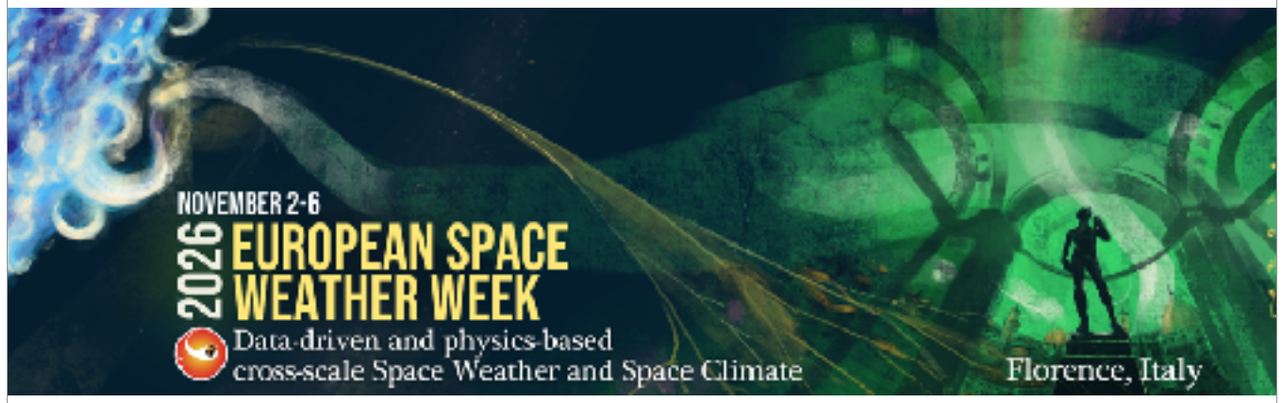
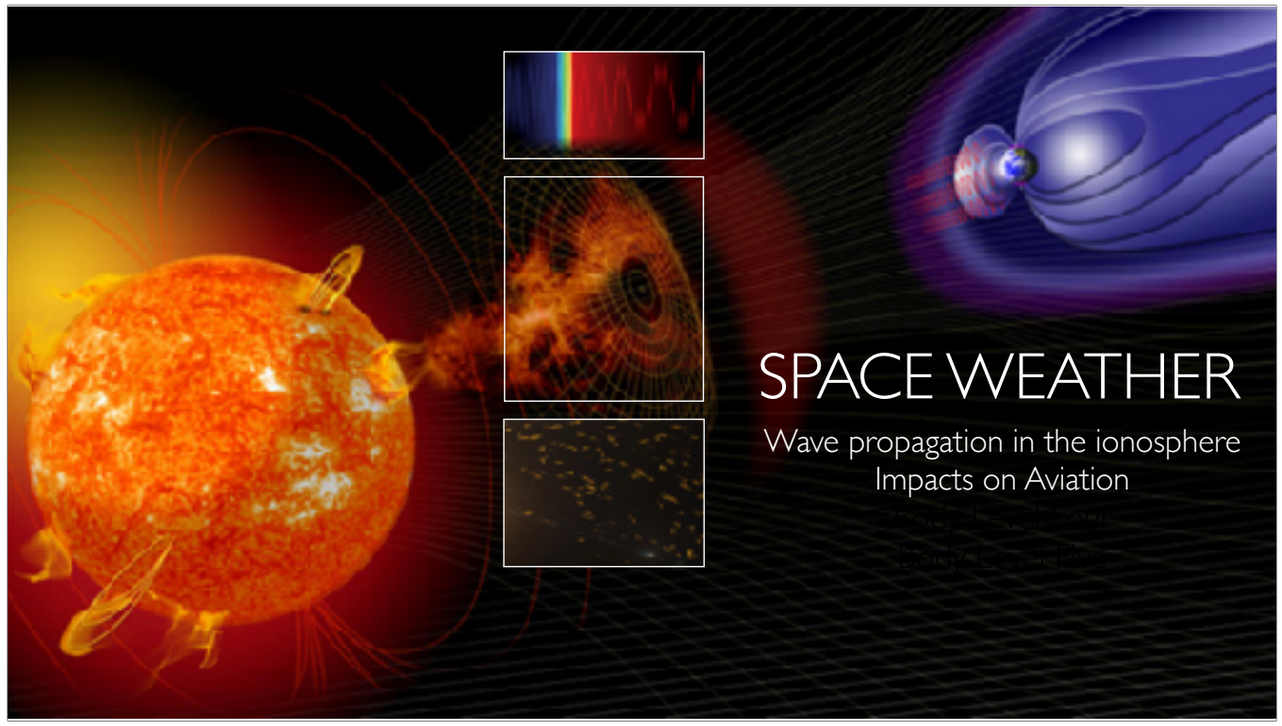
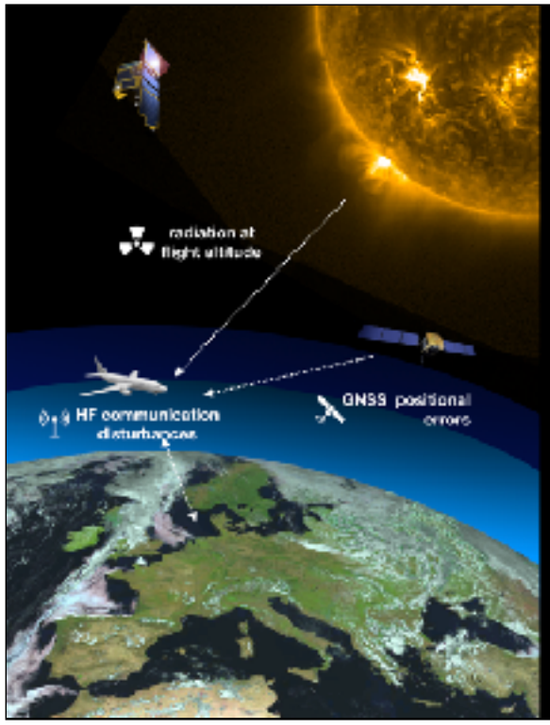
Space Weather Training Course



e-swan

SWEC
Space Weather Education Centre


SPACE WEATHER
Wave propagation in the ionosphere
Impacts on Aviation



PECASUS

Partnership of Excellence for Civil Aviation SWx User Services

Space weather can impact navigation and radio communication systems and can cause an increase of radiation levels at flight altitude.

Petra Vanlommel, Christophe Marqué

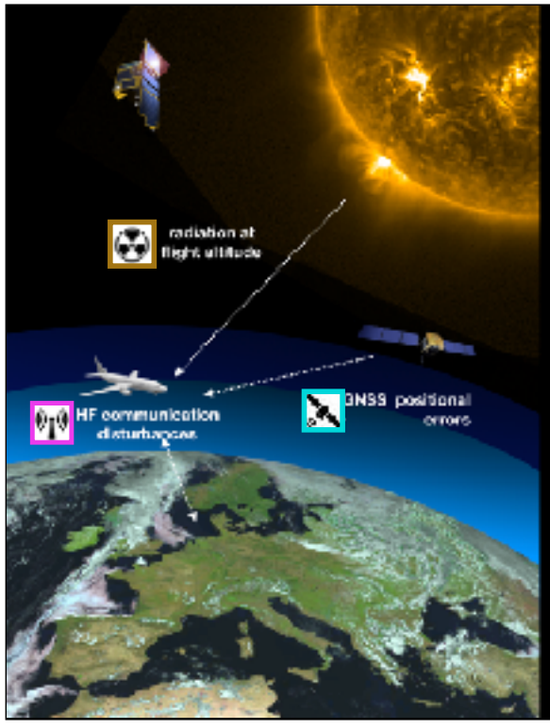
International Civil Aviation Organization
Since Nov 2019

User-oriented

Partnership: FMI, Seibersdorf Austria, INGV Italy, UKMetOffice, KNMI, DLR Germany, Poland …

GNSS —> scintillation due to
- equatorial post sunset plasma bubbles - thermospheric winds and magnetosphere
- Polar patches - solar cycle influence
- Auroral oval structures - during geomagnetic storms
- Large scale Travelling ionospheric disturbances - due to CME's banging in on the magnetosphere

Partnership of Excellence for Civil Aviation Space weather User Services
24/7 service, real-time + worldwide alerts
ICAO-compliant advisories (specified thresholds)
2-week rotation scheme with SWPC, ACFJ, CR
(on duty - primary backup - secondary backup - maintenance)
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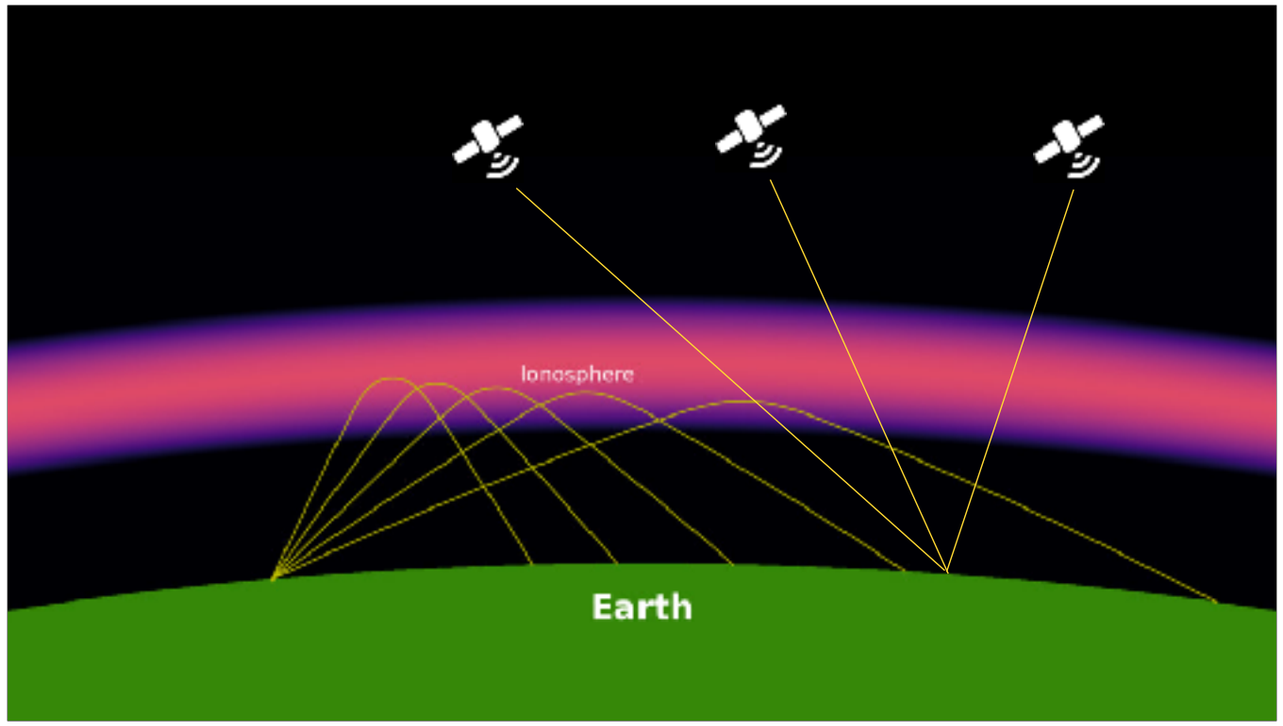
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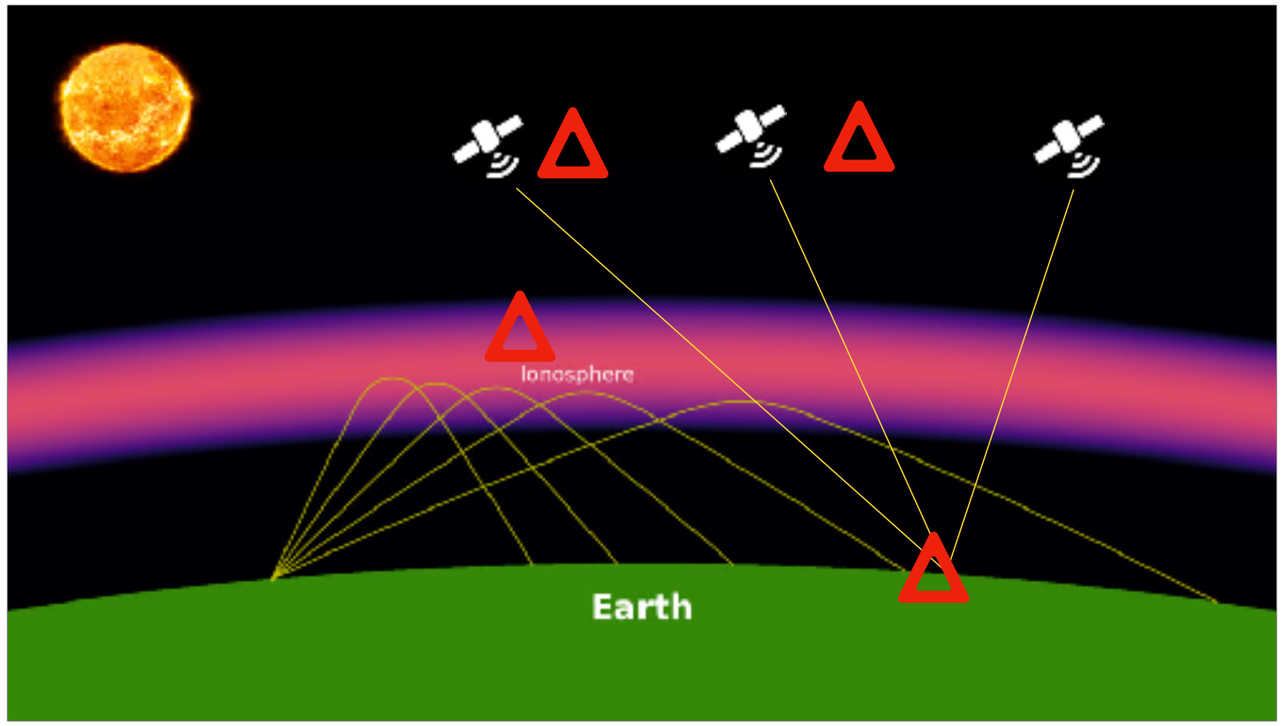
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https://svs.gsfc.nasa.gov/5240



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Emitter - transmission - receiver

space weather impact
- On the area where the transmission occurs/signal passes
- On the reflecting system: natural reflector or a satellite
- The receiving capabilities: trouble in receiving the signal because it has changed or receiving other signals (with solar origin or human origin)

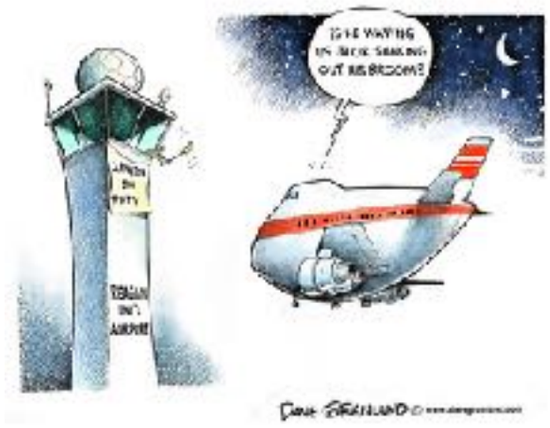
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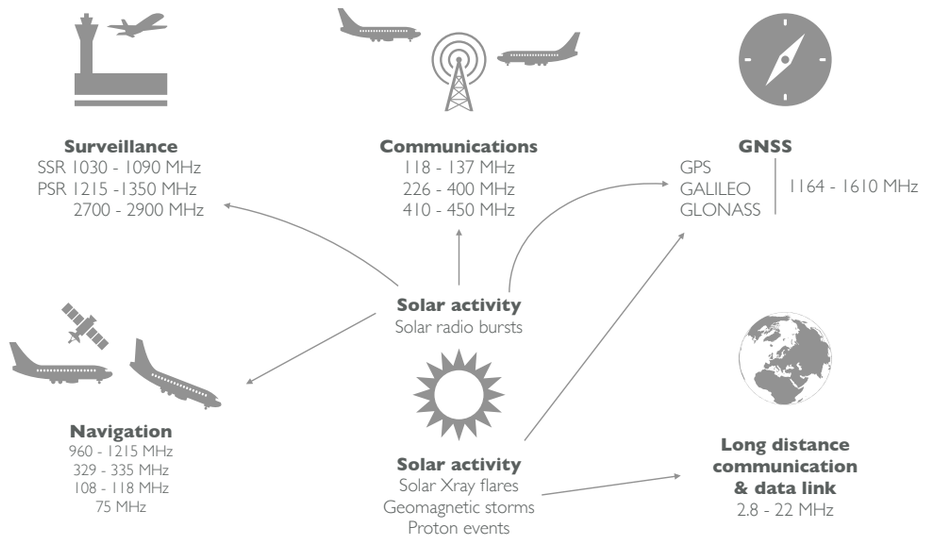
HF Advisory:

0000057501
FNXX02 EFKL 020814
SWX ADVISORY
DTG: 20260202/0814Z
SWXC: PECASUS
SWX EFFECT: HF COM
ADVISORY NR: 2026/63
OBS SWX: 02/0808Z MOD DAYSIDE
FCST SWX +6 HR: 02/1500Z NOT AVBL
FCST SWX +12 HR: 02/2100Z NOT AVBL
FCST SWX +18 HR: 03/0300Z NOT AVBL
FCST SWX +24 HR: 03/0900Z NOT AVBL
RMK: SPACE WEATHER EVENT (SOLAR FLARE) IN PROGRESS. IMPACT ON LOWER HF COM FREQUENCY BANDS EXPECTED
ON THE DAYLIGHT SIDE. HIGHER FREQUENCY BANDS MAY BE LESS
IMPACTED.
NXT ADVISORY: WILL BE ISSUED BY 20260202/1408Z=

SWXC: PECASUS/SWPC/ACFJ/CRC
Type of advisory - MOD/SEV
Sequence - per domain, across centres - no combined domains
Forecast up to 24hr
Time +impacted area/NO SWX EXP/Not AVBL
Textual explanation: observed or expected impacts on technology, no details on physics, no mitigation actions

Frequencies used in aviation





Slide from Christophe Marqué

Long Distance Communication & data link

In aviation, **HF communication** systems are required for all trans-oceanic flights. These systems incorporate frequencies down to 2 MHz to include the 2182 kHz international distress and calling channel.

