SWx impacts on ionospheric wave propagation - *focus on GNSS and HF*

SWIC

Collaboration of

Solar-Terrestrial Centre of Excellence

UNIVERSITY OF TWENTE. | RADIO SYSTEMS

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

EXTREME EVENTS and IMPACTS

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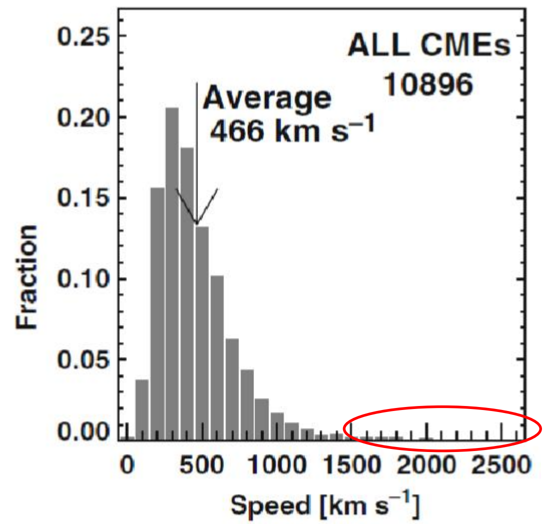
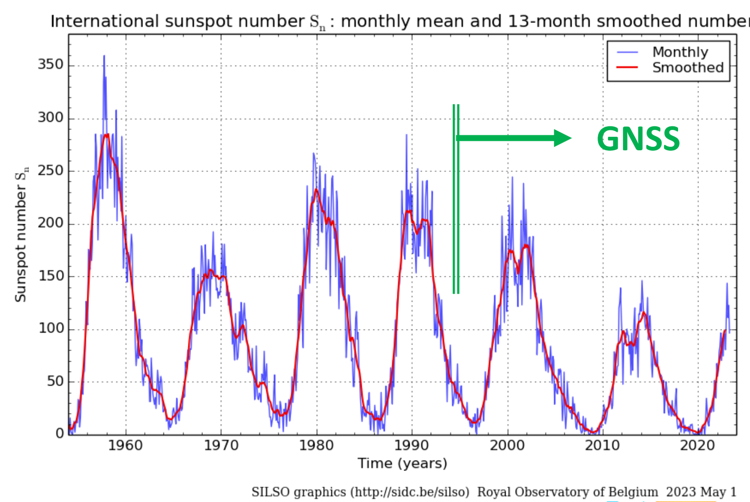
- What is an extreme event?
- SWx drivers & impacts: overview
- ***GNSS*** impacts from
  - Solar flares & solar radio bursts
  - Solar energetic particle events
  - Interplanetary coronal mass ejections
  - High speed streams from coronal holes

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
    - Only 20-30 years of GNSS data
      - 1 moderate and 1 weak solar cycle since the mid-1990s…





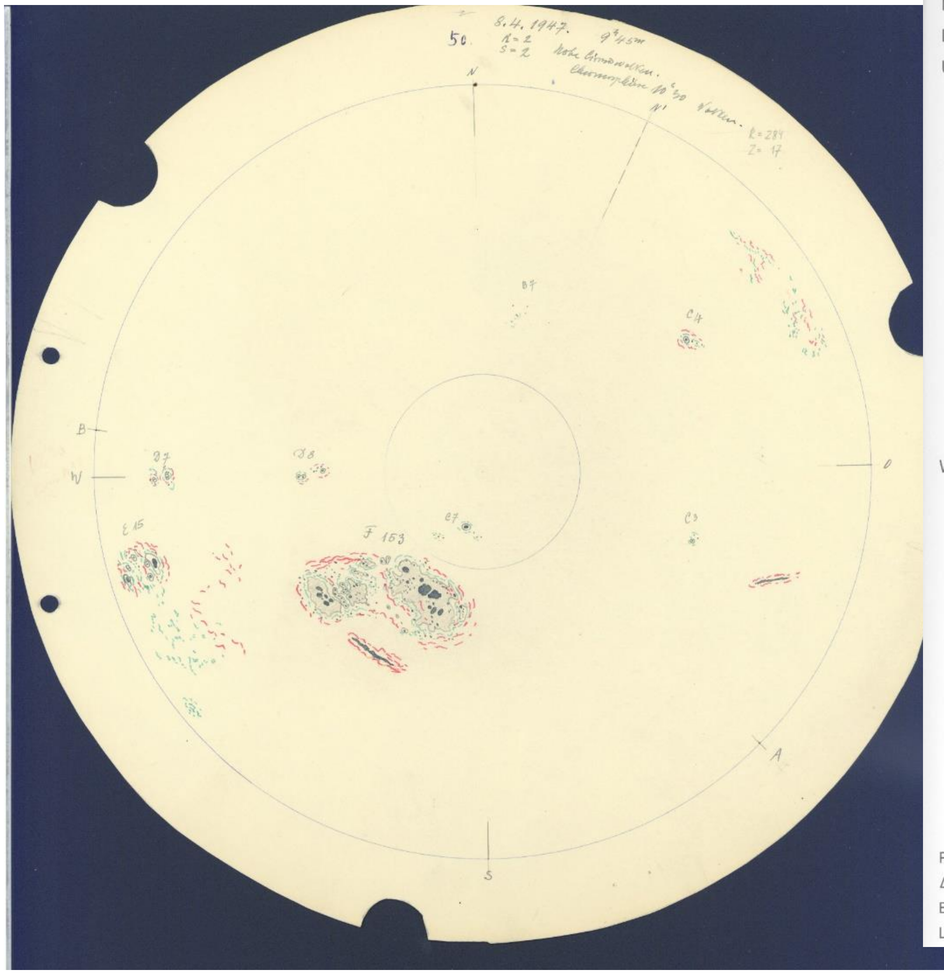
What is an extreme event?

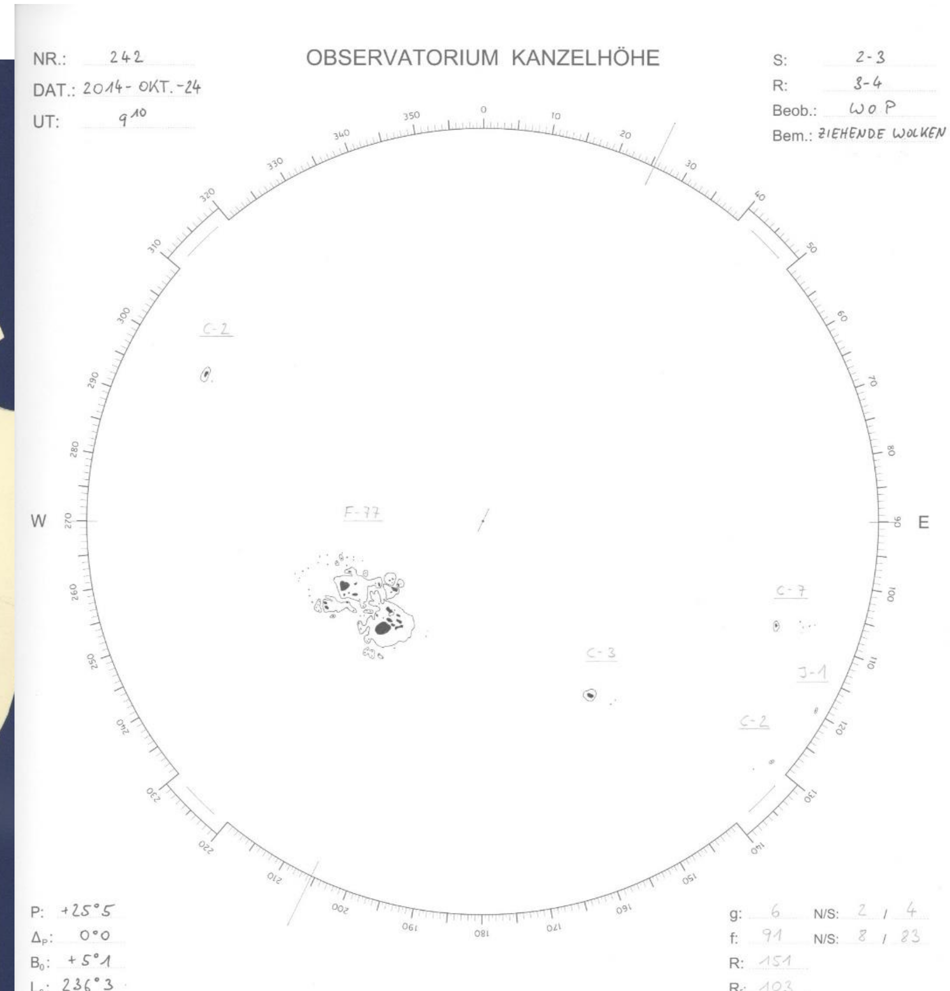
Observed, statistically expected, and modelled extreme solar and solar-terrestrial events *(based on Cliver et al. 2022 ; Gopalswamy 2018)*

