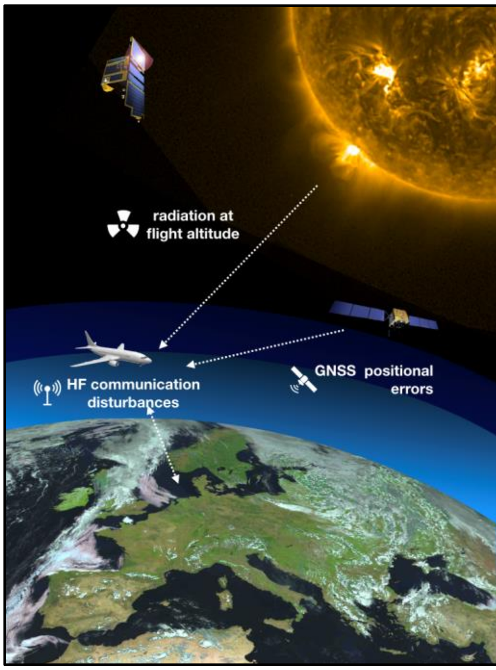


Space Weather impacts on Aviation

Course by the
Solar-Terrestrial Centre of Excellence

March 2024

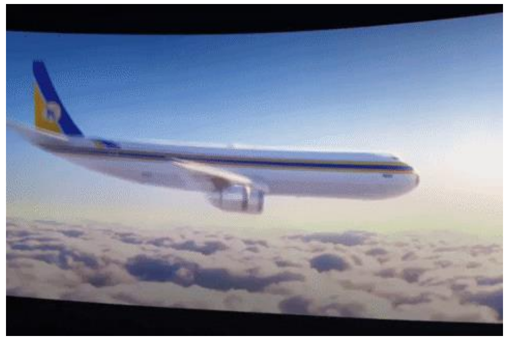
Space Weather impacts on Aviation

Disturbances seen in GNSS, HF Com and Radiation at FL

Jan Janssens

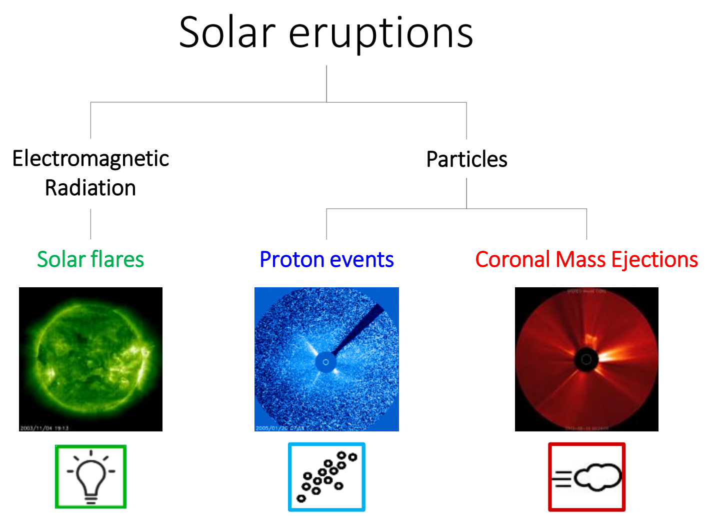
Contents

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



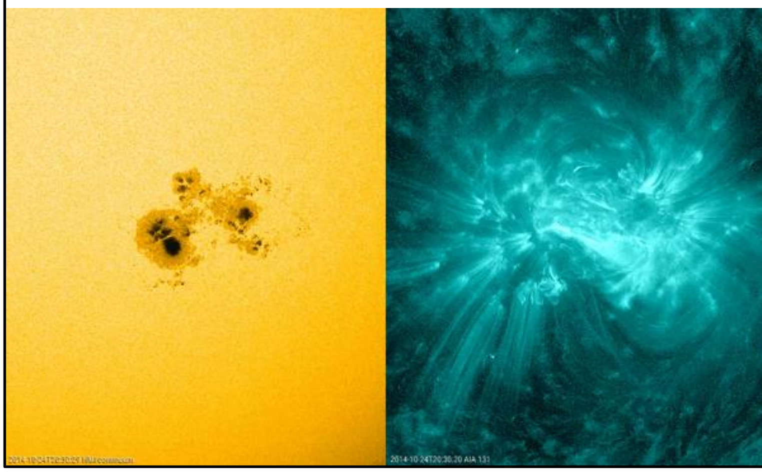
Minions – Pilots scene

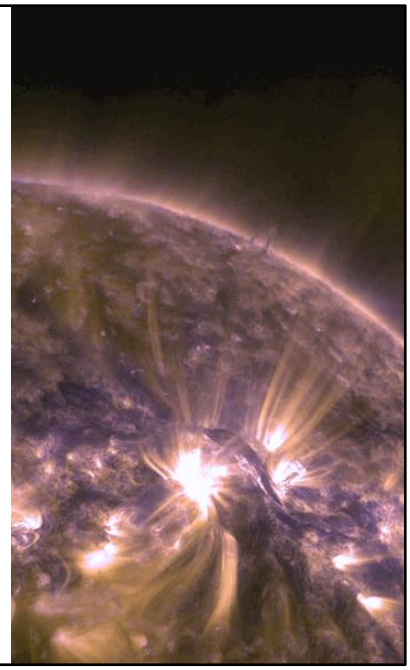
Drivers of disturbed SWx



SWx: Space weather

Examples solar flare

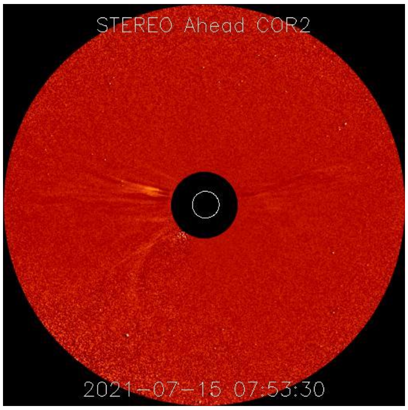


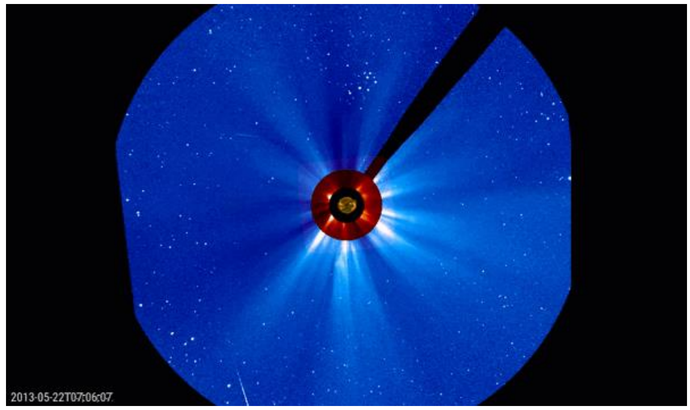


Left: X3.1 flare on 24 October 2014 - https://www.stce.be/news/276/welcome.html
The source of the eruption is once again NOAA 2192, the biggest sunspot group of the last two decades. The region has an area of about 16 times the total surface area of the Earth. It is still a very complex group. With this X3.1 flare, NOAA 2192 did not only produce its third "eXtreme" class event, it was also the most powerful flare this group has produced so far. For the moment, the number of high-energetic particles has not increased and remains stable. Recent coronagraphic images indicate there was no obvious coronal mass ejection associated to this flare, with at most a narrow jet directed away from Earth.

Right: M3.7 flare on 24 February 2023 - https://www.stce.be/news/631/welcome.html
Sunspot group NOAA 13229, source of an X-class event on 17 February, was decaying when it produced an M3.7 and an M6.3 flare (GOES soft x-ray) on respectively 24 and 25 February. The imagery from the H-alpha network from GONG shows the presence of a long filament with the middle portion intersecting active region (AR) 13229 north to south. Only a few sunspots were remaining, the two largest can be seen to the northwest of the filament. The clip shows the 24 February eruption in extreme ultraviolet (EUV) at temperatures around 700.000 degrees (SDO/AIA 171 ; yellowish) and multi-million degrees (SDO/AIA 131), the latter allowing a better contrast between the cold (dark purple) and hot (sky blue) areas of the eruption.

