SPACE WEATHER INTRODUCTORY COURSE

SWIC

Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

SWEC
Space Weather Education Center

Space weather impacts

Jan Janssens

Space Weather impacts (SWx impacts)

- ***Recap***
- *SWx impacts from*
  - *Solar flares*
  - *Proton events*
  - *ICMEs*
  - *Coronal holes*

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Space Weather (SWx)

- Space weather refers to the environmental conditions in Earth's magnetosphere, ionosphere and thermosphere due to the Sun and the solar wind that can influence the functioning and reliability of spaceborne and ground-based systems and services or endanger property or human health.

NSWP

- Space Weather is the physical and phenomenological state of natural space environments. The associated discipline aims, through observation, monitoring, analysis and modelling, at understanding and predicting the state of the Sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them, and also at forecasting and nowcasting the potential impacts on biological and technological systems.

ESA, COST Action 724

NSWP: National Space Weather Program ; ESA: European Space Agency ; COST: (European) COoperation in Science & Technology

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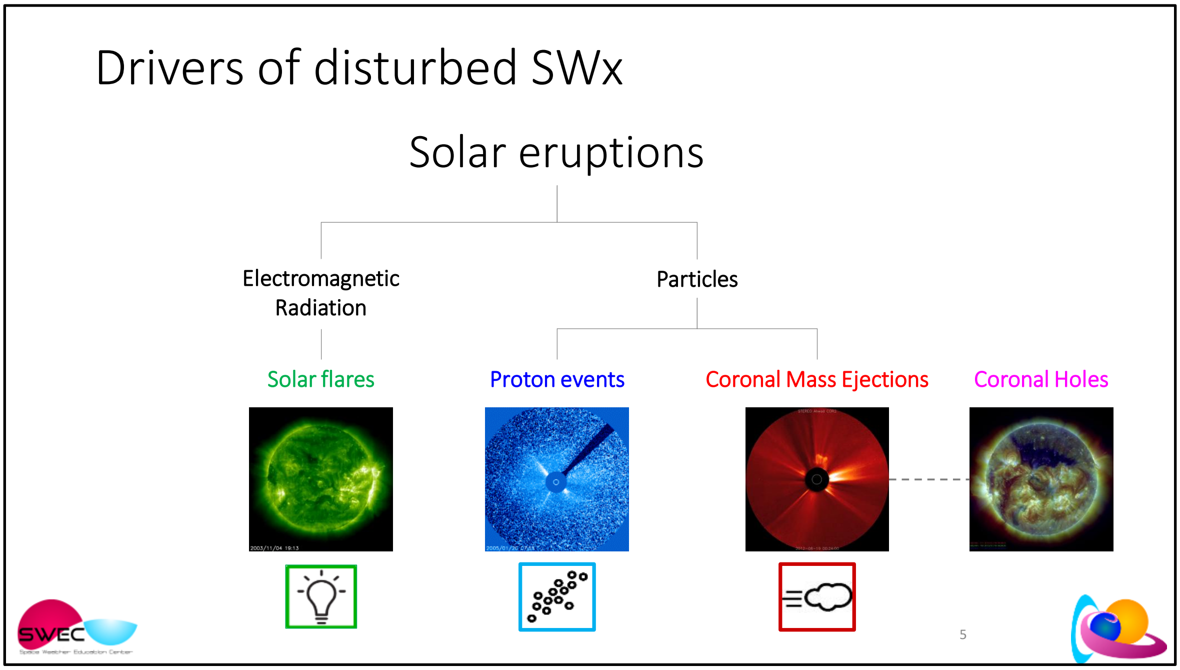
ESA: https://swe.ssa.esa.int/what-is-space-weather and Wall of Peace
Space Weather is the physical and phenomenological state of natural space environments. The associated discipline aims, through observation, monitoring, analysis and modelling, at understanding and predicting the state of the Sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them, and also at forecasting and nowcasting the potential impacts on biological and technological systems. -COST Action 724 , 2009

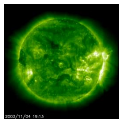
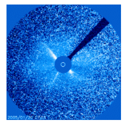
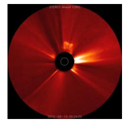
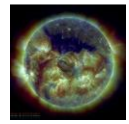
National Space Weather Program (USA)
http://www.spaceweathercenter.org/swop/NSWP/1.html



SWx: Space weather

Disturbed Space weather

Causes

Solar flares	Proton events	Coronal Mass Ejections	Coronal Holes
			

	Solar flares	Proton events	Coronal Mass Ejections	Coronal Holes
Arrival	Immediately (8')	15 min to a few hours	20 to 72+ hours	2 to 4 days
NOAA scales	R1 (minor) => R5 (extreme)	S1 (minor) => S5 (extreme)	G1 (minor) => G5 (extreme)	
Parameter	M1 => $\geq$ X20	pfu (>10MeV): 10 => 10^5	Kp = 5 => Kp = 9	
Duration	Minutes to hours	Hours to days	Days	
Protection	Earth's atmosphere	Earth's magnetic field	Earth's magnetic field	

Effects

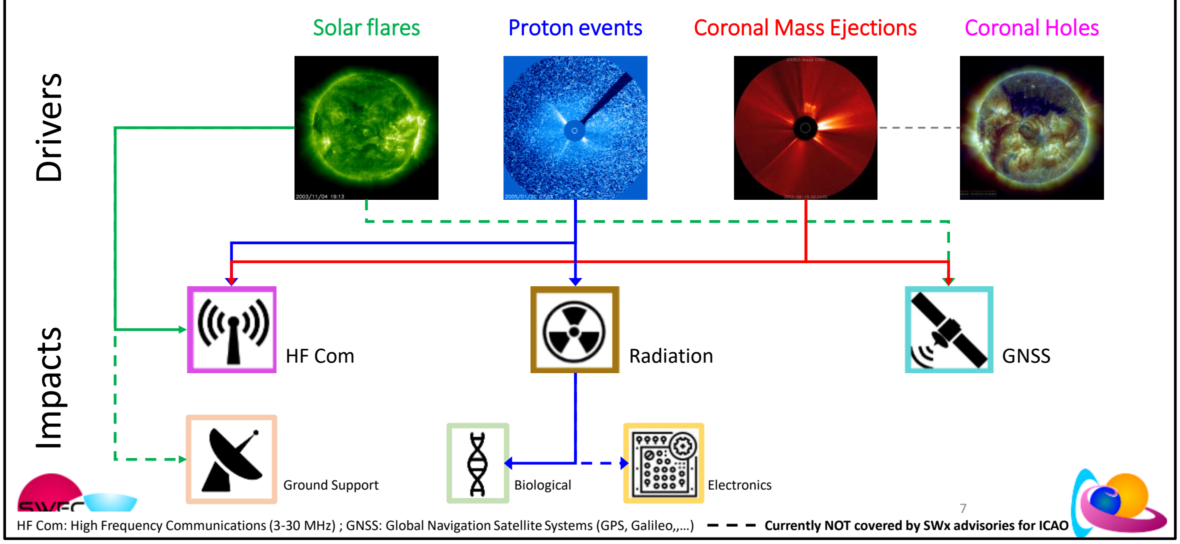
Solar flares	Proton events	Coronal Mass Ejections	Coronal Holes
Radio communications	Satellites	Satellites	
Radar interference	Astronauts & Airplanes	Aurora	
	Communication/Navigation	Communication/Navigation	
	Ozone	Electrical Currents (GIC)	

1 pfu = 1 proton / cm^2 s sr ; MeV: megaelectronvolt

Baker et al. (2016): Resource Letter SW1: Space Weather
https://ui.adsabs.harvard.edu/abs/2016AmJPh..84..166B/abstract
http://aapt.scitation.org/doi/pdf/10.1119/1.4938403

Valtonen (2004): Space Weather: Effects on Space Technology
http://slideplayer.com/slide/3603908/

SWx impacts on aviation



Kauristie et al. (2019) - Space Weather Services for Civil Aviation—Challenges and Solutions
https://www.mdpi.com/2072-4292/13/18/3685

ICAO thresholds for advisories

Table 1. Parameters and thresholds that are used to issue space weather advisories according to ICAO regulations.

Impact Area	Parameter (Unit)	Moderate	Severe
GNSS	Amplitude scintillation S4 (dimensionless)	0.5	0.8
	Phase scintillation σ_ϕ (radians)	0.4	0.7
	Vertical TEC (TEC Unit)	125	175
Radiation	Effective dose (μSievert/hour)	30	80
HF	Auroral absorption (Kp)	8	9
	PCA (dB from 30 MHz riometer data)	2	5
	Solar X-ray (W/m^2) (0.1–0.8 nm)	10^{-4}	10^{-3}
	MUF (%)	30	50

Credits: Kauristie et al. 2019

ICAO: International Civil Aviation Organization ; GNSS: Global Navigation Satellite Systems (GPS, Galileo,,...) ; (V)TEC: (Vertical) Total Electron Content ; TECU: TEC unit ; PECASUS: Pan-European Consortium for Aviation Space weather User Services ; HF: High Frequency (3-30 MHz) ; Kp: planetary K index ; PCA: Polar Cap Absorption ; dB: decibel ; MHz: megahertz ; W: Watt ; nm: nanometer (10^{-9} m) ; MUF: Maximum Usable Frequency

Kauristie et al. (2019) - Space Weather Services for Civil Aviation—Challenges and Solutions
https://www.mdpi.com/2072-4292/13/18/3685

Space Weather impacts (SWx impacts)

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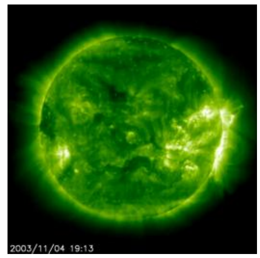
Solar flares



SWx impacts from solar flares

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
R 5	Extreme	**HF Radio:** Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2×10^{-3})	Less than 1 per cycle
R 4	Severe	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5×10^{-5})	350 per cycle (300 days per cycle)
R 1	Minor	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

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Info at:
https://www.swpc.noaa.gov/noaa-scales-explanation
SWPC: https://www.swpc.noaa.gov/phenomena/solar-flares-radio-blackouts
SWS: http://www.sws.bom.gov.au/Educational/1/3/5

Zhang et al. (2011): Impact factor for the ionospheric total electron content response to solar flare irradiation
http://onlinelibrary.wiley.com/doi/10.1029/2010JA016089/full
As one of the fastest and severest solar events, the solar flare, which is mainly classified according to the peak flux of soft x-rays in the 0.1–0.8 nm region measured on the GOES x-ray detector, has a great influence on the earth upper atmosphere and ionosphere. During a flare, the extreme ultraviolet (EUV) and x-rays emitted from the solar active region ionize the atmospheric neutral compositions in the altitudes of ionosphere to make the extra ionospheric ionization that causes many kinds of sudden ionospheric disturbance phenomenon (SID), which are generally recorded as sudden phase anomaly (SPA), sudden cosmic noise absorption (SCNA), sudden frequency deviation (SFD), shortwave fadeout (SWF), solar flare effect (SFE) or geomagnetic crochet, and sudden increase of total electron content (SITEC) [*Donnelly*, 1969; *Mitra*, 1974].

Strongest X-class flares of SC25 (earth-facing side): X8.7 on 14 May 2024 by NOAA 13664 ; X9.0 on 3 October 2024 by NOAA 13842
STCE newsitem: https://www.stce.be/news/704/welcome.html ; STCE newsitem: https://www.stce.be/news/700/welcome.html
STCE newsitem: https://www.stce.be/news/727/welcome.html ; STCE newsitem: https://www.stce.be/news/726/welcome.html
SC25 Tracking page: https://www.stce.be/content/sc25-tracking

Strongest X-class flare of SC25 (Sun's far side – PROXY only): X12 on 20 May 2024 and X14 on 22 July 2024
STCE newsitem: https://www.stce.be/news/712/welcome.html
STCE newsitem: https://www.stce.be/news/716/welcome.html

SWx impacts from solar flares

- From EUV & X-ray radiation
  - Solar flare effect (“magnetic crochet”)
    - => Effects from ICMEs
  - Shortwave fade (“Radio Blackout”)
    - => PECASUS
- From radio emission
  - GNSS disturbances
  - Radar disturbances

EUV: Extreme Ultraviolet ; GNSS: Global Navigation Satellite Systems ; VLF: Very Low frequency ; MF/HF: Medium/High Frequency
PECASUS: Pan-European Consortium for Aviation Space weather User Services

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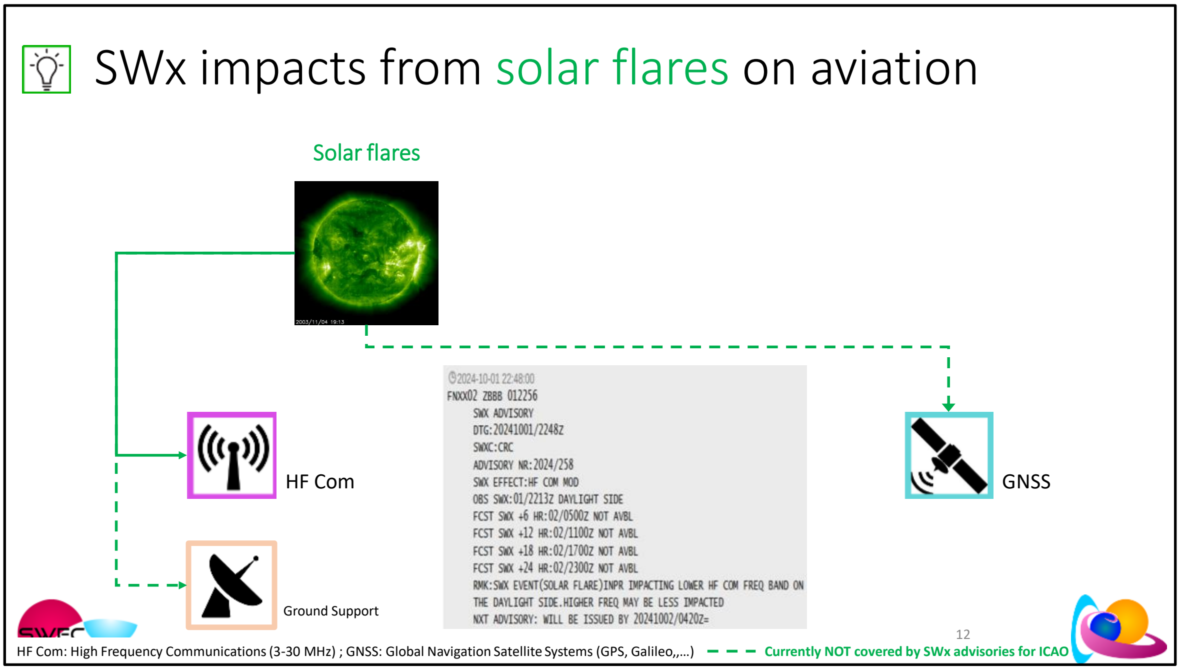
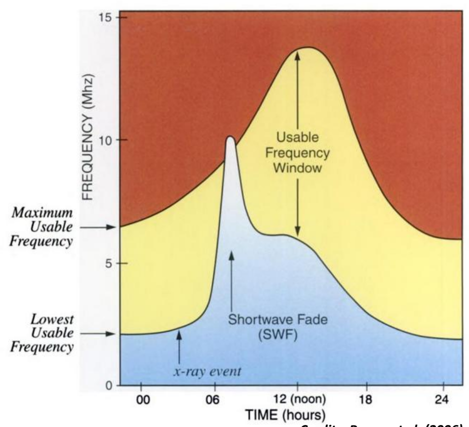
A comprehensive discussion on the immediate effects from solar flares is at
NGDC: Sudden Ionospheric Disturbance
https://www.ngdc.noaa.gov/stp/space-weather/ionospheric-data/sids/documentation/readme_sudden-ionospheric-disturbances.pdf
https://www.ngdc.noaa.gov/stp/space-weather/ionospheric-data/sids/documentation/

Sudden Ionospheric Disturbance (after Wikipedia, 2014) – A sudden ionospheric disturbance (SID) is an abnormally high ionization/plasma density in the D region of the ionosphere caused by a solar flare. The SID results in a sudden increase in radio-wave absorption that is most severe in the upper medium frequency (MF) and lower high frequency (HF) ranges, and as a result often interrupts or interferes with telecommunications systems. The Dellinger effect, or Mögel–Dellinger effect, is another name for a sudden ionospheric disturbance. The effect was discovered by John Howard Dellinger around 1935 and also described by the German physicist Hans Mögel in 1930. The fadeouts are characterized by a sudden onset and by a recovery that takes minutes or hours.
When a solar flare occurs on the Sun a blast of intense ultraviolet and x-ray radiation hits the dayside of the Earth after a propagation time of about 8 minutes. This high energy radiation is absorbed by atmospheric particles, raising them to excited states and knocking electrons free in the process of photoionization. The low-altitude ionospheric layers (D region and E region) immediately increase in density over the entire dayside. The ionospheric disturbance enhances VLF radio propagation. Scientists on the ground can use this enhancement to detect solar flares; by monitoring the signal strength of a distant VLF transmitter, sudden ionospheric disturbances (SIDs) are recorded and indicate when solar flares have taken place.
Short wave radio waves (in the HF range) are absorbed by the increased particles in the low altitude ionosphere causing a complete blackout of radio communications. This is called a short-wave fading. These fadeouts last for a few minutes to a few hours and are most severe in the equatorial regions where the Sun is most directly overhead. The ionospheric disturbance enhances long wave (VLF) radio propagation. SIDs are observed and recorded by monitoring the signal strength of a distant VLF transmitter. SIDs are classified in a number of ways including; ShortWave Fadeouts (SWF), Sudden Cosmic Noise Absorption (SCNA), Sudden Enhancement of Atmospherics (SEA/SDA), Sudden Phase Anomalies (SFA), Sudden Enhancements of Signal (SES), Sudden Field Anomalies (SFA) and Sudden Frequency Deviations (SFD).



Kauristie et al. (2019) - Space Weather Services for Civil Aviation—Challenges and Solutions
https://www.mdpi.com/2072-4292/13/18/3685

SWx impacts from solar flares on HFCom



Credits: Poppe et al. (2006)

- 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 areas
  - Duration depends on
    - Intensity/duration solar flare
      - Frequent, long duration X-class flares!
    - Solar zenith angle
  - Advisories for aviation
    - X1/X10 (moderate/severe)

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HF Com: High Frequency Communications (3-30 MHz) ; SXR: soft x-rays ; SATCom: Satellite Communication ; MHz: megahertz

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

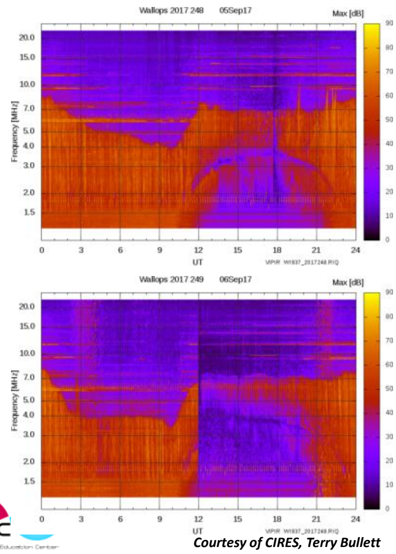
What happens to the MUF and LUF when a strong solar flare occurs?
- The usage frequency window for radio propagation lies between the lowest and maximum usable frequencies, i.e. LUF and MUF. When the window closes, as shown here, a shortwave fade occurs.
- The MUF depends on the critical ionospheric 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).

Advisories for civil aviation (PECASUS): https://pecasus.eu/

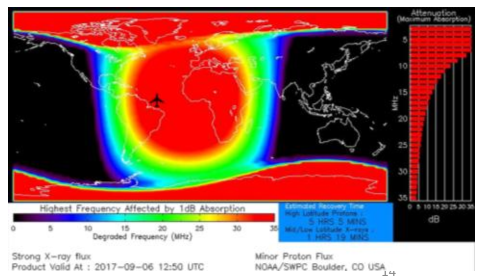
Kauristie et al. (2019) - Space Weather Services for Civil Aviation—Challenges and Solutions
https://www.mdpi.com/2072-4292/13/18/3685

SWx impacts from solar flares on HFCom



Courtesy of CIRES, Terry Bullett

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



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).

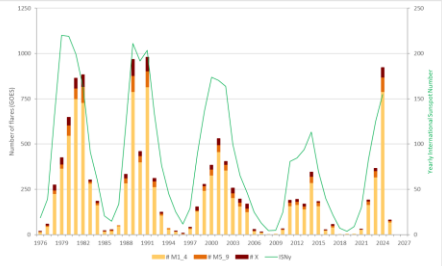
Several news stories from the American Radio Relay League (ARRL) convey the Caribbean radio operator perspective well. A few key excerpts are integrated here. Regarding the X9.3 flare on 6 September, ARRL captures HWN manager Bobby Graves perspective: “In addition to the mix of three hurricanes, the 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).