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 SC18 & 24





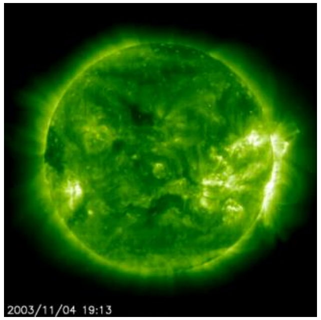
Drivers of disturbed SWx

Solar eruptions

Magnetic Reconnection

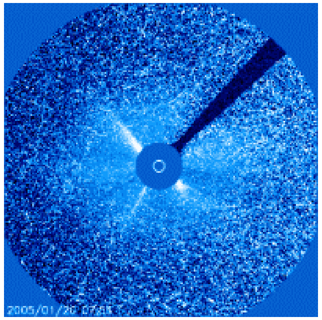
Radiation

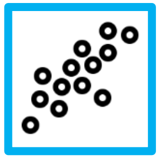
Solar flares



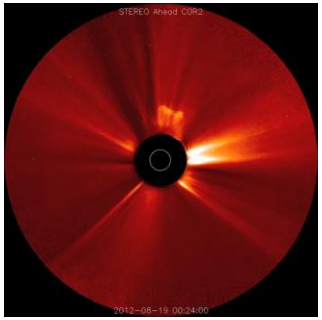
Particles

Proton events





Coronal Mass Ejections

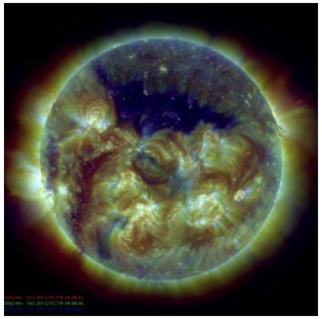


Solar corona

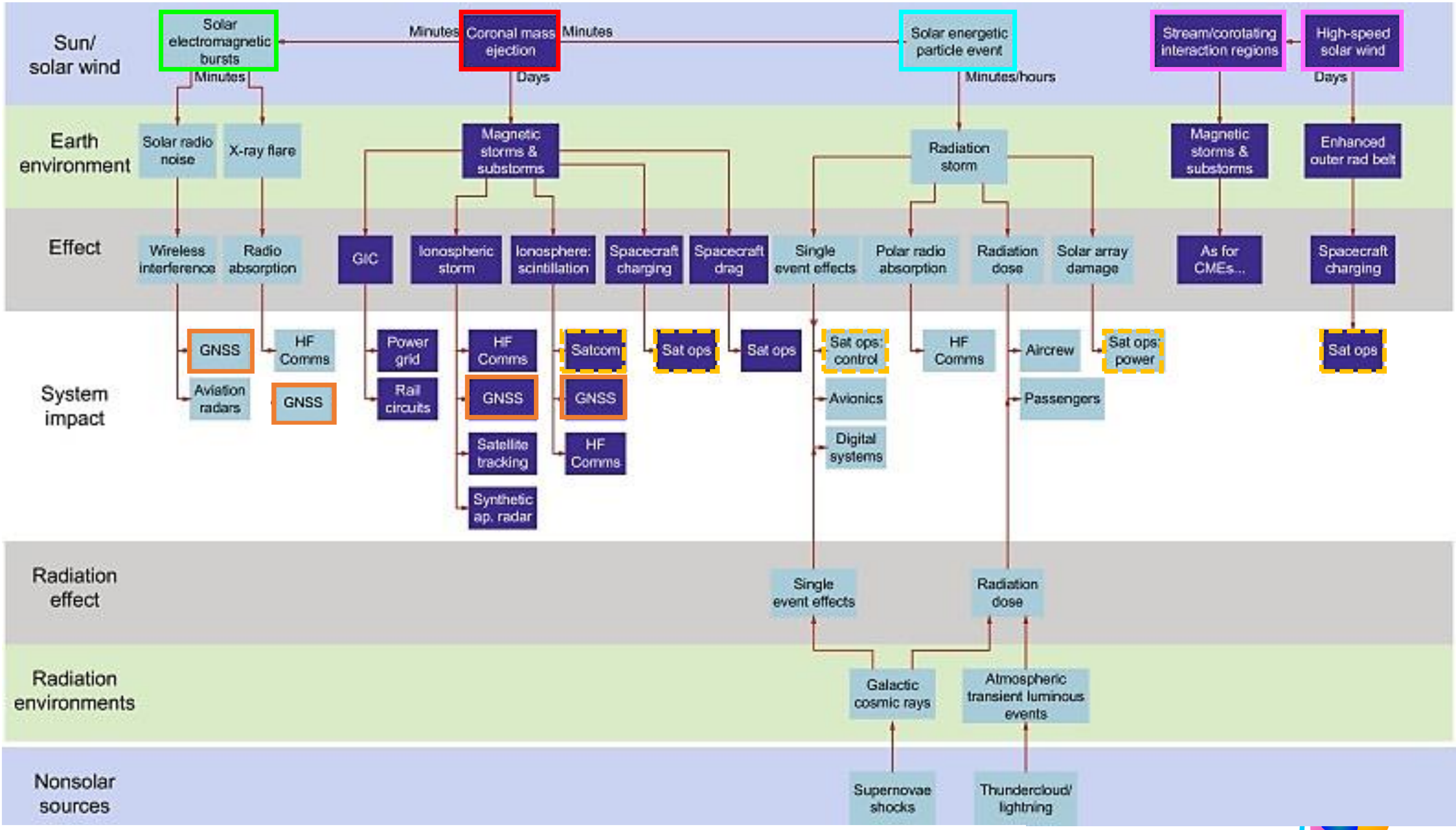
Solar wind

Particles

Coronal Holes

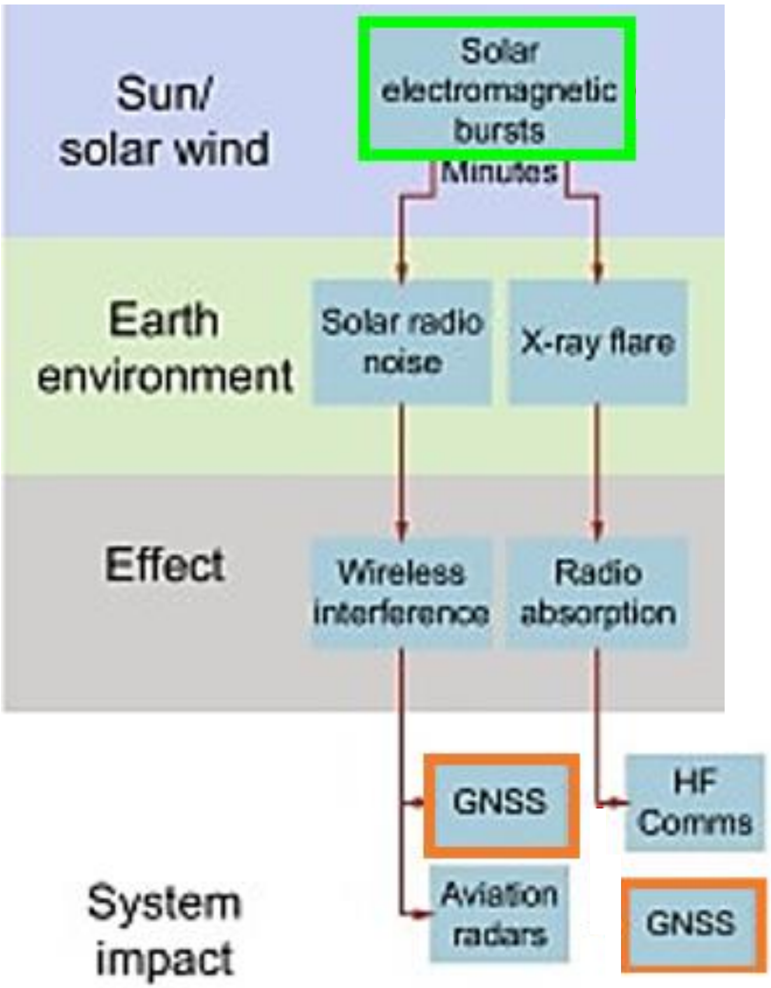


Impacts of disturbed SWx



From Hapwood 2018 (annotated). ▭ : primary GNSS impacts ; ⬚ : secondary GNSS impacts

GNSS impacts from solar flares



- From EUV & X-ray
  - Solar flare effect
    - *"magnetic crochet"*
    - Up to +/- 100 nT
  - Shortwave fadeout
    - *"Radio Blackout"*
    - Impact on HF Com
  - GNSS disturbances
- From radio emission
  - GNSS disturbances
  - Radar disturbances

HF Comms: High Frequency Communications ; EUV: extreme ultraviolet ; nT: nanotesla

GNSS impacts from solar flares

- From radio emission
  - 6 Dec 2006: X6.5
    - 1415 MHz: 10^6 sfu

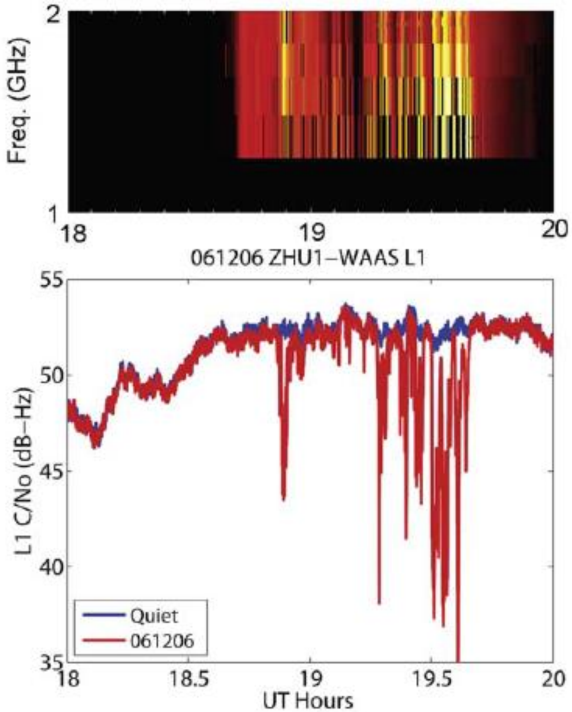


Figure 2. Response of a GPS receiver to the solar radio burst on 6 December 2006. The red line corresponds to C/N_0 on 6 December 2006, and the blue line corresponds to the previous sidereal day.