Example CMEs and proton event



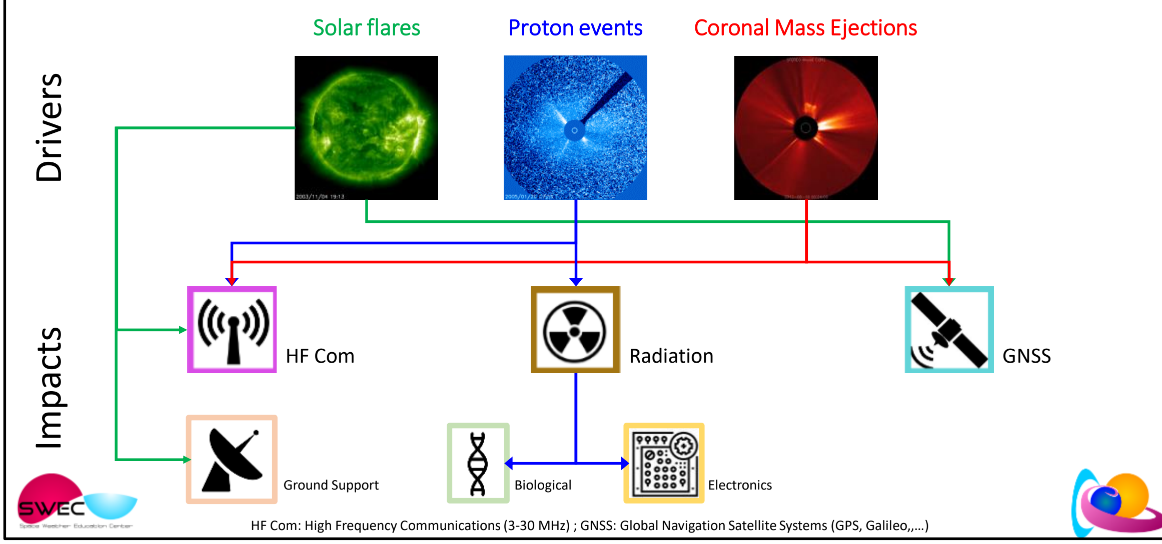


CME: Coronal Mass Ejection

Left: CME on the Sun’s farside: https://www.stce.be/news/543/welcome.html
Activity then gradually seemed to move to regions in the southern solar hemisphere, and the CME from 15 July originated indeed from a region near the southeast limb. This CME was quite spectacular, with a solid core filament ejected mainly towards the south. The source region may be NOAA 2835 or one or more regions that have developed close-by. NOAA 2835 was a rather big but mostly inactive sunspot region, producing only some low-level C-class flares while transiting the solar disk from 25 June till 6 July. As the entire active area is only now (20 July) starting to round the southeast solar limb, it's still a bit too soon to say anything about the sunspot group(s).

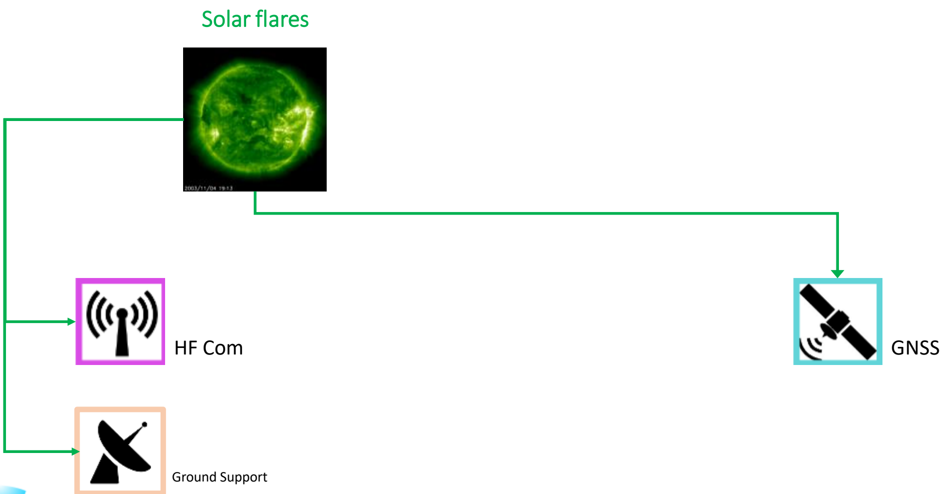
Right: Proton event (1660 pfu – S3 solar radiation storm on the NOAA scale - https://www.swpc.noaa.gov/noaa-scales-explanation) associated with an M5 flare in NOAA 1745. More importantly, the flare was also accompanied by a strong proton event, lasting for nearly 3 days. It was also the strongest so far this year, and the third strongest of the ongoing solar cycle, after the January and March 2012 events. Protons slamming unto the detectors of the solar telescopes saturate the camera's pixels which results in a lot of noise (white dots and stripes) and a reduction in the quality of the image. In extreme cases, the degraded images prohibit the finder telescope to actually find the proper reference stars, which occasionally results in the satellite pointing its solar panels away from the Sun, thus cutting itself off from the much needed electricity. This proton storm pretty much obscured the view on the Pleiades in the SOHO/Lasco imagery.