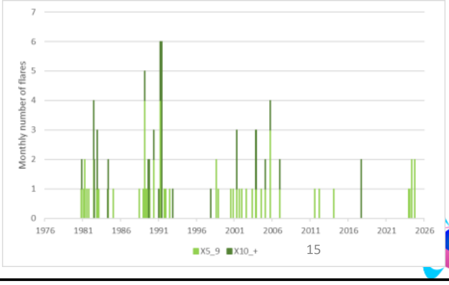
See also STCE news items at http://www.stce.be/news/402/welcome.html and http://www.stce.be/news/400/welcome.html
Some of the SWx effects are at https://phys.org/news/2017-09-massive-sunspots-huge-solar-flares.html ; https://phys.org/news/2017-10-september-intense-solar-viewed-space.html ; http://www.independent.co.uk/news/world/americas/irma-hurricane-solar-flare-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

SWx impacts from solar flares on HF Com

- From EUV and x-rays
  - Short-wave fade (SWF)
    - Disturbance of lower ionosphere
    - Absorbs HF signals
      - “Radio Black-out”
      - Dayside
  - 6-10 September 2017
  - Frequency (weak/strong SC)
    - M-class flares: 110-330 / year
    - X-class flares: 5-25 / year
    - About 9 X5+ flares per SC
      - Large variability per SC!





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

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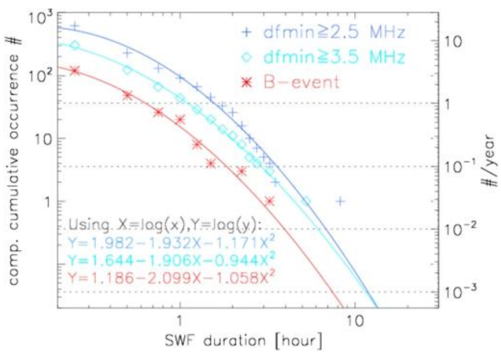
Figure from https://www.stce.be/content/sc25-tracking (February 2025)

In the graph above, the yearly number of flares are binned in 3 classes: M1 to M4, M5 to M9, and the X-class flares. The thin green line represents the yearly International Sunspot Number (ISN). The values for the current year are obviously preliminary. The data sources are NOAA/NGDC (1976-July 2017), and the NOAA/SWPC Weekly bulletins (2017-present). Rescaling of the flares' peak intensity (pre-GOES-16 era) has been performed in accordance with guidelines at NGDC/NOAA.
Following the exceptional flaring activity by NOAA 13664 in May 2024 (STCE news items here and here), *and the very high solar activity during the second half of 2024*, SC25 has now (*up to 31 January 2025*) produced *1341* flares in the M1_M4 range, *135* in the M5_M9 range, as well as *79* X-class flares. *About 9%* of these *1555* M- and X-class flares were produced in May 2024, and we have to go back to March 1991 to find a month with even more M- and X-class flares (resp. 179 vs 143). March 1991 also has 2 X-class flares more than May 2024 (23 vs 21). Finally, May 2024 was the first month with more than 10 X-class flares in a single month since September 2005 with the famous active region NOAA 10808 ... *Note that also October (122 M- and X-class flares) performed well above average. As such, 2024 is only the third year with more than 900 M- and X-class flares in a single year, after 1989 and 1991 (resp. 922, 968 and 979). For comparison; SC24 produced only 1200 M- and X-class flares during its entire duration.*

SWx impacts from solar flares on HFCom



1 (full) SWF event per	Duration (h) *(full SWF)*	Absorption (dB) *(SZA=0° ; f = 6.6MHz)*
1 year	0.63	71
10 years	1.8	130
100 years	4.0	210
1000 years	7.4	320

Estimated extreme events for full SWF (Tao et al. 2020)

HF Com: High Frequency Communications (3-30 MHz) ; SWF: Short-wave fade ; h: hour ; dB: decibel ; SZA: Solar Zenith Angle ; f: frequency ; MHz: megahertz

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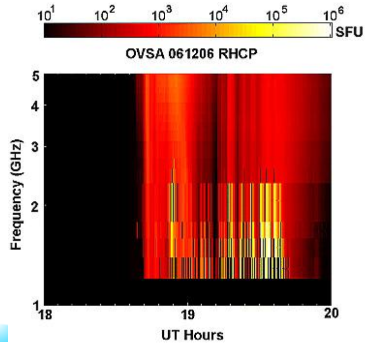
Tao et al. (2020): Statistical analysis of short-wave fadeout for extreme space weather event estimation
https://earth-planets-space.springeropen.com/articles/10.1186/s40623-020-01278-z

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.]

SWx impacts from solar flares on GNSS

- From radio emission @ GNSS frequencies
  - Solar radio burst (SRB)
- 6 December 2006



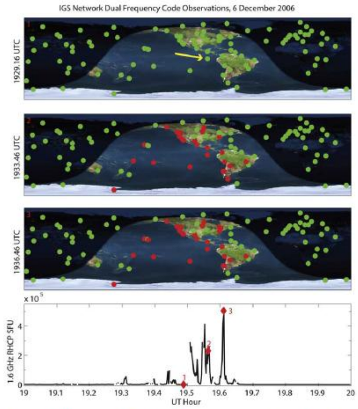


Figure 6. Receivers in the Global GPS Network that were analyzed during the solar radio burst. Green indicates the normal number of satellites being tracked. (fourth panel) During the burst (power at 1.6 GHz), several sunlit receivers tracked fewer than the four satellites needed for a full positioning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

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GNSS: Global Navigation Satellite Systems (GPS, Galileo,…) ; sfu: solar flux units ; GHz: gigahertz ; IGS: International GNSS service — — — Currently NOT covered by SWx advisories for ICAO

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.

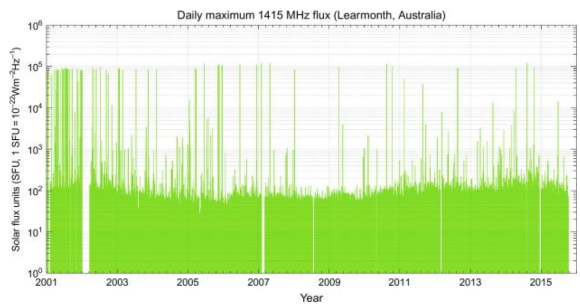
… / …

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.

SWx impacts from solar flares on GNSS

- From radio emission @ GNSS frequencies
  - Overpowers radio signals from satellites
  - 6 December 2006
  - Impact threshold
    - 1000 – 10.000 sfu
    - Not f(SXR intensity)!
    - Sunlit side ; SC minimum
  - Frequency occurrence
    - > 1000 sfu: ~ 8/year
    - > 100.000 sfu: ~ 2/year
    - Degrading effects: ~ 9/SC



Credits: Yue et al. (2018)

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

– – – Currently NOT covered by SWx advisories for ICAO

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.

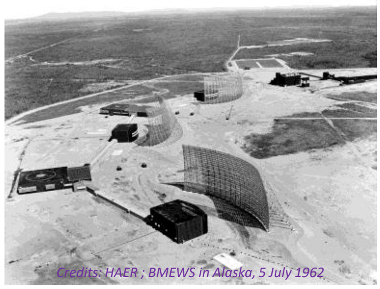
Please note that the intensities of the various radio frequencies as observed by USAF's Radio Solar Telescope Network (RSTN) are saturated at different values. For the observed frequency at 1415 MHz , this saturation level is at 100.000 sfu (Giersch et al. 2017 - https://doi.org/10.1002/2017SW001658). Typical undisturbed values for this frequency during solar cycle minimum and maximum are resp. 50 and 100-150 sfu.

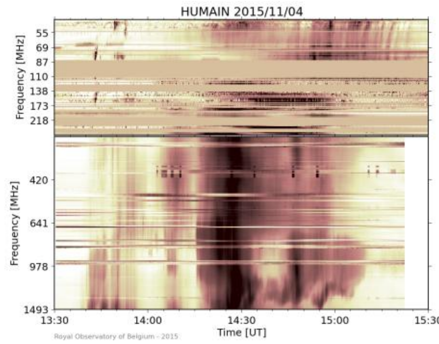
There have been 4 strong radio emission events (at GNSS frequencies) so far this solar cycle: Any effects from the 4 May 2023 radio burst (26.000 pfu), as well as from the 2 strongest bursts so far this solar cycle on 28 August 2022 (230.000 sfu, but saturation effects?) and on 13 June 2022 (98.000 sfu 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 , as well as a paper by Wright et al. (2023 - https://doi.org/10.1051/swsc/2023027) on the 28 August 2022 event reporting a fading of 13 dB at GPS L2 frequency.

The latest event dates from 14 December 2023 and was related to an X2.8 flare in NOAA 3514. At 1415 MHz, a peak of 99.000 sfu was reached, lasting from 17:20 to 18:01UTC. The Type IV burst lasted from 17:15 until 20:34UTC. Dr Marqué noted that "… the event was indeed remarkably intense in radio (about 10^6 SFU at 410 and 610 MHz (if their calibration is correct). In L band it was around 10^5, which is strong but has been seen in the past. There are not so many services at low frequency, but still a few military bands or government communication network (in Europe at least) + a few useful tools on airplanes to help landing safely or for help in positioning." NOAA/SWPC mentioned that "…An X2.8 flare (R3) occurred from Region 3514; located over the far NW area of the Sun. This is likely one of the largest solar radio events ever recorded. Radio communication interference with aircraft were reported by multiple NWS Center Weather Service Units (CWSU) co-located at FAA facilities. These impacts were felt from one end of the Nation to the other. Additionally, SWPC is analyzing a possible Earth-directed Coronal Mass Ejection (CME) associated with this flare. … " (https://www.swpc.noaa.gov/news/strongest-solar-flare-solar-cycle-25). So the impact of this event seems to have been restrained to radio frequencies (HF, VHF), with little impact on GNSS (WAAS remained perfectly operational).

SWx impacts from solar flares on Ground Suppo

- Radar disturbance
  - 4 November 2015
    - M3 flare paralyzes Swedish air traffic
  - 23 May 1967
    - BMEWS disturbed
- Radio meteors





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On 4 November, NOAA 2443 produced an M3.7 flare peaking at 13:39UT. This at first sight very normal flare was associated with strong radio and ionospheric disturbances that also affected radar and GPS frequencies. As a result, Swedish air traffic was halted for about an hour during the afternoon. The air traffic problems started at the most intense phase of the radio storm, and followed right on the heels of a minor geomagnetic storm caused by the high speed stream of a coronal hole. The CME associated with the M3 flare would cause a moderate (Kp = 6) geomagnetic storm during the first half of 7 November. During the ESWW12, it was communicated that signals from some GPS satellites were affected (degradation), but that there was always a sufficient number of satellites available to assure a properly operating GPS service.

See also STCE news item at https://www.stce.be/news/326/welcome.html ; and http://www.cbc.ca/news/technology/solar-storm-sweden-1.3304271 ; and https://phys.org/news/2015-11-sweden-solar-flare-flight.html

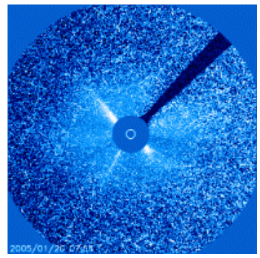
A full discussion of this event: Opgenoorth et al. (2016): Solar activity during the space weather incident of Nov 4., 2015 - Complex data and lessons learned - https://ui.adsabs.harvard.edu/abs/2016EGUGA..18120170/abstract
During the afternoon of November 4, 2015 most southern Swedish aviation radar systems experienced heavy disturbances, which eventually forced an outing of the majority of the radars. In consequence the entire southern Swedish aerospace had to be closed for incoming and leaving air traffic for about 2 hours. Immediately after the incident space weather anomalies were made responsible for the radar disturbances, but it took a very thorough investigation to differentiate disturbances from an ongoing magnetic storm caused by earlier solar activity, which had no disturbing effects on the flight radars, from a new and, indeed, extreme radio-burst on the Sun, which caused the Swedish radar anomalies. Other systems in various European countries also experienced major radio-disturbances during this extreme event, but they were not of the gravity as experienced in Sweden, or at least not causing a similar damage. One of the problems in reaching the right conclusions about the incident was that the extreme radio-burst around 1400 UT on Nov 4 (more than 50000 SFU at GHz frequencies), emerged from a medium size M3.7 Flare on the Sun, which did not trigger any immediate warnings. We will report about the analysis leading to the improved understanding of this extreme space weather event, evaluate the importance of solar radio observations, and discuss possible mitigation strategies for future events of similar nature.

Knipp et al. (2016) - **The May 1967 great storm and radio disruption event: Extreme space weather and extraordinary responses** - https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016SW001423
The solar radio bursts significantly disturbed the United States' Ballistic Missile Early Warning System, BMEWS for short. … The May 1967 event was long lasting with a series of events following McMath Region 8818 across the disk of the Sun. The largest solar radio burst of the twentieth century (at specific frequencies) produced 373,000 sfu at 606 MHz. The F10.7 cm flux rose briefly to 8000 sfu. Military radio technologies were severely impacted by (1) solar radio bursts, (2) solar energetic particle deposition, and (3) general disruption of ionospheric radio and ground-to-satellite communication channels. … Such an intense, never-before-observed solar radio burst was interpreted as jamming. … With the limited data available at the time, AWS solar forecasters were able to extract sufficient information from AFCRL solar observations to convince high-level decision makers at NORAD that the Sun was a likely culprit in contaminating the BMEWS radar signals. Thus, it appears that unlike some of the human-error and miscommunication events in the 1970s [Forden, 2001], bombers did not take to the skies but were nonetheless positioned to do so.
X3 flare on 25 October 2013 lasting from 14:51 to 15:12UTC. SWF durations reported of 80-110 minutes. The corresponding SWF lasted from 14:59 until 15:18UTC. The ***radio emission*** associated with the X3 flare was also observed in radio meteor observations above Belgium at 49.99 MHz from 14:59-15:18UTC (Credits: Felix Verbelen; BRAMS network). The noise seen in this radiospectrogram is NOT from the ionosphere disturbed by the flare's soft x-rays!

Space Weather impacts (SWx impacts)

- *Recap*
- *SWx impacts from*
  - *Solar flares*
  - ***Proton events***
  - *ICMEs*
  - *Coronal holes*

Proton events



SWx impacts from proton events

Scale	Description	Effect	Physical measure (Flux level of >= 10 MeV particles)	Average Frequency (1 cycle = 11 years)
S 5	Extreme	**Biological:** Unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** Complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	**Biological:** Unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** May experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** Blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	**Biological:** Radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** Degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	**Biological:** Passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk. **Satellite operations:** Infrequent single-event upsets possible. **Other systems:** Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	**Biological:** None. **Satellite operations:** None. **Other systems:** Minor impacts on HF radio in the polar regions.	10	50 per cycle

SWEC

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More info at
SWPC: https://www.swpc.noaa.gov/noaa-scales-explanation
SWPC: https://www.swpc.noaa.gov/phenomena/solar-radiation-storm

Listings of proton events:
- NOAA: https://umbra.nascom.nasa.gov/SEP/
- Shea, M. A.; Smart, D. F. (1990): A summary of major solar proton events
https://ui.adsabs.harvard.edu/abs/1990SoPh..127..297S/abstract

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

```
=====================================================================
-------------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
```

SWx impacts from proton events

- Polar Cap Absorption (PCA)
  - => PECASUS
- Radiation
  - Astronauts, Polar flights
    - => PECASUS
- Satellites
  - Star trackers
  - Solar arrays
  - Single Event Effects (SEE)
- Ground Level Enhancement (GLE)

PECASUS: Pan-European Consortium for Aviation Space weather User Services

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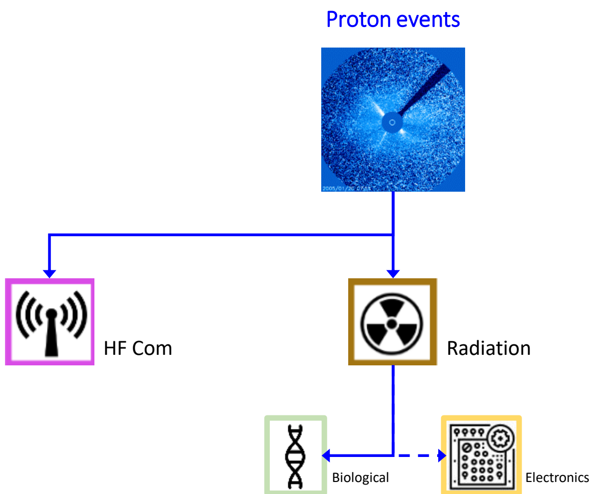
EVA: Extra-Vehicular Activity

SWx impacts from proton events on aviation

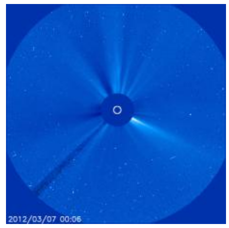


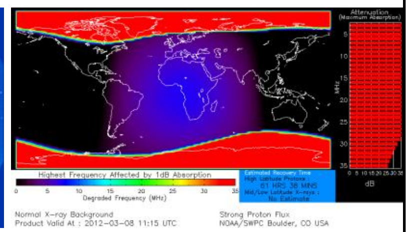
HF Com: High Frequency Communications (3-30 MHz)

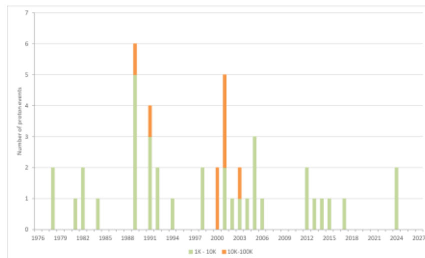
- - - **Currently NOT covered by SWx advisories for ICAO**

SWx impacts from proton events on HF Com

- Polar Cap Absorption (PCA)
  - From 10 MeV proton flux
    - Deviated by MF to poles
    - Affects lower ionosphere
    - Impacts HF Com at poles
      - Can last for days
  - Polar flight detours
    - E.g. 7-8 March 2012
  - Frequency
    - Proton events:
      - Strong: 8 per solar cycle
      - Severe: 2 per solar cycle







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

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

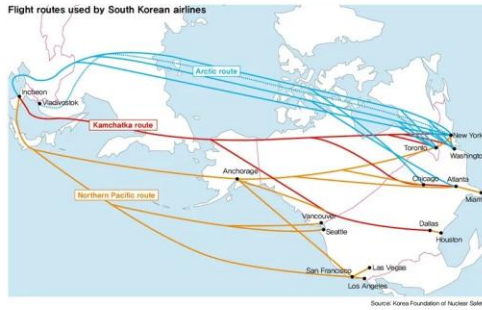
Neal et al. 2013 - Empirical determination of solar proton access to the atmosphere: Impact on polar flight paths
https://agupubs.onlinelibrary.wiley.com/doi/10.1002/swe.20066

… 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 flights 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. …

SWx impacts from proton 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



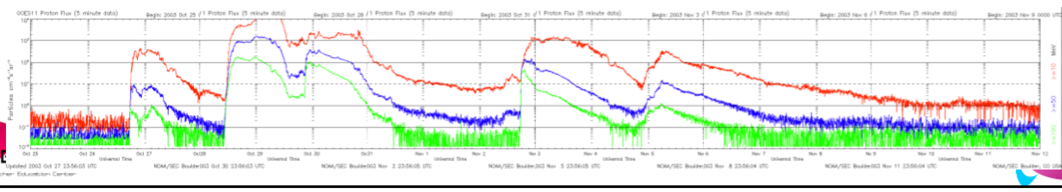


Figure from https://english.hani.co.kr/arti/english_edition/e_business/850390

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. ***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.

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

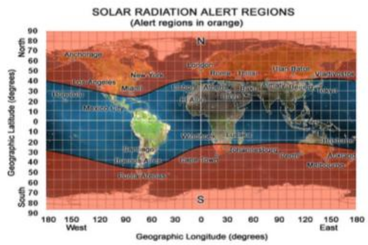
LONDON *(UP)*—The Admiralty today called off a search for the British submarine Acheron, sighted safe in gale-swept seas after being feared lost for nearly six hours. The British minesweeper Coquette radioed three hours after the Admiralty reported the Acheron overdue that she had made "visual contact"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

SWx impacts from proton events : Biological

- Energetic particles
  - Galactic Cosmic Rays (GCR)
  - South Atlantic Anomaly (SAA)
  - 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)
- Mitigation astronauts
  - Oct 1989, Jul 2000, Oct 2003, Jan 2005,…
    - Shelter in more shielded parts of ISS
    - No space walks



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.

