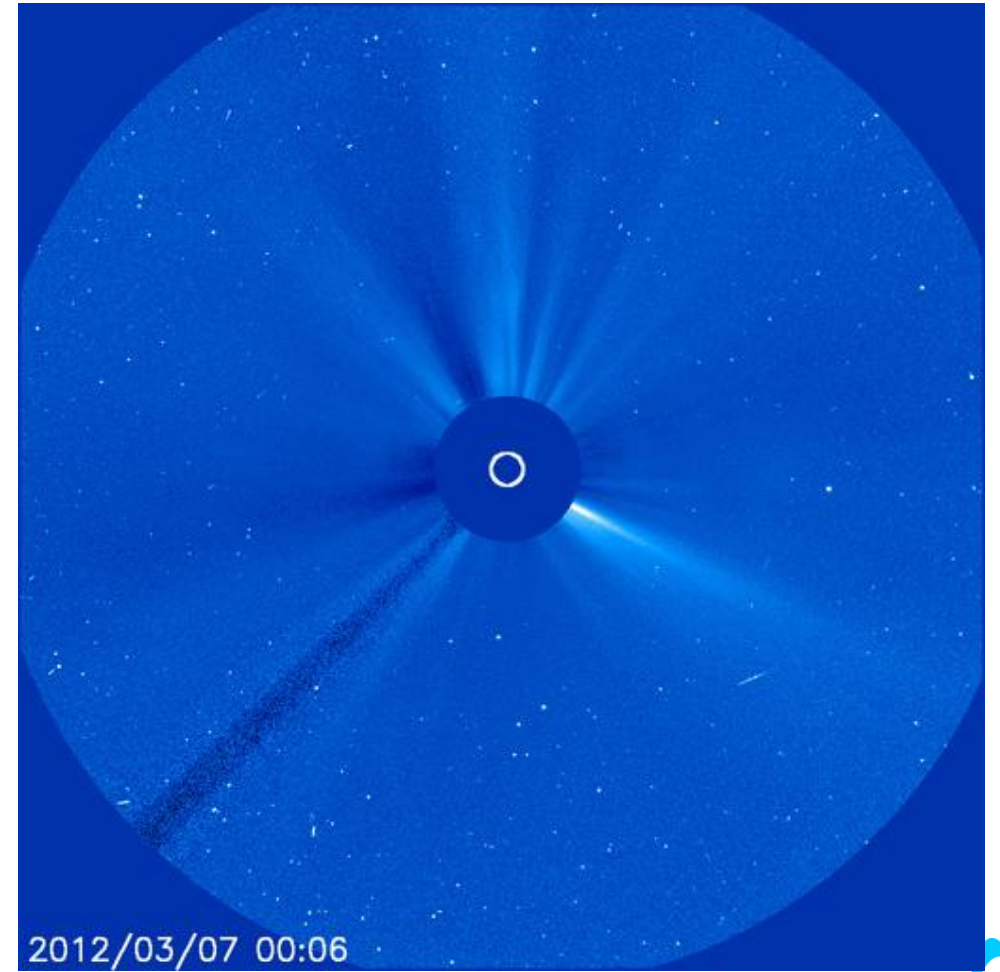


- Polar Cap Absorption (PCA)
 - From 10 MeV proton flux
 - Deviated by MF to poles
 - Affects lower ionosphere (D-region)
 - Impacts HF Com at poles
 - Can last for days
 - Polar flight
 - detours (HF Com)
 - lower altitude (radiation hazard)



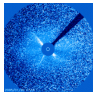
Normal X-ray Background
Product Valid At : 2012-03-08 11:15 UTC

Strong Proton Flux
NOAA/SWPC Boulder, CO USA



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





Impacts from SEP events on HF Com

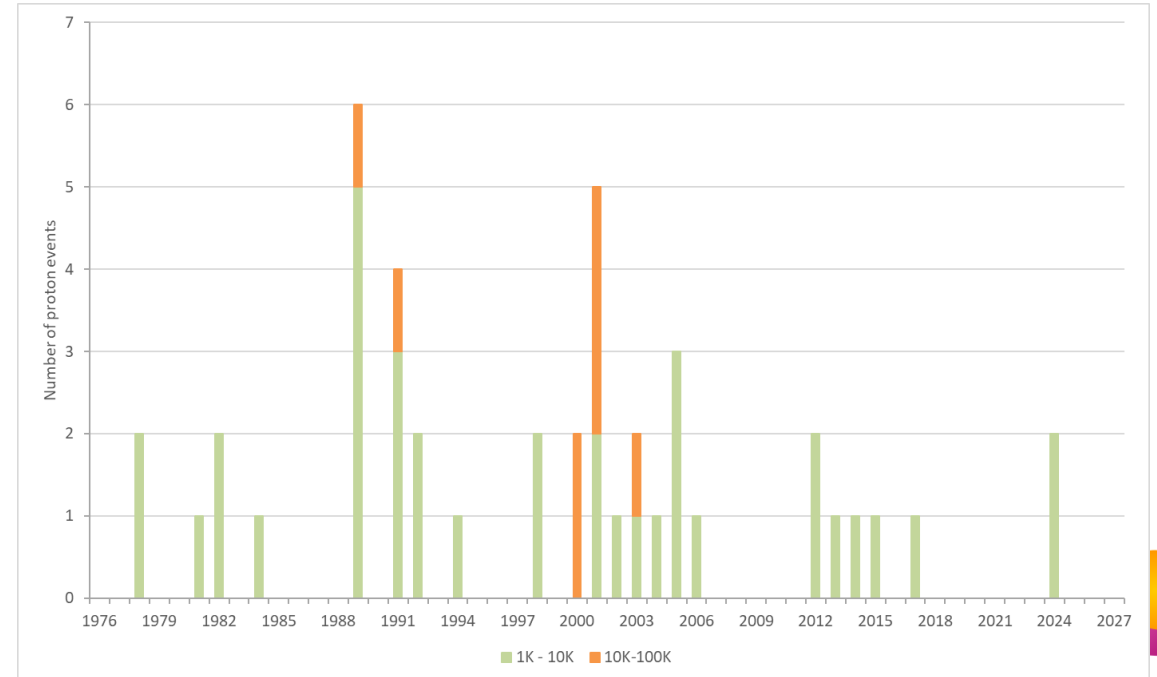
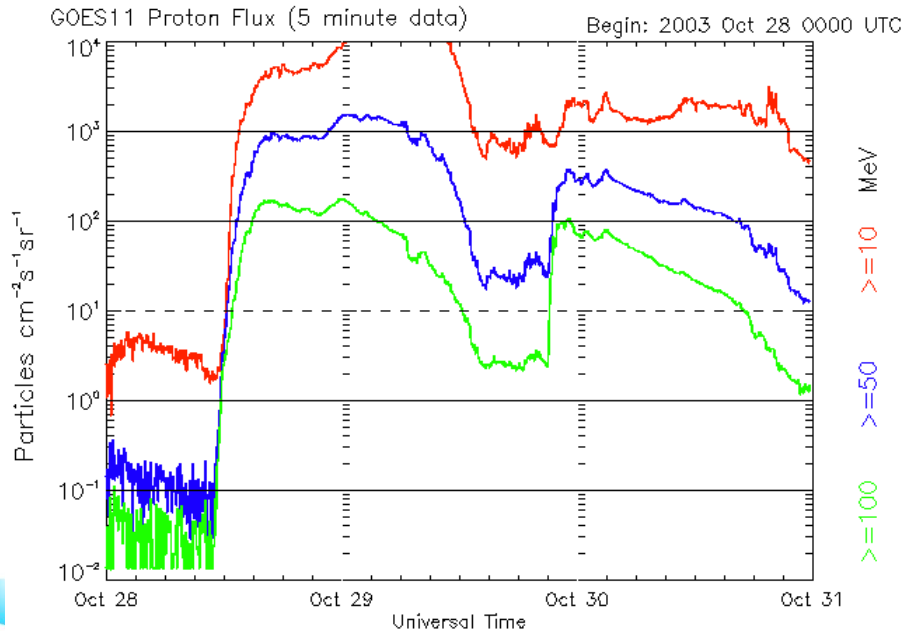


