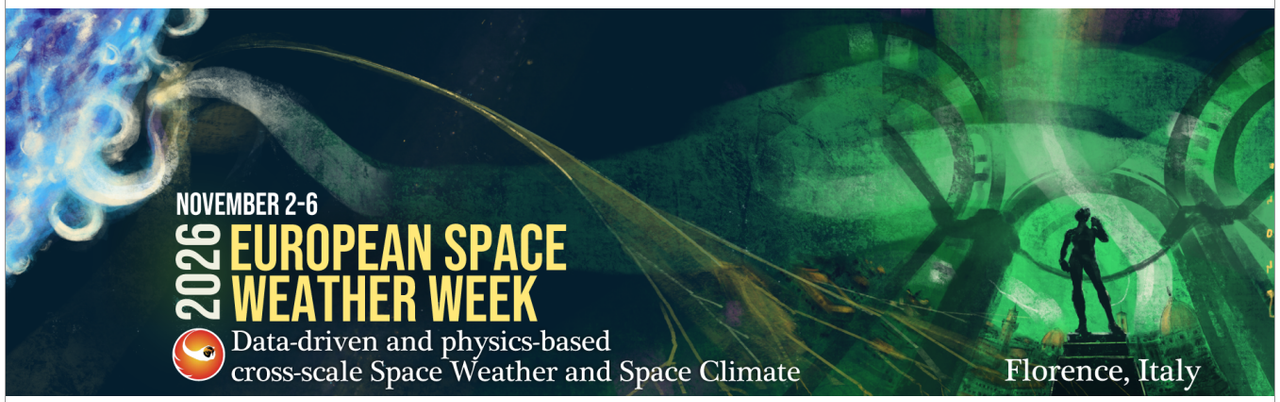
Space Weather Training Course



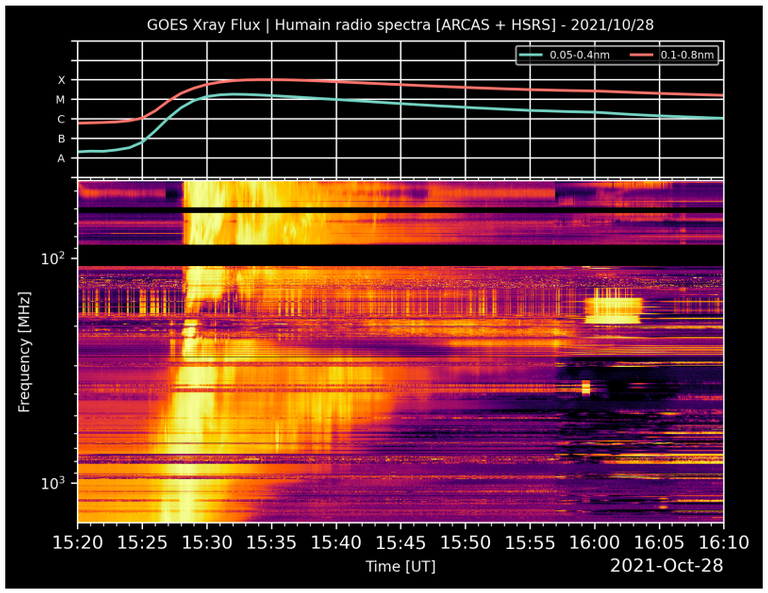
Collaboration of

e-SWAN

SWEC
Space Weather Education Centre

COMMUNITY COORDINATED MODELING CENTER

RADIO SUN



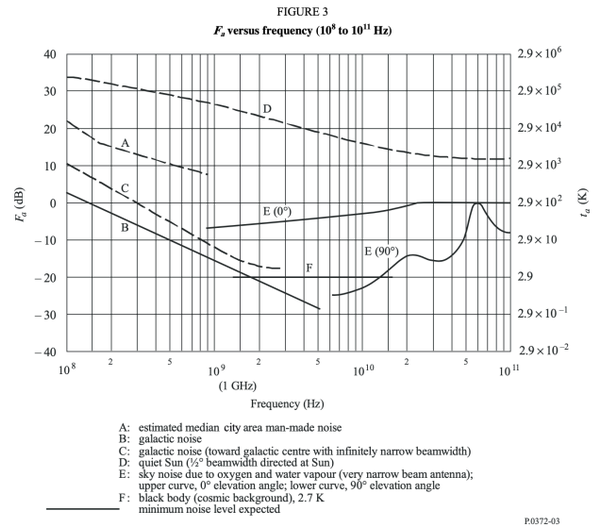
Humain

Observations in the e.m. spectrum at radio wavelengths:
•10,7 cm flux —> index for solar activity, similar like the sunspot index
•Solar Radio Bursts

Quiet Sun

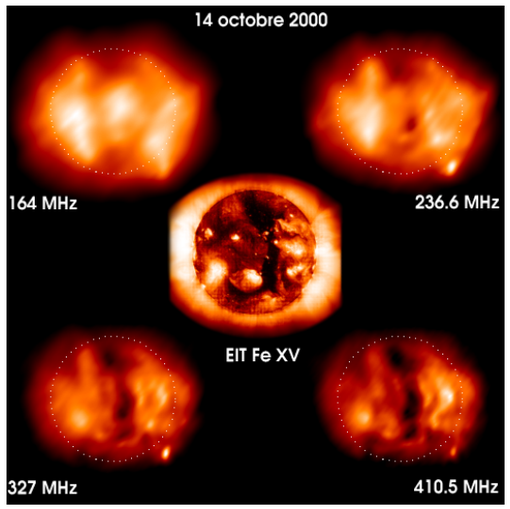
The Radio Sun

The Sun is the strongest radio source in the sky above ~100 MHz



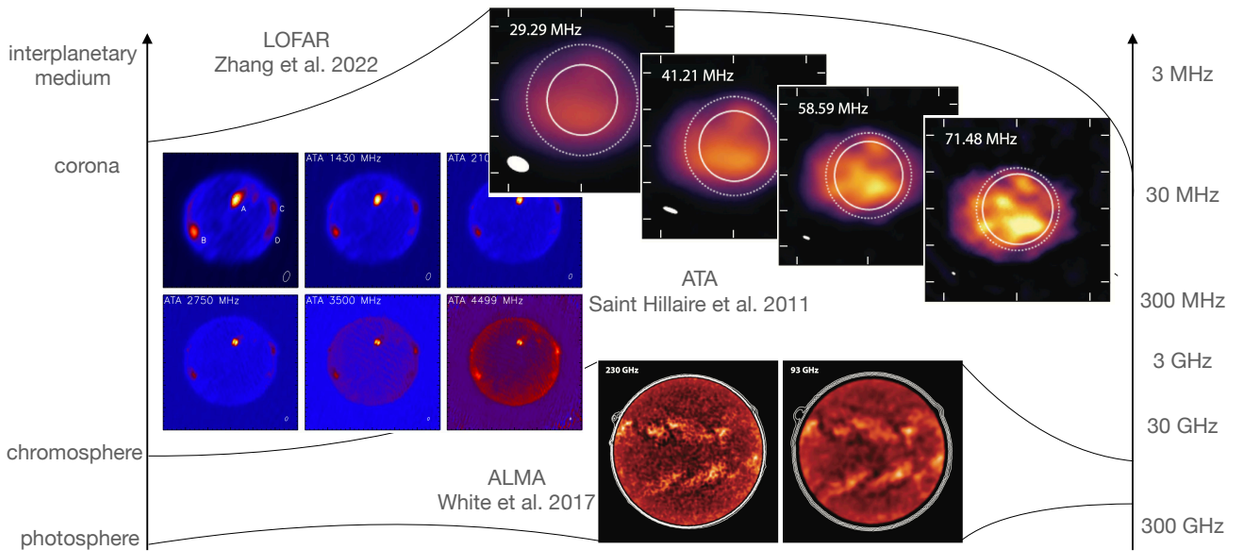
Quiet Sun

Mostly thermal emission from hot corona



Thermal emission: free—free emission

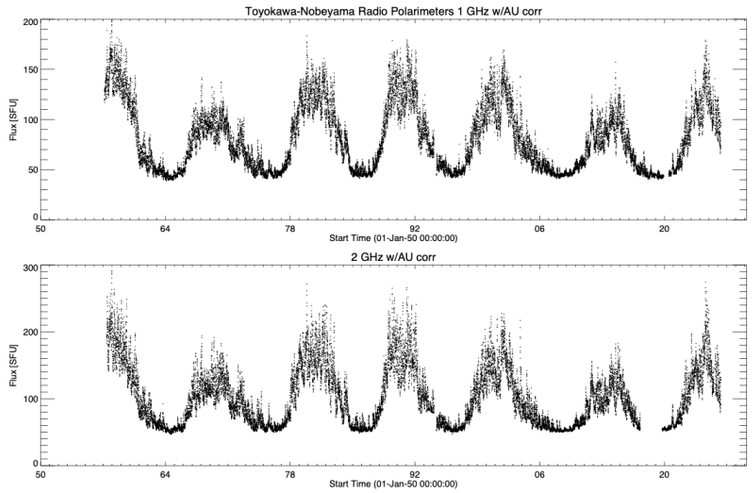
All layers of the solar atmosphere are accessible to radio observations



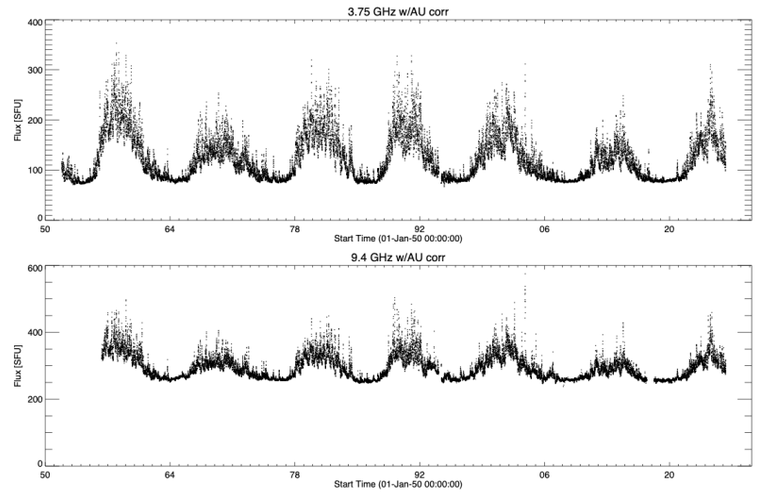
LOFAR (LOw Frequency ARray) is currently the largest radio telescope operating at the lowest frequencies that can be observed from Earth.
https://www.astron.nl/telescopes/lofar/

ALMA - Atacama Large Millimeter/submillimeter Array (ALMA)
https://www.almaobservatory.org/en/home/

Allen Telescope Array (ATA)
https://www.seti.org/projects/ata/



When we measure the total radio output in a single frequency over time, we see a cyclical behaviour that corresponds to the solar cycle


3.75 GHz w/AU corr
Flux [SFU]
400
300
200
100
0
50
64
78
92
06
20
Start Time (01-Jan-50 00:00:00)
9.4 GHz w/AU corr
Flux [SFU]
600
400
200
0
50
64
78
92
06
20
Start Time (01-Jan-50 00:00:00)

F10.7 index

$\lambda = 10.7$ cm $\equiv 2.8$ GHz



Figure 3. The flux monitors. Flux Monitor 1, the secondary instrument is in the foreground; Flux Monitor 2, the primary instrument is in the background, on the tower.

