



Role of the ionosphere and space weather in military communications

8-10 September 2025



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

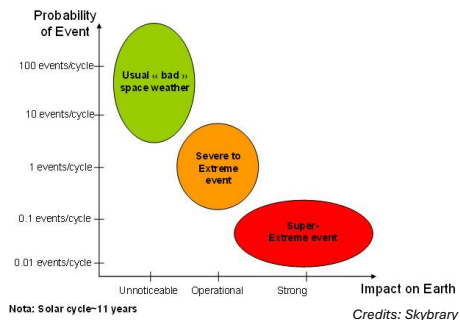
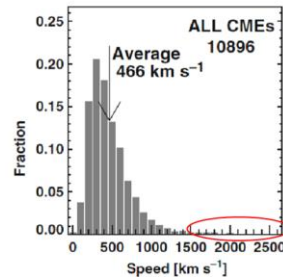
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- What is an extreme event?
- SWx drivers & impacts: overview
- **HF Com** and **SATCom** impacts from
 - Solar flares
 - Solar energetic particle events (SEP)
 - Interplanetary coronal mass ejections (ICME)
 - High speed streams from coronal holes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



What is an extreme event?

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



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/monthlylyssnplot>

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-class flares*	261	232	183	76	84
Strongest proton event (> 10 MeV; in pfu)	2900 13 Jul 1982	43000 24 Mar 1991	31700 6 Nov 2001	6530 8 Mar 2012	1810 10 Oct 2024
Number of proton events (> 10 MeV)	59	73	94	42	38
Number of Ground Level Enhancements (GLE)	13	15	16	2	4
Number of days with Kp ≥ 8-	42	42	43	9	13
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 31 May 2025. 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 4 rather weak GLEs on 28 Oct 2021, 11 May 2024, 8 Jun 2024 and 21 Nov 2024.

Note that the STIX instrument on board of Solar Orbiter may have recorded several stronger flares during this solar cycle, however they occurred 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
Sunspot group area (MH)	6132	5800	7100	8200	13600	
GOES flare SXR	X40	X44	X42	X100	X115	X180
1.5 GHz radio emission (10^6 sfu)	1		3.2 - 12		61 - 200	
> 30 MeV proton fluence (10^{10} cm ⁻²)	0.84	1.6	2.1	5	16	
> 200 MeV proton fluence (10^{10} cm ⁻²)	0.14	0.6		3.5		
CME speed (km/s)	3387	3800	4500	4700	6600	
ICME transit time (h)	14.6					11.6
Dst (nT)	~ -950	-603	-774	-845	-1470	-2000 to -2500



Acronyms: ev.: event; Exp. Law: exponential law; MH: Millionths of a solar hemisphere; GOES: Geostationary Operational Environmental Satellite; SXR: soft x-rays; GHz: gigahertz; sfu: solar flux units; MeV: Mega electronvolt; pfu: particle flux units; (ICME): (Interplanetary) Coronal Mass Ejection; Kp: planetary K-index; Dst: Disturbance storm time index; nT: nano Tesla



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)

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.

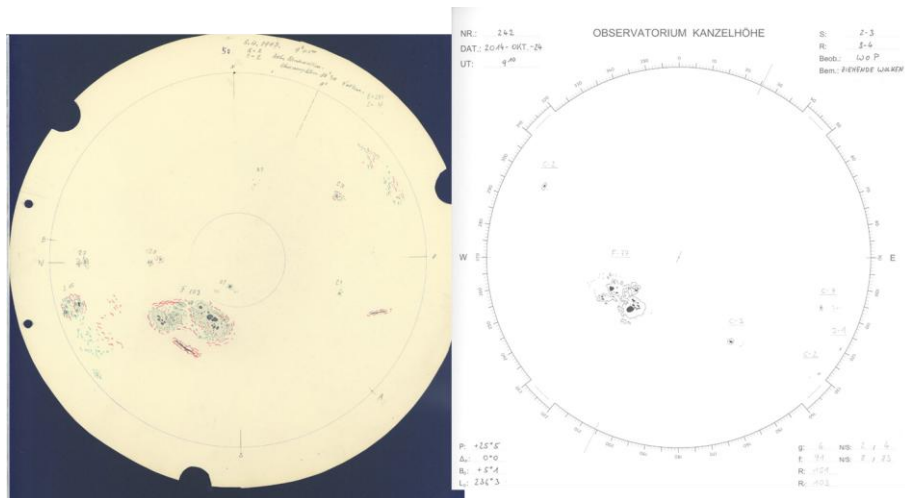
Power law distributions in general appear to yield overestimates.

