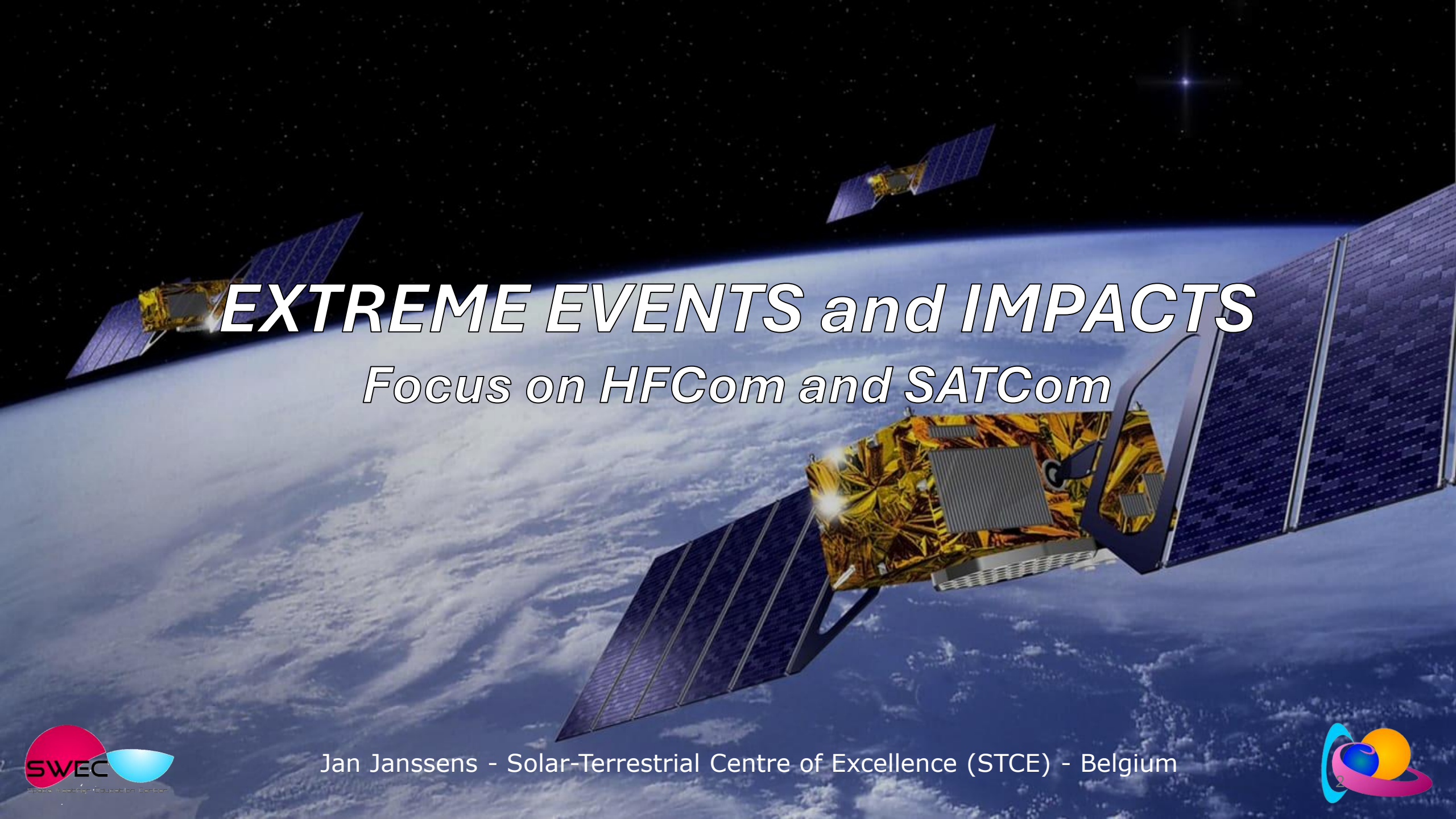
Role of the ionosphere and space weather in military communications

28-30 January 2025

Royal Observatory of Belgium

Solar Influences Data analysis Centre
www.sidc.be



EXTREME EVENTS and IMPACTS

Focus on HFCom and SATCom

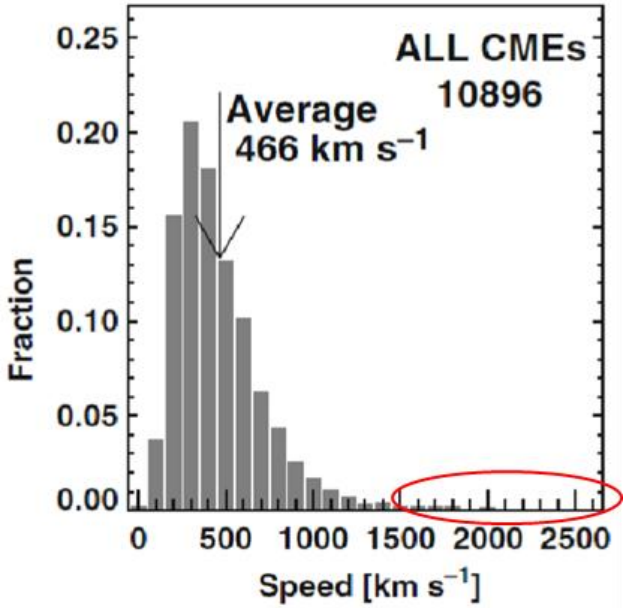
Jan Janssens - Solar-Terrestrial Centre of Excellence (STCE) - Belgium

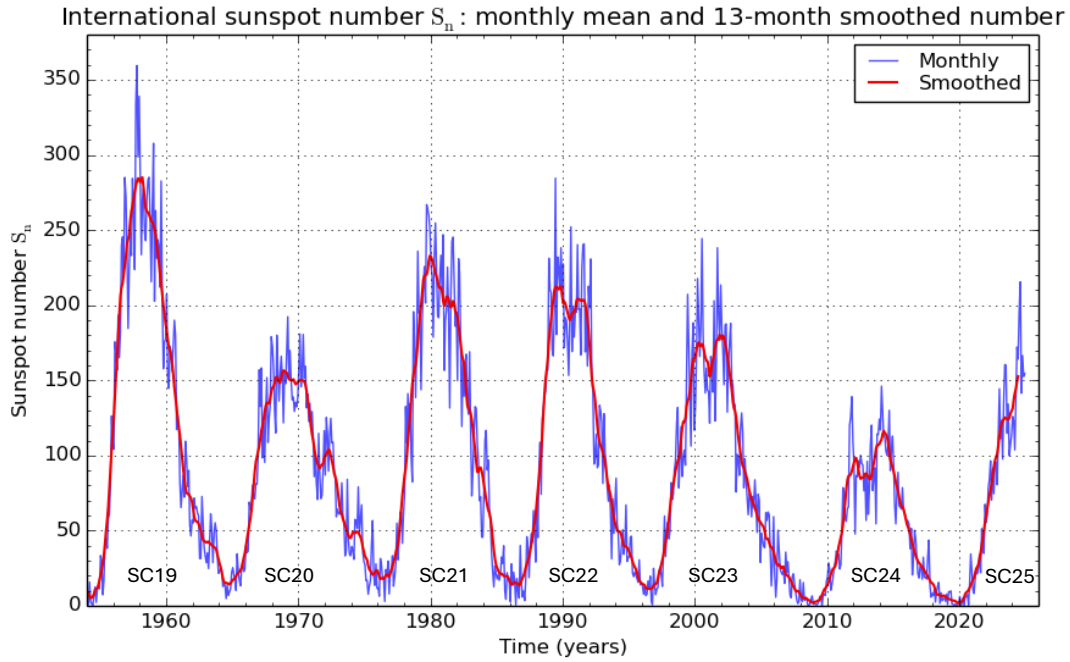
Contents

- What is an extreme event?
- SWx drivers & impacts: overview
- **HFCom** 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…





What is an extreme event?

Solar Cycle	SC21	SC22	SC23	SC24	SC25
Period	1976-1986	1986-1996	1996-2008	2008-2019	2019-present
Highest monthly sunspot number (ISN)	266.9 Sep 1979	**284.5** **Jun 1989**	244.3 Jul 2000	146.1 Feb 2014	215.5 Aug 2024
Highest monthly sunspot area (in MH)	**3719.0** **Feb 1982**	3666.6 Jun 1989	3000.2 Sep 2001	2015.2 Feb 2014	2810.2 Aug 2024
Highest monthly 10.7 cm radio flux (1AU; in sfu)	229.1 May 1980	247.2 Jun 1989	236.2 Sep 2001	166.0 Feb 2014	**251.7** **Aug 2024**
Strongest flare*	X21 NOAA 1203 11 Jul 1978	X28 NOAA 5629 16 Aug 1989	**X40** **NOAA 10486** **4 Nov 2003**	X13 NOAA 12673 6 Sep 2017	X9.0 NOAA 13842 3 Oct 2024
Total number of X-xlass flares*	**261**	232	183	76	78
Strongest proton event (> 10 MeV; in pfu)	2900 13 Jul 1982	**43000** **24 Mar 1991**	31700 6 Nov 2001	6530 8 Mar 2012	1810 10 Oct 2024
Number of proton events (> 10 MeV)	59	73	**94**	42	35
Number of Ground Level Enhancements (GLE)	13	15	**16**	2	4
Number of days with Kp $\geq$ 8-	42	42	**43**	9	12
Strongest Dst (in nT)	-325 14 Jul 1982	**-589** **13-14 Mar 1989**	-422 20 Nov 2003	-234 17 Mar 2015	-412 11 May 2024

***: The GOES-1 thru -15 flare data have been corrected for the scaling factors.**

SC: Solar Cycle ; **ISN**: International Sunspot Number ; **MH**: Millionths of a solar hemisphere ; **AU**: Astronomical Unit ; **sfu**: solar flux units ; **MeV**: Mega electronvolt ; **pfu**: particle flux units ; **Kp**: planetary K-index ; **Dst**: Disturbance storm time index ; **nT**: nano Tesla

What is an extreme event?

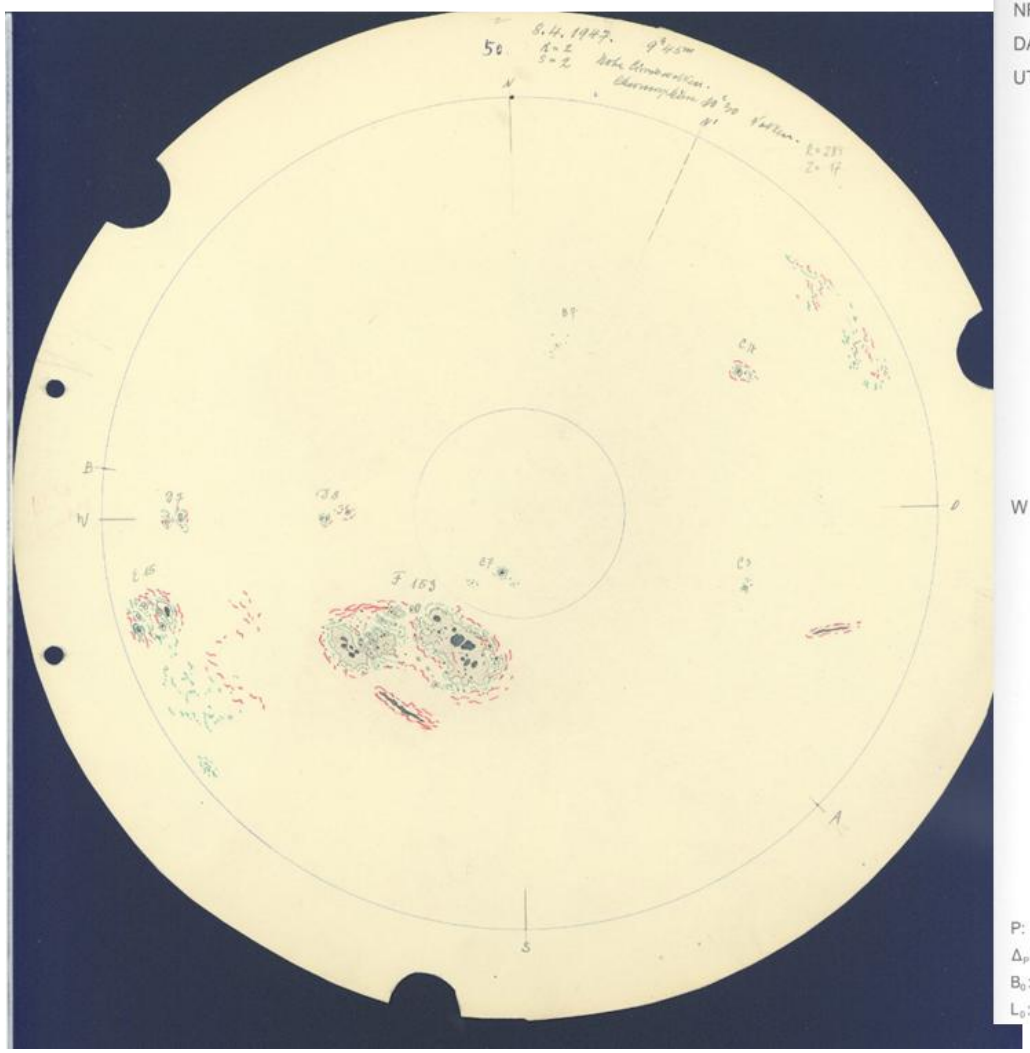
Observed, statistically expected, and modelled extreme solar and solar-terrestrial events