• Thresholds

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

• Frequency

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

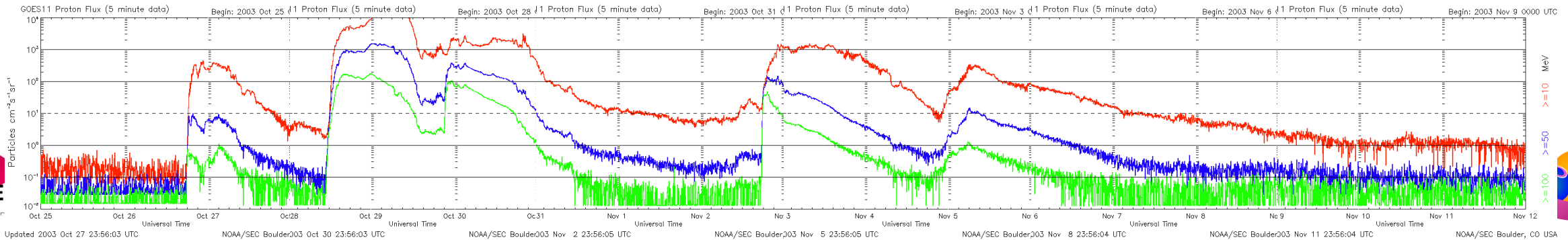
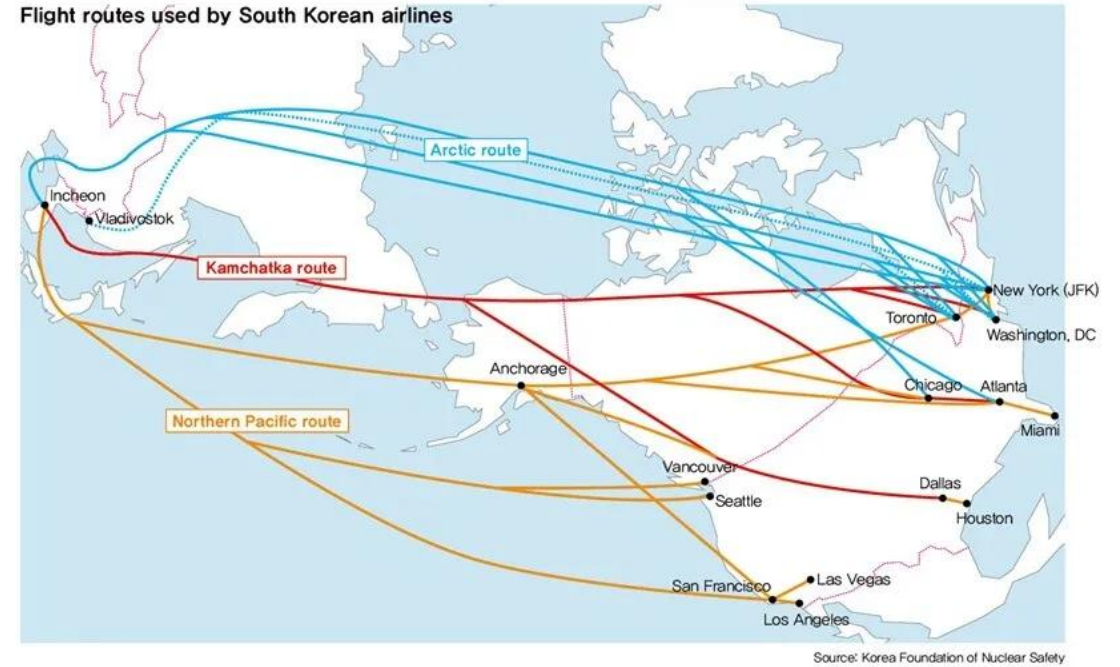




Impacts from SEP events on HF Com



- 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)

Amsterdam Evening Recorder
AND DAILY DEMOCRAT

Net Paid Circulation Over 18,350 | Weather Milder, Snow or Sleet

Vol. LXXVII, No. 158 | Recorder Established 1833—Democrat Established 1870 Consolidated 1893 | 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
Secretary of State George Marshall today announced that he would go on the right side of the Dulles-Ford administration. He said that he would support the administration's policy of "massive retaliation" against the Soviet Union.

Ousted Soviet Premier Draws
Soviet Premier Nikita Khrushchev today announced that he would resign his post as premier of the Soviet Union.

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

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."

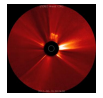
16 Aboard Safe
MIAMI, Fla. (AP)—The Coast Guard today announced that 16 men were rescued from a sinking ship in the Atlantic Ocean.

State Agencies
WASHINGTON (AP)—Senate Democratic and Republican leaders disclosed today they were working on a bill to put more teeth in the Federal Reserve Act.

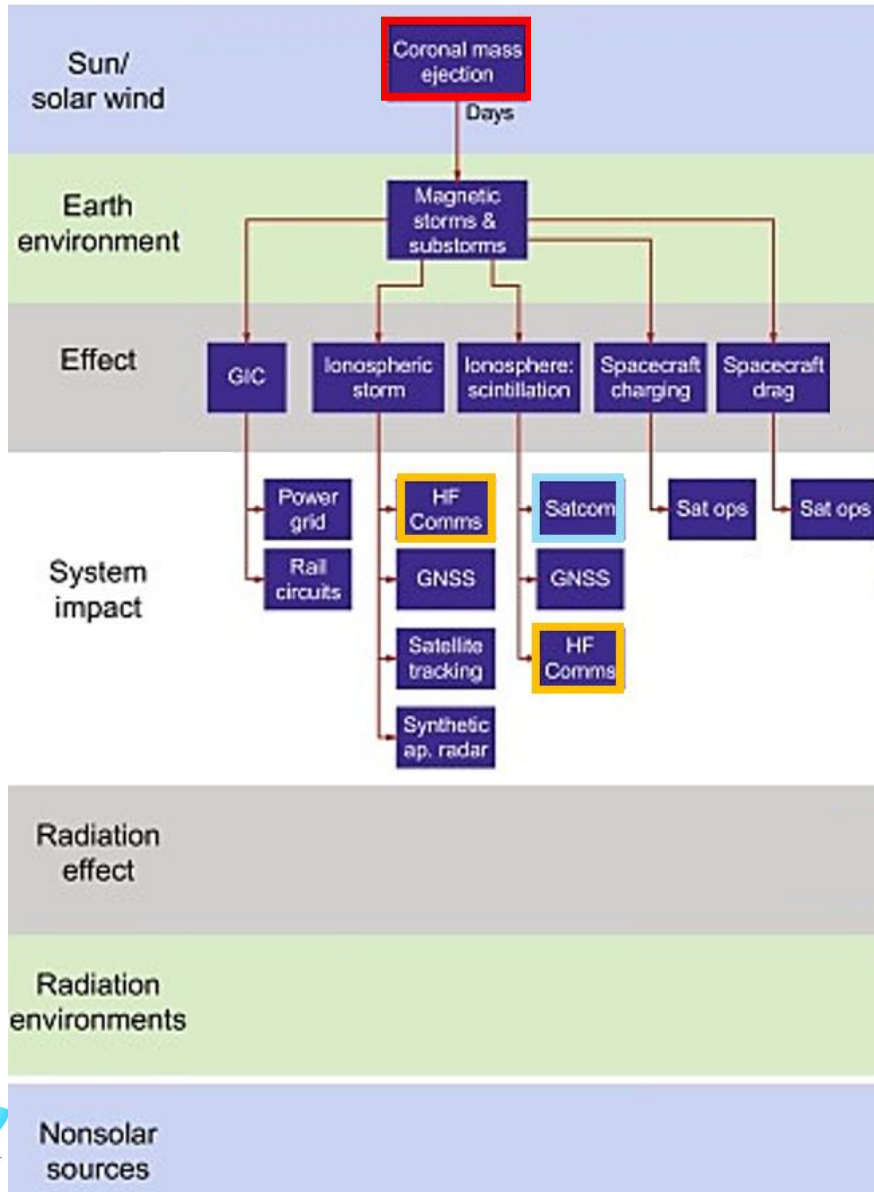
WASHINGTON (AP)—The Admiralty today called off a search for the British submarine Acheron, sighted safe in gale-swept seas after being feared lost for nearly six hours. The British minesweeper Coquette radioed three hours after the Admiralty reported the Acheron overdue that she had made "visual contact" 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.