* 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>

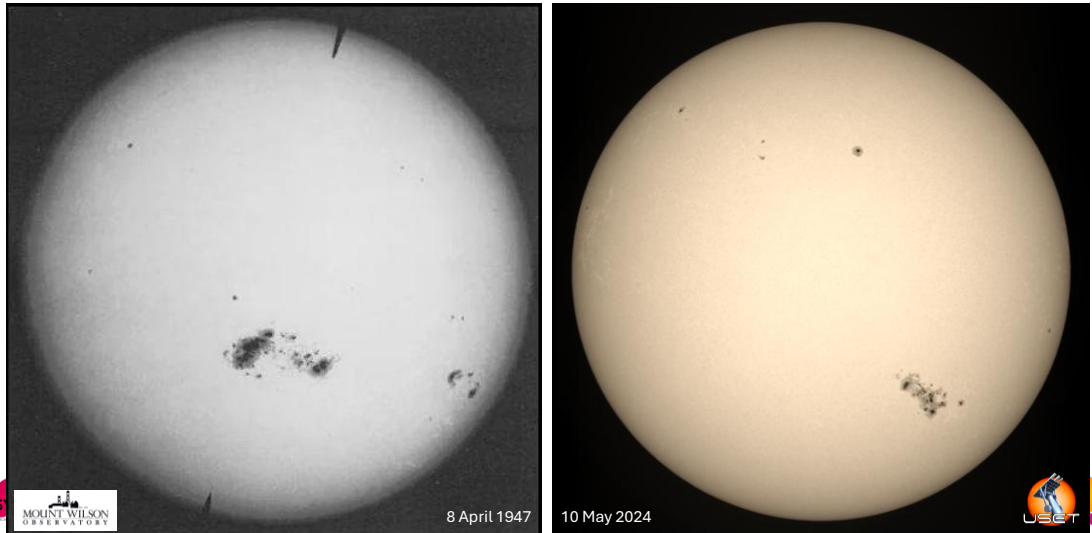
For SC25, the maximum observed values so far are as follows: NOAA 13664 (3360 MH) in May 2024; X9.0 on 3 October 2024; RBR at GNSS frequencies of 230.000 sfu on 28 August 2022; Fastest CME: 31 Dec 2023 (2427 km/s) from AR3536 (X5.0 flare) ; Dst: -406 nT on 11 May 2024.

Largest sunspot groups in SC18 and SC24



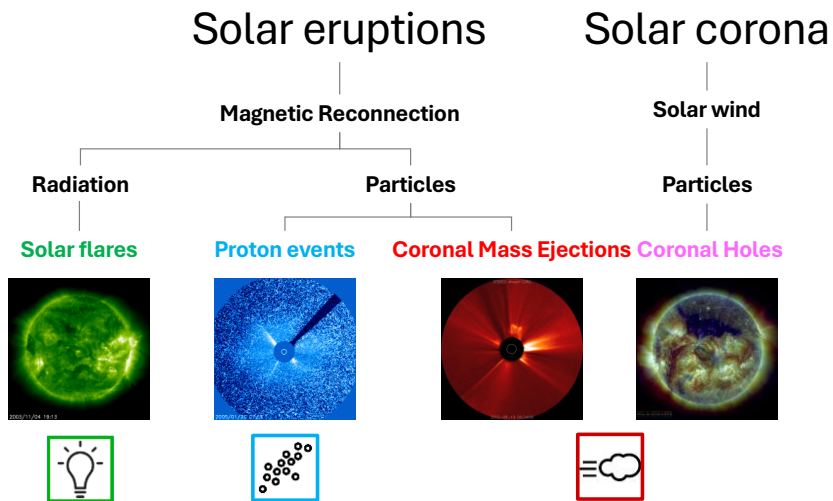
Largest sunspot groups on 8 April 1947 (Greenwich #1488603; Kanelhöhe Observatory) and 24 Oct 2014 (NOAA 12192) with areas of resp. 6132 MH and 3850 MH. The latter value has been corrected for the Greenwich-to-NOAA transition (see the Solar Cycle Science webpage at <http://solarcyclescience.com/activerregions.html>). 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