ICAO: International Civil Aviation Organization ; ISS: International Space Station ; GLE: Ground Level Enhancement ; µSv/h: microsievert per hour ; mSv: millisievert ; FL: Flight Level (100 feet) ; pfu: proton flux units

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

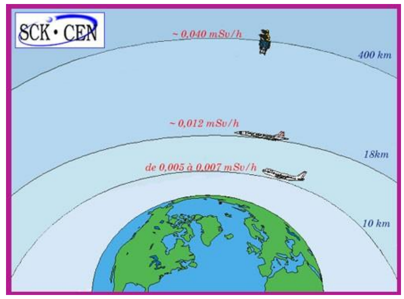
NMDB (Neutron Monitor Database): https://www.nmdb.eu/public_outreach/en/05/

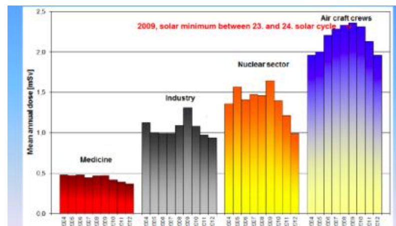
Figure from https://www.weather.gov/media/publications/assessments/SWstorms_assessment.pdf

… 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. …

SWx impacts from proton events : Biological

- Energetic particles
  - Galactic Cosmic Rays (GCR)
  - South Atlantic Anomaly (SAA)
  - 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





ICAO: International Civil Aviation Organization ; ISS: International Space Station ; GLE: Ground Level Enhancement ; µSv/h: microsievert per hour ; mSv: millisievert ; FL: Flight Level (100 feet) ; pfu: proton flux units

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

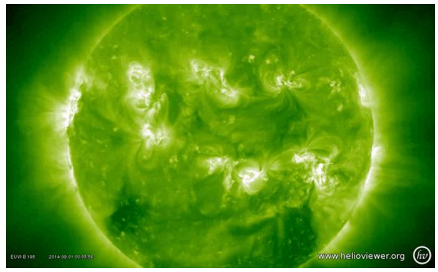
Research on the exposure of various professions to radiation has found that air crewmembers exhibit the highest annual exposure to radiation when compared with workers in the medical, industrial and nuclear industries. Source: Gerhard Frasch, German Federal Office for Radiation Protection, “Aircrew Exposure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

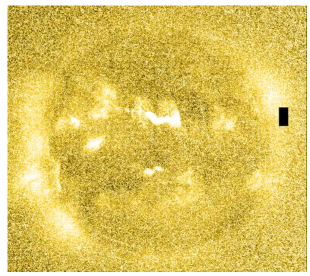
Also at https://www.cdc.gov/niosh/topics/aircrew/cosmicionizingradiation.html

Of note that the career limits for radiation exposure are 600 and 1000 mSv for resp. NASA and ESA astronauts. (http://wsn.spaceflight.esa.int/docs/Factsheets/19%20Matroshka%20LR.pdf , and https://www.nasa.gov/wp-content/uploads/2023/03/radiation-protection-technical-brief-ochmo.pdf).

SWx impacts from proton events : Satellites

- Satellites
  - Star trackers
    - Spacecraft orientation
      - Photonics noise due to proton « impacts »
        - True stars?
      - Misorientation
        - Solar panels oriented away from the Sun
          - No energy
      - Science & Data loss
        - Gravity Probe-B
        - Coronagraphs





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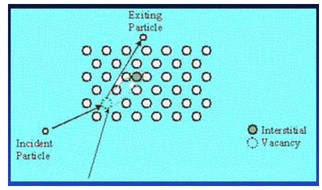
Baker et al. (2016): Resource Letter SW1: Space Weather
https://ui.adsabs.harvard.edu/abs/2016AmJPh..84..166B/abstract
http://aapt.scitation.org/doi/pdf/10.1119/1.4938403
… Satellites can be oriented by the use of star sensors (and Sun sensors). For example, scientific satellites in orbit around Earth may need to know the Sun direction for use in interpreting data from on-board scientific instruments. Star sensors are used for scientific astronomical satellites, as well as for national security and other civil satellite purposes, such as communications. Charged particle radiation can produce false signals in the optical sensors, thus confusing the electronics—with resulting confusion of the orientation. In regions of intense radiation, such as during intervals of enhanced Van Allen belt radiation within Earth's magnetosphere, and during large solar particle events outside the magnetosphere, star and Sun sensors can be severely compromised. The design of attitude control systems usually includes automatic safing procedures as the principal mitigation action.

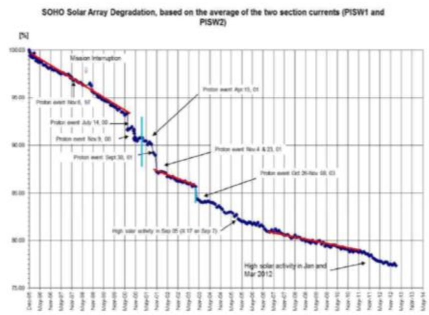
A good example of a proton storm induced orientation problem was on 1 September 2014 with ST-B.
See the news item at https://www.stce.be/news/266/welcome.html
https://sohowww.nascom.nasa.gov/pickoftheweek/old/05sep2014/
A far-side powerful flare erupted and triggered a huge and long-lasting proton storm that flew past the STEREO Behind spacecraft on Labor Day, Sept. 1, 2014. The storm was so strong that it temporarily confused the star trackers on both STEREO spacecraft. The "snowstorm effect" that you see was caused by high-energy particles hitting the spacecraft's detectors in the SECCHI instrument's extreme ultraviolet and inner coronagraph telescopes' (EUVI and COR1). The moment when the star tracker on Behind resets is evident when the spacecraft starts rolling. The spacecraft uses SECCHI's guide telescope to keep locked on the Sun, but depends on the star tracker to determine its roll angle. Once the star tracker came back online, the spacecraft almost immediately moved back to its correct orientation.

Gravity Probe B: https://en.wikipedia.org/wiki/Timeline_of_Gravity_Probe_B
January 2005 - A series of strong solar flares disrupted data taking for several days. On January 17 a very powerful radiation storm created multi-bit errors in the onboard computer memory, and saturated the telescope detectors so that *GP-B* lost track of the guide star. The science team, however, is confident that the temporary loss of science data will have no significant effect on the results. On January 20 the high level of proton flux was still generating "single bit errors" in *GP-B* memory, but the telescope is locked on the guide star again, and the gyroscope electronics seem to perform nominally.

SWx impacts from proton events : Satellites

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





Top figure taken from Valtonen (2004): Space Weather: Effects on Space Technology
http://slideplayer.com/slide/3603908/ (slide 33)

Bottom figure taken from Curdt et al. (2015): Solar and Galactic Cosmic Rays Observed by SOHO
https://ui.adsabs.harvard.edu/abs/2015CEAB...39..109C/abstract (Figure 5)
Fig. 5 shows the degradation of the solar array efficiency from Dec 1995 until Feb 2013. The total loss was ~22.5% during that time (and has reached 24% at the end of 2014). The degradation starts with a linear, continuous decrease of 0.00368% / d (1.344% per year) from launch to Jul 2000. We attribute this decrease to the CRF (Cosmic Ray Flux) during SOHO's first solar minimum. Then follows a phase of several stepwise decrements that can be associated to SEP events during the maximum of cycle 23 around 2001. Here, individual proton events start to dominate the scene. Later follow two more episodes with continuous — but less steep — decrease. Around 2002, the degradation rate is 0.00284% / d (from a starting point of 87.2%) and only 0.00168% / d (from a starting point of 82.1%) during the period from Feb 2007 to May 2011. There is no evidence for a significant solar cycle variation. It seems as if a continuous decrease of the degradation rate reduces the value by almost a factor of two. ... We speculate that in the solar arrays cells of different radiation hardness are found and that destruction of less-radiation hard cells is in progress all the time. Also, ageing effects of the cover-glass could be responsible for efficiency loss. We tried to quantify the effects of cosmic rays and the effects of SEPs during this period. In total, of the 22.5% power loss 8.5% can be attributed to proton events. Hereof, 5% occurred during a period of only 1.5 years. Altogether, 38% ± 2% of the degradation during 17 years can be attributed to proton events. In other words: the effect of a series of violent short-term events on the solar panels is comparable to the accumulated effect of the CRF over this period.

Another nice example of solar array degradation is in Hubner et al. (2012): INTEGRAL revisits Earth - Low perigee effects on spacecraft components
http://arc.aiaa.org/doi/abs/10.2514/6.2012-1291272

Some interesting statistics on solar array degradation provided by Intelsat:
http://www.intelsat.com/tools-resources/library/satellite-101/space-weather/

D. Knipp: On the Little-Known Consequences of the 4 August 1972 Ultra-Fast Coronal Mass Ejecta: Facts, Commentary, and Call
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018SW002024
Rauschenbach (1980) showed an ~5% drop in solar cell power generation capability for the INTELSAT IV F-2 solar panel arrays during the 4 August SEP event, roughly equivalent to 2 years of magnetospheric trapped-radiation exposure to the panels.

SWx impacts from proton events : Satellites

- Satellites
  - Single Event Effect (SEE)
    - Direct hit of an electronic component by an energetic particle resulting in an anomaly
    - Several variations
      - SEU (bit flip), SEL, SEB,…
    - Sources
      - Galactic Cosmic Rays (GCR)
        - DSCOVR
      - Solar proton storms
      - Radiation belts

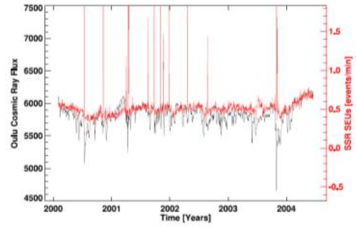
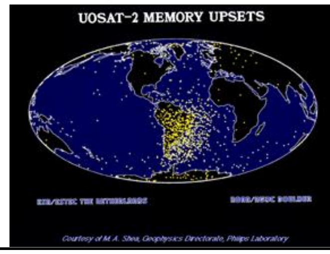


Figure 3: Subset of the data in Fig. 1 during solar maximum. The plot shows a dozen sharp spikes on top of the solar-cycle-modulated background of SSR SEUs triggered by cosmic ray hits. These spikes are caused by isolated strong SEP events. Most of them coincide with a CRF down spike.



SEU: Single Event Upset ; SEL: Single Event Latchup
SEB: Single Event Burnout ; DSCOVR: Deep Space Climate Observatory

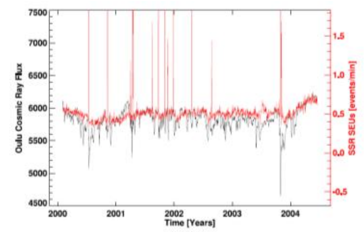
Top Figure from Curdt et al. (2015): Solar and Galactic Cosmic Rays Observed by SOHO
https://ui.adsabs.harvard.edu/abs/2015CEAB...39..109C/abstract (Figure 3)

Galvan et al. (2014): Satellite Anomalies
http://www.rand.org/content/dam/rand/pubs/research_reports/RR500/RR560/RAND_RR560.pdf
Single Event Effects (SEEs) - SEEs are anomalies caused not by a gradual buildup of charge over time as with surface or internal charging, but by the impact of a single high-energy charged particle into sensitive electronic components of a satellite subsystem, this single event causing ionization and an anomaly. They typically occur because of high-energy (> 2 MeV) protons and electrons striking memory devices in the spacecraft's electronics systems, causing the spacecraft (or a subsystem) to halt operations, either temporarily or permanently (e.g., Speich and Poppe, 2000).
SEEs include "bit flips" or SEUs, where a high-energy particle imparts its charge to a solid-state memory device, causing errors in the system software, which may or may not damage hardware and can potentially be detected and repaired with error-detection-and-correction algorithms (EDACs) in the system software. One example of an EDAC is triple-modular redundancy (TMR), in which three processors perform the same calculations in parallel and then compare their answers. If one processor's answers differ from those of the other two, the "correct" two would outvote the incorrect one, and the third processor system could be rebooted or otherwise corrected, and the subsystem in general continues to operate.4 Other types of SEEs include single-event latchups (SELs), in which a subsystem hangs/crashes as a result of a high-energy particle impact. This causes the subsystem to draw excess current from the power supply, and the device must be turned off and then back on to be operable. Sometimes SEL can lead to destruction of the device if the excess drawn current is too high for the power supply. In this case, the SEE is referred to as single-event burnout (e.g., Wertz and Larson, 1999). Susceptibility to SEEs depends strongly on system design, and the risk is higher for satellites spending time in the Van Allen radiation belts or at GEO where there is a higher fluence of galactic cosmic rays and high-energy protons from Solar Proton Events (e.g., Mikaelian, 2001; Wertz and Larson, 1999;).

A good overview of the various SEE is in
Autran and Munteanu (2015) : Soft errors: from particles to circuits
https://www.researchgate.net/publication/274192779_Soft_Errors_From_Particles_to_Circuits (Fig. I.1)

SWx impacts from proton events : Satellites

- Satellites
  - Single Event Effect (SEE)
    - Direct hit of an electronic component by an energetic particle resulting in an anomaly
    - Several variations
      - SEU (bit flip), SEL, SEB,…
    - Sources
      - Galactic Cosmic Rays (GCR)
        - DSCOVR
      - Solar proton storms
      - Radiation belts



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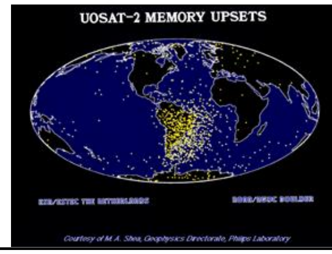


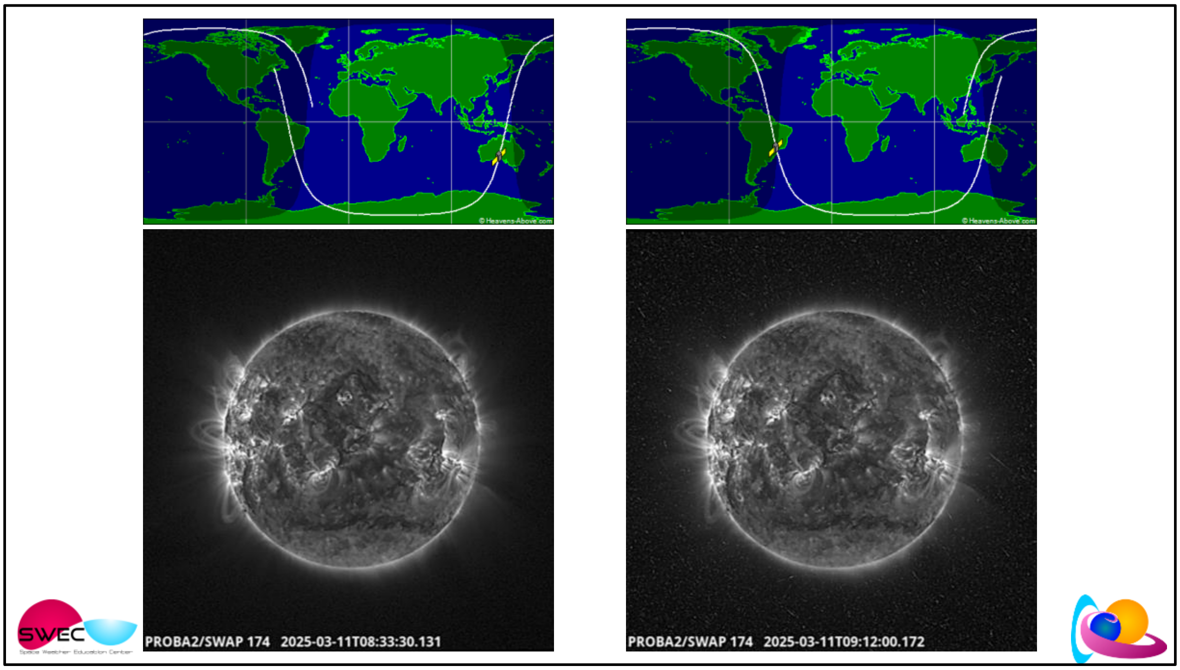
Courtesy of M.A. Shea, Geophysics Directorate, Philips Laboratory

SEU: Single Event Upset ; SEL: Single Event Latchup
SEB: Single Event Burnout ; DSCOVR: Deep Space Climate Observatory

Top Figure from Curdt et al. (2015): Solar and Galactic Cosmic Rays Observed by SOHO
https://ui.adsabs.harvard.edu/abs/2015CEAB...39..109C/abstract (Figure 3)

From: NOAA: Halloween Space Weather Storms of 2003
http://www.nuevatribuna.es/media/nuevatribuna/files/2016/10/28/2004_-noaa_halloweenstorms2003_assessment.pdf
CHIPS – The satellite computer went offline on 29 October and contact was lost with the spacecraft for 18 hours (loss of 3-axis control because its Single Board Computer (SBC) stopped executing). When contacted, the spacecraft was tumbling, but recovery was successful. It was offline for a total of 27 hrs.

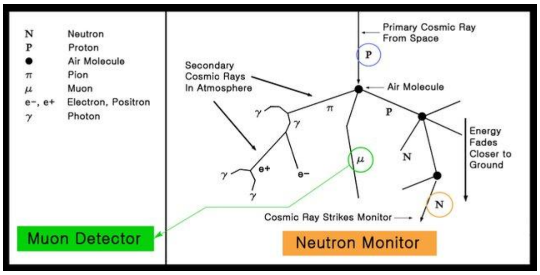
Barbieri et al.: October--November 2003's space weather and operations lessons learned
http://onlinelibrary.wiley.com/doi/10.1029/2004SW000064/epdf
Sometimes, though the effect was undesirable and serious, it was accommodated in the mission's design: The effect was a consequence that may be considered acceptable in terms of the mission's risk tolerance. For example, the Cosmic Hot Interstellar Plasma Spectrometer (CHIPS) flies a single-board computer (SBC) that is not very radiation hardened and so is built to recover autonomously, which it occasionally has to do because of the South Atlantic Anomaly. (The South Atlantic Anomaly is the region where Earth's inner van Allen radiation belt makes its closest approach to the planet's surface. For a given altitude the radiation intensity is higher over this region than elsewhere. It is produced by a "dip" in the Earth's magnetic field at that location, caused by the fact that the center of Earth's magnetic field is offset from its geographic center by 450 km. The South Atlantic Anomaly is of great significance to satellites and other spacecraft that orbit at several hundred kilometers altitude and at orbital inclinations between 35 and 60; these orbits take satellites through the anomaly periodically, exposing them to several minutes of strong radiation each time. The International Space Station, orbiting with an inclination of 51.6, required extra shielding to deal with this problem). On 29 October the CHIPS SBC experienced a problem it could not recover from autonomously because it stopped executing. With the computer off-line the attitude control system was no longer able to maintain three-axis control, and CHIPS began tumbling. The flight operations team (FOT) responded to the anomaly by sending commands to reset the SBC, and the mission continued.

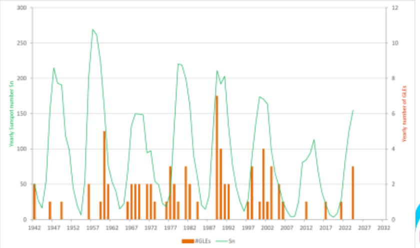


Impact from energetic particles on the PROBA2/SWAP solar imagery when PROBA2 is flying outside (left; 08:33UTC) and inside (right; 09:12UTC) the South Atlantic Anomaly (locations of PROBA2 indicated on the world maps above). The noise in the image on the right is obvious. Credits https://heavens-above.com/ and https://proba2.sidc.be/ssa

SWx impacts from proton events : Electronics

- Single Event Effects (SEE)
- 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)

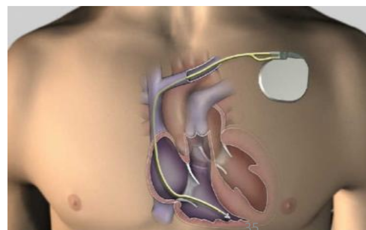
Thakur et al. (2014): Ground Level Enhancement in the 2014 January 6 Solar Energetic Particle Event
https://ui.adsabs.harvard.edu/abs/2014ApJ...790L..13T/abstract
Solar energetic particle (SEP) events, where particles accelerated to GeV energies are subsequently detected on the ground as a result of 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).