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.



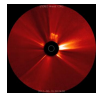


Impact from ICMEs



- 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)

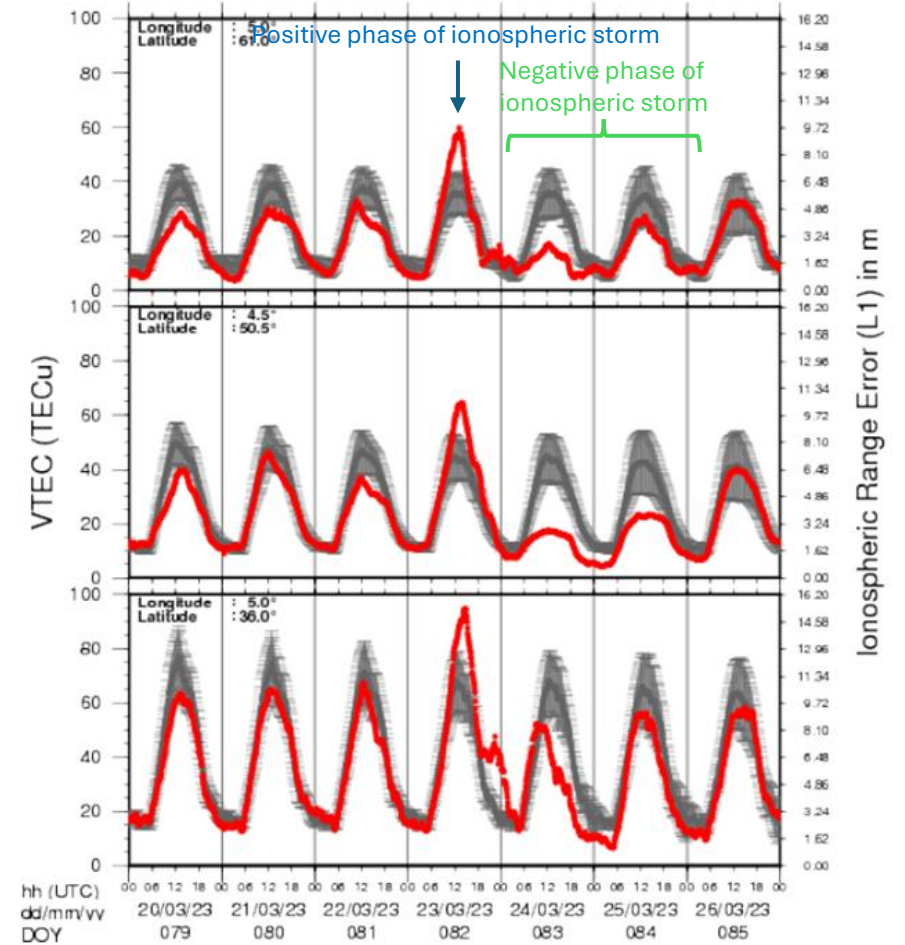
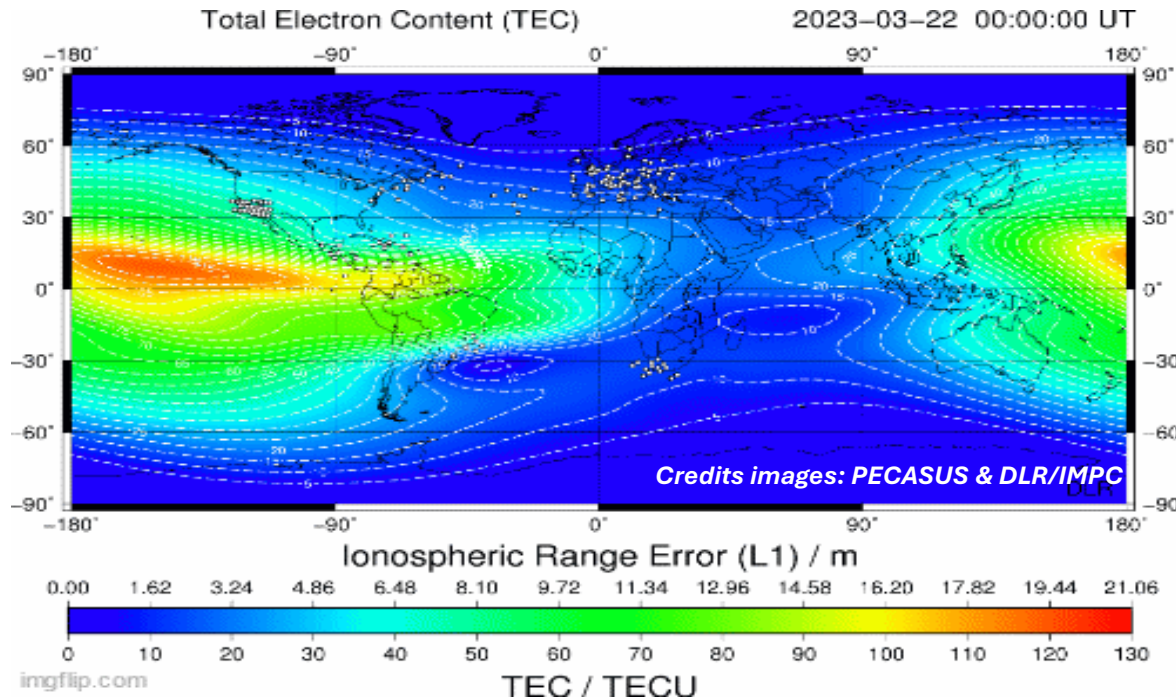
GCR: Galactic Cosmic Rays ; Comms/Nav: Communications/Navigation ;
 PECASUS: Pan-European Consortium for Aviation Space weather User
 Services ; HF: High Frequency ; (I)CME: (Interplanetary) Coronal Mass Ejection