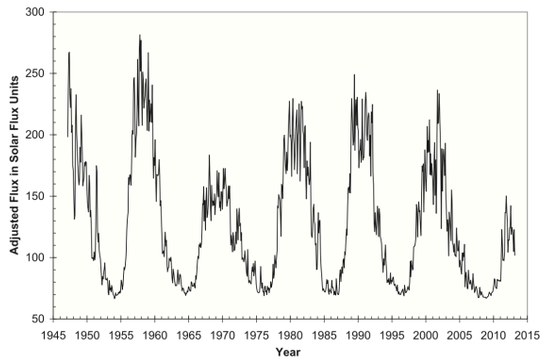


Figure 1. Monthly averages of the adjusted (scaled for an Earth-Sun distance of 1 AU) $F_{10.7}$ values since 1947.

Tapping 2013

A 10.7 cm solar flux measurement is a determination of the strength of solar radio emission in a 100 MHz-wide band centered on 2800 MHz (a wavelength of 10.7 cm), averaged over an hour. It is expressed in solar flux units (sfu), where 1 sfu = 10−22 W m−2 Hz−1.
The F10.7 is well correlated with the sunspot number, and thus a good indicator of the level of solar activity.

The wavelengths around 10.7 cm (frequencies around 2800 MHz) are ideal for monitoring the solar activity, as they are very sensitive to conditions in the upper chromosphere and at the base of the corona. As a result, this radio flux is widely used in solar research and space weather applications. It is measured three times daily: around 17UT (18UT in winter), 20UT (local noon at Penticton), and 23UT (22UT in winter). The 20UT value is usually taken as the radio flux for that particular day.

F10.7 cm is also important input parameter for thermopsheric models

The choice of 10.7 cm as a wavelength was based on what was available at the time the measurements started. After the Second World War, Arthur Covington and his colleagues at the National Research Council in Ottawa used bits of military surplus radar and test equipment to make a radio telescope. The radar system operated at a frequency of 2800MHz, that is a wavelength of 10.7cm.
https://www.spaceweather.gc.ca/forecast-prevision/solar-solaire/solarflux/sx-2-en.php

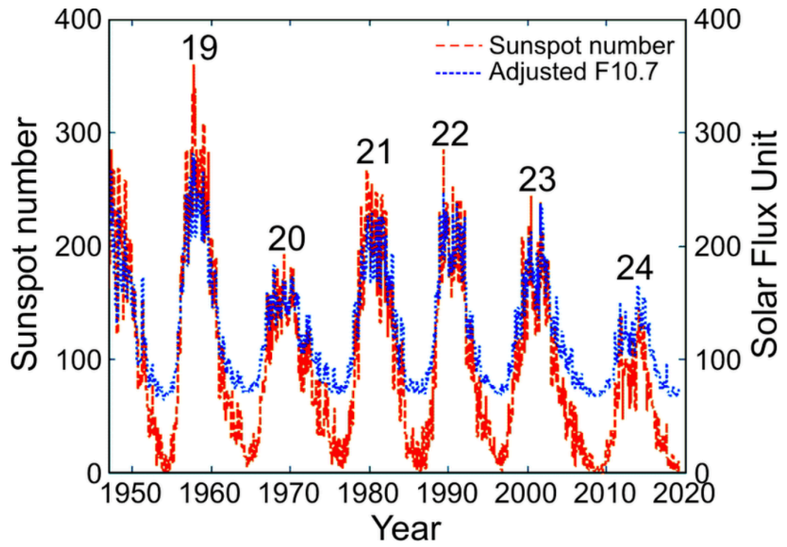
F10.7 index



Figure 3. The flux m… ondary instrument is… 2, the primary instru… the tower.

…aled for …e 1947.

F10.7 index



The sunspot numbers (red curve) and the 10.7 cm solar flux (F10.7, blue curve) from the middle of the 20th century [69-71]. The F10.7 values are in solar flux units (sfu), 1 sfu is equal to 10 -22 W m -2 ·Hz -1 . The observed F10.7 is presented on the right axis.

Graph from Grytsai et al., 2020.

The background level of the 10.7cm flux is around 75 sfu, it never goes to zero, we always receive radio waves from the quiet sun

Solar radio bursts

Solar radio bursts are other electromagnetic waves emitted from accelerated electrons around the flare site, or electrons accelerated by a CME shock front which produce the direct noise on radio receivers.
Electrons start radiating because they get an energy boost from a solar event. They are a signature of occurrence of a CME or flare. As such, a SRB are not a direct consequence of magnetic reconnection.

Radio bursts

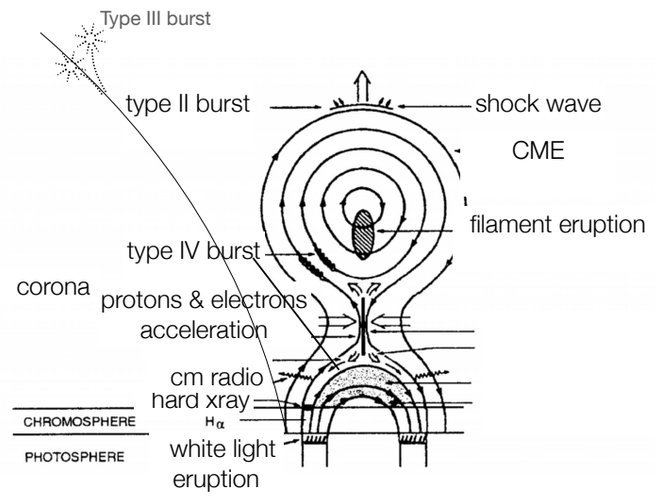
Solar radio bursts are produced by non-thermal electrons accelerated during eruptive events of all magnitudes.

For frequencies (f) below ~ 1- 2 GHz, the dominant emission is called plasma emission, where energetic electrons trigger local plasma oscillations which are then converted into E. M. radiations

$$f \propto \sqrt{n_e}$$

Spectral signatures (type I, type II, type III ...)

Above, gyroemissions, gyrosynchrotrons or bremstrahlung emissions dominate.



Oscillations of free electrons in the plasma depends on the electron density

The plasma frequency is the resonant frequency of the electrons in an ionized medium.
There is a direct relation between the electron density and the plasma frequency, which can be approximated as f ≈ 8.9 Ne^1/2.

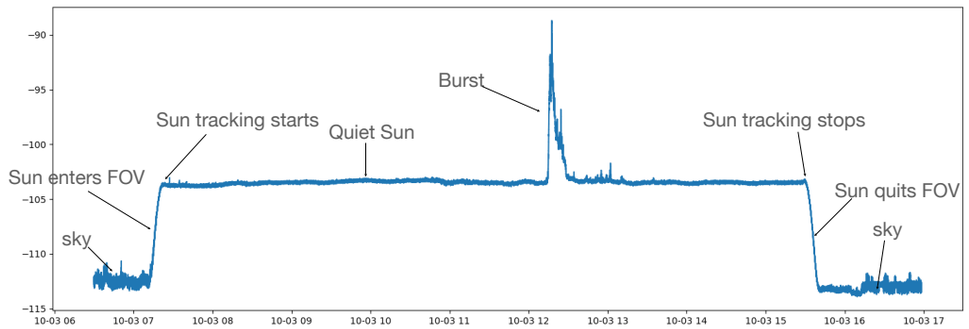
Oscilllations of free electrons in the plasma depends on the electrons density

Gyroemission (more commonly referred to as gyrosynchrotron emission or cyclotron emission depending on the speed of the particles) is the process by which charged particles, usually electrons, emit electromagnetic radiation as they spiral around magnetic field lines due to the Lorentz force.

Example in L band



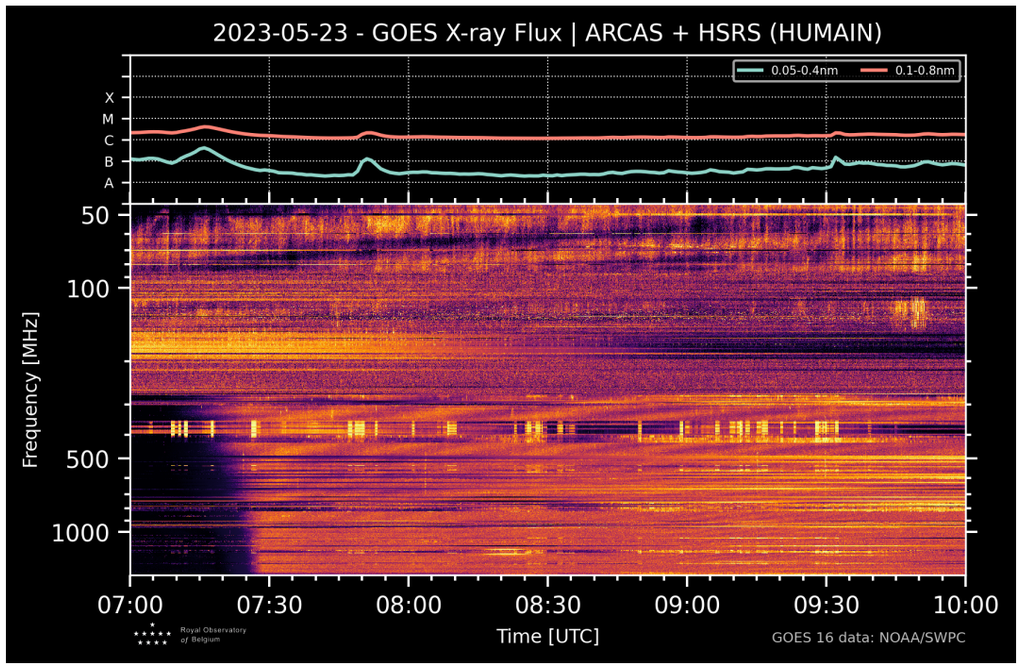
Solar Observations from Humain, Belgium



The L band is the Institute of Electrical and Electronics Engineers (IEEE) designation for the range of frequencies in the radio spectrum from 1 gigahertz (GHz) to 2 GHz. This is at the top end of the ultra high frequency (UHF) band, at the lower end of the microwave range.

