SWEC
Space Weather Education Center

Role of the ionosphere and space weather in military communications

16-18 March 2026

Royal Observatory of Belgium

Solar Influences Data analysis Centre
www.sidc.be

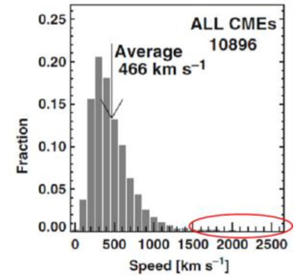
Image credits: ESA / J. Huart
https://www.esa.int/ESA_Multimedia/Images/2000/09/Galileo_satellite_system

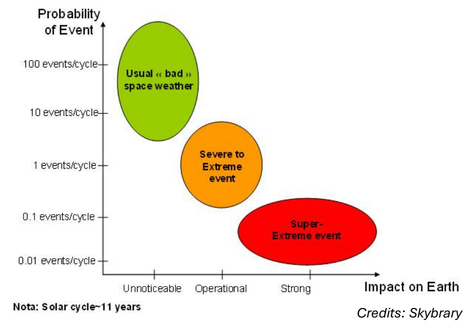
Contents

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

What is an extreme event?

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





Credits: Skybrary

Annotated figures credits:
Gopalswamy, 2010: Coronal Mass Ejections: a Summary of Recent Results
https://ui.adsabs.harvard.edu/abs/2010nspm.conf..108G/abstract
The definition of an extreme event is not very concrete, but can be thought of as an event on the tail of a distribution. An extreme event can also be thought of as an occurrence that has unique characteristics in its origin and/or in its consequences. ... We are interested in extreme events both in their origins at the Sun and their consequences and space weather effects.

A graph of solar cycles can be found at SILSO:
https://www.sidc.be/SILSO/monthlyssnplot

Skybrary: https://skybrary.aero/articles/impact-space-weather-aviation

Data for GNSS and GNSS impacts is limited:
GPS: Globally available since 1994 ; 32 satellites
WAAS since 2003
Galileo: operational since 2016 ; 24 satellites
EGNOS since 2009
24 satellites is a minimum for global GNSS coverage

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	*216.0 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	*253.9 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*	233	182	76	*101*
Strongest proton event (> 10 MeV; in pfu)	2900 13 Jul 1982	*43000 24 Mar 1991*	31700 6 Nov 2001	6530 8 Mar 2012	*37000 19 Jan 2026*
Number of proton events (> 10 MeV)	59	73	*94*	42	*44*
Number of Ground Level Enhancements (GLE)	13	15	*16*	2	*5*
Number of days with Kp ≥ 8-	42	42	*43*	9	*17*
Strongest Dst (in nT)	-325 14 Jul 1982	*-589 13-14 Mar 1989*	-422 20 Nov 2003	-234 17 Mar 2015	*-406 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

Data updated until 9 March 2026. Data sources:

- SILSO: WDC for the International Sunspot Number Brussels: https://www.sidc.be/SILSO/home
- Solar Cycle Science: http://solarcyclescience.com/index.html
- WDC for geomagnetism Kyoto: https://wdc.kugi.kyoto-u.ac.jp/index.html
- GeoForschungsZentrum (GFZ) Potsdam: https://kp.gfz-potsdam.de/en/data
- University of Oulu: https://gle.oulu.fi/#/
- NOAA/SWPC: ftp://ftp.swpc.noaa.gov/pub/indices/SPE.txt
- Penticton, Canada: https://www.spaceweather.gc.ca/forecast-prevision/solar-solaire/solarflux/sx-5-mavg-en.php
- NOAA/NGDC: ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-flares/x-rays/goes/
- NOAA/SWPC Weekly bulletins: ftp://ftp.swpc.noaa.gov/pub/warehouse/

• Note the flare values from GOES-1 thru -15 (SC21 thru ~SC24) have been corrected i.a.w. guidelines by NGDC/NOAA at https://www.ngdc.noaa.gov/stp/satellite/goes/index.html

• For SC25, there have been 5 GLEs: the first 4 were rather weak GLEs on 28 Oct 2021, 11 May 2024, 8 Jun 2024 and 21 Nov 2024. However, the 5th was a strong GLE on 11 November 2025.

Note that the STIX instrument on board of Solar Orbiter may have recorded several stronger flares during this solar cycle, however they occured on the far side of the Sun. Examples are 20 May 2024 (X12 - https://www.stce.be/news/712/welcome.html), and on 22 July 2024 (X14 - https://www.stce.be/news/716/welcome.html).

What is an extreme event?

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

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

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

6

Summary based on
Cliver et al. 2022: Extreme solar events - https://doi.org/10.1007/s41116-022-00033-8 (Table 10)
And Gopalswamy 2018: Extreme solar eruptions and their space weather consequences - https://doi.org/10.1016/B978-0-12-812700-1.00002-9 (Table 2)
The modelled Dst extremum of -2500 nT is from Vasyliunas 2011 (https://doi.org/10.1016/j.jastp.2010.05.012) : The largest imaginable magnetic storm.

Events related to the observed extrema (Column 2): Sunspot area: 8 April 1947 (Greenwich #1488603) ; GOES flare SXR (corrected*): 4 November 2003 (NOAA 10486) ; 1.5 GHz radio emission: 6 December 2006 (NOAA 10930) ; >30 MeV fluence: August 1972 event ; >200 MeV fluence: 23 February 1956 ; CME speed: 10 November 2004 (NOAA 10696) ; ICME transit: 4 August 1972 (Greenwich #2317900) ; Dst: based on the 2 September 1859, 4 February 1872 and 15 May 1921 geomagnetic storms which all 3 had minimum Dst values around -950 nT.

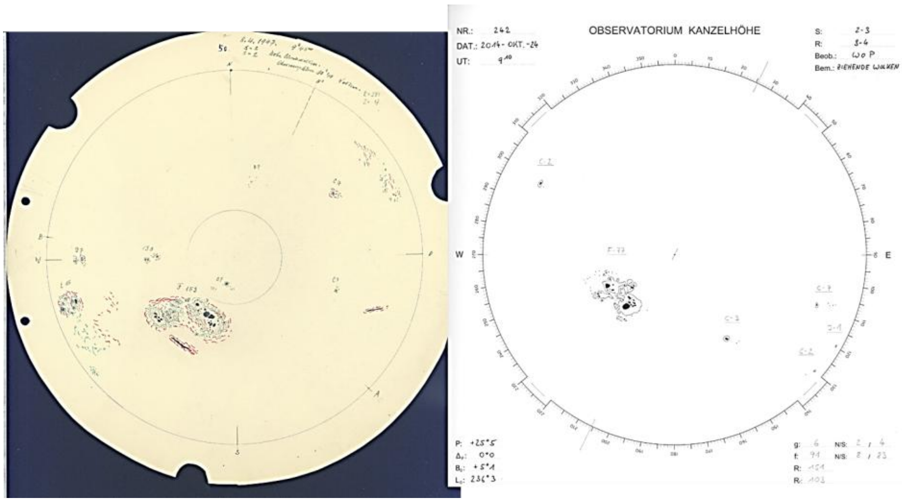
Power law distributions in general appear to yield overestimates.

* Note the flare values from GOES-1 thru -15 (SC21 thru ~SC24) have been corrected i.a.w. guidelines by NGDC/NOAA at https://www.ngdc.noaa.gov/stp/satellite/goes/index.html The X28 flare of 4 November 2003 thus turns out to be X40 . The Cliver et al. (2022) statistics also take these corrections into account.

Strong radio bursts at 1.5 GHz during this and previous solar cycle are discussed in this STCE Newsitem at https://www.stce.be/news/644/welcome.html

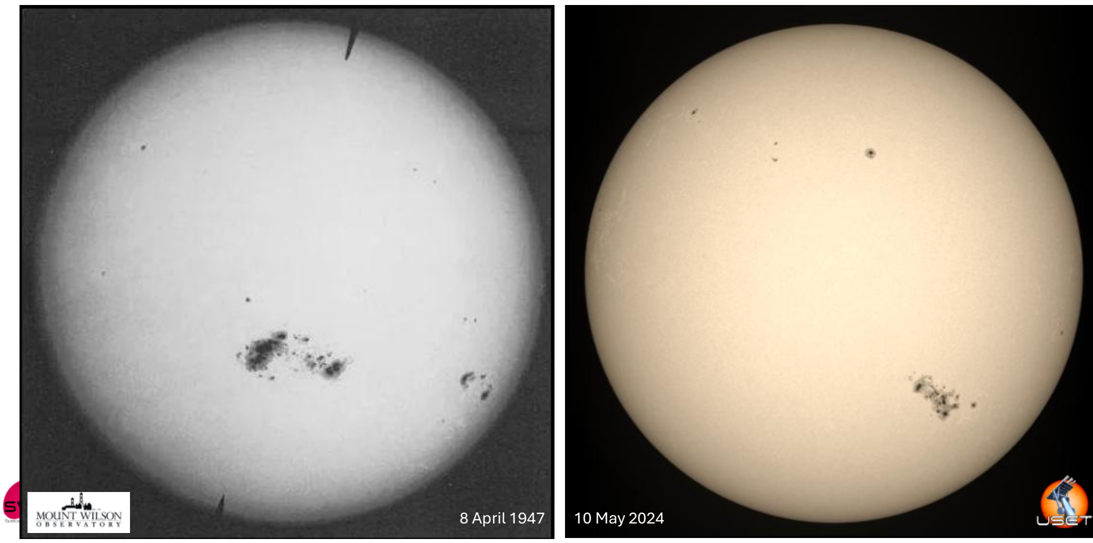
For SC25, the maximum observed values so far are as follows: NOAA 13664 (3360 MH) in May 2024; X9.0 on 3 October 2024; RBR at GNSS frequencies of 230.000 sfu 28 August 2022, 98.000 sfu on 13 Jun 2022; Fastest CME: 31 Dec 2023 (2427 km/s) from AR3536 (X5.0 flare) ; Fastest ICME transit time: 25h 18-19 January 2026; Dst: -406 nT on 11 May 2024.

Largest sunspot groups in SC18 and SC24



Largest sunspot groups on 8 April 1947 (Greenwich #1488603; Kanelhöhe Observatory) and 24 Oct 2014 (NOAA 12192) with areas of resp. 6132 MH and 3850 MH. The latter value has been corrected for the Greenwich-to-NOAA transition (see the Solar Cycle Science webpage at http://solarcyclescience.com/activeregions.html). For SC25, NOAA 3664 is the largest sunspot group so far (3360 MH corrected) – See this STCE newsitem at https://www.stce.be/news/704/welcome.html

Largest sunspot groups in SC18 and SC25



Largest sunspot groups on 8 April 1947 (Greenwich #1488603; photographed at Mount Wilson) and 10 May 2024 (NOAA 13664; photographed at SIDC/USET) with areas of resp. 6132 MH and 3360 MH. The latter value has been corrected for the Greenwich-to-NOAA transition (see the Solar Cycle Science webpage at http://solarcyclescience.com/activeregions.html). These values correspond to resp. 36 and 20 times the surface area of the Earth! For SC25, NOAA 13664 is the largest sunspot group so far – See this STCE newsitem at https://www.stce.be/news/704/welcome.html

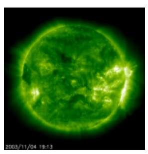
Drivers of disturbed space weather

Solar eruptions → Magnetic Reconnection → Radiation → Solar flares

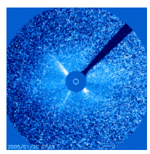
Solar eruptions → Magnetic Reconnection → Particles → Proton events, Coronal Mass Ejections