Impact from ICMEs on HF Com

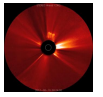


- Ionospheric storm
 - Example: 23-24 March 2023
 - Kp = 8₀ ; Dst = -163 nT



Credits: ROB/GNSS

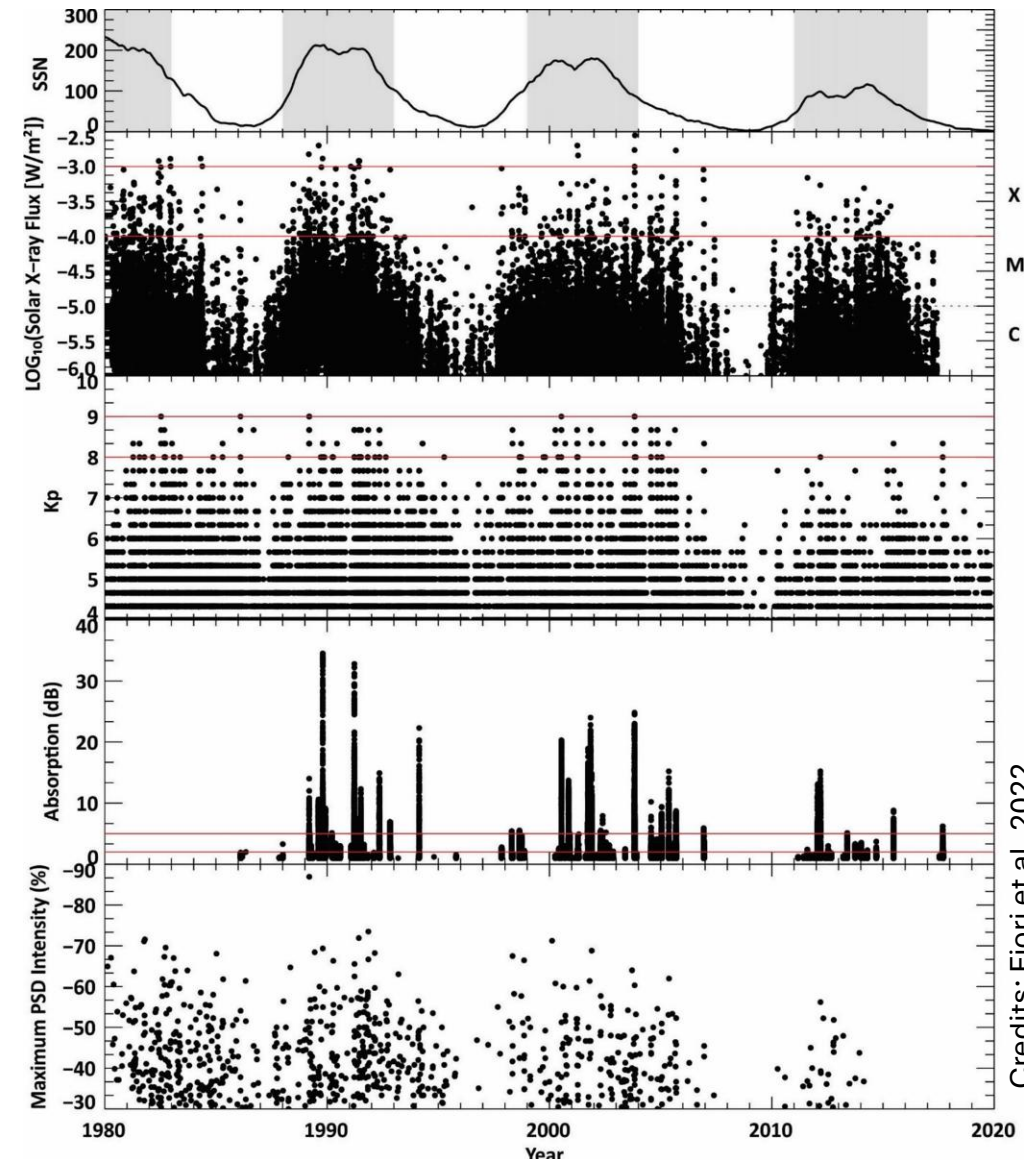




Impact from ICMEs on HF Com

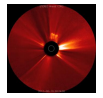


- Auroral Absorption (AA)
 - HF Com degradation due to aurora affecting lower ionosphere
- 18-19 September 1941
 - $K_p \geq 9$ - for 24 hours (!)
 - Radio broadcast disturbed
 - Bombing raids under light of aurora



Credits: Fiori et al. 2022





Impact from ICMEs on HF Com

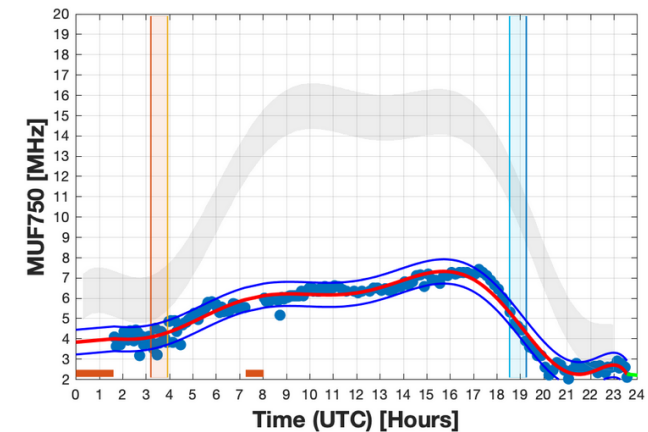


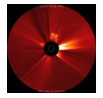
- Post-Storm Depression (PSD)
 - Negative phase of ionospheric storm
 - => strong reduction electron content ionosphere
 - = Reduction higher portion HF band
 - 25-26 May 1967
 - Most negative phase in TEC ever recorded