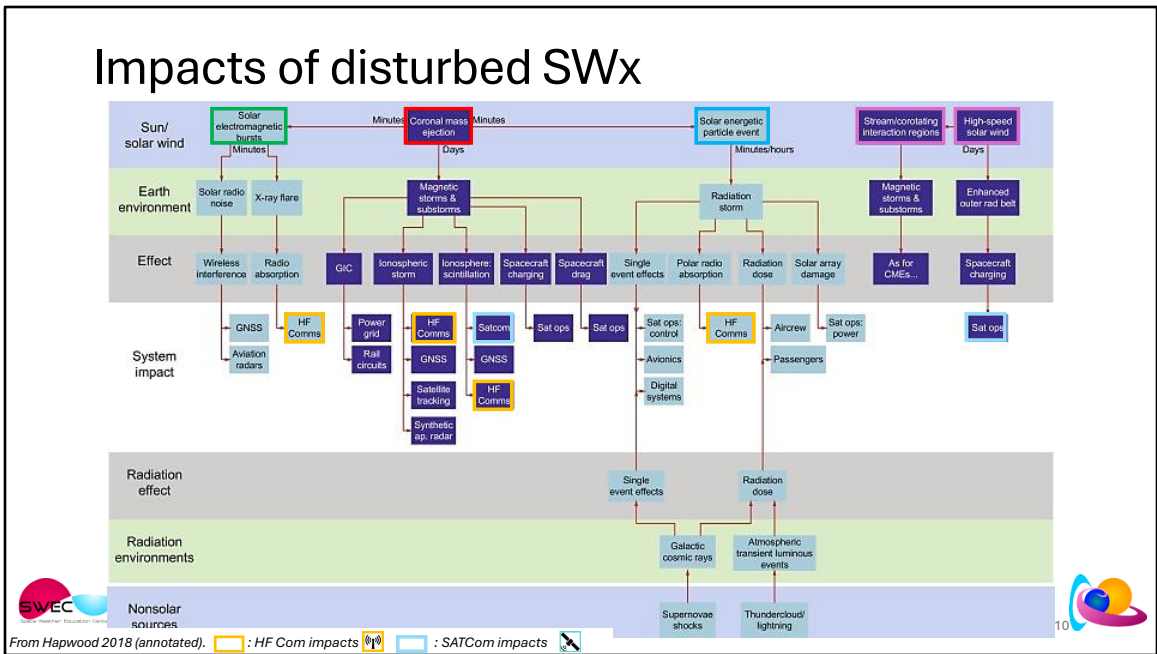


Largest sunspot groups on 8 April 1947 (Greenwich #1488603; photographed at Mount Wilson) and 10 May 2024 (NOAA 13664; photographed at SIDC/USET) with areas of resp. 6132 MH and 3360 MH. The latter value has been corrected for the Greenwich-to-NOAA transition (see the Solar Cycle Science webpage at <http://solarcyclescience.com/activeregions.html>). 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



Impacts of disturbed SWx

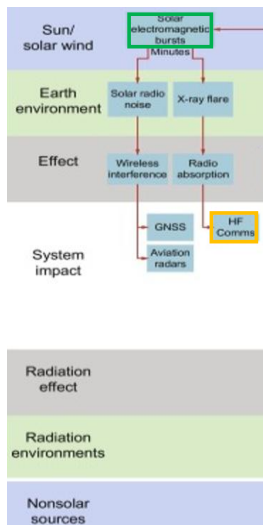


Annotated from Hapgood, M. 2018. Linking Space Weather Science to Impacts - The View From the Earth <https://doi.org/10.1016/B978-0-12-812700-1.00001-7> (Figure 1)

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



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

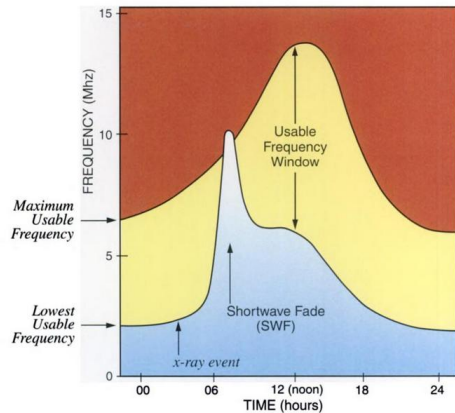


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Note there's also a non-solar source of highly energetic electromagnetic radiation that may affect the ionosphere (and VLF signals in particular): Gamma-Ray Bursts (GRB). See e.g. <https://www.stce.be/news/610/welcome.html>



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

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?

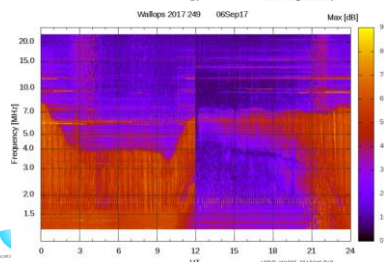
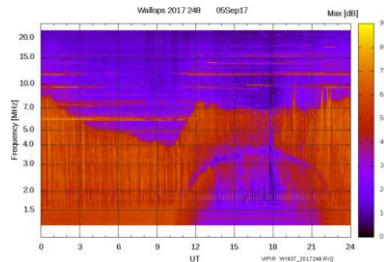
- The usage frequency window for radio propagation lies between the lowest and maximum usable frequencies, i.e. LUF and MUF. When the window closes, as shown here, a shortwave fade occurs.

- The MUF depends on critical ionospheric frequency (f_oF_2) 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>).

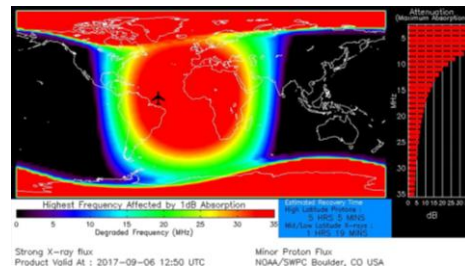


Impacts from solar flares on HF Com



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



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

Minor Proton Flux NOAA/SWPC Boulder, CO USA



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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).

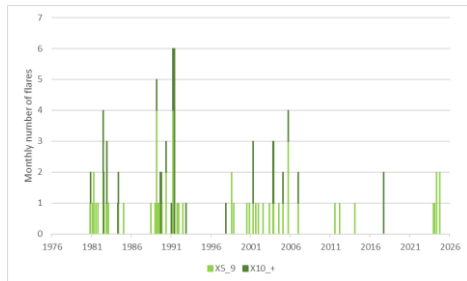
See also STCE news items at <http://www.stce.be/news/402/welcome.html> and <http://www.stce.be/news/400/welcome.html>

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



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



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)

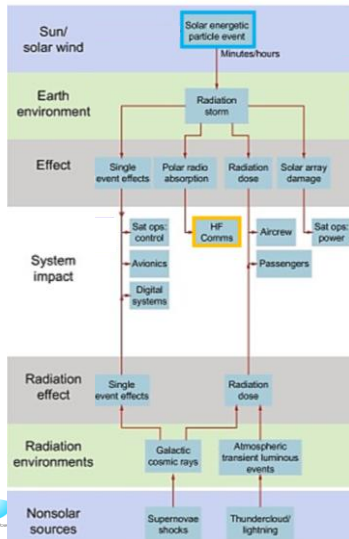
Information on Sudden Ionospheric Disturbances (1958-2014) can be found at <https://www.ngdc.noaa.gov/stp/solar/sid.html> and <https://www.aavso.org/solar>
 Classification of SID/SWF (i.a.w. duration) is at <https://www.ngdc.noaa.gov/stp/solar/sid.html>

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 $df_{min} \geq 2.5$ MHz and 11.5 h for $df_{min} \geq 3.5$ MHz. The extreme points, 8 h 15 min for $df_{min} \geq 2.5$ MHz and 5 h 15 min for $df_{min} \geq 3.5$ 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.]