SWx impacts on aviation



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

SWx impacts from solar flares on aviation

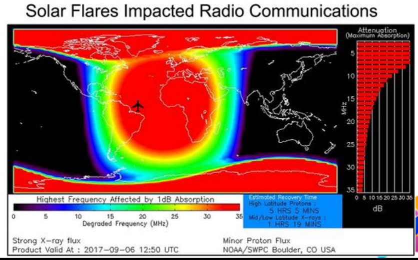


HF Com: High Frequency Communications (3-30 MHz) ; GNSS: Global Navigation Satellite Systems (GPS, Galileo,...)

SWx impacts from solar flares on HF Com

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

Solar Flares Impacted Radio Communications



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

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

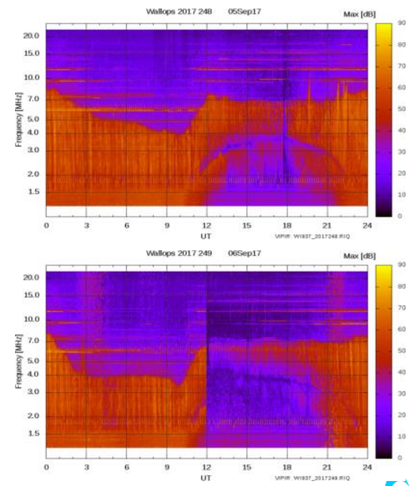
AGU press release; https://news.agu.org/press-release/solar-flares-disrupted-radio-communications-during-september-2017-atlantic-hurricane-relief-effort/
Solar flares disrupted radio communications during September 2017 Atlantic hurricane relief effort
… A class X-2.2 and major class X-9.3 solar flare erupted on the morning of September 6 at about 8 a.m. local time. NOAA's Space Weather Prediction Center warned of a strong radio blackout over most the sunlit side of Earth, including the Caribbean.
… Amateur radio operators assisting with emergency communications in the islands reported to the Hurricane Watch Net that radio communications went down for most of the morning and early afternoon on September 6 because of the Sun's activity, according to the new study. French civil aviation reported a 90-minute loss of communication with a cargo plane, according to the study's authors, and NOAA reported on September 14 that high frequency radio, used by aviation, maritime, ham radio, and other emergency bands, was unavailable for up to eight hours on September 6.
… Another large class-X flare erupted from the Sun on September 10, disrupting radio communication for three hours. The disruption came as the Caribbean community coped with Category 4 Hurricane Jose's brush with the Leeward Islands and the Bahamas, and Irma's passage over Little Inagua in the Bahamas on September 8 and passage over Cuba on September 9.

From **04-12 September 2017**, NOAA 2673 produced the two strongest flares of SC24 so far (X9.3 on 06 Sep and X8.2 on 10 Sep), as well as 27 (!) M and two other X-class flares. Two proton events were associated to all this flaring, the strongest reaching 1490 pfu on 11 September; GLE was associated with the X8 flare (proton event – S3) on 10 September. The GLE is number 72 since measurements began in the 1940's, and only the 2nd so far this solar cycle (SC24; #71 was on 17 May 2012). The flaring hampered rescue efforts in the wake of Hurricane Irma in the Caribbean: HF comms was often not available due to the continued strong flaring, as well as GPS if GPS frequencies were affected (in part also because all GPS facilities onsite were destroyed). While the G4 storm on 08 September was not as strong (Dst ~ -140 nT) as those in 2015, the ISS lost about 0.5 km in altitude. See 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 fadeout (SWF)
    - Disturbance of lower ionosphere
    - Absorbs HF signals
      - “Radio Black-out”
      - Dayside
  - 6-10 September 2017
    - Hurricanes over Caribbean
    - X9 flare on 6 September
      - 90-min loss of comms with French Cargo plane over Atlantic
      - Relief efforts hampered due to SWF from strong X-class flares
        - For more than 8 hours on 6 September
  - Frequency X1+ flares
    - 5 - 25 per year



Courtesy of CIRES, Terry Bullett

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

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

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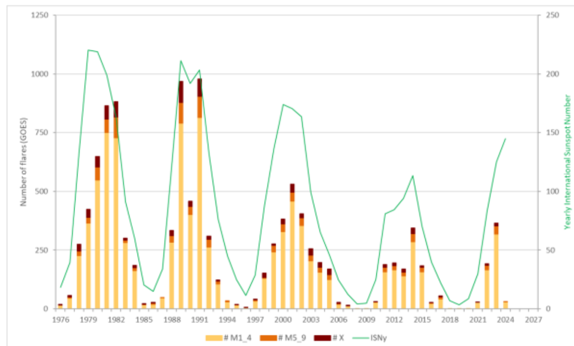
SWx impacts from solar flares on HF Com

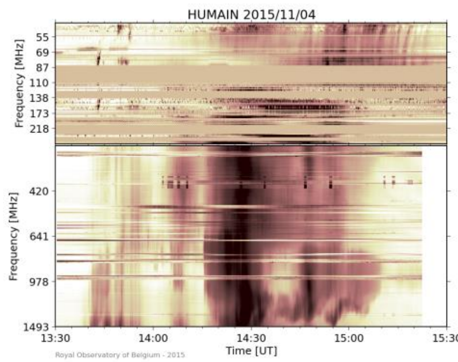
- From EUV and x-rays
  - Short-wave fadeout (SWF)
    - Disturbance of lower ionosphere
    - Absorbs HF signals
      - "Radio Black-out"
      - Dayside
  - 6-10 September 2017
  - Frequency (weak/strong SC)
    - M-class flares: 110-330 / year
    - X-class flares: 5-25 / year

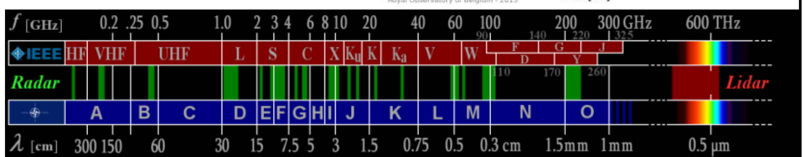


HF Com: High Frequency Communications (3-30 MHz) ; MHz: megahertz ; EUV: Extreme Ultraviolet ; SC: solar cycle

SWx impacts from solar flares on Ground Support

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





SXR: soft x-rays ; GHz: gigahertz

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.