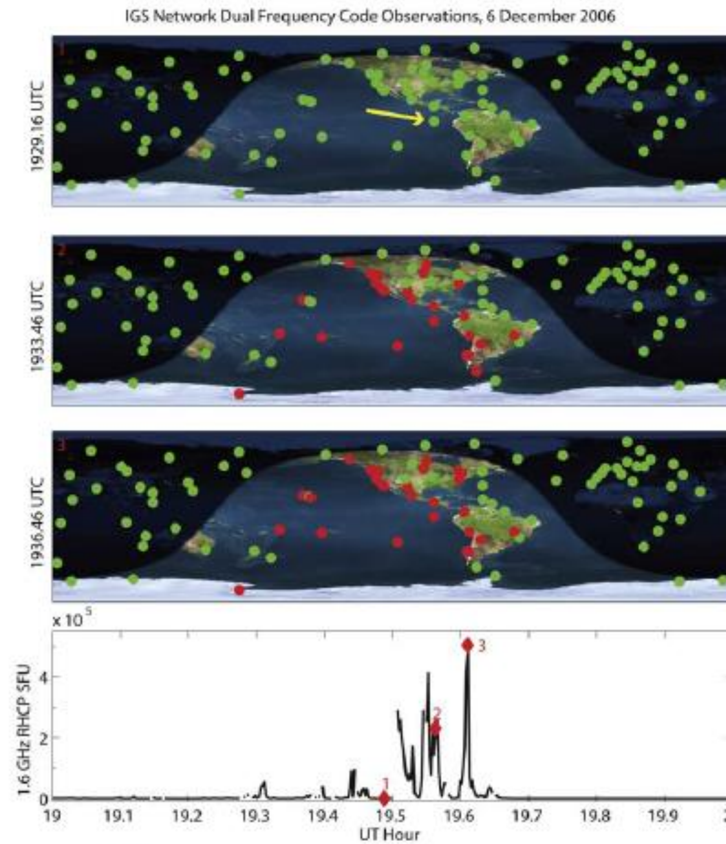


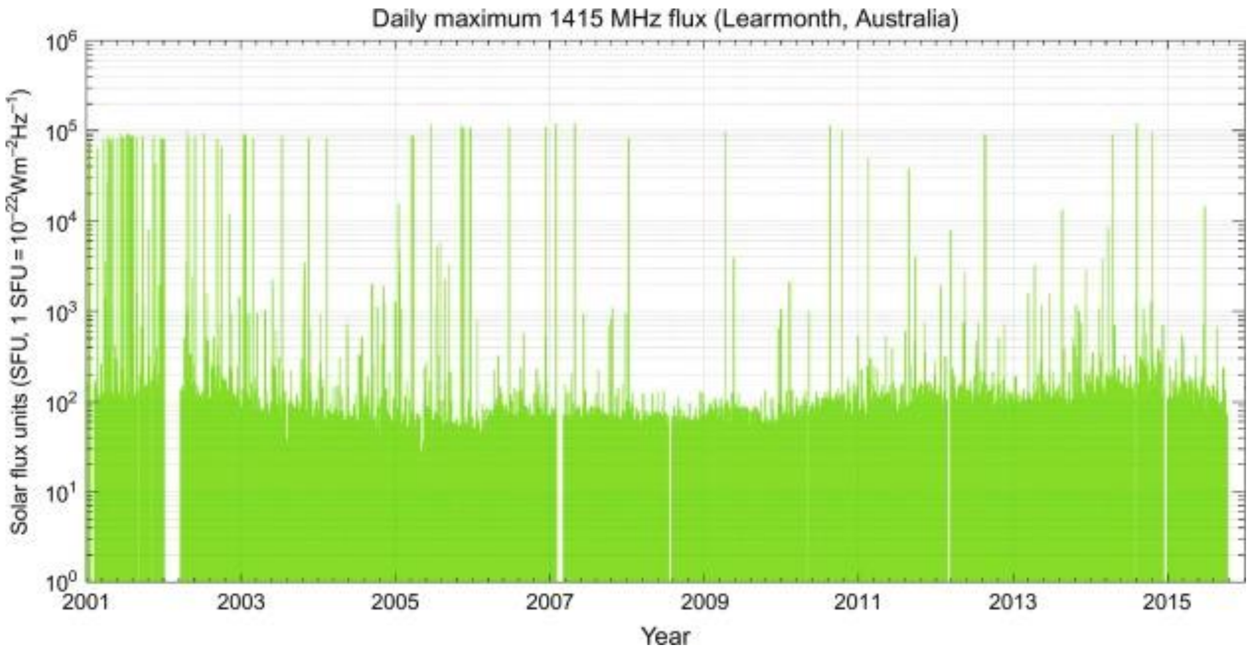
Figure 6. Receivers in the Global GPS Network that were analyzed during the solar radio burst. Green indicates the normal number of satellites being tracked. (fourth panel) During the burst (power at 1.6 GHz), several sunlit receivers tracked fewer than the four satellites needed for a full positioning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

Acronyms: **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

GNSS impacts from solar flares

- From radio emission
  - Impact threshold
    - 1000 – 10.000 sfu
    - Not f(SXR intensity)!
    - Sunlit side ; SC minimum
  - Frequency occurence
    - > 1000 sfu: ~ 8/year
    - > 100.000 sfu: ~ 2/year
    - Degrading eff.: ~ 9/**<u>SC</u>**

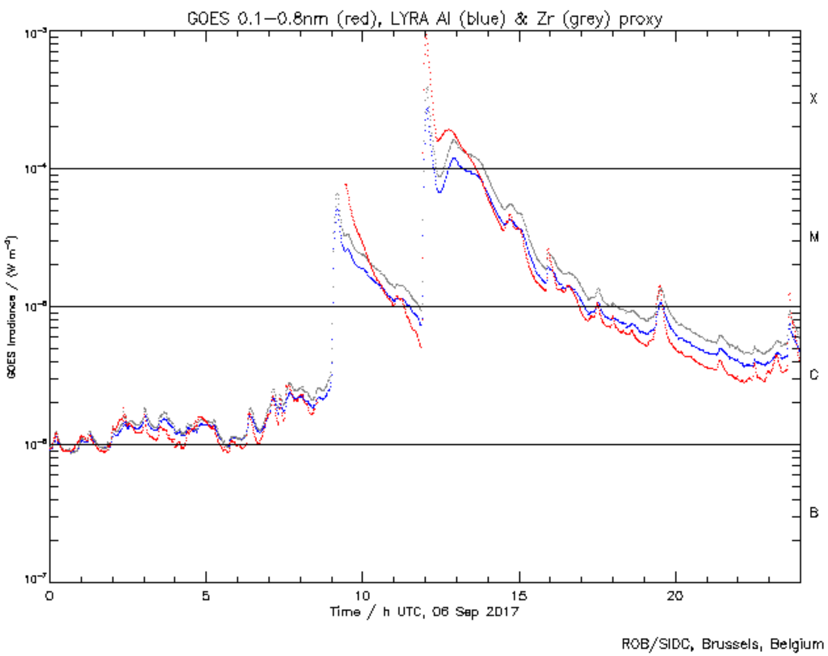


Credits: Yue et al. (2018)

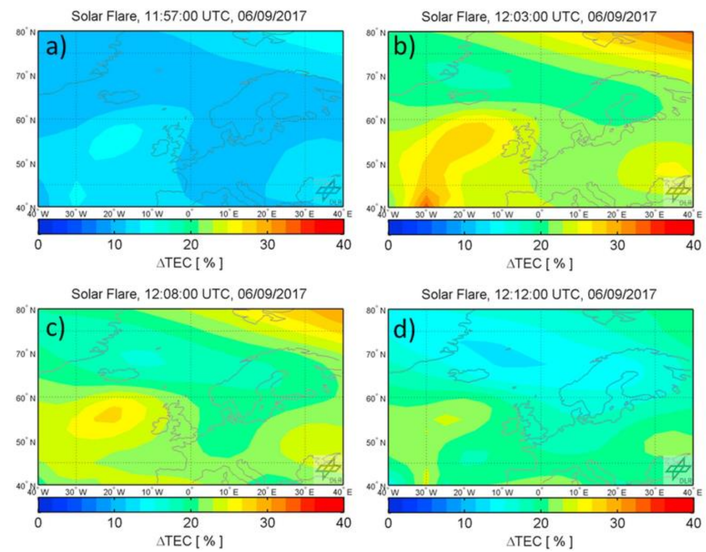
SXR: soft x-ray ; SC: solar cycle ; eff. Effect ; MHz: megahertz

GNSS impacts from solar flares

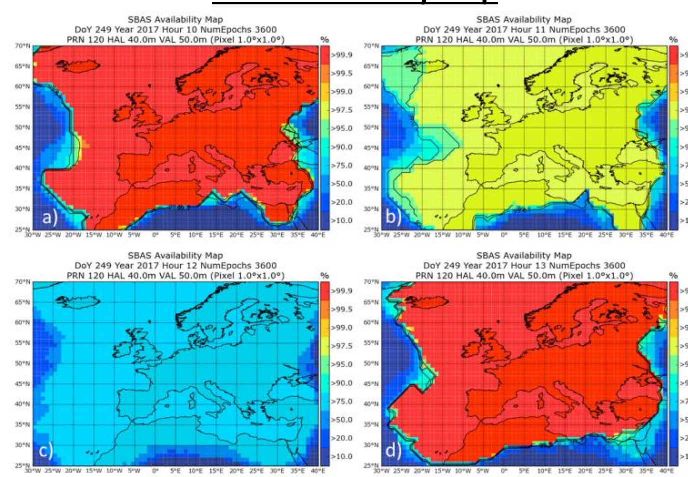
- From SXR/EUV emission
  - 6 Sep 2017: X9.3
    - Deviations up to 2m
    - Short-lived



Delta TEC compared to 11:53 UTC



SBAS availability map

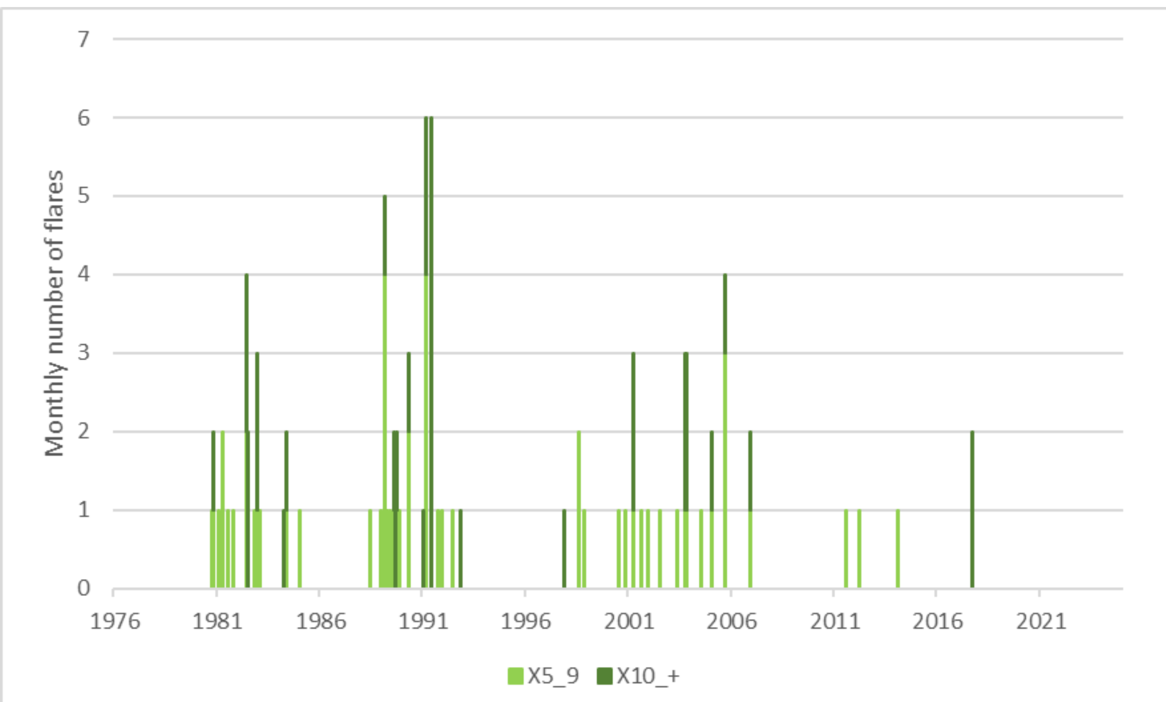


Credits: Berdermann et al. (2018)

