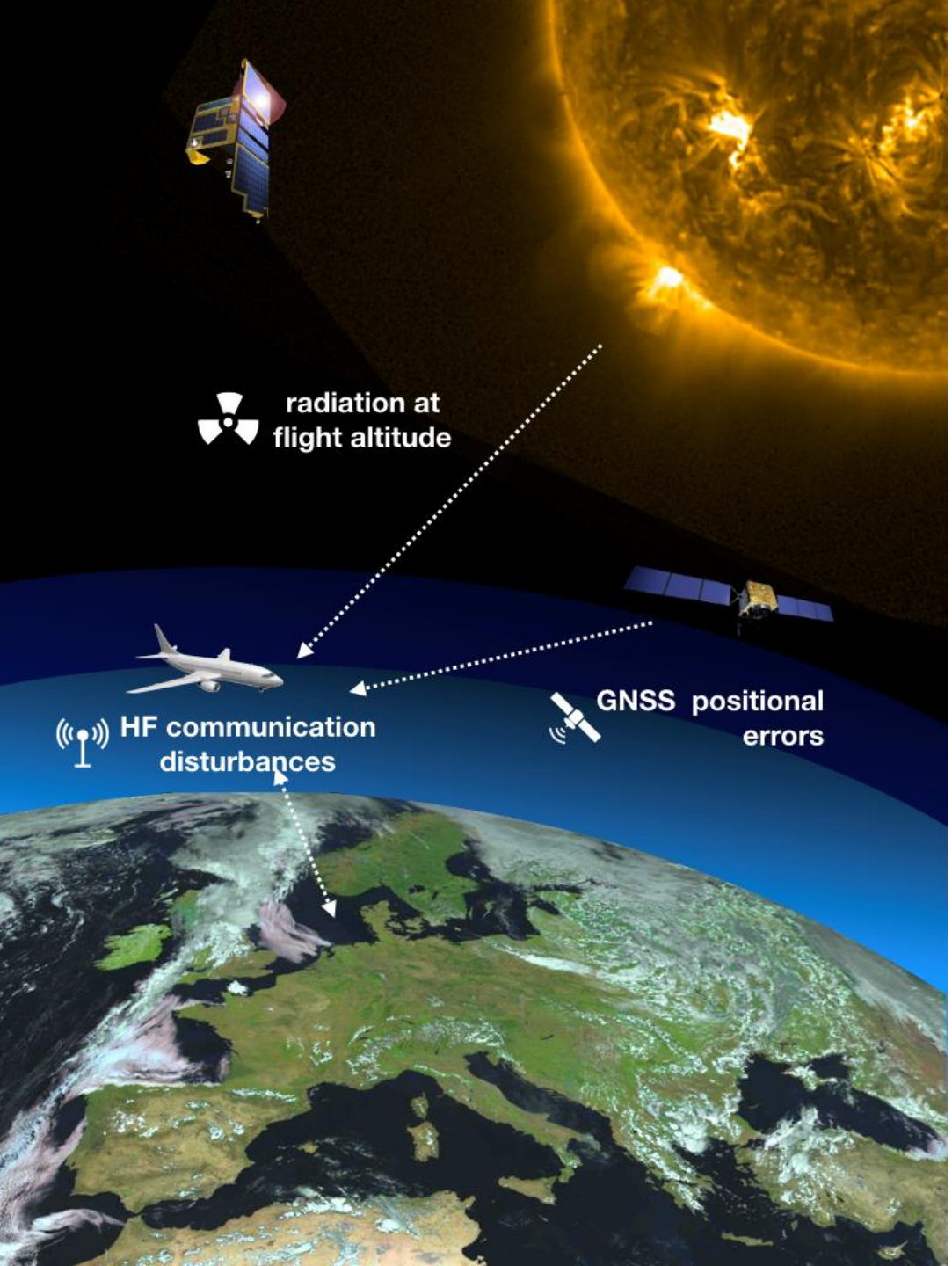


Space Weather impacts on Aviation

Course by the
Solar-Terrestrial Centre of Excellence

March 2024

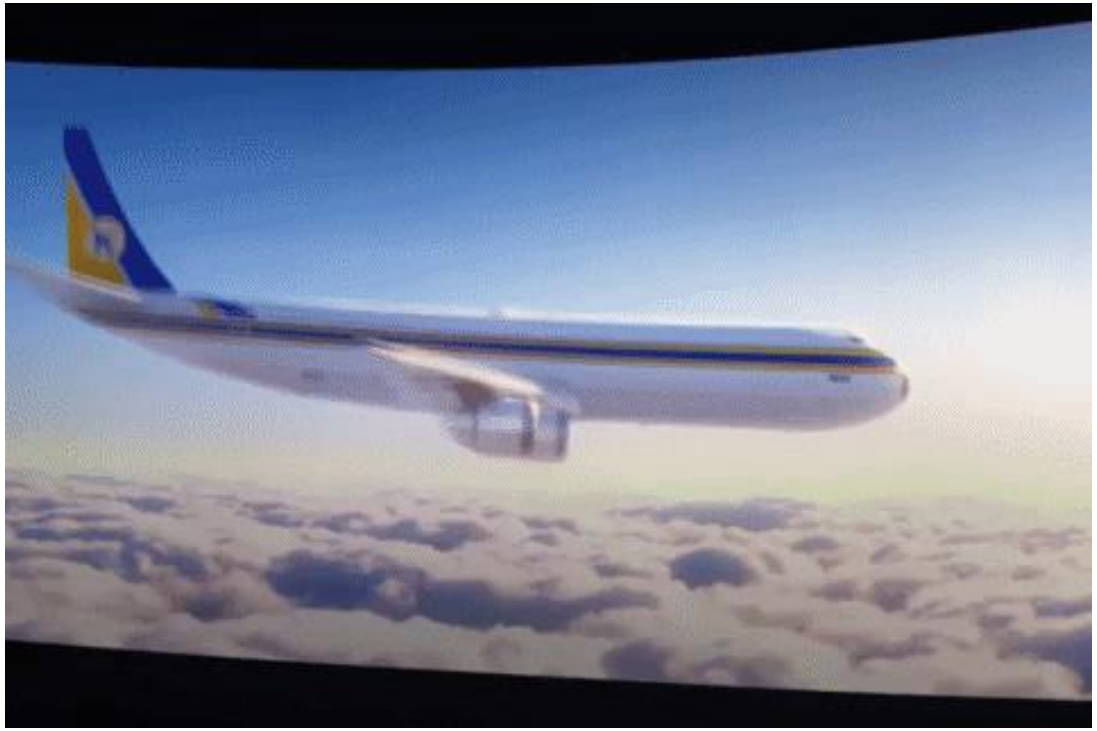
Space Weather impacts on Aviation

Disturbances seen in GNSS, HF Com and Radiation at FL

Jan Janssens

Contents

- Drivers of SWx
  - Examples
- SWx impacts on aviation
  - Diagram
  - Historical events
    - HF Com
    - Radiation
    - GNSS