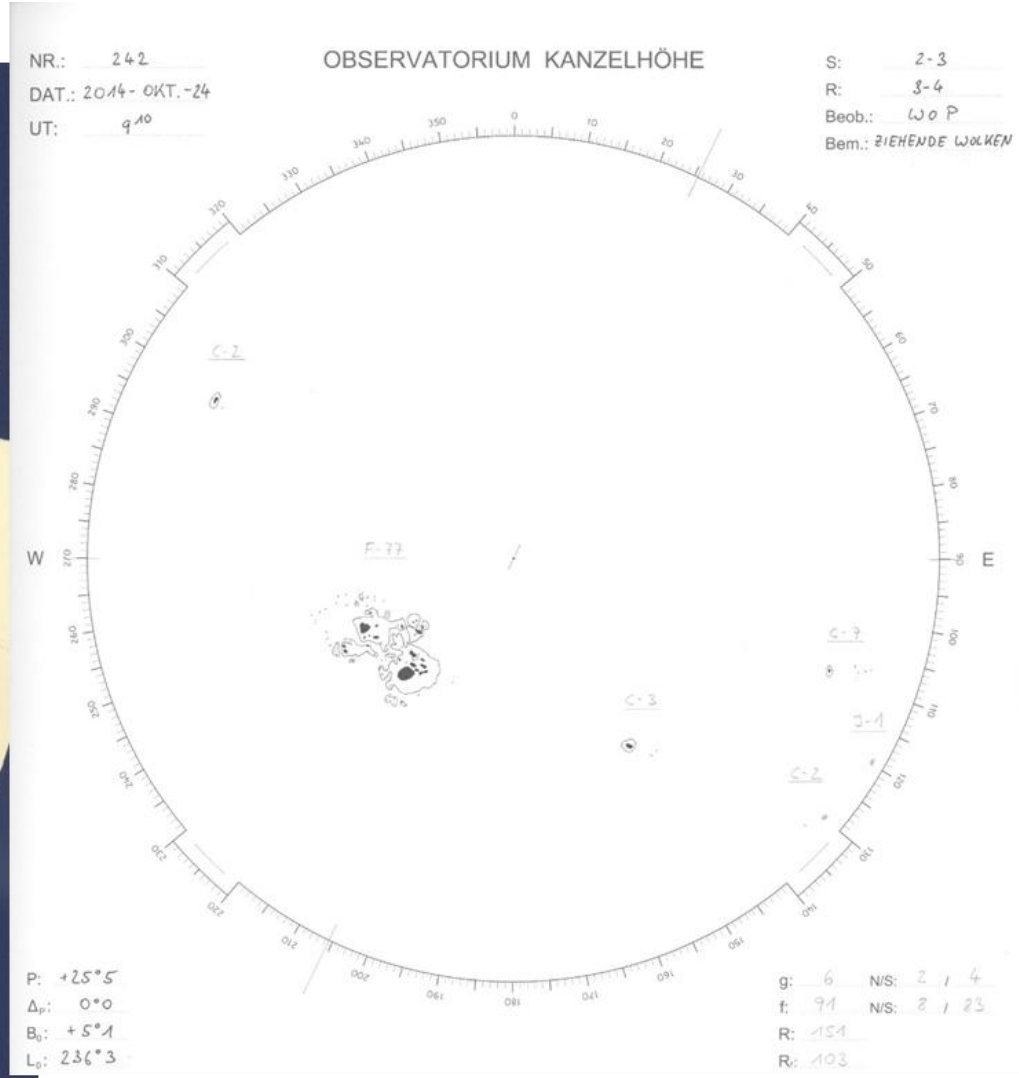
(based on Cliver et al. 2022 ; Gopalswamy 2018)

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
Sunspot group area (MH)	**6132**	5800	7100	8200	13600	
GOES flare SXR	**X40**	X44	X42	X100	X115	X180
1.5 GHz radio emission (10^6 sfu)	**1**		3.2 - 12		61 - 200	
> 30 MeV proton fluence (10^{10} cm^{-2})	**0.84**	1.6	2.1	5	16	
> 200 MeV proton fluence (10^{10} cm^{-2})	**0.14**	0.6		3.5		
CME speed (km/s)	**3387**	3800	4500	4700	6600	
ICME transit time (h)	**14.6**					11.6
Dst (nT)	**~ -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 SC24