Navigation

https://en.wikipedia.org/wiki/Air_navigation

The basic principles of air navigation are identical to general navigation, which includes the process of planning, recording, and controlling the movement of a craft from one place to another.

https://en.wikipedia.org/wiki/Communication,_navigation_and_surveillance

Communication

Communication, i.e. aviation communication, refers to radio communication between two or more aircraft, or the exchange of data or verbal information between aircraft and air traffic control.[2] For continental airspace, VHF (civil) and UHF (military) systems are used whereas for oceanic areas, high frequency systems and SATCOMs are used.[3]

Navigation

Navigation, i.e. air navigation, refers to the process of planning, recording, and controlling the movement of an aircraft from one place to another by providing accurate, reliable and seamless position determination capability.[2][4]

Surveillance

Surveillance systems are used by air traffic control to determine the position of aircraft. There are two types of surveillance systems:

Cooperative systems[edit]

Cooperative systems (a.k.a. dependent surveillance): Under this form of surveillance, systems on the ground (such as SSR) communicate with equipment (such as transponders) on board the aircraft to determine the position and other details of the aircraft. Aircraft information, which may include position from GNSS or other means is determined on board and then transmitted to ATC in response to interrogation.[2][3] Other cooperative systems such as ADS-B rely on aircraft transmitting their position and other information without interrogation from the ground.

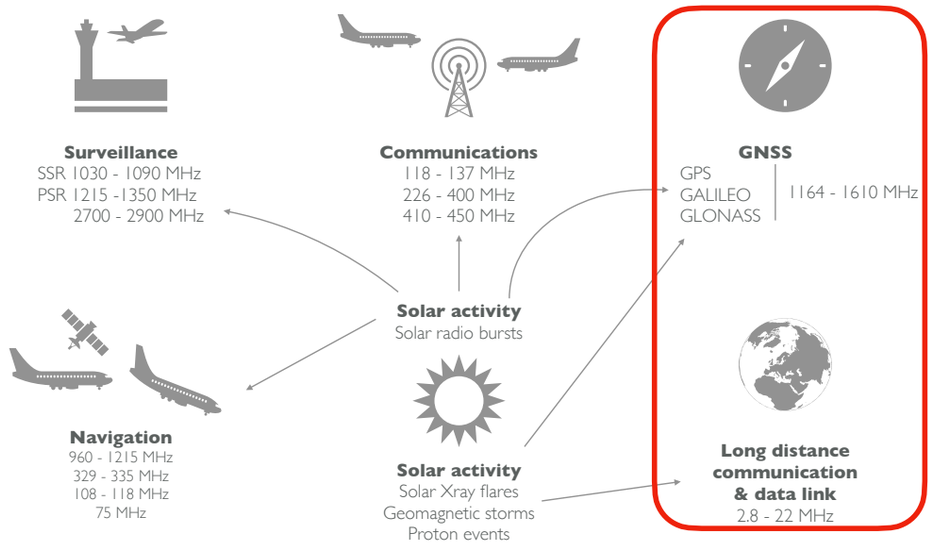
Non-cooperative systems[edit]

Non-cooperative systems (a.k.a. independent surveillance): Under this form of surveillance, systems on the ground (such as PSR) are able to locate the aircraft and measure its position from the ground by transmitting pulses of radio waves which reflect off the aircraft's hull.[2][3]

——

https://www.swpc.noaa.gov/impacts/hf-radio-communications

Space weather impacts radio communication in a number of ways. At frequencies in the 1 to 30 mega Hertz range (known as “High Frequency” or HF radio), the changes in ionospheric density and structure modify the transmission path and even block transmission of HF radio signals completely. These frequencies are used by amateur (ham) radio operators and many industries such as commercial airlines. They are also used by a number of government agencies such as the Federal Emergency Management Agency and the Department of Defense.



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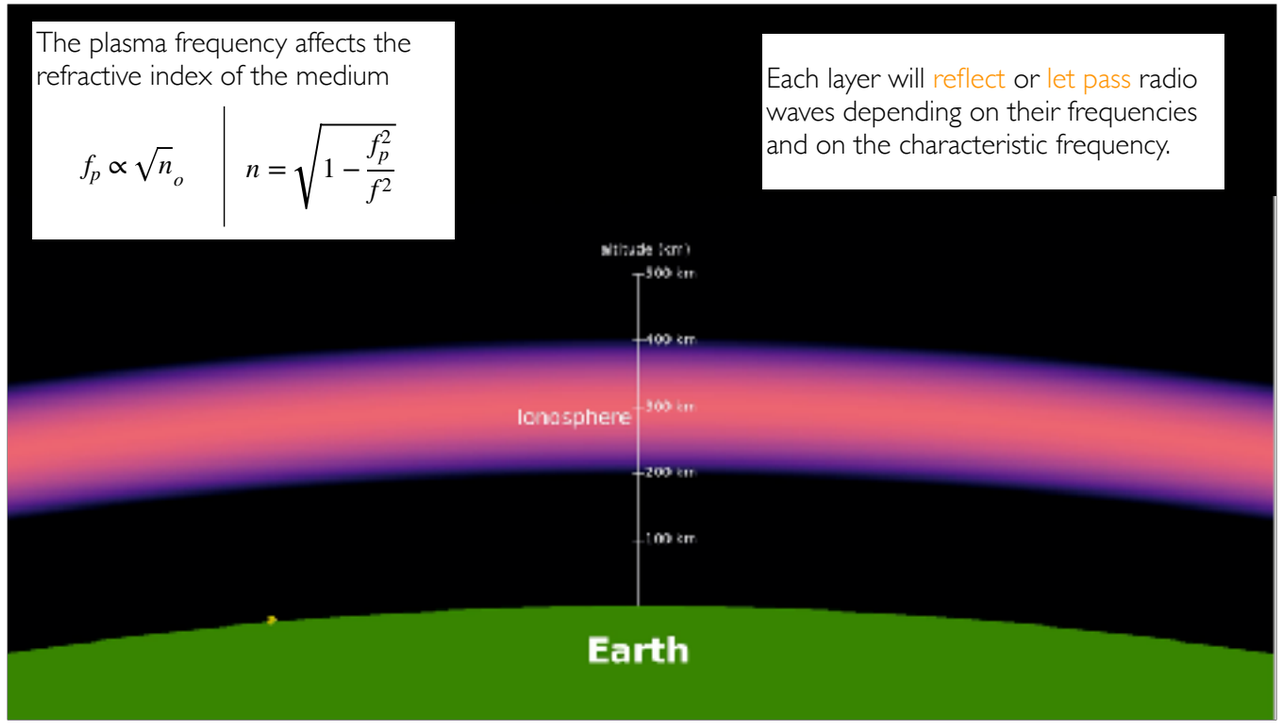
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The plasma frequency is the resonant frequency of the electrons in an ionized medium.
There is a direct relation between the electron density and the plasma frequency, which can be approximated as f ≈ 8.9 Ne^1/2.

Both GNSS and HF com use radio waves —> how do radio waves behave in an ionised medium

Both GNSS and HF com use radio waves —> how do radio waves behave in an ionised medium

n0, electron content —> critical frequency f0F2 or fp or characteristic frequency—> refractive index
n=c/v
v=c —> n=1
V<c —> n>1

A qualitative understanding of how an electromagnetic wave propagates through the ionosphere can be obtained by recalling geometric optics. **Since the ionosphere is a plasma, it can be shown that the refractive index is less than unity.** Hence, the electromagnetic "ray" is bent away from the normal rather than toward the normal as would be indicated when the refractive index is greater than unity. It can also be shown that the refractive index of a plasma, and hence the ionosphere, is frequency-dependent, see Dispersion (optics).[24]

In physics, refraction is the change in direction of a wave passing from one medium to another or from a gradual change in the medium.

f>fp—> passes through ionosphere
f< fp —> reflected by ionosphere —

The ionosphere is the key-layer for HF communication and GNSS performance: or radio waves are reflected at, or pass through the ionosphere. The reflection is used for long distance communications.

The ionosphere has the ability to reflect radio waves. If the degree of ionisation would be zero, no radio waves would be reflected and all would pass.

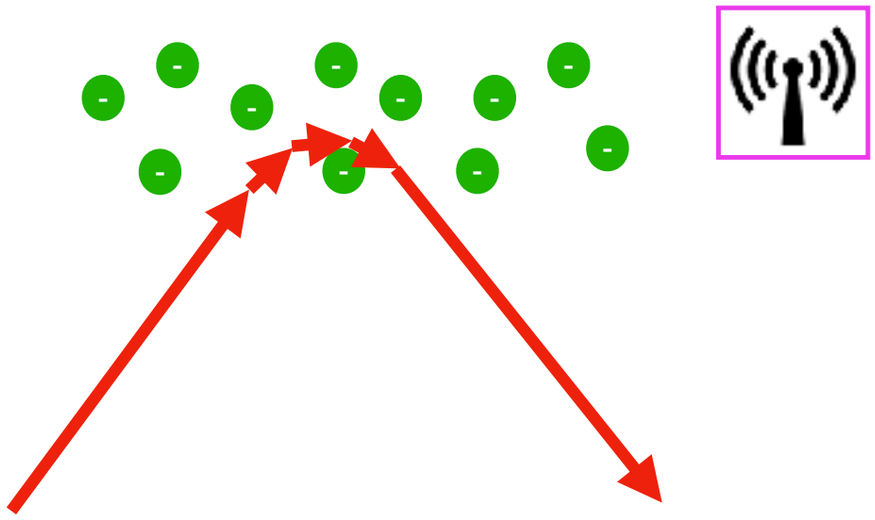
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Absorption

Ionisation can change over time.
Ionisation is not the same everywhere.

During the night, the ionisation decreases - the skill to reflect drops.
—> also LF goes through —> Maximum Usable Frequency, MUF decreases.

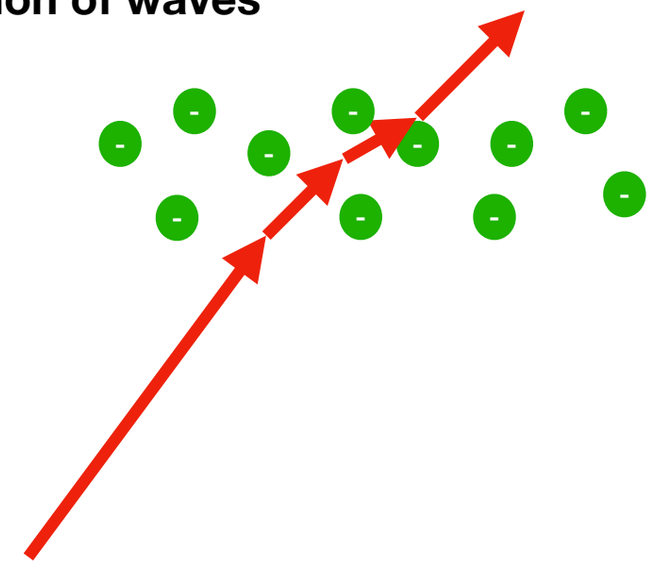
Reflection of waves



Radio wave makes the electrons move. Those moving electrons reproduce on their turn the radio signal and re-emitting it.

The ionosphere refracts radio waves
More refraction when higher the electron density or lower the frequency
When there are more electrons, the wave is more bent and again bent and again … until it is going down.
This is how reflection works in the ionosphere. It is a region full of magic (with a negative number under the square root of the refractive index).

Transmission of waves

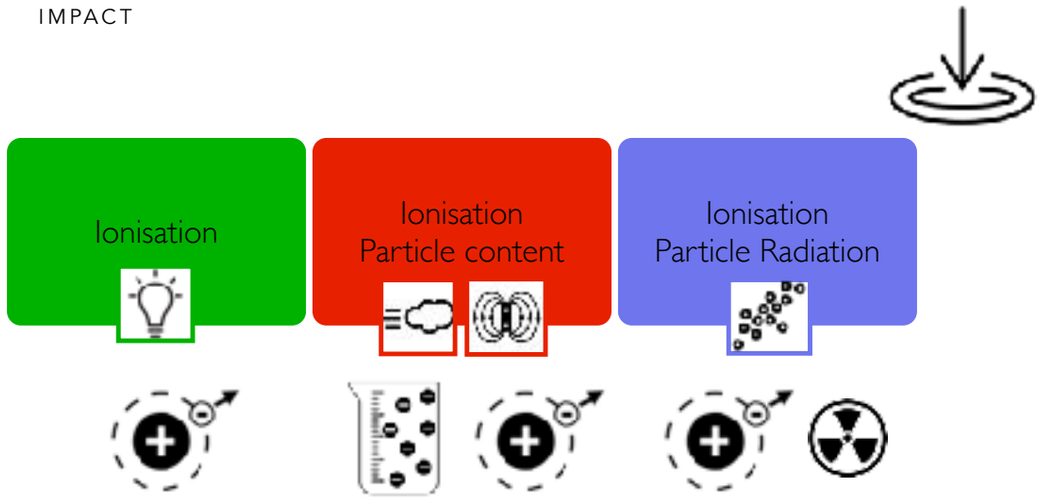




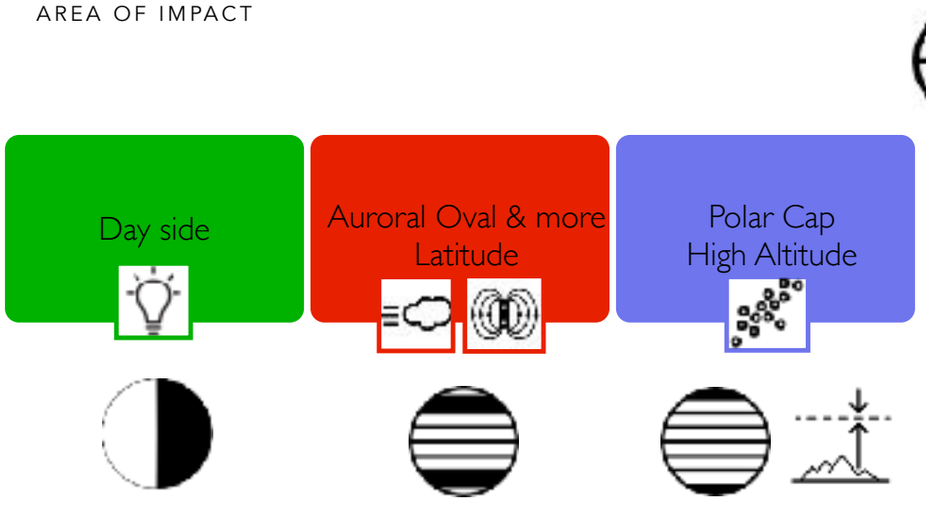
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IMPACT


Ionisation
Ionisation
Particle content
Ionisation
Particle Radiation

AREA OF IMPACT





Impacts on waves

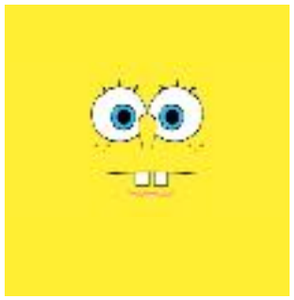
Impacts on waves due to their passage through the ionosphere