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Drivers of disturbed SWx

Solar eruptions

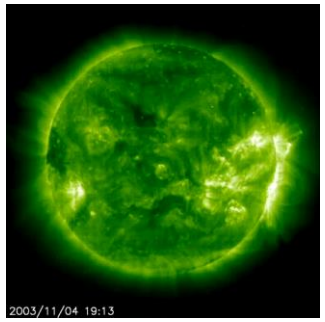
Electromagnetic Radiation

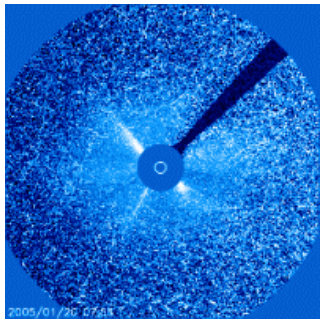
Particles

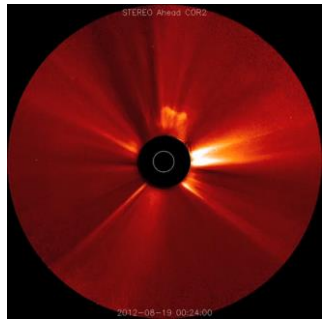
Solar flares

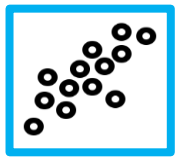
Proton events

Coronal Mass Ejections









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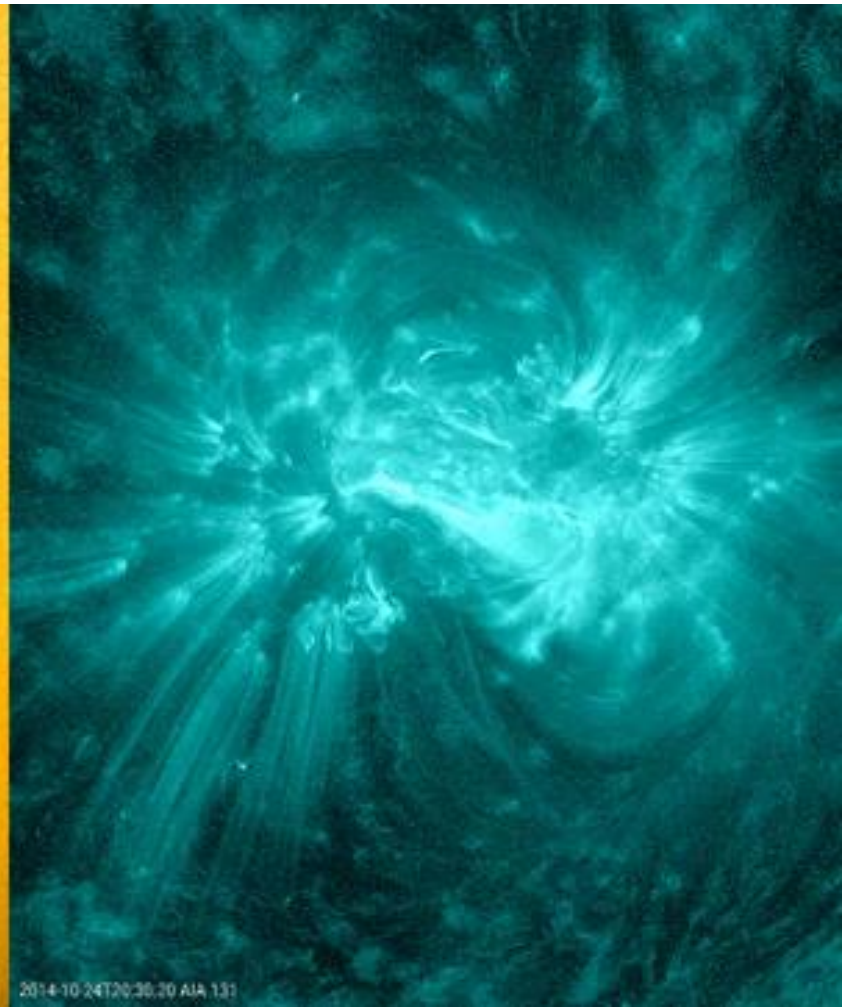
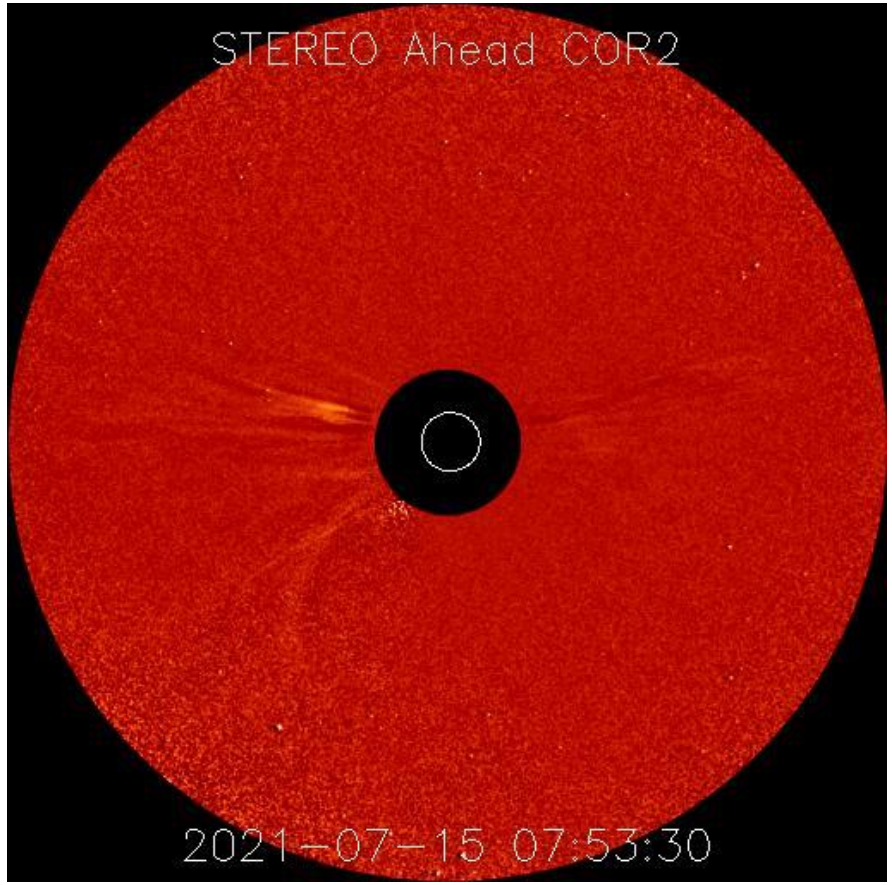
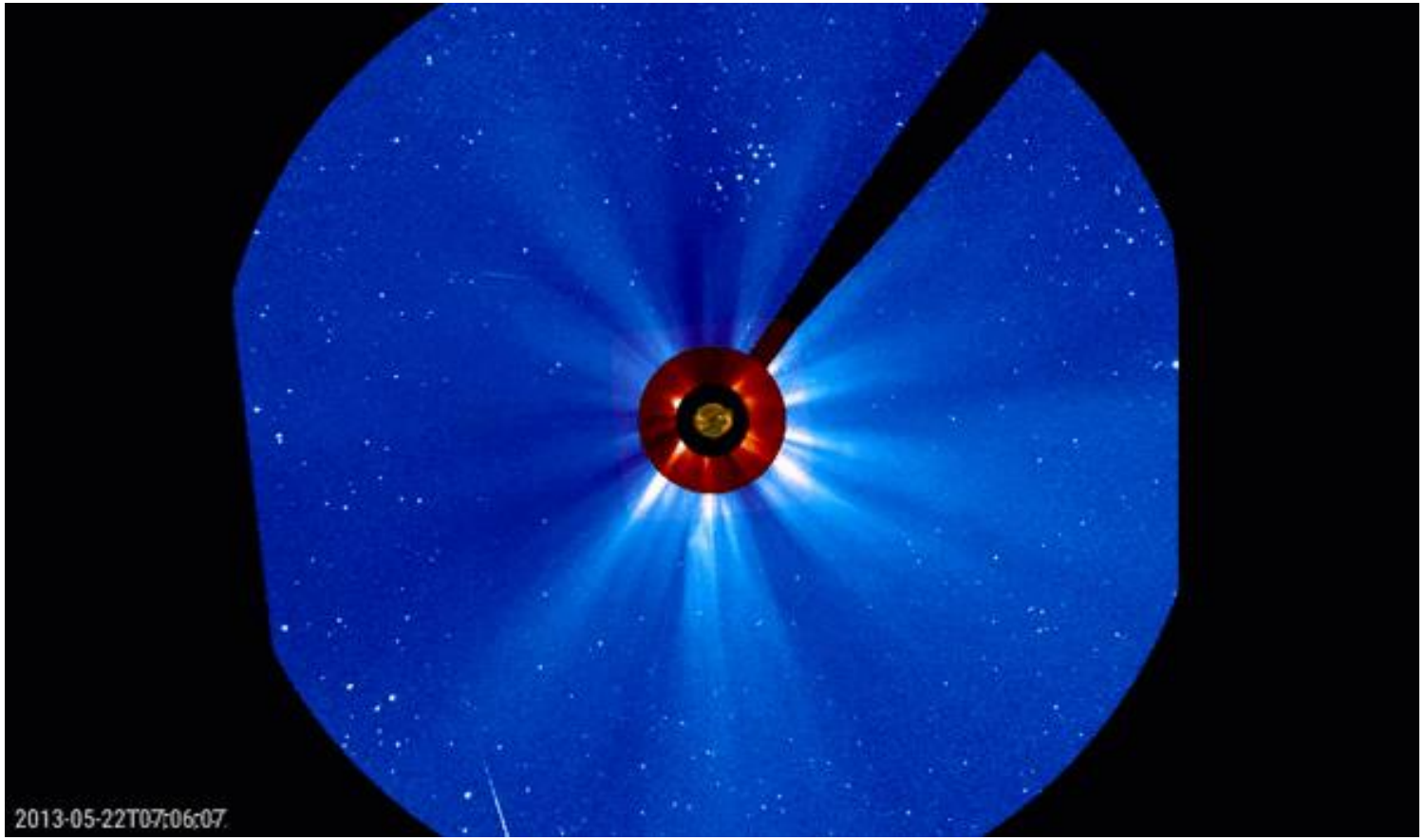
Examples solar flare