See also STCE news item at http://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

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.

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
adsabs.harvard.edu/abs/2016EGUGA..18120170
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.

Radar figure taken from http://www.radartutorial.eu/07.waves/Waves%20and%20Frequency%20Ranges.en.html

Another example: **23 May 1967** - 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.

SWx impacts from solar flares on GNSS

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

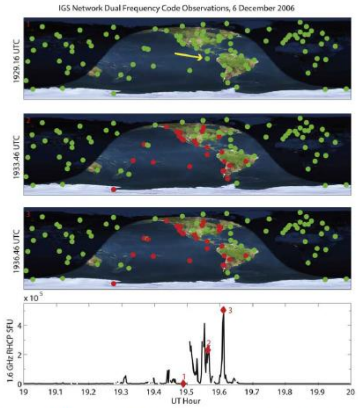


Figure 6. Receivers in the Global GPS Network that were analyzed during the solar radio burst. Green indicates the normal number of satellites being tracked. (fourth panel) During the burst (power at 1.6 GHz), several sunlit receivers tracked fewer than the four satellites needed for a full positioning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

Credits: Cerruti et al. (2008)

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

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.

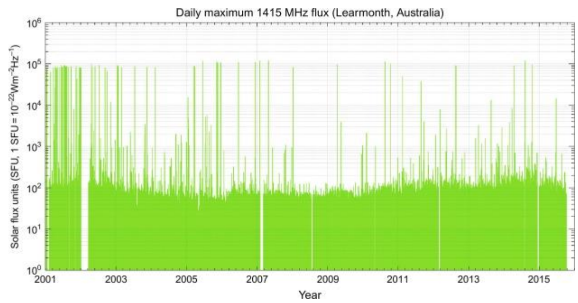
… / …

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)

GNSS: Global Navigation Satellite Systems (GPS, Galileo,,...) ; sfu: solar flux units ; MHz: megahertz ; SXR: soft x-rays ; SC: solar cycle

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.

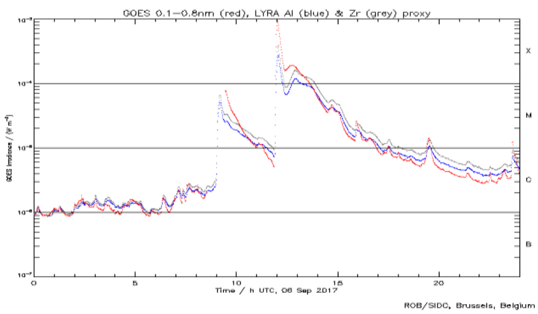
Please note that the intensities of the various radio frequencies as observed by USAF's Radio Solar Telescope Network (RSTN) are saturated at different values. For the observed frequency at 1415 MHz , this saturation level is at 100.000 sfu (Giersch et al. 2017 - https://doi.org/10.1002/2017SW001658).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

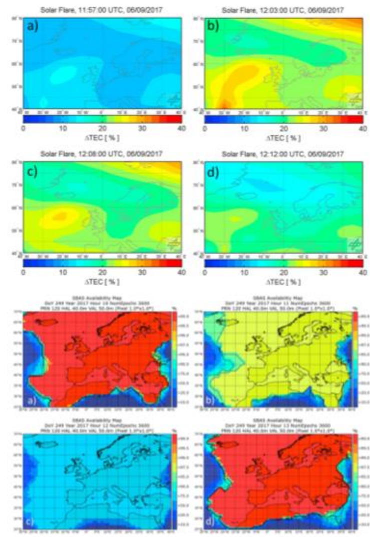
There have been 4 strong radio emission events (at GNSS frequencies) so far this solar cycle: Any effects from the 4 May 2023 radio burst (26.000 pfu), as well as from the 2 strongest bursts so far this solar cycle on 28 August 2022 (230.000 sfu, but saturation effects?) and on 13 June 2022 (98.000 sfu 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 arount 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 GNSS

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





Credits: Berdermann et al. (2018)

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

Graph on the left: PROBA2/LYRA: https://proba2.sidc.be/ssa?date=2017-09-06

Berdermann et al., 2018 - Ionospheric Response to the X9.3 Flare on 6 September 2017 and Its Implication for Navigation Services Over Europe https://doi.org/10.1029/2018SW001933 – Figures 3 and 8
Figure 3 (top right): Direct impact of the X9.3 flare on the ionosphere using the difference between the real-time assimilated TEC map over Europe and the last TEC map before the flare, which is the TEC map produced at 11.53 UTC. TEC = Total Electron Content
Figure 8 (bottom right): The hourly European Geostationary Navigation Overlay Service availability plots between 10:00 and 13:00 UT on 6 September are shown. The plots are generated with the ESA/UPC GNSS-Lab Tool (Sanz et al., 2012) and gracefully provided by ESA. Note in this figure red indicates high availability rates and blue indicates low availability rates. SBAS = satellite-based augmentation system.

The main phase, starting around 6:00 UT on 6 September and lasting till 18:00 UT on 10 September, contains two major flare events on 6 September, an X2.2 at 9:10 UT and an X9.3 at 11:53 UT as well as strong radio burst activity over a wide range of the frequency spectrum. … signals propagate within the Earth-ionosphere waveguide, they contain valuable information about the dynamic bottomside ionosphere, which is disturbed during solar X-ray flares (Wenzel et al., 2016). Therewith, VLF measurements by Global Ionospheric Flare Detection System complement X-ray measurements by GOES, providing information about cause and effect on the ionosphere system. So for both flares, the lower dayside ionosphere experienced an immediate response (a so-called sudden ionospheric disturbance) caused by the enhanced X-ray flux during solar flares. … The EUV measurements by SDO illustrate a strong impact for 30.4 nm, primarily ionizing the F region (Handzo et al., 2014). Thus, a direct impact on GNSS measurements is expected.