Spectrogram - Radio Spectrum

Humain



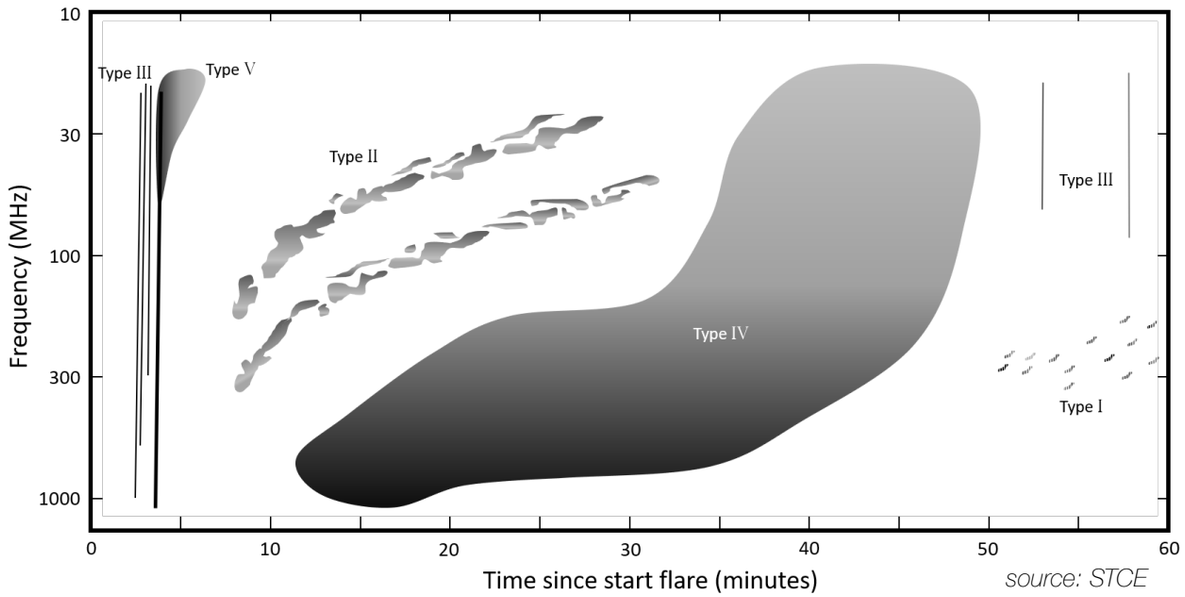
Combine multiple frequencies into one spectrogram, color scale indicates the intensity

We traditionally add the GOES flare curves at the top to clearly see the link between the solar activity and the radio bursts.

Pay attention to the inverted y-scale with higher frequencies at the bottom: as frequency is proportional to density, this corresponds to the photosphere, and we can see the bursts propagate upwards into the interplanetary space.

The ionospheric cut-off frequency is around 15MHz (due to too low frequency and so reflected by ionosphere). In order to observe radio disturbances below this frequency, one has to use satellites (above the earth atmosphere) such as STEREO/SWAVES or WIND. Radio bursts at low frequencies (< 15 MHz) are of particular interest because they are associated with energetic CMEs that travel far into the interplanetary (IP) medium and affect Earth's space environment if Earth-directed. Low frequency radio emission needs to be observed from space because of the ionospheric cutoff.
Example: https://stereo-ssc.nascom.nasa.gov/browse/2017/01/16/insitu.shtml

Radio bursts



We can measure the **solar e.m. radio output and put it into a spectrogram**.
At low frequencies, **5 types** of radio wave bursts are seen, **each with a unique signature in frequency and time.**

A type II burst is caused by a shock that triggers the local plasma to emit radio waves. While **most of the interplanetary shocks are CME-driven, coronal shock waves can be attributed to solar flares**, CMEs, or some combination of these two phenomena. Since the acceleration phase of the CME and the flare impulsive phase are usually closely synchronized, it is **hard to distinguish between the flare energy-release effects and the CME expansion**. Due to this problem the origin of the coronal shocks, i.e. metric type II bursts, still remains unresolved.

Type II

type II burst, slowly drifting, often with fundamental/2nd harmonic structure, due to plasma emission
cause is a shock wave, propagating at 500-2000 km/s outward into the corona into interplanetary space (also seen down to kilometric wavelengths).

Type III

- type III burst, rapidly drifting, often with fundamental/2nd harmonic structure, due to plasma emission. The fundamental is highly o-mode polarized, and the 2nd harmonic is weakly (15%) x-mode polarized.
  - cause is a stream, or **beam, of electrons moving at speed ~ c/3, propagating from low corona into interplanetary space** (also seen down to kilometric wavelengths).
- type III storm -- a long lasting (up to a day or more) series of type III bursts, RS (reverse slope) bursts, reverse-drift pairs, and continuum.

Type IV

- stationary type IV -- broadband continuum emission, sometimes highly polarized, due to either plasma emission (o-mode polarized) or gyrosynchrotron emission (x-mode polarized).
  - cause is a plasmoid or high, filled loops of non-thermal particles
- moving type IV -- a similar cause, but entrained in a CME or expanding arch.

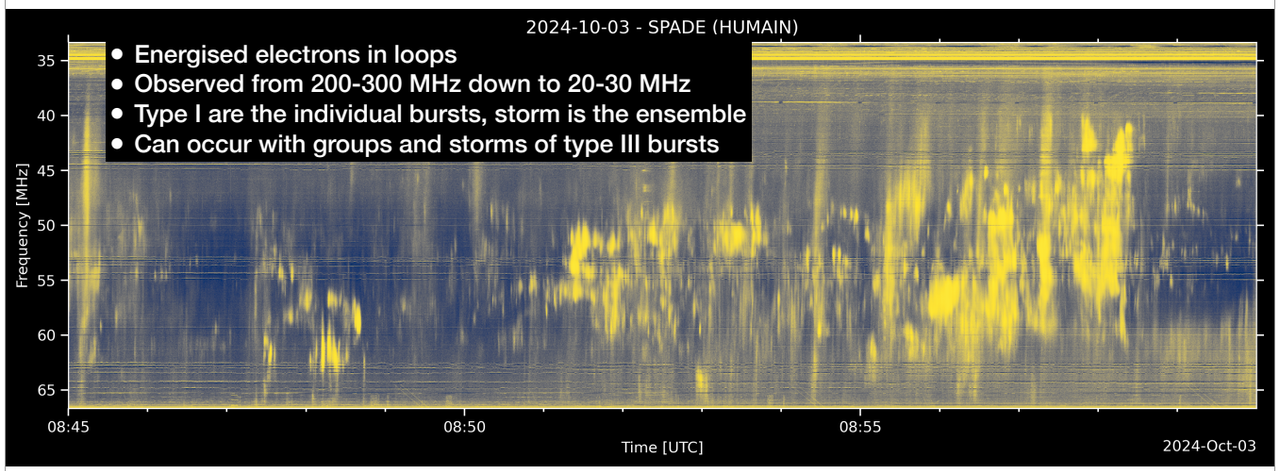
Type V

- type V burst, continuum emission following a type III burst, x-mode polarized (opposite sense to the associated type III)
  - cause is **slower type III-like electrons** in widely diverging magnetic fields, with both forward and counterstreaming langmuir waves, perhaps generated by previous passage of type III electrons.

linked with a solar event, like a flare, CME, languir waves

Type I & noise storms

Non flaring radio bursts linked to sunspots

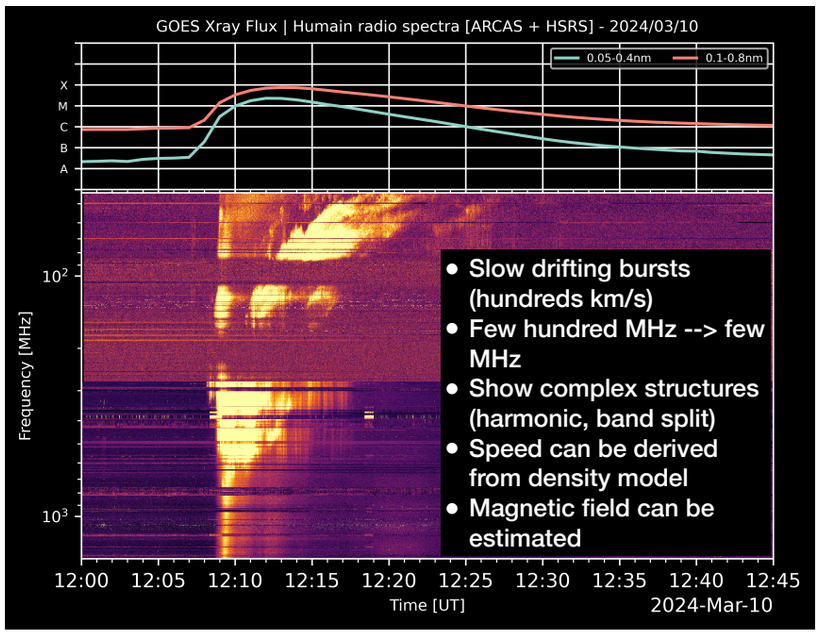


Solar noise storm

Associated phenomena: active regions, flares, eruptive prominences

Type II bursts

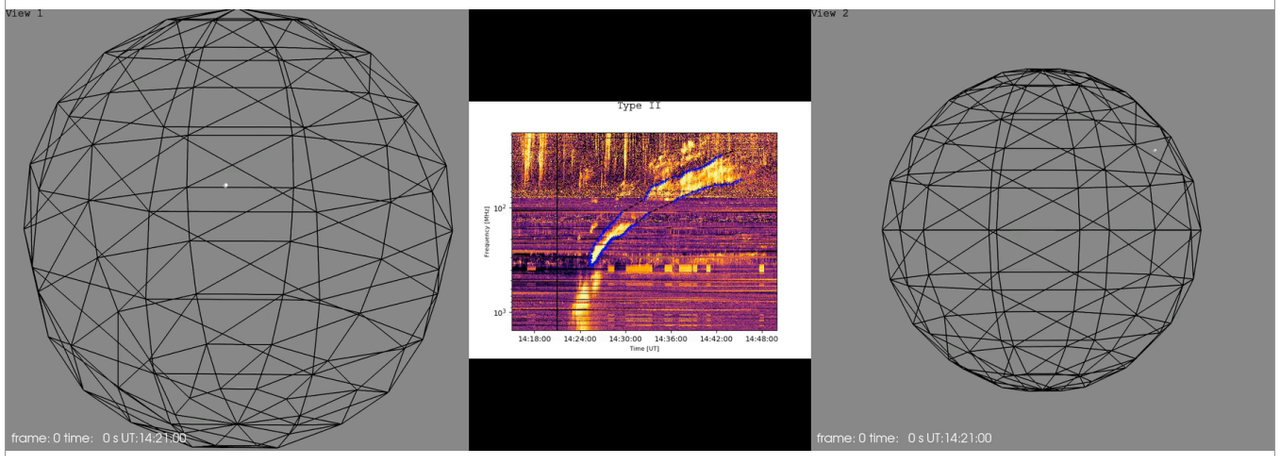
Linked to shock waves propagating out in the corona