Example CMEs and proton event





CME: Coronal Mass Ejection

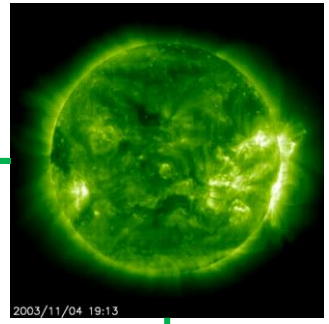
SWx impacts on aviation

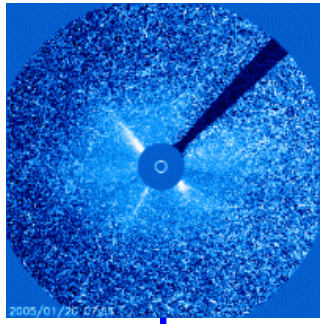
Drivers

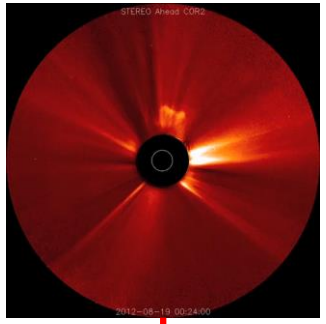
Solar flares

Proton events

Coronal Mass Ejections







Impacts

HF Com

Radiation

GNSS

Ground Support

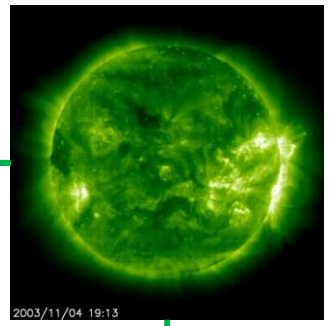
Biological

Electronics

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

SWx impacts from solar flares on aviation

Solar flares



HF Com

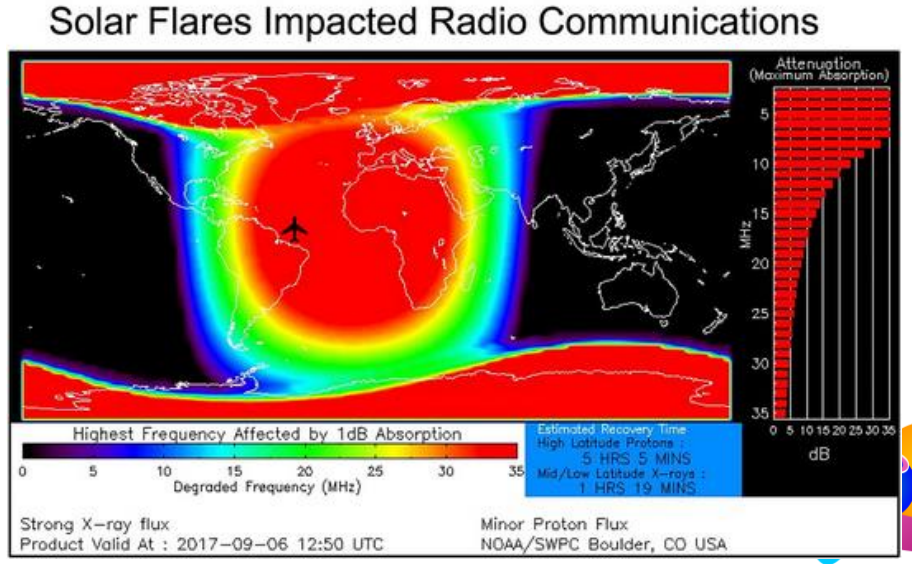
GNSS

Ground Support

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

SWx impacts from solar flares on HF Com

- From EUV and x-rays
  - Short-wave fadeout (SWF)
    - Disturbance of lower ionosphere
    - Absorbs HF signals
      - “Radio Black-out”
      - Dayside
  - 6-10 September 2017
    - Hurricanes over Caribbean
    - X9 flare on 6 September
      - 90-min loss of comms with French Cargo plane over Atlantic

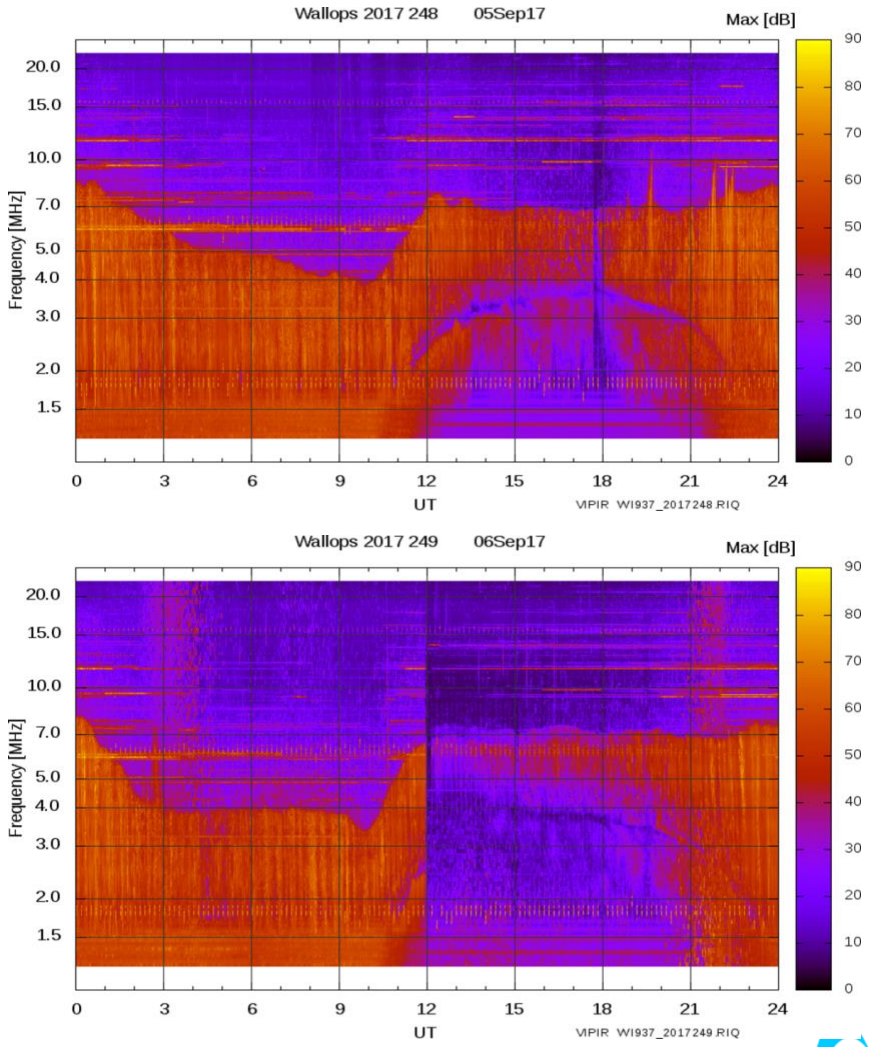


SWEC Space Weather Education Center

HF Com: High Frequency Communications (3-30 MHz) ; EUV: Extreme Ultraviolet

SWx impacts from solar flares on HF Com

- From EUV and x-rays
  - Short-wave fadeout (SWF)
    - Disturbance of lower ionosphere
    - Absorbs HF signals
      - “Radio Black-out”
      - Dayside
  - 6-10 September 2017
    - Hurricanes over Caribbean
    - X9 flare on 6 September
      - 90-min loss of comms with French Cargo plane over Atlantic
      - Relief efforts hampered due to SWF from strong X-class flares
        - For more than 8 hours on 6 September
  - Frequency X1+ flares
    - 5 - 25 per year