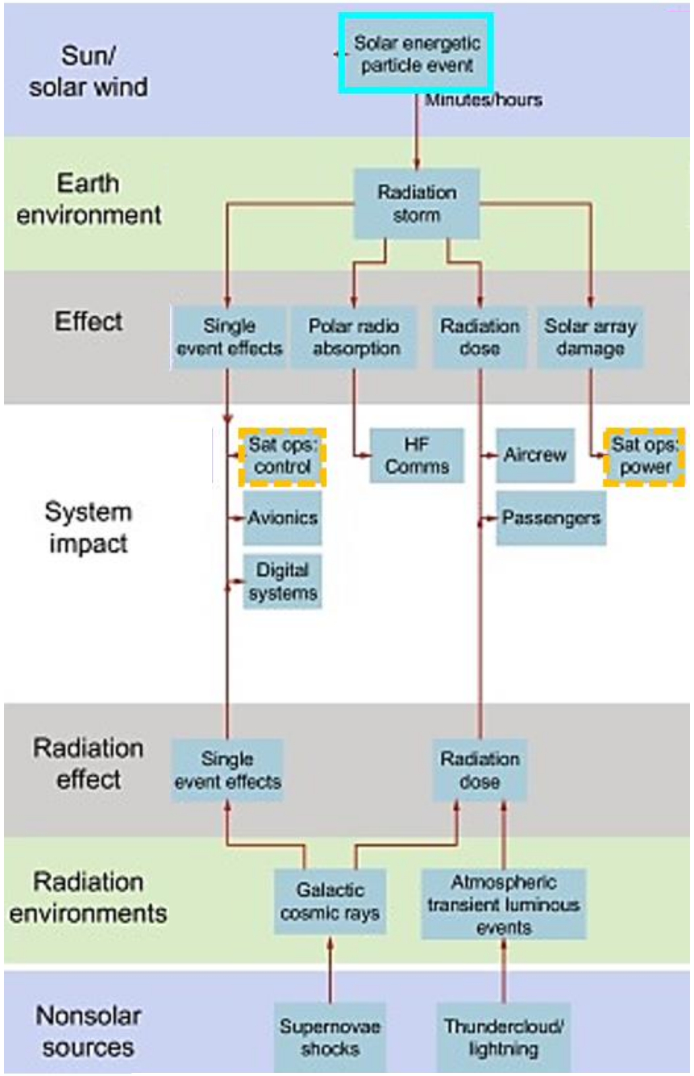
EGNOS: European Geostationary Navigation Overlay Service ; SXR: soft x-ray ; EUV: extreme ultraviolet ; TEC: Total electron content ; SBAS: Satellite Based Augmentation System

GNSS impacts from solar flares

- From SXR/EUV emission
  - Impact threshold
    - ~ X5
      - f(duration)
  - Frequency occurrence
    - ~ 2/year
    - Effects
      - Short-duration
      - Only sunlit side



GNSS impacts from SEP events

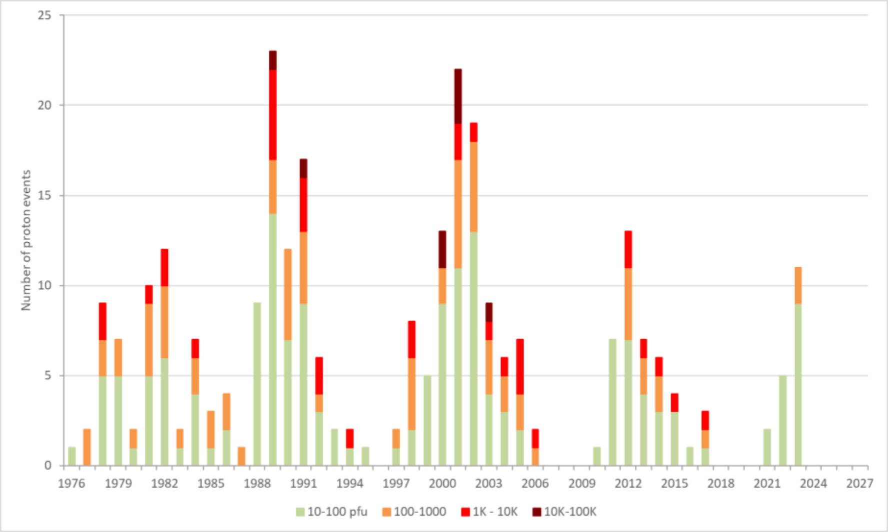


- From SEP events
  - Single event effects
    - *Ground Level Enhancement (GLE)*
  - Polar Cap Absorption
    - Deviated by MF to poles
    - Affects D-region
    - Impacts HF Com at poles
  - Radiation
    - Biological component
  - Solar array damage
- Non-solar sources
  - *Supernovae (GCR)*
  - *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

GNSS impacts from SEP events

- Single Event Effects (SEE)
  - Direct hit of an electronic component by an energetic particle resulting in an anomaly
    - Phantom commands, attitude control systems, satellite failure,…
  - Several variations
    - SEU (bit flip), SEL, SEB,…
  - Frequency
    - SEP events (≥ 10 MeV): ~ 6 / year
      - Influence GCR
    - GLE events: ~ 1 / year
      - SEPs ~500 MeV / nucleon
      - Software glitches, medical devices,…
    - 1972 event or worse:
      - ~ 1 / 30 years



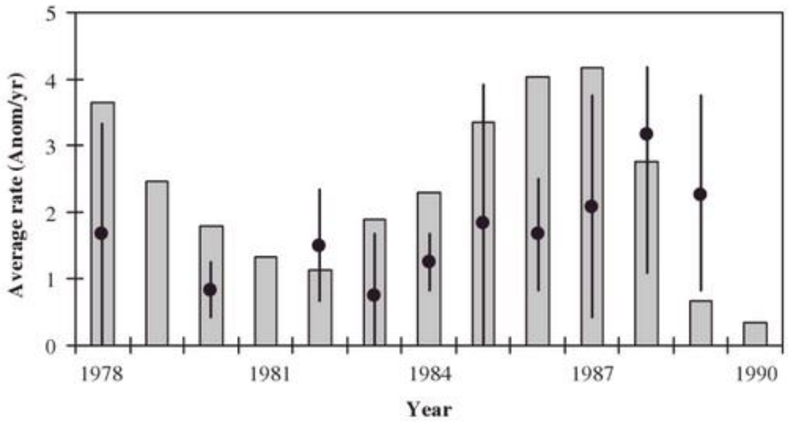


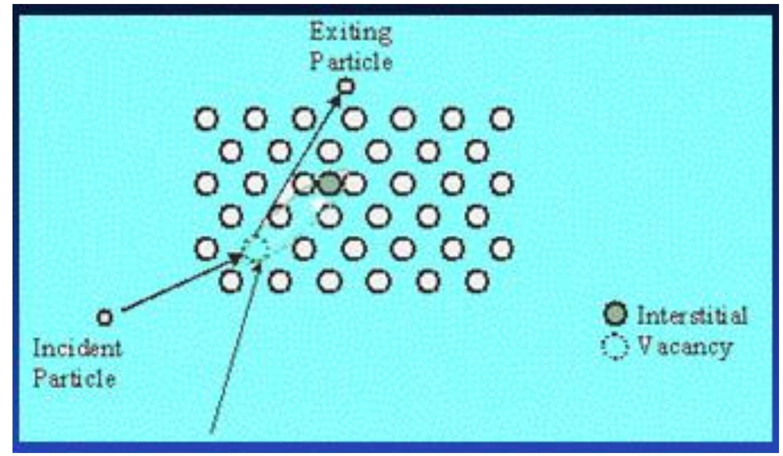
Fig. 2.5. Satellite anomaly rates for satellites in geosynchronous Earth orbit listed in the NGDC anomaly archive. The reference histogram is the annual cosmic ray flux at climax, re-scaled to show phase. (From Odenwald, 2009.)