Solar corona → Solar wind → Particles → Coronal Holes

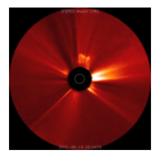
Solar flares



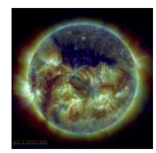
Proton events



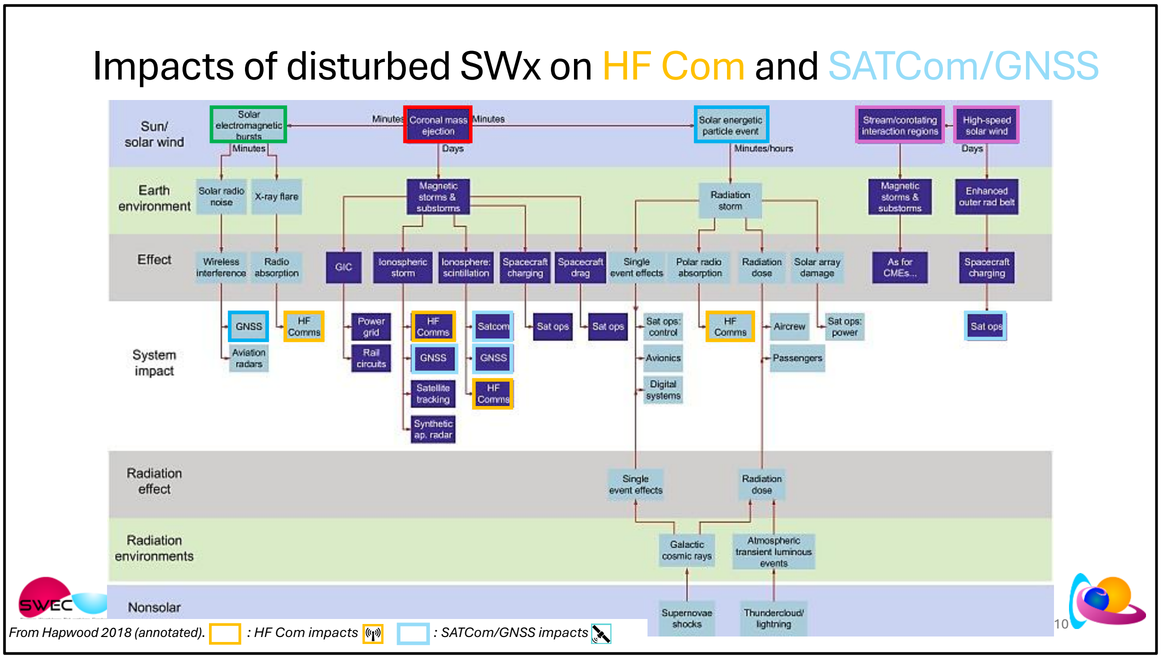
Coronal Mass Ejections



Coronal Holes



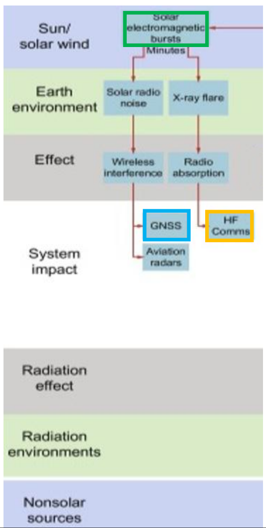
9



Annotated from Hapgood, M. 2018. Linking Space Weather Science to Impacts - The View From the Earth https://doi.org/10.1016/B978-0-12-812700-1.00001-7 (Figure 1)

Important –mostly ionospheric related- impacts on HFCom and SATCom are indicated in in resp. orange and light blue.

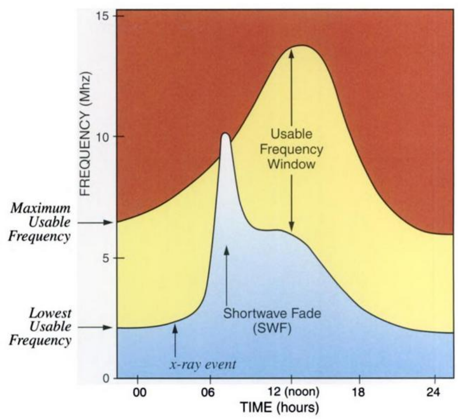
Impacts from solar flares



- 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

Note there’s also a non-solar source of highly energetic electromagnetic radiation that may affect the ionosphere (and VLF signals in particular): Gamma-Ray Bursts (GRB). See e.g. https://www.stce.be/news/610/welcome.html

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

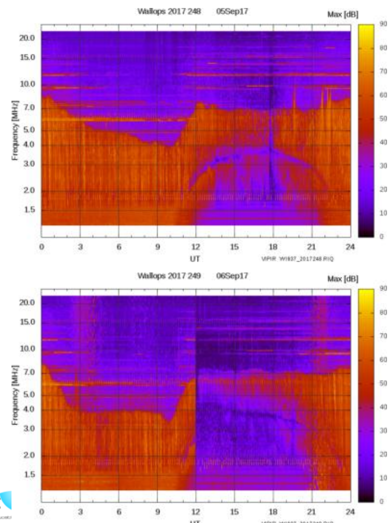
12

Tao et al. (2020): Statistical analysis of short-wave fadeout for extreme space weather event estimation
https://earth-planets-space.springeropen.com/articles/10.1186/s40623-020-01278-z

Figure source: B. Poppe (2006): Sentinels of the Sun (pp. 33) - https://books.google.be/books?id=WMh4REf3iZQC
Also at https://commons.wikimedia.org/wiki/File:ShortWaveFadeNOAA.png and NOAA: https://data.noaa.gov/onestop/collections/details/cdff1523-e9a9-4ab3-9eac-a80f2cdc5984

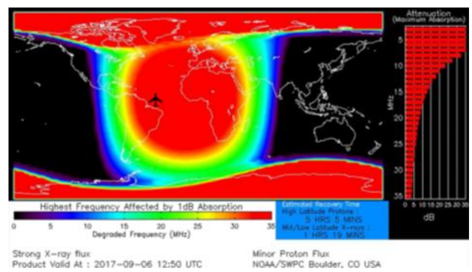
What happens to the MUF and LUF when a strong solar flare occurs?
- The usage frequency window for radio propagation lies between the lowest and maximum usable frequencies, i.e. LUF and MUF. When the window closes, as shown here, a shortwave fade occurs.
- The MUF depends on critical ionospheric frequency (foF2) and the angle of incidence of the radio wave. The LUF is determined by the amount of absorption in the D- and E-region. Then the LUF can only be used by increasing the frequency.
If the frequency is increased above the MUF, so when it will not even get reflected by the F2-layer (or still gets absorbed by the D/E region) then no HF communication is possible. This is called a short-wave fade (misleadingly also known as a radio blackout, because other radiofrequencies are not affected by the SXR effects, or may even be enhanced (e.g. VLF communication: Kumar et al. (2018) – DOI: https://doi.org/10.1186/s40623-018-0794-8 ; Hayes et al. (2021) – DOI: https://doi.org/10.1007/s11207-021-01898-y).

Impacts from solar flares on HF Com



Courtesy of CIRES, Terry Bullett

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



13

Redmon et al. (2018) - September 2017's Geoeffective Space Weather and Impacts to Caribbean Radio Communications During Hurricane Response
DOI: https://doi.org/10.1029/2018SW001897

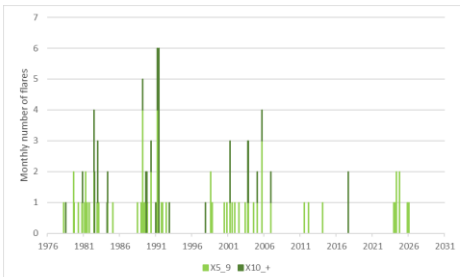
As Caribbean communities were responding to the 2017 hurricane season, the evolving active region AR12673 erupted several times releasing X-class solar flares on 6, 7, and 10 September … Rapid and comprehensive ionization of the equatorial upper atmosphere occurred, disrupting HF communications while emergency managers were struggling to provide critical recovery services (e.g., NCEI, 2017). Issues were reported by the Hurricane Weather Net (HWN), and the French Civil Aviation Authority (DGAC).

Several news stories from the American Radio Relay League (ARRL) convey the Caribbean radio operator perspective well. A few key excerpts are integrated here. Regarding the X9.3 flare on 6 September, ARRL captures HWN manager Bobby Graves perspective: "In addition to the mix of three hurricanes, the HWN has been hassled by a series of solar flares — one a massive Class X-9.3, said to be the most powerful flare in more than a decade. 'This solar flare caused a near-total communications blackout for most of the morning and early afternoon,' Graves recounted" (ARRL, 2017a). In consideration of the X8.2 flare on 10 September, he further implores via ARRL: "As if Earth's weather was not bad enough already, an X-class solar flare severely disrupted HF communication on Sunday at around 1600 UTC. Graves said the widespread communication blackout lasted for nearly 3 hours, 'which could not have happened at a worse time'" (ARRL, 2017b). In addition to issues experienced by ground operators, shortly after the September X9.3 solar flare, "French Civil Aviation authorities reported that HF radio contact was lost with one non-Controller Pilot Data Link Communications (CPDLC) equipped aircraft off the coasts of Brazil and French Guyana for approximately 90 minutes, triggering an alert phase until a position report was received by New York radio" (French Civil Aviation Authority to SWPC; Rutledge & Desbios, 2018).

See also STCE news items at http://www.stce.be/news/402/welcome.html and http://www.stce.be/news/400/welcome.html
Some of the SWx effects are at https://phys.org/news/2017-09-massive-sunspots-huge-solar-flares.html ; https://phys.org/news/2017-10-september-intense-solar-viewed-space.html ; http://www.independent.co.uk/news/world/americas/irma-hurricane-solar-flare-weather-communications-satellite-sun-x-class-orbital-earth-a7932821.html ; http://www.telegraph.co.uk/news/2017/09/09/solar-flare-energy-billion-hydrogen-bombs-lights-british-skies/ ;

Imagery from https://www.ncei.noaa.gov/news/large-solar-event-detected-during-irma

Impacts from solar flares on HF Com



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

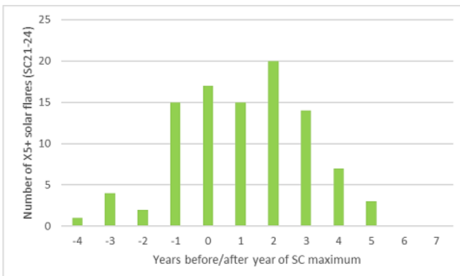
SWF: Short-Wave Fade; h: hour; dB: decibel; SZA: Solar Zentih Angle; MHz: megahertz; SC: solar cycle; HF Com: High Frequency Communication

14

Values are from Janssens et al. (2025 - https://doi.org/10.1051/swsc/2025007): Solar flare rates and probabilities based on the McIntosh classification: Impacts of GOES/XRS rescaling and revisited sunspot classifications , with updates for SC25 from the STCE SC25 tracking page at https://www.stce.be/content/sc25-tracking

230.000 sfu RBR : https://www.swsc-journal.org/articles/swsc/full_html/2023/01/swsc230040/swsc230040.html
Saturation effects: Giersch

Impacts from solar flares on HF Com



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

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)

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

15

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

Information on Sudden Ionospheric Disturbances (1958-2014) can be found at https://www.ngdc.noaa.gov/stp/solar/sid.html and https://www.aavso.org/solar
Classification of SID/SWF (i.a.w. duration) is at https://www.ngdc.noaa.gov/stp/solar/sid.html

Tao et al. (2020): Statistical analysis of short-wave fadeout for extreme space weather event estimation
https://earth-planets-space.springeropen.com/articles/10.1186/s40623-020-01278-z

In the complete blackout case, the durations are 38 min, 1.8 h, 4.0 h, and 7.4 h, respectively. In the once per 1000 years case, the duration becomes 11.9 h for dfmin ≥ 2.5 MHz and 11.5 h for dfmin ≥ 3.5 MHz. The extreme points, 8 h 15 min for dfmin ≥ 2.5 MHz and 5 h 15 min for dfmin ≥ 3.5 MHz, are associated with continuous flares X17 and X1.2, which occurred within 6 h with gradual decay on April 3, 2001 … ***This suggests that frequent explosions of long-duration flares provide long-term SWFs***. It is reported that a typical duration of compound X-class flare-driven SWF events can be much longer than that of events driven by isolated X-class flares, which is suggested to be the result of an extended ionospheric relaxation time due to a slow recovery of D-region electron temperature after large perturbations (Chakraborty et al. 2019 and references therein).

[Note the graph and values are for one location in Japan, for the period 1981-2019.]

A ratio can be expressed as a level in *decibels* by evaluating ten times the base-10 logarithm of the ***ratio*** of the measured quantity to reference value. Example: a signal that is 100 times more intense than a reference signal is said to differ from that reference level by 20 dB.

Impacts from solar flares on SatCom/GNSS

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

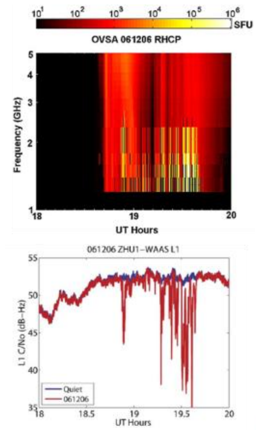


Figure 2. Response of a GPS receiver to the solar radio burst on 6 December 2006. The red line corresponds to C/N_0 on 6 December 2006, and the blue line corresponds to the previous sidereal day.