Credits: Peter Forister - <https://www.facebook.com/PeterForisterPhoto>

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

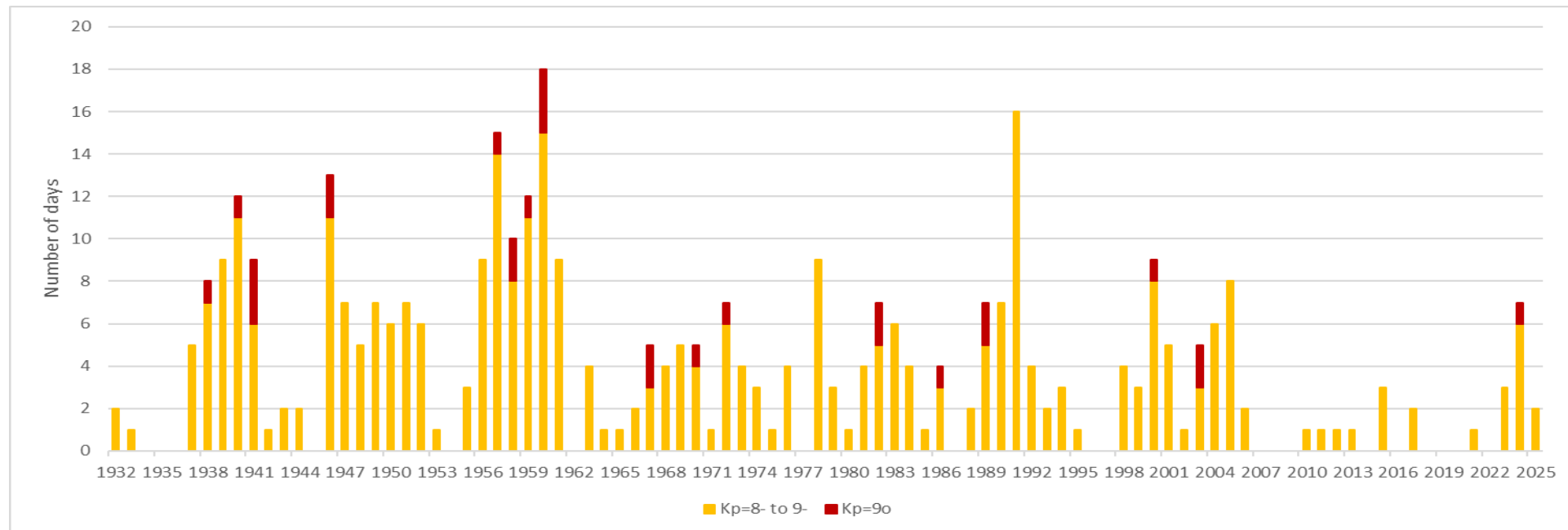




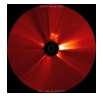
Impact from ICMEs on HF Com



- 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

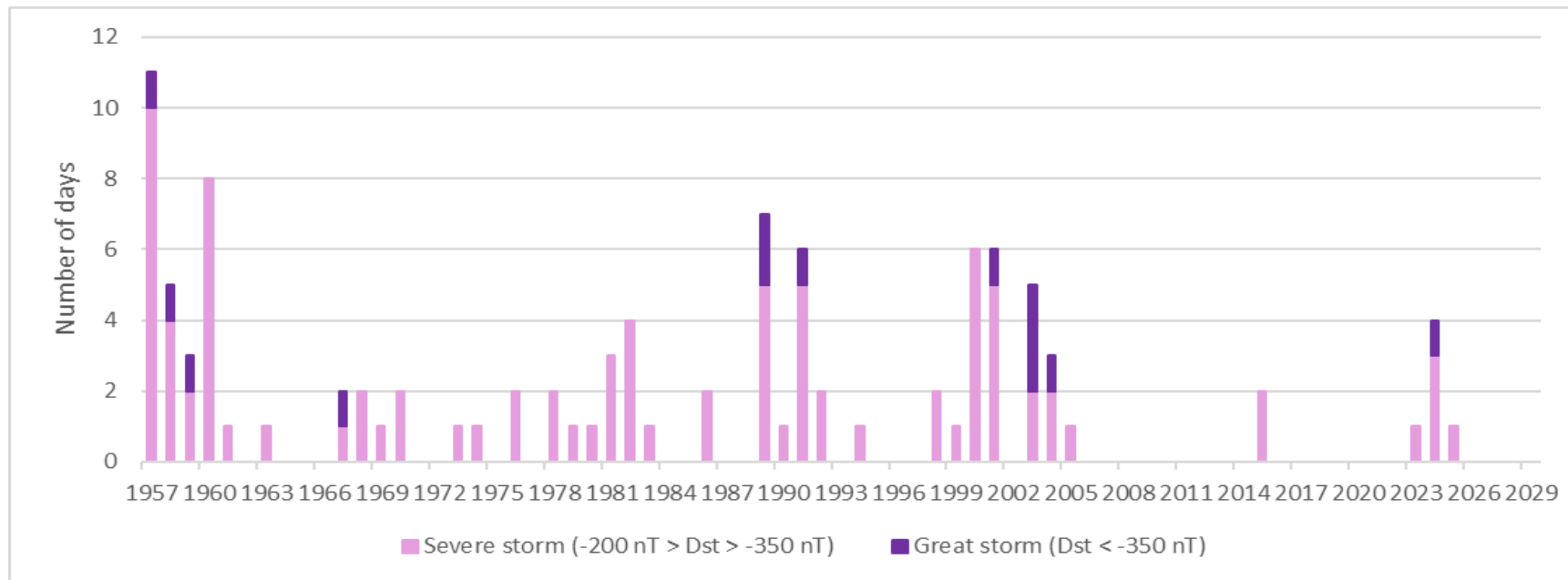
- **Kp** (*planetary K-index*)

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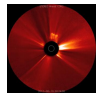
- Frequency geomagnetic storms

- **Dst** (*Disturbance storm-time index*)

- ~ 14 severe storm days / SC
- ~ 2 extreme storm days / SC



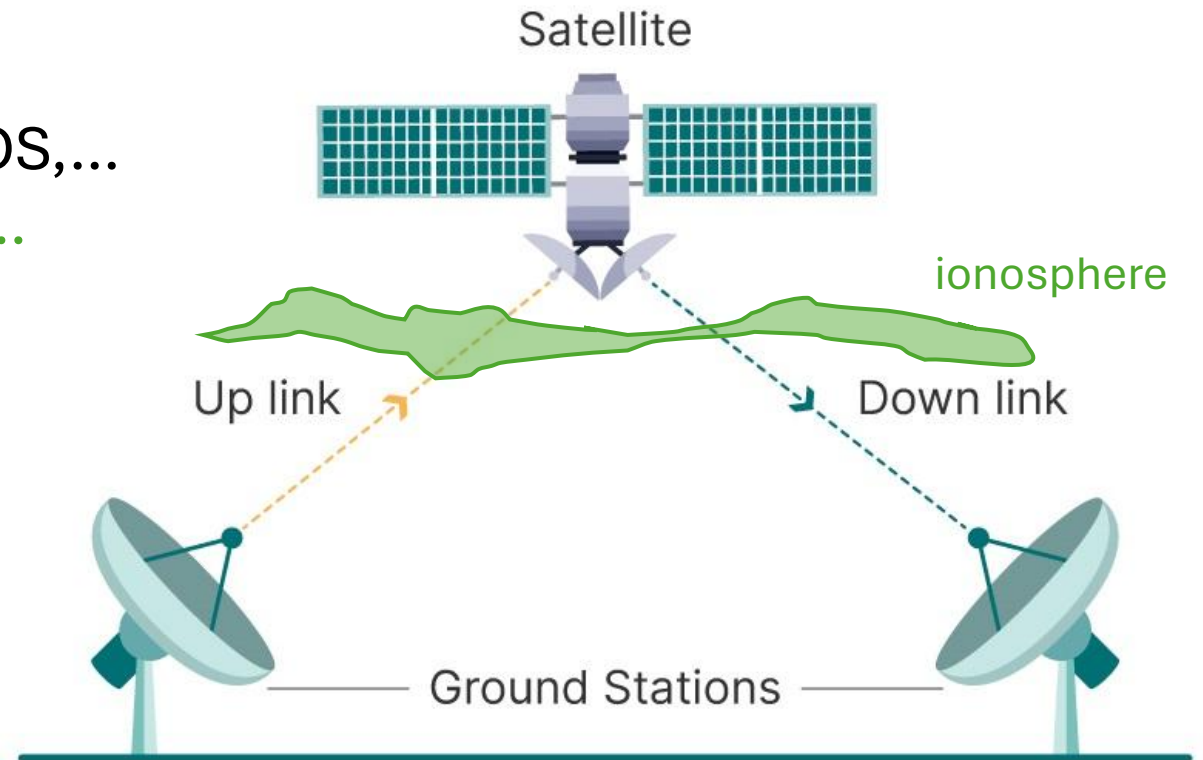
HF Com: High Frequency Communications (3-30 MHz) ; ICME: Interplanetary coronal mass ejection ; SC: solar cycle