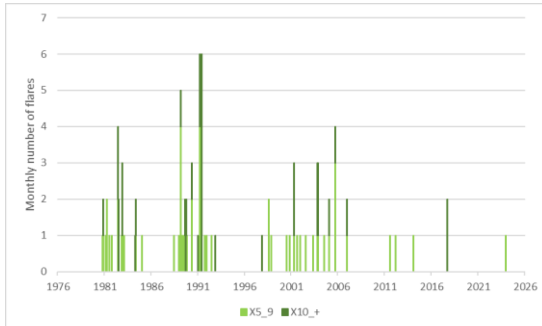
The strongest flare event started on 6 September 2017 at 11:53 UT and ended at 12:10 with the maximum at 12:02 UT. The flare had a magnitude of X9.3 making it number 14 in the ranking of all flares observed by GOES so far. The last X-class flare of this order of magnitude occurred on 5 December 2006 more than a decade ago. The X9.3 flare had a strong effect on the ionosphere over the Central European region where the impact occurred about 2 P.M. CEST.

In Figures 3a–3d the difference between the real-time assimilated TEC maps in 5-min time steps and the TEC map just before the flare produced at 11.53 UTC is shown as reference. It becomes visible how the additional radiation component of the flare is producing a sudden increase in TEC within a very short time interval (from Figure 3a to 3b), which is decreasing after 12:03 UT (from Figure 3b to 3d). This could be seen as an indication that the additional ionospheric plasma generation due to the flare is caused in the lower layers of the ionosphere, where strong recombination processes occur, thus supporting the sudden decrease of ionospheric plasma after the flare event.

The monitoring and assessment of vessel traffic is an important element of safe, secure, and efficient shipping. Collision and grounding avoidance at sea requires a reliable picture of the maritime traffic situation. The global trend toward more autonomous operations affects also the maritime world with its need of advanced, robust, and reliable systems in every situation. Some developments in this respect has been done with the introduction of the Automatic Identification System (AIS). This system improves the safety at sea, makes bridge watchkeeping duties more comfortable, and enhances vessel traffic management ashore. … During the solar flare period there are several peaks exceeding the one sigma limit. Such increased AIS messaging traffic might indicate an enhancement of navigation information messages due to GNSS tracking problems. There is still a strong excess in the data after the flare event at 12:26. The most plausible explanation for this feature is that the ionospheric disturbance causes some longer lasting effect on the AIS transponder software, since there was no special vessel with faulty equipment or other obvious failure modes in this time frame.

SWx impacts from solar flares on GNSS

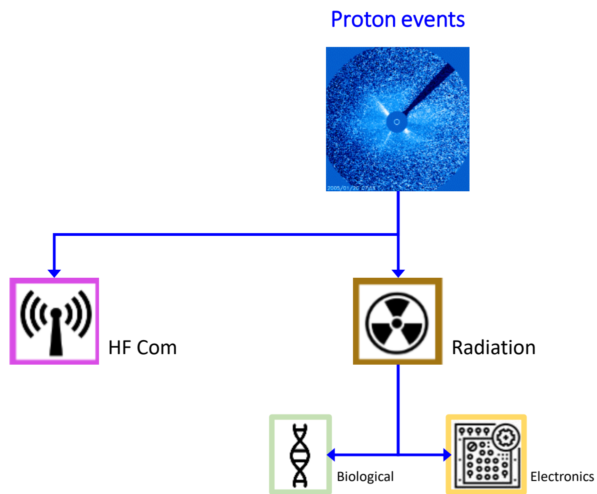
- From EUV and x-rays
  - Impact threshold
    - ~ X5
    - f(duration)
  - Frequency occurrence
    - ~ 2/year
  - Effects
    - Short-duration
    - Only sunlit side



EUV: Extreme Ultraviolet ; GNSS: Global Navigation Satellite Systems (GPS, Galileo,,...)

* Note the flare values have been corrected i.a.w. guidelines by NGDC/NOAA at https://www.ngdc.noaa.gov/stp/satellite/goes/index.html

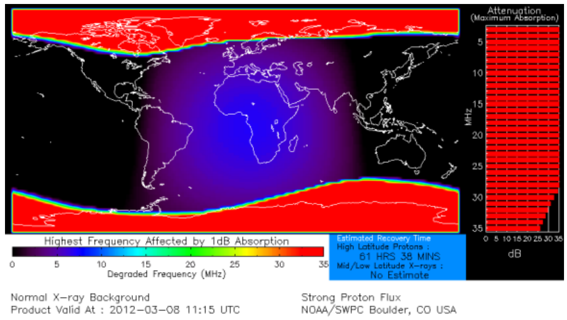
SWx impacts from proton events on aviation



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

SWx impacts from proton events on HF Com

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



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

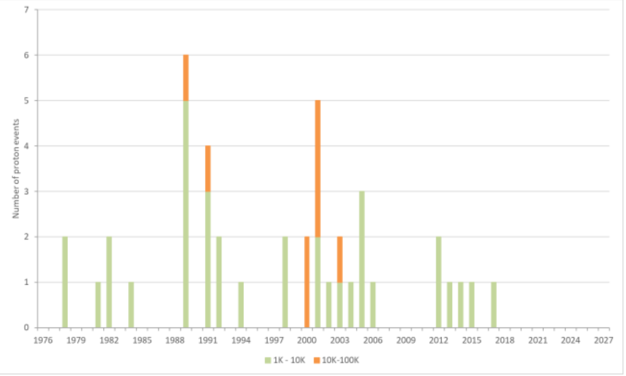
Neal et al. 2013 - Empirical determination of solar proton access to the atmosphere: Impact on polar flight paths
https://agupubs.onlinelibrary.wiley.com/doi/10.1002/swe.20066

… 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

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



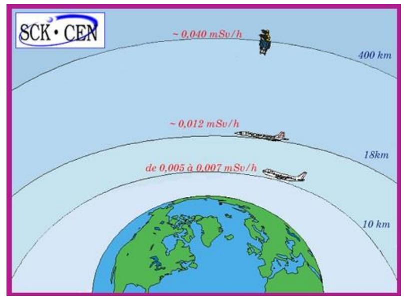
SWEC

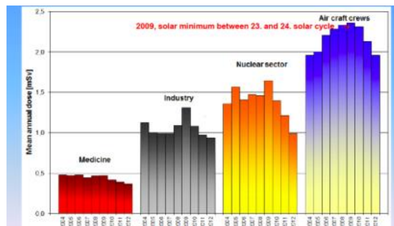
MeV: megaelectronvolt ; MF: magnetic field ; HF Com: High Frequency Communications (3-30 MHz) ; pfu: proton flux units ; dB: decibel