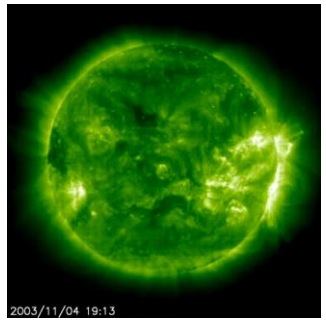
Drivers of disturbed space weather

Solar eruptions

Magnetic Reconnection

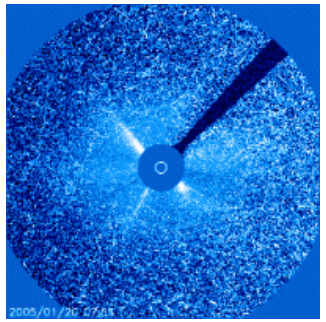
Radiation

Solar flares

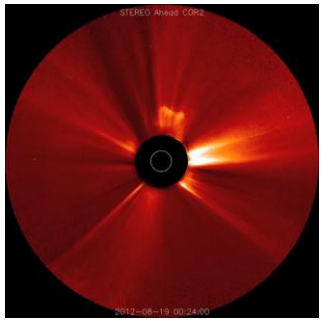


Particles

Proton events



Coronal Mass Ejections

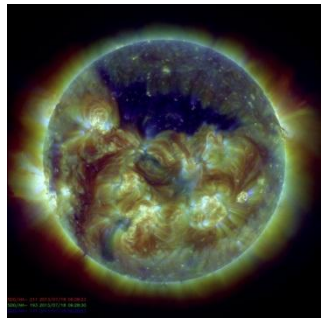


Solar corona

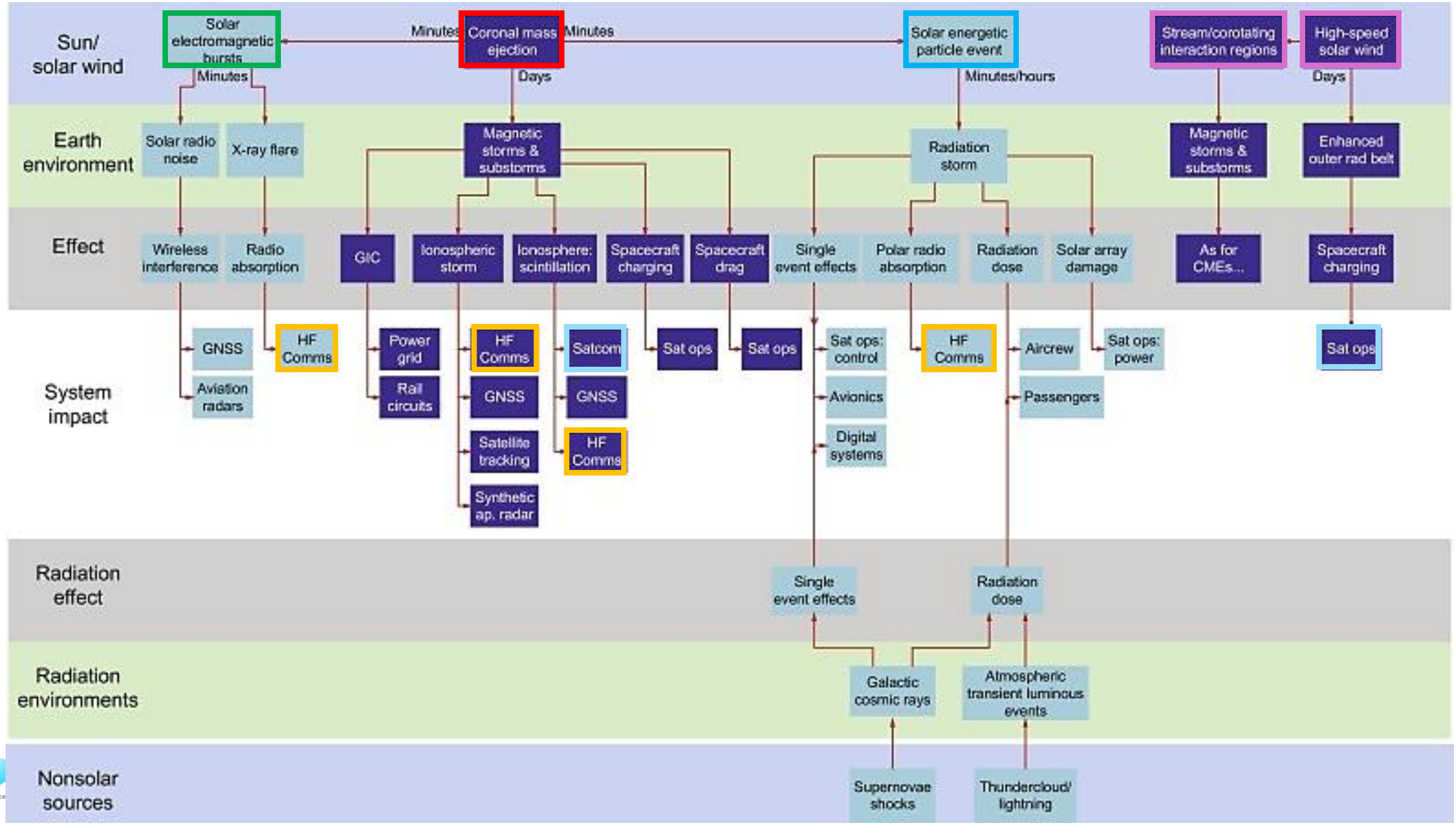
Solar wind

Particles

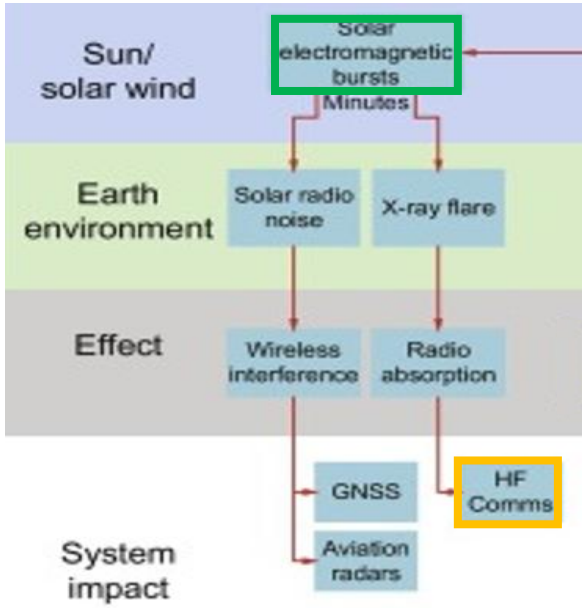
Coronal Holes

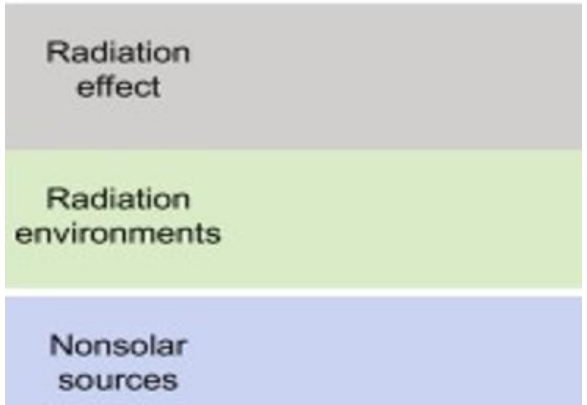


Impacts of disturbed SWx



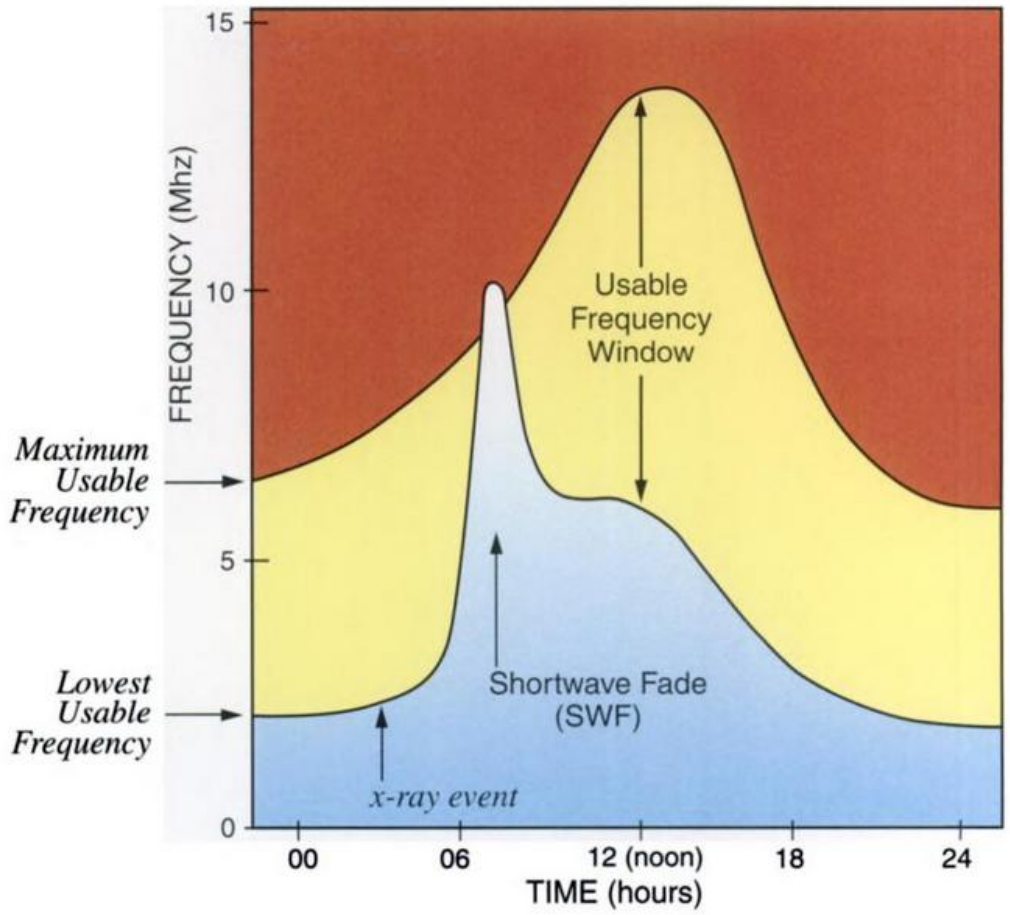
Impacts from solar flares





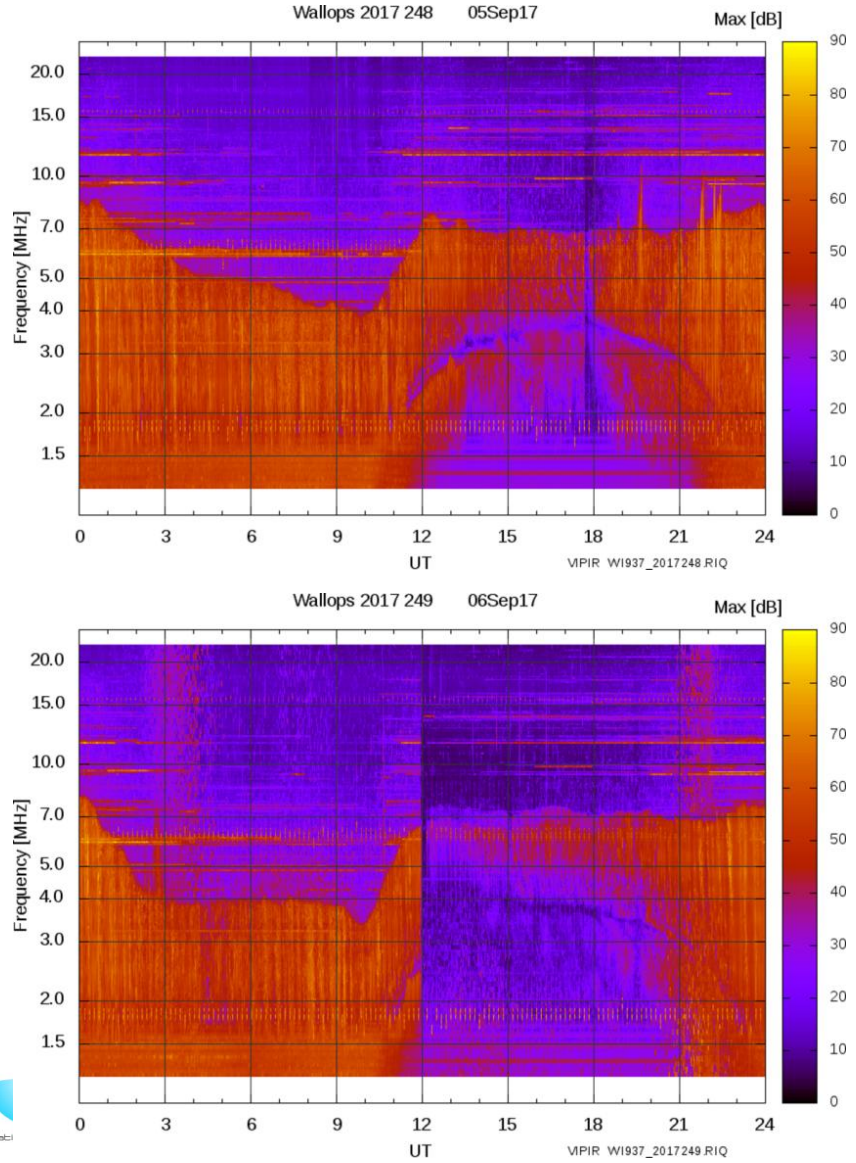
- From EUV & X-ray
  - Solar flare effect
    - *"magnetic crochet"*
    - Up to +/- 100 nT
  - Short-wave fade (SWF)
    - *"Radio Blackout"*
    - Impact on HF Com
- From radio emission
  - GNSS disturbances
  - Radar disturbances

Impacts from solar flares on HFCom



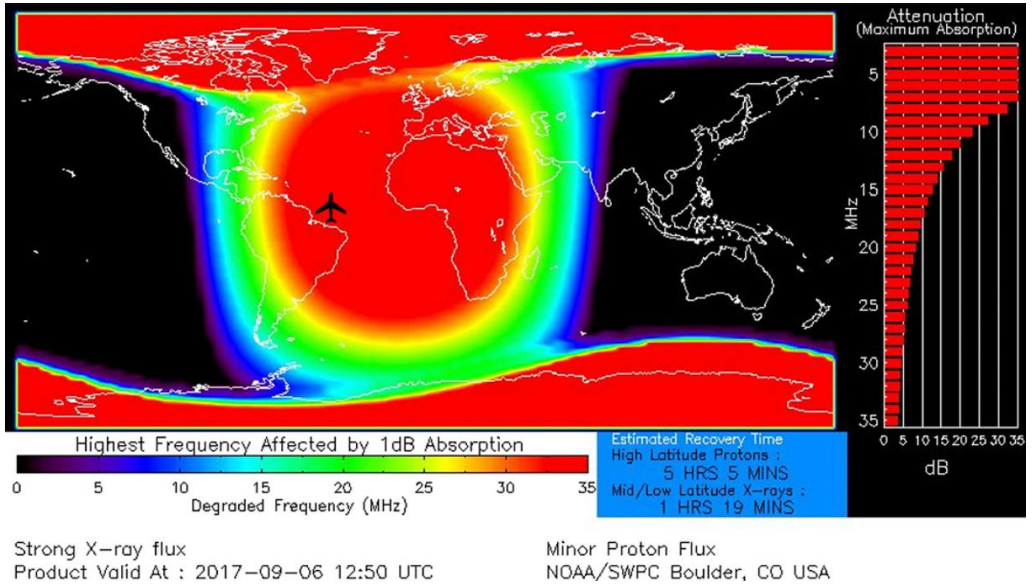
- Short-wave fade (SWF)
  - Aka “Radio blackout”
    - Misleading term
  - SXR from solar flare
    - Sunlit hemisphere of the Earth
    - Increase ionospheric plasma (D-region)
      - Increase in HF absorption
        - Affects lower frequencies most
      - => Backup systems (SATCom,…)
      - => 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 HFCom