Credits: Odenwald 2013

SEP: Solar Energetic Particles ; GLE: Ground Level Enhancement ; GCR: Galactic Cosmic Rays ; NGDC: National Geophysical Data Center ; SEU: Single Event Upset ; SEL: Single Event Latchups ; Single Event Burnout

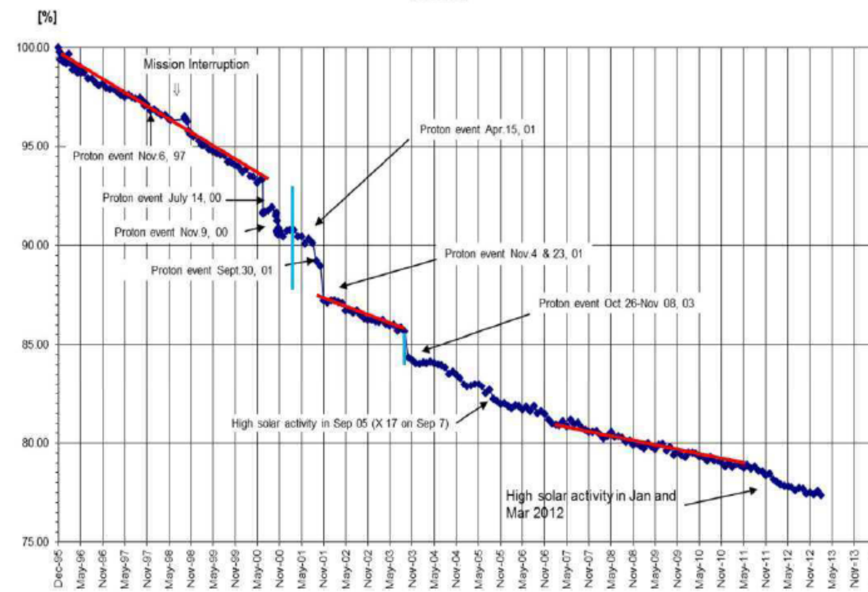
GNSS impacts from SEP events

- Solar array damage
  - Displacement damage
  - Reduces efficiency in electricity production
  - Several % loss from one proton event is possible
    - 2% loss during Bastille Day event (14 July 00)
    - 5% loss during extreme 4 August 1972 event
- Overall aging process of satellite and its instruments
  - Galactic Cosmic Rays



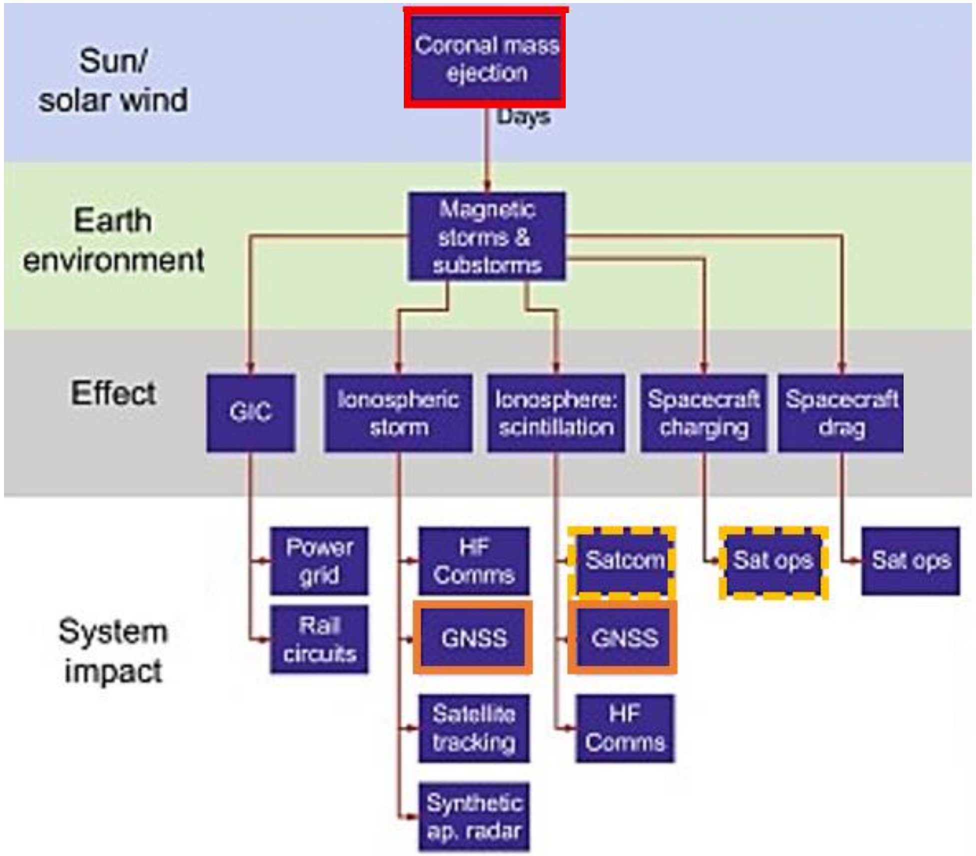
Credits: Valtonen 2004

SOHO Solar Array Degradation, based on the average of the two section currents (PISW1 and PISW2)



Credits: Curdt et al. 2015

GNSS impacts from ICMEs

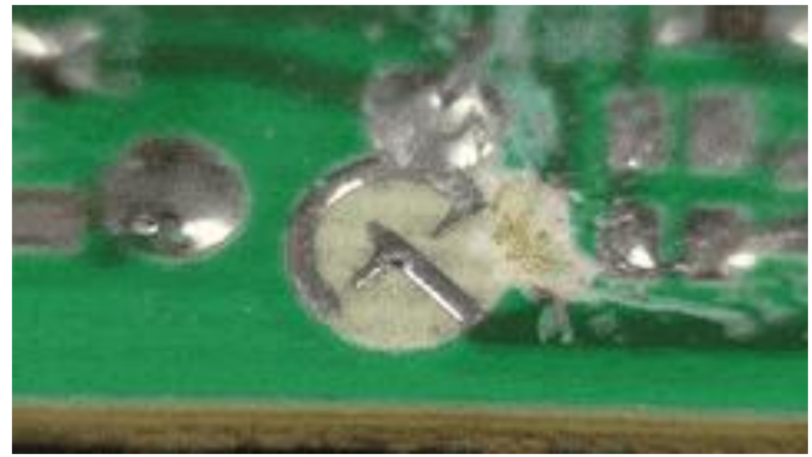


- From magnetic field
  - Satellites
    - Magnetopause crossings
  - High-Precision industry
  - GCR: Forbush decrease
- From particles
  - Satellites
    - Drag
    - Charging effects
    - Satellite-based Comms/Nav applications (GNSS)
  - HF Communication (aviation)
  - Geomagnetically Induced Currents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

GCR: Galactic Cosmic Rays ; Comms/Nav: Communications/Navigation ; PECASUS: Partnership for Excellence in Civil Aviation Space weather User Services ; HF: High Frequency ; (I)CME: (Interplanetary) Coronal Mass Ejection

GNSS impacts from ICMEs

- Charging effects
  - Surface charging
    - Low energy plasma
      - ~10-50 keV electrons
    - Substorm related
      - SWPC: likely if K $\geq$ 6
    - Electrostatic discharge (ESD)
      - Surface damage
      - Phantom commands
  - Internal charging
    - ~100s keV electrons
    - Galaxy 15 outage in April 2010
  - Accumulation effect



Credits: eevblog.com

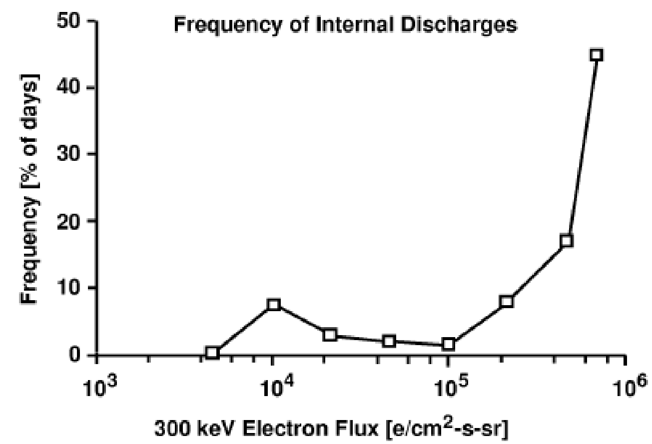
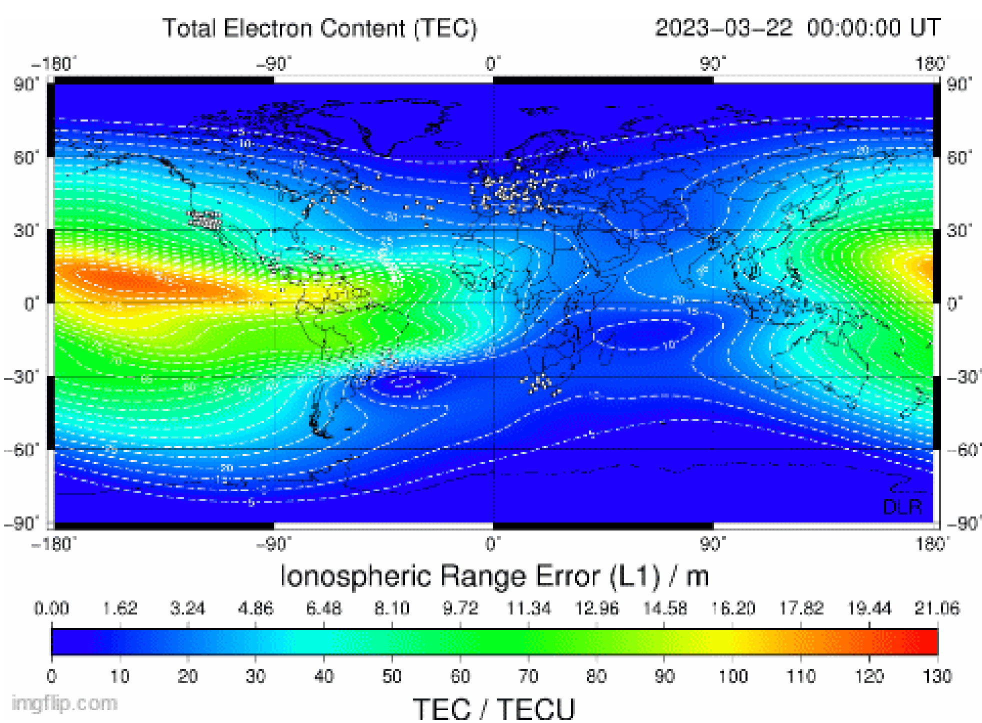