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

SWx impacts from proton events : Biological

- Energetic particles
  - Galactic Cosmic rays (GCR)
  - Solar Energetic Particles (SEP)
  - Can damage DNA and cause cancer & reproductive problems
- Radiation dose
  - µSv/h , mSv/year
  - Doses
    - Chest x-ray: 0.1 mSv
    - Public: 1mSv per year
    - Radiation workers: 20 mSv per year
    - NASA astronauts: 500 mSv per year
  - ICAO thresholds
    - Advisories for FL460 ; GLE required
    - Moderate: 30 µSv/h
    - Severe: 80 µSv/h





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

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

The atmospheric shield

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

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

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

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

SWx impacts from proton events : Biological

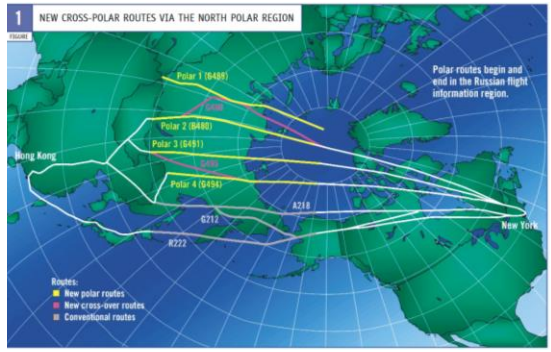
- Energetic particles
  - Galactic Cosmic rays (GCR)
  - Solar Energetic Particles (SEP)
  - Can damage DNA and cause cancer & reproductive problems
- Radiation dose
  - μSv/h , mSv/year
  - Doses
    - Chest x-ray: 0.1 mSv
    - Public: 1mSv per year
    - Radiation workers: 20 mSv per year
    - NASA astronauts: 500 mSv per year
  - ICAO thresholds
    - Advisories for FL460 ; GLE required
    - Moderate: 30 μSv/h
    - Severe: 80 μSv/h

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

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

SWx impacts from proton events : Biological

- Energetic particles
  - Galactic Cosmic rays (GCR)
  - Solar Energetic Particles (SEP)
  - Can damage DNA and cause cancer & reproductive problems
- Radiation dose
  - µSv/h , mSv/year
  - Doses
  - ICAO thresholds
- Mitigation polar flights
  - Decrease altitude
  - Reroute (away from poles)

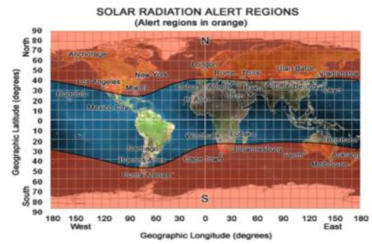


GLE: Ground Level Enhancement ; µSv/h: microsievert per hour ; mSv: millisievert ; FL: Flight Level (100 feet)

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

SWx impacts from proton events : Biological

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



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

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

Avoiding excessive radiation exposure during pregnancy is particularly important.

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

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

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

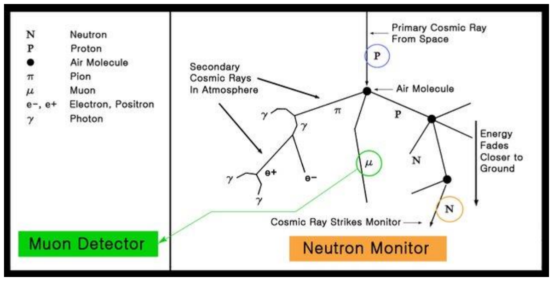
NMDB (Neutron Monitor Database): https://www.nmdb.eu/public_outreach/en/05/

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 : Electronics

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



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

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

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

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

10.4 GNSS - summary and recommendations

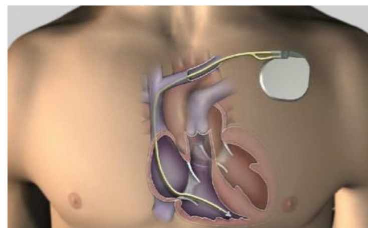
Assuming that the satellites – or enough of them – survive the impact of high energy particles, we anticipate that a solar superstorm will render GNSS partially or completely inoperable for between one and three days. The outage period will be dependent on the service requirements. For critical timing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

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

SWx impacts from proton events : Electronics

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


Qantas Airbus A330 – 7 Oct 2008



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

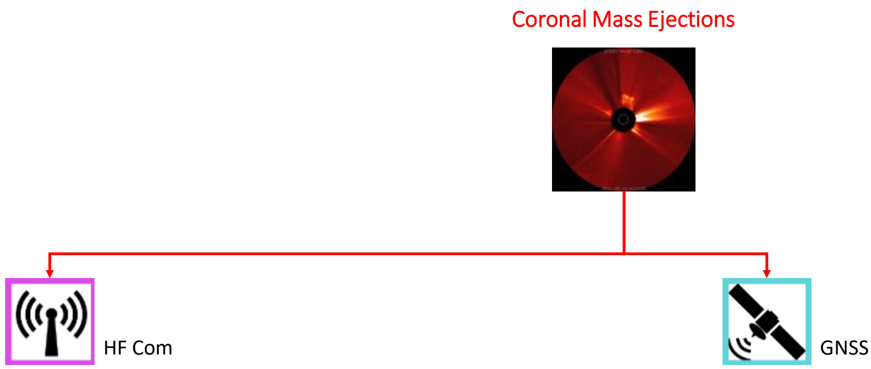
Qantas Flight 72 – https://www.engineeringpilot.com/post/single-event-effects-the-achilles-heel-of-modern-aerospace-electronics ;

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

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

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

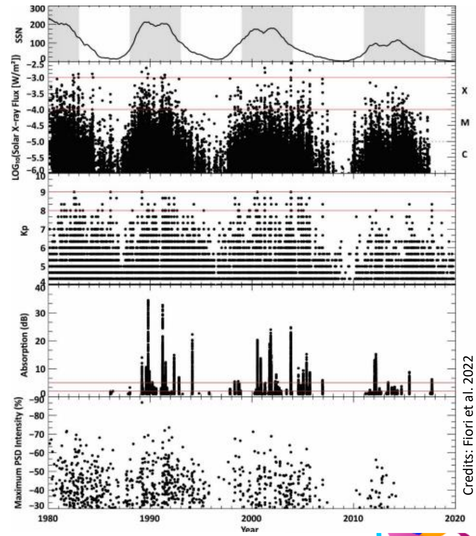
SWx impacts on aviation



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

SWx impacts from ICMEs on HF Com

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



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

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

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.