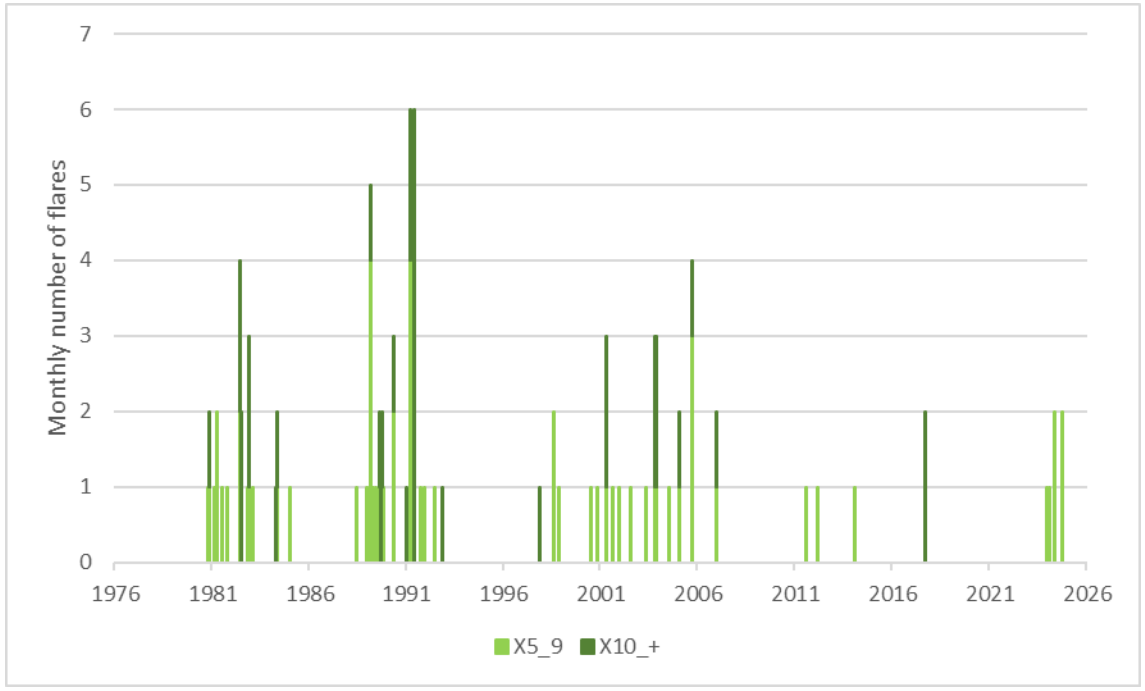


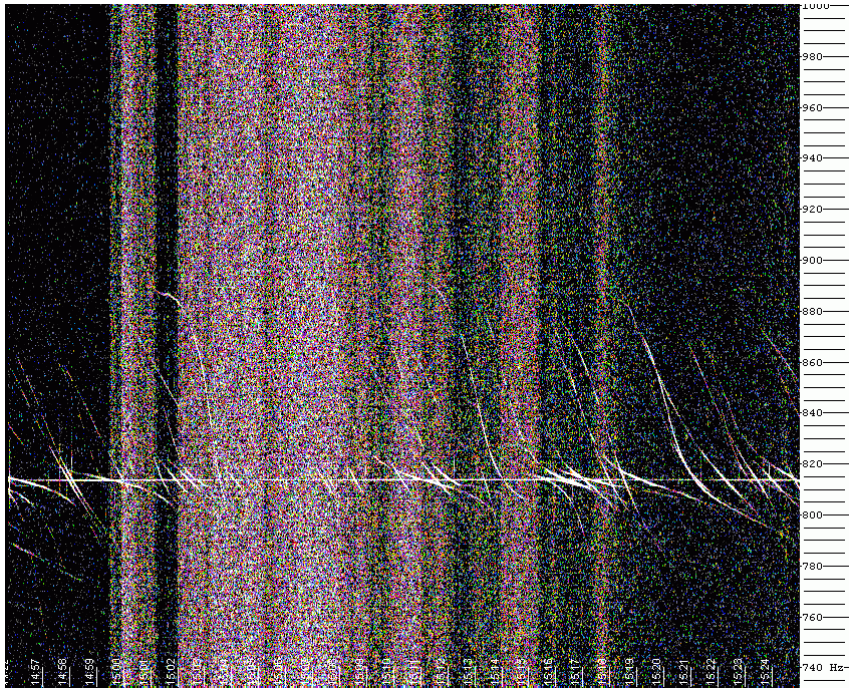
Courtesy of CIRES, Terry Bullett

- 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



Impacts from solar flares on HFCom

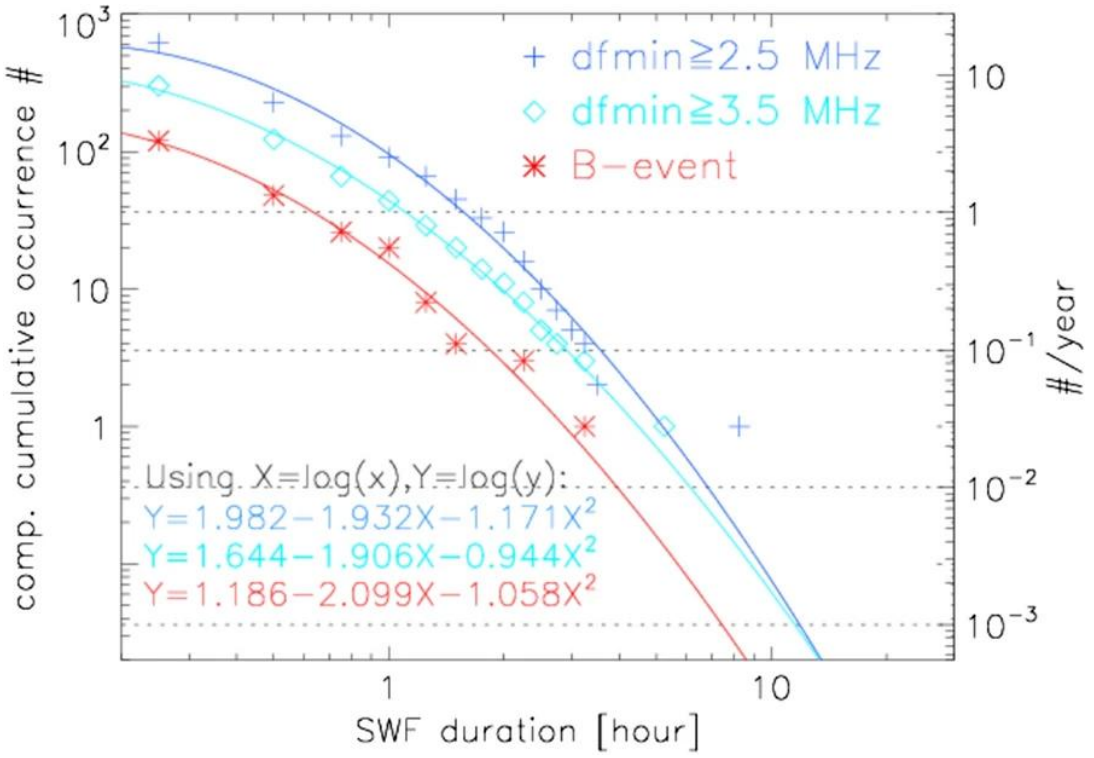




- About 9 X5+ flares per SC
  - Large variability per SC!
  - Median duration of 1 hour
    - Extremes from 5 up to 10 hours

- X3 flare on 25 October 2013
  - 14:51-15:12UTC (21 minutes)
  - SWF durations reported of 80-110 minutes
  - Meteor radio beacon at 49 MHz: 14:59-15:18UTC
    - Due to radio emission from the X3 flare (NOT from soft x-rays!)

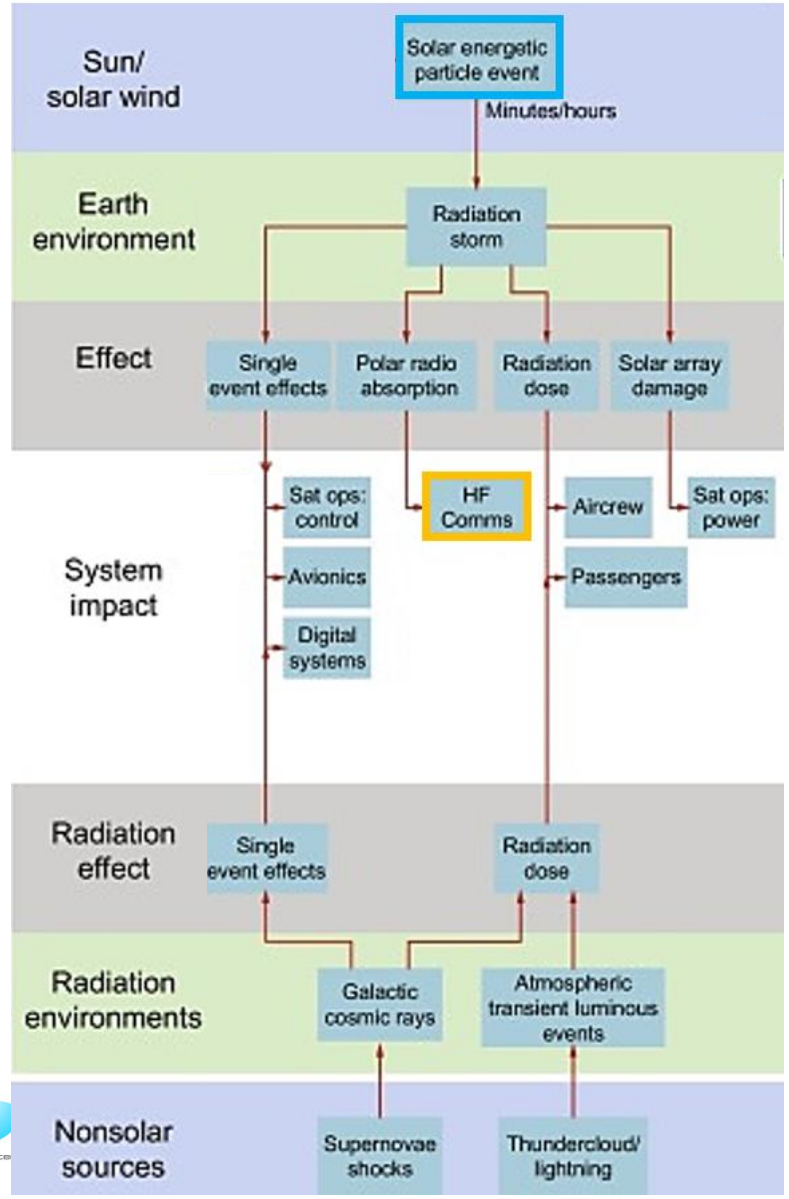
Impacts from solar flares on HFCom



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

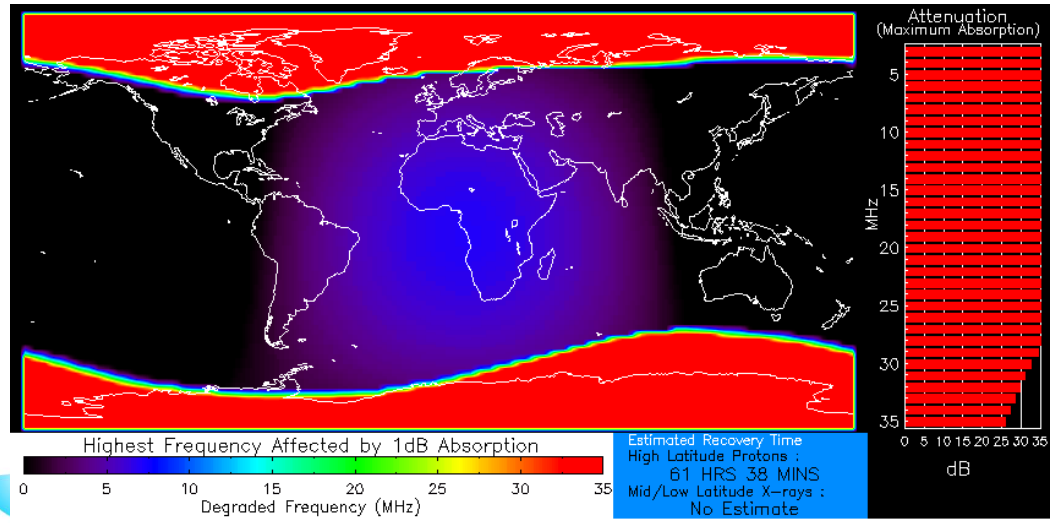


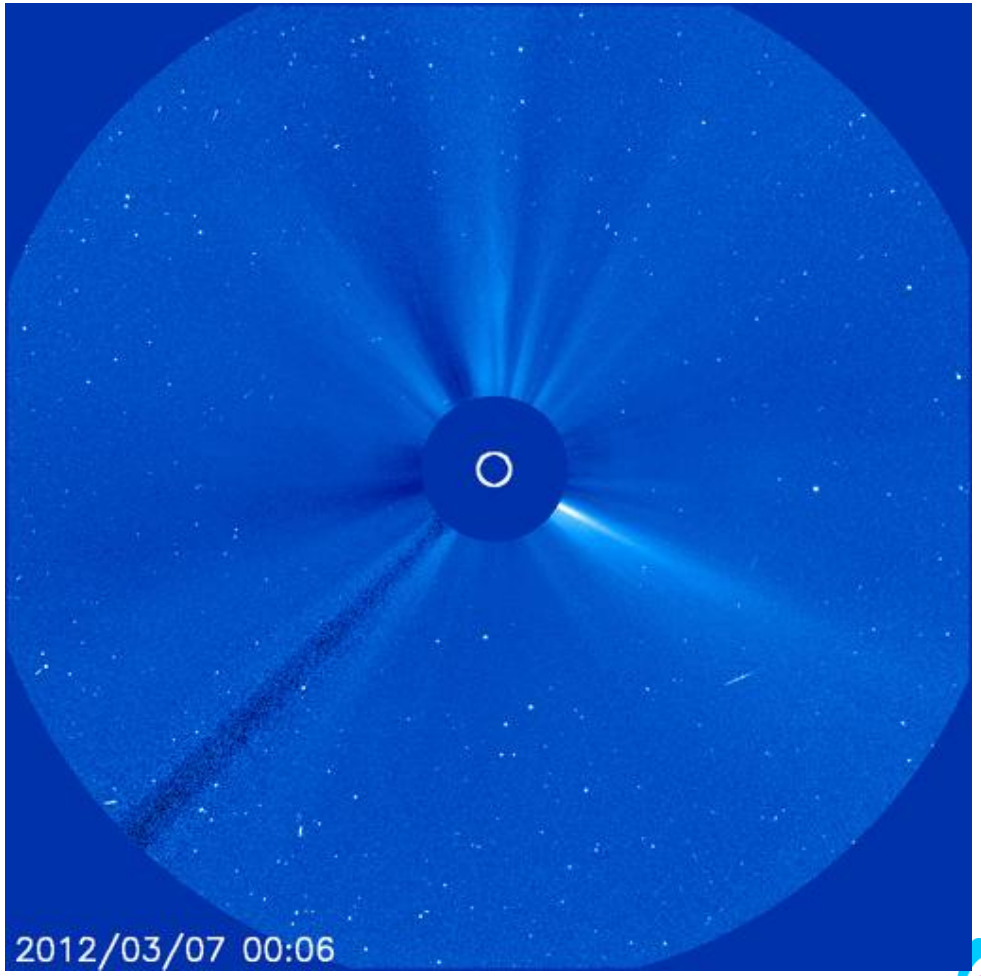
- From SEP events
  - Single event effects
    - Affect mainly avionics/electronics
    - Ground Level Enhancement (GLE)
  - Polar Cap Absorption (PCA)
    - Deviated by MF to poles
    - Affects D-region
    - Impacts HF Com at polar regions
  - Radiation
    - Biological component
  - Solar array damage
- 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 HFCom

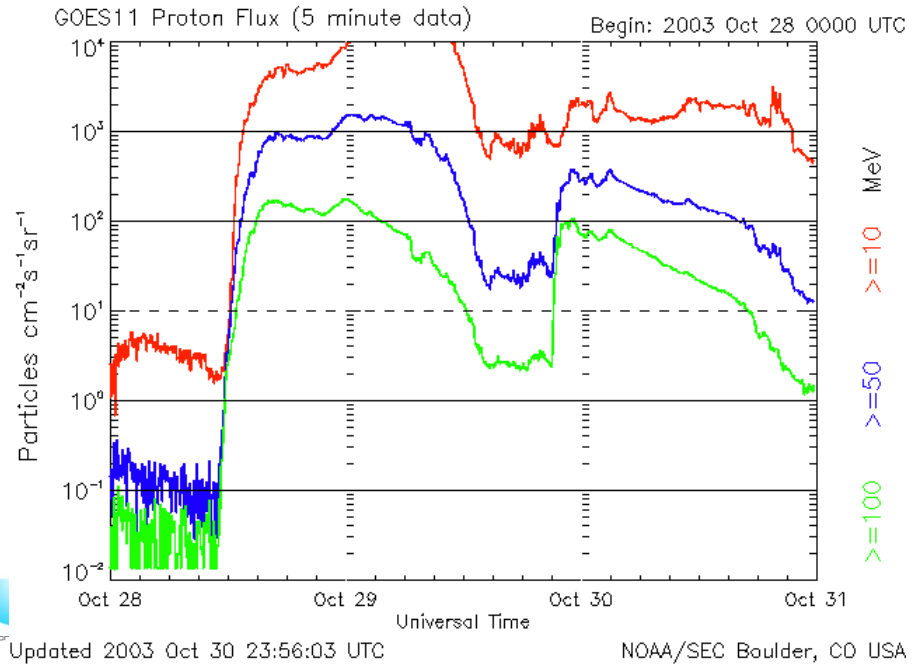
- Polar Cap Absorption (PCA)
  - From 10 MeV proton flux
    - Deviated by MF to poles
    - Affects lower ionosphere (D-region)
    - Impacts HF Com at poles
      - Can last for days
  - Polar flight
    - detours (HFCom)
    - lower altitude (radiation hazard)