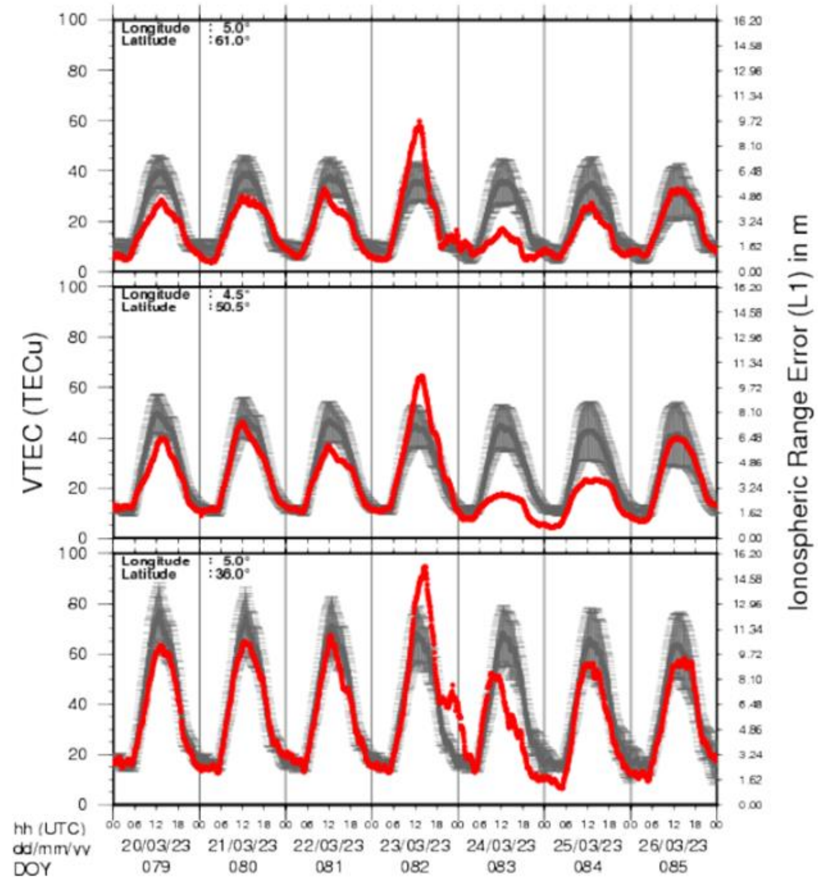
Figure 11. Comparison of SCATHA anomalies with energetic electron fluxes.

Credits: Fennell et al. (2001)

GNSS impacts from ICMEs

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



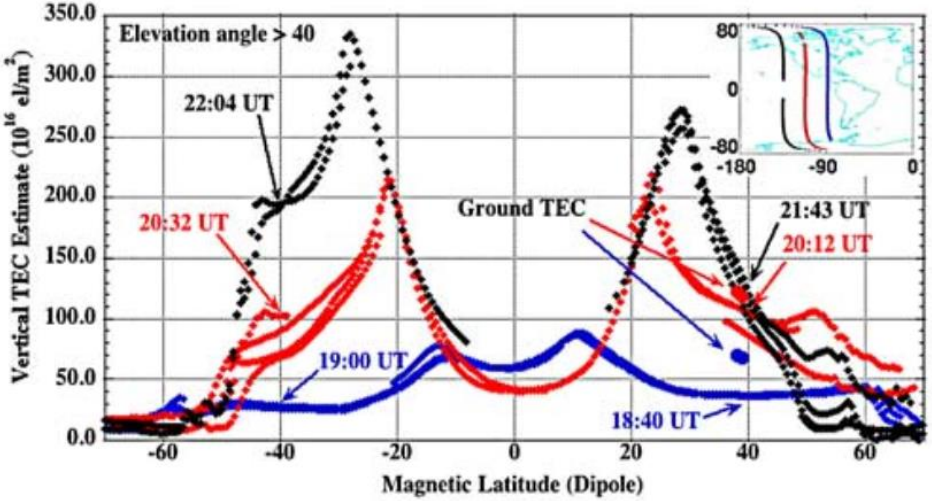


Credits images: PECASUS & DLR/IMPC

Credits: ROB/GNSS

GNSS impacts from ICMEs

- Ionospheric storm
  - VTEC based
    - Local values
  - Geomagnetic storms in March and April 2023
    - $VTEC_{max}$ ~170 TECu ; Dst resp. -163 nT and -212 nT



Credits: Mannucci et al. 2005

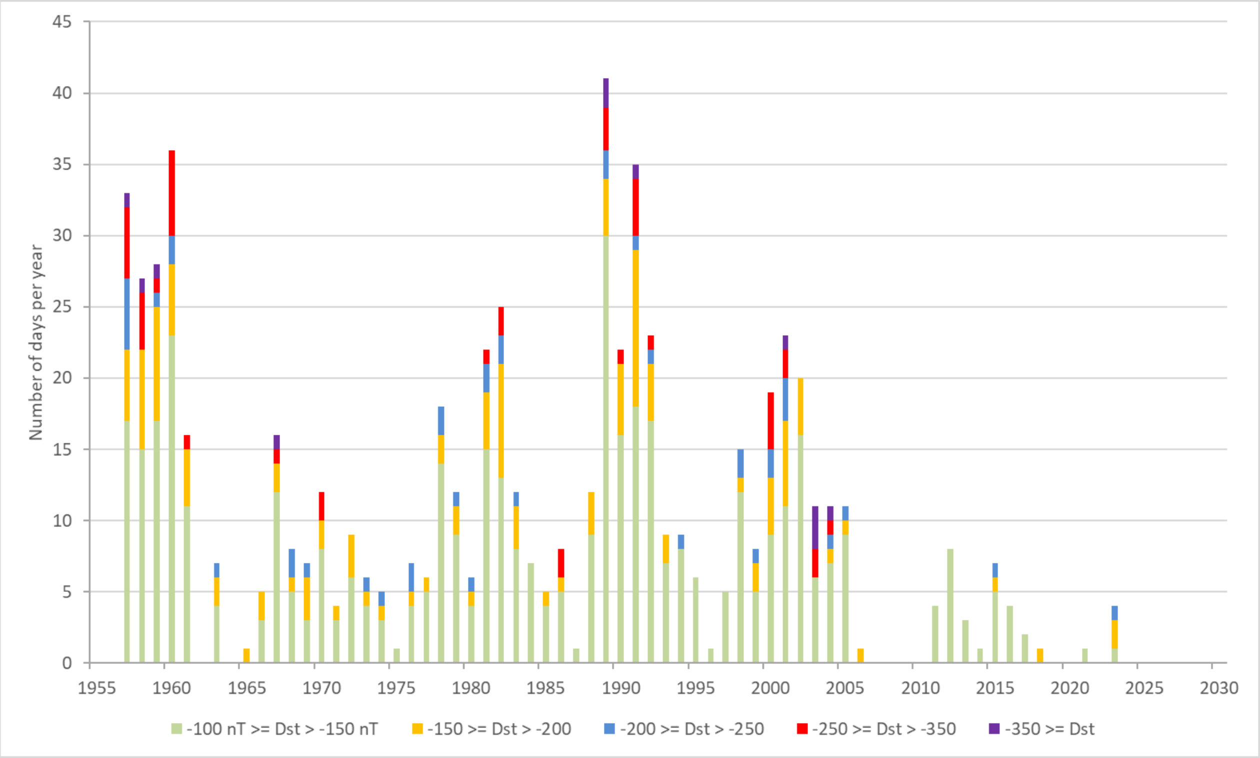
 30 October 2003 – Kp = 9o – Dst = -383 nT

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

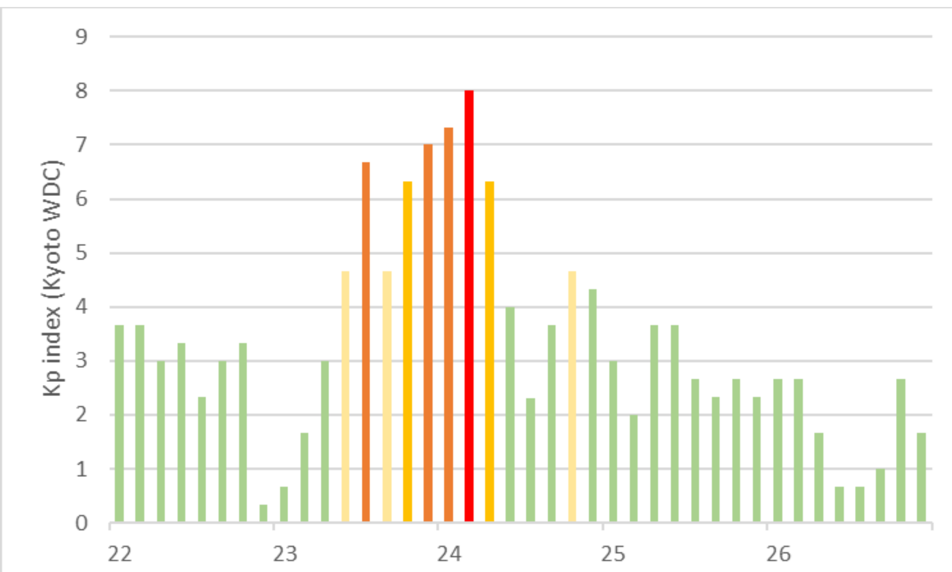
GNSS impacts from ICMEs

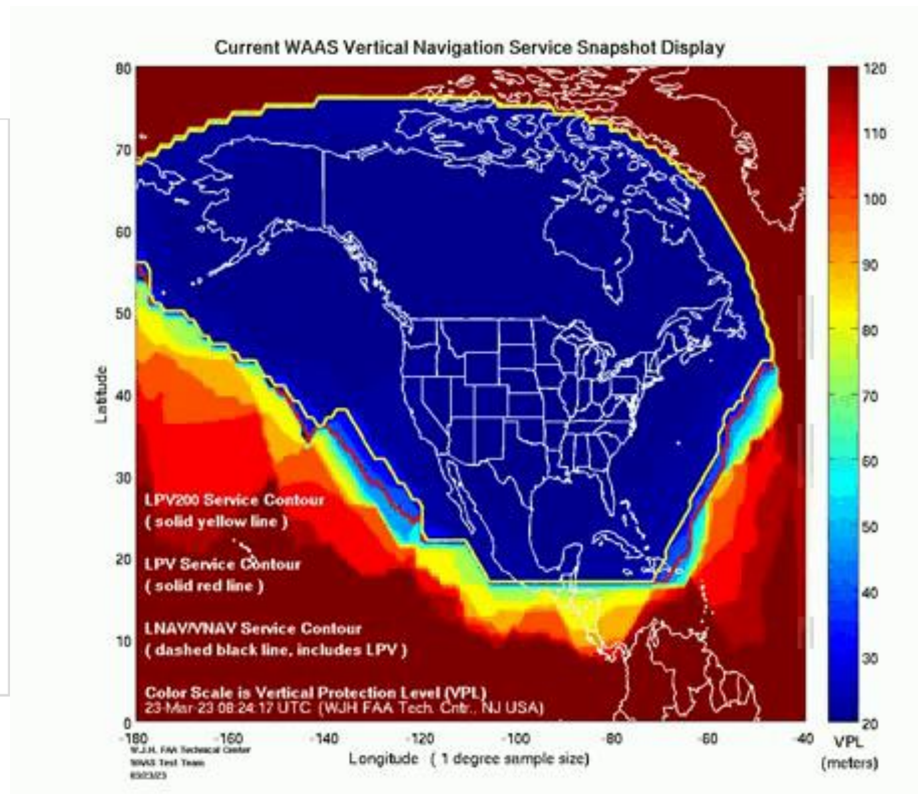
- Severe ionospheric storm frequency
  - Dst ≤ -200 nT: 1.4 days / year ; 16 days / SC
  - Dst ≤ -250 nT: 0.8 days / year ; 9 days / SC
    - But none since 2005…