Note: Refraction - pass from 1 medium to another
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Impacts on waves

Absorption



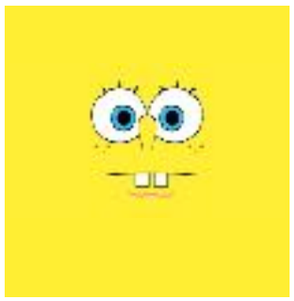
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Impacts on waves

Absorption



No reflection



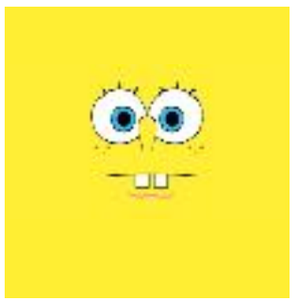
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Impacts on waves

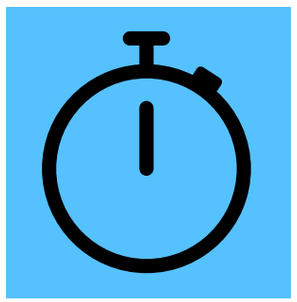
Absorption



No reflection



Delay

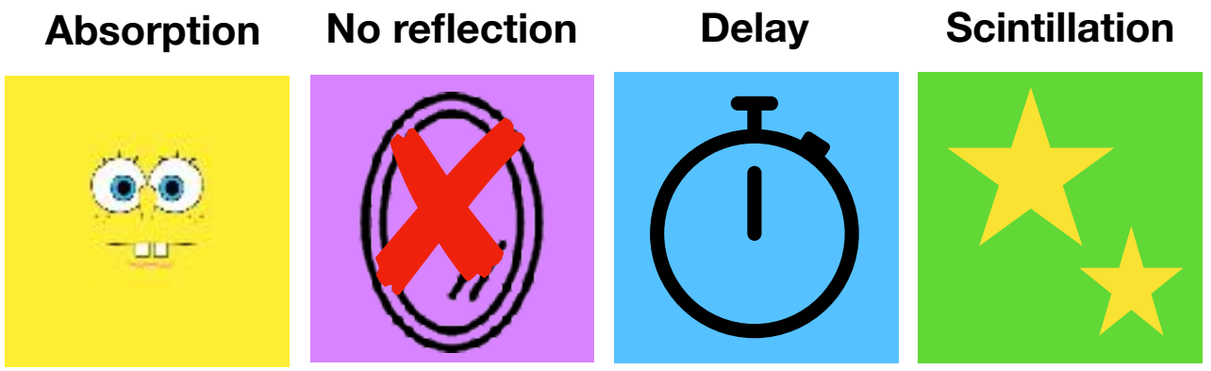


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Impacts on waves



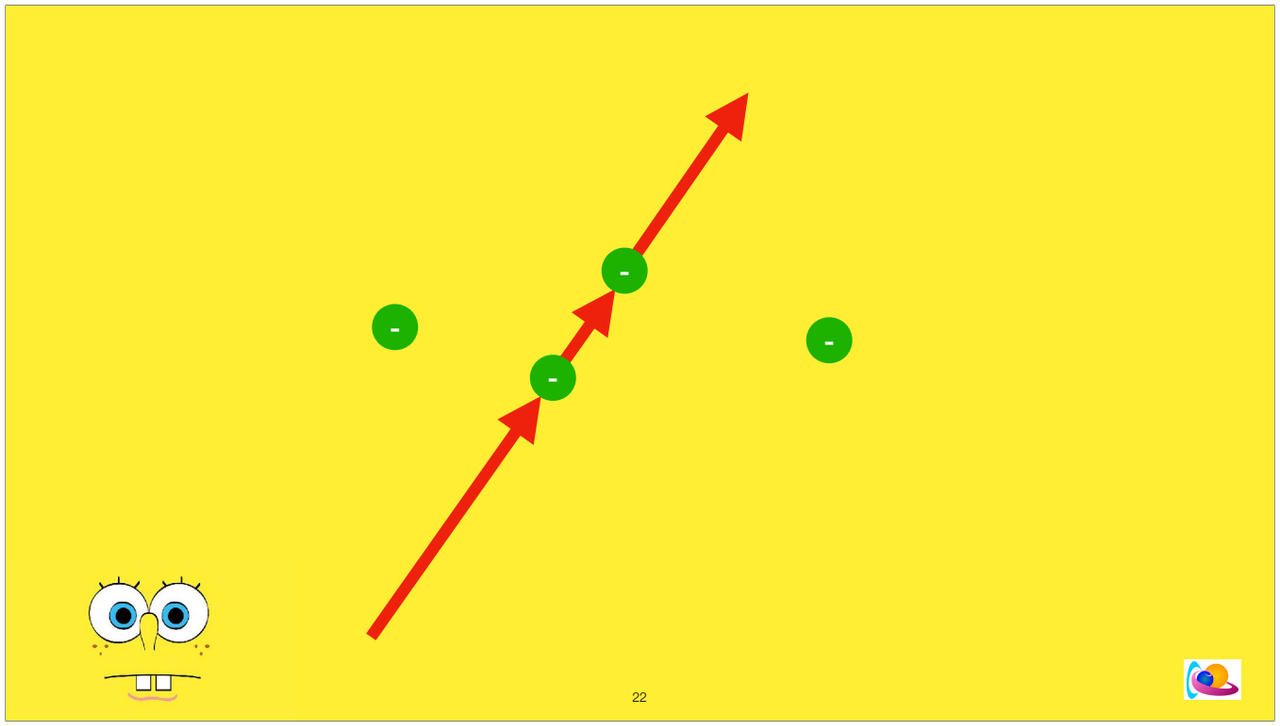
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Impact: Absorption of HF waves

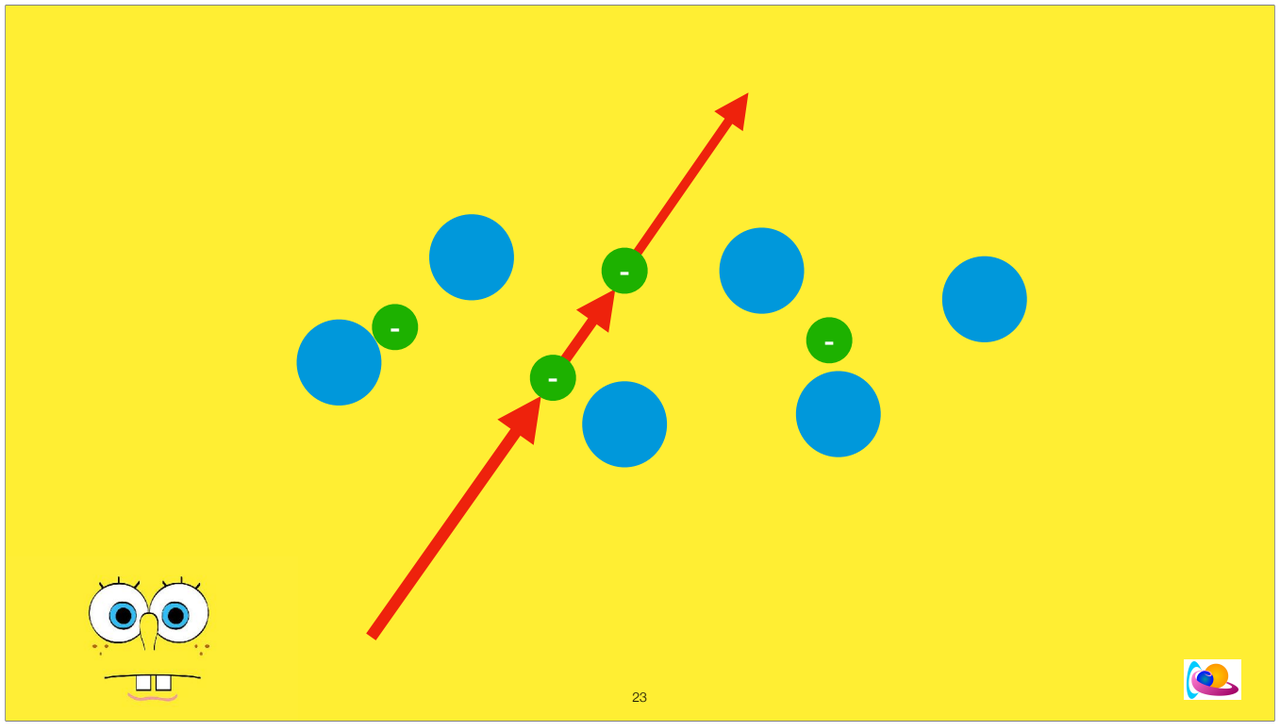


Absorption



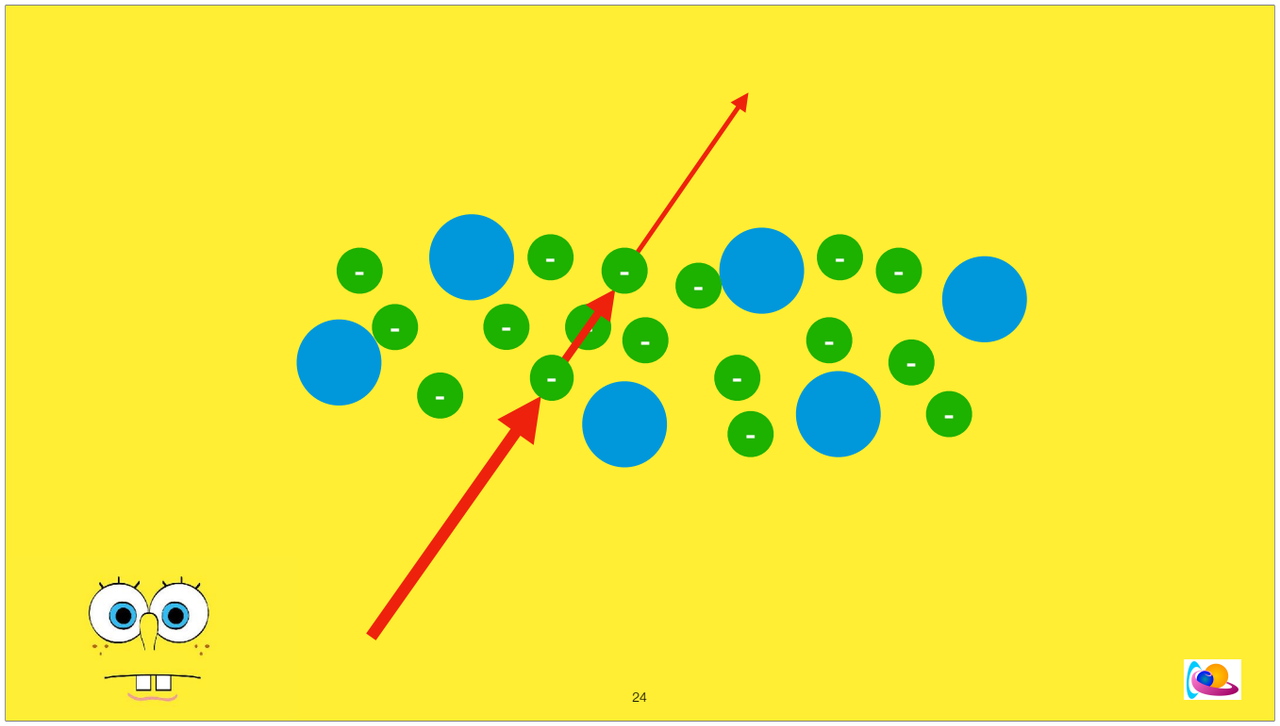
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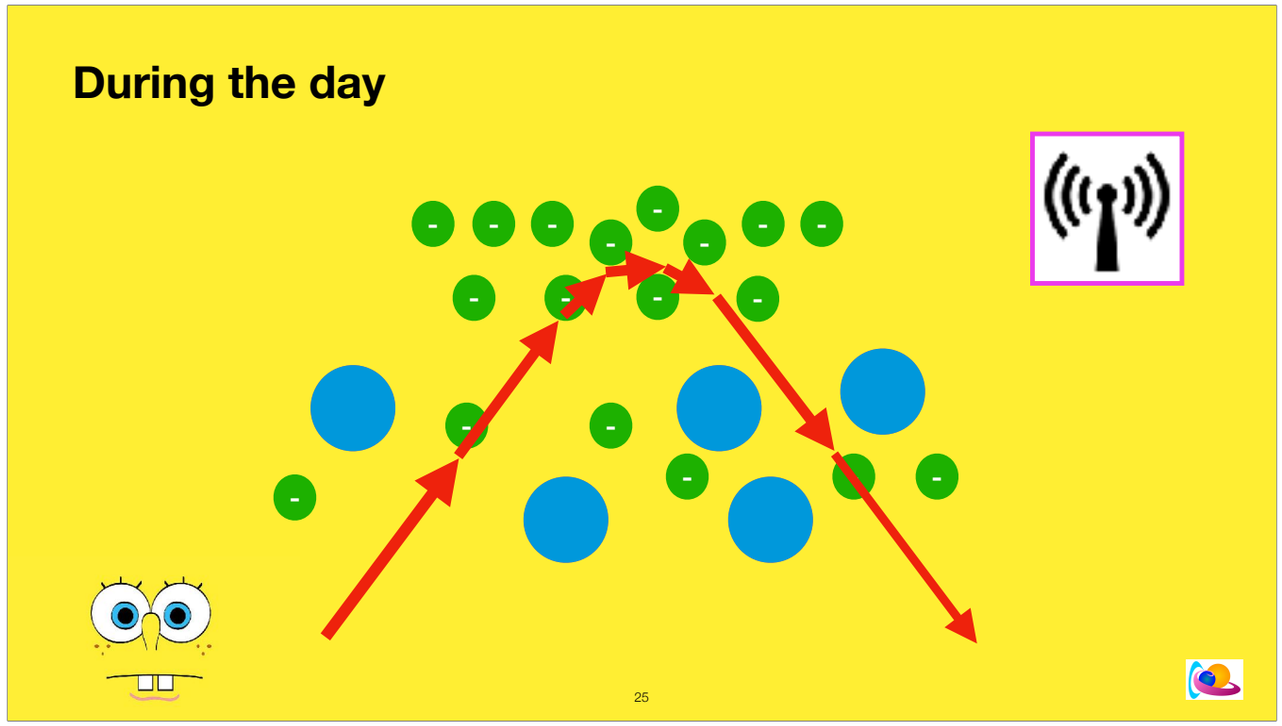
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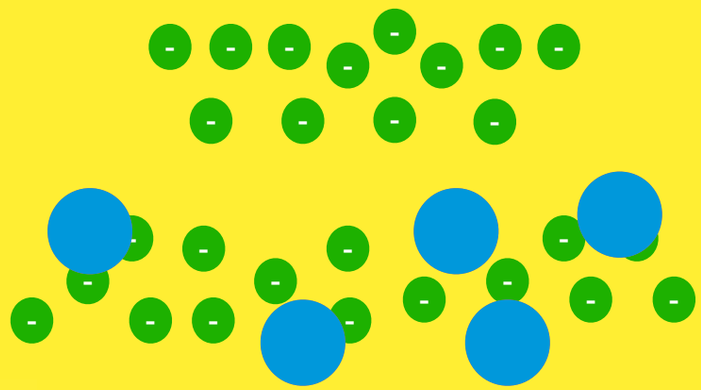
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This is the D-layer during the day.
The radio wave also meets electrons in the D-layer. These electrons can’t move as much due to the neutral —> absorption.
Luckily, there are not many electrons and the absorption is minimal.

Extra ionisation due to a solar event





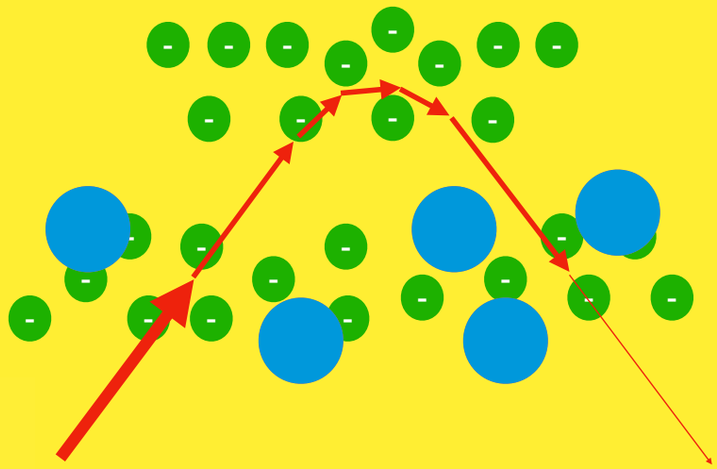




The incoming solar energetic particles ionise the D-layer.

The radio wave meets more electrons in the D-layer. During each encounter, the wave is being absorbed.