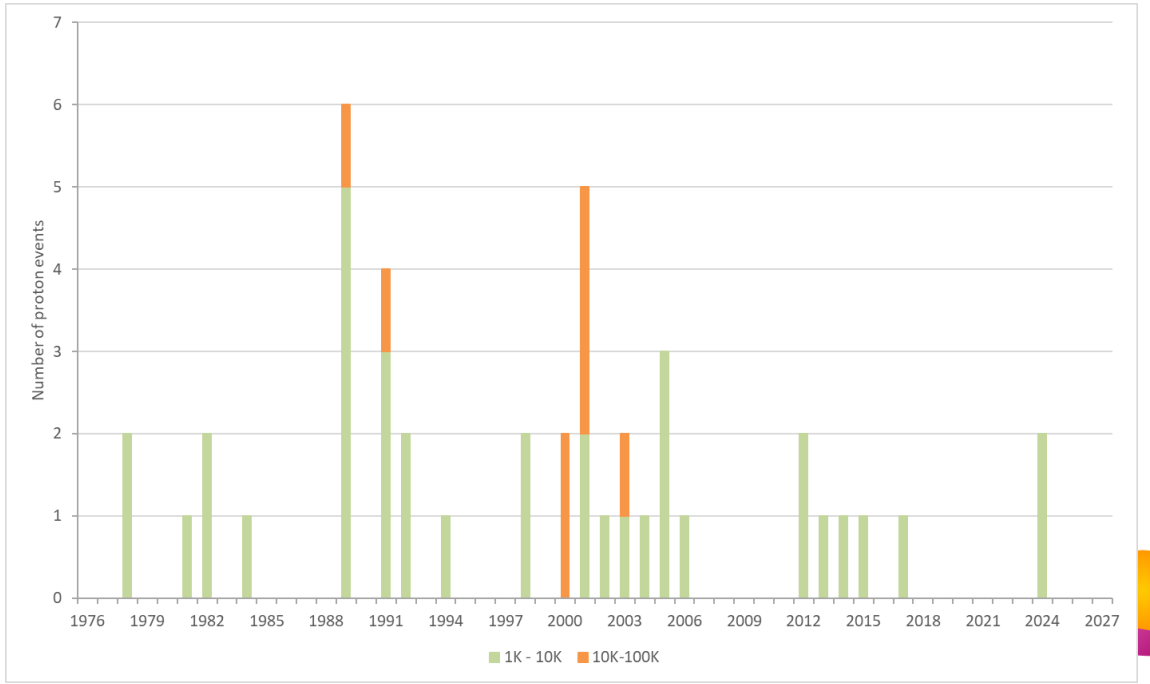


Impacts from SEP events on HFCom

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

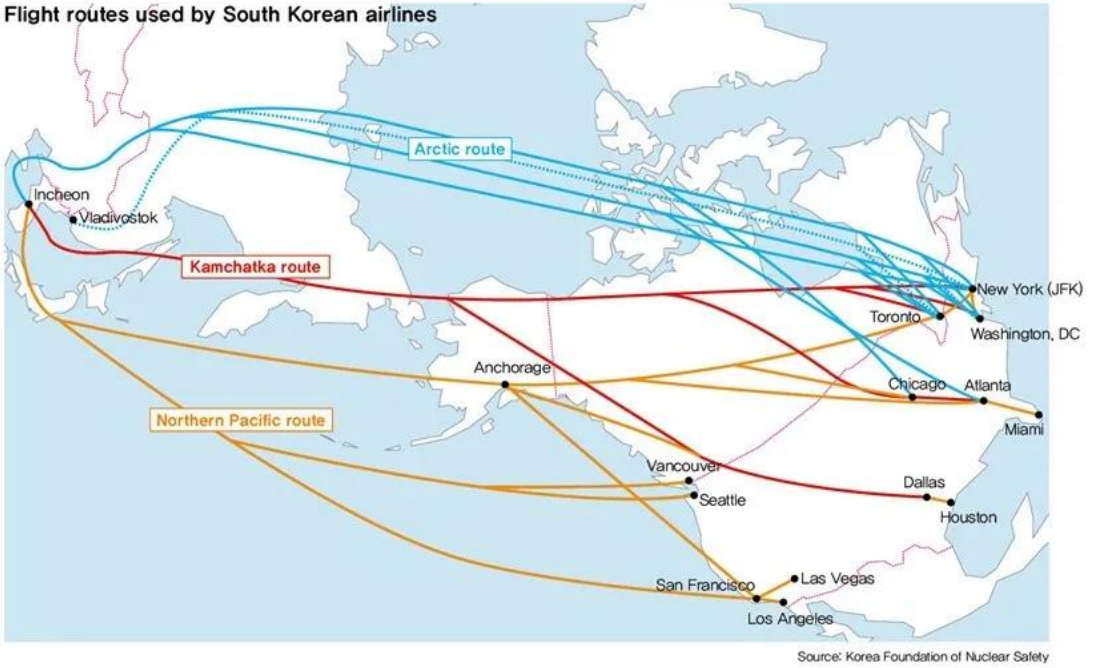


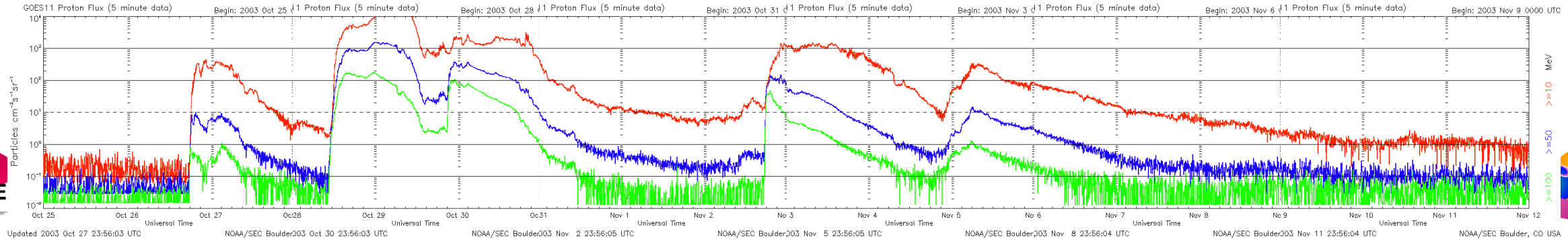
- Frequency
  - Proton events:
    - Strong: 8 per solar cycle
    - Severe: 2 per solar cycle



Impacts from SEP events on HFCom

- 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 HFCom

- 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 60c Weekly by Carrier

Critics Demand Dulles Explain Poli

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

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...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

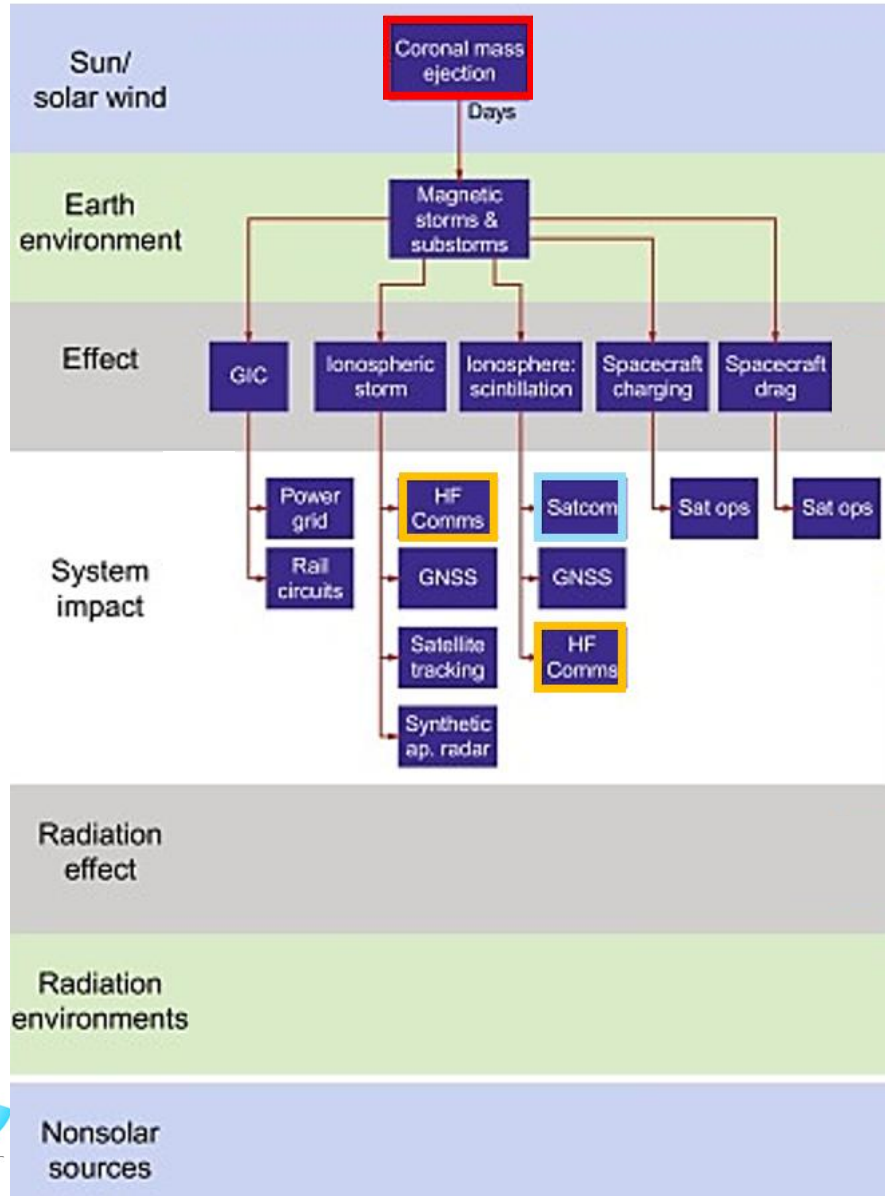
ODENTON, Md. (AP) — Seven cars of a Pennsylvania Railroad passenger train, racing at 80 m.p.h. through the flat countryside between Washington and Baltimore, jumped the track last night and three overturned down an embankment. Five persons were killed and more than 100 injured.

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.

Impact from ICMEs

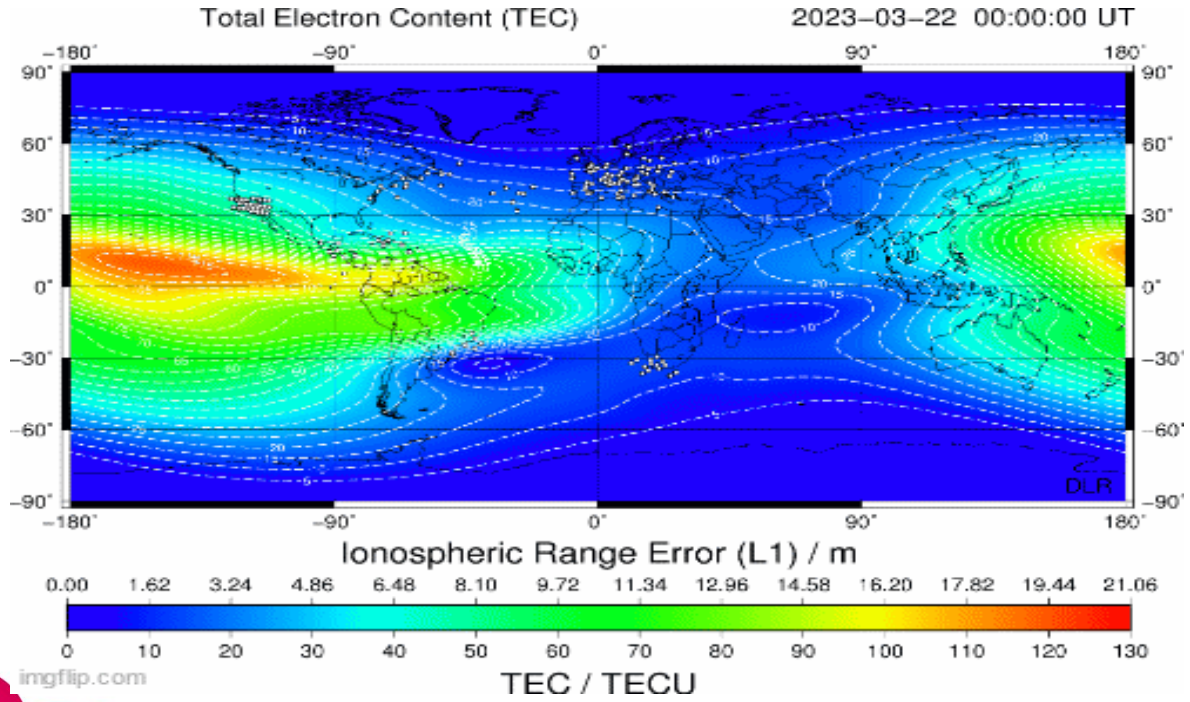


- From magnetic field
  - Satellites
    - Magnetopause crossings
  - High-Precision industry
  - GCR: Forbush decrease
- From particles (ionospheric)
  - Aurora
  - Geomagnetically Induced Currents (GIC)
  - HF Communication
  - Satellites
    - Drag
    - Charging effects
  - Satellite-based Comms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