Source: electrons accelerated in shocks, Indicates CME
Shock speed can be derived from fundamental band (B)
Start at peak in soft X-ray flux of flare

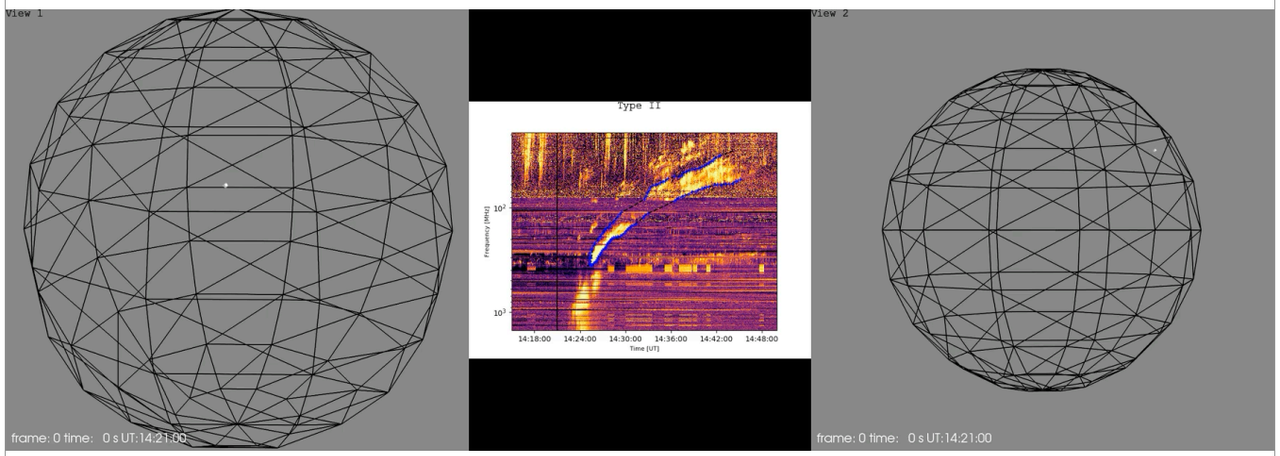
Type II bursts

Linked to shock waves propagating out in the corona



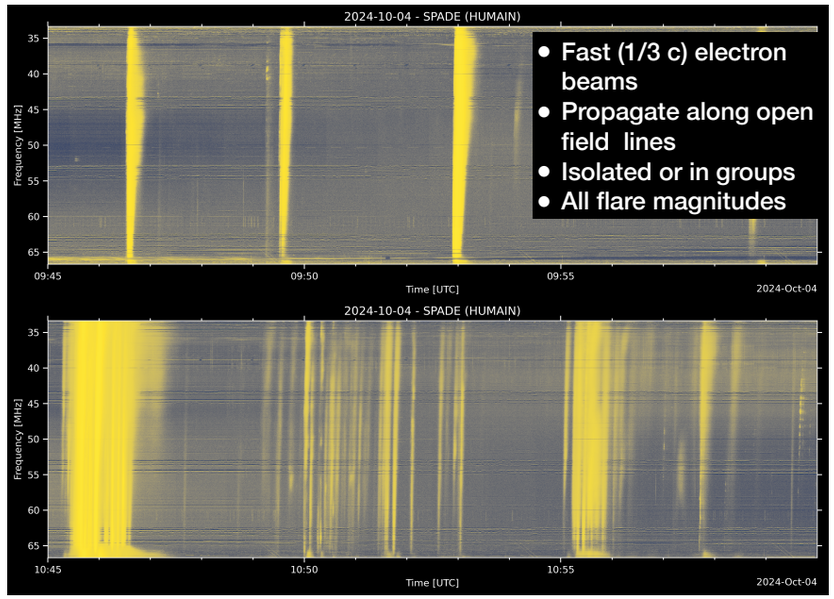
Type II bursts

Linked to shock waves propagating out in the corona



Type III bursts

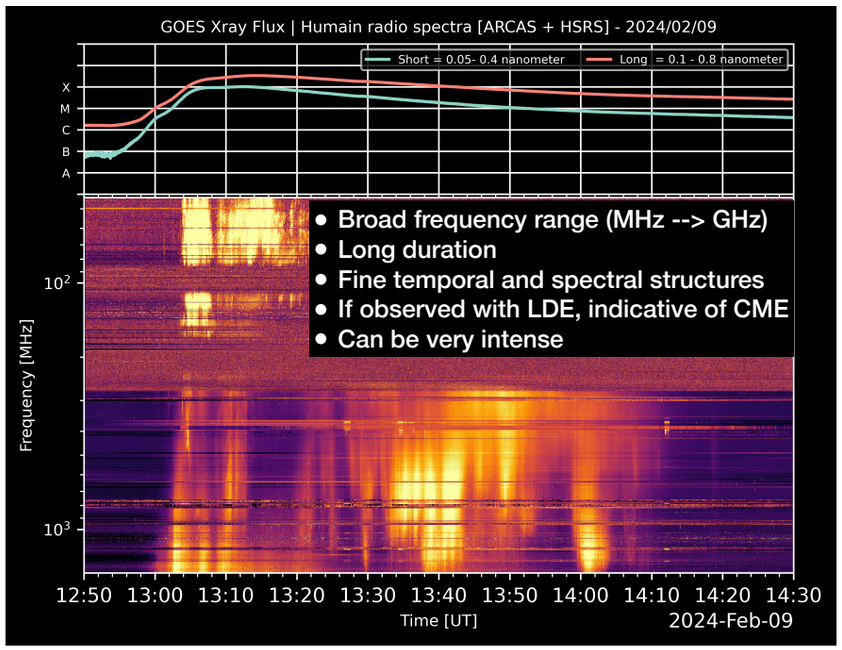
Most frequent type of bursts



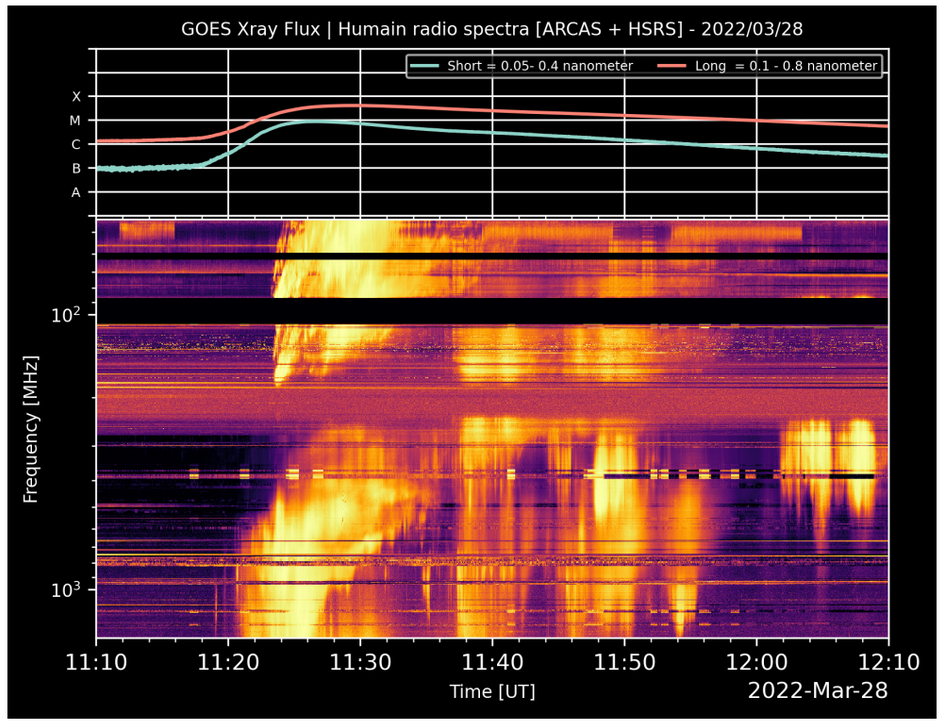
Type IIIs are commonly seen in the impulsive phase of solar flares, and the connection they imply between the acceleration region in solar flares and open field lines that reach the solar wind makes them important for understanding field line connectivity in flares and the access of flare–accelerated particles to the Earth.