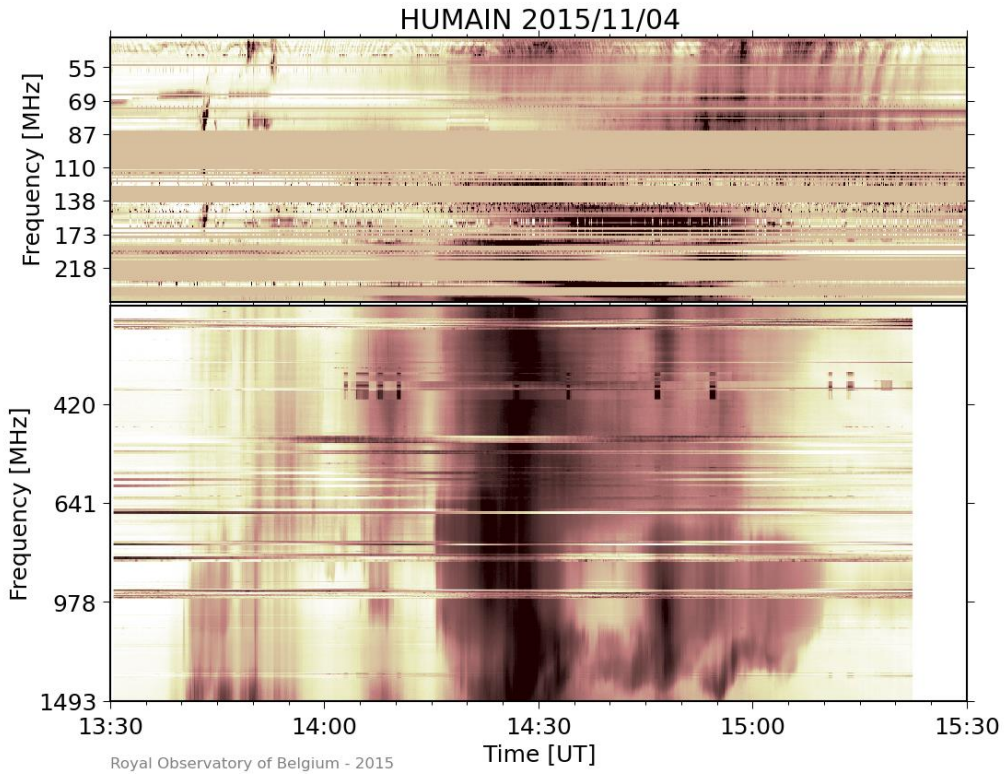


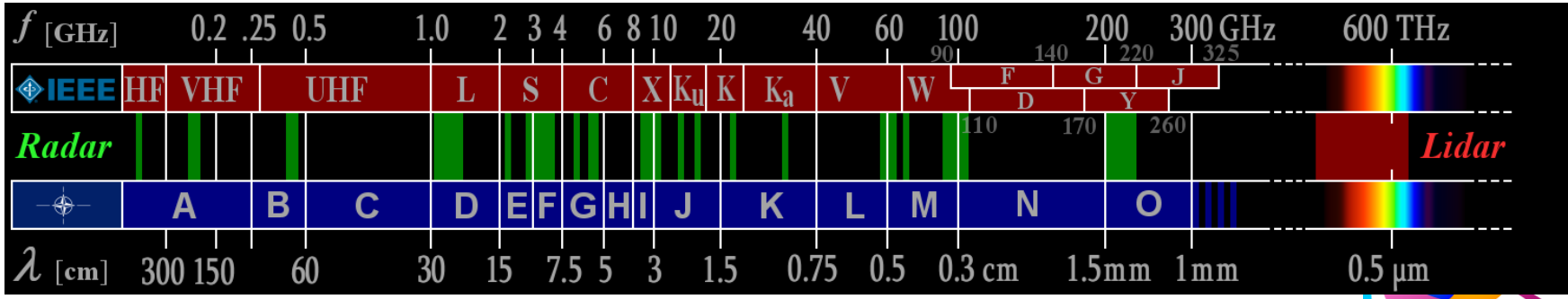
Courtesy of CIRES, Terry Bullett

HF Com: High Frequency Communications (3-30 MHz) ; MHz: megahertz ; EUV: Extreme Ultraviolet ; dB: decibel

SWx impacts from solar flares on Ground Suppor

- From radio emission
  - Overpowers radar signals at affected frequencies
  - Independent of SXR intensity solar flare
- 4 November 2015
  - M3 flare paralyzes Swedish air traffic
  - Seems to require a set of special conditions





SXR: soft x-rays ; GHz: gigahertz

SWx impacts from solar flares on GNSS

- From radio emission @ GNSS frequencies
  - Overpowers radio signals from satellites
- 6 December 2006
  - X6.5 flare
  - 1415 MHz: 10^6 sfu
    - Normally around 100 sfu…
    - Radio bursts > 100.000 sfu
      - About 2 per year

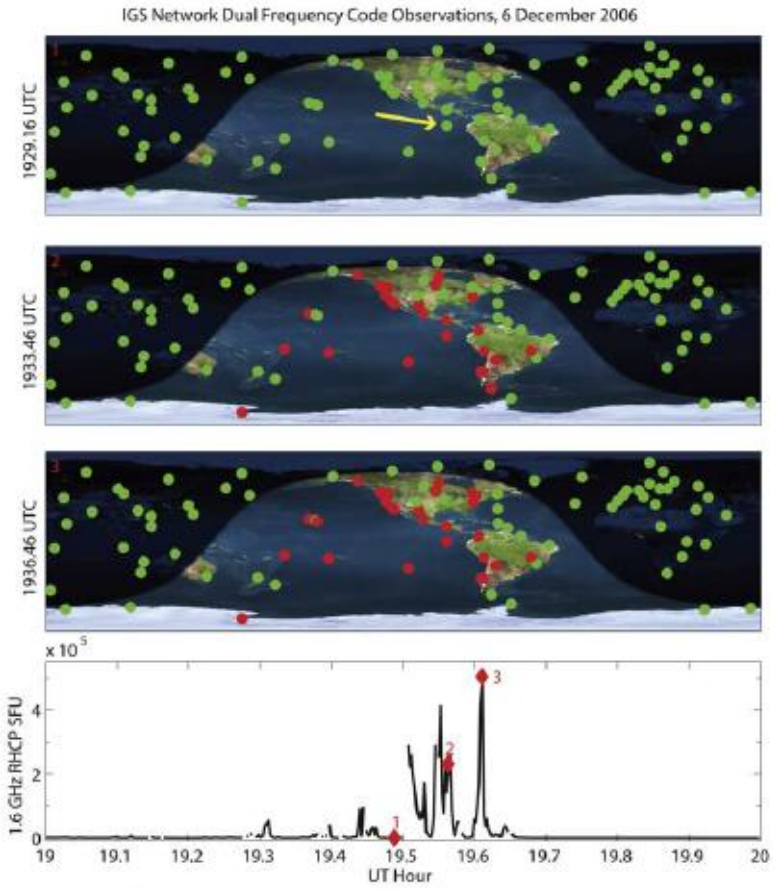


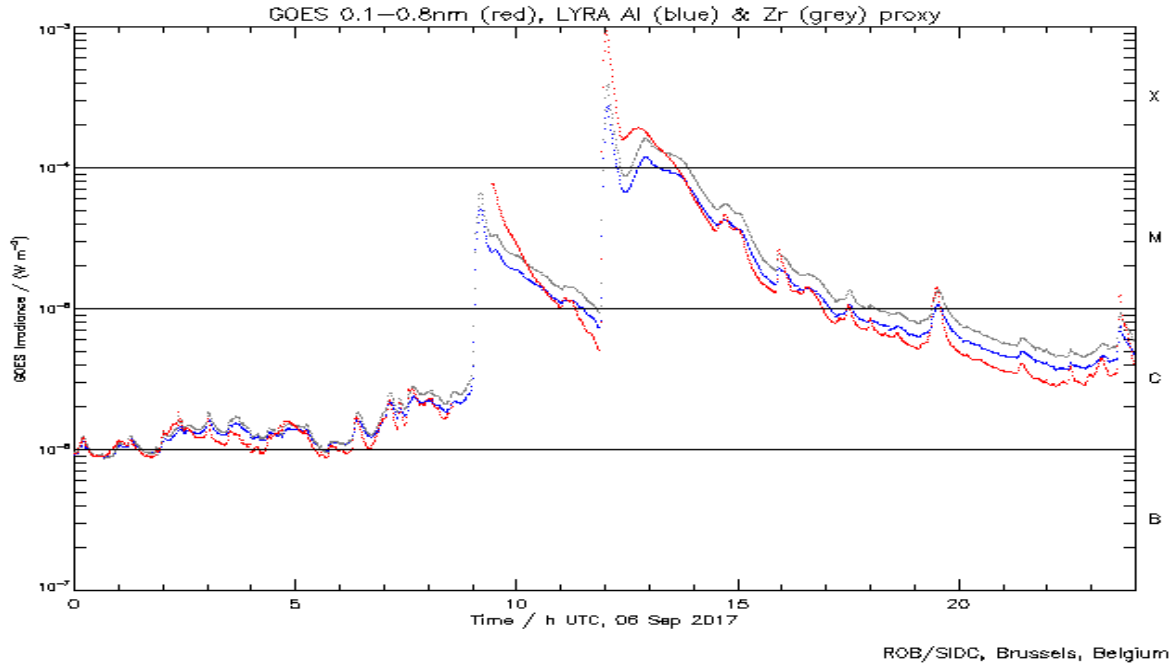
Figure 6. Receivers in the Global GPS Network that were analyzed during the solar radio burst. Green indicates the normal number of satellites being tracked. (fourth panel) During the burst (power at 1.6 GHz), several sunlit receivers tracked fewer than the four satellites needed for a full positioning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