GNSS impacts from ICMEs

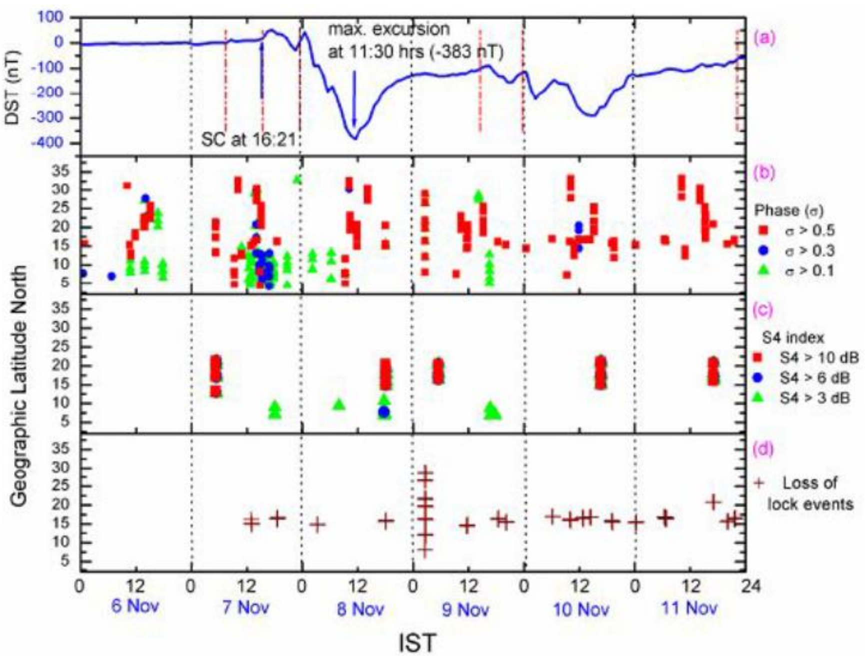
- Ionospheric scintillations
  - Example: 23-24 March 2023
    - Kp = 8o ; Dst = -163 nT



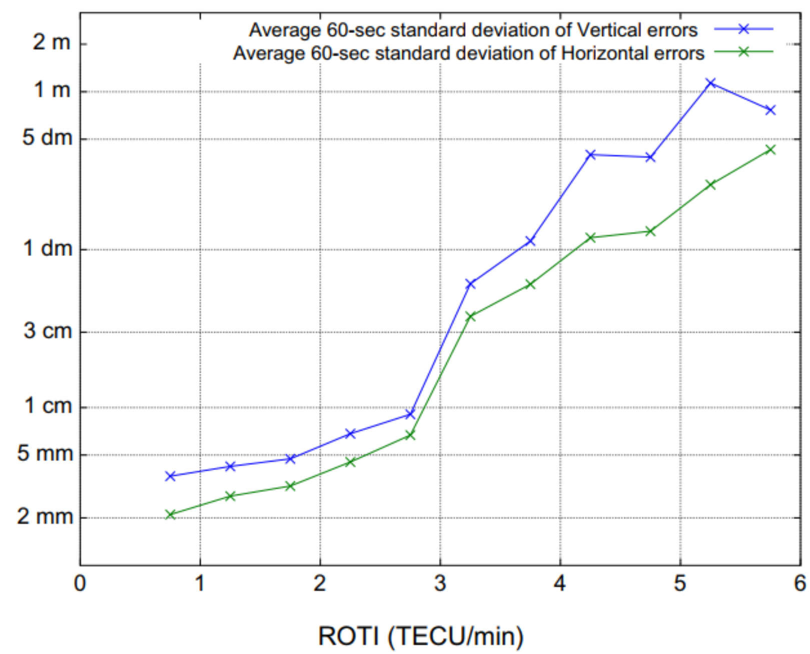


GNSS impacts from ICMEs

- Ionospheric scintillations
  - 8 November 2004
    - Kp=9o ; Dst=-374 nT
  - 24-25 October 2011
    - Kp=7+ ; Dst=-147 nT



Credits: Rama Rao et al. 2009

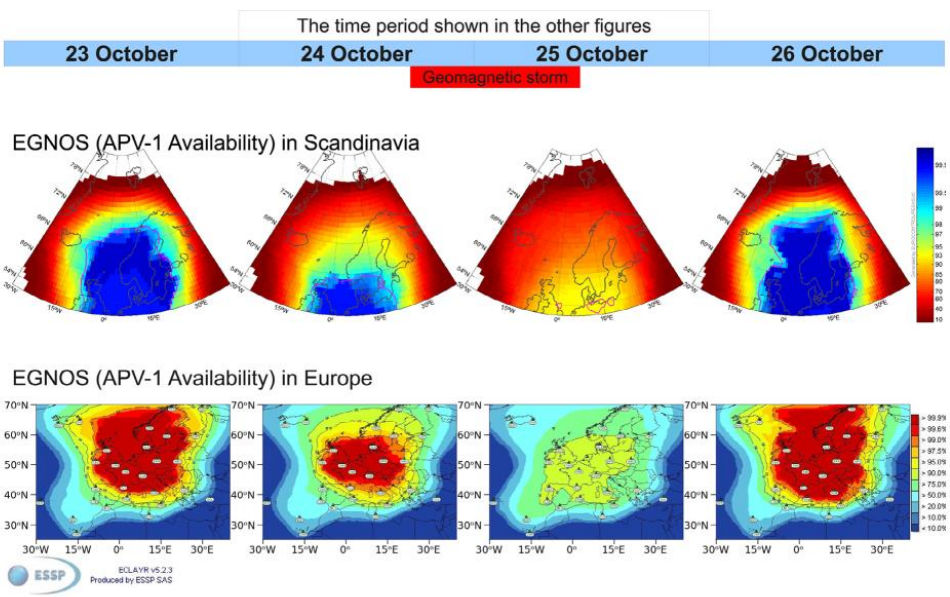


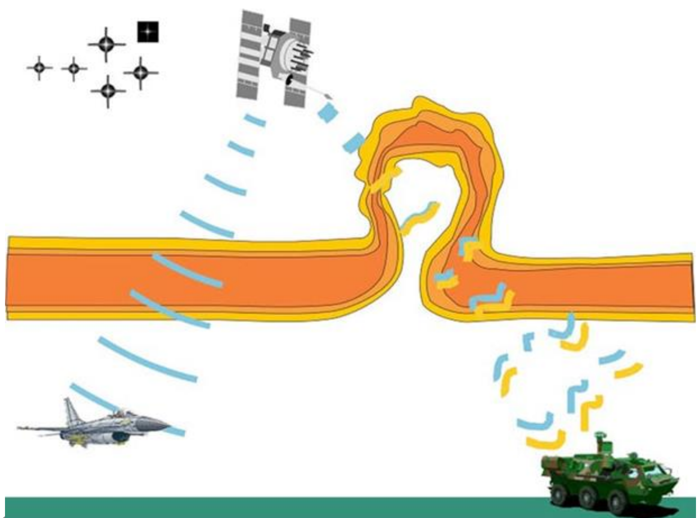
Credits: Jacobsen et al. 2012

GNSS impacts from ICMEs

- Ionospheric scintillations
  - Reminder
    - Also when geomagnetic activity is quite low
      - Battle of Takur Ghar!
        - Satcom (2002)
  - 24-25 October 2011
    - Kp=7+ ; Dst=-147 nT

EGNOS: European Geostationary Navigation Overlay Service ;
APV: APproach with Vertical guidance