Extra ionisation due to a solar event



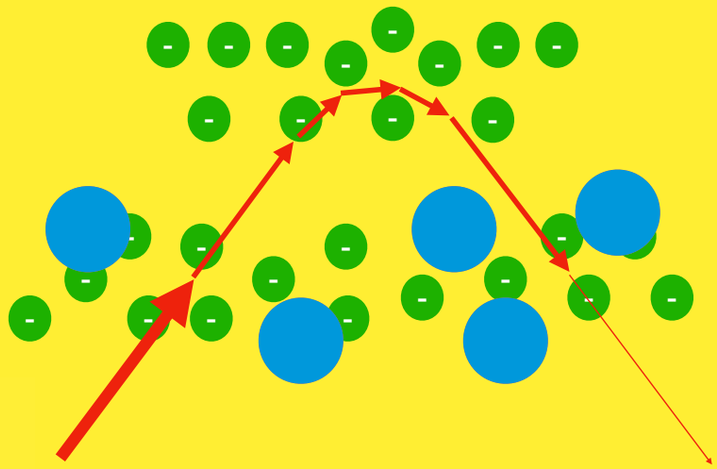




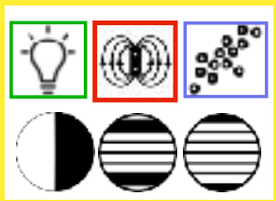


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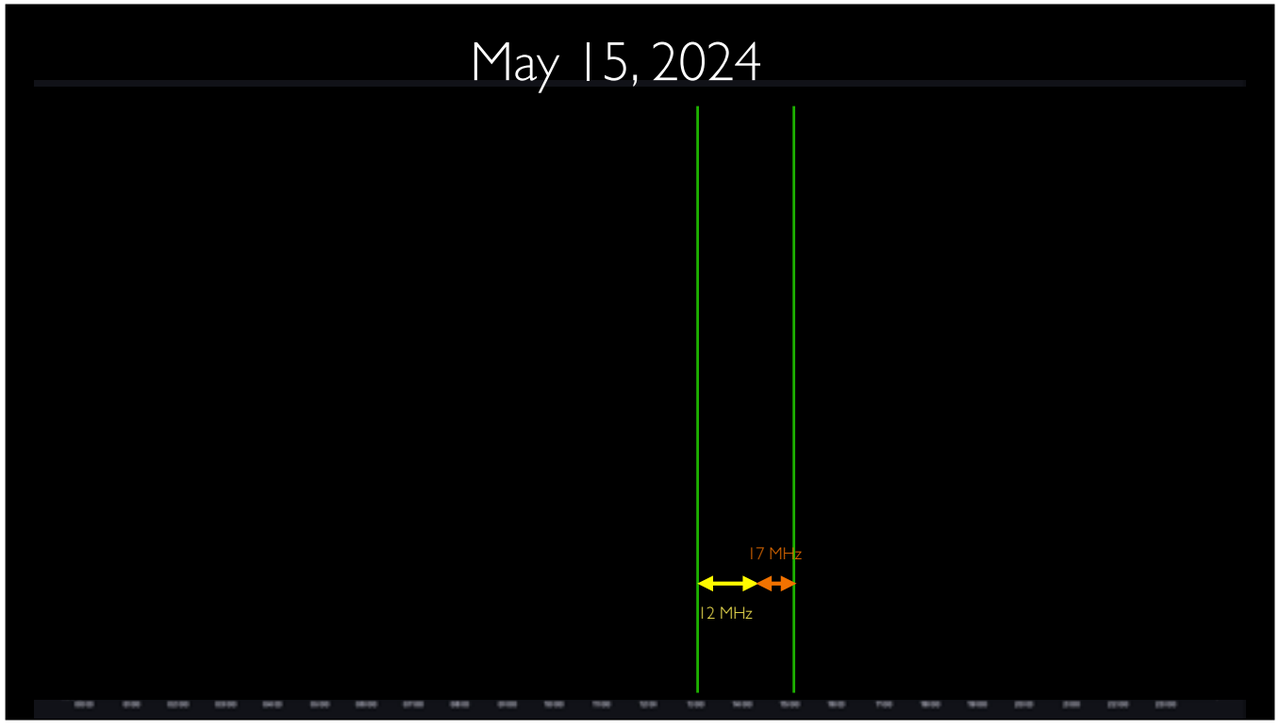
Short Wave Fadeout, auroral absorption, PCA

Lower HF range





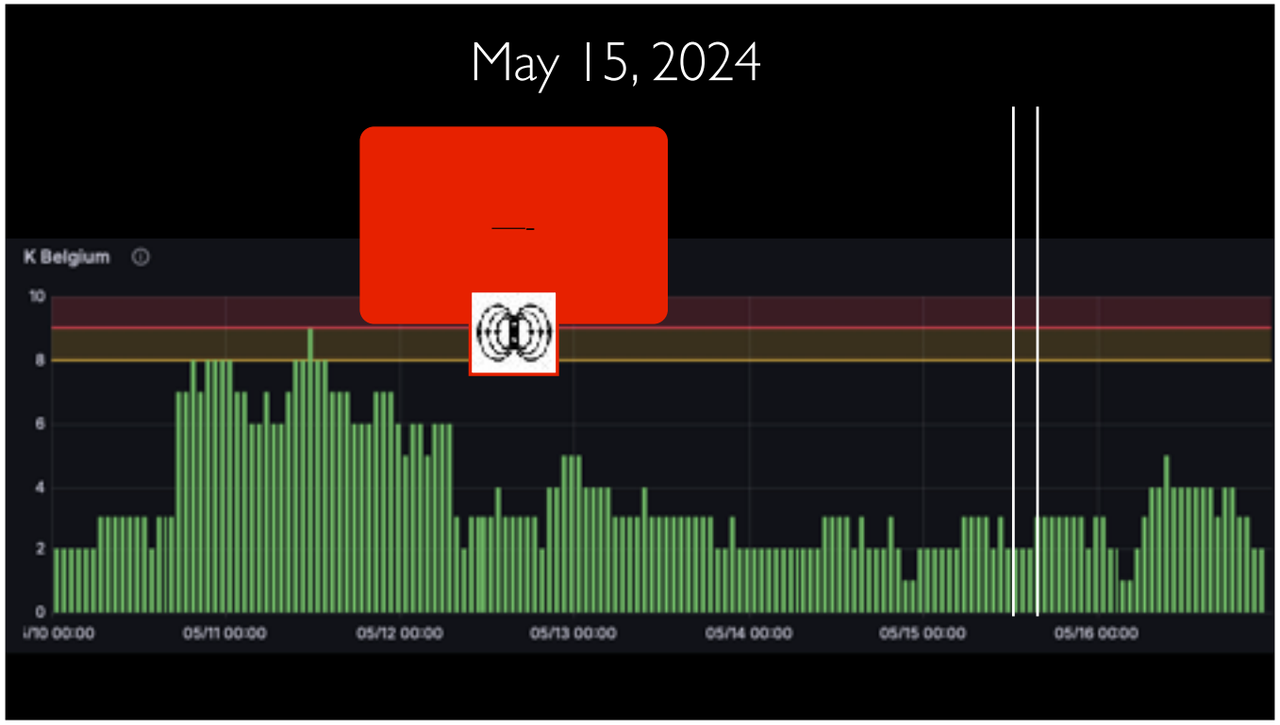
And on May 15, 2024, Dries is doing an HF test with his Canadian colleagues.



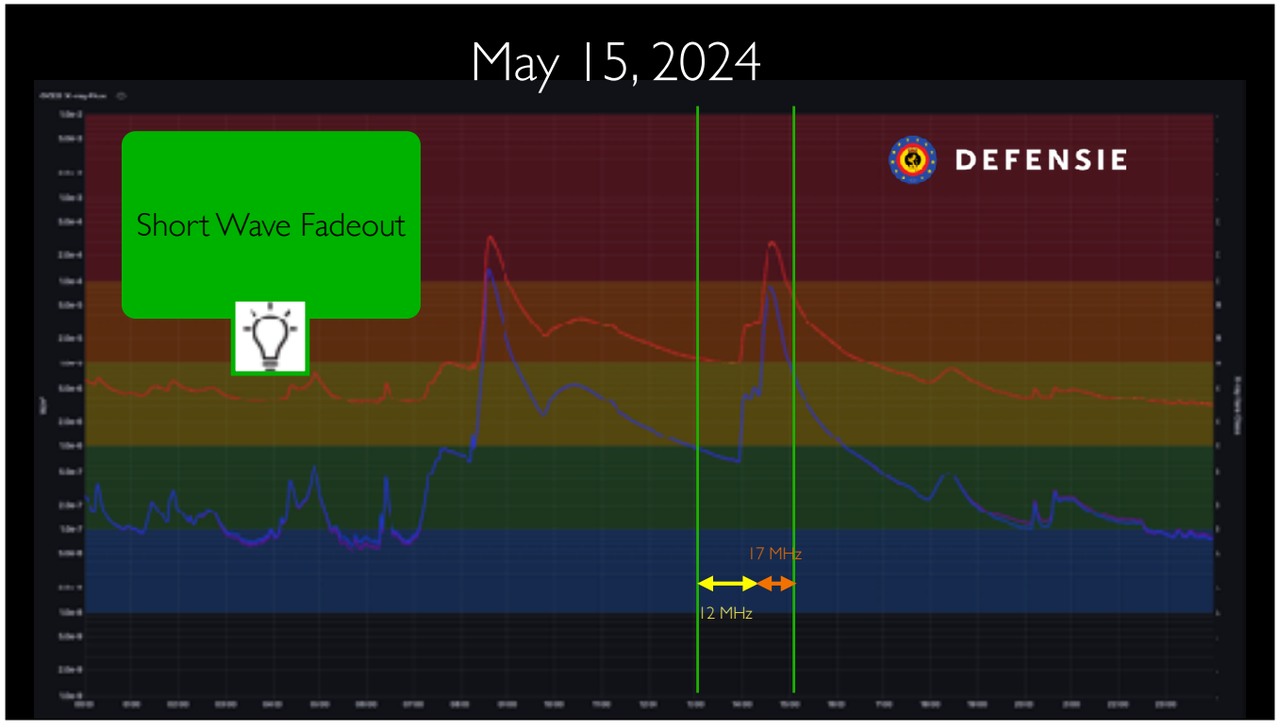
15 mei was een test tussen België en Canada.

We hebben toen getest van 13u tot laat in de avond en niets heeft gewerkt. Dat heeft een aantal redenen, maar ik ben ervan overtuigd dat SWx er een belangrijke rol in heeft gespeeld.
13u-14u: Gestart op 12 MHz, mogelijks niet een ideale frequentie, maar ik denk het eigenlijk wel. Ik denk dat er hier niets gelukt was wegens andere verkeerde instellingen. Rond 14u zijn ze dan overgeschakeld naar 17 MHz, maar het is net op dat moment dat er een M class flare begon, gevolgd door een X class flare! Spreekt voor zich dat er met die ionosfeer niet te veel meer aan te vangen viel.
Men is dan blijven testen op 17 MHz, maar dat is waarschijnlijk al te hoogfrequent, en zeker naar de avond toe.

De volgende dag heeft men de testen hervat in de namiddag, toen was er een Kp van 4, ook toen kwam er niets door.

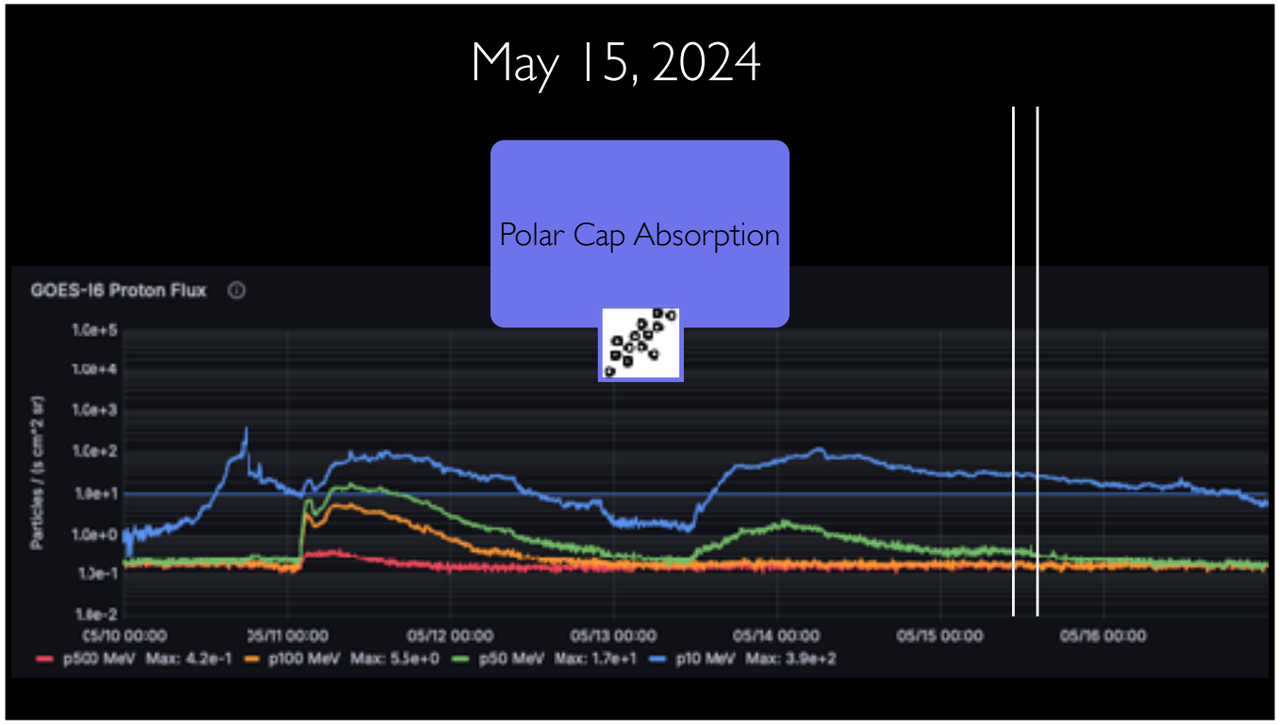

May 15, 2024
K Belgium
10
8
6
4
2
0
05/10 00:00
05/11 00:00
05/12 00:00
05/13 00:00
05/14 00:00
05/15 00:00
05/16 00:00

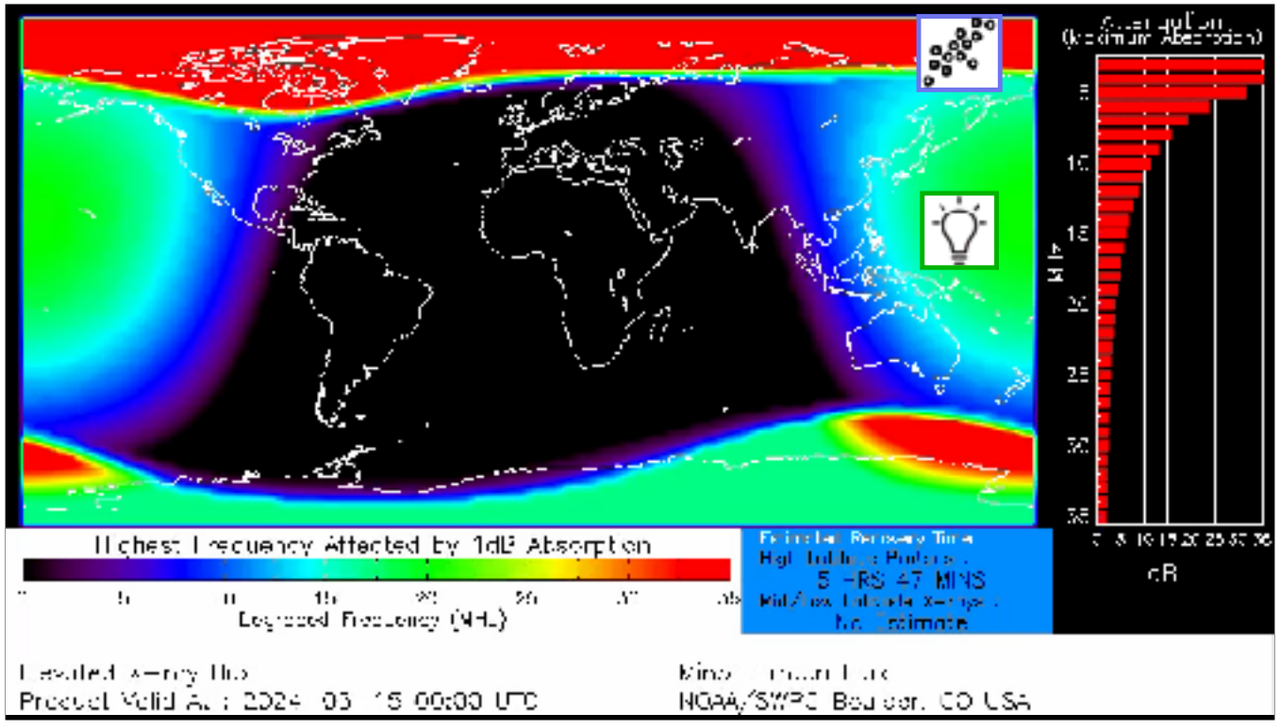
May 15, 2024



May 15, 2024

Polar Cap Absorption





Flare
Solar energetic particles
Causing absorption of radio waves
DRAP model - D region absorption predictions