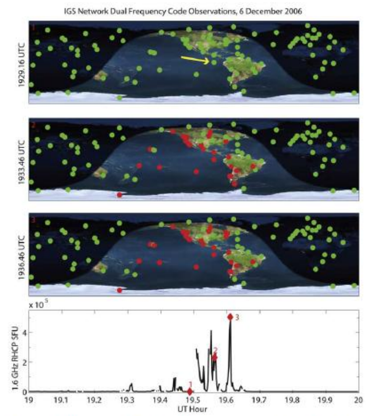


Figure 6. Receivers in the Global GPS Network that were analyzed during the solar radio burst. Green indicates the normal number of satellites being tracked. (fourth panel) During the burst (power at 1.6 GHz), several sunlit receivers tracked fewer than the four satellites needed for a full positioning solution (marked in red). (Image of Earth from the The Living Earth, 1996 and is used here by permission of the publisher. Day/night overlay created using Earth Viewer by J. Walker.)

Credits: Cerruti et al. (2008)

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

Figures and text taken from:
Cerruti et al. (2008): Effect of intense December 2006 solar radio bursts on GPS receivers
https://ui.adsabs.harvard.edu/abs/2008SpWea...610D07C/abstract
On 6 December 2006, an X6 flare generated a solar radio burst with measured powers of 1,000,000 SFU RHCP [Right Hand Circularly Polarized] at 1.4 GHz, and lesser levels of 650,000 and 500,000 SFU at 1.2 and 1.6 GHz, respectively. This solar radio burst had significant effects on GPS receivers over the entire sunlit hemisphere of Earth.
Solar radio bursts during December 2006 were sufficiently intense to be measurable with GPS receivers. The strongest event occurred on 6 December 2006 and affected the operation of many GPS receivers. This event exceeded 1,000,000 solar flux unit (SFU) and was about 10 times larger than any previously reported event.
Prior to the events of December 2006, the record solar burst near the GPS frequencies, according to reports collected by the National Oceanic and Atmospheric Administration (NOAA), was 165,000 SFU at 1415 MHz for a SRB in April 1973. Second place was 88,000 SFU at 1415 MHz in February 1979.
The strength of the event was especially surprising since the solar radio bursts occurred near solar minimum. The strongest periods of solar radio burst activity lasted a few minutes to a few tens of minutes and, in some cases, exhibited large intensity differences between L1 (1575.42 MHz) and L2 (1227.60 MHz).
Civilian dual frequency GPS receivers were the most severely affected, and these events suggest that continuous, precise positioning services should account for solar radio bursts in their operational plans.
This investigation raises the possibility of even more intense solar radio bursts during the next solar maximum that will significantly impact the operation of GPS receivers.
The receiver indicated by the yellow arrow is located on the Galapagos Islands. It was the receiver closest to the subsolar point at that time.
The 6 December event marks the first time a SRB was detected on the FAA (Federal Aviation Administration) WAAS. Although the effects of this SRB were less intense on WAAS than on other operational systems, mainly because of the robust system design, it is important to consider the potential impact of future, more powerful, solar radio bursts during periods of high solar activity.
.../...

Impacts from solar flares on SatCom/GNSS

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

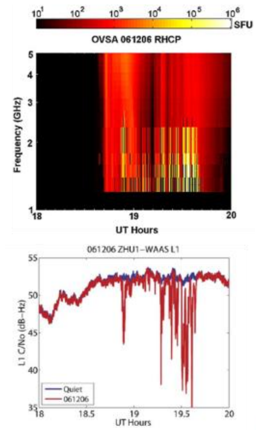


Figure 2. Response of a GPS receiver to the solar radio burst on 6 December 2006. The red line corresponds to C/N_0 on 6 December 2006, and the blue line corresponds to the previous sidereal day.

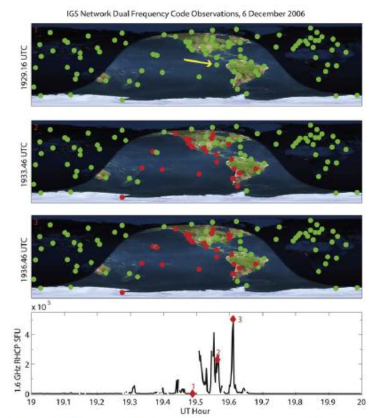


Figure 6. Receivers in the Global GPS Network that were analyzed during the solar radio burst. Green indicates the normal number of satellites being tracked (fourth panel) During the burst (power at 1.6 GHz), several sunlit receivers tracked fewer than the four satellites needed for a full positioning solution (marked in red). (Image of Earth from the The Living Earth, 1996 and is used here by permission of the publisher. Day/night overlay created using Earth Viewer by J. Walker.)

Credits: Cerruti et al. (2008)

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

Figures and text taken from:
Cerruti et al. (2008): Effect of intense December 2006 solar radio bursts on GPS receivers
https://ui.adsabs.harvard.edu/abs/2008SpWea...610D07C/abstract
... / ...

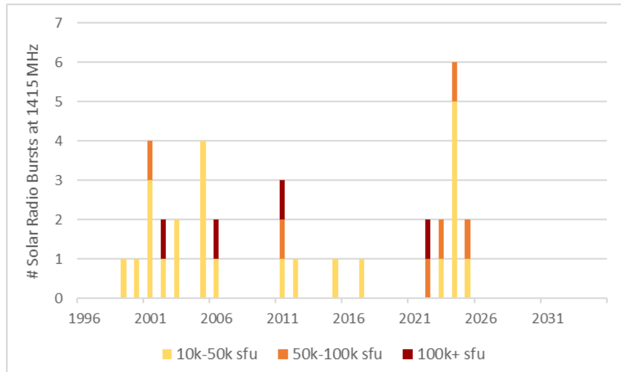
For the original scientific purpose of long-term geodetic monitoring, solar radio bursts have a negligible impact because they are short-lived (tens of minutes) compared to the timescales over which geodetic changes are being monitored. Data loss, even though worldwide, has minimal implications to geodetic science. However, these same receivers have been adapted for other uses, including a few critical real-time applications that rely on round-the-clock 24/7 availability of the GPS signals (an example is the positioning of offshore oil rigs discussed in section 3.3). These high-precision real-time positioning applications require that users receive dual frequency corrections to their GPS signals within a few seconds of real time. Global positioning accuracies of 10–20 cm have been demonstrated with such systems. The real-time and latency standards are required to compensate for clock errors in the GPS satellites. If the data latency is beyond a few seconds, the GPS clocks will have drifted sufficiently that users cannot make the corrections needed to meet the 10–20 cm requirement. Therefore, continuous high-rate data from the network are essential for real-time global differential positioning systems.

The burst impact was detected in real time (within 1 s) by the Global Differential GPS (GDGPS) system operated by NASA's Jet Propulsion Laboratory (JPL). Tracking was interrupted for many receivers that generate real-time corrections for users. The GDGPS corrections for satellites within the SRB affected service volume were unavailable for several minutes. The SRB not only affected individual receivers but prevented GDGPS from generating corrections for certain satellites. GDGPS computes corrections to the GPS satellite orbits and clocks on a continuous basis at a cadence of 1 Hz. The corrections are sent to users to improve on the direct GPS signals they acquire on their own receivers. The wide footprint of the SRB, affecting all sunlit receivers, caused certain satellites to be so poorly observed by the global network that the clock corrections could not be computed for those GPS satellites for several minutes. Automated integrity checking within the system caused a loss of corrections for users tracking certain GPS satellites. Without corrections to sufficient satellites in view, positioning accuracy for users degraded or was not even possible using the system. ... During the event, NASA/JPL's GDGPS system detected anomalous conditions, although the cause was not immediately known. Some users were immediately notified. It was later discovered that certain users were significantly affected. Significant economic impact would have resulted had the burst lasted longer, since users would have been required to operate in standby mode and suspend certain operations.

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

Impacts from solar flares on SatCom/GNSS

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



Based on reports from the NOAA/USAF network

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

Yue et al. , 2018 - The Effect of Solar Radio Bursts on GNSS Signals https://doi.org/10.1016/B978-0-12-812700-1.00022-4 (Figure 2)
SRBs will mainly affect the stations located in the sunlit hemisphere during radio flux enhancement, while the influence strength depends on the solar incidence angle, antenna pattern, tracking algorithm, and some other factors. ... The SRB occurrence does not really depend on the intensity of solar flares. The threshold value SRB flux that could result in visible effect on GNSS signals is believed to be between 1000 and 10.000 sfu in the L-band. During 2003-12, there were 8 SRB events that showed degrading effects on GNSS signals in the literature, which is 8.8 per solar cycle. ... Significant SRBs could occur during solar minimum.

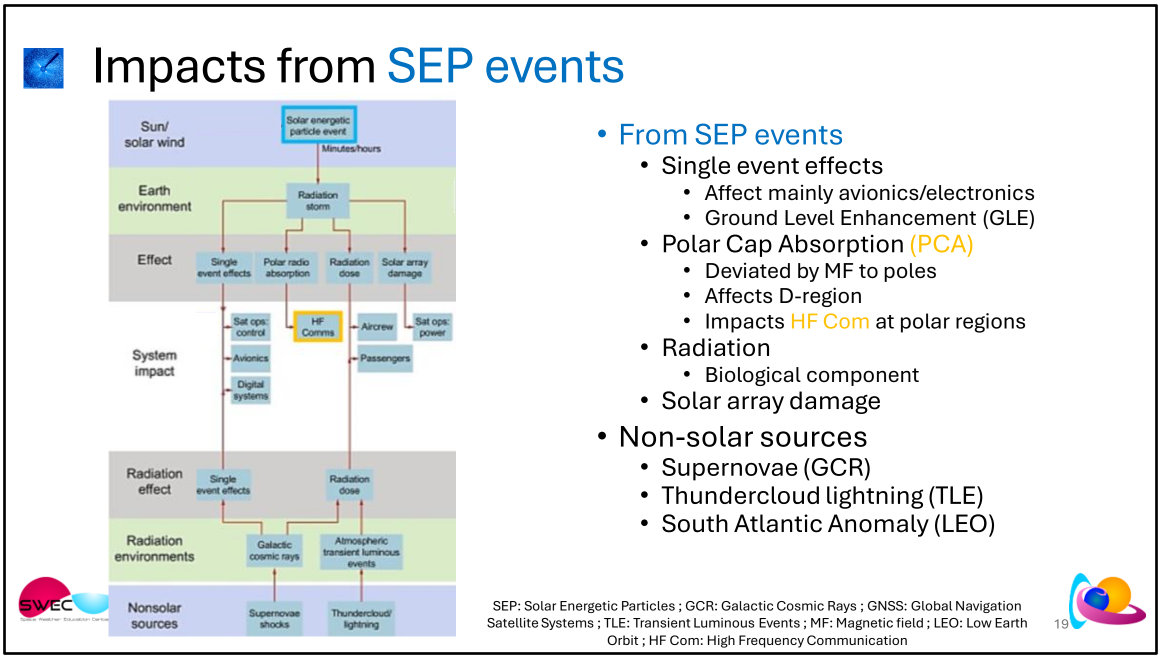
Wright et al. (2023 - https://doi.org/10.1051/swsc/2023027): Estimates of the lower bound of the strength of an SRB required to affect L1 GNSS signals vary from 40,000 SFU (Klobuchar et al., 1999) to 10,000 SFU (Demyanov et al., 2012).

Please note that the intensities of the various radio frequencies as observed by USAF's Radio Solar Telescope Network (RSTN) are saturated at different values. For the observed frequency at 1415 MHz , this saturation level is at 100.000 sfu (Giersch et al. 2017 - https://doi.org/10.1002/2017SW001658)

There have been 3 strong radio emission events (at GNSS frequencies) so far this solar cycle: Effects from the 14 December 2023 radio burst (99.000 pfu), as well as from the strong bursts on 28 August 2022 (230.000 sfu, but saturation effects?) and on 13 June 2022 (98.000 sfu by San Vito (Italy) at 1415 MHz; 64.000 sfu by Nobeyama (Japan) at 1 GHz) are thought to be much smaller and of much shorter duration than the 2006 event, and are currently being scrutinized. See this STCE newsitem at https://www.stce.be/news/644/welcome.html

The 28 August 2022 burst has been discussed by Wright et al. (2023 - https://doi.org/10.1051/swsc/2023027): On the detection of a solar radio burst event that occurred on 28 August 2022 and its effect on GNSS signals as observed by ionospheric scintillation monitors distributed over the American sector.