From the Royal Academy of Engineering (2013)
https://raeng.org.uk/media/lz2fs5ql/space_weather_full_report_final.pdf
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)
- 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!
      - E.g. Jetblue Airways Flight 1230 (A320) on 28 October 2025



SEP: Solar Energetic Particles ; GCR: Galactic Cosmic Rays ; MeV: megaelectronvolt
SEU: Single Event Upset ; SEL: Single Event Latchup ; SEB: Single Event Burnout

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):

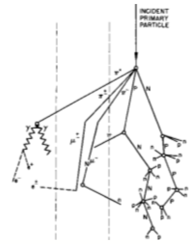
At 0132 Universal Time Coordinated (0932 local time) on 7 October 2008, an Airbus A330-303 aircraft, registered VH-QPA and operated as Qantas flight 72, departed Singapore on a scheduled passenger transport service to Perth, Western Australia. … At 0442:27, the aircraft suddenly pitched nose down. The 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.

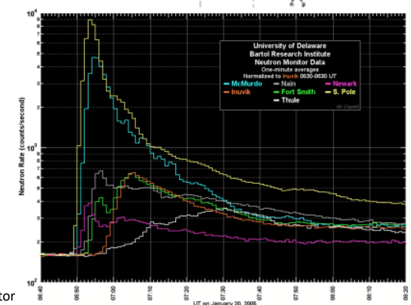
Pacemaker incident: Baraniuk 2022 - https://www.bbc.com/future/article/20221011-how-space-weather-causes-computer-errors ; https://www.linkedin.com/posts/mariegmoe_the-computer-errors-from-outer-space-activity-6987414548366422016-v3AU/?trk=public_profile_like_view ; Other examples in Meier et al. 2020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

STCE newsitem - https://www.stce.be/news/797/welcome.html
JetBlue Airways Flight 1230 (A320) incident on 28 November 2025 - The 2025 recall of roughly 6000 A320-family jets represents one of the most sweeping safety measures in modern commercial aviation. The precipitating event - the sudden pitch-down on JetBlue Flight 1230 - exposed a critical vulnerability in the ELAC flight control computer to radiation-induced data corruption. While Airbus publicly cited "intense solar radiation", the lack of any documented major solar flare or proton event on 30 October makes a cosmic ray induced Single Event Upset the most plausible root cause.
A comparison with the 2008 Qantas Flight 72 incident underscores that pitch-down failures in fly-by-wire aircraft are not new; what is new in 2025 is the scale of the affected fleet, and the involvement of spaceweather threats rather than internal soft- or hardware bugs.
The powerful solar storm of 11-12 November 2025 - though unrelated to the JetBlue incident - demonstrated that the atmospheric radiation environment at cruising altitudes can, under extreme conditions, surge to levels at least an order of magnitude above normal cosmic ray background. Such events significantly raise the risk of SEUs in aircraft electronics. As solar activity remains at high levels during the current solar cycle maximum, it seems good practice to harden critical avionics against particle-induced bit flips through technical hard- and software improvements, applying redundant systems as well as using real-time spaceweather monitoring.

SWx impacts from proton events : Electronics

- Ground Level Enhancement (GLE)
  - Sharp increase of #neutrons @ ground
  - Main source
    - Strong SEPs ~500 MeV/nucleon
      - X-class flares
      - Western hem.
      - Fast halo CMEs
      - => RARE!!
        - Only 76 GLEs since the 1940s
        - GLE#73/74: 28 Oct 2021 and 11 May 2024 (both weak events)
  - Thresholds GLE
      - SWPC: 10% above B/Gr GCR
        - Practice: 3% above B/Gr
      - At least 2 independent stations
  - Realtime monitoring
      - https://www.nmdb.eu/
      - List: https://gle.oulu.fi/#/





GCR: Galactic Cosmic Rays ; SC: solar cycle ; GeV: Giga electronvolt ;
SEP: Solar Energetic Particles ; B/Gr: Background ; NMDB: Neutron Monitor

Figure taken from Wikimedia Commons (NGDC/NOAA): https://www.ngdc.noaa.gov/stp/image/shower.gif

Perrone et al. (2004): **Polar cap absorption events of November 2001 at Terra Nova Bay, Antarctica**
https://ui.adsabs.harvard.edu/abs/2004AnGeo..22.1633P/abstract
The occurrence of SPE during minimum solar activity is very low, while in active Sun years, especially during the falling and rising phase of the solar cycle, the SPEs may average one per month. It is well recognized that these solar particles have prompt and nearly complete access to the polar atmosphere via magnetic field lines interconnected between the interplanetary medium and the terrestrial field (van Allen et al., 1971). Consequently, they cause excess ionization in the ionosphere, particularly concentrated in the polar cap, which, in turn, leads to an increase in the absorption of HF radio waves, termed polar cap absorption (PCA).
The ionization occurs at various depths which depends on the incident particle energies, so that the ionization in the D-region during PCA events is due mainly to protons with energy in the range of 1 to 100MeV that corresponds to an altitude between 30–80 km (Ranta et al., 1993; Sellers et al., 1977; Collis and Rietveld, 1990; Reid, 1974). Particles with even greater energies (>500 MeV) are recorded on the ground by a cosmic-ray detector; these events are called Ground Level Enhancement (GLE) (Davies, 1990).

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).

Usoskin et al. (2016): Database of Ground Level Enhancements (GLE) of High Energy Solar Proton Events
https://pos.sissa.it/236/054

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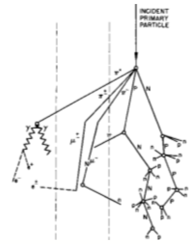
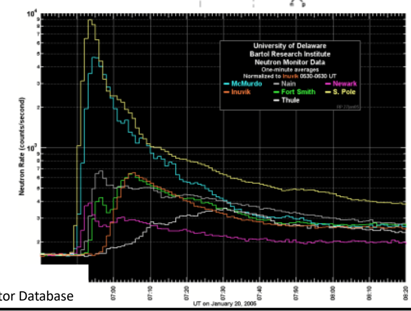




GCR: Galactic Cosmic Rays ; SC: solar cycle ; GeV: Giga electronvolt ;
SEP: Solar Energetic Particles ; B/Gr: Background ; NMDB: Neutron Monitor Database

Event tresholds:

- SWPC glossary: https://www.swpc.noaa.gov/content/space-weather-glossary#groundlevelevent

ground-level event (GLE) A sharp increase in ground-level cosmic ray count to at least 10% above background, associated with solar protons of energies greater than 500 MeV. GLEs are relatively rare, occurring only a few times each solar cycle. When they occur, GLEs begin a few minutes after flare maximum and last for a few tens of minutes to hours. Intense particle fluxes at lower energies can be expected to follow this initial burst of relativistic particles. GLEs are detected by neutron monitors, e.g., the monitor at Thule, Greenland.

- Practice: List of GLE events from Gopalswamy et al. (2012): Properties of Ground Level Enhancement Events and the Associated Solar Eruptions During Solar Cycle 23 - https://ui.adsabs.harvard.edu/abs/2012SSRv..171...23G/abstract (Table 1: SC23 events)

NOTE: The 6 January 2014 event is currently not considered as a genuine GLE, despite its 2.5% increase, its increase in >700 MeV protons, and the fact that other events of similar intensity (such as e.g. 17 January 2005) barely reached 3%. Together with 4 other events in SC24, they are considered as « sub-GLEs ».
There were only 2 real GLEs during SC24 (out of 31 proton events: 6%): GLE71 from 17 May 2012 , and GLE72 from 10 September 2017.
See the papers by Thakur (https://ui.adsabs.harvard.edu/abs/2014ApJ...790L..13T/abstract) and Gopalswamy (https://ui.adsabs.harvard.edu/abs/2013ApJ...765L..30G/abstract).
See https://gle.oulu.fi/#/ for an overview of the GLEs

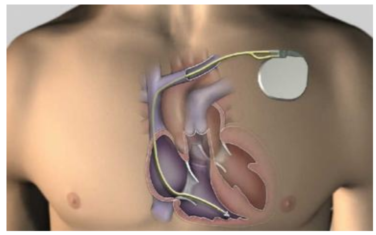
So far this solar cycle (February 2025), 4 GLEs have already been observed. The first one was associated with the X1.0 flare of 28 October 2021, but the related proton event was only a minor event (peak of 29 pfu). Curiously, it was accompanied by an increase in the flux of more energetic protons, and as such resulted in a weak GLE #73 (Oulu GLE database). A very similar scenario for the second GLE (GLE #74), which took place on 11 May 2024 and was associated with an X5.8 flare produced by - oh surprise- NOAA 13664. Here, the greater than 10 MeV proton flux reached a modest 116 pfu. The other two GLEs took place on 8 June 2024 (NOAA 13697) and 21 November 2024 (far side). These 4 GLEs were quite weak events, with maximum increases in neutron counts between 8% and 17%. For comparison, the GLEs associated with the Bastille Day and Halloween events in resp. 2000 and 2003 reached resp. 58% and 45%.

Since measurements started in 1942, only 76 GLEs have been recorded, the strongest in 1956.
See list at http://neutronm.bartol.udel.edu/~pyle/GLE_List.txt and at http://natural-sciences.nwu.ac.za/neutron-monitor-data
The GLE database is currently maintained and available at the University of Oulu (https://gle.oulu.fi/#/).

There are some good presentations on GLE and associated radiation risk from Bartols http://neutronm.bartol.udel.edu/

SWx impacts from proton events : Electronics

- Ground Level Enhancements
  - Various systems
    - Computer glitches, servers,…
      - Errors increase with altitude
    - Pacemakers, defibrillators, and other medical devices,…
      - SEUs (very low rates)
  - Solar cycle (SC) effect noted
    - More errors during SC min than SC max



SWEC

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From the Royal Academy of Engineering (2013)
https://raeng.org.uk/media/lz2fs5ql/space_weather_full_report_final.pdf

9.3 Engineering consequences of an extreme event on ground systems

The atmosphere provides considerable protection to ground level systems and for this reason this study focuses on airborne systems. Yet we know that SEEs are occasionally seen on ground systems [*normand*, 1996; *Ziegler et al.*, 1996] and are likely to be of increasing concern in the design of automotive electronics, miniaturized devices and safety-critical systems in general. Medical devices such as implantable cardiac defibrillators have been shown to give errors from cosmic rays [*bradley and normand*, 1994].

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.

SWx impacts from proton events : Electronics

- Ground Level Enhancements
  - Various systems
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    - Pacemakers, defibrillators, and other medical devices,…
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  - Solar cycle (SC) effect noted
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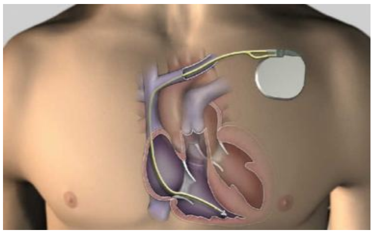

SWEC

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Pacemaker and other medical devices: http://www.solarstorms.org/SPacemakers.html

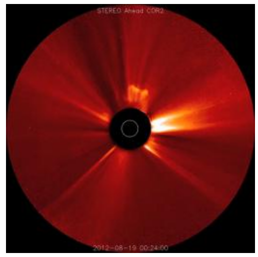
- Bradley et al. (1998): Single Event Upsets in Implantable Cardioverter Defibrillators
http://cardiacos.net/wp-content/uploads/ArticulosMedicos/20170707/1994---Single-Event-Upsets-in-Implantable-Cardioverter-Defibrillators.pdf
Also at http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/29/003/29003514.pdf
- Karnik et al. (2004): Characterization of Soft Errors Caused by Single Event Upsets in CMOS Processes
https://ieeexplore.ieee.org/document/1350778
- Santarini (2005): Cosmic radiation comes to ASIC and SOC design
http://www.edn.com/design/integrated-circuit-design/4324957/Cosmic-radiation-comes-to-ASIC-and-SOC-design
- DiCello (1989): An estimate of error rates in integrated circuits at aircraft altitudes and at sea level
https://ui.adsabs.harvard.edu/abs/1989NIMPB..40.1295D/abstract
- New Scientist (2008): Should every computer chip have a cosmic ray detector?
https://web.archive.org/web/20111202020146/https://www.newscientist.com/blog/technology/2008/03/do-we-need-cosmic-ray-alerts-for.html
- Normand (2013): Single Event Upset at Ground Level
https://web.archive.org/web/20131021190327/http://pdf.yuri.se/files/art/2.pdf
- Kobayashi (2001): Evaluation of LSI Soft Errors Induced by Terrestrial Cosmic rays and Alpha Particles
http://www.rcnp.osaka-u.ac.jp/~annurep/2001/genkou/sec3/kobayashi.pdf
- Wiki: https://en.wikipedia.org/wiki/Soft_error#cite_note-cosmicRayAlert-4
- Autran and Munteanu (2015) : Soft errors: from particles to circuits
https://www.researchgate.net/publication/274192779_Soft_Errors_From_Particles_to_Circuits (Table 1.4)

*** Stock market crash on 16 August 1989??
https://www.newscientist.com/article/mg12316812.400-solar-storms-halt-stock-market-as-computers-crash
http://www.edn.com/electronics-blogs/edn-moments/4394205/Solar-flare-impacts-microchips--August-16--1989
https://en.wikipedia.org/wiki/Solar_cycle_22#August_1989_geomagnetic_storm
http://www.solarstorms.org/SWChapter6.html
Coincided with a GLE, not necessarily a causal relationship.

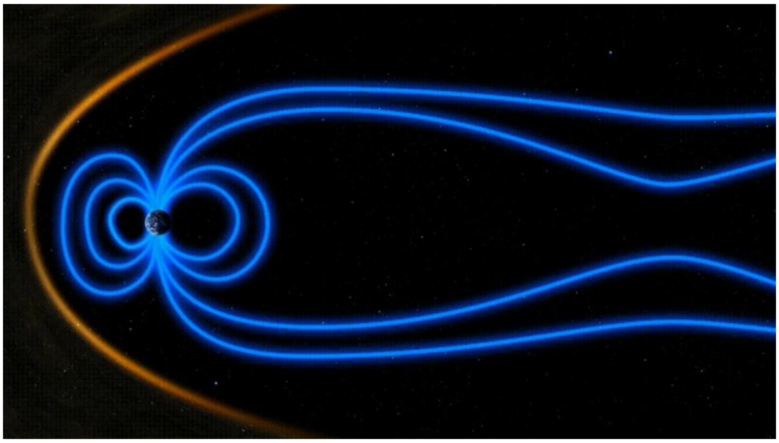
Space Weather impacts (SWx impacts)

- *Recap*
- *SWx impacts from*
  - *Solar flares*
  - *Proton events*
  - ***ICMEs***
  - *Coronal holes*

Coronal Mass Ejections



SWx impacts from ICMEs



Credits: ESA

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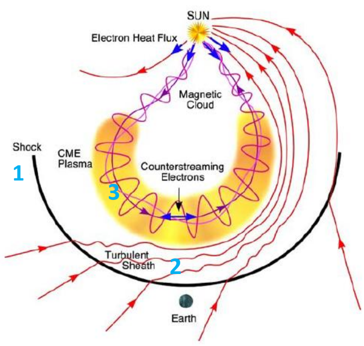
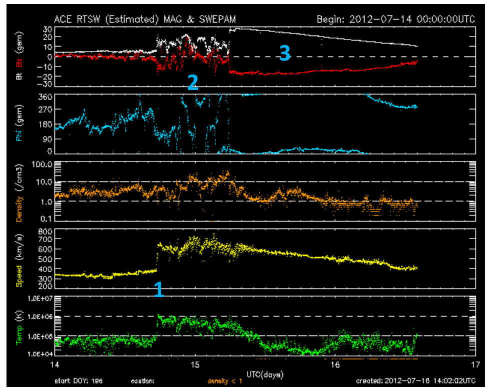
https://www.esa.int/ESA_Multimedia/Videos/2021/12/Magnetic_reconnection_in_Earth_s_magnetosphere

SWx impacts from ICMEs

- Solar wind features





Zurbuchen et al. (2006): In-Situ Solar Wind and Magnetic Field Signatures of Interplanetary Coronal Mass Ejections
https://ui.adsabs.harvard.edu/abs/2006SSRv..123...31Z/abstract

The solar wind example is discussed at http://www.stce.be/news/150/welcome.html

On shock identification in solar wind - Scolini et al. (2018) - https://www.swsc-journal.org/articles/swsc/abs/2018/01/swsc170032/swsc170032.html
the following criteria have been applied:
Bdown/Bup ≥1.2; Np down / Np up ≥1.2; Vdown - Vup ≥ 20km·s-1;
where upstream and downstream values were calculated over a fixed time interval Dtup = Dtdown = 10 min before and after the shock.

SWx impacts from ICMEs

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	**Extreme**	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	**Severe**	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	**Strong**	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	**Moderate**	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	**Minor**	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

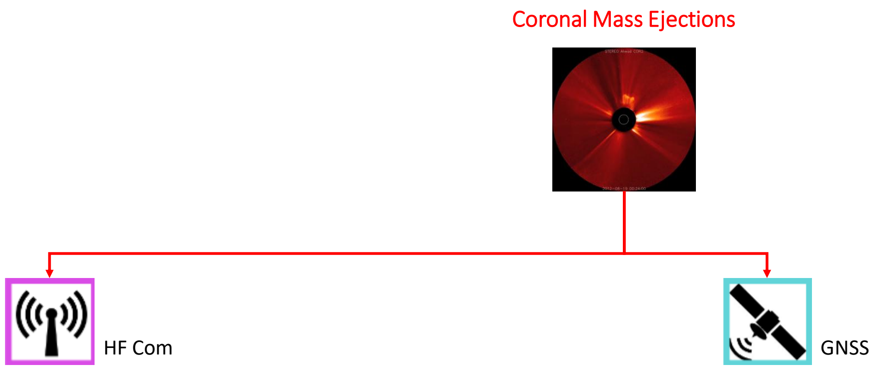
More info at
SWPC: https://www.swpc.noaa.gov/noaa-scales-explanation
https://www.swpc.noaa.gov/phenomena/geomagnetic-storms

SWx impacts from ICMEs

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

GCR: Galactic Cosmic Rays ; GNSS: Global Navigation Satellite Systems ; Comms/Nav: Communications/Navigation
PECASUS: Pan-European Consortium for Aviation Space weather User Services ; HF: High Frequency

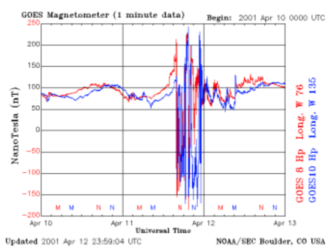
SWx impacts from ICMEs on aviation



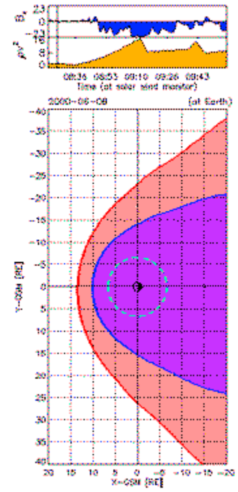
HF Com: High Frequency Communications (3-30 MHz) ; GNSS: Global Navigation Satellite Systems (GPS, Galileo,,...)

SWx impacts from ICMEs

- Satellites
  - Magnetopause crossings
    - CME pushes magnetopause inside GEO
    - Satellites directly exposed to solar wind
      - Orientation problem



GEO: geostationary (equatorial) orbit



From: NOAA: Halloween Space Weather Storms of 2003
http://www.nuevatribuna.es/media/nuevatribuna/files/2016/10/28/2004_-noaa_halloweenstorms2003_assessment.pdf
Earth's magnetopause is the boundary that separates the solar wind from the region in space dominated by Earth's magnetic field. On the line between Earth and the Sun, the magnetopause is typically located about 10 Earth radii from Earth's center. On the downstream side, in the midnight region, the magnetopause forms the boundary of the elongated geomagnetic tail that extends for hundreds of Earth radii. When the solar wind dynamic pressure is very large and the interplanetary field is directed southward, conditions are ripe for moving the upstream, dayside magnetopause, from its typical location to a location closer to Earth and sometimes within geosynchronous orbit (6.6 Earth radii). At these times, when geosynchronous spacecraft on the dayside become located outside of Earth's magnetic field, they encounter highly variable magnetic fields that can be directed opposite to what is normally expected. These conditions can have undesirable effects on spacecraft that use torquer currents as part of their attitude control and momentum management. Under these conditions, spacecraft operators will sometimes turn off the spacecraft torquer currents to avoid torquing against the abnormal magnetic fields. Furthermore, the plasma environment surrounding the spacecraft is altered since the plasma density is often greater when the spacecraft crosses the magnetopause.