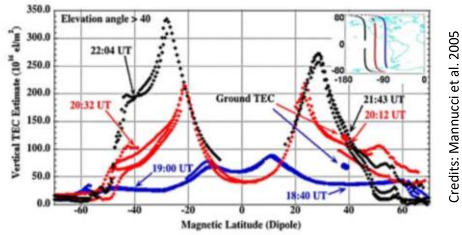
First, on the afternoon of 18 September, the Pittsburgh Pirates hosted the Brooklyn Dodgers in a game of baseball. Red Barber, a well-known sports commentator, was calling the game for WOR Radio. In the fourth inning, with the score tied at 0–0, the broadcast lost signal for 15 minutes. By the time the 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."

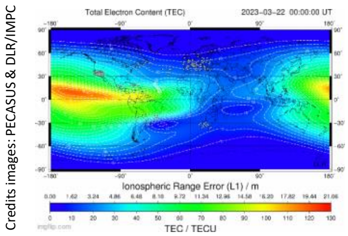
Space weather effects from the May 1967 events: Knipp et al. (2016):
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016SW001423

SWx impacts from ICMEs on GNSS

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



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



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

Credits data: Bergeot et al. 2011

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

23-24 March storm: STCE Newsitems at https://www.stce.be/news/640/welcome.html and https://www.stce.be/news/638/welcome.html

Severe ionospheric storm frequency

Dst ≤ -200 nT: 1.4 days / year ; 16 days / SC

Dst ≤ -250 nT: 0.8 days / year ; 9 days / SC (But none since 2005…)

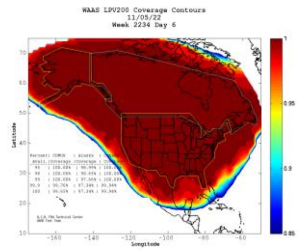
Top right figure from Mannucci et al. 2005 - Dayside global ionospheric response to the major interplanetary events of October 29–30, 2003 ''Halloween Storms''
https://doi.org/10.1029/2004GL021467

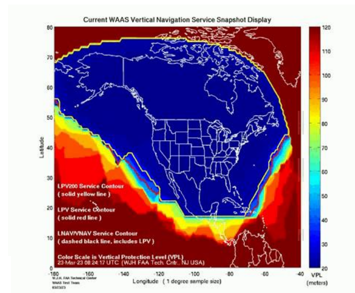
Figure 3. The supersatellite integrated electron content (IEC) as measured by the CHAMP spacecraft is shown just prior (blue trace) and after (red and black traces) the onset of the interplanetary event of October 30 (see Figure 1). The different sets of points for each trace correspond to IEC measured towards the different GPS satellites at each epoch, which are all used to estimate vertical TEC directly above the CHAMP satellite altitude of 400 km, using an elevation angle cut-off of 40 degrees to reduce the error in the vertical IEC estimation procedure. The local time of the CHAMP orbit ranges from 1230–1330 LT for latitudes within ±60 degrees. Points missing near the anomaly trough are due to the elevation angle cut-off. The universal times of the -40 and +40 degree latitude cross-over points are shown for each trace. Also shown in the upper right are the geographical locations of the traces. Total electron content averages from ground data near to the CHAMP ground track are shown as round dots.

Lower-right: Data from Bergeot et al. 2011 - Impact of the Halloween 2003 ionospheric storm on kinematic GPS positioning in Europe
https://link.springer.com/article/10.1007/s10291-010-0181-9
In order to understand the impact of an ionospheric storm on high-precision kinematic GPS applications, we computed the position of 36 EPN stations every 5 min during the October 29–30, 2003 ionospheric storm using the commonly adopted first-order ionosphere-free combination. These 5-min positions were computed for each station separately, in a network of stations with fixed positions, and tropospheric parameters and ambiguities determined in preliminary daily processing. Under normal ionospheric conditions during solar minimum activity in 2008, the repeatability is better than 1 cm in the horizontal and close to 2.5 cm in vertical. During the Halloween storm, the position repeatability of the kinematic positions for locations in northern Europe turned out to reach 12.8, 8.1 and 26.1 cm for the North-East-Up components. For stations in central Europe, the position repeatability turned out better, i.e. in the range of 1–2 cm in the horizontal and 3.1 cm in the up component.

SWx impacts from ICMEs on GNSS

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





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

7 November 2022 – STCE Newsitem: https://www.stce.be/news/616/welcome.html
GNSS, the Global Navigation Satellite System, has become a household term over the last 2 decades. It refers to a fleet of satellites that transmit positioning and timing data to receivers on the ground who can then use these data to accurately determine e.g. their location. Examples of GNSS include Europe's Galileo, the USA's Global Positioning System (GPS), Russia's GLONASS and China's BeiDou. The transmitted satellite data can be disturbed in various ways, e.g. by space weather, and thus a number of systems have been developed to correct the transmitted data and improve the positional and timing accuracy. One of these "augmented" systems is called WAAS, which is short for Wide Area Augmentation System. It is based on GPS satellites and provides various services that enable aircraft to rely on GPS for all phases of flight, including precision approaches to any airport within its coverage area. Europe has a similar system called EGNOS (European Geostationary Navigation Overlay Service) which is based on Galileo satellites.
One of the WAAS services is called "LPV200", which is basically a vertically-guided landing approach aid for airplanes to as low as 200 feet (61 meters) above ground level. In the maps underneath, the availability of the LPV200 service for Canada, Alaska, and the "Contiguous US" (CONUS, aka "Lower 48") is shown on 6, 7 and 8 November. The redder, the better the LPV200 service coverage. It is evident that on 7 November, which corresponds to the day of the above-mentioned minor geomagnetic storm, the LPV200 service was significantly disturbed over large portions of Canada. No less than 82% of its area could not benefit from the full 100% of the LPV200 service, meaning that -if so required- they had to rely on back-up solutions to get the planes safely on the ground. These back-ups exist and can be used at all times, so no worries! The CONUS was significantly less affected, with only a few percent that could not rely on the full 100% LPV200 on 7 November. Similar conclusions can also be drawn for the EGNOS services over Europe, with a significant reduction in the LPV200 availability over large portions of Scandinavia on that day, and a better coverage over central and southern Europe.