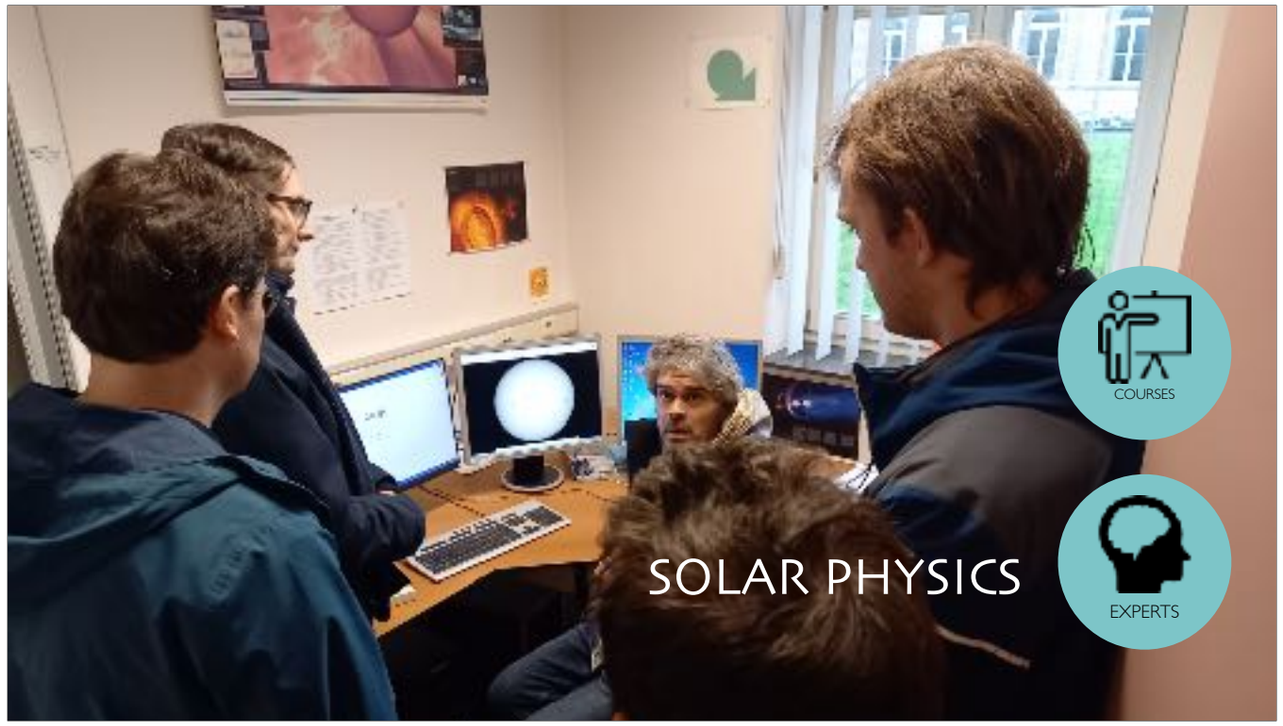
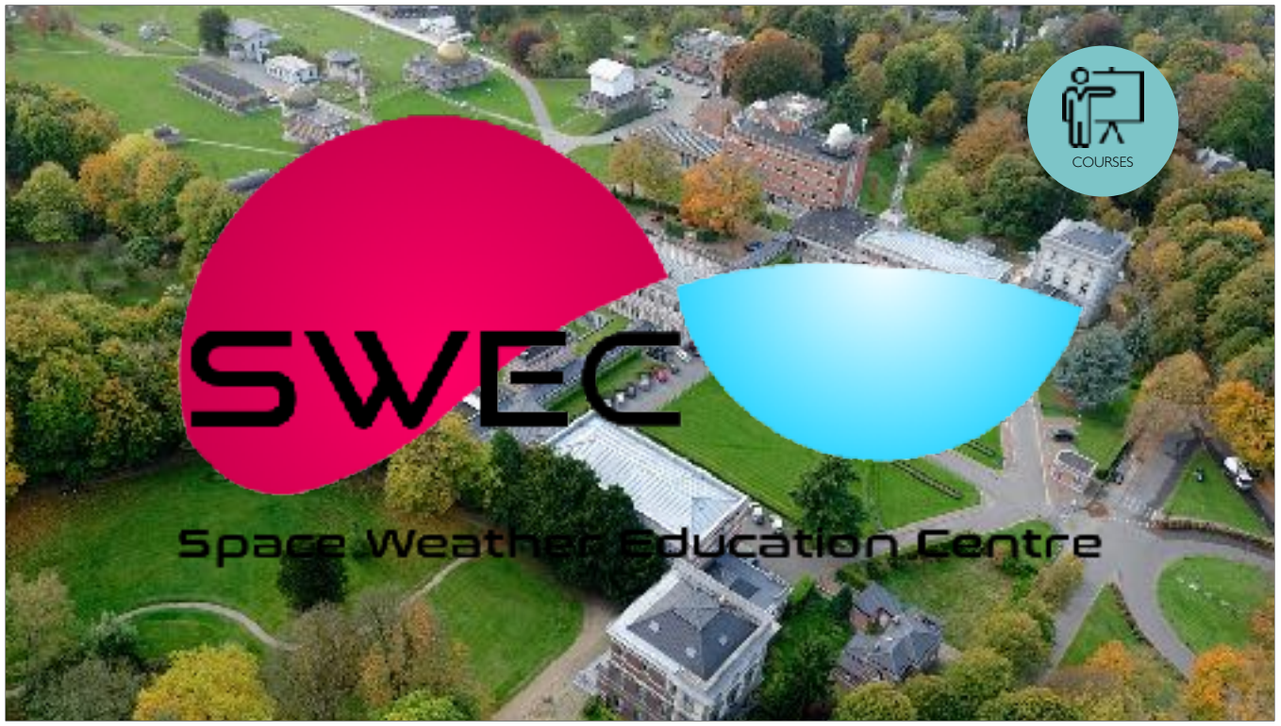


Photo taken during a course that we set up in 2023 : SWx impacts on ionospheric wave propagation, focus on GNSS and HF com.



Provide information/transfer knowledge through education

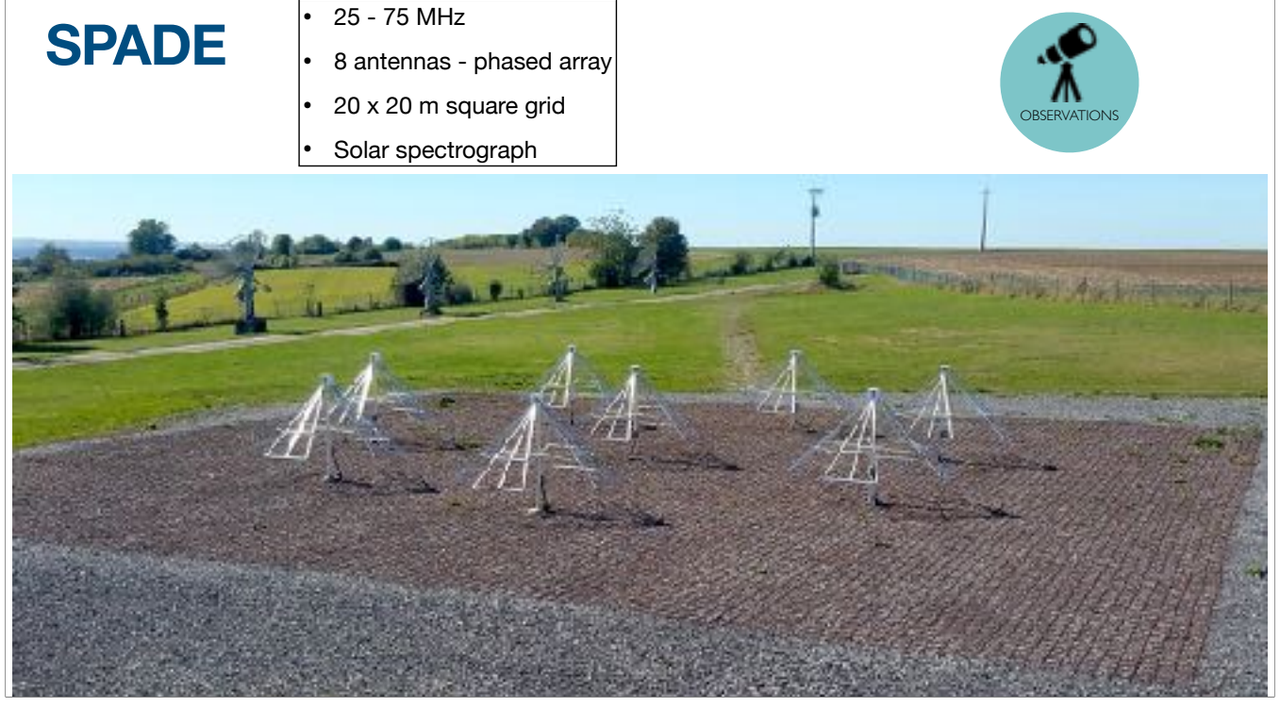
The Space Weather Education Center of the STCE offers **certified Space Weather courses**, **tailored to the needs and level of the participants**.



Antonio - Engineer- expert

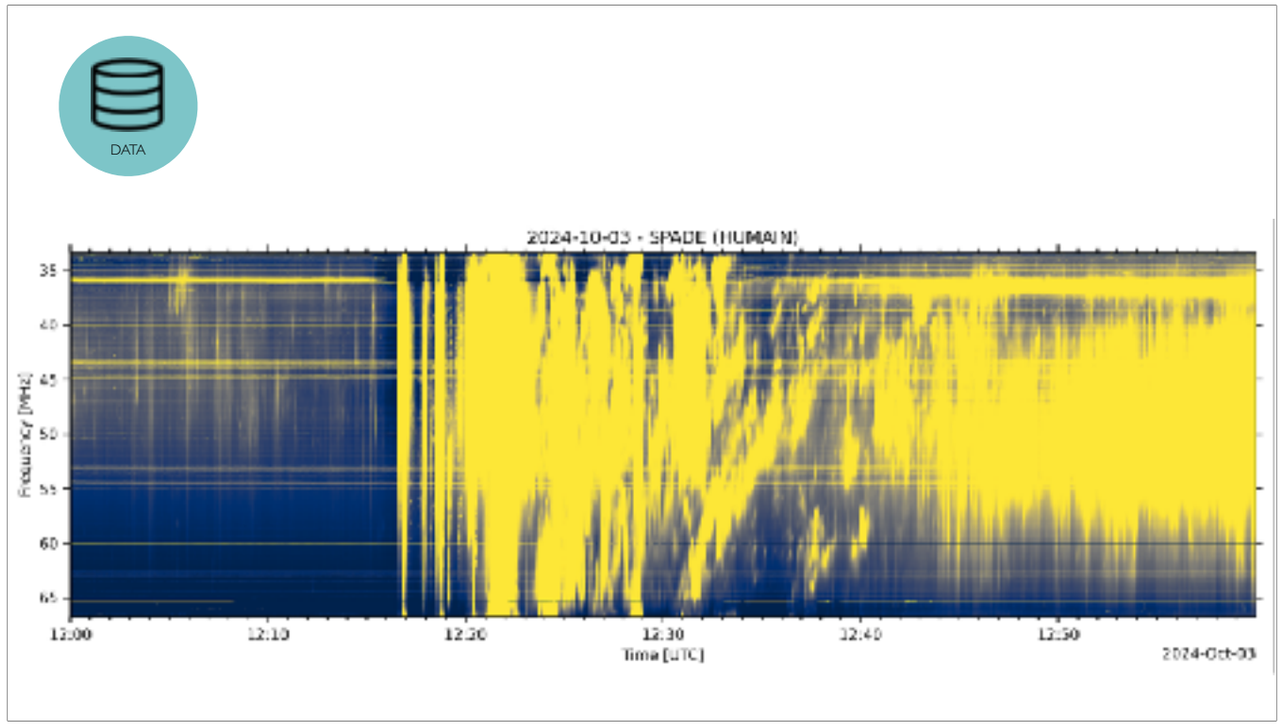
SPADE

- 25 - 75 MHz
- 8 antennas - phased array
- 20 x 20 m square grid
- Solar spectrograph



Solar Radio Station in Humain

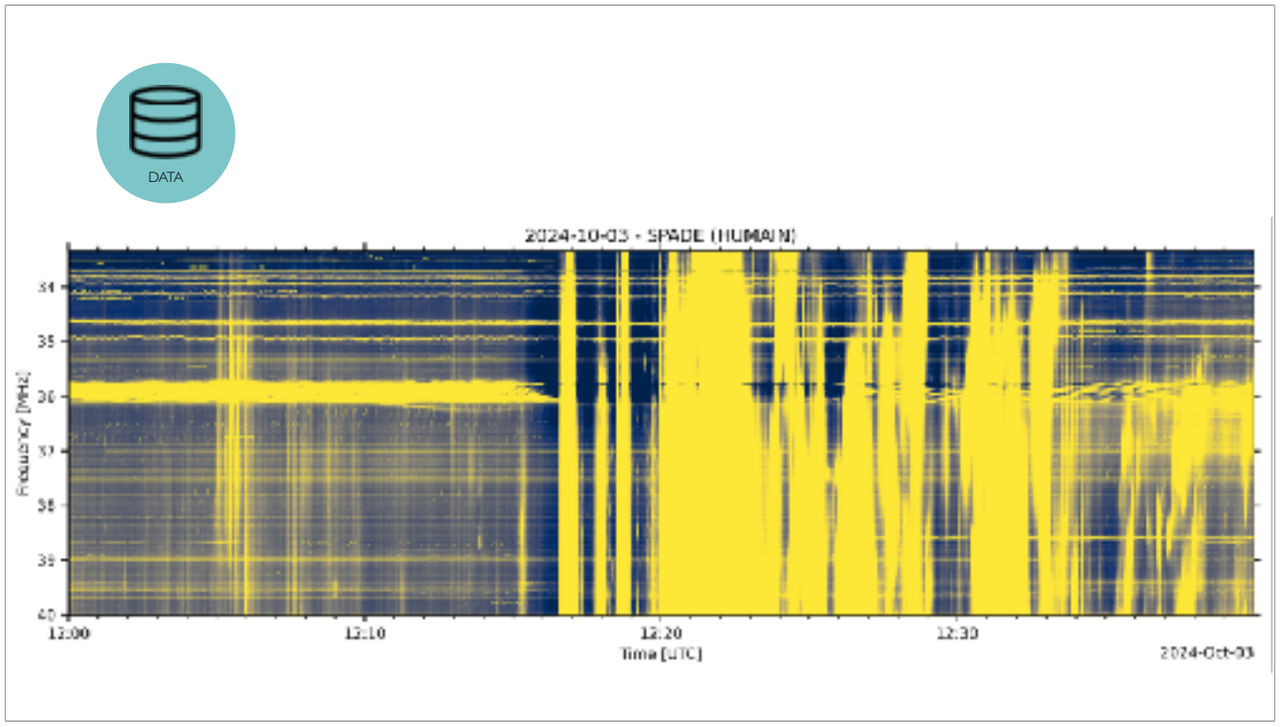
Receivers
Christophe Marqué and Antonio Martinez



X9.9 flare - 12:08 - 12:18 - 12:27
SRB
type III (three lines)
Type II
type IV (at the right)

Horizontal lines: selfmade interference at 40, 50, 60 MHz

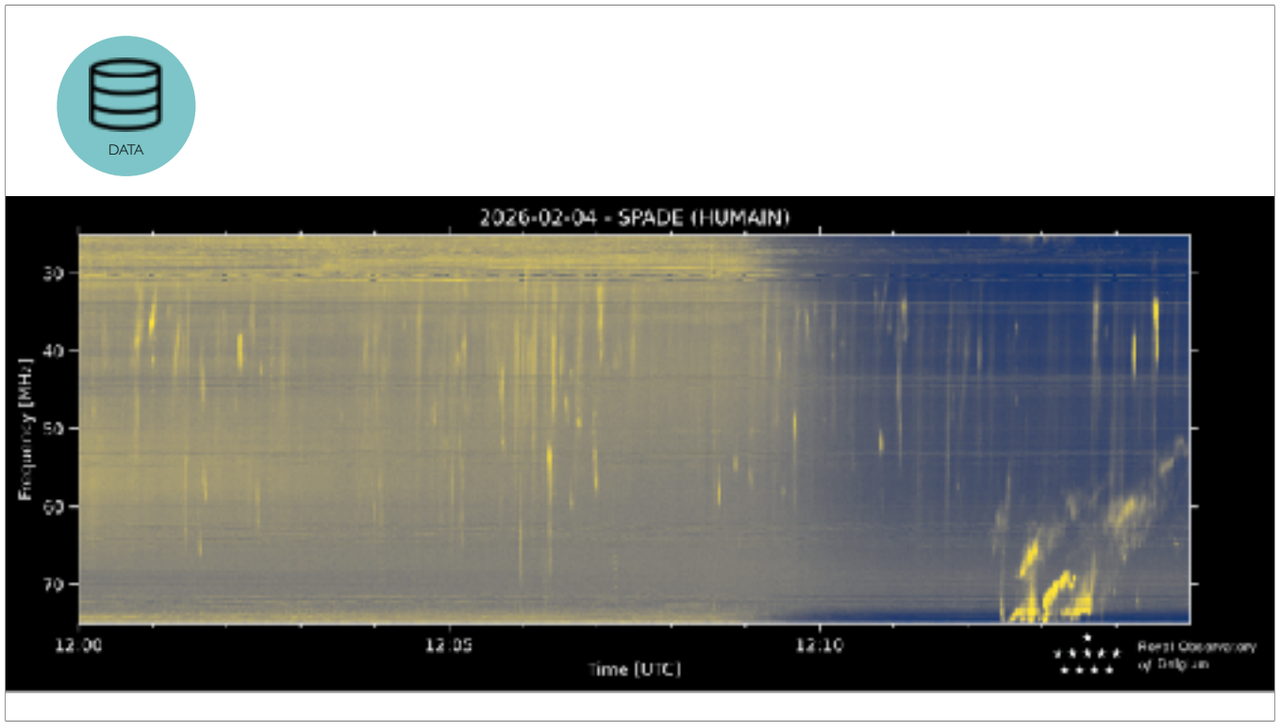
Riometer (looks at zenith): same principle as the solar radio telescope (looks at the sun) of Antonio/Christophe



Zoom
Due to X-rays
36 MHz - terrestrial beacon - is being absorbed —> background is little bit darker
36 MHz line stops when it is being absorbed.