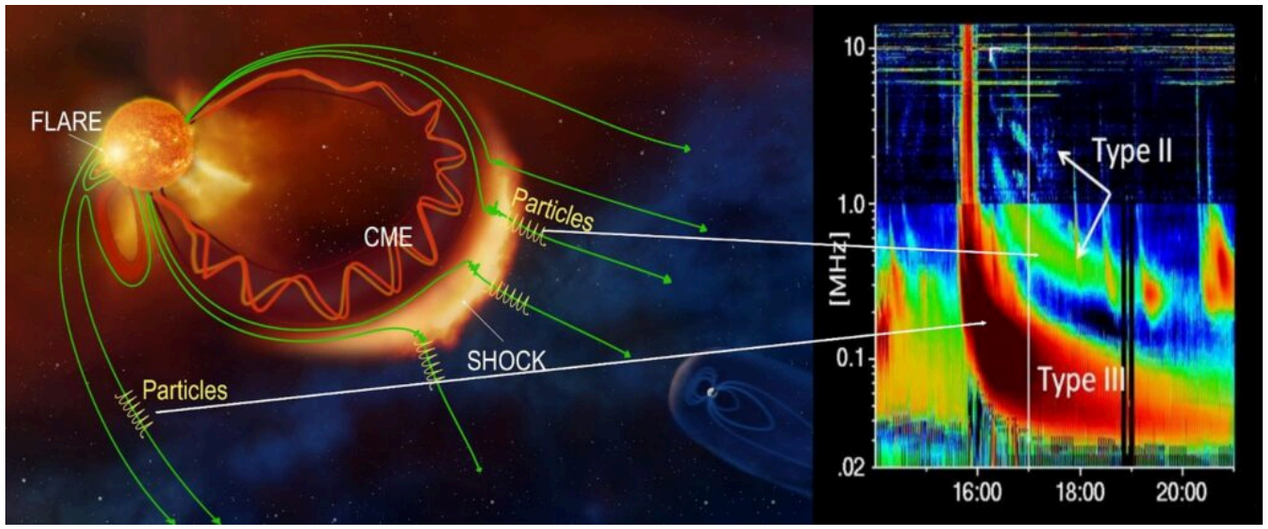
Type IV bursts

Energetic electrons trapped in post-flare loops



Electrons trapped in post-eruption arcades behind CMEs
Related to very energetic CMEs (average speed: 1200 km/s)

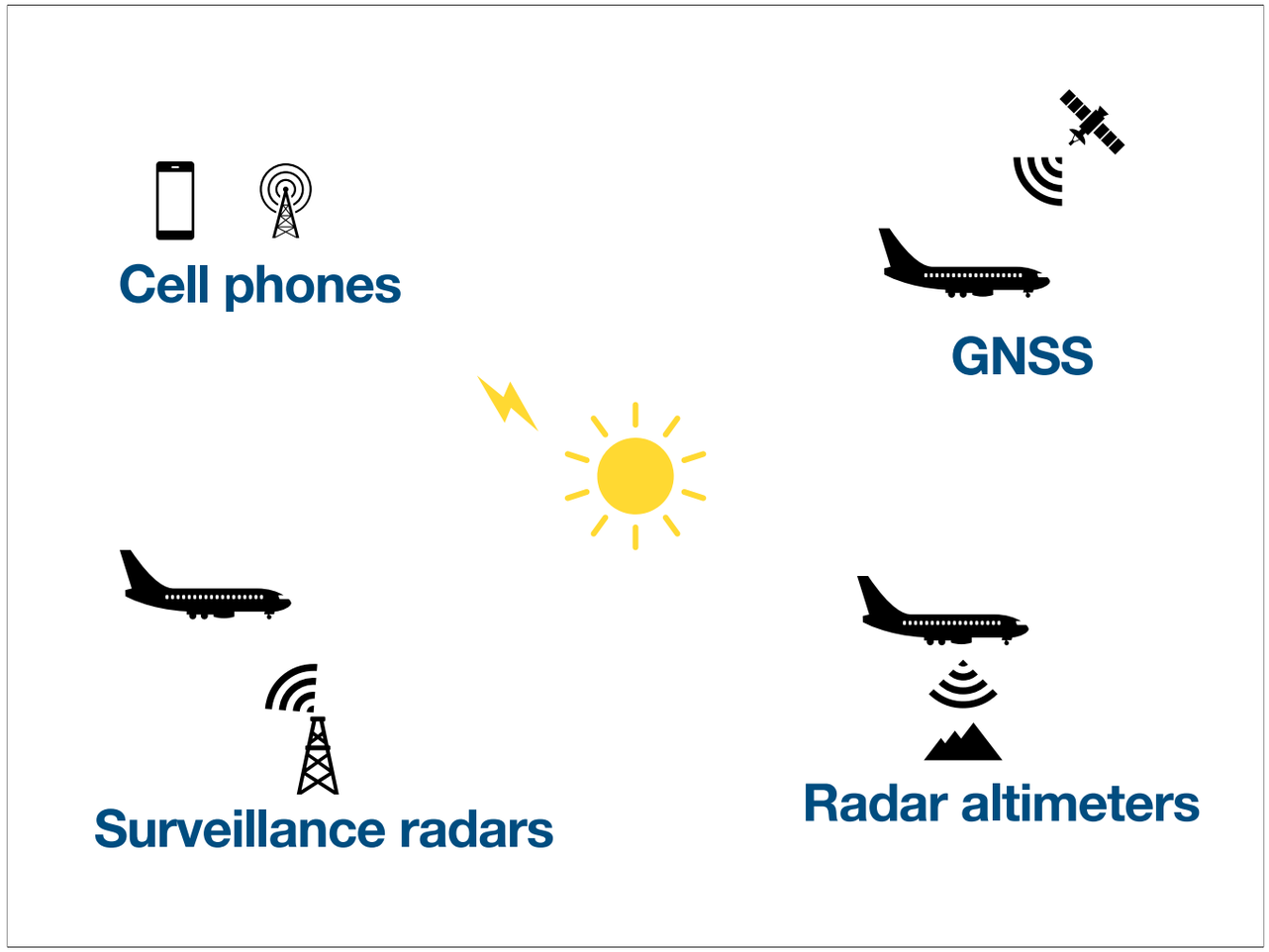

GOES Xray Flux | Humain radio spectra [ARCAS + HSRS] - 2022/03/28
Short = 0.05- 0.4 nanometer
Long = 0.1 - 0.8 nanometer
X
M
C
B
A
10^2
10^3
Frequency [MHz]
11:10
11:20
11:30
11:40
11:50
12:00
12:10
Time [UT]
2022-Mar-28



Often, for strong bursts, multiple signatures can be seen at the same time.

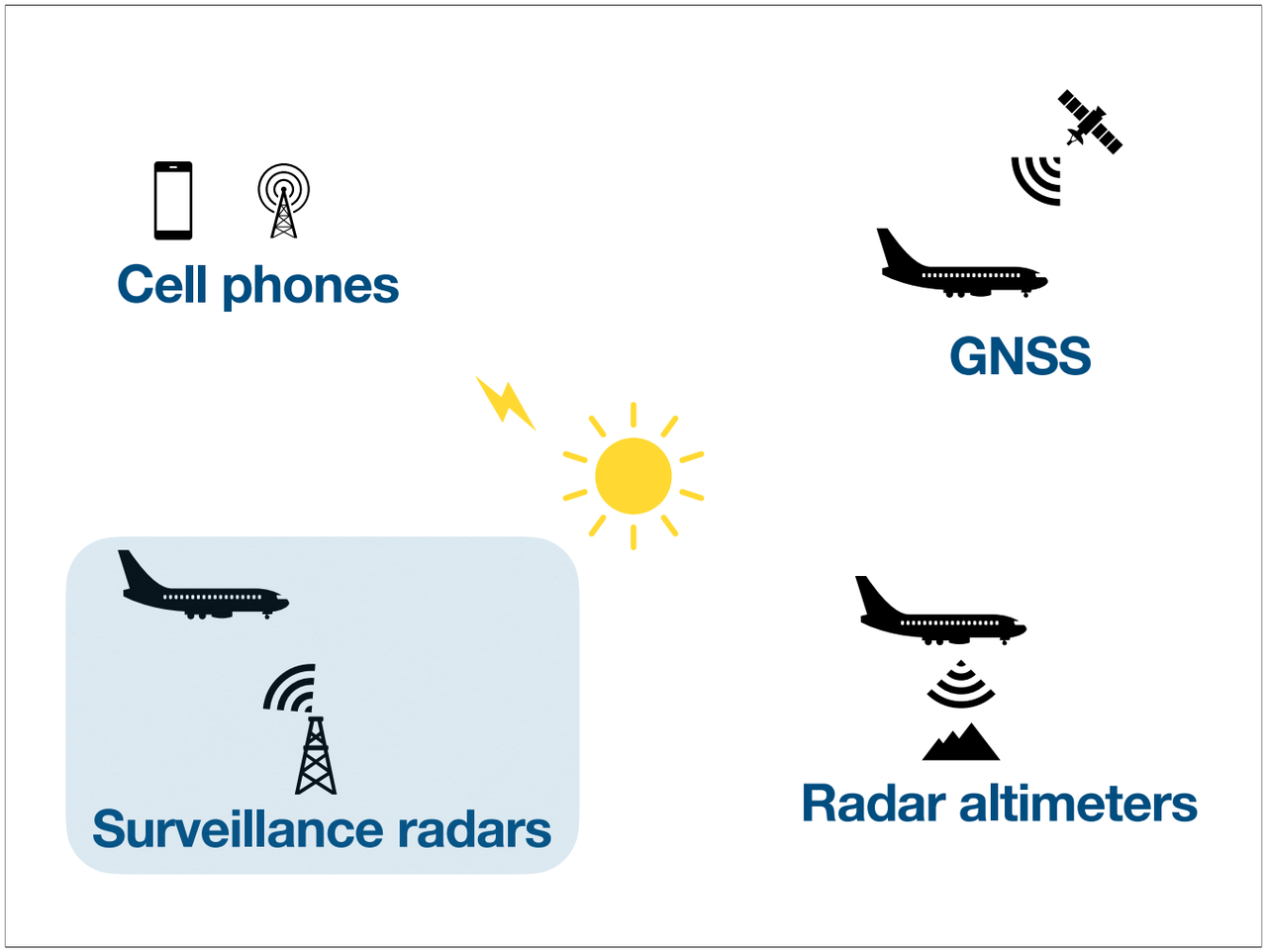
Solar radio bursts are other electromagnetic waves emitted from accelerated electrons around the flare site, or electrons accelerated by a CME shock front which produce the direct noise on radio receivers.
Electrons start radiating because they get an energy boost from a solar event. They are a signature of occurrence of a CME or flare. As such, a SRB are not a direct consequence of magnetic reconnection.