Another event that took place over the American sector was the one from 14 December 2023, discussed by De Abreu (2025 - https://doi.org/10.1016/j.asr.2025.07.045): Effects of X2.8-class solar flare on the ionosphere occurred during the recovery phase of a geomagnetic storm over South American and Antarctic sectors

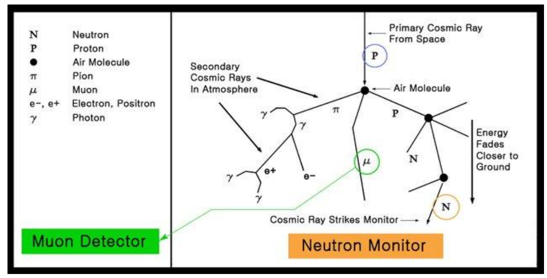


Non-solar sources

- Supernovae and Black Hole activity contribute to the Galactic Cosmis Rays (GCR), a continuous low flux of highly energetic particles (think several GeV) that penetrates into the solar system. The effects are similar to the ordinary SEP events. The stream is solar cycle modulated, with the highest numbers of GCR during the solar cycle minimum and during weak solar cycles. See https://www.stce.be/content/sc25-tracking#cosmicrays for an example graph and https://www.stce.be/news/433/welcome.html for more information. See also the SPENVIS page at https://www.spenvis.oma.be/help/background/gcr/gcr.html
- Severe thundercloud lighning may sometimes be accompanied by Transient Luminous Events (TLE) , such as Blue Jets, Sprites, Elves,… It has been shown these TLEs may cause some ionospheric scintillation. See e.g. https://commons.erau.edu/cgi/viewcontent.cgi?article=1028&context=db-srs
- The South Atlantic Anomaly is an extension of Earth’s inner radiation belt that is getting closer to the Earth surface. It affects only satellites in Low Earth Orbits (LEO).

SWx impacts from SEP 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 — — — · **Currently NOT covered by SWx advisories for ICAO**

Sketch from Oh and Kang (2013 - DOI: 10.5140/JASS.2013.30.3.175)

Thakur et al. (2014): Ground Level Enhancement in the 2014 January 6 Solar Energetic Particle Event
https://ui.adsabs.harvard.edu/abs/2014ApJ...790L..13T/abstract
Solar energetic particle (SEP) events, where particles accelerated to GeV energies are subsequently detected on the ground as a result of the air-shower process, are known as ground level enhancements (GLEs). With a typical detection rate of a dozen GLEs per cycle, an average of 16.3% SEP events were GLEs in cycles 19–23 (Cliver et al. 1982; Cliver 2006; Shea & Smart 2008; Mewaldt et al. 2012; Nitta et al. 2012; Gopalswamy et al. 2012a). In cycle 24, this fraction is much smaller (6.4%) with 2 GLEs out of 31 large SEP events (Gopalswamy et al. 2014). This is also much smaller than the ratio of 18% obtained when the first five years of cycle 23 are considered. GLEs are typically associated with intense flares (median soft X-ray intensity ~X3.8) and fast coronal mass ejections (CMEs; average CME speed ~2000 km s−1; see Gopalswamy et al. 2012a).

Upsets in major computing facilities correlate with altitude and, since a major server suffered significant outages and caused economic losses, certain server technologies have been tested in neutron radiation facilities [*lyons*, 2000]. In light of this evidence, safety-critical ground systems such as those in nuclear power stations should consider the impact of superstorm radiation at ground level within its electronic system reliability - and safety assessments. In the case of nuclear power a Carrington event may not be a sufficient case since relevant timescales for risk assessment may be as long as 10,000 years.

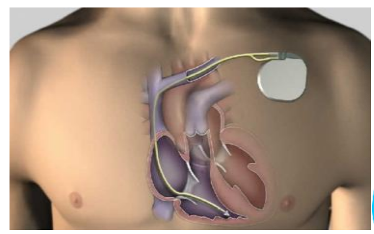
10.4 GNSS - summary and recommendations

Assuming that the satellites – or enough of them – survive the impact of high energy particles, we anticipate that a solar superstorm will render GNSS partially or completely inoperable for between one and three days. The outage period will be dependent on the service requirements. For critical timing infrastructure, it is important that holdover oscillators be deployed capable of maintaining the requisite performance for these periods. UK networked communications appear to meet this requirement.
With current forecast skills, it is inevitable that aircraft will be flying and ships will be in transit when the superstorm initiated. Aircraft use differential and augmented systems for navigation and in the future possibly for landing. With these applications set to increase, the potential for significant impact from an extreme space weather event will likewise increase. Fortunately, the aviation industry is highly safety conscious and standard operating procedures appropriate to other emergency situations are likely to provide sufficient mitigation to an extreme space weather event. These include other terrestrially based navigation systems. The challenge will be to maintain those strategies over the long term as GNSS become further bedded into operations.

- Pacemaker incident
BBC: https://www.bbc.com/future/article/20221011-how-space-weather-causes-computer-errors
- Bradley et al. (1998): Single Event Upsets in Implantable Cardioverter Defibrillators
http://cardiacos.net/wp-content/uploads/ArticulosMedicos/20170707/1994---Single-Event-Upsets-in-Implantable-Cardioverter-Defibrillators.pdf
Also at http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/29/003/29003514.pdf
- Normand (2013): Single Event Upset at Ground Level
https://web.archive.org/web/20131021190327/http://pdf.yuri.se/files/art/2.pdf

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:

Currently NOT covered by SWx advisories for ICAO

Qantas Flight 72 – https://www.engineeringpilot.com/post/single-event-effects-the-achilles-heel-of-modern-aerospace-electronics ;

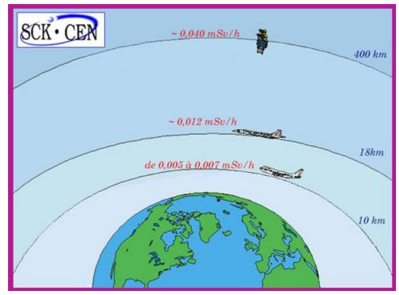
From the incident investigation report (https://www.atsb.gov.au/publications/investigation_reports/2008/aair/ao-2008-070 ; https://reports.aviation-safety.net/2008/20081007-0_A333_VH-QPA.pdf):

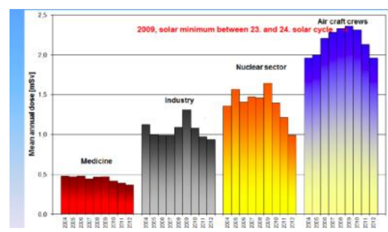
At 0132 Universal Time Coordinated (0932 local time) on 7 October 2008, an Airbus A330-303 aircraft, registered VH-QPA and operated as Qantas flight 72, departed Singapore on a scheduled passenger transport service to Perth, Western Australia. ... At 0442:27, the aircraft suddenly pitched nose down. The FCPCs commanded the pitch-down in response to AOA data spikes from ADIRU 1. Although the pitch-down command lasted less than 2 seconds, the resulting forces were sufficient for almost all the unrestrained occupants to be thrown to the aircraft's ceiling. At least 110 of the 303 passengers and nine of the 12 crew members were injured; 12 of the occupants were seriously injured and another 39 received hospital medical treatment. The FCPCs commanded a second, less severe pitch-down at 0445:08.
The flight crew's responses to the emergency were timely and appropriate. Due to the serious injuries and their assessment that there was potential for further pitch-downs, the crew diverted the flight to Learmonth, Western Australia and declared a MAYDAY to air traffic control. The aircraft landed as soon as operationally practicable at 0532, and medical assistance was provided to the injured occupants soon after. ...
The in-flight upset on 7 October 2008 occurred due to the combination of a design limitation in the flight control primary computer (FCPC) software of the Airbus A330/A340, and a failure mode affecting one of the aircraft's three air data inertial reference units (ADIRUs). The design limitation meant that, in a very rare and specific situation, multiple spikes in angle of attack (AOA) data from one of the ADIRUs could result in the FCPCs commanding the aircraft to pitch down. ... The other trigger type considered by the investigation was a single event effect (SEE). Although the intensity of high-energy particles was not unusual at the time of the three data-spike occurrences, such particles are always present. ... It would seem very unlikely that an SEE could occur at the same location within the
same unit, and produce the same effect, without also occurring on many other units of the same type. However, susceptibility to SEE can vary significantly between components with the same part number, and there may have been more than one location that could produce the same effect from an SEE. In addition, having a particle strike in the same area on the same unit is conceivable given the level of exposure to high-energy particles that occurs at cruise altitudes.
Overall, the probability that the failure mode was triggered by SEE could not be reliably estimated without knowing the exact mechanism involved in the failure mode, or by demonstrating that the failure mode could occur during testing of the affected units. It was unfortunately not practicable for the investigation to test the units at an appropriate facility.
In summary, the investigation had sufficient evidence to conclude that most of the potential types of triggers were probably not associated with the data-spike failure mode. However, there was insufficient evidence available to determine whether SEE could have triggered the failure mode.

Pacemaker incident: Baraniuk 2022 - https://www.bbc.com/future/article/20221011-how-space-weather-causes-computer-errors ; https://www.linkedin.com/posts/mariegmoe_the-computer-errors-from-outer-space-activity-6987414548366422016-v3AU/?trk=public_profile_like_view ; Other examples in Meier et al. 2020 - doi:10.3390/atmos11121358)

SWx impacts from SEP 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
  - Doses
    - Chest x-ray: 0.1 mSv
    - Public: 1mSv per year
    - Radiation workers: 20 mSv per year
    - NASA astronauts: 500 mSv per year
  - ICAO thresholds
    - Advisories for FL460 ; GLE required
    - Moderate: 30 µSv/h
    - Severe: 80 µSv/h





GLE: Ground Level Enhancement ; µSv/h: microsievert per hour ; mSv: millisievert ; FL: Flight Level (100 feet)

Top right figure: https://radioactivity.eu.com/in_daily_life/polar_routes

The atmospheric shield
The layers of air in the atmosphere give a protection against cosmic rays which decrease with altitude and depends on the route taken. For commercial aircraft flying at an altitude of 10km the dose received varies from 0.005 mSv to 0.007 mSv per hour depending on whether the airplanes do or do not pass through the Poles. At 18km the dose is approximately doubled. For an astronaut in a space station at 400km of altitude the dose rate reaches 0.040 mSv per hour. Two and a half days in orbit are enough to be exposed to a year of natural radioactivity on earth (2,4 mSv) © SCK.CEN (source L.de Saint-Georges).

Bottom right figure: https://aviationweek.com/business-aviation/cosmic-radiation-exposure-polar-flights-part-1

Research on the exposure of various professions to radiation has found that air crewmembers exhibit the highest annual exposure to radiation when compared with workers in the medical, industrial and nuclear industries. Source: Gerhard Frasch, German Federal Office for Radiation Protection, “Aircrew Exposure to Cosmic Rays: Challenges and Management,” International Conference on Occupational Radiation Protection, Dec. 15, 2014, in Vienna

Also at https://www.cdc.gov/niosh/topics/aircrew/cosmicionizingradiation.html

SWx impacts from SEP 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
  - Doses
    - Chest x-ray: 0.1 mSv
    - Public: 1mSv per year
    - Radiation workers: 20 mSv per year
    - NASA astronauts: 500 mSv per year
  - ICAO thresholds
    - Advisories for FL460 ; GLE required
    - Moderate: 30 µSv/h
    - Severe: 80 µSv/h

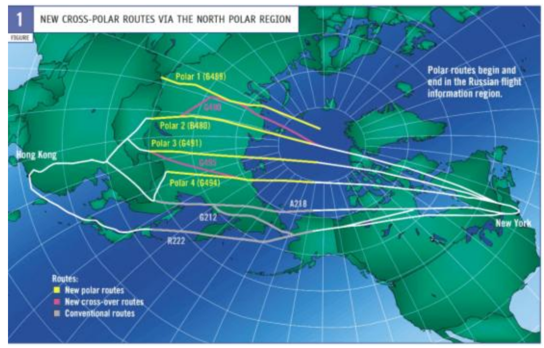
SWEC

GLE: Ground Level Enhancement ; µSv/h: microsievert per hour ; mSv: millisievert ; FL: Flight Level (100 feet)

Figure from https://www.theguardian.com/news/datablog/2011/mar/15/radiation-exposure-levels-guide

SWx impacts from SEP 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
  - Doses
  - ICAO thresholds
- Mitigation polar flights
  - Decrease altitude
  - Reroute (away from poles)

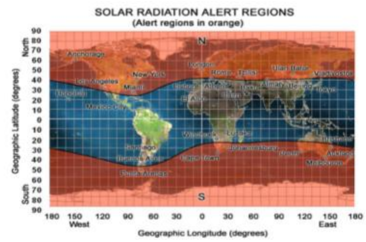


GLE: Ground Level Enhancement ; µSv/h: microsievert per hour ; mSv: millisievert ; FL: Flight Level (100 feet)

More info at https://english.hani.co.kr/arti/english_edition/e_business/850390

SWx impacts from SEP 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.