From ESWW19 (Lidia Nikitina) on 7 Nov 2022: GNSS application problems (WAAS as well as EGNOS); In Canada, errors of 40 m (horizontal) and 50 meters (vertical GIVE) due to scintillation errors were recorded. CADORS (Canadian event reports) reported that one plane missed its approach landing strip and do it all over. Also, during the major geomagnetic storm of 25-27 Feb 2023, several pilots reported problems with LPV and approach navigation. Another strong WAAS disturbance was reported on 5 Nov 2023.

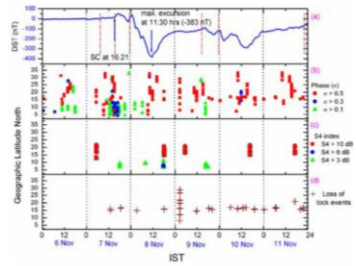
23-24 March 2023 storm: STCE Newsitems at https://www.stce.be/news/640/welcome.html and https://www.stce.be/news/638/welcome.html
…As a result of this severe geomagnetic storm, some GNSS-based applications for the civil aviation did not reach their typical availability, as can be gauged from the imagery underneath for the USA/Canada (WAAS), covering the period 23 March (09:00 UTC) until 24 March (10:00 UTC). Blue colours mean good availability, red/brown means significantly degraded availability. Clearly the systems were underperforming while the geomagnetic storm was ongoing. In Europe, similar observations were made for the EGNOS system.

This daily 24-hour plot below depicts the Wide Area Augmentation System (WAAS) Lateral Precision with Vertical Guidance 200 (LPV200) service in North America. Vertical Protection Level (VPL). The Vertical Protection Level is half the length of a segment on the vertical axis (perpendicular to the horizontal plane of WGS-84 ellipsoid), with its center being at the true position, which describes the region that is assured to contain the indicated vertical position. It is based upon the error estimates provided by WAAS. LPV Service (Solid Red Line). Area encompassed meets WAAS LPV operational service level with horizontal alert limit (HAL) equal to 40 meters and a vertical alert limit (VAL) equal to 50 meters.

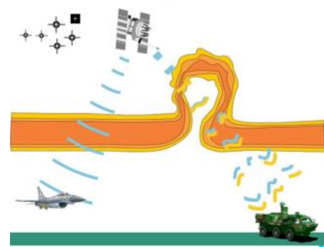
EGNOS LPV200 Availability is defined as the percentage of epochs which the Protection Level are below Alert Limits for this service (HPL<40m and VPL<35m) over the total period. The pictures present the current EGNOS LPV200 Availability over the last 24 hours and the last hour and the corresponding VPL and HPL for the operational GEO satellites and Combined GEO satellites.

SWx impacts from ICMEs on GNSS

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



Credits: Rama Rao et al. 2009



Credits: US Air Force Research Laboratory

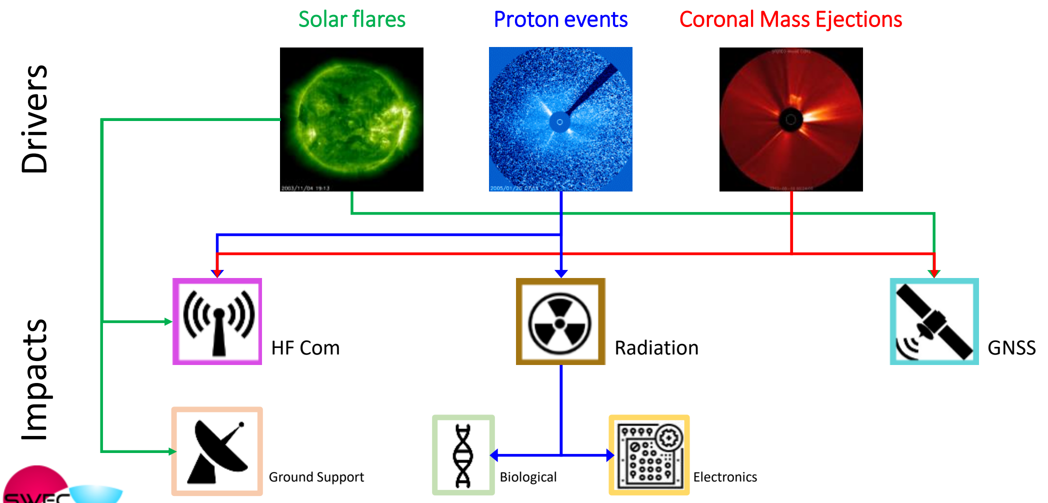
GNSS: Global Navigation Satellite Systems (GPS, Galileo,…) ; ICME: Interplanetary coronal mass ejection ; nT: nanotesla ; Dst: Disturbance storm time ; dB: decibel

Top right figure: **8 November 2004** from Rama Rao et al. 2009 - Geomagnetic storm effects on GPS based navigation
https://doi.org/10.5194/angeo-27-2101-2009
In Fig. 7, where the phase (σ) and amplitude (S4) indexes are presented along with the loss of lock events as a function of latitude and local time during the storm period, also shows the occurrences of phase slips for the entire period 6 to 11 November 2004, when the 8 and 10 November storms have occurred. Figure 7b shows the phase slips and the associated phase scintillation (σ) index of three different intensity levels (>10 dB, >6 dB, >3 dB) and Fig. 7c shows the phase slips that are accompanied with reduced signal-to-noise ratio as indicated by the amplitude scintillation (S4 index) at the three different power levels. Some of these phase slips, resulting in the loss of lock of the GPS receiver that are detected from the lock time of the receiver, are shown in Fig. 7d. It may also be seen from this figure that most of the slips are associated with phase (σ) index rather than with S4 index. These loss of locks are caused as a result of rapid phase fluctuations in the received signal carrier exceeding the receiver's phaselock-loop (PLL) bandwidth, and in some cases resulting in the decrease of the signal-to-noise ratio beyond the threshold value of the receiver, which may also vary from receiver to receiver. However, from the communications and navigation point of view, these loss of lock events are undesirable and need to be accounted for in an appropriate manner.

Penn State University: https://www.e-education.psu.edu/geog862/node/1728
A cycle slip is a discontinuity in a receiver's phase lock on a satellite's signal.

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.

Summary



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

Questions?

Minions – Pilots scene - https://www.youtube.com/watch?v=D4-CpIJCKoQ