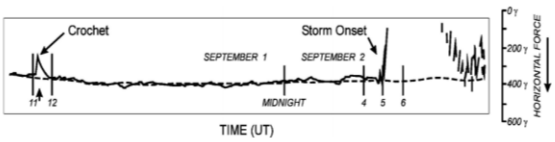
Animation from ESA/Cluster: http://sci.esa.int/cluster/36447-direct-observation-of-3d-magnetic-reconnection/
Top panel: z-component of the IMF (B_z), displayed in blue, and the dynamic pressure (ρv^2), displayed in orange, measured by the ACE spacecraft in the solar wind on 8 June 2000 (see text for details). Bottom panel: magnetopause position (blue line) and bow shock position (bright red line) estimated from the solar wind data as displayed in the top panel. Pink area between these two borders depicts the magnetosheath, while the purple area symbolizes the magnetosphere. The dashed green circle, located at 6.6 R_E, depicts where many communication and weather satellites orbit the Earth.(Acknowledgments: S.M. Petrinec, Lockheed Martin)

The 8 June 2000 storm had a Kp = 7 and Dst = -90 nT.

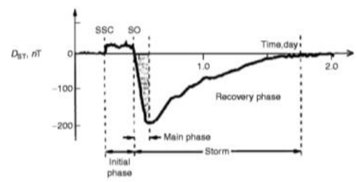
SWx impacts from ICMEs

Rapid geomagnetic variations

- Solar flare effect (SFE)
  - Aka “magnetic crochet”
  - Source
    - Strong solar flare
      - Hα: 2B (30%)
      - X-ray: X1 (50%)
    - f(local time & latitude)
  - Examples
    - 4 Nov 2003: + 115nT
    - 1 Sep 1859: + 110nT



- Storm Sudden Commencement (SSC)
  - Sudden impulse (SI)
    - = no geomagnetic storm
  - Source
    - Dayside compression by strong ICME
    - Global, but f(local sit.)
  - Max. Amplitude: +/- 300 nT
    - 10-11 May 2024: 108 nT



Smith at el. (2019): **The Influence of Sudden Commencements on the Rate of Change of the Surface Horizontal Magnetic Field in the United Kingdom**
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019SW002281
Sudden commencements (SCs) are rapid increases in the northward component of the surface geomagnetic field, related to sharp increases in the dynamic pressure of the solar wind.
SCs can be further subdivided into two categories: storm sudden commencements (SSCs) and sudden impulses (SIs), which share the same physical origin (Curto et al., 2007). If the sharp increase in the *H* component is followed within a few hours by a geomagnetic storm, then it is termed an SSC, and if a storm is not initiated, then it is known as an SI.

Curto (2020): **Geomagnetic solar flare effects: a review**
https://www.swsc-journal.org/articles/swsc/full_html/2020/01/swsc190079/swsc190079.html
Solar flare effects (Sfe) are rapid variations in the Earth’s magnetic field and are related to the enhancement of the amount of radiation produced during solar flare events. They mainly appear in the Earth’s sunlit hemisphere at the same time as the flare observation and have a crochet-like shape.

Lists of SSC and SFE can be found at the Ebre Observatory (http://www.obsebre.es/en/rapid) and at the International Service of Geomagnetic Indices (http://isgi.unistra.fr/events_sc.php)

Figures were taken from
- Cliver et al. (2005): The 1859 Solar–Terrestrial Disturbance And the Current Limits of Extreme Space Weather Activity
https://link.springer.com/article/10.1007/s11207-005-4980-z
- Lakhina et al. (2011): Supermagnetic Storms: Hazard to Society
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2011GM001073

Lakhina et al. (2016): Geomagnetic storms: historical perspective to modern view
https://geoscienceletters.springeropen.com/articles/10.1186/s40562-016-0037-4
From the deduced horizontal component magnetogram of September 1–2, 1859 from the Colaba Observatory recordings, the sudden commencement preceding the storm had an intensity of about +120 nT.

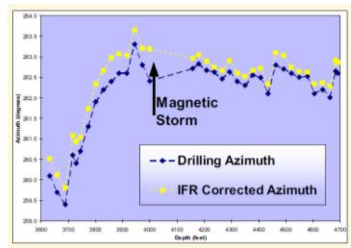
NOAA/SWPC Weekly 2541: … Geomagnetic field activity reached extreme levels, and saw the largest geomagnetic storm since the 2003 Halloween superstorms. Dst dipped to -412 nT on 11 May at 0300 UT. … Interplanetary shock passage was observed at 10/1639 and followed by a sudden impulse at 1645 of 108 nT at the Boulder magnetometer.

NASA/Heliowiki/SolarNuggets: The X9 flare from 03 October 2024 generated an SFE of -35 nT in Dunsink (Ireland).
(https://heliowiki.smce.nasa.gov/wiki/index.php/An_X9_flare_and_its_huge_crochet_(SFE)).

SWx impacts from ICMEs

Rapid geomagnetic variations

- High-precision industry
  - Industries depending on amplitude of magnetic field
    - magnetic anomaly surveys
    - directional wellbore drilling
  - Performance degradation
    - Mitigation possible
  - 4 August 1972
    - Vietnam: sea mine detonation
  - 10-11 May 2024
    - ONC – Ocean Networks Canada
      - Deep-sea compasses activated



IIFR: Interpolated In-Field Referencing

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Off-shore drilling: http://www.geomag.bgs.ac.uk/documents/estec_iifr.pdf

Precision drilling: ESA: http://swe.ssa.esa.int/nso_res

Watermann et al. (2007): The Magnetic Environment - GIC and Other Ground Effects https://ui.adsabs.harvard.edu/abs/2007ASSL..344..269W/abstract - The two physically oriented categories of geomagnetic effects on technological systems concern
• systems and operations which are sensitive to the magnetic field amplitude, dB. They include magnetic anomaly surveys (e.g., aeromagnetic surveys) and directional wellbore drilling.
• systems and operations which are sensitive to the magnetic field time derivative, dB/dt. They include electric power transmission grids, oil and gas pipelines and long-distance communication cables.
The two techno-economically oriented categories of geomagnetic effects on technological systems concern
• systems which are not directly damaged by large geomagnetic perturbations but whose operational performance degrades during geomagnetically active times. They include magnetic anomaly surveys, directional wellbore drilling and communication via long-distance cables.
• systems which may suffer equipment damage as a result of enhanced geomagnetic activity. They include electric power transmission grids and gas and oil pipelines where the damage in the former case can be immediate and in the latter cumulative and long-term.

Also at http://swe.ssa.esa.int/TECEES/spweather/workshops/esww/proc/watermann.pdf

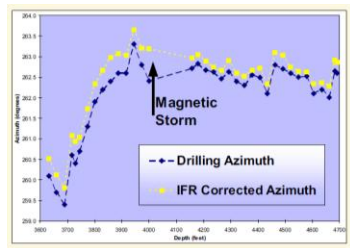
Also at FMI (top image)
Magnetic surveys are used for example in oil and gas exploration. The measurements concern changes of the magnetic field, so there is a problem of separating space weather-related variations from the desired spatial variations. Scheduling surveys for periods when disturbances are forecast to be small could be a solution.

Deep sea compasses: https://www.albernivalleynews.com/news/northern-lights-affected-university-of-victorias-deep-sea-observatories-7360032 and https://www.uvic.ca/news/topics/2024+onc-solar-storm-in-deep-sea-observatories+media-release

SWx impacts from ICMEs

Rapid geomagnetic variations

- High-precision industry
  - Industries depending on amplitude of magnetic field
    - magnetic anomaly surveys
    - directional wellbore drilling
  - Performance degradation
    - Mitigation possible
  - 4 August 1972
    - Vietnam: sea mine detonation
  - 10-11 May 2024
    - ONC – Ocean Networks Canada
      - Deep-sea compasses activated



IIFR: Interpolated In-Field Referencing

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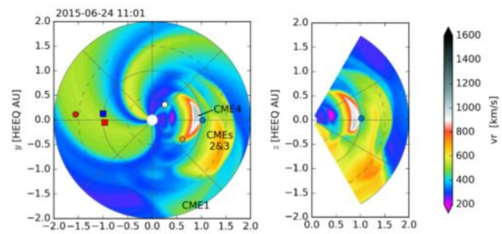
Mitigation possible:
Clark and Clarke (2001): Space weather services for the offshore drilling industry (bottom image)
https://nora.nerc.ac.uk/id/eprint/20528/
https://nora.nerc.ac.uk/id/eprint/20528/1/Clark_Clarke_ESTEC2001_SW_IIFR.pdf
The offshore oil industry uses magnetic data in borehole surveying as a cheaper alternative to using gyroscopic survey tools. The technique known as Interpolated In-Field Referencing (IIFR) has been jointly developed by BGS and Sperry-Sun Drilling Services to give accurate one-minute magnetic values at the oil well locations, enabling the technique of measurement-while-drilling (MWD) to be used.

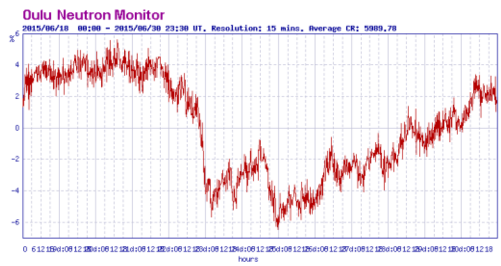
Buchanan et al. (2013): Geomagnetic referencing: The real-time compass for directional drillers
https://www.scribd.com/document/365274025/Geomagnetic-Referencing-The-Real-Time-Compass-for-Directional-Drillers
⇒ Accuracy of 0.1 to 0.01nT !!!

D. Knipp: On the Little-Known Consequences of the 4 August 1972 Ultra-Fast Coronal Mass Ejecta: Facts, Commentary, and Call
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018SW002024
Today the extreme space weather events of early August 1972 are discussed as benchmarks for Sun-Earth transit times of solar ejecta (14.6 hr) and for solar energetic particle fluxes (10 MeV ion flux >70,000 cm-2·s-1·sr-1). Although the magnetic storm index, Dst, dipped to only -125 nT, the magnetopause was observed within 5.2 RE and the plasmapause within 2 RE. Widespread electric- and communication-grid disturbances plagued North America late on 4 August. There was an additional effect, long buried in the Vietnam War archives that add credence to the severity of the storm impact: a nearly instantaneous, unintended detonation of dozens of sea mines south of Hai Phong, North Vietnam on 4 August 1972. The U.S. Navy attributed the dramatic event to *magnetic perturbations of solar storms*.

SWx impacts from ICMEs

- Cosmic rays
  - Forbush decrease
    - Decrease in neutron count over background levels
      - Due to the passage of strong ICME / multiple ICMEs
    - Threshold: > 3%
    - Amplitude:
      - Typical: 3-20%
      - Depends on
        - Size and # CMEs
        - B of CME
        - Proximity CME to Earth
        - cut-off rigidity (GCR)
    - Gradual recovery
      - 3-10 days





B: magnetic field strength ; GCR: Galactic Cosmic Rays

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A discussion of the June 2015 events that lead to the Solstice storm (2nd strongest geomagnetic storm of SC24) can be found in the STCE Newsletter at http://www.stce.be/newsletter/pdf/2015/STCEnews20150703.pdf

Topright figure: Pomoell et al. 2018: EUHFORIA: European heliospheric forecasting information asset https://www.swsc-journal.org/articles/swsc/full_html/2018/01/swsc170062/swsc170062.html

Other important Forbush decreases discussed in these STCE news items:
- https://www.stce.be/news/353/welcome.html
- https://www.stce.be/news/288/welcome.html
- https://www.stce.be/news/339/welcome.html
- https://www.stce.be/news/561/welcome.html

The strongest Forbush decreases in SC24 were those in March 2012 and June 2015.
https://cosmicrays.oulu.fi/

SWS: http://www.sws.bom.gov.au/Geophysical/1/4
The magnetic fields entrapped in and around coronal mass ejections exert a shielding effect on the galactic cosmic radiation (GCR) which is detected by the neutron monitors. This causes a reduction in the count rate from the monitor. The reduction is typically from about 3 to 20%. The reduction occurs typically over a timescale of several hours to a few days.
Forbush decrease events must be at least 3% for a Forbush decrease alert to be issued.
The reduction in the GCR due to a coronal mass ejection (CME) is dependent upon:
- the size of the CME
- the strength of the magnetic fields in the CME
- the proximity of the CME to the Earth
- the number of CMEs
- cut-off rigidity (GCR)

SWx impacts from ICMEs

- Cosmic rays
  - Forbush decrease
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      - Due to the passage of strong ICME / multiple ICMEs
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        - cut-off rigidity (GCR)
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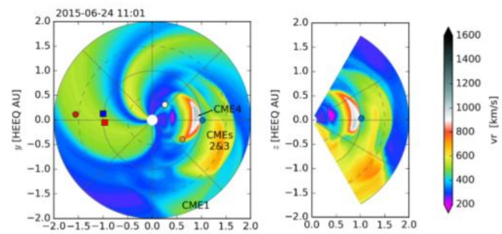

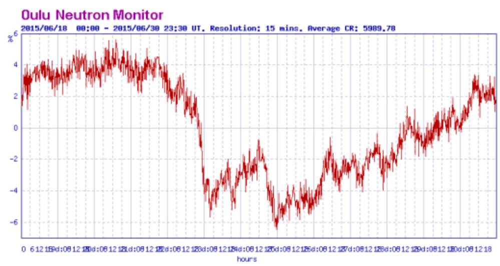

B: magnetic field strength ; GCR: Galactic Cosmic Rays

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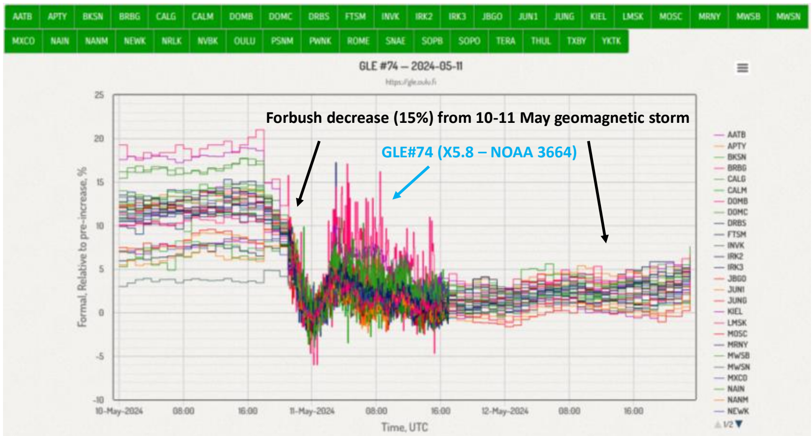
Because the reduction is dependent on three factors (rather than one), it is difficult to forecast the time from a Forbush Decrease to the arrival of a coronal mass ejection at the Earth. However, previous experience in SWS is that a Forbush Decrease is a reliable indicator of a geomagnetic storm, and that warning times of up to 24 hours or more may be made. The Forbush Decrease can be used in conjunction with other indications (e.g. coronagraph imagery) to further confirm the event. Detection of a Forbush Decrease is in use at the SWS ASFC for assistance in prediction of geomagnetic storms.

- Cane (2000): Coronal Mass Ejections and Forbush Decreases
https://ui.adsabs.harvard.edu/abs/2000SSRv...93...55C/abstract
- Lockwood (1971): Forbush Decreases in the Cosmic Radiation
https://ui.adsabs.harvard.edu/abs/1971SSRv...12..658L/abstract

Cut-off rigidity: https://spaceweather.surrey.ac.uk/
It is difficult for any electrically charged particles originating from outside of the Earth's magnetosphere to enter inside it, as they tend to be deflected away via the Lorentz force. However, the tendency to be deflected is opposed to some extent by the particles' momentum. Thus, the ability of a particle to penetrate into the geomagnetic field actually depends upon a quantity called the particle's magnetic rigidity, *P.* The rigidity parameter is extremely useful in describing the motion of particles in the geomagnetic field. This is because particles injected into the field with the same rigidity will follow identical trajectories, whereas particles with the same momentum or energy, but different charges, will not. For each point in the magnetosphere there will be a minimum rigidity (called the cut-off or threshold rigidity) required to reach that point. Particles with less rigidity than the cut-off will be deflected before they reach the point, whereas those with more than the cut-off will penetrate to it.
For a particle to penetrate the Earth's field successfully, the cut-off rigidity must be low. Thus, it is easier for particles to penetrate at high magnetic latitudes L (where cos4L is minimized) than near to the magnetic equator. The equation also shows the asymmetry in cut-off rigidity with respect to arrival direction. For example, for a positive ion, it is easiest to penetrate from the West (a = 0°). Cut-off rigidity is also inversely proportional to the square of geocentric radius. Therefore, at a given latitude, penetration to lower altitudes requires a greater rigidity. In other words, at a given latitude, the particles with the highest values of rigidity will be at the lowest altitude, and the particles of lowest rigidity will be at the highest altitude.

SWx impacts from ICMEs

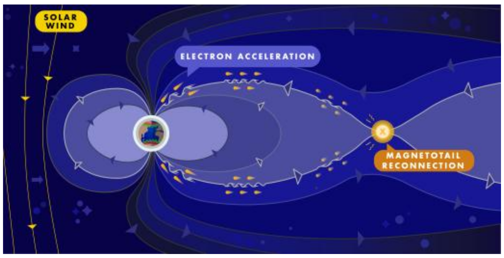
Forbush decrease and GLE on 10-11 May 2024



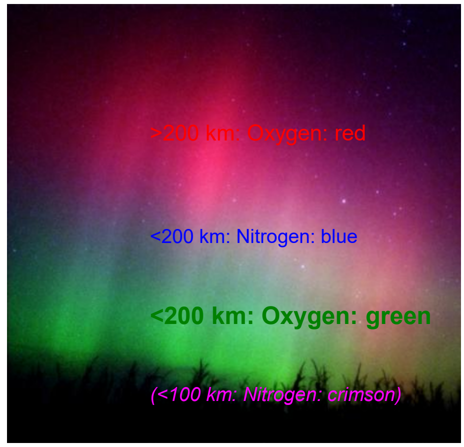
STCE newsitem: https://www.stce.be/news/704/welcome.html

SWx impacts from ICMEs

- Aurora



© G. G. Howes, University of Iowa, 2021



© G. Gonzales, Iowa State University, Oct 2003

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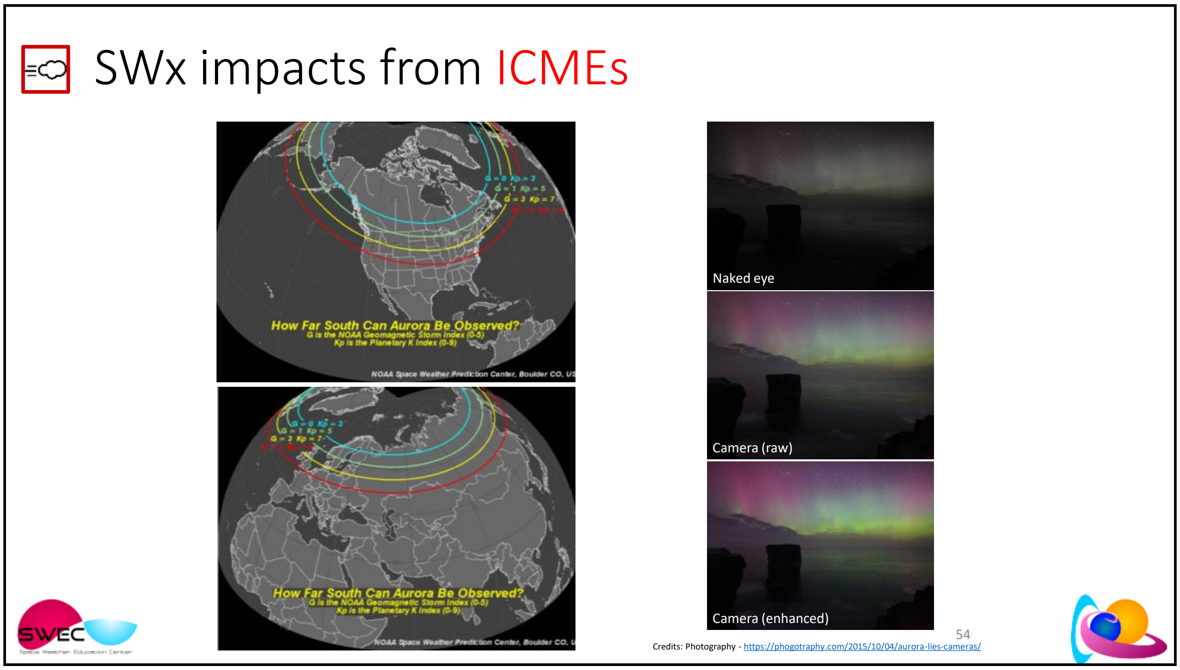
Abbott et al. (2016): New historical records and relationships among 14C production rates, abundance and color of low latitude auroras and sunspot abundance
https://ui.adsabs.harvard.edu/abs/2016AdSpR..58.2181A/abstract
Auroras are generated in the ionosphere by the excitation of specific atmospheric gas species by energetic charged particles. As the gas transitions to its normal, unexcited state, it emits energy, some in the form of visible light. Auroras have a characteristic suite of emission lines in the visible spectrum. Each emission line is associated with a transition in a specific gas species. The emission line's color reflects the energy of the transition (Fig. 1B) and its intensity depends on the flux of the exciting particles and on the excitation potential of the gas species (Fig. 1A). Many visible-light auroral emissions are due to trace gasses that require different excitation energies than major components of the atmosphere, so that some important auroral emissions do not originate with the gases N2 and O2 that compose 99% of the bulk atmosphere. Atmospheric composition varies both with elevation and time. Thus, the mix of emission lines changes, depending on the mixture of gases that are being excited, the relative intensities of excitation and the depth range of the excitation within the ionosphere. The perceived color of an aurora is determined by the response of the human visual system to the mix of emission lines.
Auroral emissions are dominated by monatomic nitrogen (N1), molecular nitrogen (N2) and molecular oxygen (O2) at altitudes of 90–150 km. From altitudes of 150 to 900 km, the most important gas is monatomic oxygen (O1). Above 900 km, the most important gases are helium (He) and monatomic hydrogen (H1) (Russell, 2005b).