Impact of solar radio bursts



All these systems operate with radio waves within the radio window
Receivers - picking up radio signals

Problem is often noise



All these systems operate with radio waves within the radio window
Receivers - picking up radio signals

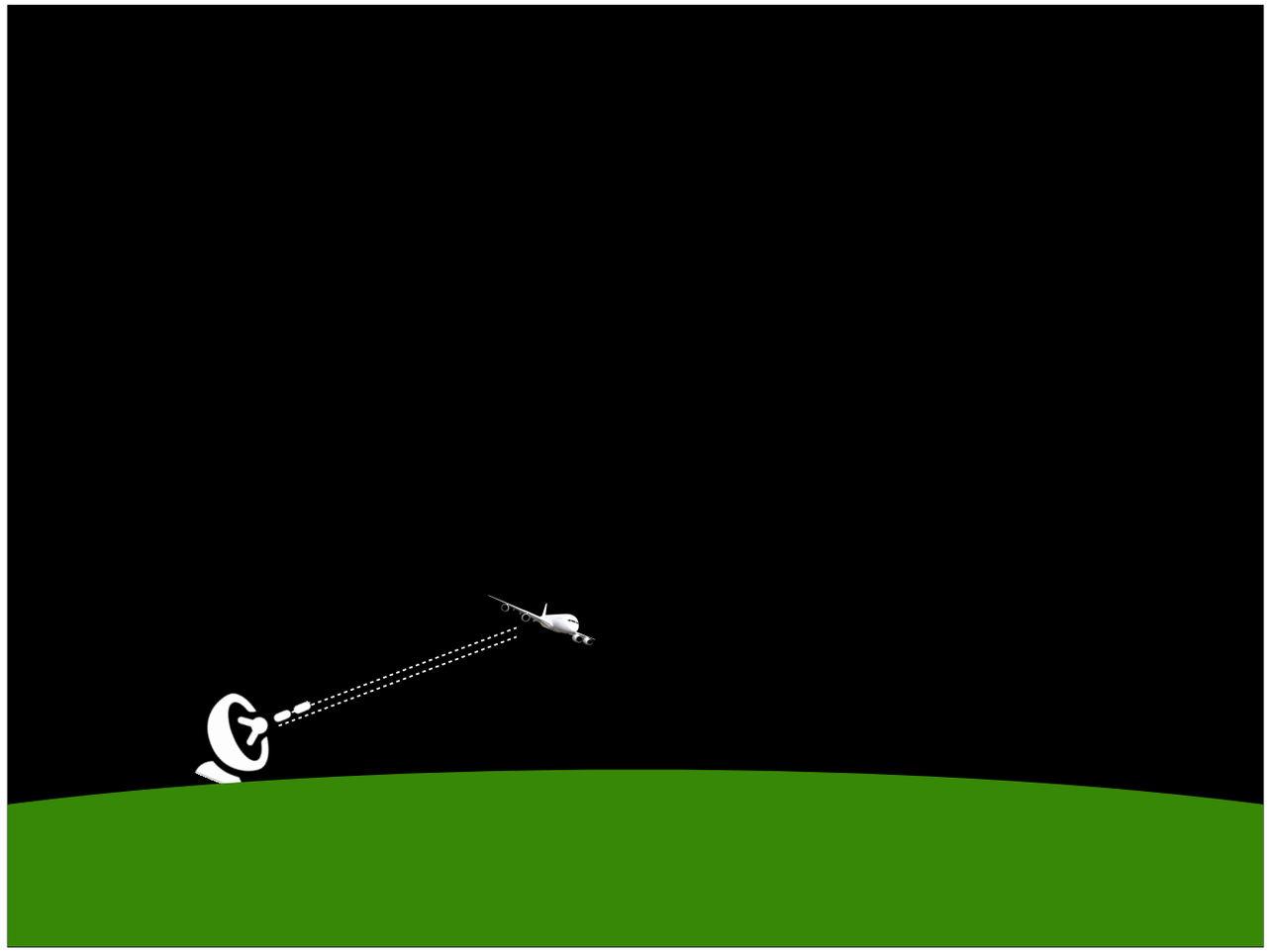
Problem is often noise

November 4, 2015 - a media storm

- ATC radars in Sweden suffered severe disturbances between 14:20 UT and 16:00 UT
- Sweden: Partial closure of air space for an hour (Incoming flights were deviated, no departures allowed)
- Minor disturbances in Norway, Belgium
- Geomagnetic storm was initially considered as the source of disturbances (media)



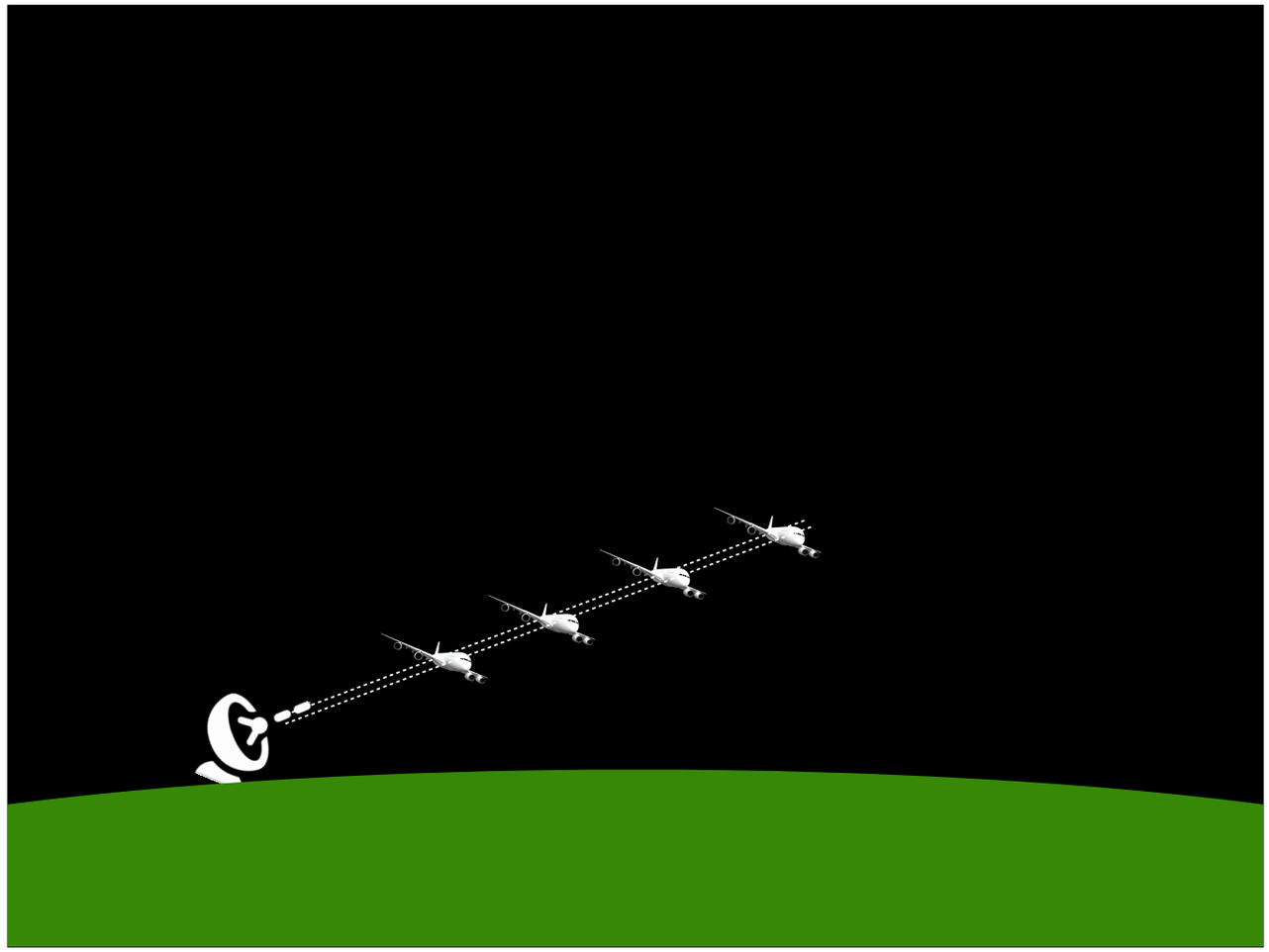




Radar interference

Radars are monitoring the planes near the horizon - descending and ascending planes.

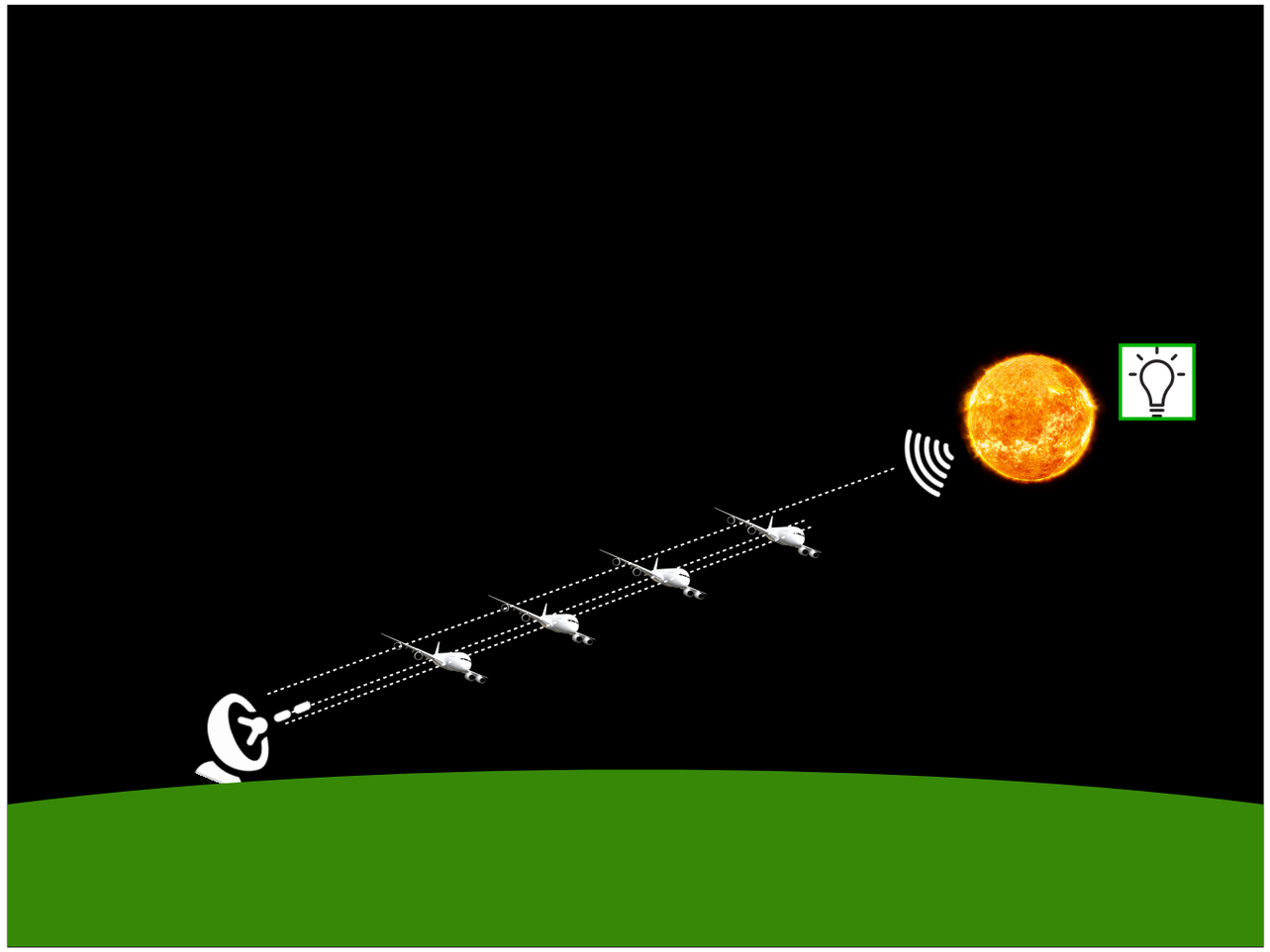
Radar ‘ziet’ vliegtuigen door de reflectie van radio-signaal. Radio-signalen van de zon kunnen geïnterpreteerd worden als ‘spook’-vliegtuigen: vliegtuigen die je ziet op het radar-scherm maar er in werkelijkheid niet zijn.