SWEC

25

GLE: Ground Level Enhancement ; µSv/h: microsievert per hour ; mSv: millisievert ; FL: Flight Level (100 feet) ; pfu: proton flux units

https://english.hani.co.kr/arti/english_edition/e_business/850390

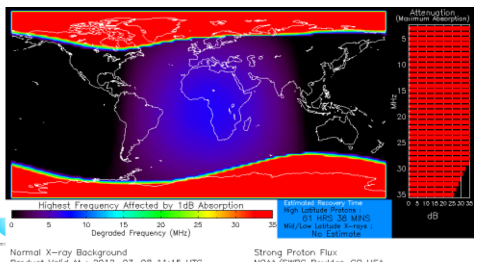
NMDB (Neutron Monitor Database): https://www.nmdb.eu/public_outreach/en/05/

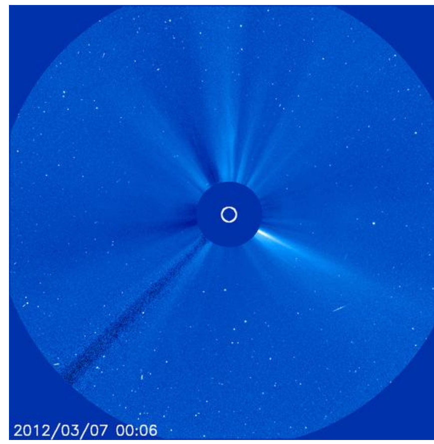
Figure from https://www.weather.gov/media/publications/assessments/SWstorms_assessment.pdf

... SEC [Space Environment Center – today's SWPC)] staff participated in teleconferences with major airlines at an average rate of three to five times a day. Teleconferences were conducted by SEC staff with airline dispatchers, pilots, and airline safety personnel as an important part of their decision making process. With SEC's help, airlines made critical decisions about route and/or altitude restrictions to flight operations during solar activity. Flight Centers restricted flight paths due to degraded communications, but it was each individual airline's responsibility to assess the radiation threat and take appropriate action. All commercial aviation interests were made aware of the radiation storm levels on October 28-29, when the Federal Aviation Administration (FAA) issued their first ever advisory suggesting that flights traveling north and south of 35 degrees latitude were subject to excessive radiation doses (Figure 9). This FAA product is based on data from the NOAA GOES particle sensors and is an advisory only. Airlines are not required to take action based on this advisory. Currently, two major U.S. airline companies conduct flight operations over the poles, and both took action to limit radiation exposure to passengers and crew. Polar flights were rerouted during this period (e.g., between October 24 – 31, one major airline rerouted six polar flights to non-polar routes requiring fuel stops in Japan and/or Anchorage). Flights on the U.S. to Europe routes did fly at lower altitudes during this severe radiation storm. ...

Impacts from SEP events on HF Com

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





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

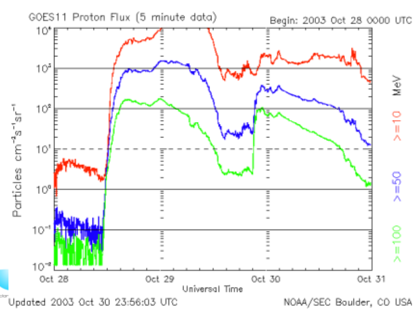
Neal et al. 2013 - Empirical determination of solar proton access to the atmosphere: Impact on polar flight paths
https://agupubs.onlinelibrary.wiley.com/doi/10.1002/swe.20066

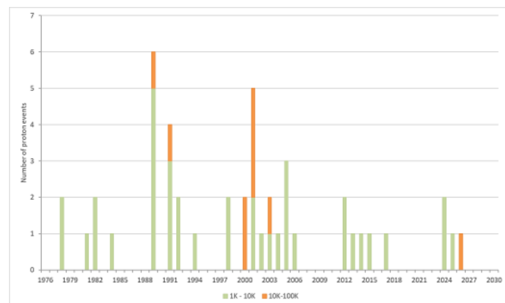
... HF radio communications blackouts are of importance to commercial aviation using polar flight routes. For example, it is a U.S. Federal regulation commonly followed by all international airlines that flights must maintain communications with Air Traffic Control and their company over the entire route of flight. Many airlines rely on SATCOM, Satellite Communications with geostationary satellites. Unfortunately, above 82° latitude, they are unable to use SATCOM, due to lack of satellite transmission access (line of sight) [Sauer and Wilkinson, 2008]. Thus, for latitudes above 82°, HF radio is used for aircraft communication which is susceptible to PCA during solar proton events. For safety when SPEs occur, aircraft traveling on polar routes need to be diverted to latitudes below 82°, to keep line of sight with the satellites and be able to communicate via SATCOM [National Research Council, 2008]. A schematic of this is shown in Figure 1, where PCA disrupts HF communications in the polar regions, but not at midlatitude. Airlines who do not use SATCOM or who want to retain HF communications as a backup would need to avoid large parts of the polar regions, due to the impact of PCA; this will also apply to ground-based installations including HF receivers at some airports. ...

... [8] Even with the availability with SATCOM, airline operations are still disrupted by SPE. In practice, airlines change their flight paths during large SPE, and air traffic control modifies its operation. In January 2005, United Airlines diverted 26 flights to nonpolar or less-than-optimum polar routes for several days to avoid the risk of HF radio blackouts during PCA events [National Research Council, 2008]. Similarly in January 2012, Delta Airlines rerouted some transpolar flights between Asia and the U.S. to avoid the impact of the largest SPE which had occurred in almost a decade [Cameron, 2012], where “largest” refers to the >10 MeV proton flux. In this event, eight Delta airline flights were routed outside the pole entirely due to concerns around HF communications and travelers health, with at least another eight flights affected in March 2012 due to another large SPE [Fahey and Scott, 2012]. Polar Air Traffic controllers also reported significant communications difficulties in the January and March 2012 events. The Federal Aviation Administration provided the following report: “limited reliable HF communications forced aircraft operators to use other communication methods,” but despite the availability of SATCOM in the latitudes of the flight paths “at times, communications were impossible” [Federal Aviation Administration, 2012]. In March 2012, SPE aircraft operators moved their flight paths from above 80°N to those around 70–72°N, leading to congestion on these paths. The SPE-produced HF communication disruptions caused the air traffic control centers to increase the separation of the aircraft from 10 min to 15 min. ...

Impacts from SEP events on HF Com

- Alert thresholds
  - 10 MeV protons: 10 pfu
  - 100 MeV protons: 1 pfu
- Frequency
  - Proton events:
    - Strong: 8 per solar cycle
    - Severe: 2 per solar cycle





MeV: megaelectronvolt ; pfu: proton flux unit

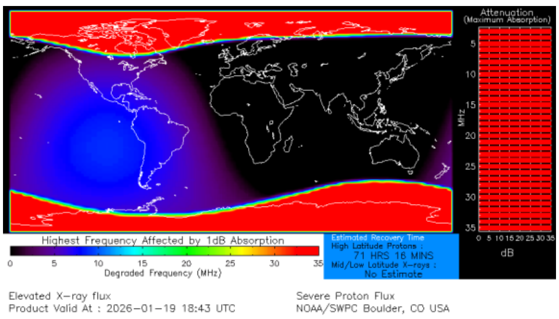
Fiori et al. 2022 - Occurrence rate and duration of space weather impacts on high-frequency radio communication used by aviation
https://www.swsc-journal.org/articles/swsc/pdf/2022/01/swsc220003.pdf

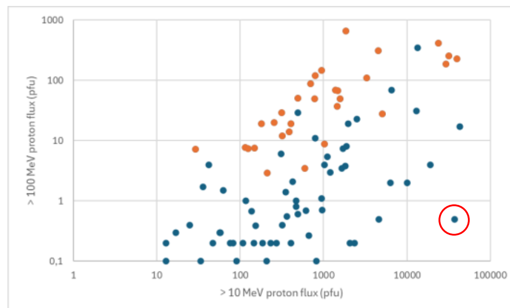
From NOAA/SWPC : ftp://ftp.swpc.noaa.gov/pub/indices/SPE.txt
Updated NOAA/SWPC list at https://www.ngdc.noaa.gov/stp/space-weather/interplanetary-data/solar-proton-events/SEP%20page%20code.html

```
=========================================================================
-------------PARTICLE EVENT----------        ASSOCIATED    ---------FLARE AND ACTIVE REGION----------
 Start              Maximum   Proton Flux    CME           Flare Max.  Importance  Location Region#
(Day/UT)                  (pfu @ >10 MeV)           (Loc./ Day UT)(Xray/Opt.)        (SWO)
------------------------------------------------------------------------------------------
1989 Oct 19/1305     Oct 20/1600   40000                        Oct 19/1258   X13/4B     S27E10    5747
1991 Mar 23/0820     Mar 24/0350   43000                        Mar 22/2247   X9/3B      S26E28    6555
(1994 Feb 20/0300     Feb 21/0900   10000                         Feb 20/0141   M4/3B      N09W02 7671 ***9000
according to Kurt et al. (2004)
2000 Jul 14/1045     Jul 15/1230   24000      Halo/14 1054   Jul 14/1024   X5/3B       N22W07   9077
2000 Nov 08/2350     Nov 09/1555   14800      Halo/08 2306   Nov 08/2328   M7/multiple N00-10W75-80
9212,13,18
2001 Sep 24/1215     Sep 25/2235   12900      Halo/24 1030   Sep 24/1038   X2/2B       S16E23    9632
2001 Nov 04/1705     Nov 06/0215   31700      Halo/ 04 1635 Nov 04/1620   X1/3B       N06W18   9684
2001 Nov 22/2320     Nov 24/0555   18900      Halo/22 2330   Nov 22/2330   M9/2N       S15W34   9704
2003 Oct 28/1215     Oct 29/0615   29500      Halo/28 1054   Oct 28/1110   X17/4B      S16E08    0486
2026 Jan 18/2255     Jan 19/1915   37000      Halo/18 1821   Jan 18/1809   X1/3B       S11E20    4341
```

Impacts from SEP events on HF Com

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





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

GLE: Ground Level Enhancement

MeV: megaelectronvolt ; pfu: proton flux unit

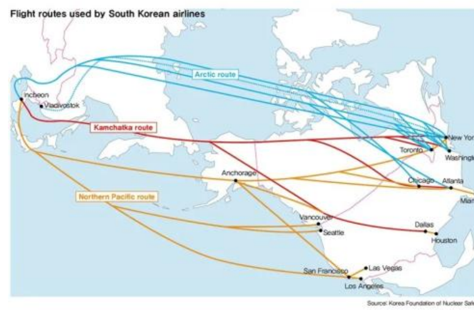
Fiori et al. 2022 - Occurrence rate and duration of space weather impacts on high-frequency radio communication used by aviation
https://www.swsc-journal.org/articles/swsc/pdf/2022/01/swsc220003.pdf

From NOAA/SWPC : ftp://ftp.swpc.noaa.gov/pub/indices/SPE.txt
Updated NOAA/SWPC list at https://www.ngdc.noaa.gov/stp/space-weather/interplanetary-data/solar-proton-events/SEP%20page%20code.html

PARTICLE EVENT Start (Day/UT)	Maximum	Proton Flux (pfu @ >10 MeV)	ASSOCIATED CME	FLARE AND ACTIVE REGION Flare Max. (Loc./ Day UT)	Importance (Xray/Opt.)	Location	Region# (SWO)
1989 Oct 19/1305	Oct 20/1600	40000		Oct 19/1258	X13/4B	S27E10	5747
1991 Mar 23/0820	Mar 24/0350	43000		Mar 22/2247	X9/3B	S26E28	6555
(1994 Feb 20/0300	Feb 21/0900	10000		Feb 20/0141	M4/3B	N09W02	7671 ***9000 according to Kurt et al. (2004)
2000 Jul 14/1045	Jul 15/1230	24000	Halo/14 1054	Jul 14/1024	X5/3B	N22W07	9077
2000 Nov 08/2350	Nov 09/1555	14800	Halo/08 2306	Nov 08/2328	M7/multiple	N00-10W75-80	9212,13,18
2001 Sep 24/1215	Sep 25/2235	12900	Halo/24 1030	Sep 24/1038	X2/2B	S16E23	9632
2001 Nov 04/1705	Nov 06/0215	31700	Halo/ 04 1635	Nov 04/1620	X1/3B	N06W18	9684
2001 Nov 22/2320	Nov 24/0555	18900	Halo/22 2330	Nov 22/2330	M9/2N	S15W34	9704
2003 Oct 28/1215	Oct 29/0615	29500	Halo/28 1054	Oct 28/1110	X17/4B	S16E08	0486
2026 Jan 18/2255	Jan 19/1915	37000	Halo/18 1821	Jan 18/1809	X1/3B	S11E20	4341