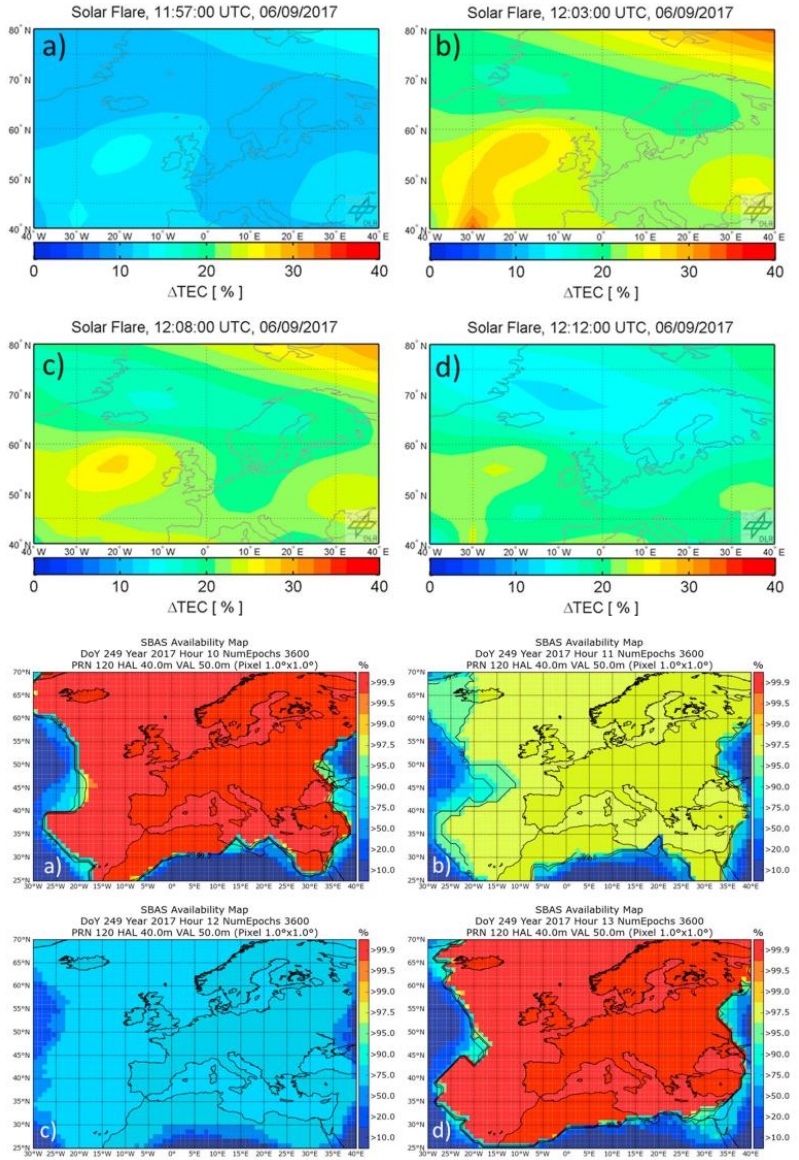
Credits: Cerruti et al. (2008)

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

SWx impacts from solar flares on GNSS

- From EUV and x-rays
  - 6 September 2017: X9.3
    - Deviations up to 2 meter
    - Short-lived ; dayside

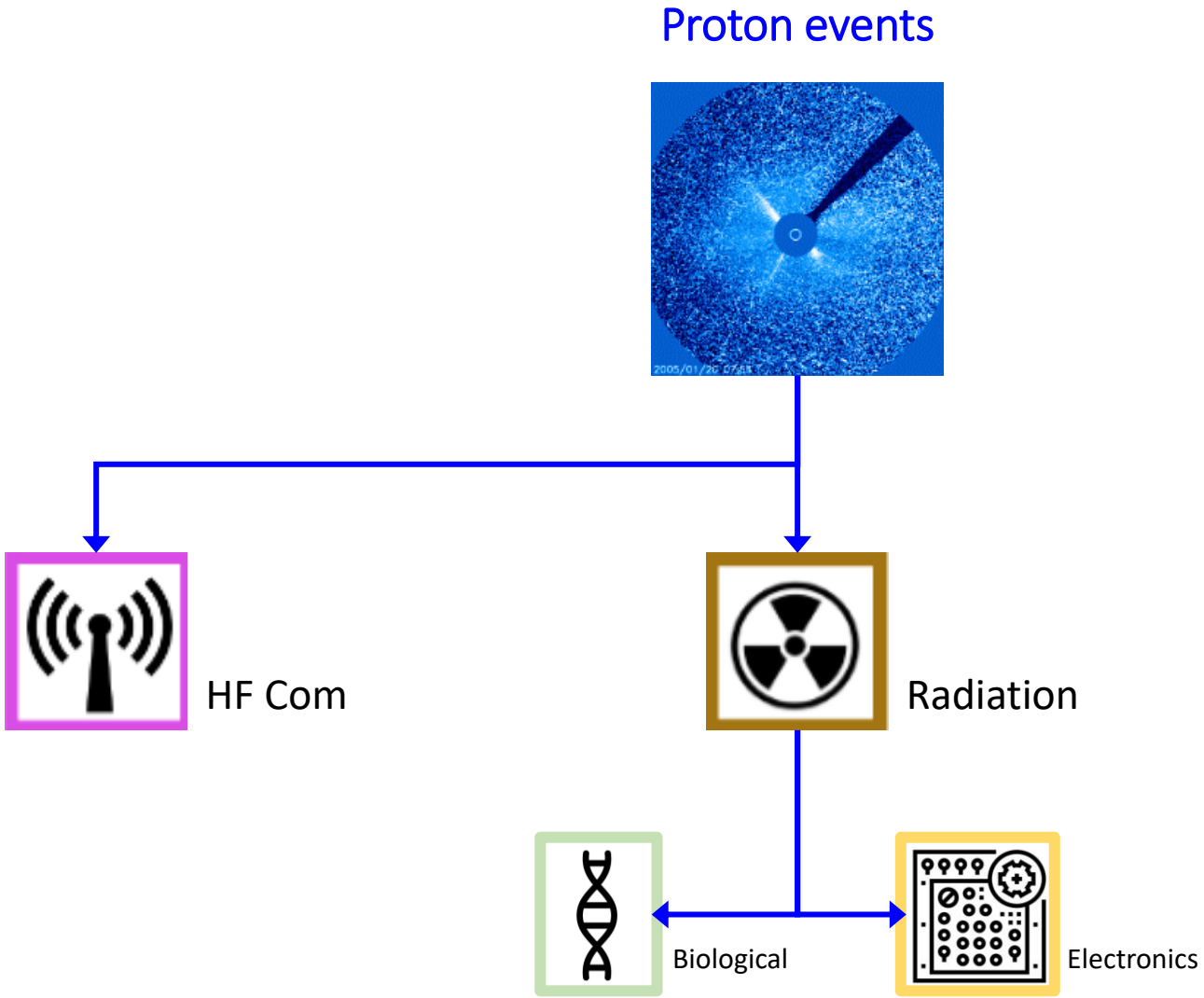




Credits: Berdermann et al. (2018)

EUV: Extreme Ultraviolet ; SBAS: Satellite Based Augmentation System ; EGNOS: European Geostationary Navigation Overlay Service