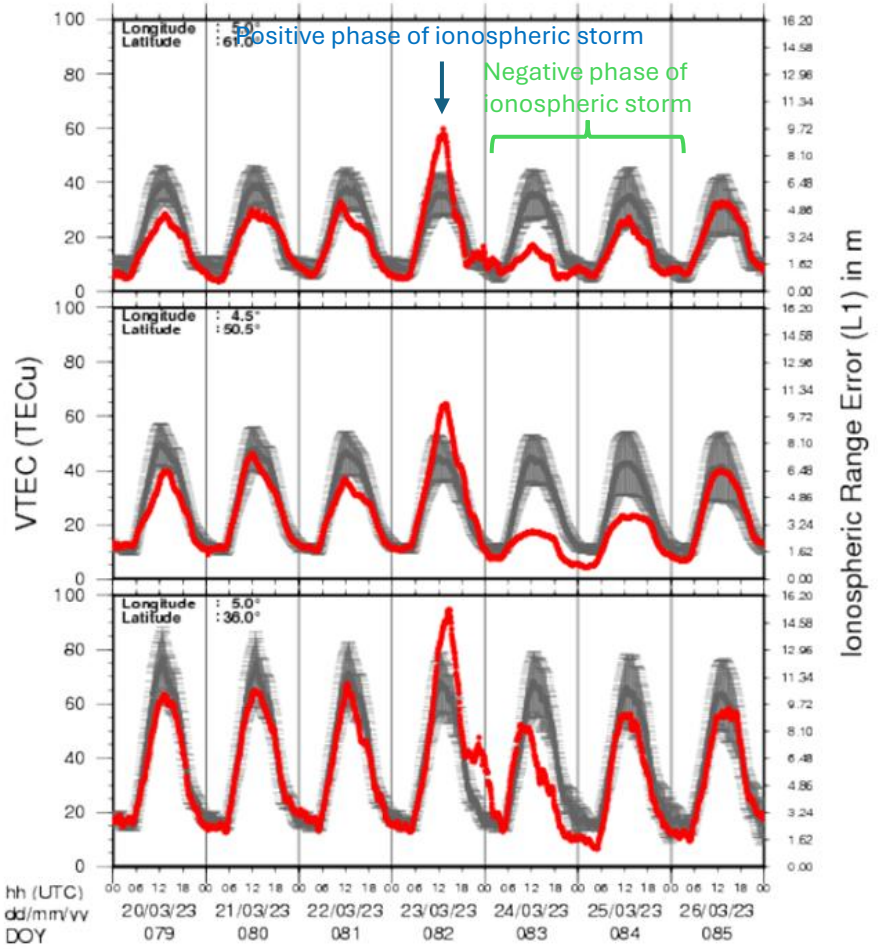
GCR: Galactic Cosmic Rays ; Comms/Nav: Communications/Navigation ; PECASUS: Pan-European Consortium for Aviation Space weather User Services ; HF: High Frequency ; (I)CME: (Interplanetary) Coronal Mass Ejection

Impact from ICMEs on HFCom

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



Credits images: PECASUS & DLR/IMPC

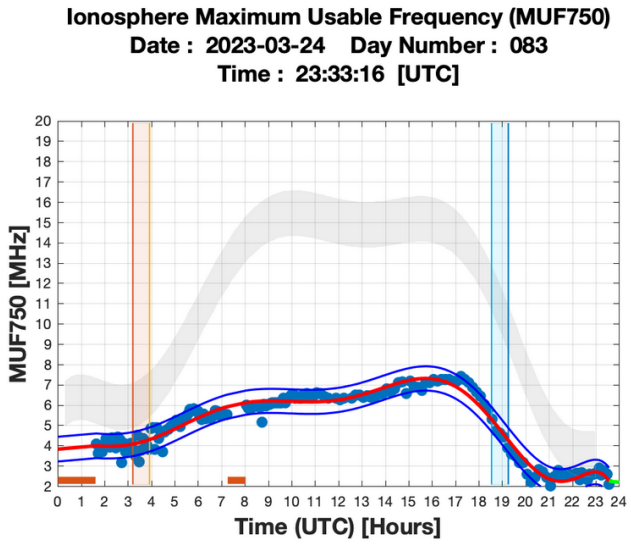


Credits: ROB/GNSS

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

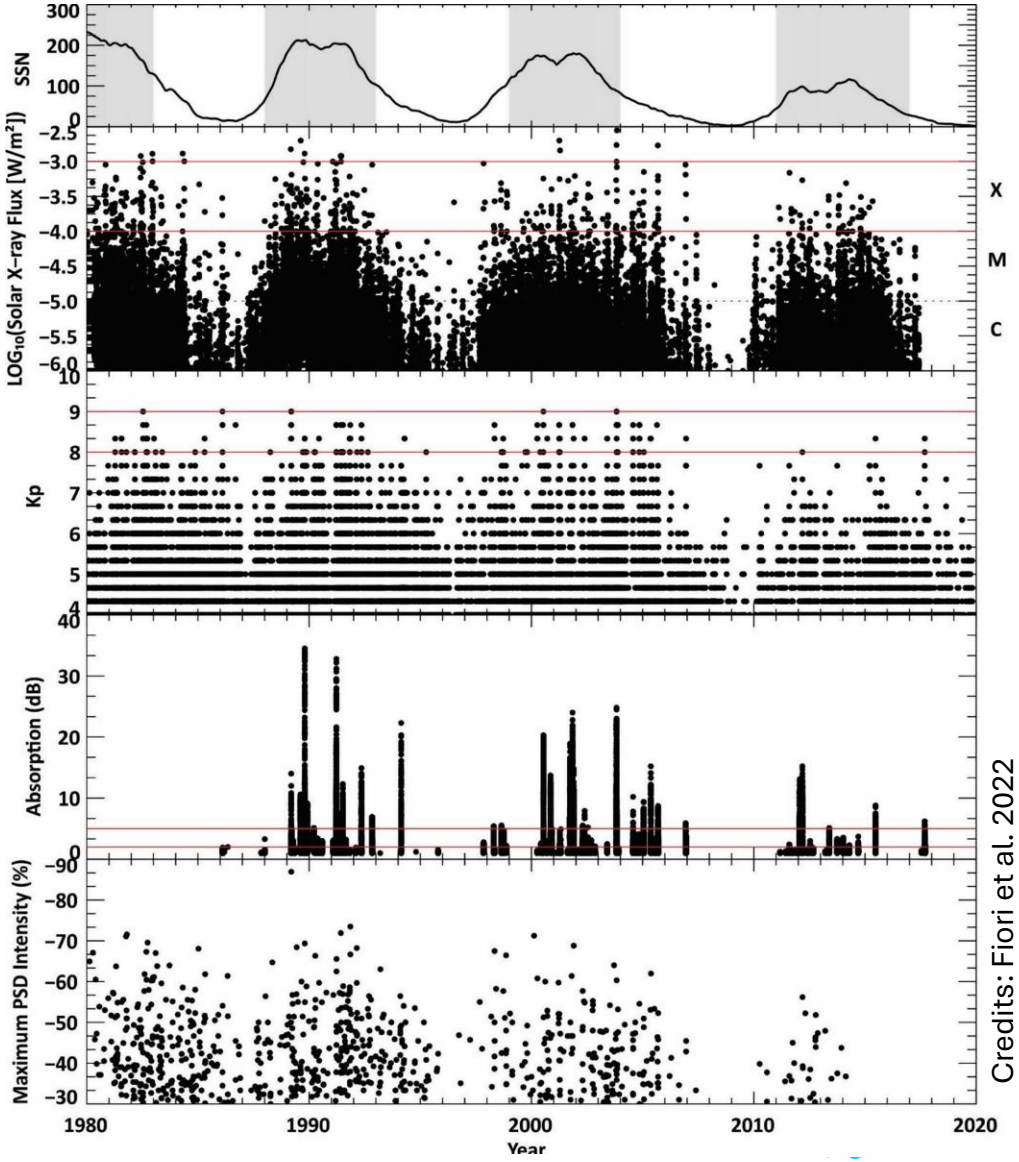
Impact from ICMEs on HFCom

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



Impact from ICMEs on HFCom

- 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

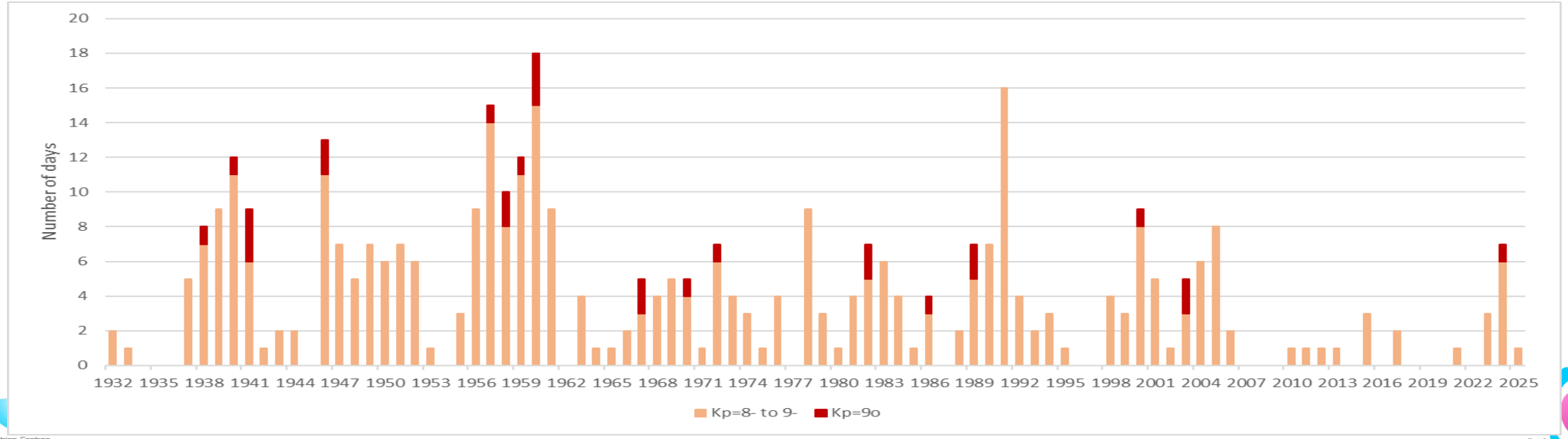


Credits: Fiori et al. 2022

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

Impact from ICMEs on HFCom

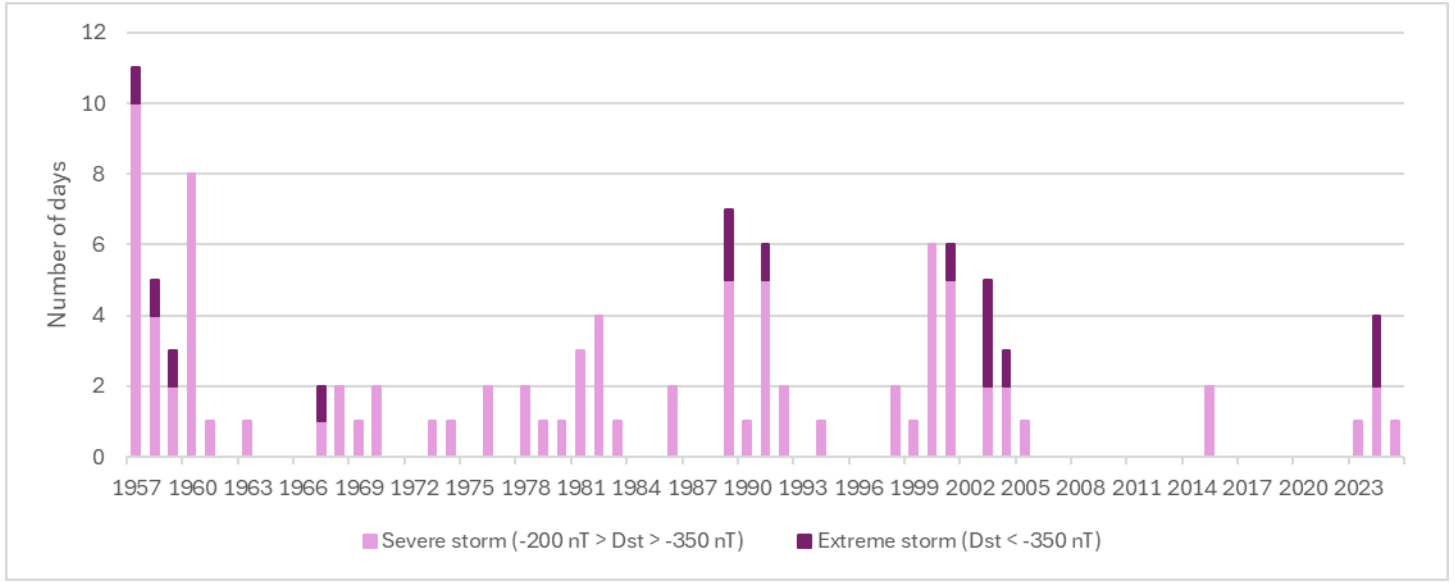
- Frequency geomagnetic storms
  - Kp
    - ~ 40 severe storms / SC
    - ~ 3 extreme storms / SC