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



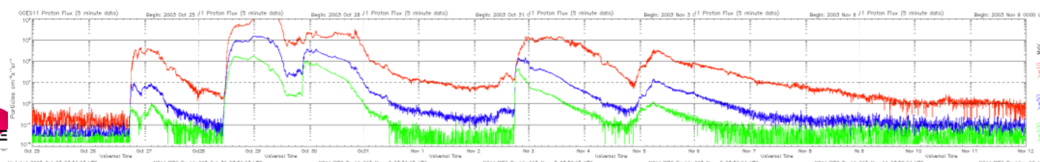


Figure from https://english.hani.co.kr/arti/english_edition/e_business/850390

From https://www.weather.gov/media/publications/assessments/SWstorms_assessment.pdf

… SEC [Space Environment Center – today's SWPC)] staff participated in teleconferences with major airlines at an average rate of three to five times a day. Teleconferences were conducted by SEC staff with airline dispatchers, pilots, and airline safety personnel as an important part of their decision making process. With SEC's help, airlines made critical decisions about route and/or altitude restrictions to flight operations during solar activity. Flight Centers restricted flight paths due to degraded communications, but it was each individual airline's responsibility to assess the radiation threat and take appropriate action. All commercial aviation interests were made aware of the radiation storm levels on October 28-29, when the Federal Aviation Administration (FAA) issued their first ever advisory suggesting that flights traveling north and south of 35 degrees latitude were subject to excessive radiation doses (Figure 9). This FAA product is based on data from the NOAA GOES particle sensors and is an advisory only. Airlines are not required to take action based on this advisory. Currently, two major U.S. airline companies conduct flight operations over the poles, and both took action to limit radiation exposure to passengers and crew. Polar flights were rerouted during this period (e.g., between October 24 – 31, one major airline rerouted six polar flights to non-polar routes requiring fuel stops in Japan and/or Anchorage). Flights on the U.S. to Europe routes did fly at lower altitudes during this severe radiation storm. …

And From The Antarctic Sun: https://antarcticsun.usap.gov/pastIssues/2003-2004/2003_11_09.pdf
Antarctic Operations The Antarctic science groups and staff rely on MacRelay radio operations to provide essential radio communications between McMurdo Station and remote sites on the Antarctic. MacRelay is also responsible for communication links with aircraft and ships supporting the United States Antarctic Program. The primary source of communication is HF radio. ***<u>MacRelay experienced over 130 hours of HF communication blackout during the October – November activity.</u>*** *[Red.: from both solar flares and SEP events]* Following an extended solar flare-induced HF outage earlier in this solar cycle, McMurdo staff developed a contingency plan to use Iridium satellite phones as backup during HF outages. During these previous periods of severe solar activity (2000 – 2001), numerous support flights were delayed for several days. During the October – November 2003 activity, the LC-130 aircraft that service the remote sites used Iridium phones to communicate with McMurdo and the remote locations. And to ensure safety, take-off and landing restrictions changed during the HF blackout periods. The 150-meter cloud ceiling and 3.2 km of visibility was increased to 900 meters with 4.8 km of visibility.
Scientific missions in the field (at camp) in Antarctica are required to 'check in' with MacRelay communications under normal circumstances via HF. If they miss their 'check in' then a rescue mission is considered. MacRelay was made aware that space weather was causing significant HF blackout conditions, allowing them to implement contingency plans. MacRelay received SEC alerts and warnings, but SEC staff also coordinated with MacRelay staff via telephone during the October-November activity.

From the « Amsterdam Evening Recorder » (24 February 1956) - Via https://en.wikipedia.org/wiki/HMS_Acheron_(P411)#cite_note-5 and via http://www.solarstorms.org/SRefStorms.html

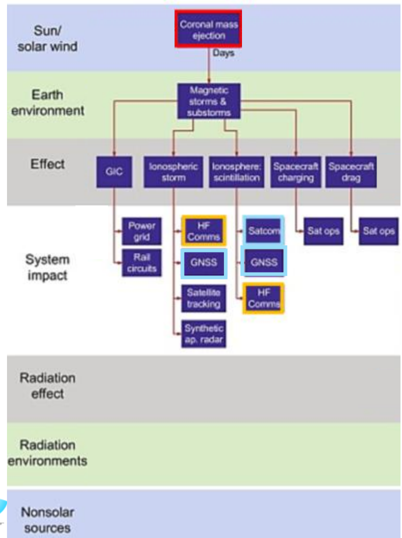
Missing British Sub Feared Lost, Safe; Search Called Off - Acheron Sighted in Gale-Swept Arctic Sea by Minesweeper; Failure of Communications System Made Contact With Admiralty Impossible; Was Unreported Since Wednesday When It Made Trial Dive

LONDON *(UP)*—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. Dived 2 Days Ago The Acheron dived two days ago during arctic trials in the Denmark Strait between Iceland and Greenland and should have reported by radio at 10:05 a.m. (5:05 a.m. EST) today. This message never came.

The Admiralty said it was possible unusual sunspot activity over the past two days might have blacked it out. Gigantic explosions on the sun have bombarded the earth with cosmic rays, interfering with communications. In Copenhagen, the Danish government's telegraph authority said no radio messages had been received from Greenland stations since yesterday "morning. "Frankly," a spokesman for the authority said, "we cannot see how a vessel could get signals through while we cannot receive a word from powerful land stations.“ At 11:05 am. the Admiralty flashed the "sub-miss" signal alerting all ships, planes and rescue services—military ' and civilian— to stand by for possible help. An hour later a "sub-sunk" order was flashed—signaling an immediate search with all available ships and planes. Royal Air Force planes roared off for Reykjavik, Iceland, to set up a base for search operations. U.S. Air Force units on Iceland already were standing by. Ships steamed out from Scotland and Iceland.

Some figures on the associated Ground Level Event (GLE) is in Bieber et al. (2005): Largest GLE in Half a Century: Neutron Monitor Observations of the January 20, 2005 Event http://neutronm.bartol.udel.edu/reprints/2005bieber.pdf
The Sun occasionally emits cosmic rays of sufficient energy and intensity to increase radiation levels on the surface of Earth. From the time systematic observations by neutron monitors began in the 1950’s, such “ground level enhancements” (GLEs) have occurred at a rate of about 15 per solar cycle. The largest GLE on record is the famous 1956 event [1] during which radiation levels near sea level increased by as much as 47 times in some regions.

Impact from ICMEs



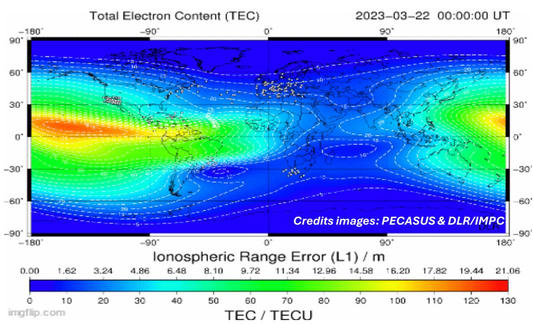
- From magnetic field
  - Satellites
    - Magnetopause crossings
  - High-Precision industry
  - GCR: Forbush decrease
- From particles (ionospheric)
  - Aurora
  - Geomagnetically Induced Currents (GIC)
  - HF Communication
  - Satellites
    - Drag
    - Charging effects
  - Satellite-based Comms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

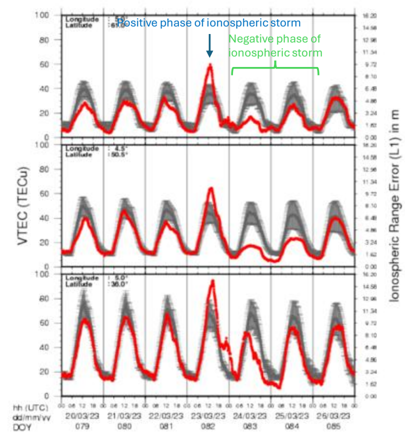
GCR: Galactic Cosmic Rays ; Comms/Nav: Communications/Navigation ; PECASUS: Pan-European Consortium for Aviation Space weather User Services ; HF: High Frequency ; (I)CME: (Interplanetary) Coronal Mass Ejection

31

Impact from ICMEs on HF Com

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





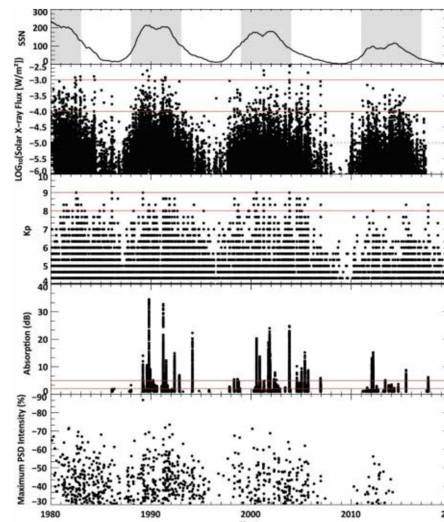
Credits: ROB/GNSS

(I)CME: (Interplanetary) Coronal Mass Ejection ; Kp: planetary K index ; Dst: Disturbance storm-time index ; nT nano tesla ; (V)TEC: (Vertical) Total Electron Content ; TECU: TEC unit ; PECASUS: Pan-European Consortium for Aviation Space weather User Services ; DLR: German Aerospace Centre; IMPC: Ionosphere Monitoring and Prediction Center; GNSS: Global Navigation Satellite Systems (GPS, Galileo,,...); DOY: Day Of Year

https://www.stce.be/news/640/welcome.html
https://www.stce.be/news/638/welcome.html

Impact from ICMEs on HF Com

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



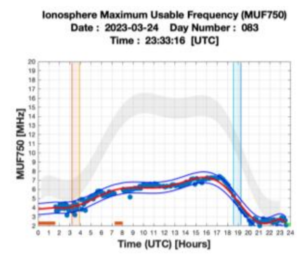
Credits: Fiori et al. 2022

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

Figure from Fiori et al. 2022 - https://www.swsc-journal.org/articles/swsc/full_html/2022/01/swsc220003/swsc220003.html
Occurrence rate and duration of space weather impacts on high-frequency radio communication used by aviation
(a) The 13-month smoothed mean total sunspot number. Grey shading indicates solar maximum years. Occurrence of (b) solar X-ray flux for 01 January 1980 until 28 June 2017, (c) Kp for 1980–2020, and (d) D-RAP modelled absorption >1 dB for all PCA event observed in 1986–2020. Red horizontal lines indicate MOD and SEV event thresholds for (b) SWF (X1 and X10 solar X-ray flare), (c) AA (Kp = 8, 9), and (d) PCA (2 dB and 5 dB absorption at 30 MHz). (e) Maximum intensity of PSD events, represented by hourly relative foF2.
18-19 September 1941 - Newspapers, for example, succinctly reported that the British Royal Air Force carried out a raid on a German supply base on the Baltic Sea [*Washington Post,* 1941b] and that the Germans bombarded Leningrad [*Chicago Tribune,* 1941b], each under the lights of the aurora borealis. A German submarine torpedoed a cargo convoy and sunk the freightship HMCS Lévis. ***This concerned a CME that arrived at Earth only 20 hours after a flare was observed by RGO on 17 September. This flare caused a magnetic crochet and interfered with HF radio comms.***
https://eos.org/features/the-geomagnetic-blitz-of-september-1941
... The National Bureau of Standards [1941] reported a great ionospheric disturbance starting at about 06:00 UT on 18 September, 2 hours after the sudden commencement of the magnetic storm. We might retrospectively infer that this was caused by substorm precipitation of charged particles into the Earth's auroral zone. This would have disrupted over-the-horizon radio signals that are normally calibrated for a set level of ionospheric reflectivity.
- And, sure enough, as a result of the 18–19 September storm, widespread interference was reported for radio transmissions around the world [e.g., General Electric, 1941; Conklin, 1941]. As part of these developments, two amusing happenings were reported in the New York Times [1941a, 1941b], Newsweek [1941], and Time [1941], paraphrased here.
- First, on the afternoon of 18 September, the Pittsburgh Pirates hosted the Brooklyn Dodgers in a game of baseball. Red Barber, a well-known sports commentator, was calling the game for WOR Radio. In the fourth inning, with the score tied at 0–0, the broadcast lost signal for 15 minutes. By the time the broadcast resumed, the Pirates had 4 accumulated runs. Irate Brooklyn fans phoned the radio station to complain, but they found "little satisfaction" with the "explanation that the sun," sunspots, and the related magnetic storm were to blame for the outage. To top it off, the Dodgers went on to lose to the Pirates, 5-6.
- The next morning, radio station WAAT was broadcasting a program of Bing Crosby songs. Suddenly, during "Where the Blue of the Night (Meets the Gold of the Day)," a phone conversation between two men discussing their previous night's amours could be heard in background. Workers at the radio station tried without success to clear up what was apparently some sort of silly mix-up of signals. Station representatives later claimed that although the conversation was "strong," it was also "not particularly objectionable."