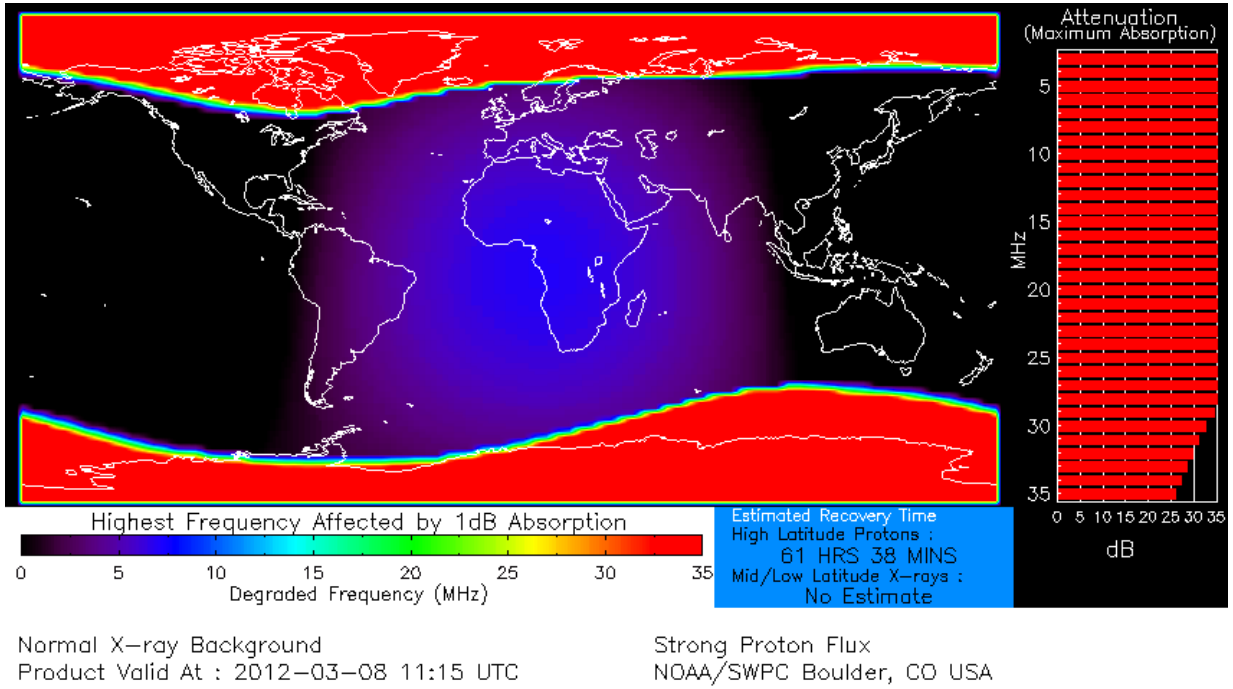
SWx impacts from proton events on aviation



HF Com: High Frequency Communications (3-30 MHz)

SWx impacts from proton events on HF Com

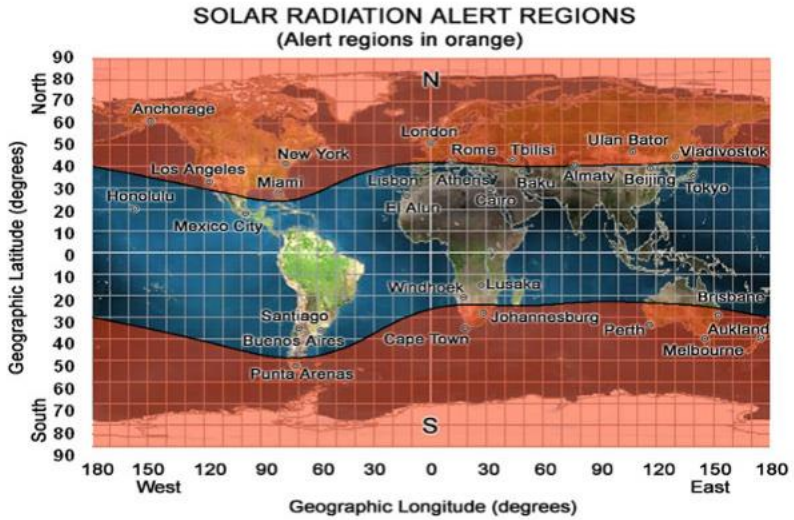
- Polar Cap Absorption (PCA)
  - From 10 MeV proton flux
    - Deviated by MF to poles
    - Affects lower ionosphere
    - Impacts HF Com at poles
      - Can last for days
      - +/- 10 per solar cycle
  - 7-8 March 2012
    - Strongest proton event of SC24
      - 6530 pfu
    - 8 polar flights detoured
    - Also in Mar-Apr 2001, Jan 2012, Oct 2003, Jan 2005, Dec 2006,...



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

SWx impacts from proton events : Biological

- Energetic particles
  - Galactic Cosmic rays (GCR)
  - Solar Energetic Particles (SEP)
  - Can damage DNA and cause cancer & reproductive problems
- Radiation dose
  - µSv/h , mSv/year
  - ICAO thresholds
- Mitigation polar flights
  - Halloween storms October 2003
    - Severe storm (29.500 pfu) + GLE (3!)
    - Decrease altitude
    - Reroute (away from poles)



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.

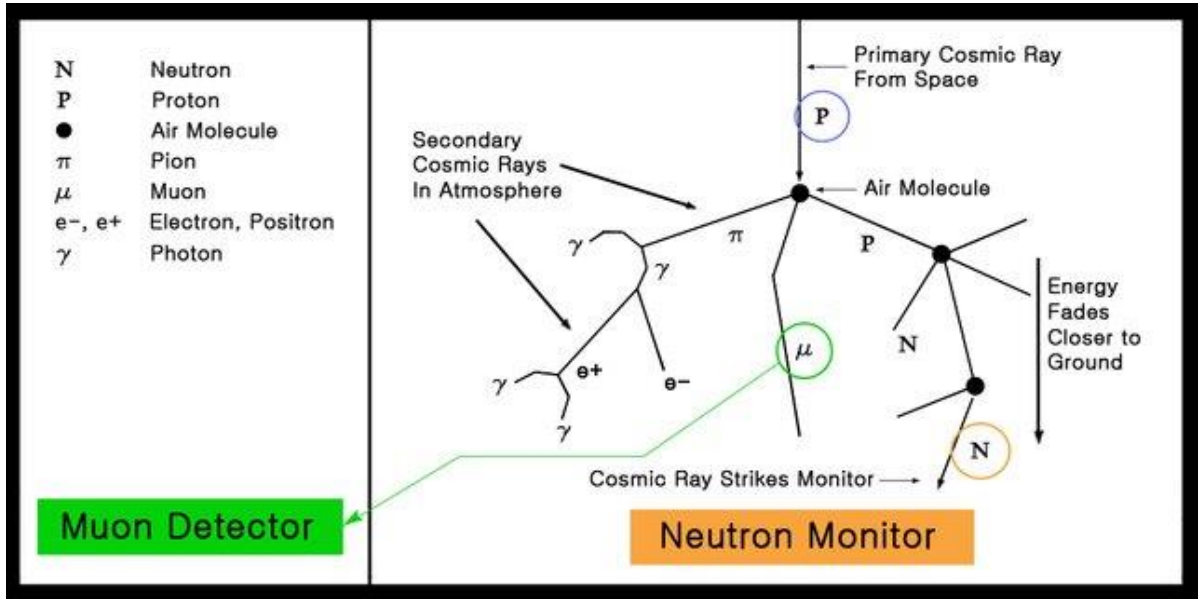
Avoiding excessive radiation exposure during pregnancy is particularly important.

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.

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 : Electronics

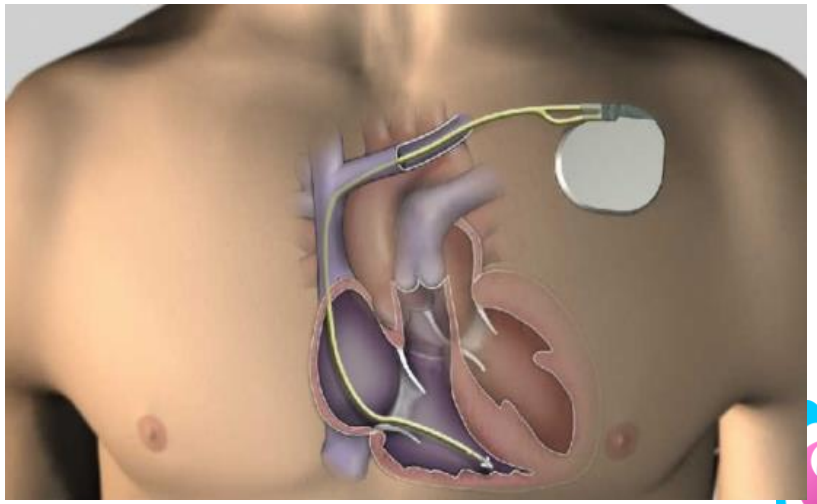
- Single Event Effects (SEE)
  - Direct hit of an electronic component by an energetic particle (GCR, SEP) resulting in an anomaly
    - Phantom commands, attitude control systems, satellite failure,…
- Ground Level Enhancement (GLE)
  - Sharp increase #neutrons @ ground
  - Main source
    - Strong SEPs ~500 MeV per nucleon
      - => RARE!! (about 1 per year)



SEP: Solar Energetic Particles ; GCR: Galactic Cosmic Rays ; MeV: megaelectronvolt

SWx impacts from proton events : Electronics

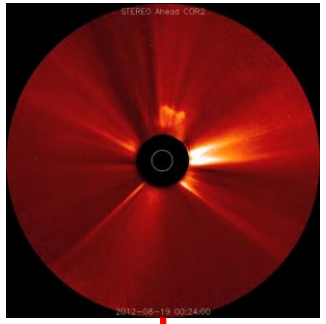
- Single Event Effects (SEE)
  - Direct hit of an electronic component by an energetic particle (GCR, SEP) resulting in an anomaly
    - Phantom commands, attitude control systems, satellite failure,…
- Ground Level Enhancement (GLE)
  - Sharp increase #neutrons @ ground
  - Main source
    - Strong SEPs ~500 MeV per nucleon
      - => RARE!! (about 1 per year)
  - Impacts
    - Computer glitches, servers,…
    - Pacemakers, defibrillators, and other medical devices,…
    - Difficult to prove connection!