Impacts from SEP events



• From SEP events

- Single event effects
 - Affect mainly avionics/electronics
 - Ground Level Enhancement (GLE)
- Polar Cap Absorption (PCA)
 - Deviated by MF to poles
 - Affects D-region
 - Impacts HF Com at polar regions
- Radiation
 - Biological component
- Solar array damage
- Non-solar sources
 - Supernovae (GCR)
 - Thundercloud lightning (TLE)
 - South Atlantic Anomaly (LEO)



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



Non-solar sources

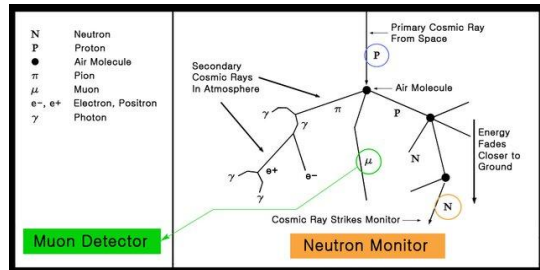
- Supernovae and Black Hole activity contribute to the Galactic Cosmic Rays (GCR), a continuous low flux of highly energetic particles (think several GeV) that penetrates into the solar system. The effects are similar to the ordinary SEP events. The stream is solar cycle modulated, with the highest numbers 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 lightning 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



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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

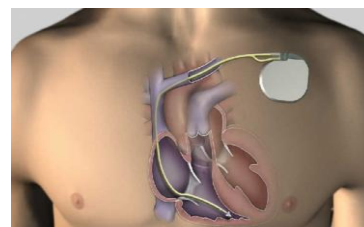
<https://web.archive.org/web/20131021190327/http://pdf.yuri.se/files/art/2.pdf>



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/air/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.

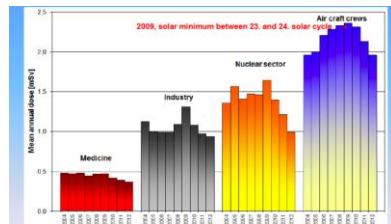
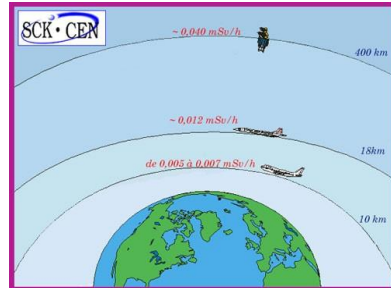
Pacemaker incident: Baraniuk 2022 - <https://www.bbc.com/future/article/20221011-how-space-weather-causes-computer-errors> ; https://www.linkedin.com/posts/mariemgmo_the-computer-errors-from-outer-space-activity-6987414548366422016-v3AU/?trk=public_profile_like_view ; Other examples in Meier et al. 2020 - 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
 - $\mu\text{Sv/h}$, 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 $\mu\text{Sv/h}$
 - Severe: 80 $\mu\text{Sv/h}$



GLE: Ground Level Enhancement ; $\mu\text{Sv/h}$: 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>



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Exposure measured in mSv

10,000	Fatal within weeks
6,000	Typical dosage recorded in those Chernobyl workers who died within a month
5,000	Single dose which would kill half of those exposed to it within a month
1,000	Single dose which could cause radiation sickness, nausea, but not death
400	Max radiation levels recorded at Fukushima plant 14 March, per hour
350	Exposure of Chernobyl residents who were relocated
100	Recommended limit for radiation workers every five years
10	Dose in full-body CT scan
9	Airline crew NYC -Tokyo polar route, annual
2	Natural radiation we're all exposed to, per year
1.02	Radiation per hour detected Fukushima site, 12 March
0.4	Mammogram breast x-ray
0.1	Chest x-ray
0.01	Dental x-ray

SOURCE: WNA, RADIOLOGYINFO.ORG, REUTERS



GLE: Ground Level Enhancement ; $\mu\text{Sv/h}$: microsievert per hour ; mSv: millisievert ; FL: Flight Level (100 feet)

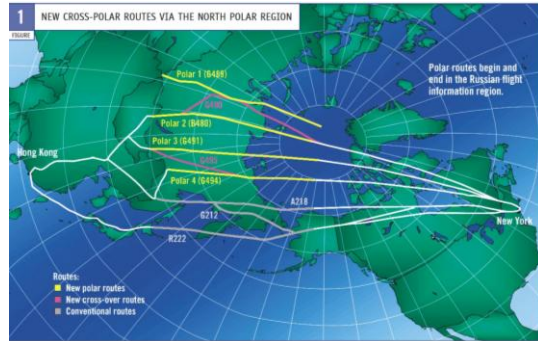
Figure from <https://www.theguardian.com/news/datablog/2011/mar/15/radiation-exposure-levels-guide>