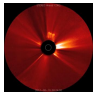


Impact from ICMEs on SATCom



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





Impact from ICMEs on SATCom



- 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

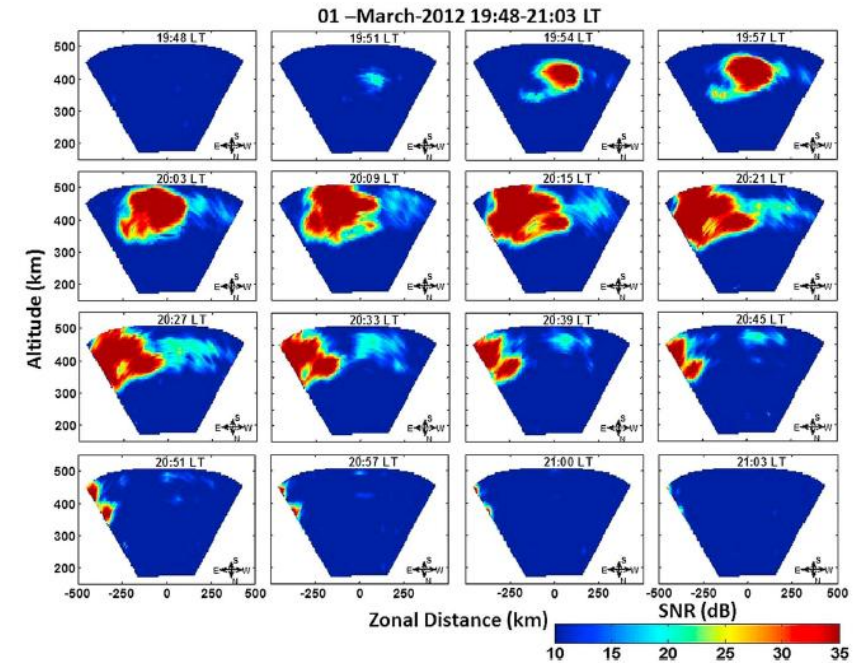
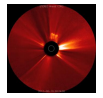


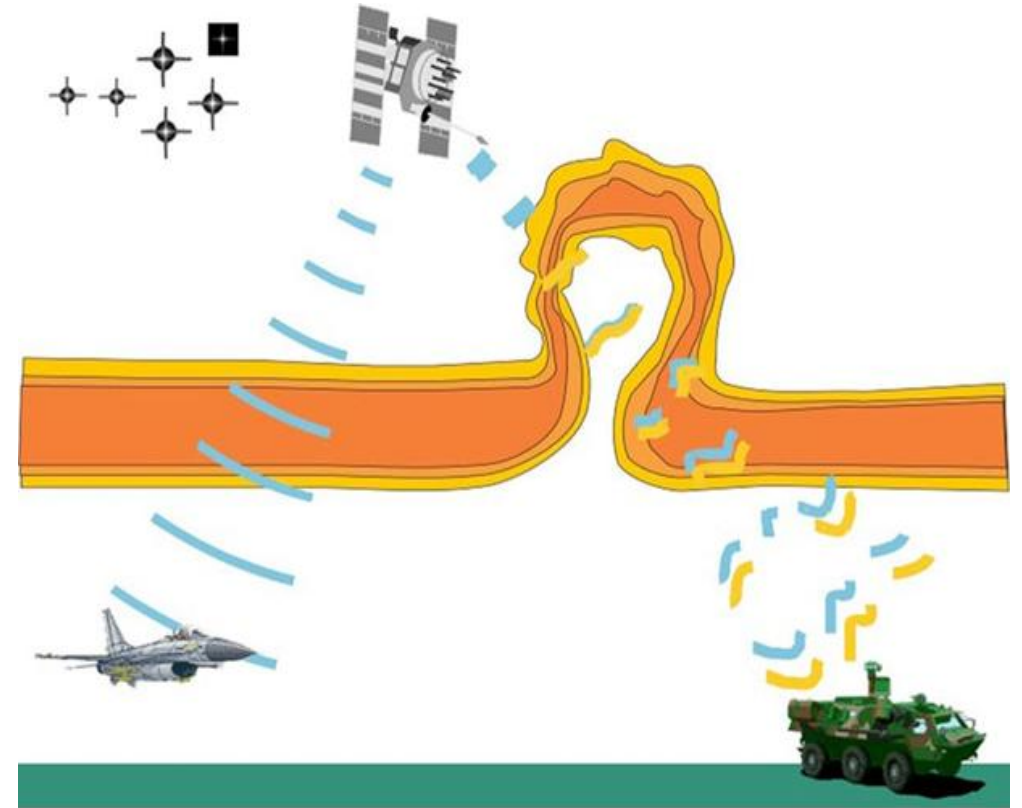
Figure 1. An example showing the genesis and successive development of EPB (evolving-type) over Kototabang observed from the fan sector maps of EAR on 1 March 2012.



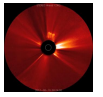
Impact from ICMEs on SATCom



- 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



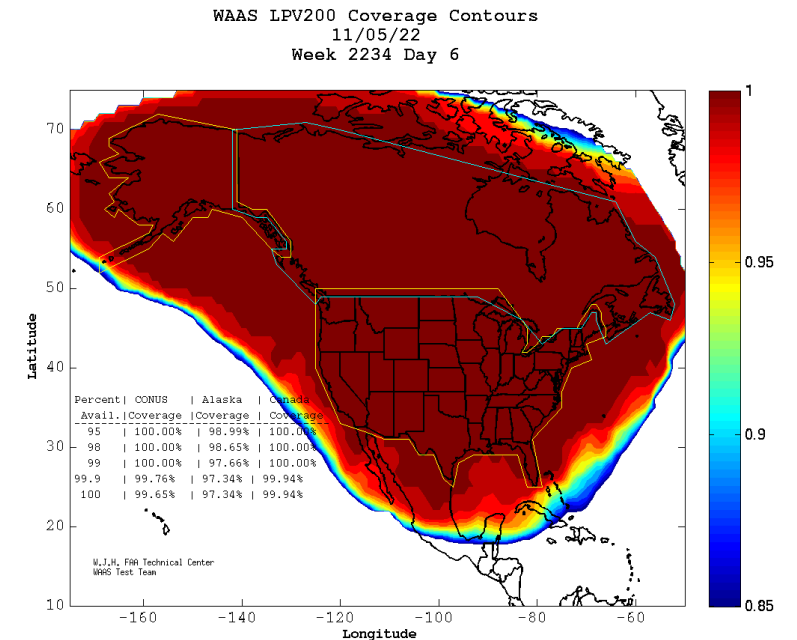
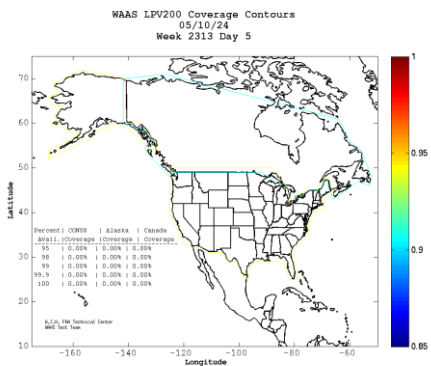
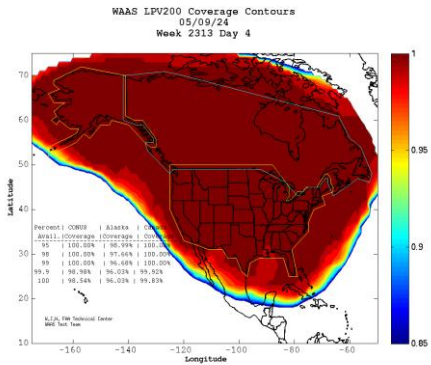
Impact from ICMEs on SATCom