SEP: Solar Energetic Particles ; GCR: Galactic Cosmic Rays ; MeV: megaelectronvolt

SWx impacts on aviation

Coronal Mass Ejections



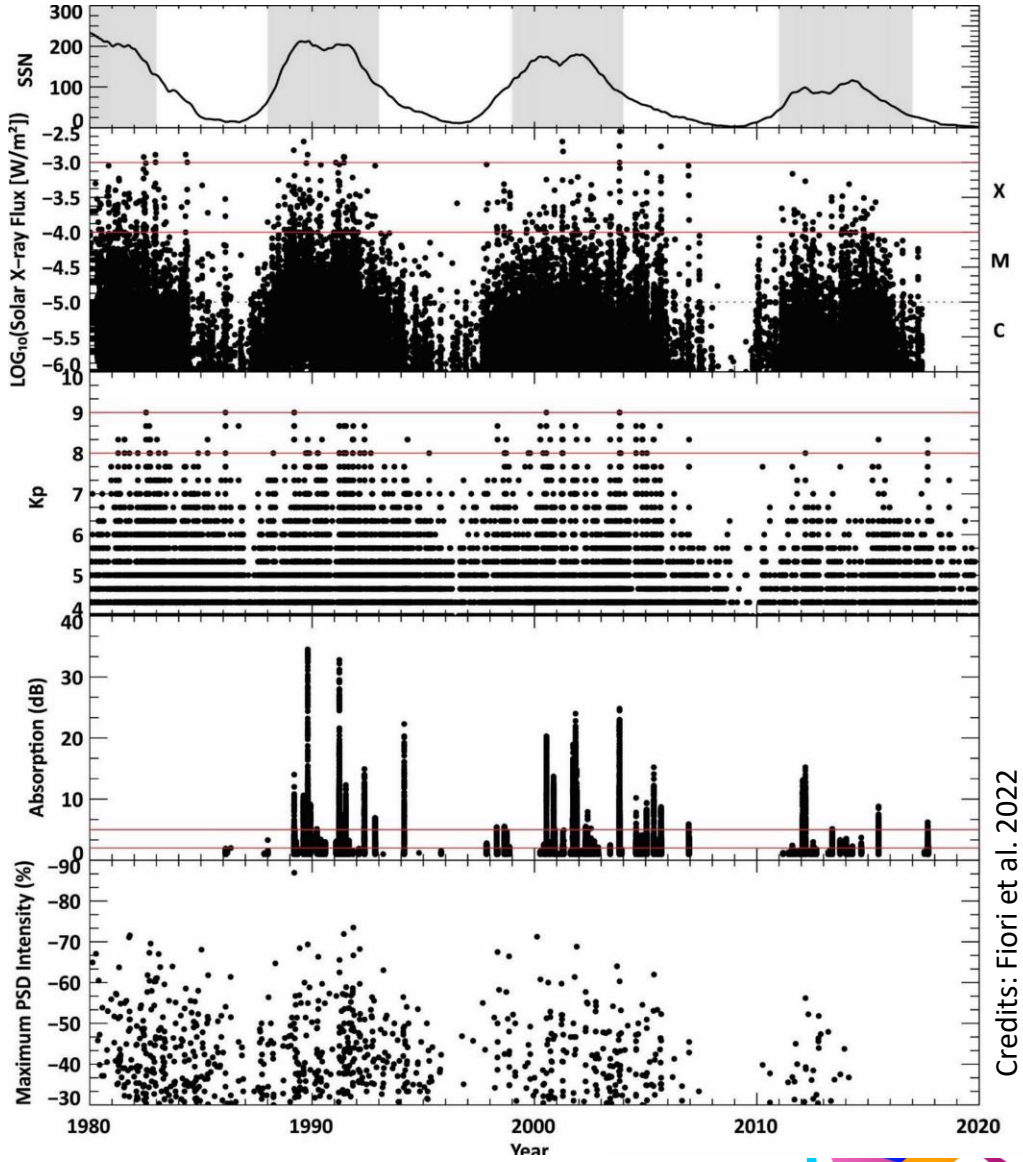
HF Com

GNSS

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

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

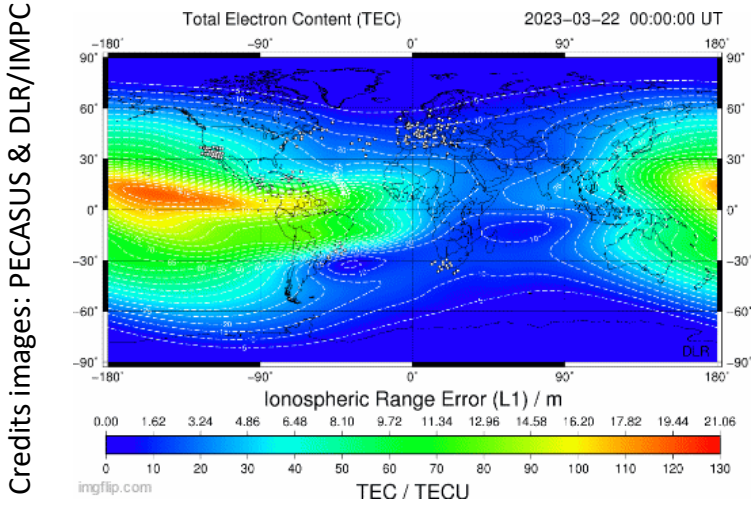


Credits: Fiori et al. 2022

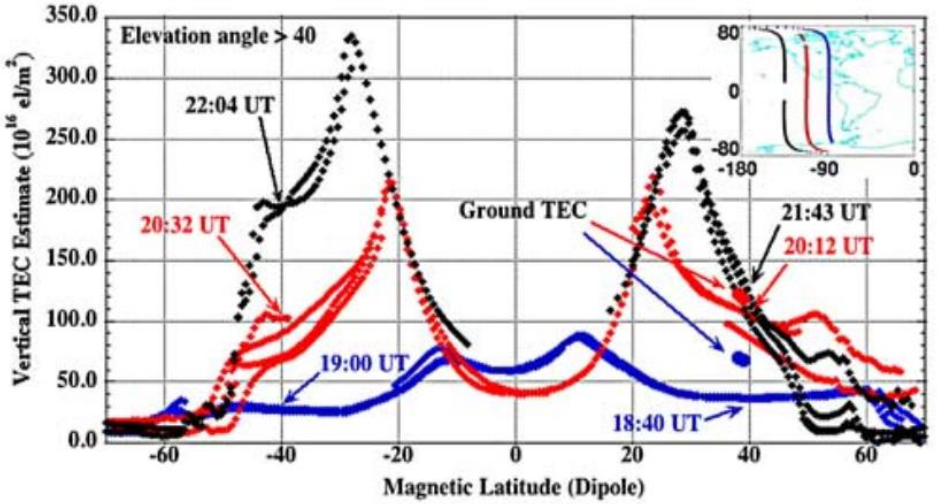
HF Com: High Frequency Communications (3-30 MHz) ; ICME: Interplanetary coronal mass ejection ; TEC: Total Electron Content

SWx impacts from ICMEs on GNSS

- Ionospheric storm
  - VTEC based (Local values)
  - 23-24 March and 23-24 April 2023
    - VTECmax ~170 TECu ; Dst resp. -163 nT and -212 nT
  - October 2003
    - VTEC max ~340 TECu ; Dst: -383 nT