SWx impacts from SEP events : Biological



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 - Decrease altitude
 - Reroute (away from poles)



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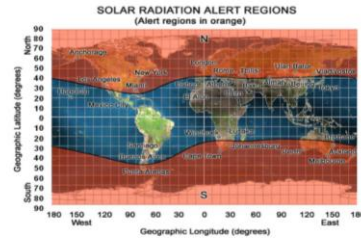
More info at https://english.hani.co.kr/arti/english_edition/e_business/850390



SWx impacts from SEP events : Biological



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 - Can damage DNA and cause cancer & reproductive problems
- Radiation dose
 - $\mu\text{Sv/h}$, mSv/year
 - ICAO thresholds
- Mitigation polar flights
 - Halloween storms October 2003
 - Severe storm (29.500 pfu) + GLE (3!)
 - Decrease altitude
 - Reroute (away from poles)



Space Weather Message Code: ALTPAV Issue Time: 2003 Oct 28 2123 UTC
 ALERT: Solar Radiation Alert at Flight Altitudes
 Conditions Began: 2003 Oct 28 2113 UTC

Comment:
 Satellite measurements indicate unusually high levels of ionizing radiation, coming from the sun. This may lead to excessive radiation doses to air travelers at Corrected Geomagnetic (CGM) Latitudes above 35 degrees north, or south.

Avoiding excessive radiation exposure during pregnancy is particularly important.

Reducing flight altitude may significantly reduce flight doses. Available data indicates that lowering flight altitude from 40,000 feet to 36,000 feet should result in about a 30 percent reduction in dose rate. A lowering of latitude may also reduce flight doses but the degree is uncertain. Any changes in flight plan should be preceded by appropriate clearance.



GLE: Ground Level Enhancement ; $\mu\text{Sv/h}$: 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

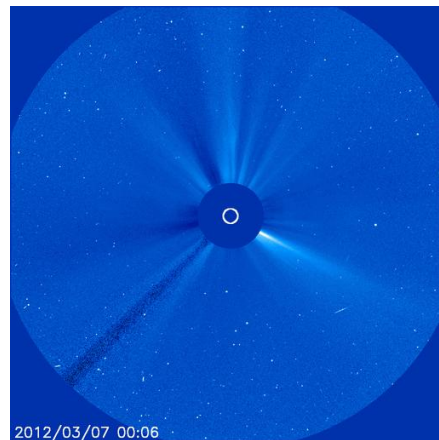
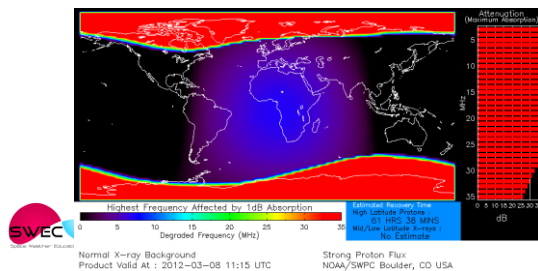
... SEC [Space Environment Center – today’s SWPC] staff participated in teleconferences with major airlines at an average rate of three to five times a day. Teleconferences were conducted by SEC staff with airline dispatchers, pilots, and airline safety personnel as an important part of their decision 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

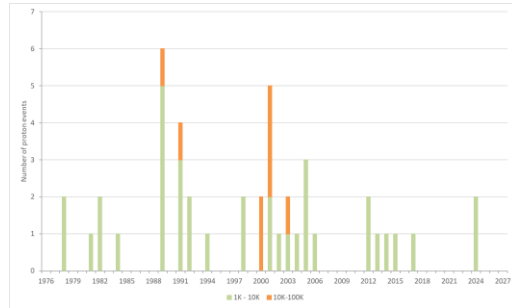
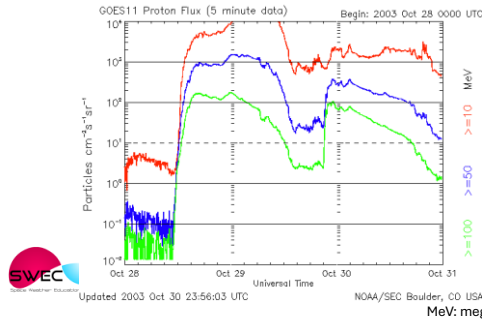


• Thresholds

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

• Frequency

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



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 (Day/UT)	Maximum Proton Flux (pfu @ >10 MeV)	Proton Flux	CME	Flare Max. (Loc./ Day UT)	Importance (Xray/Opt.)	Location Region# (SWO)	Region#
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



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

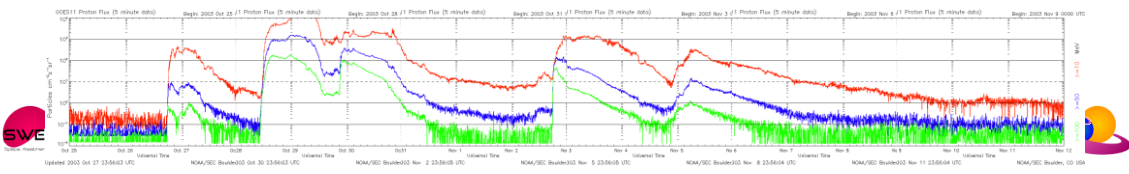
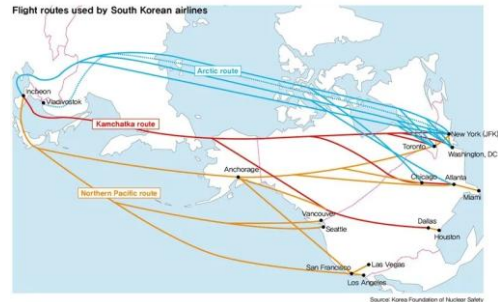


Figure from https://english.hani.co.kr/arti/english_edition/e_business/850390

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

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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. **MacRelay experienced over 130 hours of HF communication blackout during the October – November activity.** [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.