Sketch from Hyperphysics: http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/aurora.html

Some comments on « red aurora »:
Spaceweather.com: http://spaceweather.com/archive.php?view=1&day=09&month=09&year=2015
Space.com: http://www.space.com/13383-spellbinding-northern-lights-display-skywatcher-photos.html

Left figure from Prof G. G. Howes (University of Iowa)
https://homepage.physics.uiowa.edu/~ghowes/research/scibackground.html
… the dynamics of geomagnetic storms drive magnetic reconnection in the distant magnetotail, around 120,000 km (or 80,000 mi) away from the Earth. The resulting shifting of the Earth's magnetic field lines launches Alfven waves towards the Earth. Electrons surfing along those Alfven waves accelerate towards the Earth, up to speeds of 20,000 km/s (or 45 million mph), ultimately colliding with the Earth's atmosphere. These collisions cause the air atoms and molecules to emit light, resulting in the glowing of the aurora. Because the regions of magnetic reconnection shift over time during the geomagnetic storm, the Alfven waves are launched on different field lines over time, ultimately leading to the unparalleled beauty of the undulating curtains of light observed in discrete auroral arcs.



Tips on viewing the aurora:
SWPC: https://www.swpc.noaa.gov/content/tips-viewing-aurora

The average equatorward boundary of the midnight aurora is shown for levels of magnetic activity ranging from relatively low, Kp=3, to very high, Kp=9. These maps were created using satellite observations to determine the average equatorward boundary of the aurora as a function of the Kp index**. Using those data, the typical maximum extent of the aurora toward the equator for the hours around midnight for four levels of geomagnetic activity is displayed.

Another visibility chart for Western Europe: https://www.swpc.noaa.gov/products/aurora-30-minute-forecast

Visibility criteria (clear and moonless midnight, north direction without city light)

	Photographic	Visual
Belgium	Kp >= 6	Kp > 8 (9-)
Netherlands	Kp >= 5	Kp >= 7

Franky Dubois 27 February 2014 (Kp=6) : http://www.youtube.com/watch?v=_cw-tys0Ax8

Examples (photographic from Friesland):
12 Sep 2014 (Kp=7): https://www.stce.be/news/268/welcome.html
04 Jan 2015 (Kp=5): https://www.stce.be/news/289/welcome.html

SWx impacts from ICMEs

Aurora on 10-11 May 2024

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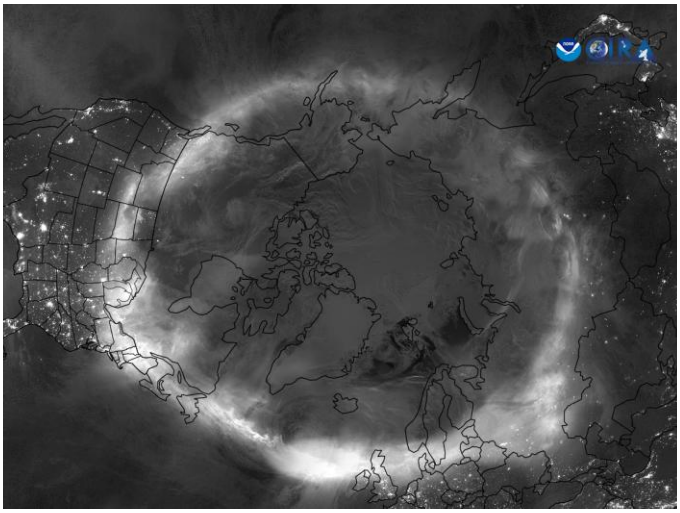
STCE Newsitem: Aurora lookalikes
https://www.stce.be/news/673/welcome.html

Another aurora lookalike are the Stable Auroral Red arcs (SARs) which were observed for the first time in the 1950s. Not knowing what they were, they were initially thought to be linked to aurora and named after them, but that was premature. SARs are pure red arcs of light that ripple across the sky during strong geomagnetic storms. They are a sign of heat energy leaking into the upper atmosphere from Earth's ring current system (SWIC space weather course). SAR arcs occur during geomagnetic storms when the inner edge of the ring current interacts with a contracted plasmasphere. A portion of ring current energy is dissipated as heat that gets conducted along geomagnetic field lines into the topside ionosphere. If ambient ionospheric electrons at about 400 km get heated to temperatures near 3000 degrees, collisions with thermospheric oxygen atoms can transfer the necessary energy to make them emit the familiar red color (Mendillo et al. 2015). SARs can also be observed at low latitudes, such as e.g. in November 2021 when a SAR was photographed as far south as Texas, USA (Spaceweatherarchive).

SWx impacts from ICMEs

Aurora on 10-11 May 2024



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Wikipedia - https://en.wikipedia.org/wiki/May_2024_solar_storms#/media/File:Northern_Lights_From_Over_the_North_Pole_(NESDIS_2024-05-15_nhem-aurora-labels).png

Phenomena: Auroras Satellite: NOAA-20, NOAA-21, S-NPP Product: Day/Night Band Instrument: VIIRS Timespan: May 11, 2024 03:49 UTC – May 11, 2024 12:19 UTC NOAA's JPSS Program satellites captured imagery of the stunning auroras that were visible in locations across the globe on May 11, 2024. Multiple coronal mass ejections from the sun sparked an extreme geomagnetic storm around the Earth last week, creating stunning auroras, even in places where the northern lights are rarely seen. The Southern Hemisphere also reported remarkable auroras from the storm. … This combined image was captured by NOAA's JPSS satellites as they passed over North America. JPSS is the Nation's advanced series of polar-orbiting environmental satellites and is made up of the Suomi-NPP, NOAA-20, and NOAA-21 satellites. JPSS represents significant technological and scientific advancements in observations used for severe weather prediction and environmental monitoring. These data are critical to the timeliness and accuracy of forecasts three to seven days in advance of a severe weather event. JPSS is a collaborative effort between NOAA and NASA.

SWx impacts from ICMEs

Aurora on 19-20 January 2026

Credits: Jonas Piontek - https://www.youtube.com/watch?v=MxM-h5pU9mE ; STCE newsitem: https://www.stce.be/news/802/welcome.html

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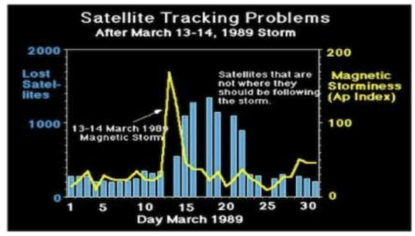
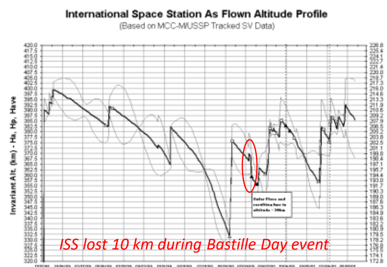
STCE Newsitem: Aurora lookalikes
https://www.stce.be/news/673/welcome.html

Another aurora lookalike are the Stable Auroral Red arcs (SARs) which were observed for the first time in the 1950s. Not knowing what they were, they were initially thought to be linked to aurora and named after them, but that was premature. SARs are pure red arcs of light that ripple across the sky during strong geomagnetic storms. They are a sign of heat energy leaking into the upper atmosphere from Earth's ring current system (SWIC space weather course). SAR arcs occur during geomagnetic storms when the inner edge of the ring current interacts with a contracted plasmasphere. A portion of ring current energy is dissipated as heat that gets conducted along geomagnetic field lines into the topside ionosphere. If ambient ionospheric electrons at about 400 km get heated to temperatures near 3000 degrees, collisions with thermospheric oxygen atoms can transfer the necessary energy to make them emit the familiar red color (Mendillo et al. 2015). SARs can also be observed at low latitudes, such as e.g. in November 2021 when a SAR was photographed as far south as Texas, USA (Spaceweatherarchive).

SWx impacts from ICMEs

- Satellites
  - Atmospheric drag
    - Low Earth Orbit (LEO)
    - Sources
      - Shortterm: ICME
        - NOAA: Kp > 6
      - Longterm: Solar EUV radiation (solar cycle)
        - NOAA: F10.7 > 250 sfu
    - Slows down satellite
      - Burns up in atmosphere
    - Examples
      - March 1989
        - 1000 satellites off-track
      - Premature mission end
        - Solar Max, Skylab, Starlink
      - 10-11 May 2024: ISS lost 0.5 km
    - Space debris
      - Cleaned up by high solar activity
        - SpaceX Dragon crew capsule trunk
          - Early re-entry (27 April 2023)





Top Image from UCAR (available at https://www.swpc.noaa.gov/impacts/satellite-drag)
ISS chart from Chad Hammons – Other charts with evolution ISS altitude: https://www.quora.com/Is-there-a-graph-showing-historical-altitudes-for-the-iss
It's easy to view the graphs and see that the ISS lost about 15 km altitude because of this one flare. [ed.: CME].

Drag: Bean (CCAR)
Usually fluctuations in the Earth's magnetic field only slightly affect the atmosphere. However, perturbations in atmospheric density under extreme conditions such as geomagnetic storms are important because it causes large orbital perturbations. Geomagnetic storms are major disturbances in the earth's magnetic field driven by strong energy input from the solar wind. Large perturbations in the solar wind velocity are supplied by sources such as coronal holes and solar flares.
[3] During a coronal mass ejection (CME), the sun spews out large amounts of solar mass consisting of charged particles including solar protons at speeds exceeding 700 km/s. A coronal mass ejection directed at the earth takes about 3-4 days to make the journey to the earth. When the charged particles reach the earth, the charged particles interact with the earth's magnetosphere. The charged particles have an electric charge so the magnetic field lines around the earth influence the charged particles. The interaction of the magnetic field with the solar wind deforms the earth's magnetic field. The effect of this interaction is the compression of magnetic field lines on the dayside and stretching of field lines on the night-side to form a comet-like tail known as the magnetotail. Some of the charged particles are trapped in the magnetic field lines and eventually enter the magnetosphere. In the magnetotail, particles can move along the magnetic field lines and precipitate into the atmosphere at the earth's poles.
[4] Atmospheric density is strongly influenced by atmospheric heating from solar extreme ultraviolet (EUV) radiation and Joule heating associated with enhancements in local ionospheric and geomagnetic field currents. Solar EUV radiation makes the strongest contribution to upper atmospheric heating. Thus, satellite drag variations are mainly driven by solar influences.

Minor storm, major impact (Starlink disaster): https://www.stce.be/news/573/welcome.html

Australian SWx forecasting center: https://www.sws.bom.gov.au/Educational/1/3

Very early re-entry of SpaceX Dragon Capsule trunk on 28 April after the strong 23-24 April 2023 geomagnetic storm
https://www.spaceweather.com/archive.php?day=28&month=04&year=2023&view=view

SWx impacts from ICMEs

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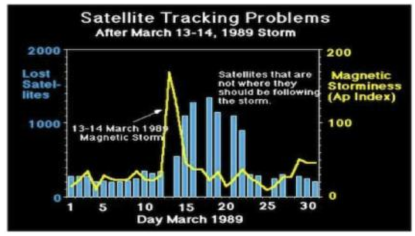
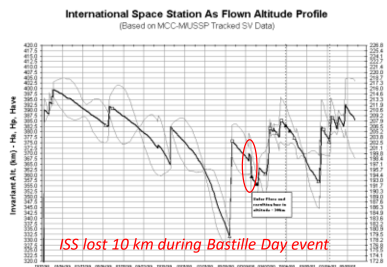




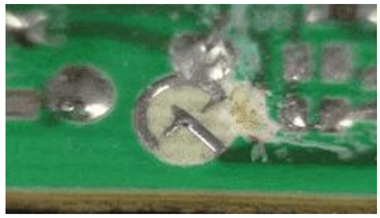
More info on space debris at SWPC: https://www.swpc.noaa.gov/impacts/satellite-drag
It is extremely important to keep track of spacecraft and objects flying in the space to avoid collisions with space junk and orbital debris that may be in their path. Collision avoidance has become of increasing concern due to the recent accidental hypervelocity collision of two intact spacecraft in February, 2009. The collision occurred at an altitude of 790 km, leaving pieces of debris that have been gradually separated into different orbital planes around the Earth, threatening other satellites for the next few decades. Since 1957, more than 25,000 artificial space debris have been cataloged (Figure 3), many of which have naturally decayed into the lower atmosphere. Currently, the U.S. Space Surveillance Network (SSN) tracks over 20,000 man-made objects larger than 10 cm in size, which are known as the "catalogued" population. Debris between 1 cm and 10 cm (approximately 500,000), referred to as the "lethal" population, are the most concerning as they cannot be tracked or cataloged and can cause catastrophic damage when colliding with a satellite. Objects smaller than 1 cm (approximately 135 million measuring from 1mm to 1cm, and many more smaller than 1 mm) that could disable a satellite upon impact are termed the "risk" population [3].

Skylab: Wiki: https://en.wikipedia.org/wiki/Skylab#After_departure
British mathematician Desmond King-Hele of the Royal Aircraft Establishment predicted in 1973 that Skylab would de-orbit and crash to earth in 1979, sooner than NASA's forecast, because of increased solar activity.[162] Greater-than-expected solar activity[165] heated the outer layers of Earth's atmosphere and increased drag on Skylab. By late 1977, NORAD also forecast a reentry in mid-1979;[161] a National Oceanic and Atmospheric Administration (NOAA) scientist criticized NASA for using an inaccurate model for the second most-intense sunspot cycle in a century, and for ignoring NOAA predictions published in 1976. Re-entry on 11 July 1979.

Also from SWPC: https://ccmc.gsfc.nasa.gov/RoR_WWW/SWREDI/2015/SatDrag_YZheng_060415.pdf (Delores Knipp; Slide 4)
Spacecraft in LEO experience periods of increased drag that causes them to slow, lose altitude and finally reenter the atmosphere. Short-term drag effects are generally felt by spacecraft <1,000 km altitude. Drag increase is well correlated with solar Ultraviolet (UV) output and additional atmospheric heating that occurs during geomagnetic storms. Solar UV flux varies in concert with the 11-year solar cycle and to a lesser degree with the 27-day solar rotation period. Geomagnetic storms are sporadic, but most major storms occur during solar maximum years.
Most drag models use radio flux at 10.7 cm wavelength as a proxy for solar UV flux. (Before long, the GOES spacecraft will have continuous UV monitoring) Kp is the index commonly used as a surrogate for short-term atmospheric heating due to geomagnetic storms. In general, 10.7 cm flux >250 solar flux units and Kp>=6 result in detectably increased drag on LEO spacecraft. Very high UV/10.7 cm flux and Kp values can result in extreme short-term increases in drag. During the great geomagnetic storm of 13-14 March 1989, tracking of thousands of space objects was lost and it took North American Defense Command (NORAD) many days to reacquire them in their new, lower, faster orbits. One LEO satellite lost over 30 kilometers of altitude, and hence significant lifetime, during this storm.

SWx impacts from ICMEs

- Satellites
  - Surface charging
    - Low energy plasma
      - 0-100 keV electrons
    - Midnight to dawn region
      - Substorm related
      - SWPC: likely if K > 6
    - Differential charging
      - Shadow effect (GEO/HEO)
      - Wake effect (LEO)
    - Electrostatic discharge (ESD)
      - Surface damage
      - Phantom commands
  - Internal charging
    - 100s keV electrons
      - More uniform distribution
      - Galaxy 15 outage in April 2010
  - Accumulation effect



Credits: eevblog.com

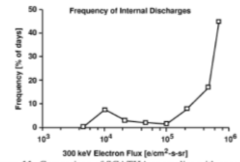
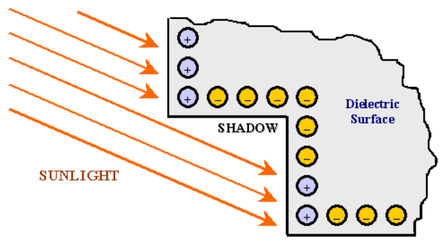


Figure 11. Comparison of SCATHA anomalies with energetic electron fluxes.

Credits: Fennell et al. (2001)



Low Earth orbit (LEO) ; Medium Earth orbit (MEO)
Geostationary/Geosynchronous orbit (GEO) ; High Earth orbit (HEO)

SWPC: Space Weather Prediction Center

Top left figure: Spark gap gif from https://www.eevblog.com/2014/10/31/eevblog-678-what-is-a-pcb-spark-gap/
Top right figure:
Fennell et al. (2001): Spacecraft Charging: Observations and Relationship to Satellite Anomalies
https://ui.adsabs.harvard.edu/abs/2001ESASP.476..279F/abstract

2. Satellite Surface Charging

In the early 1970's, it became clear that many of the anomalies on geosynchronous satellites occurred in the near midnight to dawn region of the magnetosphere', as shown in Figure 1. This was reminiscent of the path that the hot substorm-injected electrons from the magnetotail take as they drift around the magnetosphere. Thus, it was thought that the anomalies might be substorm related and could be caused by satellite charging.

As we know, 10's of keV electrons do not penetrate the satellite surface materials but reside near the surface. The incident plasma and the solar UV also interact with materials to generate secondary electrons. The satellite's surface materials will take on a charge such that the net current between the surfaces and the plasma is zero under quiescent conditions. The result is that the surface voltages would not be zero. The sunlit areas are usually slightly positive and the shadowed areas are usually negative relative to the plasma at "infinity". If the surface was a conductor, the potential of the surface would be uniform and either positive or negative relative to the plasma.

More info at
Dr Holbert - bottom image
Valtonen (2004): https://link.springer.com/chapter/10.1007/978-3-540-31534-6_8 (top left image)
Gubby et al. (2002): Space environment effects and satellite design
https://ui.adsabs.harvard.edu/abs/2002JASTP..64.1723G/abstract

Also from SWPC/KSWC: https://www.spaceweather.go.kr/effect/english/07_03_01

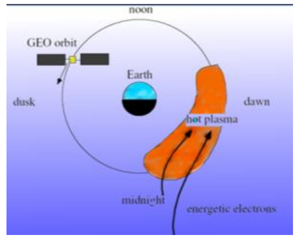
Surface Charging

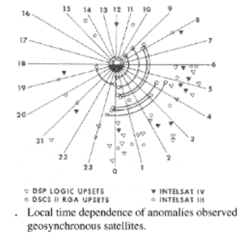
Surface charging to a high voltage does not usually cause immediate problems for a spacecraft. However, electrical discharges resulting from differential charging can damage surface material and create electromagnetic interference that can result in damage to electronic devices. Variations in low energy plasma parameters around the spacecraft, along with the photoelectric effect from sunlight, cause most surface charging. Due to the low energy of the plasma, this type of charging does not penetrate directly into interior components. Surface charging can be largely mitigated through proper materials selection and grounding techniques.

Surface charging occurs predominantly during geomagnetic storms. It is usually more severe in the spacecraft local times of midnight to dawn but can occur at any time. Night to day, and day to night transitions are especially problematic during storms since the photoelectric effect is abruptly present or absent, which can trip discharges. Additionally, thruster firings can change the local plasma environment and trigger discharges.

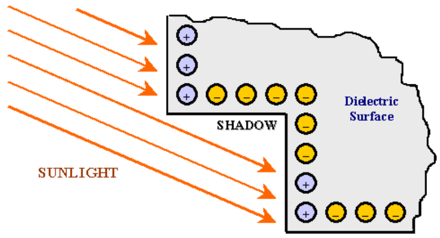
SWx impacts from ICMEs

- Satellites
  - Surface charging
    - Low energy plasma
      - 0-100 keV electrons
    - Midnight to dawn region
      - Substorm related
      - SWPC: likely if K > 6
    - Differential charging
      - Shadow effect (GEO/HEO)
      - Wake effect (LEO)
    - Electrostatic discharge (ESD)
      - Surface damage
      - Phantom commands
  - Internal charging
    - 100s keV electrons
      - More uniform distribution
      - Galaxy 15 outage in April 2010
  - Accumulation effect





Local time dependence of anomalies observed geosynchronous satellites.