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



34

From the STCE Newsitem « Severe geomagnetic storm! » at https://www.stce.be/news/638/welcome.html

The source of the ICME was most likely a solar eruption that took place on 20 March, i.e. a long duration C4 flare in NOAA 3258 in the northeast solar quadrant. The solar imagery from GOES/SUVI 094 (multi-million degrees ; green) is overlaid on the coronographic images from SOHO/LASCO C2, showing the eruption was associated with a coronal mass ejection (CME). The CME moving to the southwest (lower right) is on the Sun's farside (no optical source seen on the earth-facing side.

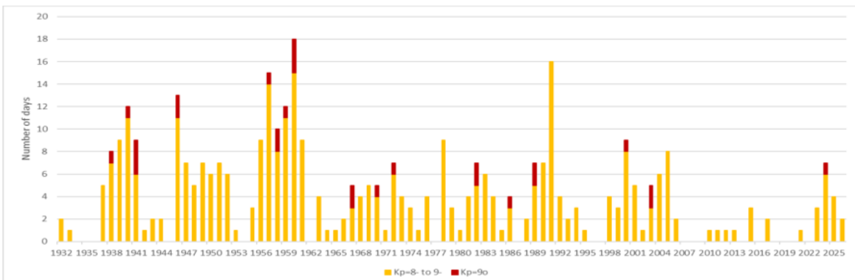
Kp eventually reached severe storming levels (Kp = 8-) during the 03-06 UTC interval in the morning of 24 March (see the bottom chart above). Kp-wise, this was the strongest storm since 4 November 2021 (see this STCE newsitem). The (provisional) Dst index reached -184 nT, a value not seen since the "Solstice storm" on 23 June 2015 when it was at -198 nT (Kyoto WDC).

The severe geomagnetic storm resulted in aurora that were visible and/or photographed at relatively low latitudes (source: https://www.spaceweather.com/). Most of these pictures showed the red hues of the aurora, which are typically found at higher altitudes (200 km or higher) than the green coloured aurora (between 100 and 200 km) and thus can be seen from further away (see BIRA-IASB). Thus, long-exposed pictures taken in Europe (Slovenia) and the United States (New Mexico, North Carolina, and even Florida) showed faint reddish aurora just above the horizon. For these locations near 30 degrees latitude, the polar lights were not visible to the naked eye. But that gradually changed for sites located about 5 to 10 degrees more poleward. Peter Forister (https://www.facebook.com/PeterForisterPhoto ; image underneath) photographed the aurora from Stanley, Virginia (latitude +38.7 degrees). The photos were taken in Shenandoah National Park between 22:45 and 23:45 local time, looking northwest. He reported that "The lights were visible to my naked eye for about an hour. The vibrant green and red colors only lasted about 15 minutes during an intense "Substorm" around 23:00. These are long exposure photographs (between 4 and 6 seconds long each), and so are brighter than what I was able to see. The colors are accurate to the very deep reds and greens that I could see!"

The geomagnetic storm affected GNSS applications and HF communications. The figure in the lower right is from IMPC (https://impc.dlr.de/projects/current-projects/) and shows that -for that day- the maximum useable HF frequency (MUF) to cover a distance of 750 km was only about 7-8 MHz, whereas during quiet days (greyish area) the MUF 750 was up to 15-16 MHz.

Impact from ICMEs on HF Com

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

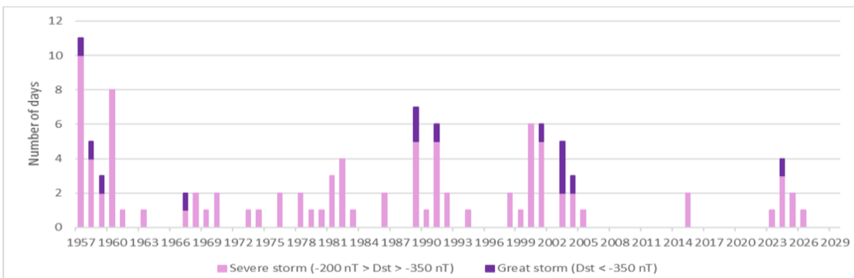


35

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

Impact from ICMEs on HF Com

- Frequency geomagnetic storms
  - Kp *(planetary K-index)*
    - ~ 40 severe storm days / SC
    - ~ 3 extreme storm days / SC
- Frequency geomagnetic storms
  - Dst *(Disturbance storm-time index)*
    - ~ 14 severe storm days / SC
    - ~ 2 extreme storm days / SC



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

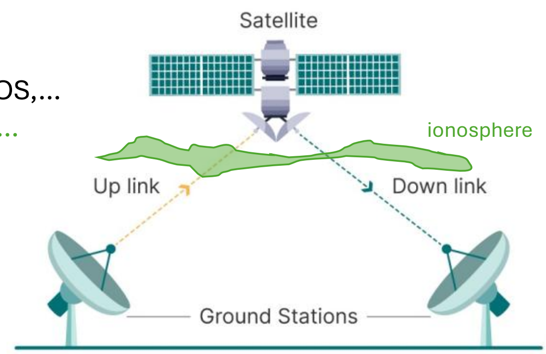
36

Kp
Severe storms: Kp = 8- to 8+, 9-
Extremely severe storms: Kp = 9o

Dst
Severe storms: -200 ≥ Dst > -350
Extreme storms: Dst ≤ -350 nT

Impact from ICMEs on SATCom/GNSS

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



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

37

Sketch (annotated) from https://www.shiksha.com/online-courses/articles/satellite-communication/

Basic info on SATCom from Wikipedia: https://en.wikipedia.org/wiki/Communications_satellite

Impact from ICMEs on SATCom/GNSS

- Satellite Communication (SATCom)
  - Media, Meteo, Military, Internet,...
  - Wide frequency range
    - usually UHF/SHF
  - Applications such as WAAS, EGNOS,...
  - Signals travel through ionosphere...
    - Ionospheric scintillation
      - Plasma bubbles
      - = small scale irregularities in e^- density
        - May develop in large structures
      - Rapid fluctuations in satellite signal
        - Phase and intensity
        - May result in signal loss

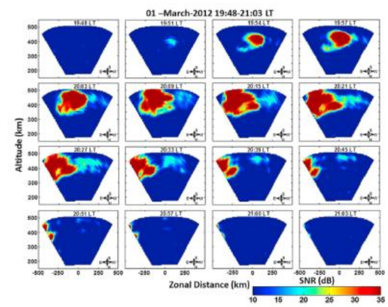


Figure 1. An example showing the genesis and successive development of EPB (evolving-type) over Kototabang observed from the fan sector maps of EAR on 1 March 2012.

Credits: Ajith et al. (2015)

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

38

Picture taken from
Ajith et al. (2015): Explicit characteristics of evolutionary-type plasma bubbles observed from Equatorial Atmosphere Radar during the low to moderate solar activity years 2010-2012
http://adsabs.harvard.edu/abs/2015JGRA..120.1371A
The equatorial plasma bubbles (EPBs)/equatorial spread F (ESF) irregularities are an important topic of space weather interest because of their impact on trans-ionospheric radio communications, satellite-based navigation and augmentation systems. This local plasma-depleted structures develop at the bottom side F layer through Rayleigh-Taylor instability and rapidly grow to topside ionosphere via polarization electric fields within them.
The EPBs are essentially a nighttime phenomena when the E region conductivity becomes negligible that liberates the polarization electric fields in F region to grow nonlinearly. The steep vertical gradients due to quick loss of bottom side ionization and rapid uplift of equatorial F layer via pre-reversal enhancement (PRE) of zonal electric field makes the post-sunset hours as the most preferred local time for the formation of EPBs [Kelley, 1989; Fejer et al., 1999; Tulasi Ramet al., 2006]. Once developed, these EPBs generally drift eastward with velocities ranging from 50 to 200 m/s [Aarons et al., 1980; Bhattacharyya et al., 2001; Rama Rao et al., 2005]. The seasonal and longitudinal variability of EPBs are influenced by the alignment between sunset terminator and magnetic meridian.

From the STCE Newsitem:
http://www.stce.be/news/420/welcome.html
The main cause of the ionospheric unrest is the presence of equatorial plasma bubbles, i.e. depletions of electron density in the ionosphere. Their number correlates with the solar activity level, and they also are more numerous during the equinoxes (spring and autumn) than during the solstices (summer and winter). They usually form after sunset at the bottom of the F-region (main ionospheric layer), where small low-density irregularities can grow into turbulent bubbles - see a model underneath (covering 40 minutes) developed by Dr Yokoyama (NICT/AERI). The bubbles have a typical size of about 100 km and their effects usually end around midnight. They can occur during relatively minor levels of geomagnetic activity, especially during solar maximum. Radio wave propagation can be severely affected in terms of power and intensity as these waves travel through small scale structures in the ionosphere (i.e. scintillation of radio waves).

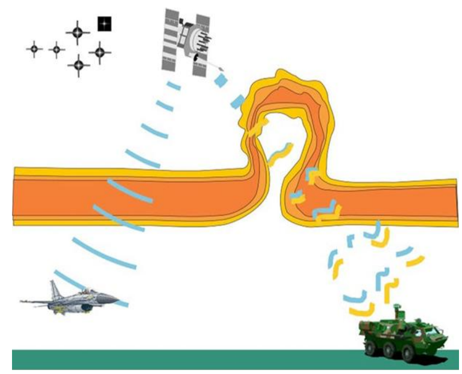
More info on ionospheric scintillation: SWS: http://www.sws.bom.gov.au/Satellite/6/3

Also at Inside GNSS, Kintner et al. (2009): GNSS and Ionospheric Scintillation How to Survive the Next Solar Maximum
http://www.insidegnss.com/node/1579 or http://www.insidegnss.com/auto/julyaug09-kintner.pdf

Also Traveling Ionospheric Disturbances: https://www.tech-tide.eu/

Impact from ICMEs on SATCom/GNSS

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



Credits: US Air Force Research Laboratory

39

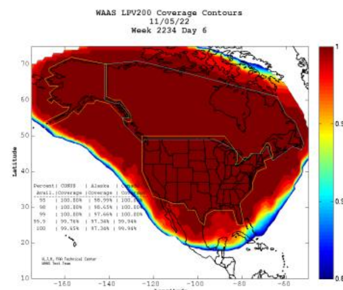
Lower left figure from US Air Force Research Laboratory - https://www.nasa.gov/mission_pages/cindi/five-years.html

Battle of Takur Ghar (4 March 2002) - https://www.stce.be/news/420/welcome.html

Kelly et al. 2014 - Progress toward forecasting of space weather effects on UHF SATCOM after Operation Anaconda
https://doi.org/10.1002/2014SW001081
During Operation Anaconda, the Battle of Takur Ghar occurred at the summit of a 3191 m Afghan mountaintop on 4 March 2002 when the ionosphere was disturbed and could have affected UHF Satellite Communications (SATCOM). In this paper, we consider UHF SATCOM outages that occurred during repeated attempts to notify a Quick Reaction Force (QRF) on board an MH-47H Chinook to avoid a "hot" landing zone at the top of Takur Ghar. During a subsequent analysis of Operation Anaconda, these outages were attributed to poor performance of the UHF radios on the helicopters and to blockage by terrain. However, it is also possible that ionospheric anomalies together with multipath effects could have combined to decrease the signal-to-noise ratio of the communication links used by the QRF. A forensics study of Takur Ghar with data from the Global Ultraviolet Imager on the NASA Thermosphere Ionosphere Mesosphere Energetics and Dynamics mission showed the presence of ionospheric bubbles (regions of depleted electron density) along the line of sight between the Chinook and the UHF communications satellites in geostationary orbit that could have impacted communications.

Impact from ICMEs on SATCom/GNSS

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



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

WAAS clip from FAA at https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/howitworks

Space Based Augmentation Systems (SBAS): Based on corrections from ground-based stations and use of GEO sats to distribute these corrections to users (aviation, navigation,...).

From the FAA (Karen Shelton, Amanda Watson)
The May 10-11 storm was the most intense in over two decades. However, it caused fewer impacts because of the early warning allowing end users to safeguard their equipment and infrastructure
(1) The primary aviation impacts were limited to frequency issues on overseas flights as well as experiencing some brief radio transmission or equipment blips. Additionally, trans-oceanic flights were rerouted due to HF radio communication loss.
(2) WAAS is a satellite-based system that enhances GPS signals for aircraft flight paths. LPV is an instrument approach procedure that uses WAAS to provide more stable vertical guidance than an ILS approach. LPV approaches are similar to ILS approaches in appearance and flight, but are more precise.
WAAS software has a functionality called an Extreme Storm Detector (ESD) - implemented in September 2007. The ESD is meant to trip during a severe ionospheric storm where it's unlikely WAAS can safely protect the user due to the severity and unpredictability of the storm. When ESD trips, it disables WAAS vertical service. Note that all the ESD functionality is in the WAAS software without human intervention.
Two NOTAMs were issued warning operational folks of the potential disruptions to WAAS.