Impacts from SEP events on HF Com



- The disappearance of the HMS Acheron (1956)



From the « Amsterdam Evening Recorder » (24 February 1956) - Via [https://en.wikipedia.org/wiki/HMS_Acheron_\(P411\)#cite_note-5](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

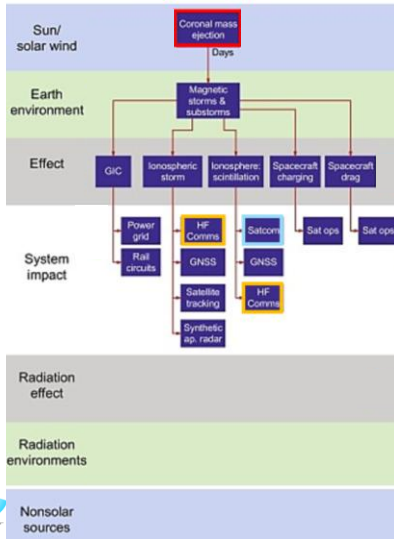
LONDON (UP)—The Admiralty today called off a search for the British submarine Acheron, sighted safe in gale-swept seas after being feared lost for nearly six hours. The British minesweeper Coquette radioed three hours after the Admiralty reported the Acheron overdue that she had made "visual contact"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

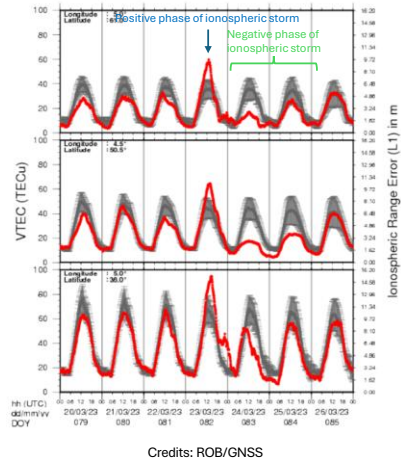
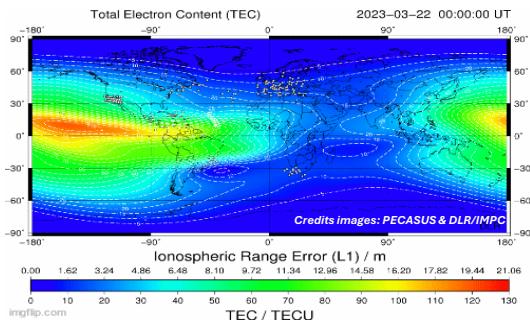




Impact from ICMEs on HF Com



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



(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>

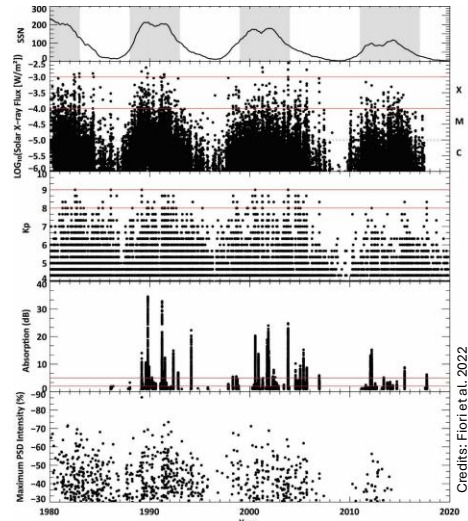
<https://www.stce.be/news/638/welcome.html>



Impact from ICMEs on HF Com



- Auroral Absorption (AA)
 - HF Com degradation due to aurora affecting lower ionosphere
 - 18-19 September 1941
 - $K_p \geq 9$ - 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-](https://www.swsc-journal.org/articles/swsc/full_html/2022/01/swsc220003/swsc220003.html)

[journal.org/articles/swsc/full_html/2022/01/swsc220003/swsc220003.html](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 ($K_p = 8, 9$), 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.”



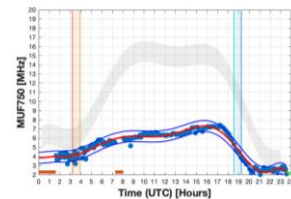
Impact from ICMEs on HF Com



- 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



Ionosphere Maximum Usable Frequency (MUF750)
Date : 2023-03-24 Day Number : 063
Time : 23:33:16 [UTC]



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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!"