SRB adds noise - is so strong that it is not absorbed.

During the night we don’t measure:
—> not possible
—> This is not a problem, because there is no absorption



the yellowish background is the normal background noise which turns blueish at the time of the flare around 12:10. The bright yellow patches are solar radio bursts (before and during the flare time), including a small type II burst at 12:13 UT from 75 down to ~ 50 MHz



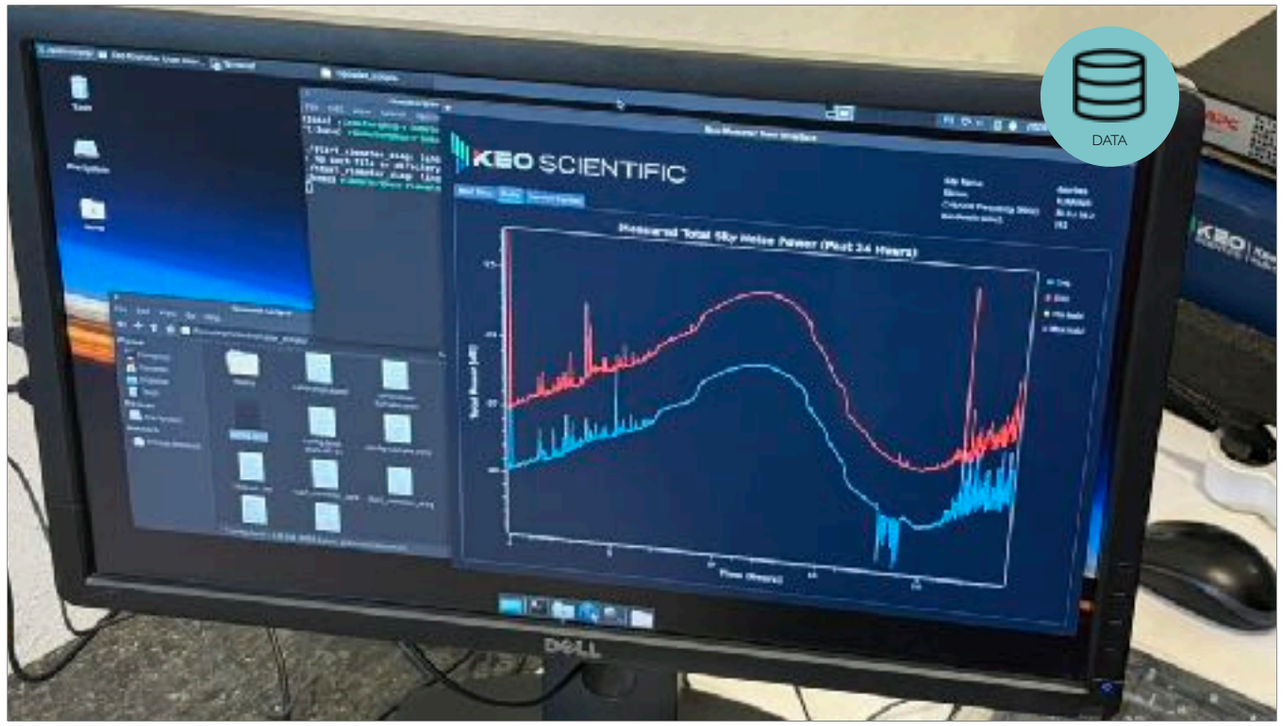
Tobias Expert in Ionosphere



Photo taken during an excursion

riometer receiver - passive instrument which measures the galatic radio noise

Riometer looks at zenith: same principle as the solar radio telescope of Antonio/Christophe that look at the sun



M-flare that morning

30 MHz
38,2 MHz

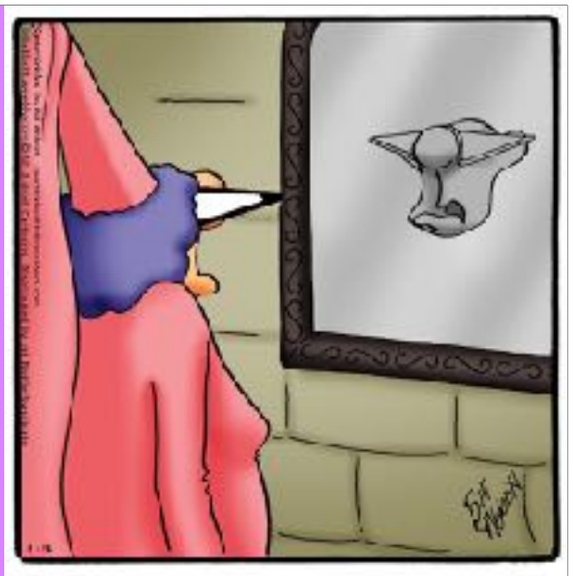
The dip in the curve is due to absorption of the signal



Impact: decrease of MUF

Post storm depression

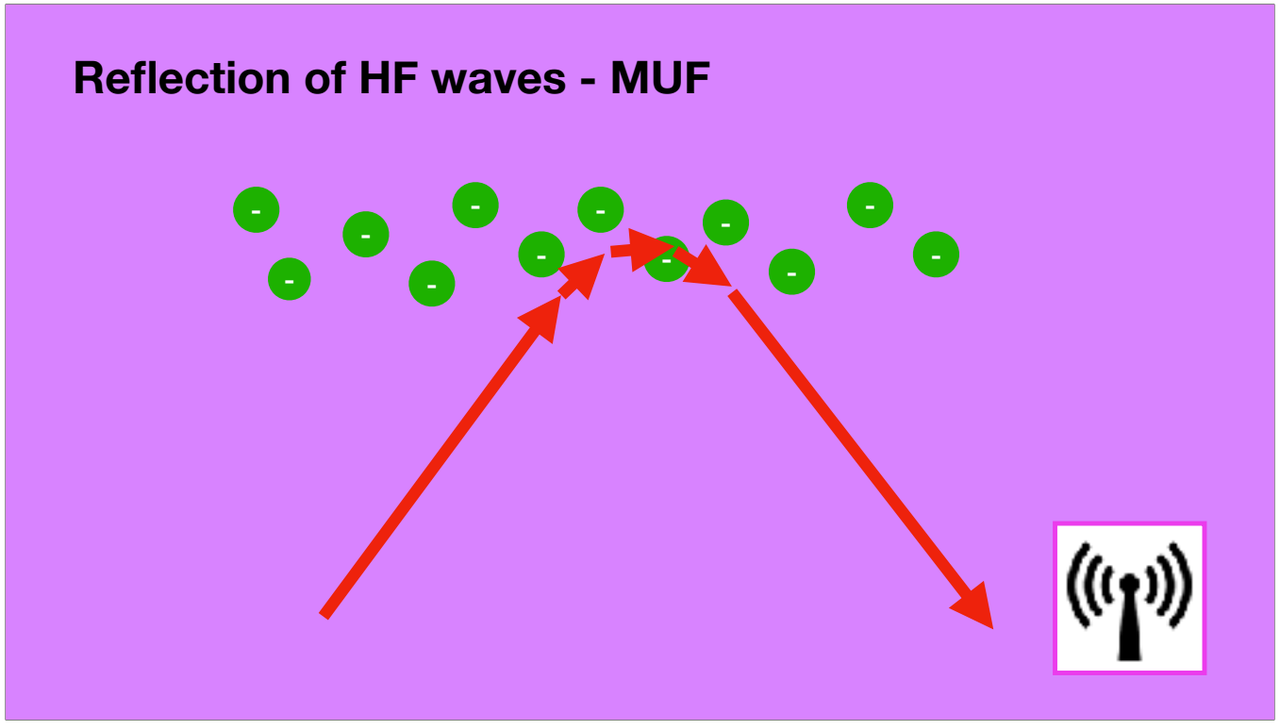




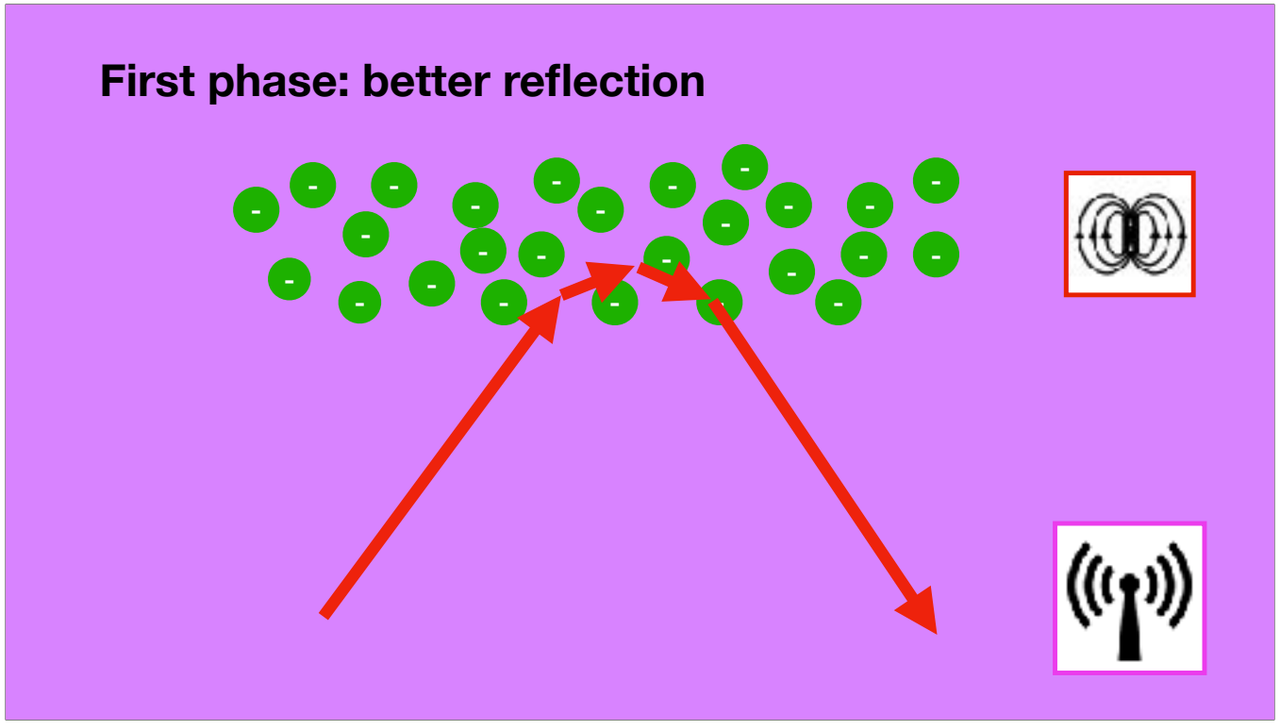
"Before I answer that, may I remind you that it's seven years of bad luck to break a mirror?"

Post storm depression

What is the MUF?



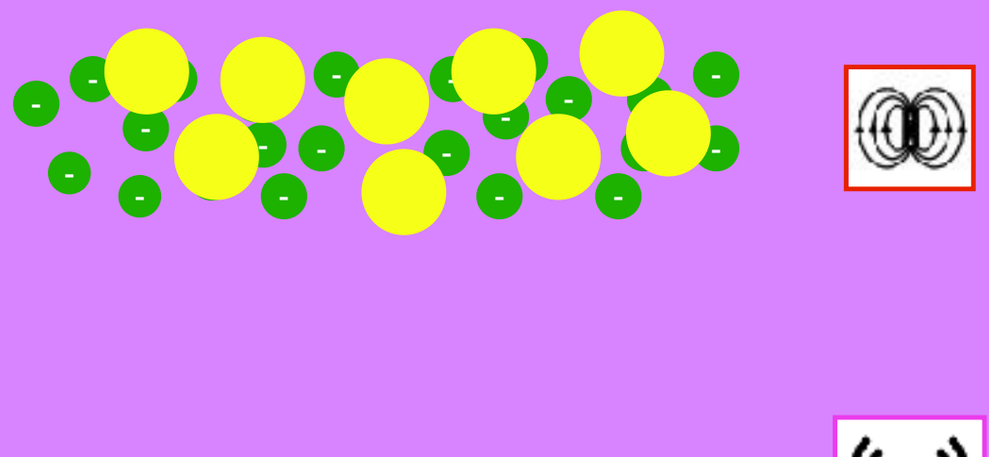
The ionosphere can reflect waves
When the ionosphere is not ionised, which waves are being reflected?
As soon as the ionisation increases, waves under the MUF are being reflected.
The higher the ionisation, the higher the MUF.



Increase of electrons - positive phase of the storm - VTEC increases
Better HF communication because more waves are being reflected.
Also waves with a higher freq are being reflected. MUF increases

1 Energy injected into the ionosphere, mainly at high latitude.
2 As a result, the air in the auroral oval expands in height and width (to equator)
3 The plasma moves together with the expanding air.
4 Drift along the magnetic field lines cause the plasma to move up, which can increase electron density (“positive storm phase”).
5 Finally, upwelling of N2 causes increased recombination, leading to a depletion of ionisation (“negative storm phase”).