Credits images: PECASUS & DLR/IMPC



Credits: Mannucci et al. 2005

30 October 2003 – Kp = 9o – Dst = -383 nT

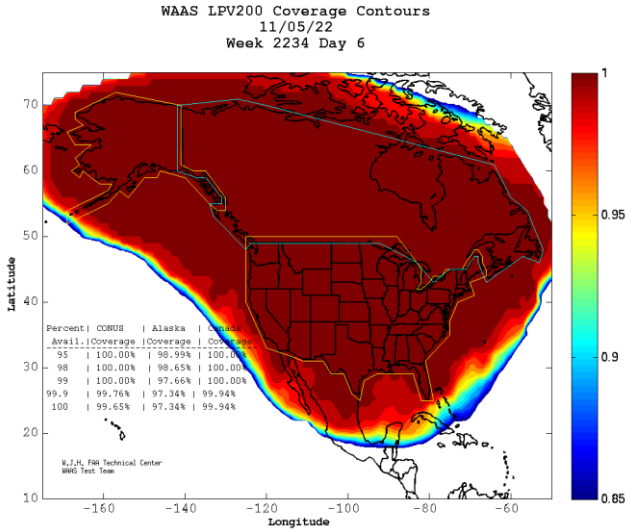
30 October 2003		
Kp	9o	
Dst	-383 nT	
Position repeatability	*North-Europe*	*Central Europe*
Quiet Sun (2008)	2,5 cm	2,5 cm
30 October 2003	26,1 cm	3,1 cm

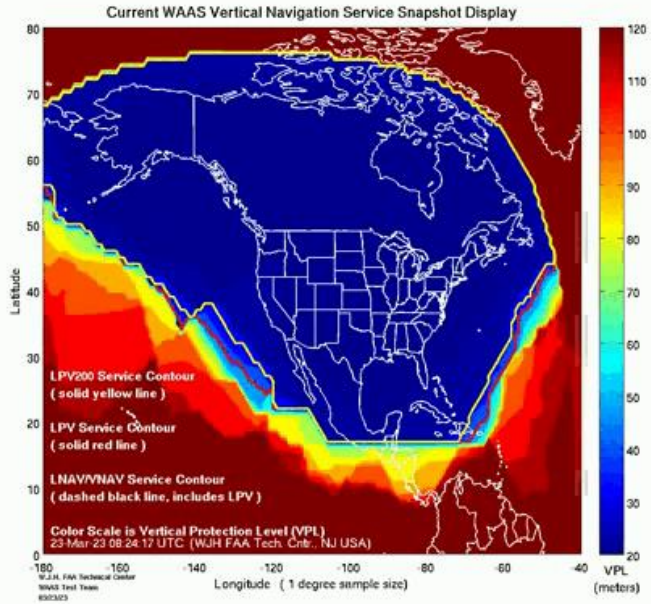
Credits data: Bergeot et al. 2011

HF Com: High Frequency Communications (3-30 MHz) ; ICME: Interplanetary coronal mass ejection ; VTEC: Vertical Total Electron Content ; nT: nanotesla ; Dst: Disturbance storm time ; TECu: TEC units

SWx impacts from ICMEs on GNSS

- Ionospheric scintillations
  - Small-scale density variations in ionosphere
    - Affect GNSS signals
  - 7 November 2022
    - Kp = 5o ; Dst = -89 nT
  - 23-24 March 2023
    - Kp = 8o ; Dst = -163 nT

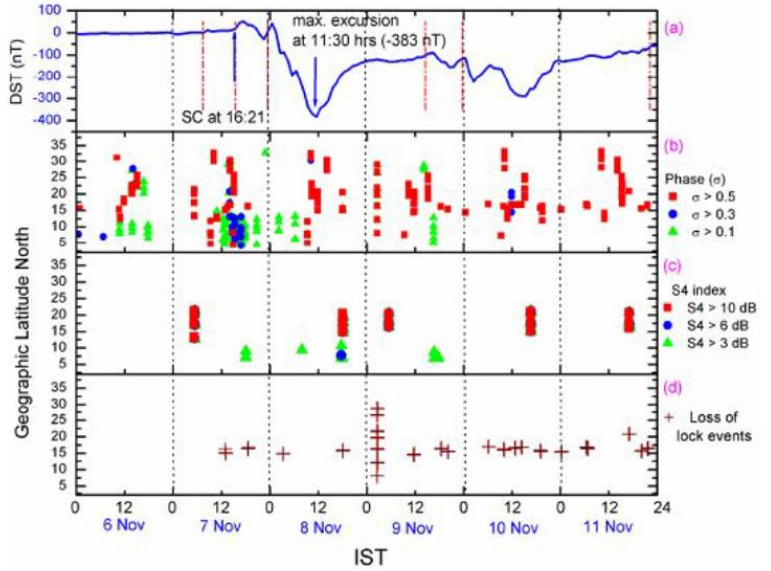




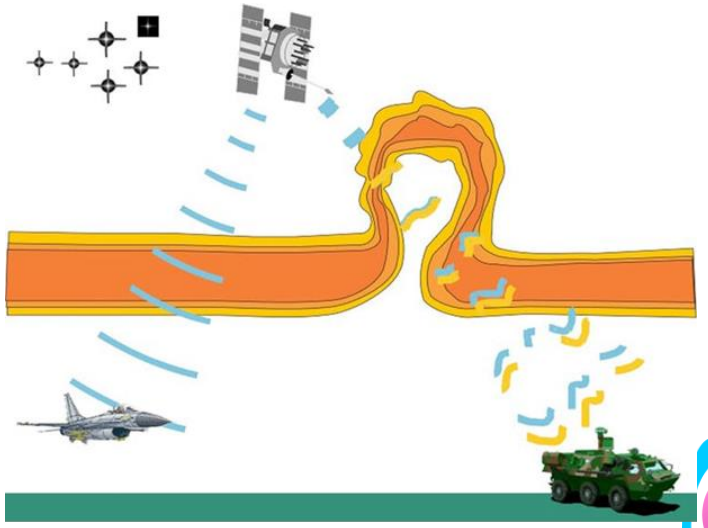
GNSS: Global Navigation Satellite Systems (GPS, Galileo,,…) ; ICME: Interplanetary coronal mass ejection ; nT: nanotesla ; Dst: Disturbance storm time ; WAAS: Wide Area Augmentation System ; LPV: Localizer Performance with Vertical guidance

SWx impacts from ICMEs on GNSS

- Ionospheric scintillations
  - Small-scale density variations in ionosphere
    - Affect GNSS signals
  - 7 November 2022
    - Kp = 5o ; Dst = -89 nT
  - 23-24 March 2023
    - Kp = 8o ; Dst = -163 nT
  - 8 November 2004
    - Kp=9o ; Dst=-374 nT
  - Reminder
    - Also when geomagnetic activity is quite low
      - Battle of Takur Ghar! (2002)



Credits: Rama Rao et al. 2009



Credits: US Air Force Research Laboratory

GNSS: Global Navigation Satellite Systems (GPS, Galileo,,…) ; ICME: Interplanetary coronal mass ejection ; nT: nanotesla ; Dst: Disturbance storm time ; dB: decibel

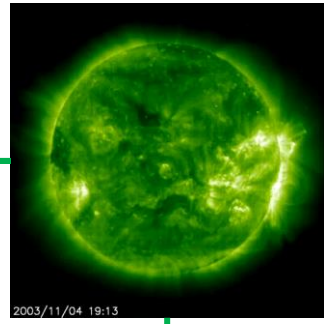
Summary

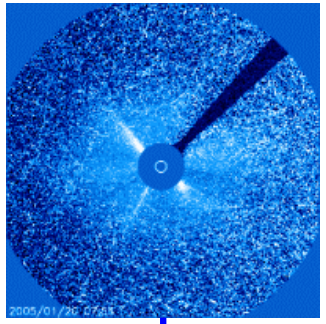
Drivers

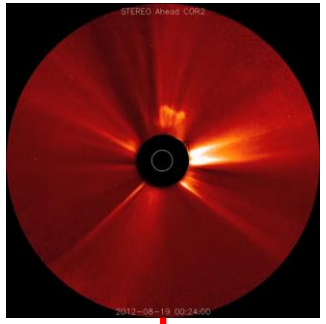
Solar flares

Proton events

Coronal Mass Ejections





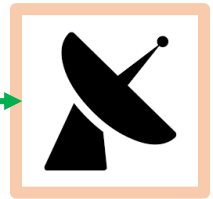


Impacts

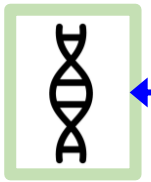
HF Com

Radiation

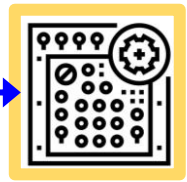
GNSS



Ground Support



Biological



Electronics

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

Questions?

SWEC
Space Weather Education Center