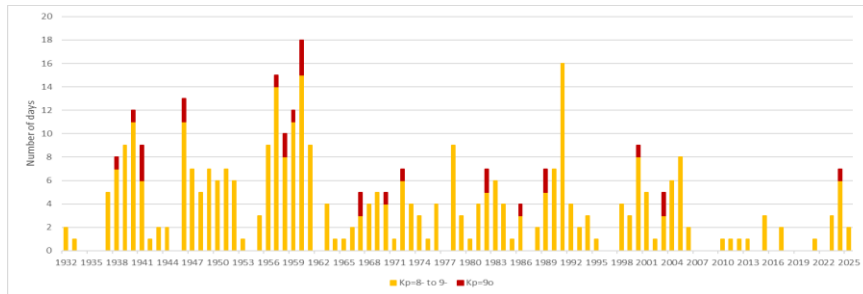
The geomagnetic storm affected GNSS applications and HF communications. The figure in the lower right is from IMPC (<https://impc.dlr.de/projects/current-projects/>) and shows that -for that day- the maximum useable HF frequency (MUF) to cover a distance of 750 km was only about 7-8 MHz, whereas during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



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



30



Impact from ICMEs on HF Com

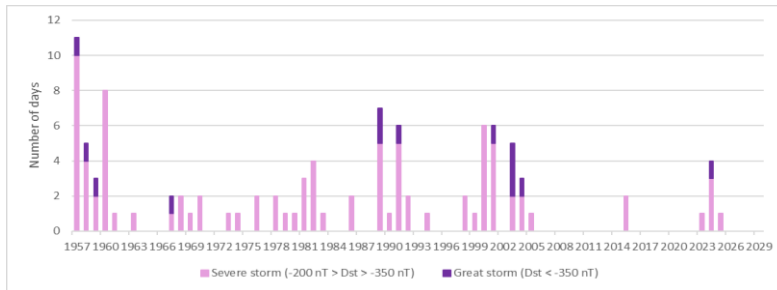


• Frequency geomagnetic storms

- **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

Kp

Severe storms: Kp = 8- to 8+, 9-

Extremely severe storms: Kp = 9o

Dst

Severe storms: $-200 \geq Dst > -350$

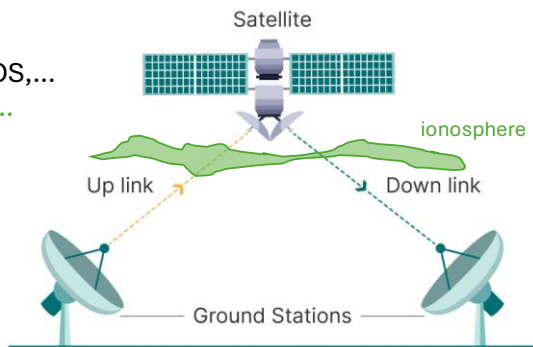
Extreme storms: $Dst \leq -350$ nT



Impact from ICMEs on SATCom



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



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



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



• Satellite Communication (SATCom)

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

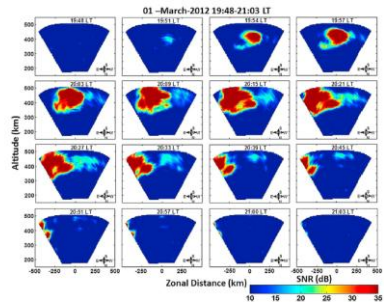


Figure 1. An example showing the genesis and successive development of EPB (looking type) over Kottabang observed from the fan sector maps of EAI on 1 March 2012.



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



33

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>

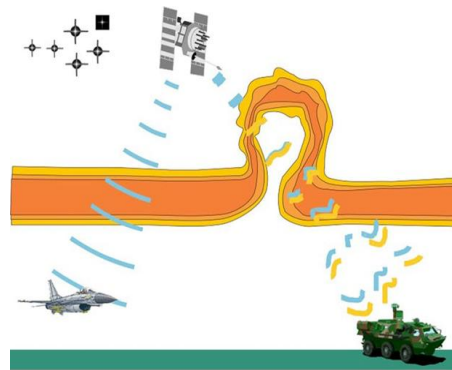
Also Traveling Ionospheric Disturbances: <https://www.tech-tide.eu/>



Impact from ICMEs on SATCom



- 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



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>

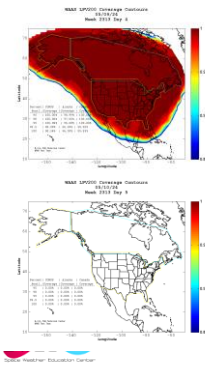
During Operation Anaconda, the Battle of Takur Ghar occurred at the summit of a 3191 m Afghan mountaintop on 4 March 2002 when the ionosphere was disturbed and could have affected UHF Satellite Communications (SATCOM). In this paper, we consider UHF SATCOM outages that occurred during repeated attempts 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

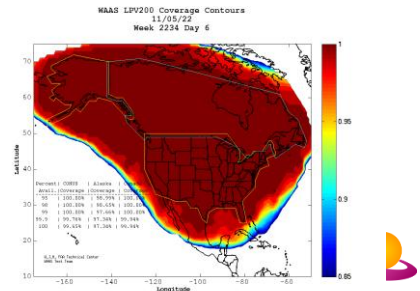


- Satellite Communication (SATCom)
 - GNSS applications such as WAAS / EGNOS
 - 10-11 May 2024 ($Kp = 9.0$)



- WAAS Extreme storm detector (ESD) tripped for the first time since its inception in 2007 causing an extended loss of LPV/LPV200 over entire WAAS coverage volume
 - NOTAMs issued advising on navigational disruptions
 - EGNOS limited over Europe
 - ESD tripped again during the 10-11 Oct 2024 storm...