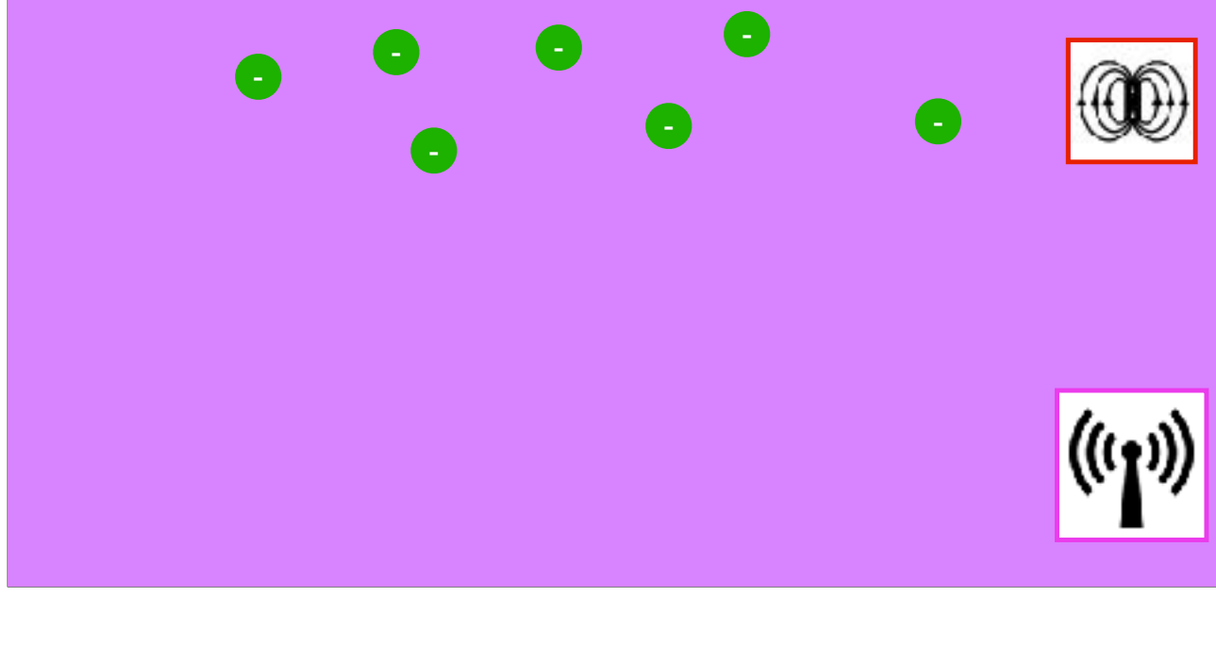
Second phase: Slower neutrals arrive



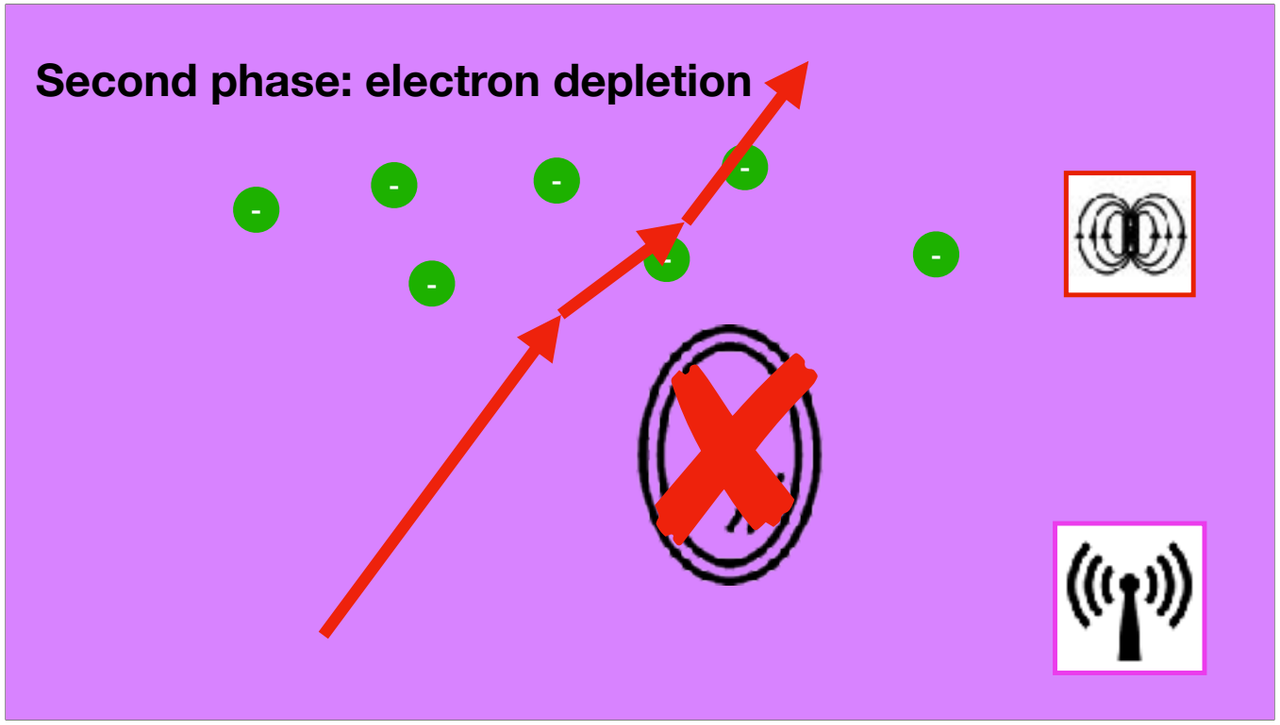


1 Energy injected into the ionosphere, mainly at high latitude.
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Second phase: electron depletion

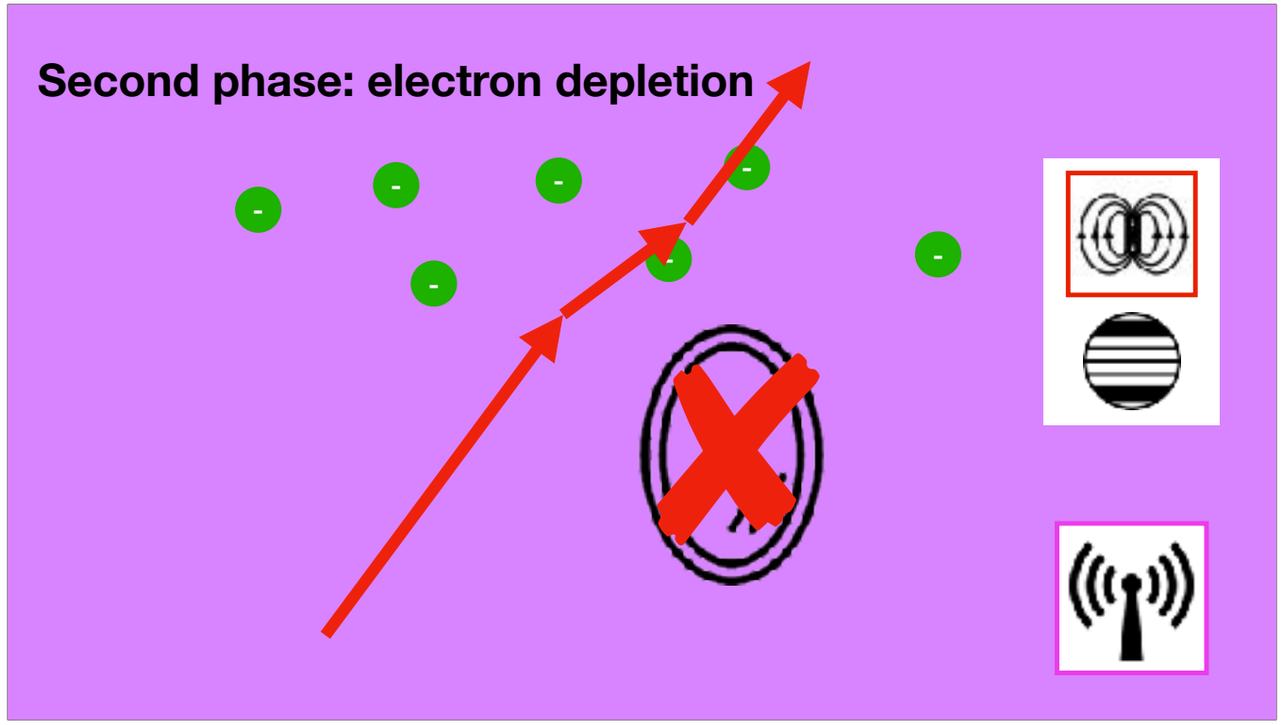


Neutrals are being transported to the F2 layer.
—> second, negative phase of the storm - electron are being eaten by neutrals.
Electron depletion



Impacts higher HF COM range

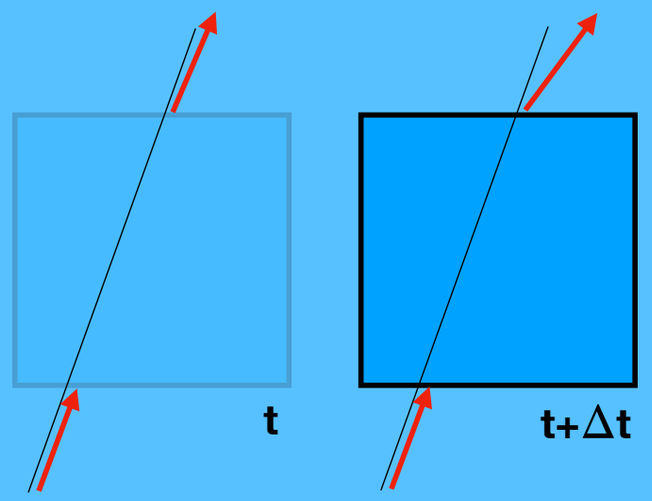
Less electrons, the MUF decreases
Less frequencies available for HF com because Higher freq radio waves pass through
No reflection possible



—> mid-latitude because of the expansion of the air towards these regions



Impact: Delay



At still higher frequencies, the radio waves do not longer deviate much from a straight line, just a little bit. However, there is still a delay, which depends on (again) the electron density and the frequency.

The examples are all shown with signals going upward, but the explanations also hold for downward signals.

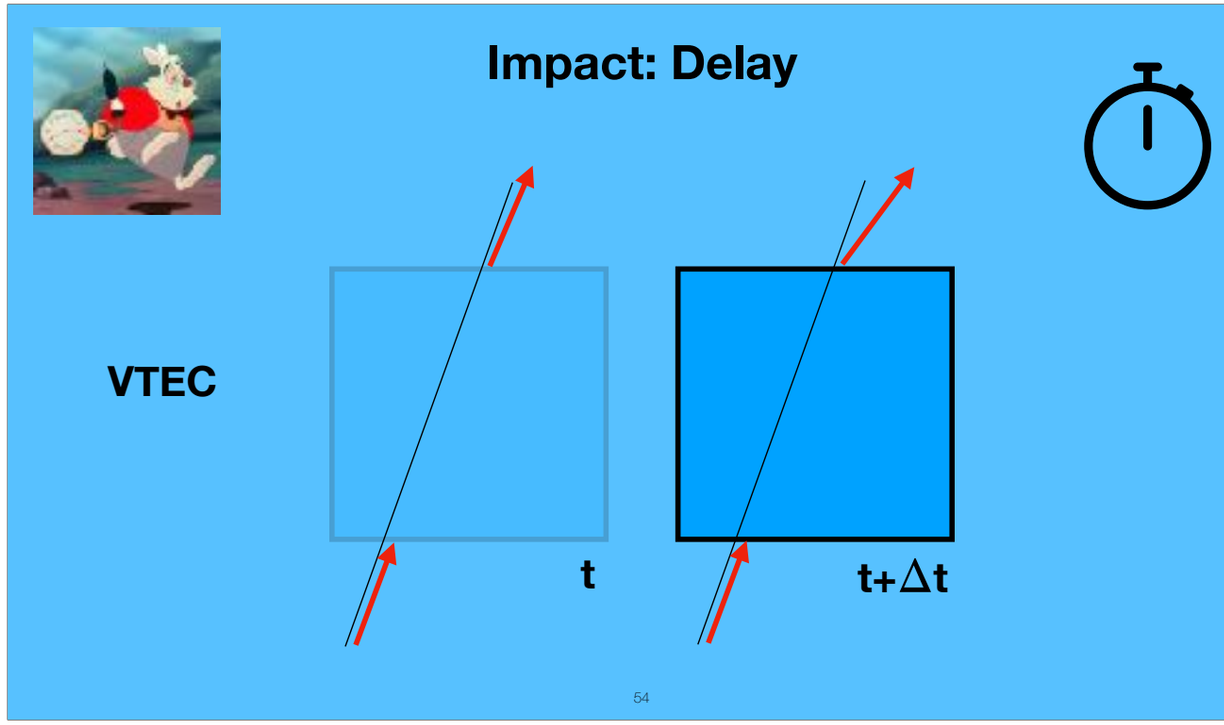
delay due to higher density or lower frequency

http://www.trimbleionoinfo.com/Library/IonosphericEffects.htm
Ionospheric Signal Delay
An important descriptive quantity in describing the effect of the ionosphere on the GNSS signal is the total electron content (or TEC). TEC is the total number of electrons present along a path between the satellite and the receiver on earth, with units of electrons per square meter, where 1016 electrons/m^2 = 1 TEC unit (TECU).

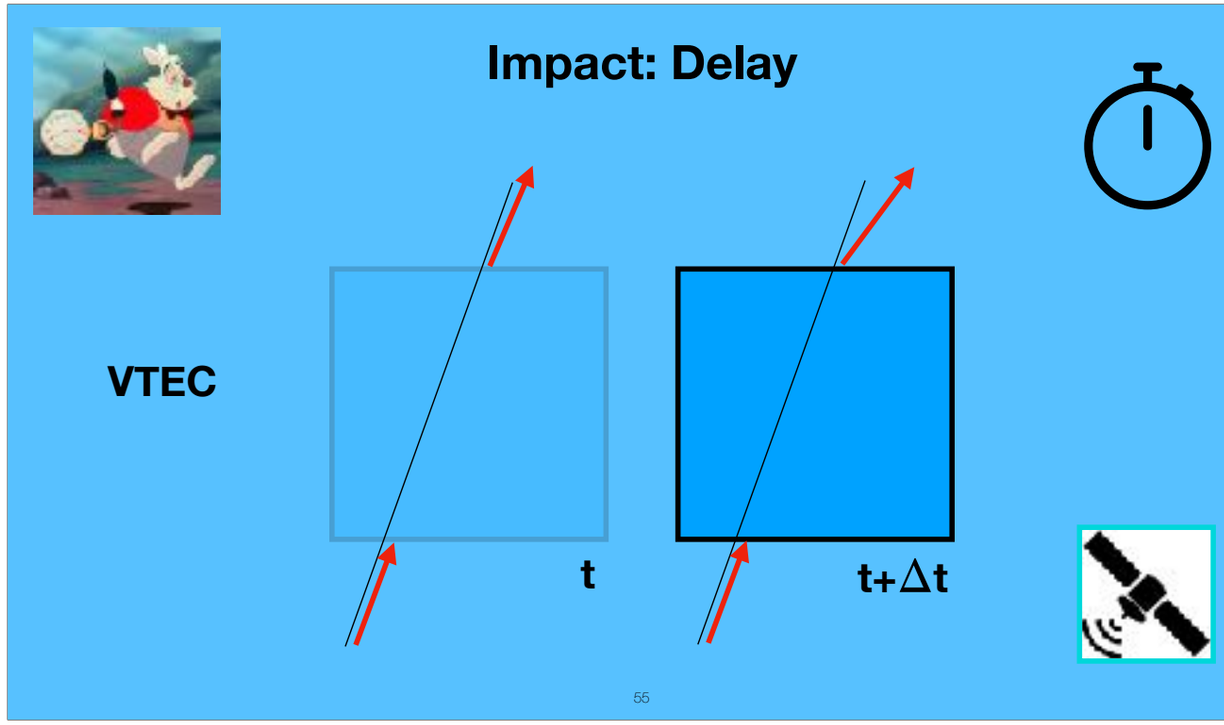
https://www.swpc.noaa.gov/impacts/space-weather-and-gps-systems
Geomagnetic storms create large disturbances in the ionosphere. The currents and energy introduced by a geomagnetic storm enhance the ionosphere and increase the total height-integrated number of ionospheric electrons, or the Total Electron Count (TEC). GPS systems cannot correctly model this dynamic enhancement and errors are introduced into the position calculations. This usually occurs at high latitudes, though major storms can produce large TEC enhancements at mid-latitudes as well.
— —
https://www.swpc.noaa.gov/phenomena/total-electron-content

The TEC in the ionosphere is modified by changing solar Extreme Ultra-Violet radiation, geomagnetic storms, and the atmospheric waves that propagate up from the lower atmosphere. The TEC will therefore depend on local time, latitude, longitude, season, geomagnetic conditions, solar cycle and activity, and troposphere conditions. The propagation of radio waves is affected by the ionosphere. The velocity of radio waves changes when the signal passes through the electrons in the ionosphere. The total delay suffered by a radio wave propagating through the ionosphere depends both on the frequency of the radio wave and the TEC between the transmitter and the receiver. At some frequencies the radio waves pass through the ionosphere. At other frequencies, the waves are reflected by the ionosphere.