Low Earth orbit (LEO) ; Medium Earth orbit (MEO)
Geostationary/Geosynchronous orbit (GEO) ; High Earth orbit (HEO)

SWPC: Space Weather Prediction Center

The common measure for geomagnetic storms, and hence the occurrence of surface charging, is the K index. This index is a 3 hourly measure ranging from 0-9 (0=quiet, 9=severely disturbed.). It is derived from ground-based magnetometer data and is used as a surrogate for actual plasma measurements at satellite altitudes. In general, surface charging effects begin at the K=4 to K=5 level. Charging is probable at K>=6 (see Today's Space Weather). Geomagnetic substorms can be somewhat localized in space so the use of the planetary K index (Kp) may mask the severity of effect upon a specific spacecraft.

Also at STCE news item: Itchy satellites: https://www.stce.be/news/207/welcome.html

Denig et al. (2010): **Space Weather Conditions at the Time of the Galaxy 15 Spacecraft Anomaly**
https://www.ngdc.noaa.gov/stp/satellite/anomaly/2010_sctc/docs/1-2_WDenig.pdf
Solar activity was elevated but not remarkable. Global geomagnetic activity described by the AL auroral electrojet index and Kp were extreme. Other SWx indices were more moderate. Local measurements near Galaxy 15 show that a large geomagnetic substorm occurred 48 minutes prior to the anomaly. The substorm caused remarkable increases in the measured local flux of energetic particles known to cause surface or internal satellite charging.

Internal charging: Valtonen (2004): https://link.springer.com/chapter/10.1007/978-3-540-31534-6_8

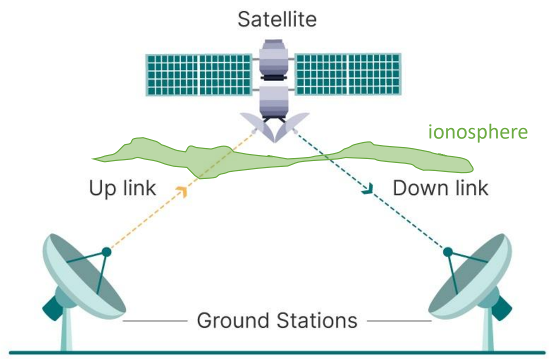
Another example of internal charging by CME is the Telstar-401 (11 January 1997):
Odenwald: http://www.solarstorms.org/SWChapter2.html
http://sdoisgo.blogspot.be/2016/06/telstar-401-ghost-of-space-weather-past.html

A less clear example (based more on circumstantial evidence) was the failure of the Galaxy-IV satellite, more than a week after the passage of several strong CMEs that even created a third radiation belt. The official report mentioned only technical causes, no link to the geomagnetic storms.
NASA: https://pwg.gsfc.nasa.gov/istp/outreach/events/98/
SPACECAST: http://fp7-spacecast.eu/help/bg_sa.pdf

Also at SWS: http://www.sws.bom.gov.au/Educational/1/3/2 : **Satellite Communications and Space Weather**

SWx impacts 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 ; SHF: super high frequency

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

SWx impacts 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
      - Small scale irregularities in e^- density
        - May develop in large structures
      - Rapid fluctuations in satellite signal
        - Phase and intensity
        - May result in signal loss

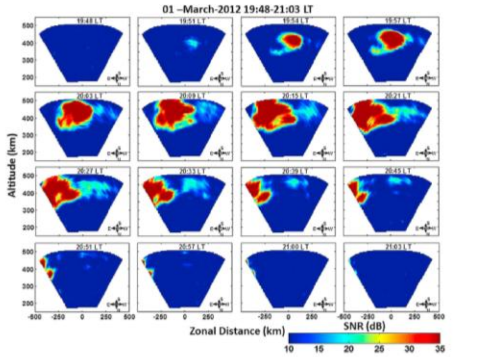


Figure 1. An example showing the genesis and successive development of EPB (evolving-type) over Kototabang observed from the fan sector maps of EAR on 1 March 2012.

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

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).

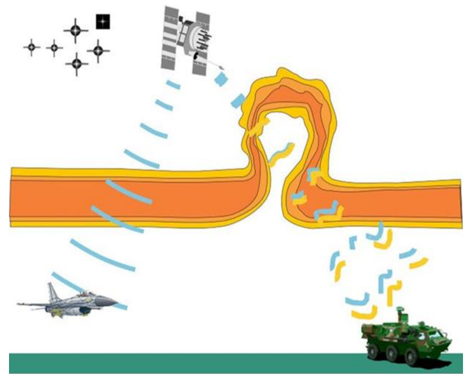
More info on ionospheric scintillation: SWS: http://www.sws.bom.gov.au/Satellite/6/3

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/

SWx impacts 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

SWEC Space Weather Education Center

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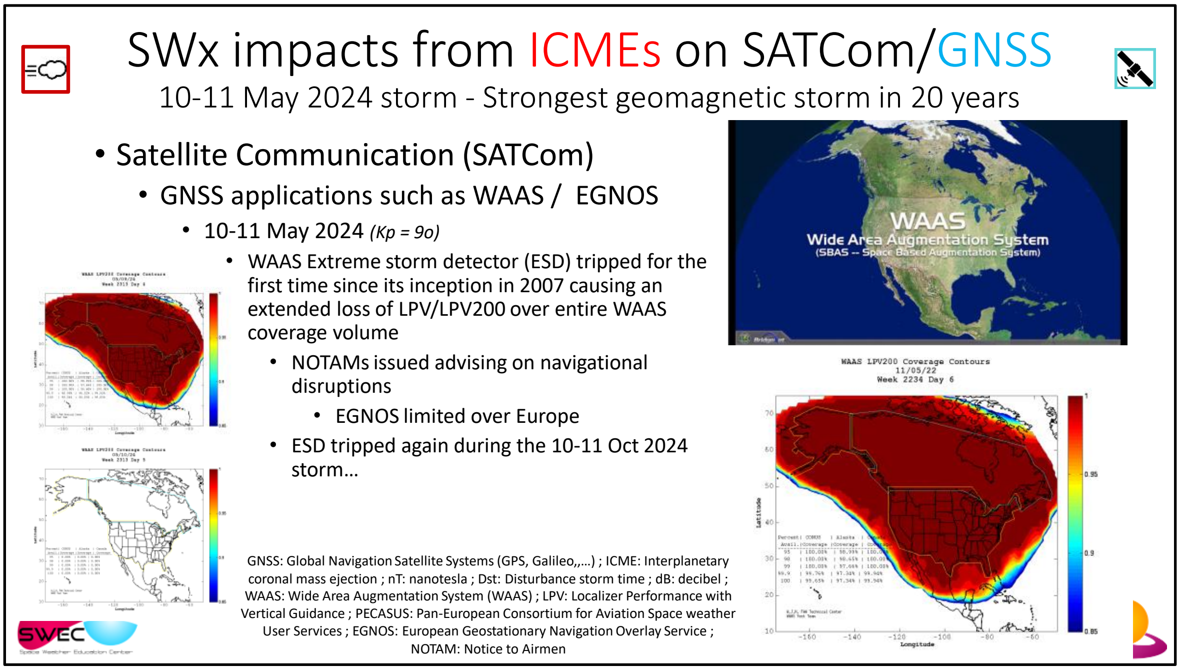
Lower left figure from US Air Force Research Laboratory - https://www.nasa.gov/mission_pages/cindi/five-years.html

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.



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.

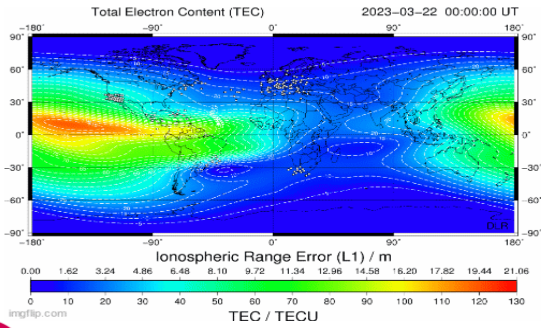
- EXTRA INFO: WAAS LPV-200 refers to the Wide Area Augmentation System (WAAS) Localizer Performance with Vertical Guidance (LPV) procedure that allows aircraft to descend to as low as 200 feet above the runway.

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

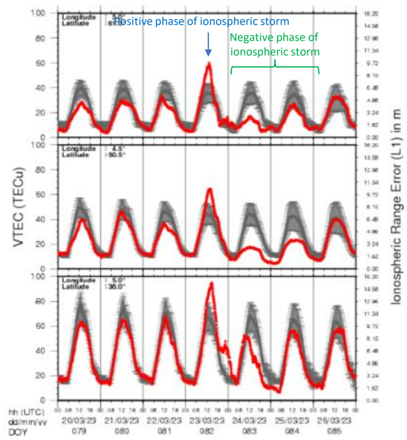
<u>Sources</u>: Input from presentations during the ESWW2024 in Coimbra, Portugal (https://esww2024.org/)
- Impacts of Space Weather on Aviation and FAA Insights from the May Solar Storms - by Samantha Watson, Karen Shelton-Mur (FAA)
- Four years of ICAO space weather advisories - by Kasper van Dam (KNMI),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

SWx impacts from ICMEs on HF Com

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



Credits images: PECASUS & DLR/IMPC



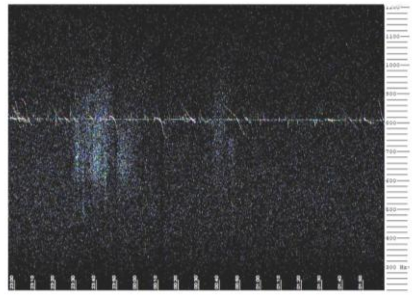
Credits: ROB/GNSS

HF: High Frequency ; (I)CME: (Interplanetary) Coronal Mass Ejection ; Kp: planetary K index ; Dst: Disturbance storm-time index ; nT nano tesla ; (V)TEC: (Vertical) Total Electron Content ; TECU: TEC unit

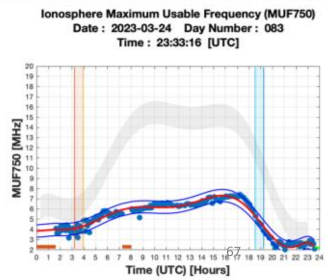
https://www.stce.be/news/640/welcome.html
https://www.stce.be/news/638/welcome.html

SWx impacts from ICMEs on HF Com

- Auroral Absorption (AA)
  - HF Com due to aurora affecting lower ionosphere
  - 18-19 Sep 1941
    - Kp=9- for 24 hours (!)
    - Radio broadcast disturbed
    - Bombing raids under light of aurora
- Post-Storm Depression (PSD)
  - Negative phase of ionospheric storm
    - => strong reduction electron content ionosphere
    - = Reduce HF higher frequencies
  - 25-26 May 1967
    - Most negative phase in TEC ever recorded



Credits: Felix Verbelen (BRAMS) 10-11 October 2024



Credits: IMPC – 24 March 2023

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

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Figure top right: Felix Verbelen (10-11 October 2024)
Impacts from a severe geomagnetic storm
https://www.stce.be/news/729/welcome.html
Belgian radio meteor observers from the BRAMS network (Belgian RAdio Meteor Stations ; see this STCE newsitem for more info on BRAMS) recorded considerable noise in their radio displays hampering a good detection of any radio signature from a passing meteor. In the image underneath, time is on the horizontal axis and vertically there's band of a few 100 Hz wide near the radio frequency of the beacon at 49.99 MHz (Ypres, Belgium; *courtesy Felix Verbelen*). The reversed "S"-shapes are reflections from passing airplanes. The strongest noise is visible between 23:30 and 24:00UTC on 10 October, right around the time of the most severe phase of the geomagnetic storm. The disturbance on these radio beacons was much less pronounced than during the May storm, when even the direct signal was barely visible in the spectrograms during the main phase of the storm (see the STCE newsitem).

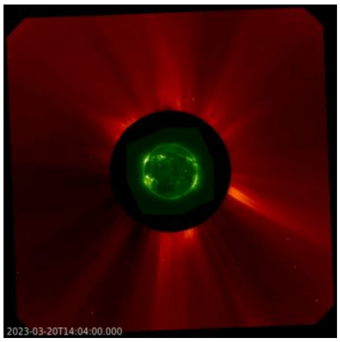
The geomagnetic storm of 23-24 March 2023 affected GNSS applications and HF communications. *The figure in the lower right* is from IMPC (https://impc.dlr.de/projects/current-projects/) and shows that -for that day- the maximum usable HF frequency (MUF) to cover a distance of 750 km was only about 7-8 MHz, whereas during quiet days (greyish area) the MUF 750 was up to 15-16 MHz.

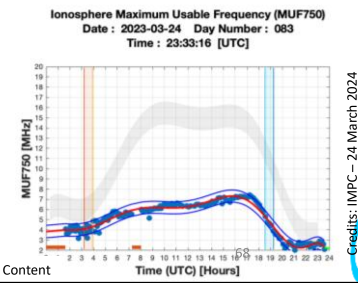
18-19 September 1941 - Newspapers, for example, succinctly reported that the British Royal Air Force carried out a raid on a German supply base on the Baltic Sea [*Washington Post,* 1941b] and that the Germans bombarded Leningrad [*Chicago Tribune,* 1941b], each under the lights of the aurora borealis. 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."

Space weather effects from the May 1967 events: Knipp et al. (2016): https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016SW001423

SWx impacts from ICMEs on HF Com

- Auroral Absorption (AA)
  - Aurora affecting lower ionosphere
- Post-Storm Depression (PSD)
  - Negative phase ionospheric storm





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

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 far side (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. 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 colored 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!"

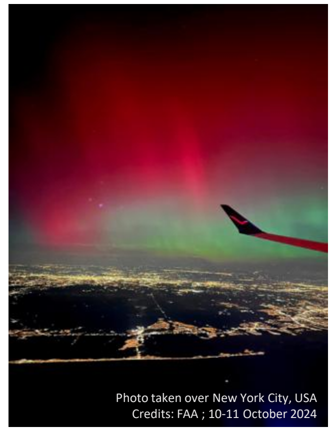
The geomagnetic storm affected GNSS applications and HF communications. The figure in the lower right is from IMPC (https://impc.dlr.de/projects/current-projects/) and shows that -for that day- the maximum useable HF frequency (MUF) to cover a distance of 750 km was only about 7-8 MHz, whereas during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

See also 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

SWx impacts from ICMEs on HFCom

10-11 May 2024 storm - Strongest geomagnetic storm in 20 years

- Federal Aviation Administration:
  - Frequency issues on overseas flight
    - Brief radio transmission/equipment blips
    - Transoceanic flight rerouted due to HF radio comms loss
  - 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…
- PECASUS
  - 9 reports of HF Com loss (8-14 May)
    - Few ; Difficult to link to source (location)
  - Iceland Radio (HF Com Tower)
    - Black out on 11-12 May (above 70N)



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

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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.

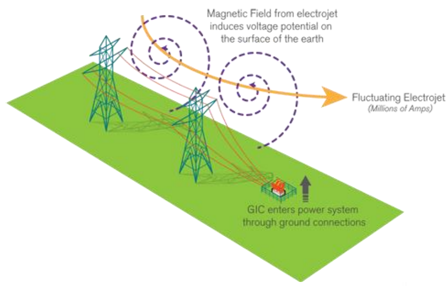
- EXTRA INFO: WAAS LPV-200 refers to the Wide Area Augmentation System (WAAS) Localizer Performance with Vertical Guidance (LPV) procedure that allows aircraft to descend to as low as 200 feet above the runway.

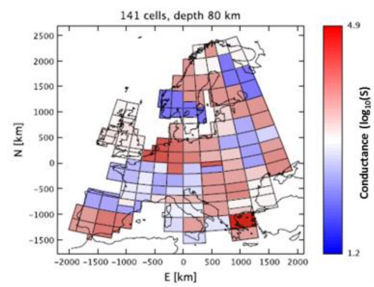
NOTAMs, or Notices to Airmen, were issued by the FAA advising of the potential communication and navigation disruptions.

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.

SWx impacts from ICMEs

- Geomagnetically Induced Currents (GIC)
  - Electrons from magnetotail => ionospheric currents => Magnetic field => currents in crust surface
  - Affects all long conductors
    - Enters via ground connections
  - GIC depends on
    - Strength ICME
    - Geomagnetic latitude
      - Eq. Latitudes too!
    - Local conductance
    - Network details





Top figure from SPX Transformer Solutions (https://www.waukeshatransformers.com/)

Bottom figure:
Viljanen et al. (2014): Geomagnetically induced currents in Europe. Modelled occurrence in a continent-wide power grid
https://ui.adsabs.harvard.edu/abs/2014JSWSC...4A..09V/abstract
Figure 2 shows the blocks and the conductances calculated by integrating the conductivity from the surface down to 80 km. This map indicates qualitatively the expected magnitudes of the electric field. If the magnetic variation field is identical everywhere then the electric field is larger in blue areas with smaller conductivities in the top ground layers.

Carter et al. (2015): Interplanetary shocks and the resulting geomagnetically induced currents at the equator
https://ui.adsabs.harvard.edu/abs/2015GeoRL..42.6554C/abstract
Power grid infrastructure in the equatorial region is more susceptible to space weather than previously thought. The equatorial electrojet is the primary cause of this newly recognized threat, due to its ability to amplify magnetic perturbations from interplanetary shock arrivals by several fold. These d*B/*dt amplifications occur on the dayside for every interplanetary shock; including those that are precursors to geomagnetic storms and those that are not. While the focus of previous research on severe geomagnetic storms has been justified (given the many reports of equipment failures in the past), the present study clearly indicates that quiet geomagnetic periods must also be considered because of the influence of the electrojet at the magnetic equator.
For equatorial countries that are relying on infrastructure not designed to cope with space weather, this finding has profound implications. Given previous equipment failures reported at midlatitudes for d*B/*dt levels less than 100 nT/min [*Kappenman*, 2005; *Gaunt and Coetzee*, 2007], space weather impacts are likely to be a significant factor in power stability problems at the equator. As such, future studies investigating the direct impact of interplanetary shocks on equatorial power grids are strongly encouraged.

SWx impacts from ICMEs

- GICs
  - Power grids
    - Distortions voltage pattern
    - Transformer damage
      - South-Africa, Oct 2003
    - Grid collapse
      - Québec, March 1989
      - Malmö, Sweden, 2003
    - 10-11 May 2024
      - No major impacts on grids
    - Longterm effects of power loss!

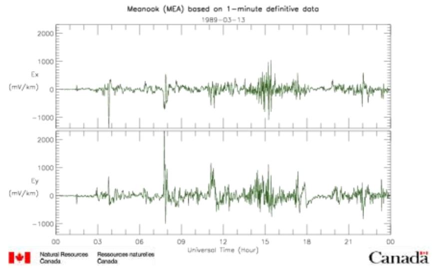


Table 3 Parameters for the GIC emergency alert model. The criterion for each alert level is shown in the second column, and the following columns show the expected extreme dB/dt values for RC-, AE-, and SC-type GICs

		dB/dt of GICs		
Alert level	Criterion	RC (nT/h)	AE (nT/min)	SC (nT/s)
Caution	Dst < −300 nT	100–150	2000	40–110
Warning	Dst < −600 nT	150–400	4000	40–110
Emergency	Dst < −900 nT	400–1250	6000	40–110
Transient alert	High SEP flux			40–110

Credits: Metatech

Lower right figure from Girgis et al. 2012 - https://ieeexplore.ieee.org/document/6281595
Fig. 11 – Winding series – connection overheating in PSE&G Transformer caused by the March 13, 1989 GIC Event.
Another example at http://www.spaceweather.org/ISES/swxeff/5.pdf (South Africa transformers damaged in October 2003)

GIC graphs available at
NR CAN: https://geomag.nrcan.gc.ca/plot-tracee/sdp-en.php
EURISGIC: http://eurisgic.org/

Lower left table from Kataoka et al. (2016): Extreme geomagnetically induced currents
https://ui.adsabs.harvard.edu/abs/2016PEPS....3...23K/abstract
Large-amplitude dB/dt values are the major cause of hazards associated with three different types of GICs: (1) slow dB/dt with ring current evolution (RC-type), (2) fast dB/dt associated with auroral electrojet activity (AE-type), and (3) transient dB/dt of sudden commencements (SC-type). We set "caution," "warning," and "emergency" alert levels during the main phase of superstorms with the peak Dst index of less than -300 nT (once per 10 years), -600 nT (once per 60 years), or -900 nT (once per 100 years), respectively. The extreme dB/dt values of the AE-type GICs are 2000, 4000, and 6000 nT/min at caution, warning, and emergency levels, respectively. For the SC-type GICs, a "transient alert" is also proposed for dB/dt values of 40 nT/s at low latitudes and 110 nT/s at high latitudes, especially when the solar energetic particle flux is unusually high.