Radar interference

Radars are monitoring the planes near the horizon - descending and ascending planes.

Radar ‘ziet’ vliegtuigen door de reflectie van radio-signaal. Radio-signalen van de zon kunnen geïnterpreteerd worden als ‘spook’-vliegtuigen: vliegtuigen die je ziet op het radar-scherm maar er in werkelijkheid niet zijn.



air traffic radars are affected when the Sun is low above the horizon

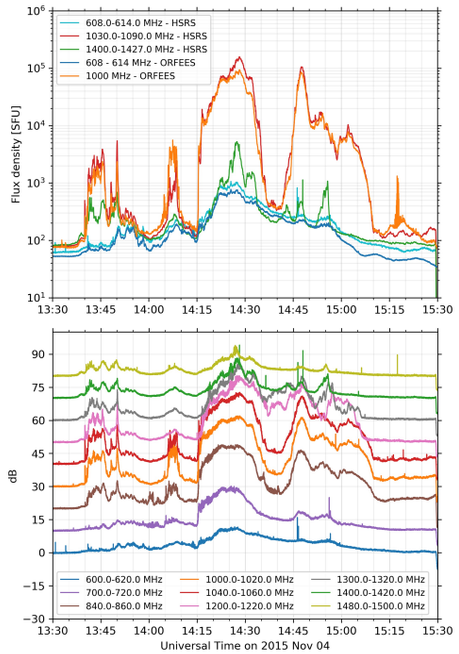
November 4,

Belgium: sunset on Nov 4
4:42 PM CET (UTC +1). This converts to 3:42 PM UTC.

Radar interference

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Impact on radar systems



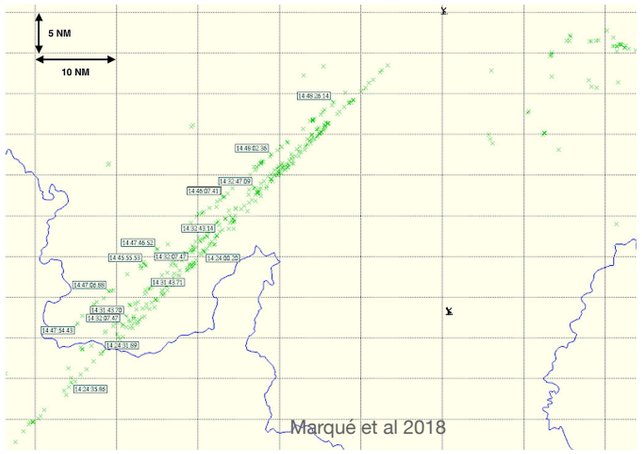
Belgium: sunset on Nov 4
15:42 UTC - 16:42 CET (UTC +1)

Fig. 1. False echoes (in green) observed in the direction of the Sun at a Belgian A/C radar station, located to the top right. The border with France and Luxembourg appears in blue. The scale of the map, in Nautical Miles is indicated at the top left.

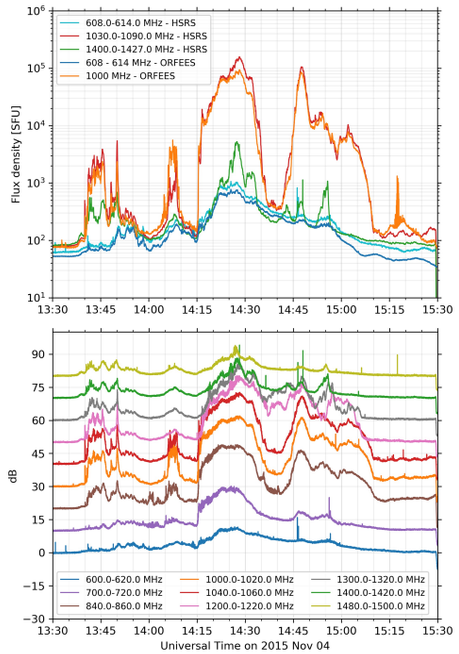
Fig. 3. Top: light curves in SFU of the November 4th 2015 event from the HSRS and ORFEES spectrographs. Bottom: light curves in relative dB from the HSRS spectrograph at several frequencies between 600 and 1500 MHz.

The interference threshold for such radars is about -102 dBm (6,3 . 10-14 W) at receiver input.
The quiet sun level on that day was about 75 SFU (75 . 10-22 W.m-2.Hz-1), which results in a power at receiver input of -101 dBm
At the peak of the burst the Sun emission level was more than 100 000 SFU, which gives at least a power at receiver input of -68 dBm
-> > 34 dB above interference threshold (~ 2500 times that level)

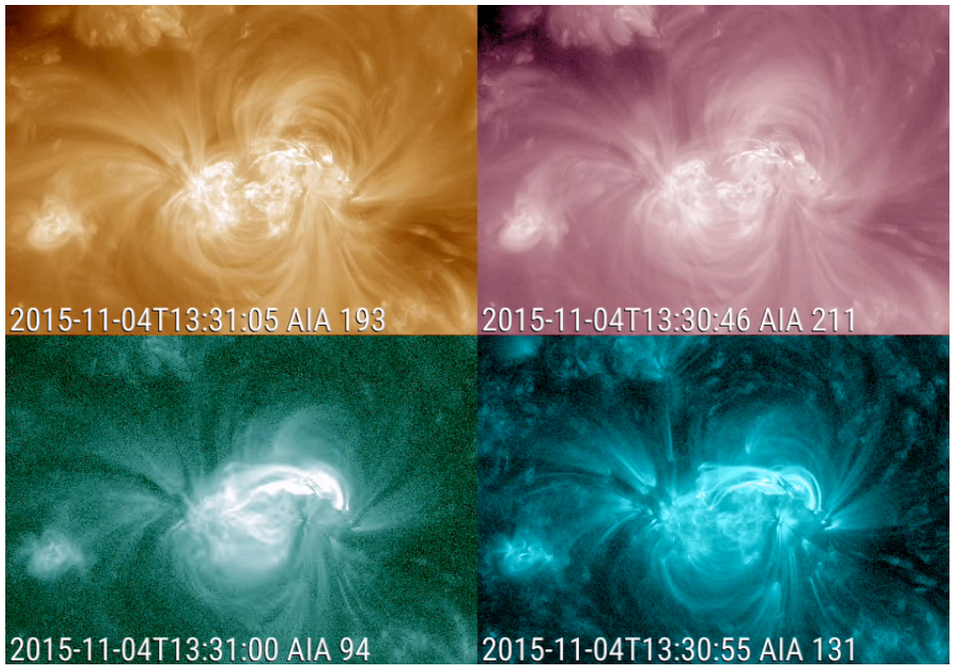
Impact on radar systems



Marqué et al 2018



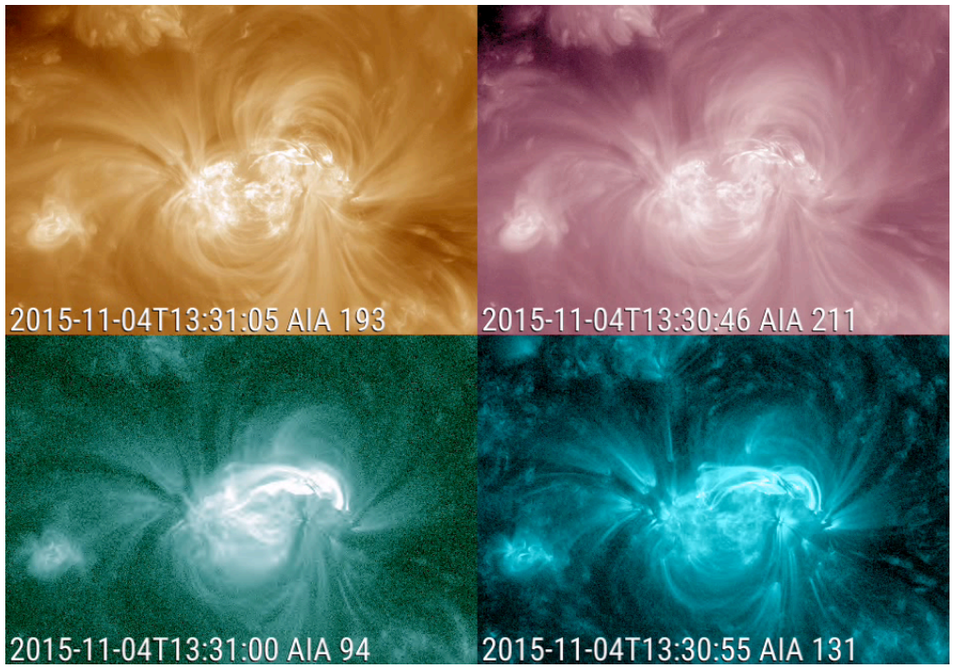
Solar event



M3.7 flare - peak at 13:52 UT

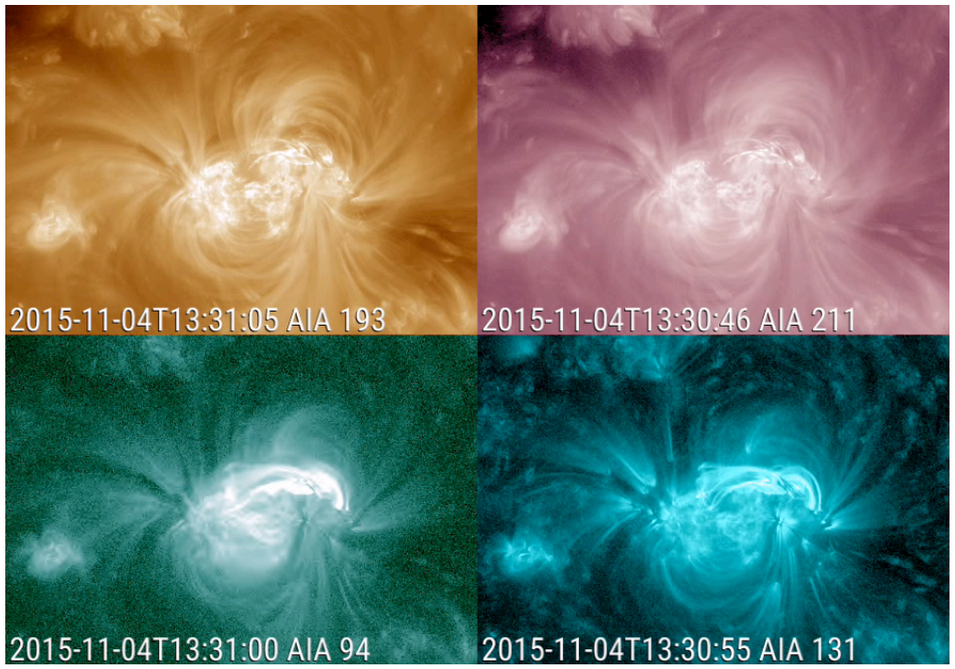
Belgium: sunset on Nov 4
15:42 UTC – 16:42 CET (UTC +1)
Flare peak 1352 UTC – 1452 CET