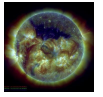


- Satellite Communication (SATCom)
 - GNSS applications such as WAAS / EGNOS
 - 10-11 May 2024 ($Kp = 9.0$)
 - WAAS Extreme storm detector (ESD) tripped for the first time since its inception in 2007 causing an extended loss of LPV/LPV200 over entire WAAS coverage volume

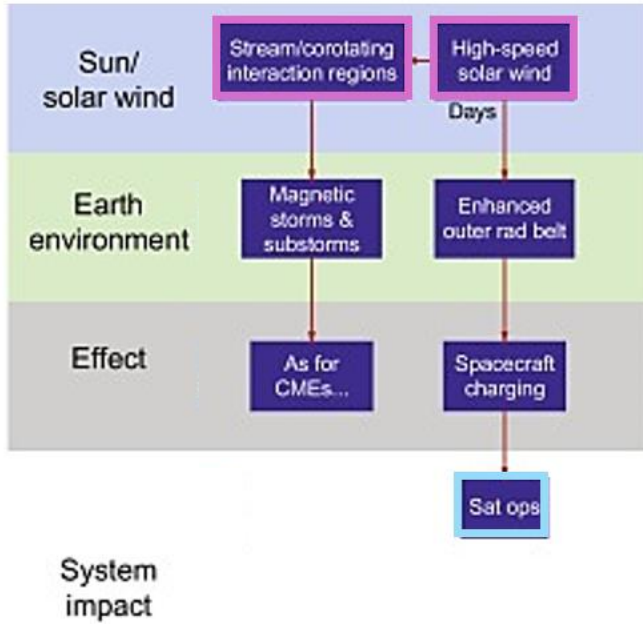
- NOTAMs issued advising on navigational disruptions
 - EGNOS limited over Europe
- ESD tripped again during the 10-11 Oct 2024 storm...

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



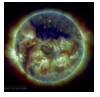


Impact from CH HSS on SATCom



- Similar to effects from ICMEs but less intense
- except...
- From particles
 - Satellites
 - Deep di-electric charging
 - *NOT ionosphere related*

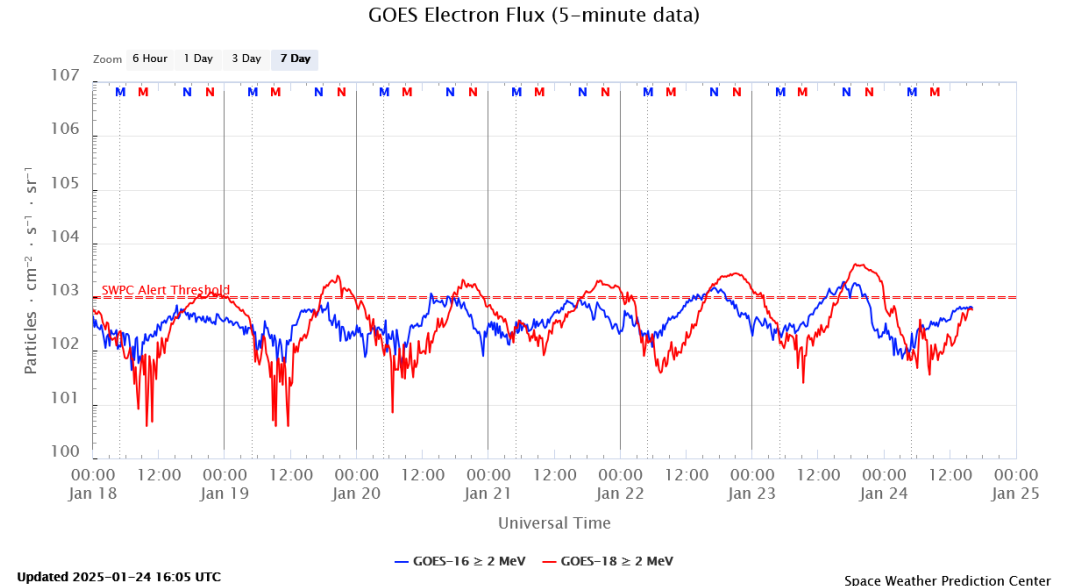


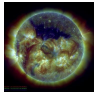


Impact from CH HSS on SATCom



- 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)

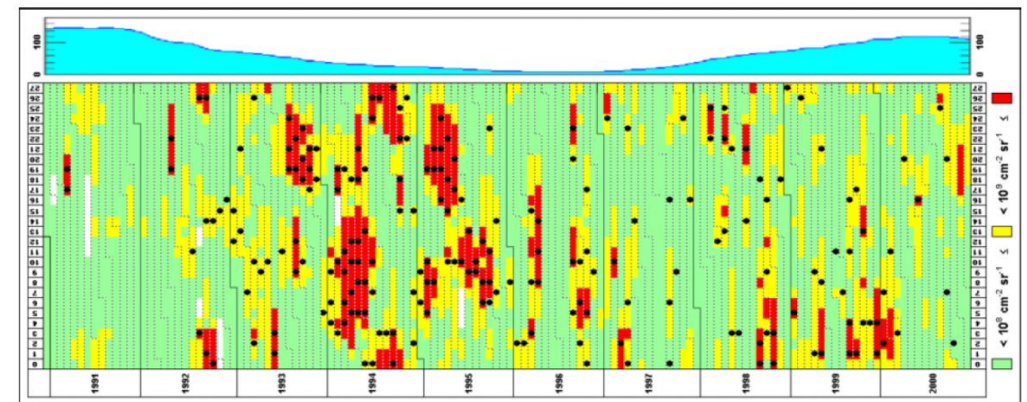
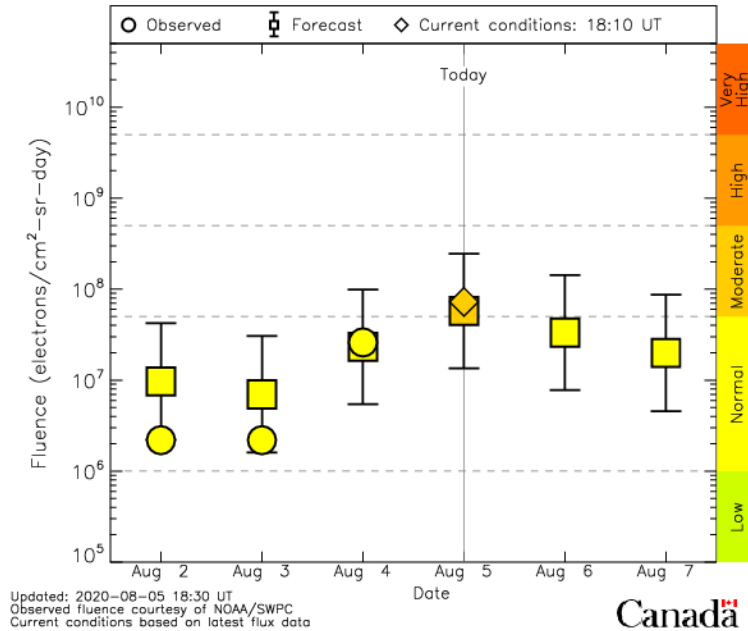