10-11 May 2024 geomagnetic storm – Wikipedia (https://en.wikipedia.org/wiki/May_2024_solar_storms)
In Canada, power companies BC Hydro and Hydro-Québec stated that they had prepared for the storm, and monitored it as its ejecta struck Earth on 10–11 May. Unlike in 1989 where a previous solar storm caused a nine-hour long power outage in Québec, no outages were reported as a result of the storm's effects.

In New Zealand, Transpower declared a grid emergency, and took some transmission lines out of service as a precaution against the storm.

In the United States, telecommunications companies AT&T and T-Mobile stated that they were prepared to respond to disruptions in their networks, but it was predicted that significant impacts to cell service were unlikely because the networks rely on different frequencies than the HF bands affected by the solar storm. While the National Oceanic and Atmospheric Administration (NOAA) reported that there were power grid irregularities and degradation in GPS and high-frequency radio communications, both the Federal Emergency Management Agency (FEMA) and the United States Department of Energy reported no significant impacts to the population.

Effects from ICMEs

- GICs
  - Railways
    - New York (USA), 14-15 May 1921
    - Sweden, 13-14 July 1982
    - China, 17 March & 23 June 2015
  - Pipelines
    - Corrosion => Oil leaks
  - Telephone/Telegraph
    - Carrington event (1859),…
    - Transcontinental cables
      - 4 August 1972
  - Transatlantic cables
    - Copper to optical fiber
      - But « optical repeaters »!
      - March 1989 event
  - High-precision industry
    - Wellbore drilling
      - Manitoba, Canada, 27 February 2023

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Top left image from https://www.alyeska-pipe.com/
Top right image from https://www.submarinecablesystems.com/history
Bottom image from https://www.facebook.com/groups/manitobaauroraandastronomy/permalink/987702122615480/ and https://rntfnd.org/2023/02/28/solar-weather-impacting-gps-oil-drilling-what-else/

- Railways:
Liu et al. (2016): Analysis of the monitoring data of geomagnetic storm interference in the electrification system of a high-speed railway
https://ui.adsabs.harvard.edu/abs/2016SpWea..14..754L/abstract
Wik et al. (2009): Space Weather events in July 1982 and October 2003…
https://ui.adsabs.harvard.edu/abs/2009AnGeo..27.1775W/abstract
13–14 Jul 1982: 4 transformers and 15 lines tripped in the high-voltage power system. Railway traffic lights turned erroneously to red

- Pipelines:
Hejda et al. (2005): Geomagnetically induced pipe-to-soil voltages in the Czech oil pipelines during October-November 2003
https://ui.adsabs.harvard.edu/abs/2005AnGeo..23.3089H/abstract
- Also at https://www.windows2universe.org/?page=/space_weather/sw_in_depth/pipeline_effects.html
- Also at NRCan: https://www.spaceweather.gc.ca/tech/index-en.php#pip

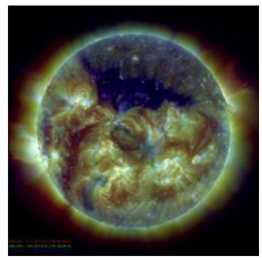
Systems affected by GIC
- GIC now! (FMI): https://space.fmi.fi/gic/
- Transatlantic cables
Medford et al. (1981): Geomagnetic induction on a transatlantic communications cable
https://ui.adsabs.harvard.edu/abs/1981Natur.290..392M/abstract
NRCan: https://www.spaceweather.gc.ca/tech/index-en.php#cab
- Transcontinental cables
Boteler et al. (1999): August 4, 1972 revisited: A new look at the geomagnetic disturbance that caused the L4 cable system outage - https://ui.adsabs.harvard.edu/abs/1999GeoRL..26..577B/abstract

RAE (2013): Extreme space weather: impacts on engineered systems and infrastructure
https://raeng.org.uk/media/lz2fs5ql/space_weather_full_report_final.pdf
However, electric power is required to drive optical repeaters distributed along the transoceanic fibers and this is supplied by long conducting wires running alongside the fiber. These wires are vulnerable to GIC effects as was demonstrated during the geomagnetic storm of March 1989. The first transatlantic optical fiber cable, TAT-8, had started operations in the previous year and experienced potential changes as large as 700 volts [*Medford et al.*, 1989]. Fortunately the power system was robust enough to cope. Similar but smaller effects were also seen during the Bastille Day storm of July 2000 [*Lanzerotti et al.*, 2001]. We are not aware of any effects occurring during the Halloween event of 2003, but that event was relatively benign in terms of GIC effects.

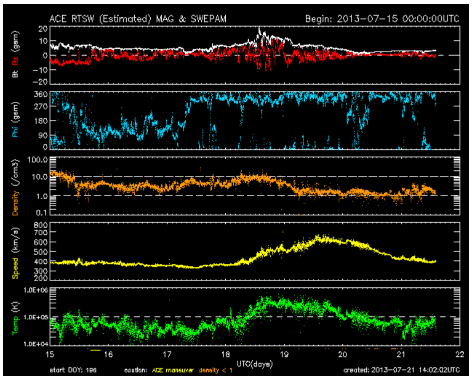
Space Weather impacts (SWx impacts)

- *Recap*
- *SWx impacts from*
  - *Solar flares*
  - *Proton events*
  - *ICMEs*
  - ***Coronal holes***

Coronal Holes



SWx impacts from CHs



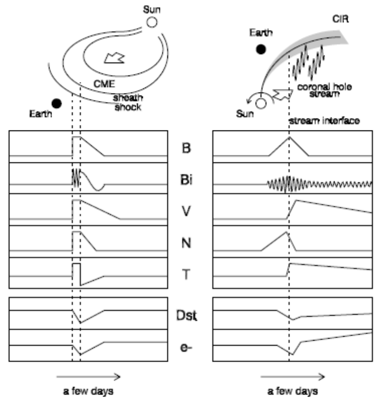


Figure 1. Schematic illustration of typical solar wind structures of coronal mass ejections (CMEs) and corotating interaction regions (CIRs): (top to bottom) magnetic field strength B, one of the Cartesian component B_i, solar wind speed V, density N, temperature T, expected response of the Dst index, and >2.0 MeV electron flux at geosynchronous orbit.

Credits: Kataoka et al. (2006)

Top right picture
Kataoka et al. (2006): Flux enhancement of radiation belt electrons during geomagnetic storms driven by coronal mass ejections and corotating interaction regions
https://ui.adsabs.harvard.edu/abs/2006SpWea...4.9004K/abstract

Topleft: 7 day solar wind parameter chart from ACE

SIR/CIR
Jian et al. (2006): Properties of Stream Interactions at One AU During 1995 2004
https://ui.adsabs.harvard.edu/abs/2006SoPh..239..337J/abstract

Jian et al. (2010): http://www-ssg.sr.unh.edu/mag/JointMeet/Jian_SIRs.pdf

More info on (C)IR and SBC in this STCE News item: SBC or CIR?
https://www.stce.be/news/269/welcome.html

More info on associated shocks in this news item: Shocking news
https://www.stce.be/news/229/welcome.html

On shock identification in solar wind - Scolini et al. (2018) - https://www.swsc-journal.org/articles/swsc/abs/2018/01/swsc170032/swsc170032.html
the following criteria have been applied:
Bdown/Bup ≥1.2; Np down / Np up ≥1.2; Vdown - Vup ≥ 20km·s-1;
where upstream and downstream values were calculated over a fixed time interval Dtup = Dtdown = 10 min before and after the shock.

SWx impacts from CHs

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

More info at
SWPC: https://www.swpc.noaa.gov/noaa-scales-explanation
https://www.swpc.noaa.gov/phenomena/geomagnetic-storms

SWx impacts from CHs

- Similar to effects from ICMEs but less intense

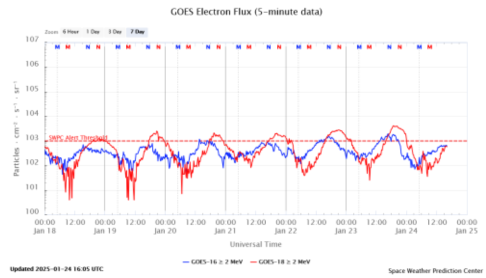
- except…

- From particles
  - Satellites
    - **Deep di-electric charging**

GCR: Galactic Cosmic Rays ; GNSS: Global Navigation Satellite Systems ;
PECASUS: Pan-European Consortium for Aviation Space weather User Services

SWx impacts from CHs on satellites

- 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



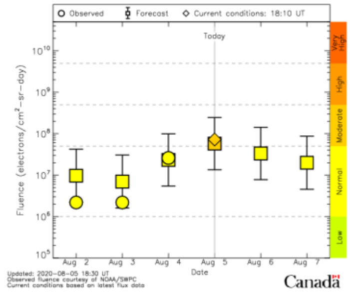
Top right figure: https://www.spaceweather.gc.ca/forecast-prevision/space-spatiale/sffl-en.php

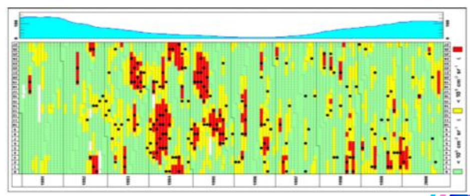
Bottom right figure:
Wrenn et al. (2002): A solar cycle of spacecraft anomalies due to internal charging
https://ui.adsabs.harvard.edu/abs/2002AnGeo..20..953W/abstract
The maximum of the smoothed sunspot number for cycle 22 was in July 1989; the minimum in May 1996, then heralded as the start of cycle 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 news items: 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

SWx impacts from CHs on satellites

- 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



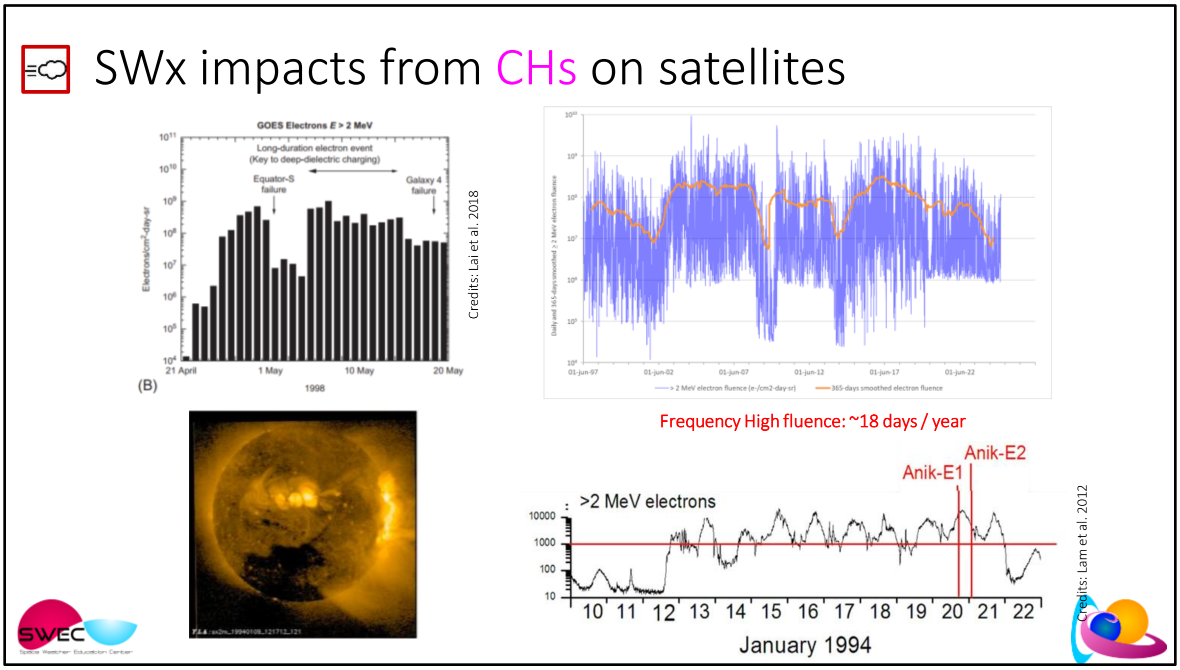


Credits: Wrenn et al. (2002)

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

:Issued: 2024 Mar 17 1231 UTC
:Product: documentation at http://www.sidc.be/products/tot
#--#
DAILY BULLETIN ON SOLAR AND GEOMAGNETIC ACTIVITY from the SIDC #
#--#
SIDC URSIGRAM 40317
SIDC SOLAR BULLETIN 17 Mar 2024, 1231UT
SIDC FORECAST
SOLAR FLARES : M-class flares expected (probability >=50%)
GEOMAGNETISM : Quiet (A<20 and K<4)
SOLAR PROTONS : Quiet
PREDICTIONS FOR 17 Mar 2024 10CM FLUX: 144 / AP: 007
PREDICTIONS FOR 18 Mar 2024 10CM FLUX: 146 / AP: 007
PREDICTIONS FOR 19 Mar 2024 10CM FLUX: 148 / AP: 007

Finding your way in the URSIgram

Solar Active Regions and flaring: There are five active regions visible on the solar disk. They all have simple beta or alpha magnetic field configuration and produced minor C-class flaring. The main activity in the last 24 hours has been observed from active regions behind the east limb, that will rotate into view in the next hours. The strongest was an M3.5 flare peaking at 16:35 UTC on 16 March, from a region not yet visible, located behind the east limb. As these regions rotate into view, we expect more M-class and possible X-class flares in the next 24 hours.

Coronal mass ejections: There was a partial halo CME (angular width about 180 degrees) directed towards the south, first seen at 03:24 UTC by LASCO C2. This CME originates from a filament eruption in the southern hemisphere. Since the filament was located close to the disk center, an ICME may arrive to the Earth on 20-21 March (a better estimation will be given when more data become available).

Solar wind: The Earth is inside slow solar wind, with speeds close to 350 km/s and an interplanetary magnetic field around 5 nT. Similar conditions are expected for the next 24 hrs.

Geomagnetism: Geomagnetic conditions were quiet both global and locally (NOAA_Kp up to 1 and K_BEL up to 1). Similar conditions can be expected for the next 24 hours.

Proton flux levels: The 10 MeV proton flux (measured by GOES-18) has come below the 10 pfu threshold, but remains elevated. It is expected that it will go back to low levels in the next 24 hrs.

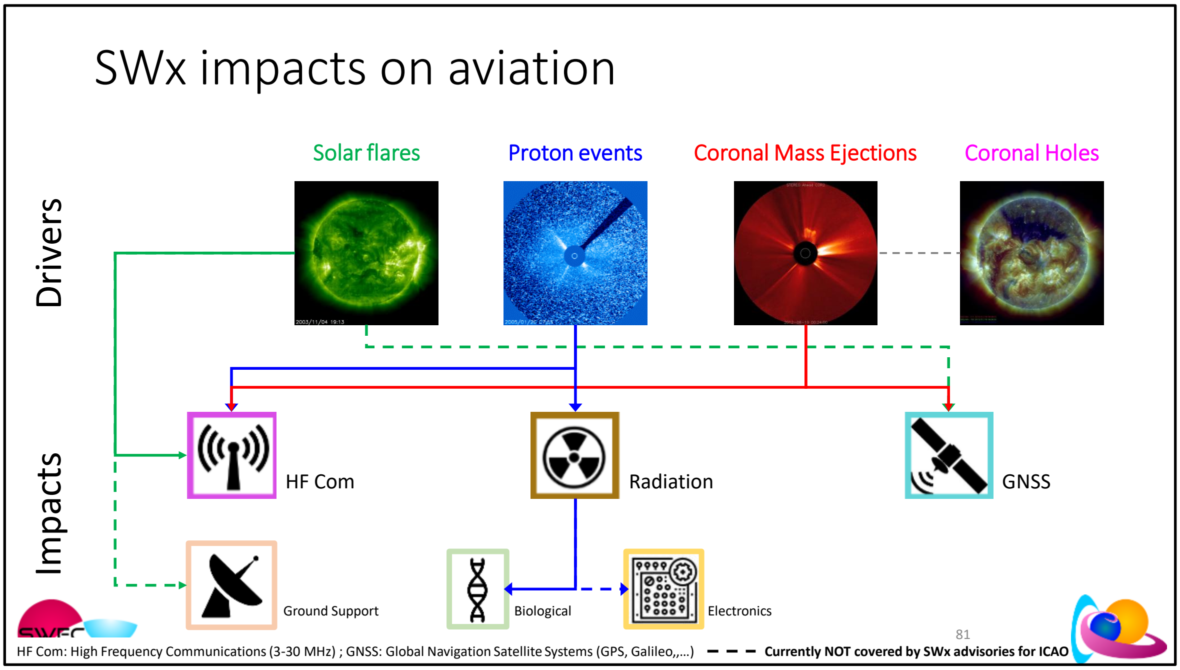
Electron fluxes at GEO: The greater than 2 MeV electron flux from GOES 16 was below the threshold level in the last 24 hours. It is expected to remain below the threshold during the next 24 hours. The 24h electron fluence was at normal level and is expected to remain so.

TODAY'S ESTIMATED ISN : 074, BASED ON 10 STATIONS.

SOLAR INDICES FOR 16 Mar 2024
WOLF NUMBER CATANIA : ///
10CM SOLAR FLUX : 144
AK CHAMBON LA FORET : 005
AK WINGST : 002
ESTIMATED AP : 002
ESTIMATED ISN : 058, BASED ON 23 STATIONS.

$\geq$ 2MeV electron flux & fluence

NOTICEABLE EVENTS SUMMARY
DAY BEGIN MAX END LOC XRAY OP 10CM Catania/NOAA RADIO_BURST_TYPES
16 1622 1635 1644 ////// M3.5 ///////
16 2127 2155 2211 ////// M1.1 ///////
END



SWx impacts on aviation
Drivers
Impacts
Solar flares
Proton events
Coronal Mass Ejections
Coronal Holes
HF Com
Radiation
GNSS
Ground Support
Biological
Electronics
81
HF Com: High Frequency Communications (3-30 MHz) ; GNSS: Global Navigation Satellite Systems (GPS, Galileo,,...)
Currently NOT covered by SWx advisories for ICAO

Summary SWx effects (1/2)

- Solar flares
  - NOAA scale (R)
  - From EUV & X-ray radiation
    - Solar flare effect (“magnetic crochet”)
      - => Effects from ICMEs
    - Shortwave fade (“Radio Blackout”)
      - => PECASUS
  - From radio emission
    - GNSS disturbances
    - Radar disturbances

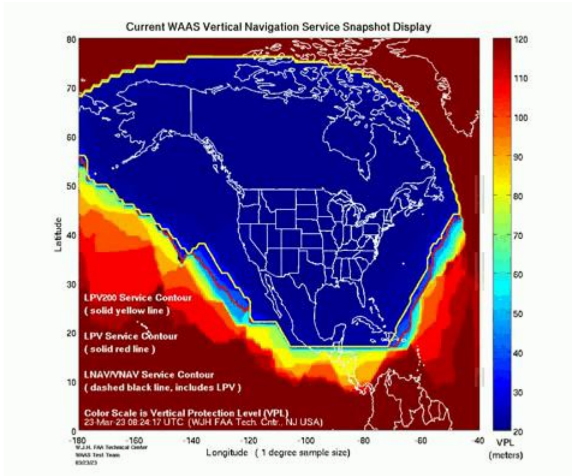
- Proton events
  - NOAA scale (S)
  - Polar Cap Absorption (PCA)
    - => PECASUS
  - Radiation
    - Astronauts, Polar flights
      - => PECASUS
  - Satellites
    - Star trackers
    - Solar arrays
    - Single Event Effects (SEE)
  - Ground Level Enhancement (GLE)

Summary SWx effects (2/2)

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

- Coronal Holes
  - NOAA scale (G)
    - Impacts similar but less severe than from (strong) ICMEs
    - Especially during the declining phase of Solar Cycle
  - Satellites
    - Deep di-electric charging

Questions?



Current WAAS Vertical Navigation Service Snapshot Display
Latitude
Longitude (1 degree sample size)
LPV200 Service Contour
(solid yellow line)
LPV Service Contour
(solid red line)
LNAV/VNAV Service Contour
(dashed black line, includes LPV)
Color Scale is Vertical Protection Level (VPL)
23-Mar-23 08:24:17 UTC (WJH FAA Tech. Cntr., NJ USA)
VPL
(meters)