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

Impact from ICMEs on HFCom

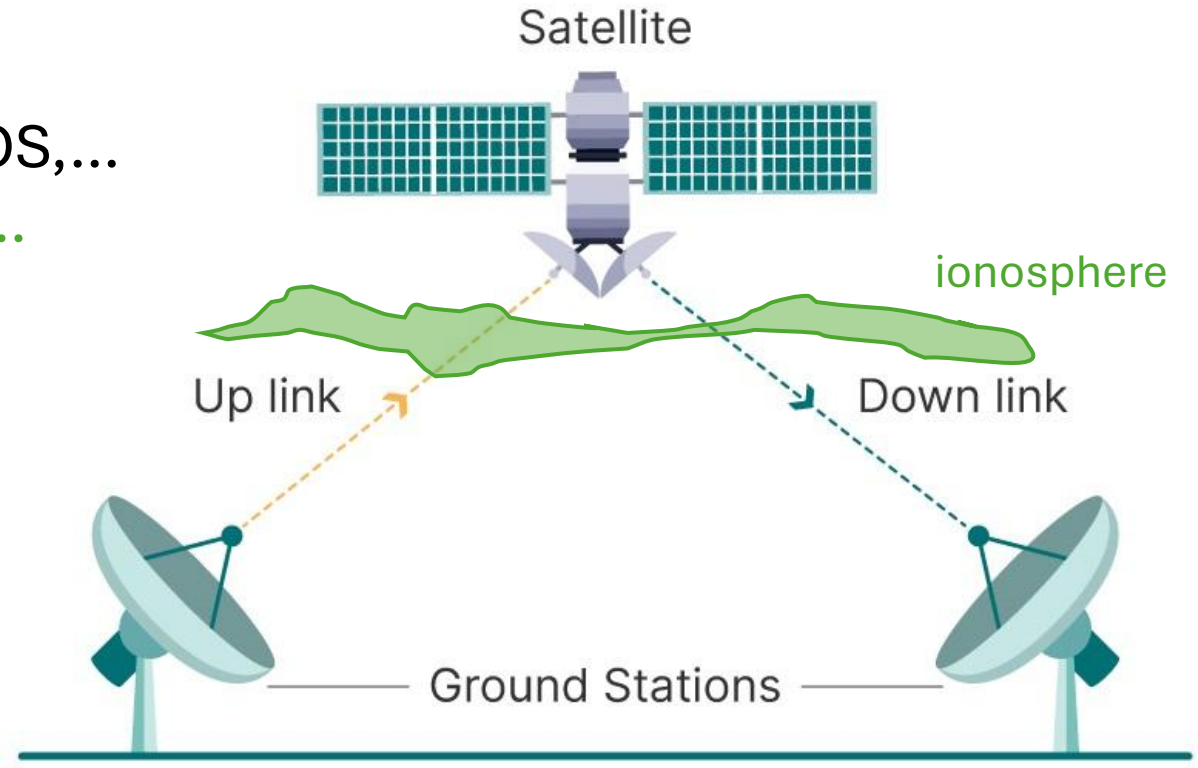
- Frequency geomagnetic storms
  - Kp
    - ~ 40 days severe storms / SC
    - ~ 3 days extreme storms / SC
- Frequency geomagnetic storms
  - Dst
    - ~ 14 days severe storms / SC
    - ~ 2 days extreme storms / SC



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…



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

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

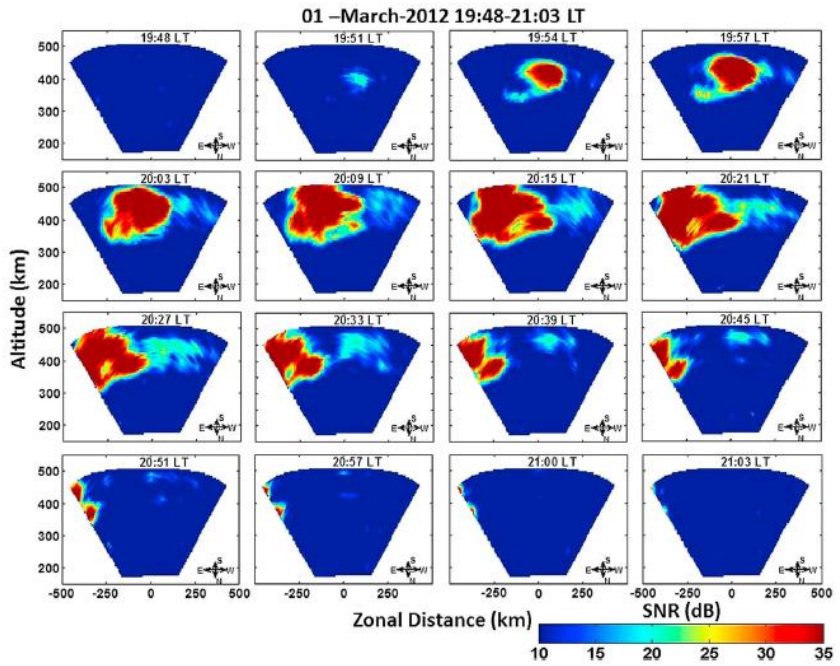


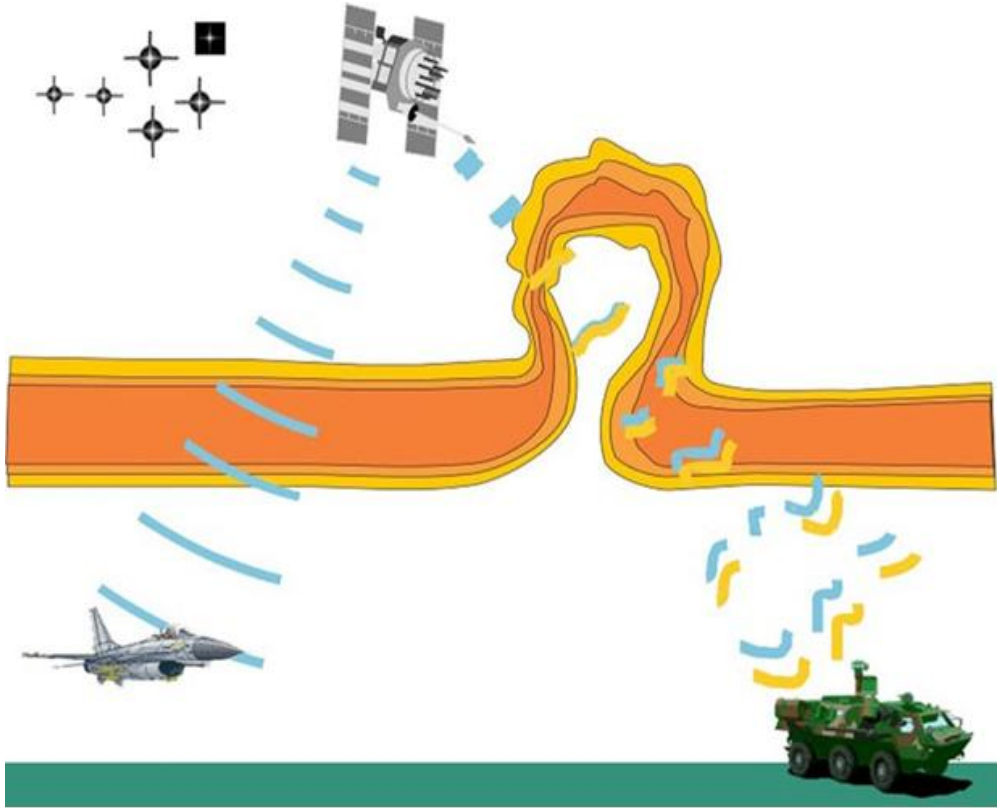
Figure 1. An example showing the genesis and successive development of EPB (evolving-type) over Kototabang observed from the fan sector maps of EAR on 1 March 2012.

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

SWEC
Space Weather Education Center

Impact from ICMEs on SATCom

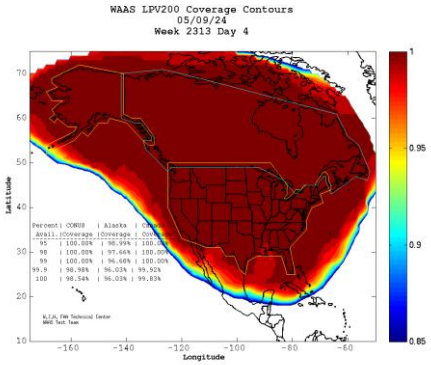
- Battle of Takur Ghar
  - 4 March 2002
  - Ionospheric disturbance contributed to SATCom outage during Mil operation
    - Despite active to unsettled geomagnetic conditions
      - Can occur anytime!

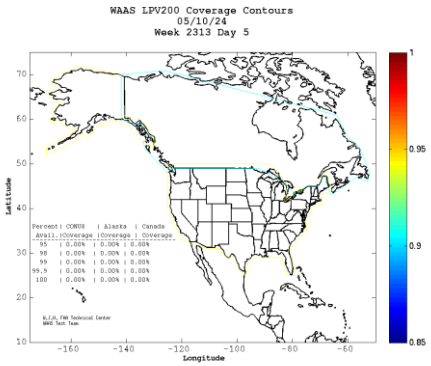


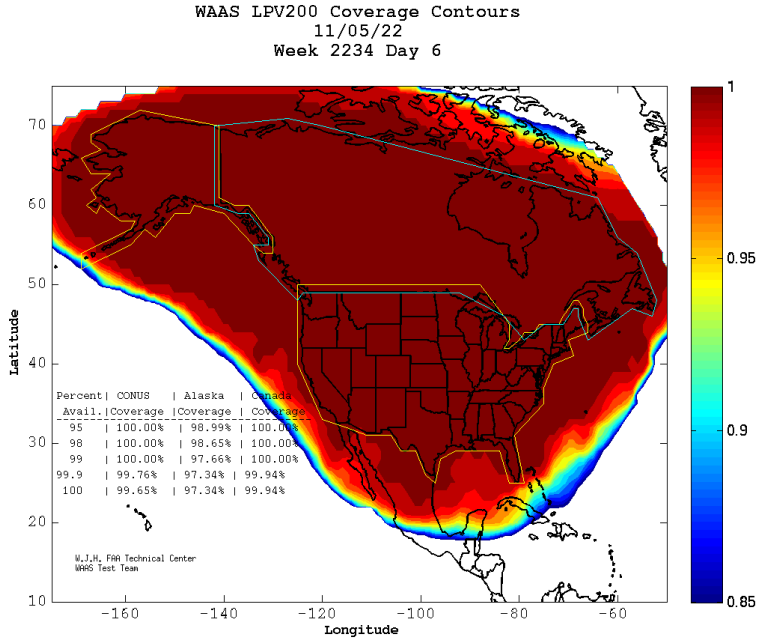
Credits: US Air Force Research Laboratory

Impact from ICMEs on SATCom

- Satellite Communication (SATCom)
  - GNSS applications such as WAAS / EGNOS
    - 10-11 May 2024 *(Kp = 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…

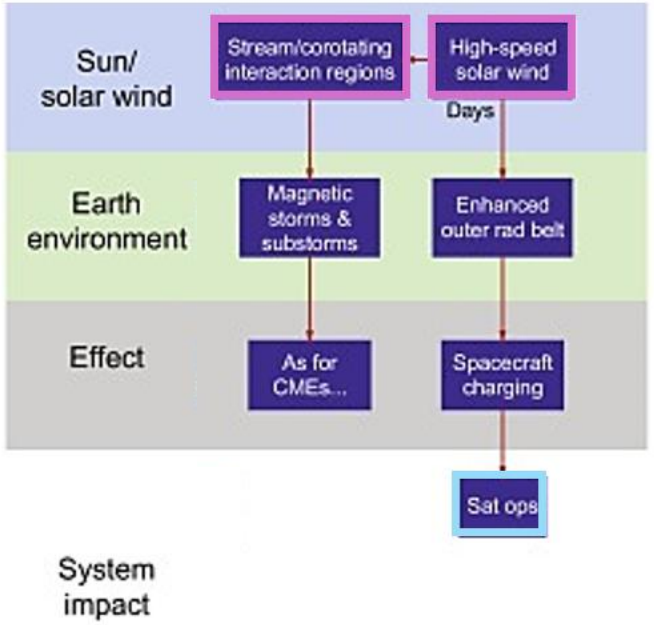






GNSS: Global Navigation Satellite Systems (GPS, Galileo,,…) ; ICME: Interplanetary coronal mass ejection ; nT: nanotesla ; Dst: Disturbance storm time ; dB: decibel ; WAAS: Wide Area Augmentation System (WAAS) ; LPV: Localizer Performance with Vertical Guidance ; PECASUS: Pan-European Consortium for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