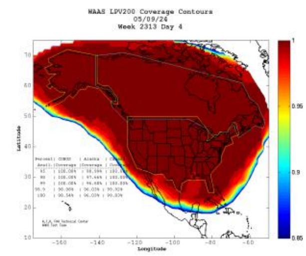
- EXTRA INFO: WAAS LPV-200 refers to the Wide Area Augmentation System (WAAS) Localizer Performance with Vertical Guidance (LPV) procedure that allows aircraft to descend to as low as 200 feet above the runway.

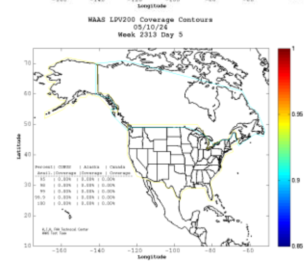
NOTAMs, or Notices to Airmen, were issued by the FAA advising of the potential communication and navigation disruptions.

<u>Sources</u>: Input from presentations during the ESWW2024 in Coimbra, Portugal (https://esww2024.org/)
- Impacts of Space Weather on Aviation and FAA Insights from the May Solar Storms - by Samantha Watson, Karen Shelton-Mur (FAA)
- Four years of ICAO space weather advisories - by Kasper van Dam (KNMI), on behalf of PECASUS consortium
- Harmonize HF COM advisories for Maximum Usable Frequency (MUF) within all global centres providing space seather service to ICAO - by Loredana Perrone (INGV) et al.

Impact from ICMEs on SATCom/GNSS

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





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41

WAAS clip from FAA at https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/howitworks

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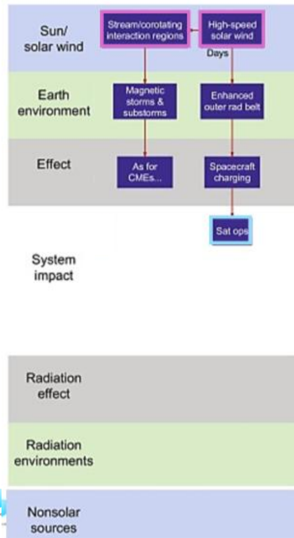
Impact from CH HSS on SATCom

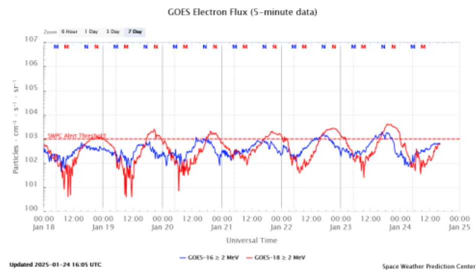


- Similar to effects from ICMEs but less intense
- except…
- From particles
  - Satellites
    - Deep di-electric charging
      - *NOT ionosphere related*

42

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)



43

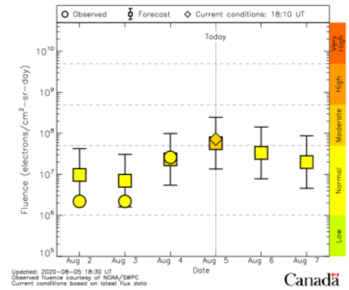
Top right figure: https://www.spaceweather.gc.ca/forecast-prevision/space-spatiale/sffl-en.php

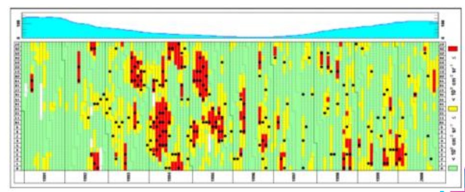
Bottomright figure:
Wrenn et al. (2002): A solar cycle of spacecraft anomalies due to internal charging
https://ui.adsabs.harvard.edu/abs/2002AnGeo..20..953W/abstract
The maximum of the smoothed sunspot number for cycle 22 was in July 1989; the minimum in May 1996, then heralded as the start of cycle 23, which peaked in April 2000. Each day of the years 1991 through 2000 is displayed in Fig. 1 as a traffic light presentation based on the 2-day fluences of >2MeV electrons measured at geostationary GOES satellites. The days are ordered by 27.4-day Carrington solar rotations, starting with 1837 and ending with 1971; the righthand panel plots the smoothed sunspot number on a scale from 0 to 180. Black spots mark those days on which the mode switching anomalies occurred.
The outer belt electron enhancements (OBEEs) tend to last for several days but often exhibit a 27-day recurrence that reflects the persistence of coronal holes on the Sun. Their occurrence peaks not at solar maximum, but during the declining phase when high-speed streams of solar wind are more stable and long-lived. Although there is no direct correlation, the long-lived high-speed streams do occur during 1994 and 1995, approaching solar minimum, but not near solar maximum. A few bursts and associated OBEEs are obviously non-recurrent and appear to be associated with solar proton events, or perhaps coronal mass ejections. This solar cycle pattern fits well with earlier measurements made during cycle 21 (Baker et al., 1993).
Figure 3 reinforces the main message by showing the distribution of anomalies with respect to fluence, but it also explores the significance of season by plotting the switches against displacement from equinox (the line is a simple linear fit). Since coupling between the solar wind and the magnetosphere
is easier near equinox, the electron fluences are generally higher and ESD [ElectroStatic Discharges] occurrence frequency can be expected to increase.

More info in these STCE Newsitems: https://sidc.be/news/207/welcome.html , https://www.stce.be/news/463/welcome.html , https://www.stce.be/news/513/welcome.html , https://www.stce.be/news/561/welcome.html
Also at the STCE's SWx Classification page https://www.stce.be/educational/classification#electrons and the STCE's SC25 Tracking page https://www.stce.be/content/sc25-tracking#electron

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



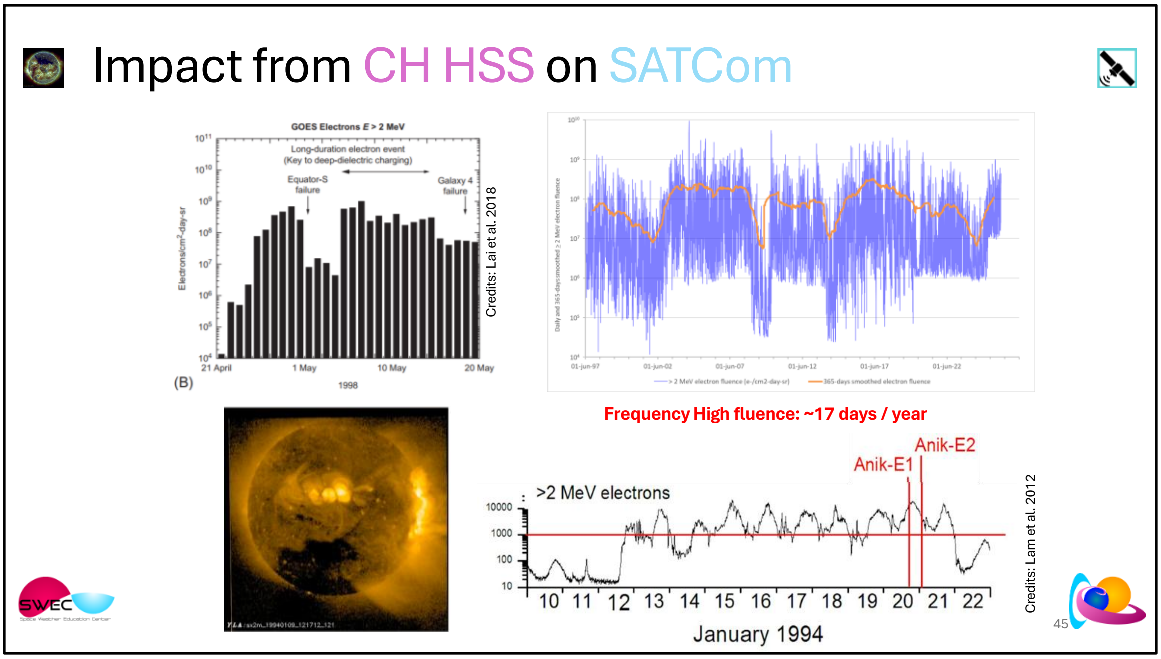


Credits: Wrenn et al. (2002)

High-speed solar-wind streams and geospace interactions
Kavanagh, Andrew; Denton, Michael in Astronomy & Geophysics, Volume 48, Issue 6, pp. 6.24-6.26, 2007
https://ui.adsabs.harvard.edu/abs/2007A%26G....48f..24K/abstract

As well as driving more obvious geomagnetic activity such as aurora, fast solar-wind streams also drive ultra-low-frequency (ULF) waves in the magnetosphere. These can transfer energy directly from the solar wind through the system to the ionosphere. These magnetic oscillations have periods ranging from 10s to 100s of seconds (known as Pc5 waves) and have been shown to depend strongly on solar-wind speed (e.g. Mathie and Mann 2000).
The production mechanism for these waves is not completely understood, but a leading candidate is the Kelvin–Helmholtz instability at the magnetopause, which can energize waveguide modes that carry pulsation power into the inner magnetosphere and ionosphere. Recent estimates based on observations suggest that the energy can be significant in comparison with substorms (e.g. Rae et al . 2007). One important aspect of the Pc5 waves is their potential ability to accelerate electrons to relativistic energy within the outer radiation belts (e.g. Elkington et al. 1999).

Relativistic electrons
One area that is the subject of a concentrated research effort is the mechanism for generation and loss of relativistic electrons in the radiation belts. Large geomagnetic storms can have drastic effects on the population of relativistic electrons in the inner magnetosphere; this can include the creation of new radiation belts at low latitudes (e.g. Baker et al. 2004). The effect of CIRs and HSSs on the relativistic electron flux is almost as dramatic. During CIRs dramatic drop-outs occur in the electron fluxes in the outer radiation belt; this is followed by a gradual increase to above pre-CIR levels during the HSS and subsequent decay. The cause of the initial drop-out is unknown, though there is evidence to suggest enhanced precipitation (e.g. Green et al. 2004) through possible interaction with a number of different magnetospheric waves. The mechanisms for accelerating electrons to MeV energies are clearly efficient. Radial diffusion though interaction with Pc5 waves is one possible mechanism and energy diffusion by cyclotron resonance with electromagnetic whistler mode waves is another. The relative strengths of these mechanisms are currently unknown but it is clear that acceleration is enhanced during HSSs (e.g. Mathie and Mann 2000).



Upper right figure is from the STCE’s SC25 Tracking webpage https://www.stce.be/content/sc25-tracking
More info also at https://www.stce.be/educational/classification#electrons
The highest electron fluence since 1997 was recorded on 29 July 2004, when it reached a value of 9.3 . 10^9 electrons / (cm2 sr day). From 2003 to 2008, and again from 2015-2019, elevated fluence levels were recorded because of the declining phase of the solar cycle when (equatorial) coronal holes and the extensions of polar coronal holes are most numerous. The two dips early 2002 and mid-2014 mark solar cycle maximum when the polar magnetic fields were reversing their polarity and coronal holes were pretty much absent and in the process of being recreated.
A period of enhanced (moderate to high) levels of electron fluence was recorded from 5 till 14 September 2022. Operators reported numerous satellite glitches at the end of the period, in particular a few days after maximum fluence on 8 September. This shows again the importance of the electron accumulation effect on the satellite's instruments.
From 2 June 1997 till 5 February 2023, there have been 471 days with high fluence (> 5. 10^8 electrons/cm^2 sr day). This is an average of about 18 per year.

Figure at the upper left:
Fig. 7 from Lai et al. (2018): Deep Dielectric Charging and Spacecraft Anomalies
DOI: 10.1016/B978-0-12-812700-1.00016-9
https://www.researchgate.net/publication/323630151_Deep_Dielectric_Charging_and_Spacecraft_Anomalies
Original figure 3a from Baker et al. (1998) - Disturbed Space Environment May Have Been Related to Pager Satellite Failure
https://doi.org/10.1029/98EO00359

Two other figures from Lam et al. (2012): Anik-E1 and E2 satellite failures of January 1994 revisited
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2012SW000811 (Fig. 1a and 3)

Failure of the ANIK-1 and -2 satellites occurred during a substorm following active to minor storming activity from a number of CHs (13-19 January). Both satellites were recovered, but at a cost of about $50-70 million, and plenty of problems for cable TV, telephone, newswire and data transfer services throughout Canada.
http://www.solarstorms.org/SWChapter6.html
Leach and Alexander (1995): Failures and anomalies attributed to spacecraft charging
https://ntrs.nasa.gov/search.jsp?R=19960001539

Summary

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