Impact from CH HSS on SATCom

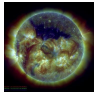


- High-Speed Stream (HSS)
 - Satellite charging
 - Deep di-electric charging
 - About 1 to a few MeV e⁻
 - Deeply penetrate spacecraft (S/C)
 - Fluxes > 2 MeV e⁻
 - Accumulation effect within S/C (ESD: electrostatic discharge)
 - Dayside effect
 - Fluence (24h)
 - Declining phase solar cycle (coronal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

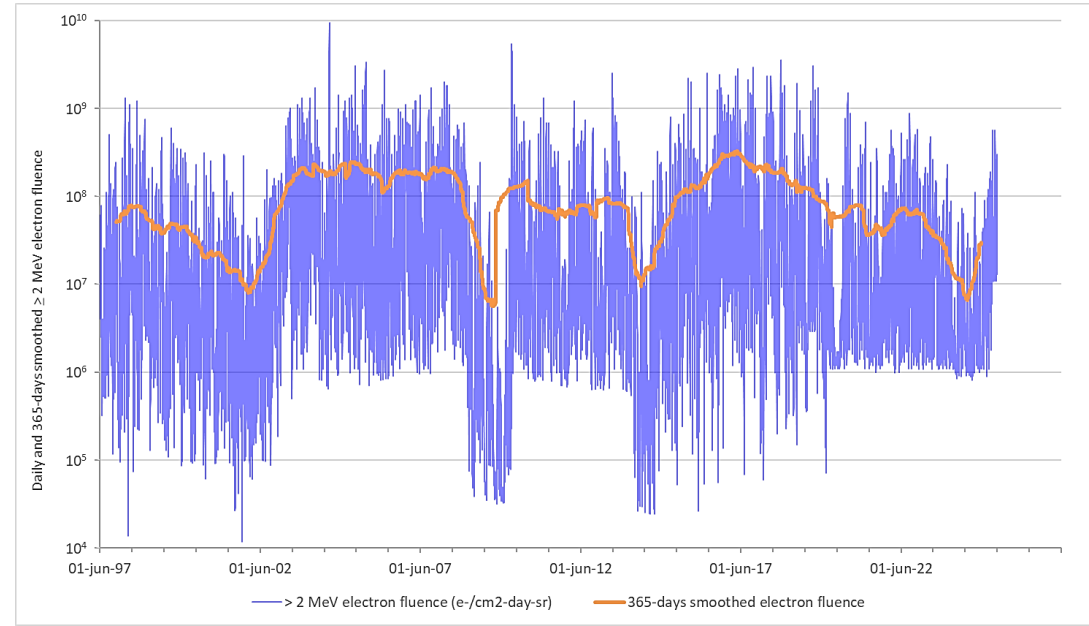
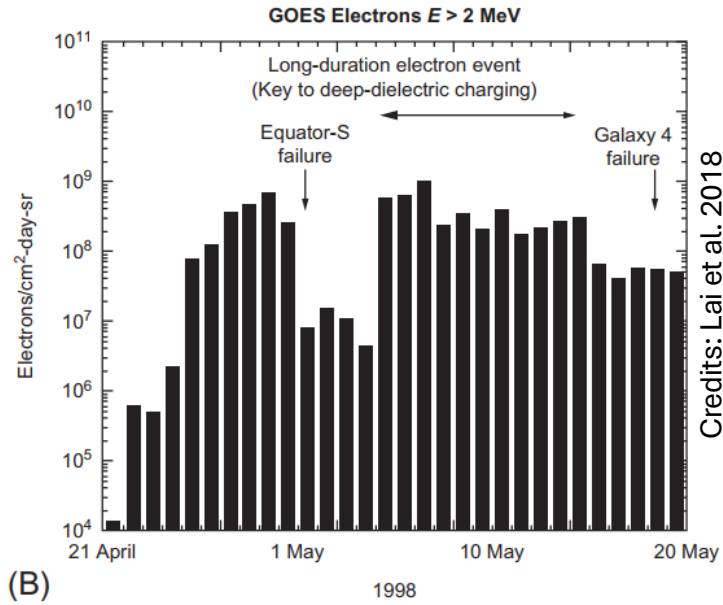


Credits: Wrenn et al. (2002)

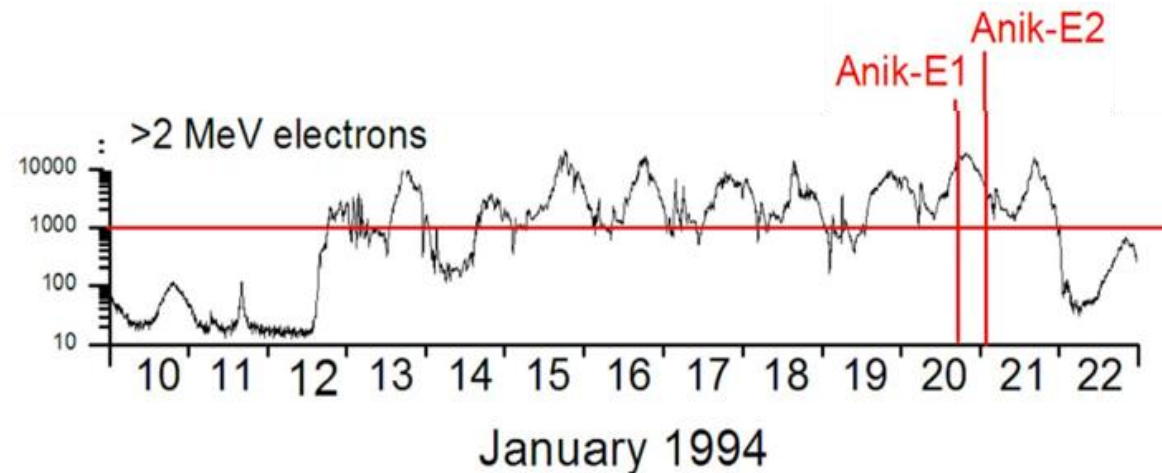
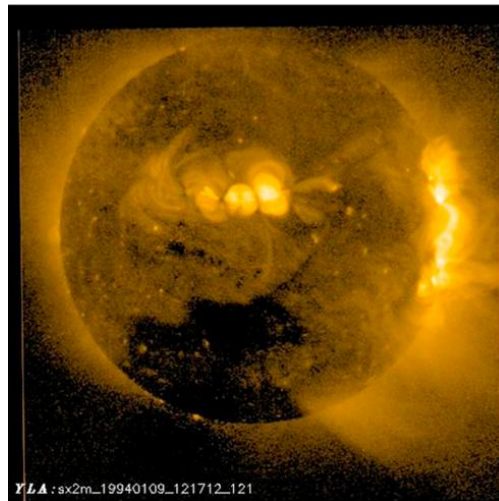




Impact from CH HSS on SATCom

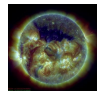
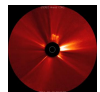
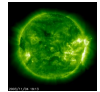


Frequency High fluence: ~17 days / year



Credits: Lam et al. 2012

Summary



	HF Com	SATCom
Solar flares	Short-Wave Fade (SWF)	
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