Impact from CH HSS on SATCom

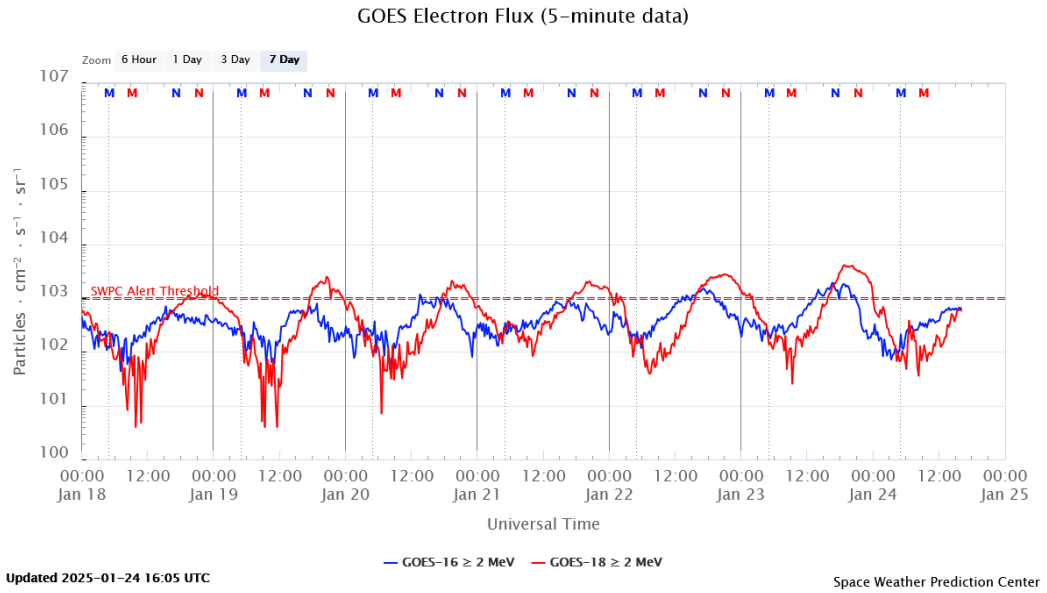


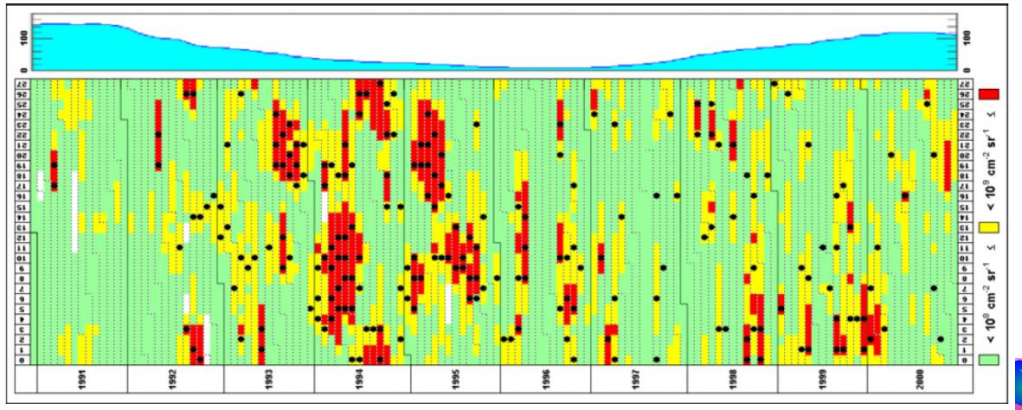
- Similar to effects from ICMEs but less intense
- except…

- From particles
  - Satellites
    - Deep di-electric charging

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

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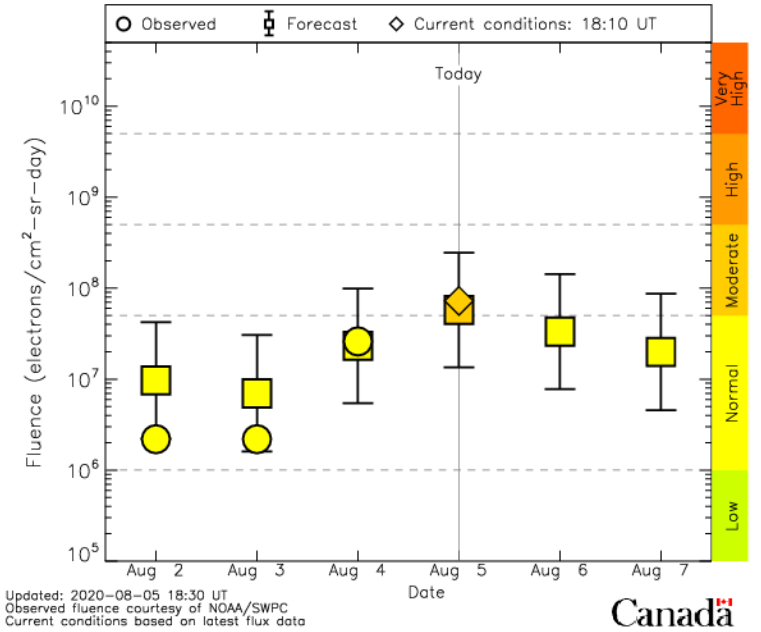
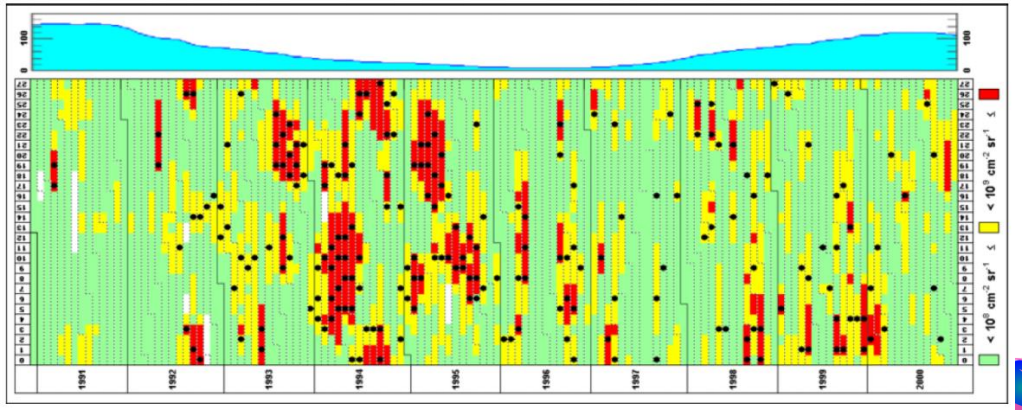
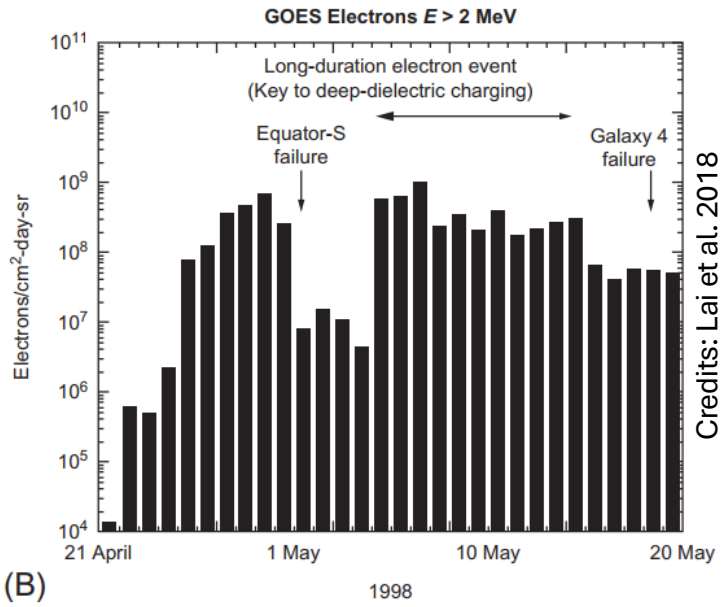


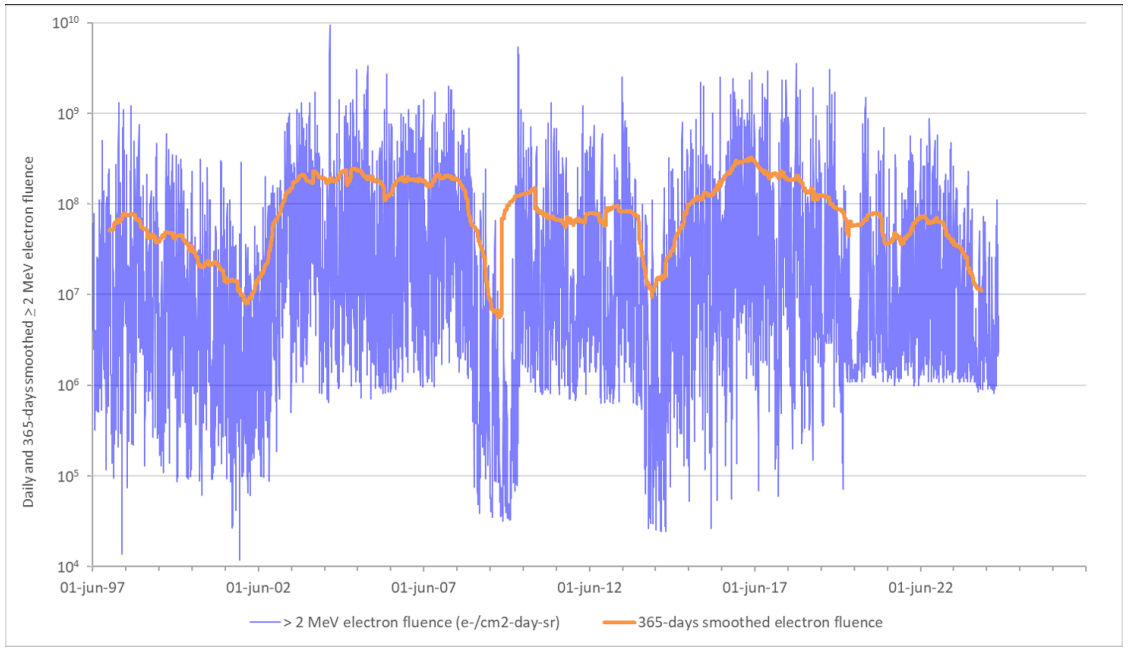


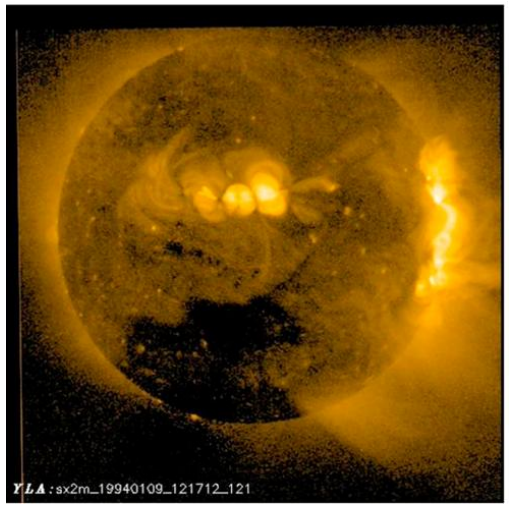
Credits: Wrenn et al. (2002)

Impact from CH HSS on SATCom

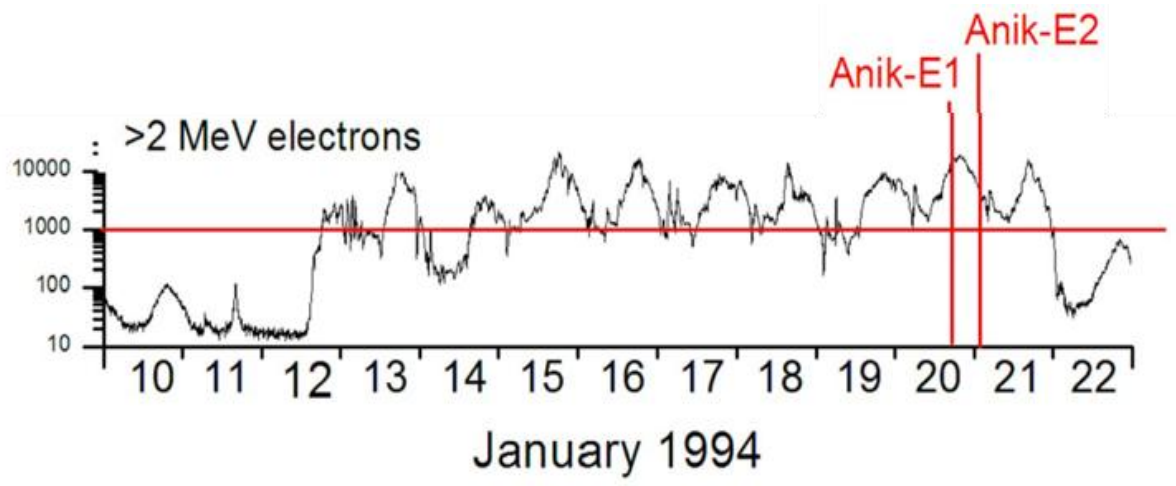


Credits: Lai et al. 2018





Frequency High fluence: ~18 days / year



Credits: Lam et al. 2012

Summary

	HFCom	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