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



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.

Sources: Input from presentations during the ESWW2024 in Coimbra, Portugal (<https://esww2024.org/>)

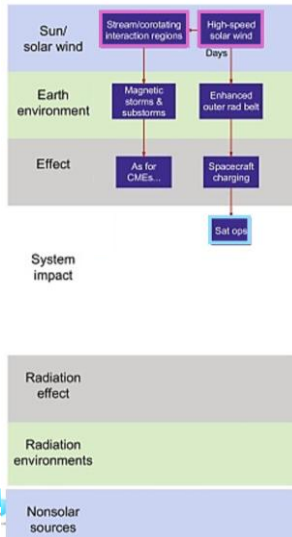
- Impacts of Space Weather on Aviation and FAA Insights from the May Solar Storms - by Samantha Watson, Karen Shelton-Mur (FAA)

- 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 weather service to ICAO - by Loredana Perrone (INGV) et al.



Impact from CH HSS on SATCom



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

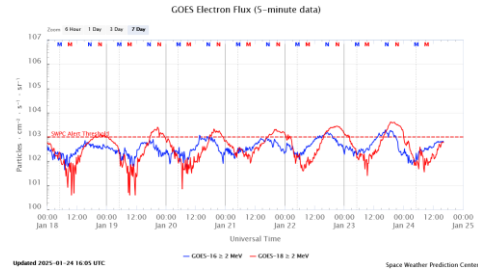




Impact from CH HSS on SATCom



- High-Speed Stream (HSS)
 - Satellite charging
 - Deep di-electric charging
 - About 1 to a few MeV e⁻
 - Deeply penetrate spacecraft (S/C)
 - Fluxes > 2 MeV e⁻
 - Accumulation effect within S/C (ESD: electrostatic discharge)



Top right figure: <https://www.spaceweather.gc.ca/forecast-previous/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>

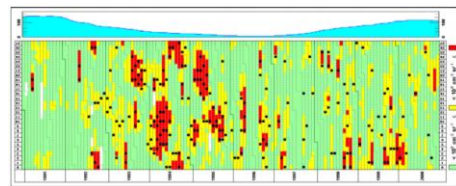
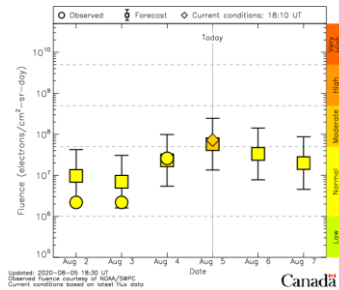
Also at the STCE's SWx Classification page <https://www.stce.be/educational/classification#electrons> and the STCE's SC25 Tracking page <https://www.stce.be/content/sc25-tracking#electron>



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).

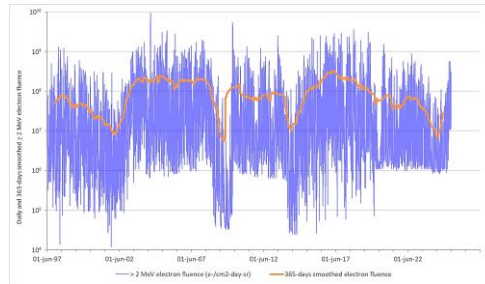
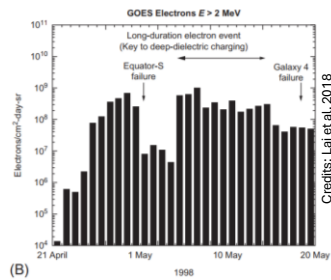
The production mechanism for these waves is not completely understood, but a leading candidate is the Kelvin-Helmholtz instability at the magnetopause, which can energize waveguide modes that carry pulsation power into the inner magnetosphere and ionosphere. Recent estimates based on observations suggest 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

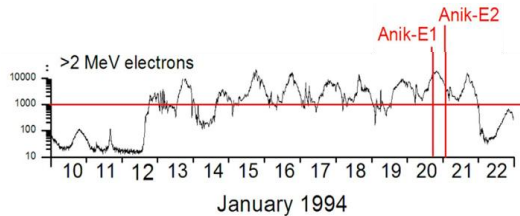
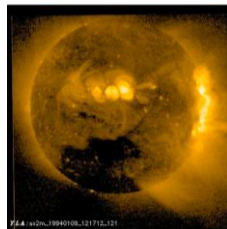
One area that is the subject of a concentrated research effort is the mechanism for generation and loss of relativistic electrons in the radiation belts. Large geomagnetic storms can have drastic effects on the population of relativistic electrons in the inner magnetosphere; this can include the creation 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 through 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).



Impact from CH HSS on SATCom



Frequency High fluence: ~17 days / year



Credits: Lam et al., 2012



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 $9.3 \cdot 10^9$ 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 ($> 5 \cdot 10^8$ electrons/cm² 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/ful/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
 Solar flares	Short-Wave Fade (SWF)	
 Solar energetic particle events (SEP)	Polar Cap Absorption (PCA)	
 Interplanetary coronal mass ejections (ICME)	Auroral Absorption (AA) Post-Storm Depression (PSD)	Ionospheric scintillation
 High speed streams from coronal holes (HSS/CH)		Deep di-electric charging