Solar event



M3.7 flare - peak at 13:52 UT

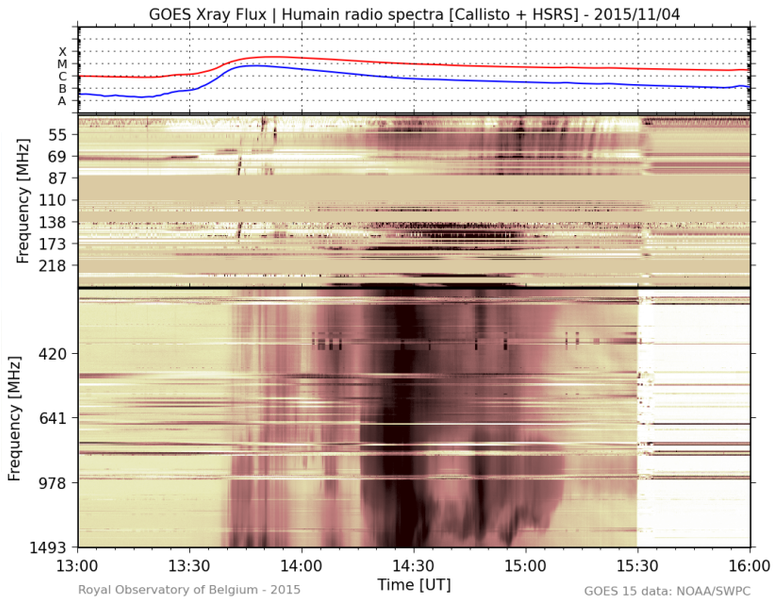
Solar event



M3.7 flare - peak at 13:52 UT

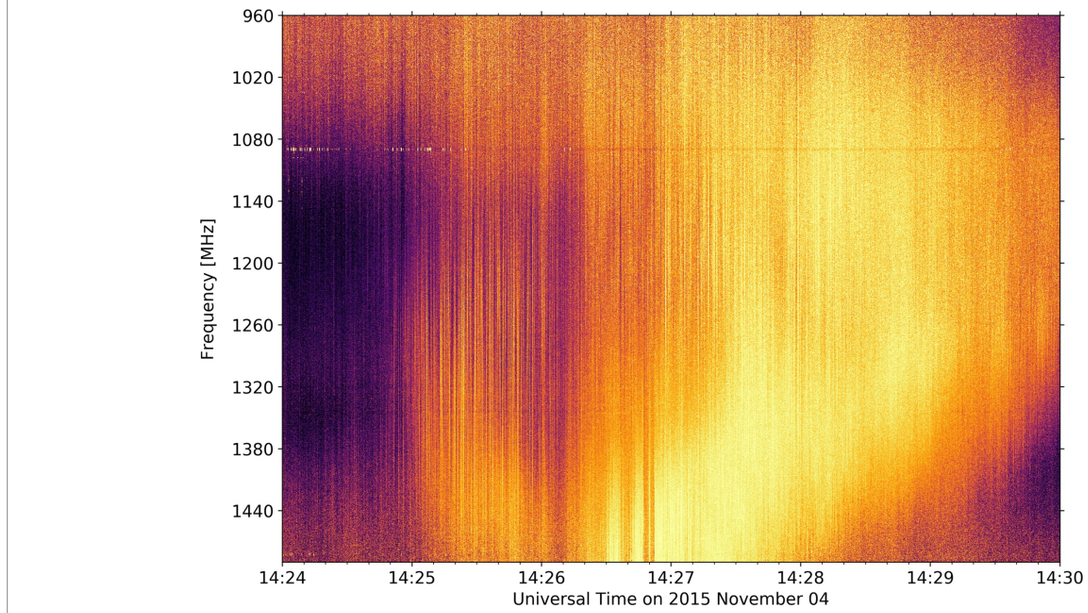
In Humain





https://www.sidc.be/humain

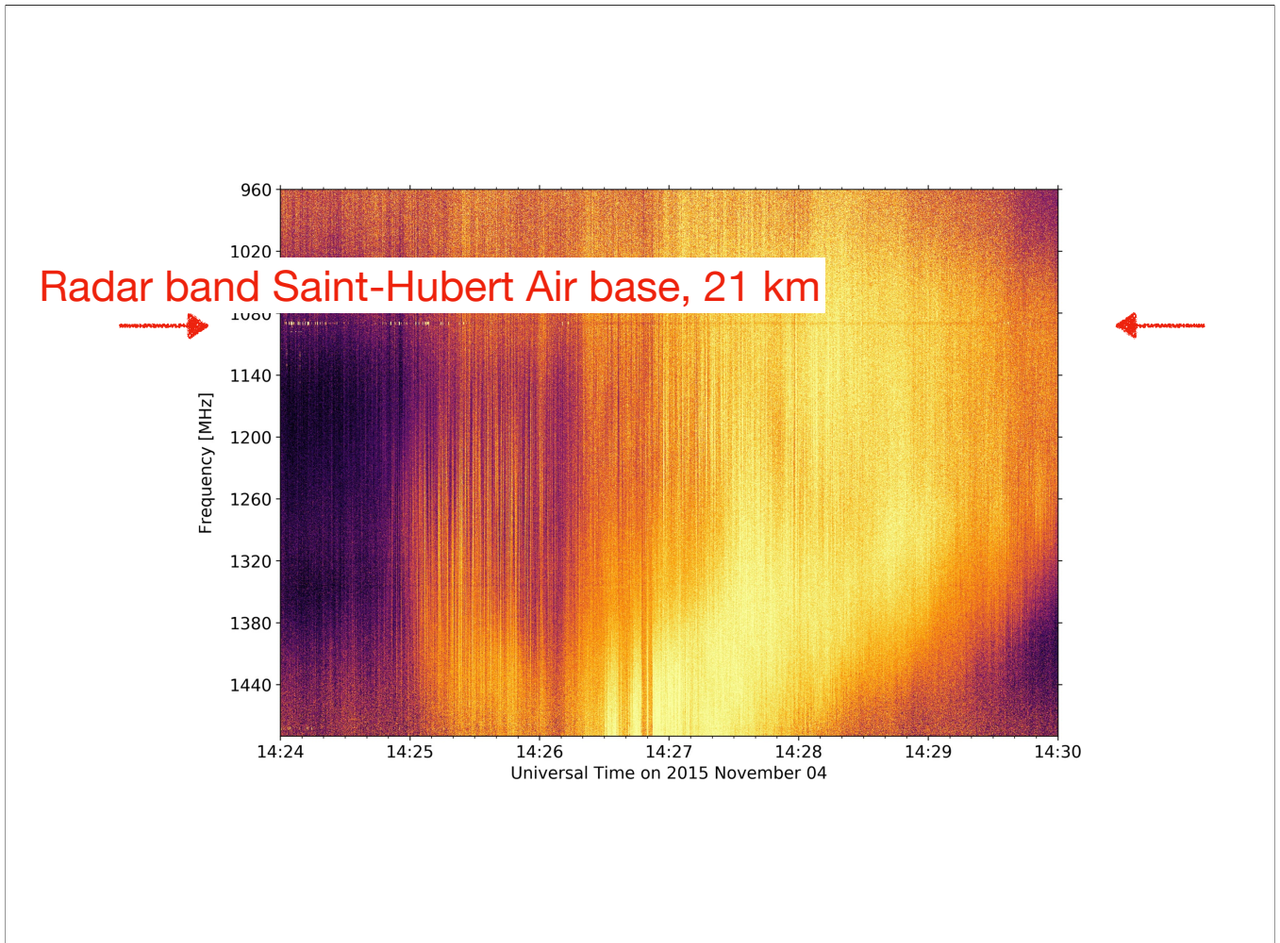
Belgium: sunset on Nov 4
15:42 UTC - 16:42 CET (UTC +1)



The output of the Sun was not in the noise level anymore. It was overruling the echo.

Surveillance radars ATC (1060 MHz) - Air Trafic control
Radar band saint-hubert air base, 21 km
Nov 4 2015

Fig. 6. Dynamic radio spectrum observed with HSRS around the peak of the strong emission. Note that the flux density scale was set independently for the individual frequencies. The apparent maximum near 1400 MHz is an artifact of this procedure. The horizontal line at 1090 MHz, is actually the downlink part of a secondary ATC radar transmission close the station of Humain.


Radar band Saint-Hubert Air base, 21 km
960
1020
1080
1140
1200
1260
1320
1380
1440
Frequency [MHz]
14:24
14:25
14:26
14:27
14:28
14:29
14:30
Universal Time on 2015 November 04

	Frequency range	Properties	Impact
Noise storms / Type I	HF, VHF	can be intense, long duration (days), frequent	**Possible**
Type II	HF, VHF	last few minutes, rare	**No**
Type III	HF, VHF	Intense, short duration, very frequent	**No**
Type IV	HF, VHF, UHF	Intense, long duration, broadband	**Yes**

Links

Where to find solar radio data?

Bursts & radio events	https://www.swpc.noaa.gov/products/solar-and-geophysical-event-reports https://www.ncei.noaa.gov/products/space-weather/partners/swpc-products-and-data
Recent radio flux	https://services.swpc.noaa.gov/text/solar_radio_flux.txt
F10.7	https://spaceweather.gc.ca/forecast-prevision/solar-solaire/solarflux/sx-5-en.php
Humain data	https://www.sidc.be/humain 🇧🇪