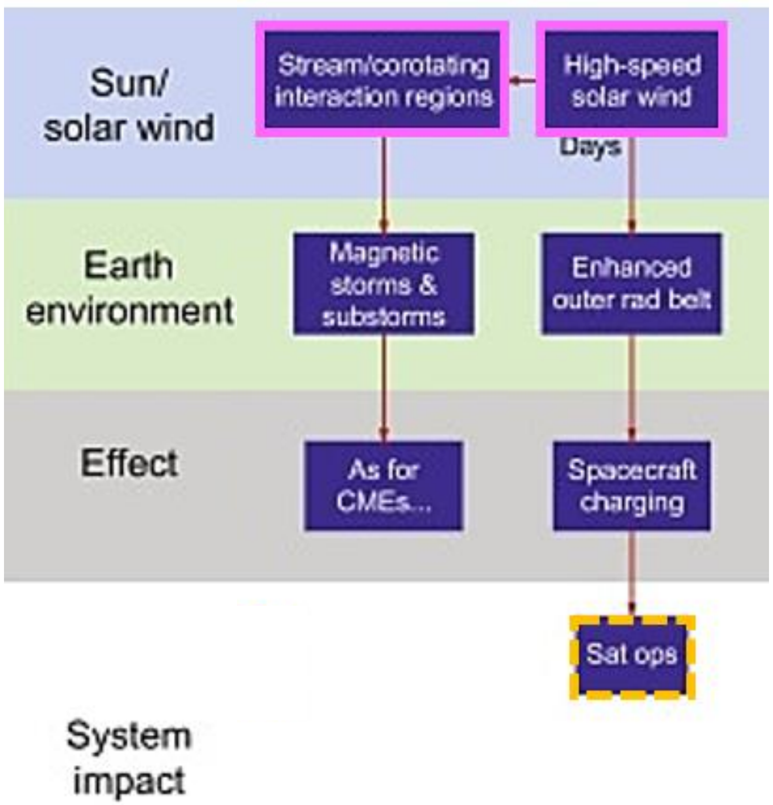




Credits: US Air Force Research Laboratory

Credits: Jacobsen et al. 2012

GNSS impacts from CH HSS

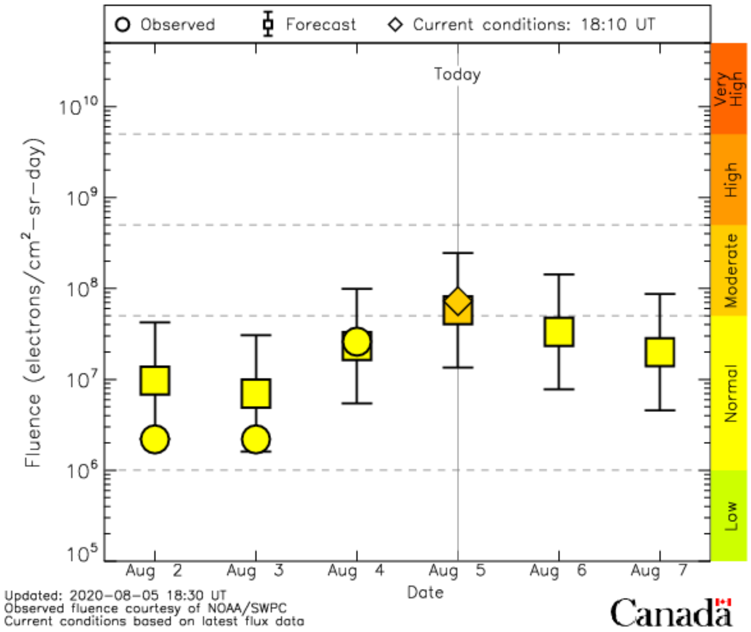


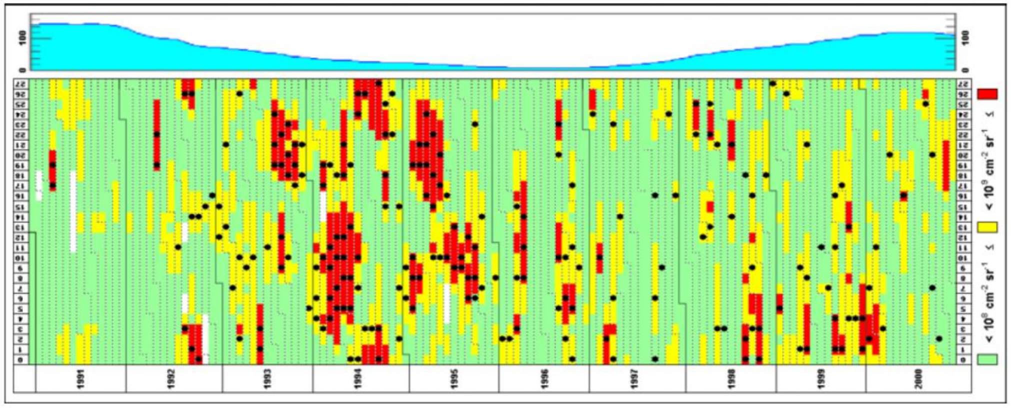
- Similar to effects from ICMEs but less intense
- except…
- From particles
  - Satellites
    - Deep di-electric charging

CH: coronal hole ; HSS: high speed stream ; (I)CME: (Interplanetary) Coronal Mass Ejection ; Sat ops: satellite operations

GNSS impacts from CH HSS

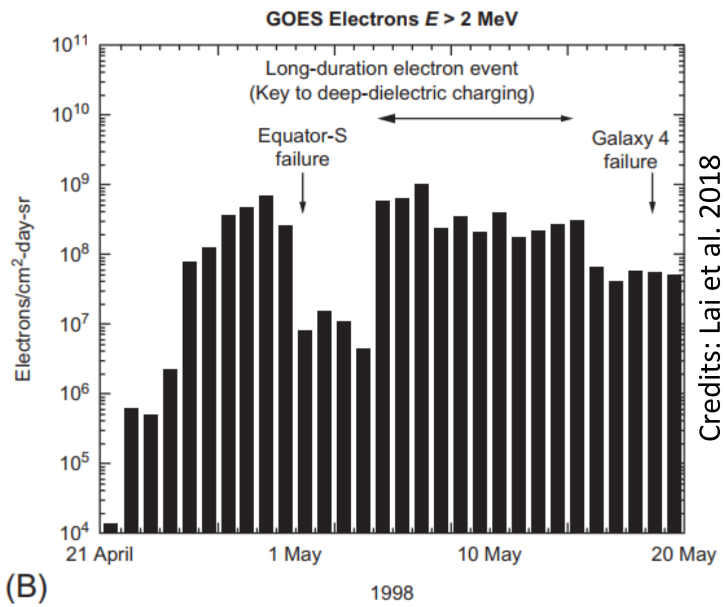
- High-Speed Stream (HSS)
  - Satellite charging
    - Deep di-electric charging
      - About 1 to few MeV e^-
        - Deeply penetrate spacecraft (S/C)
      - Fluxes $\geq$ 2 MeV e^-
        - Accumulation effect within S/C (ESD)
      - Due to day-night effect
        - Fluence (24h)
    - Declining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



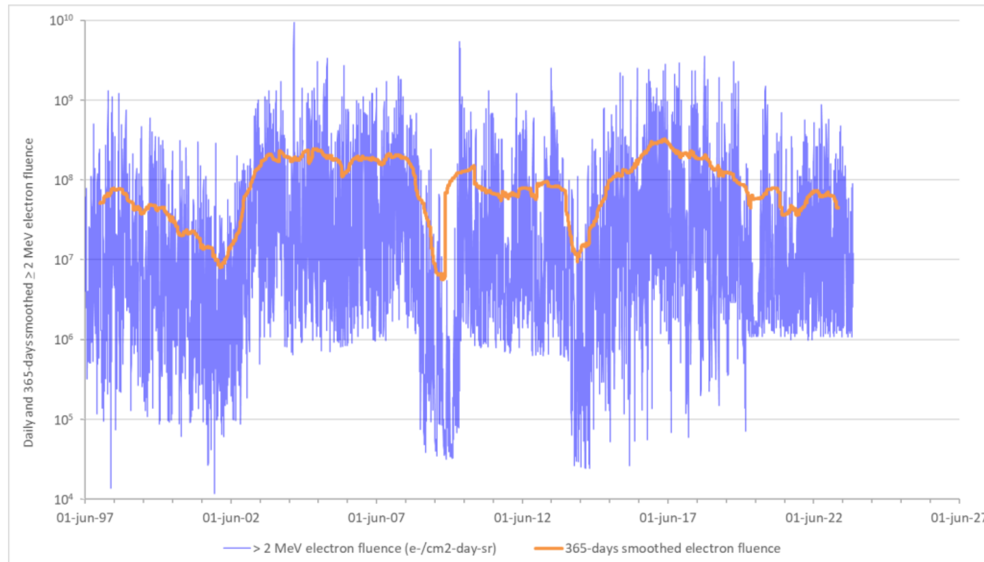


#ESDs on a GEO communications satellite
Credits: Wrenn et al. (2002)

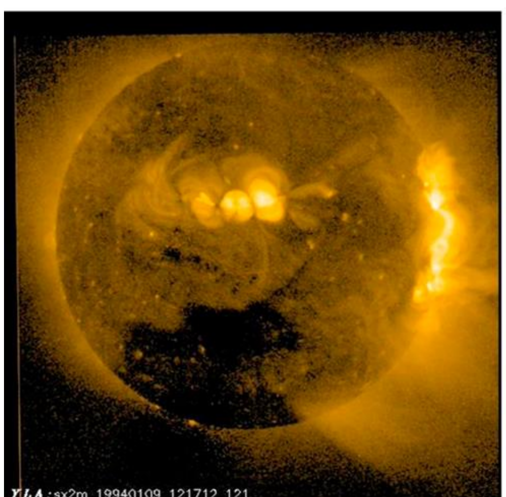
GNSS impacts from CH HSS

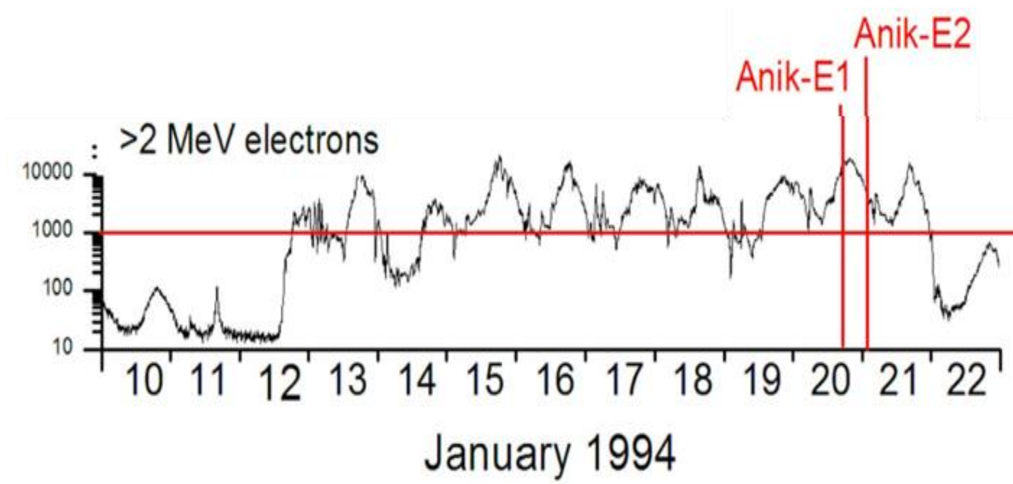


Credits: Lai et al. 2018



Frequency High fluence: ~18 days / year





Credits: Lam et al. 2012

Summary

- GNSS applications impacted by extreme SWx:
  - Solar flares
    - Solar radio bursts
  - Geomagnetic storms (ICMEs)
    - Ionospheric storms
    - Ionospheric scintillations
- GNSS satellite fleet may suffer from:
  - Charging effects
  - Solar energetic particle events
  - Deep di-electric charging
  - …