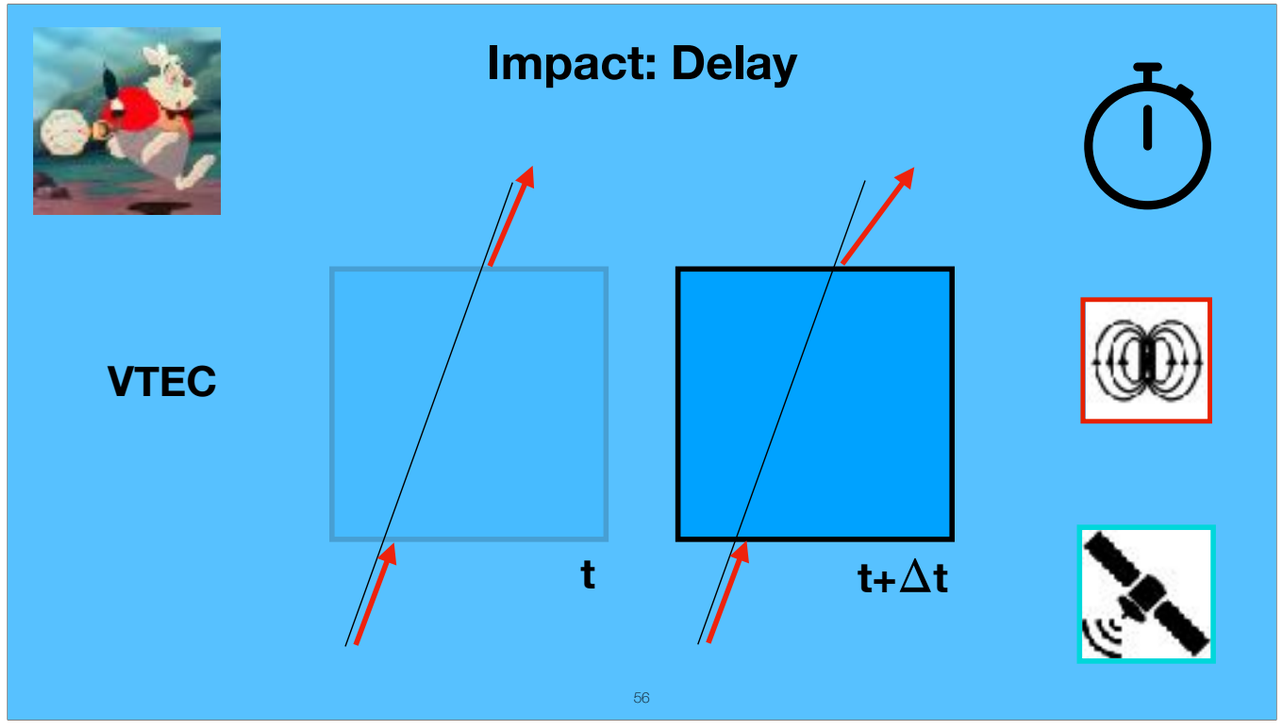
The change in the path and velocity of radio waves in the ionosphere has a big impact on the accuracy of satellite navigation systems such as GPS/GNSS. Neglecting changes in the ionosphere TEC can introduce tens of meters of error in the position calculations. The Global Positioning System (GPS), the US part of GNSS, uses an empirical model of the ionosphere, the Klobuchar model, to calculate and remove part of the positioning error caused by the ionosphere when single frequency GPS receivers are used. When conditions deviate from those predicted by the Klobuchar model, GPS/GNSS systems will have larger positioning errors.



VTEC = electron density



Important for GNSS, not for HF, where a delay in your signal is not important.



Even if a dense ionosphere is everywhere equally dense, it still causes major problems.

- The Satellites are at Different Angles (Elevation): Even if the atmosphere is perfectly uniform, a satellite directly above you (zenith) shoots its signal straight down through a thin layer of the ionosphere. A satellite low on the horizon shoots its signal diagonally through a much thicker slice of the ionosphere. This means the actual delay (Slant TEC) is never equal for all satellites, even if the vertical atmosphere (VTEC) is perfectly uniform.



Impact

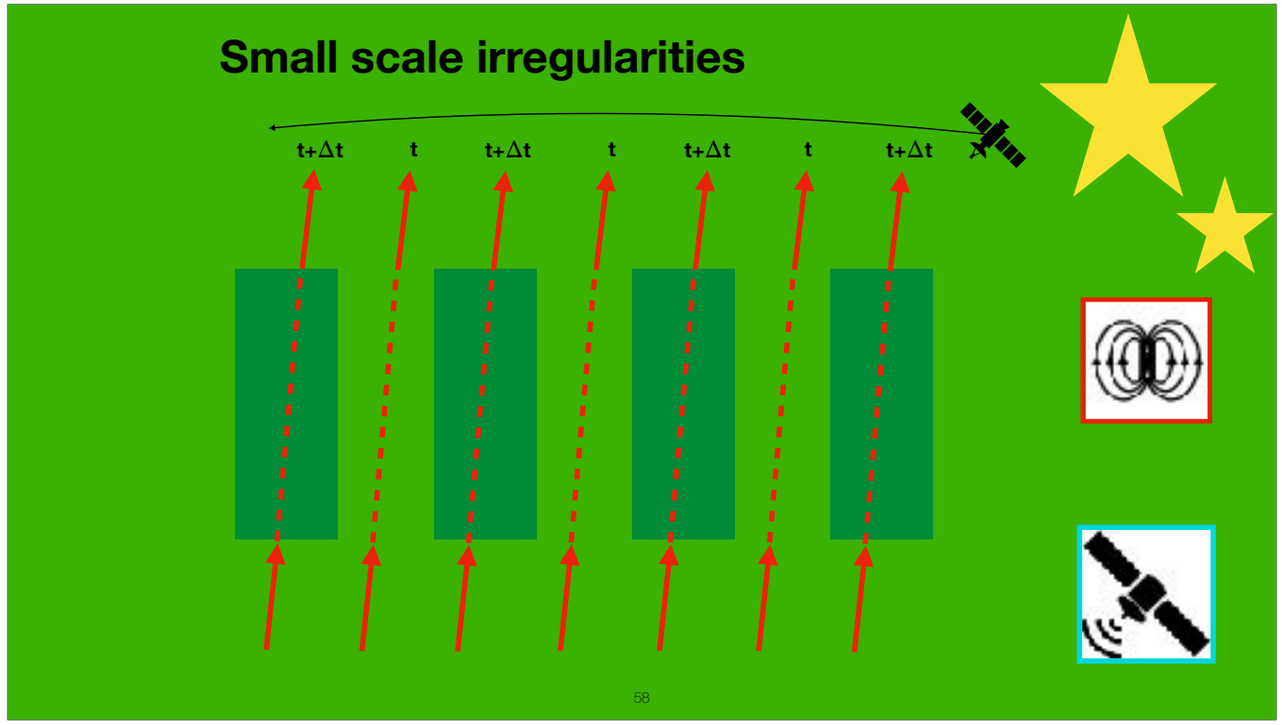
Scintillation







Wave Phase or wave amplitude changes rapidly

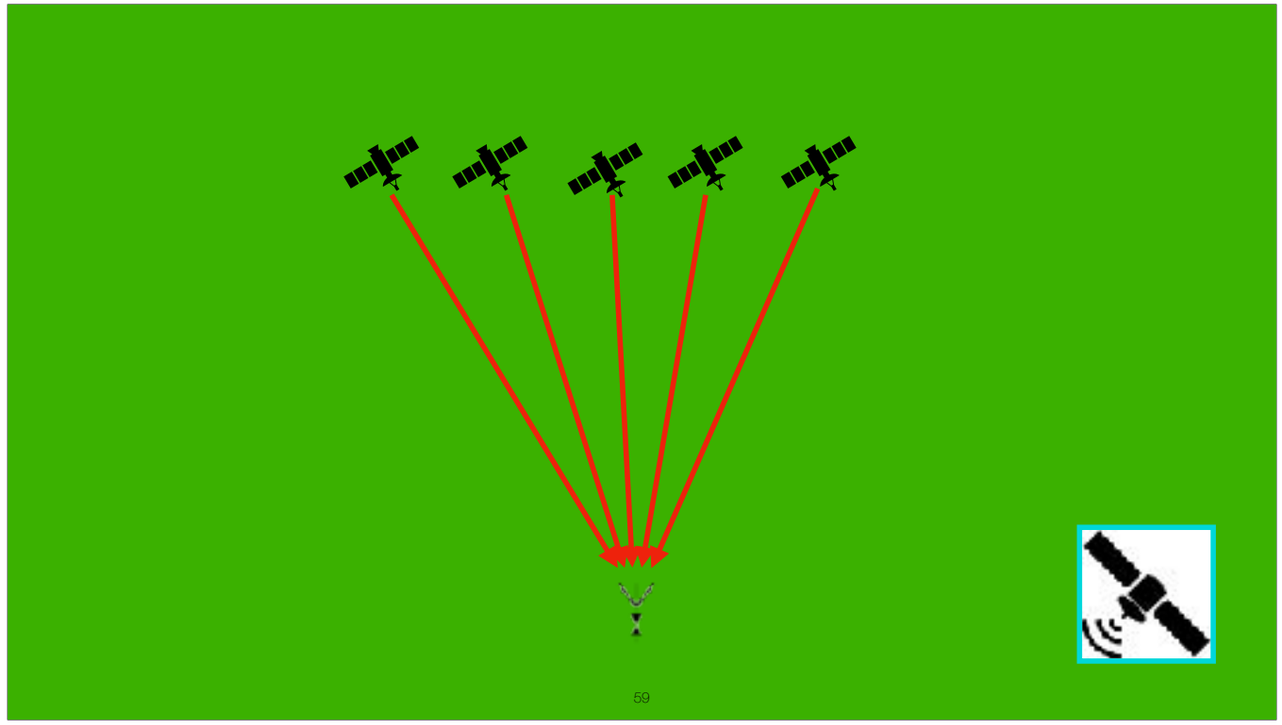


At still higher frequencies, the radio waves do not longer deviate much from a straight line, just a little bit. However, there is still a delay, which depends on (again) the electron density and the frequency.

At high frequencies, were there is only a little refraction, the delay imposed on radio waves may still be important. When – either due to the movement of the satellite or due to traveling ionospheric disturbances - the radio signals travel through dense and underdens sections of the ionosphere, **a variation in path delay will occur**. As a result, a satellite moving about or through an inhomogeneous ionosphere will receive the **signal, but with rapid variations** superimposed on it.
Path delay —> phase scintillation
Absorption —> amplitude scintillation

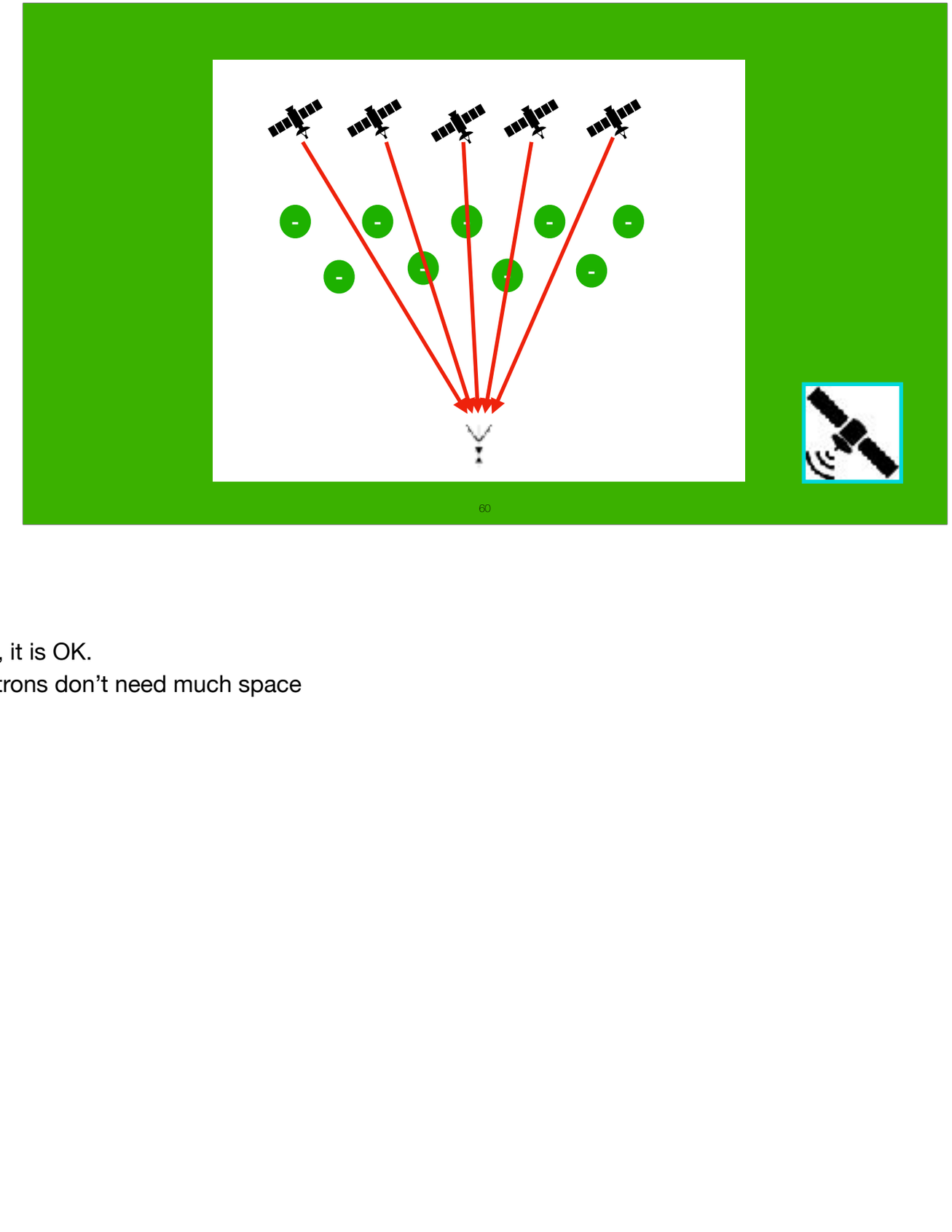
Depending on the severity of these variations, the receiver may loss signal lock.

The examples are all shown with signals going upward, but the explanations also hold for downward signals. The upward case is easier to draw and explain without resorting to more complex animations.

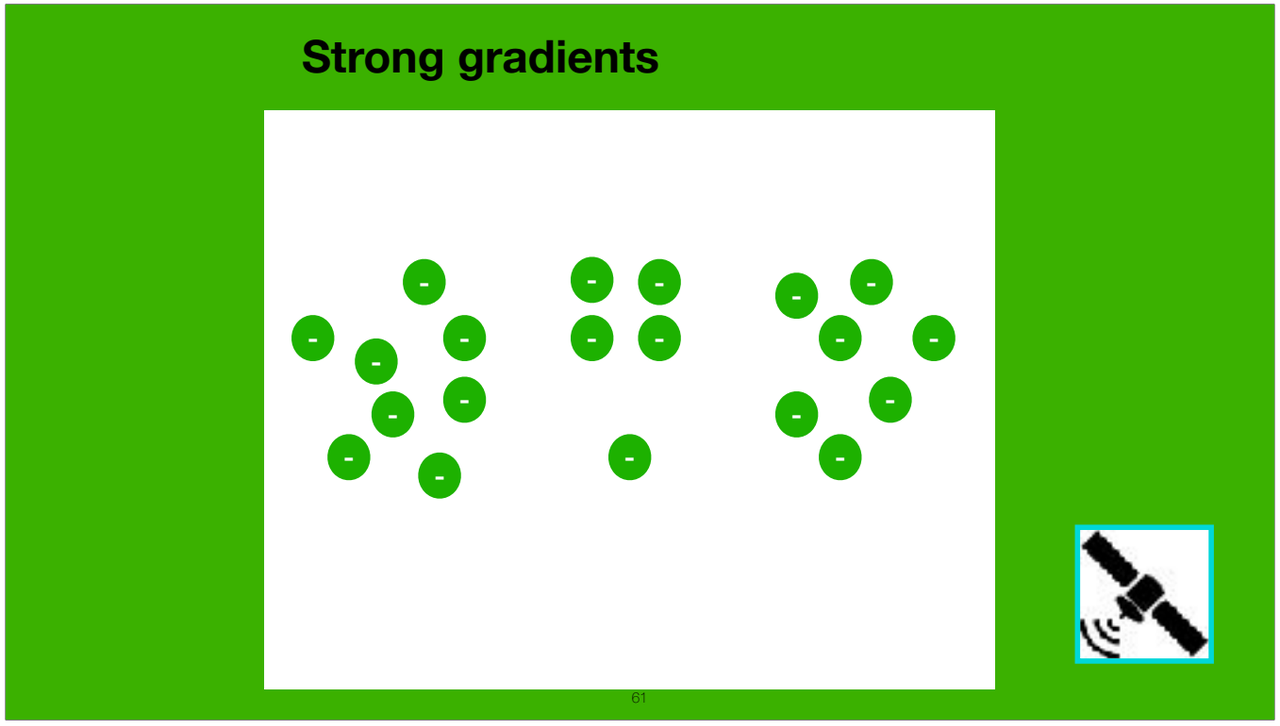


no ionosphere - or an ionosphere that behaves as expected

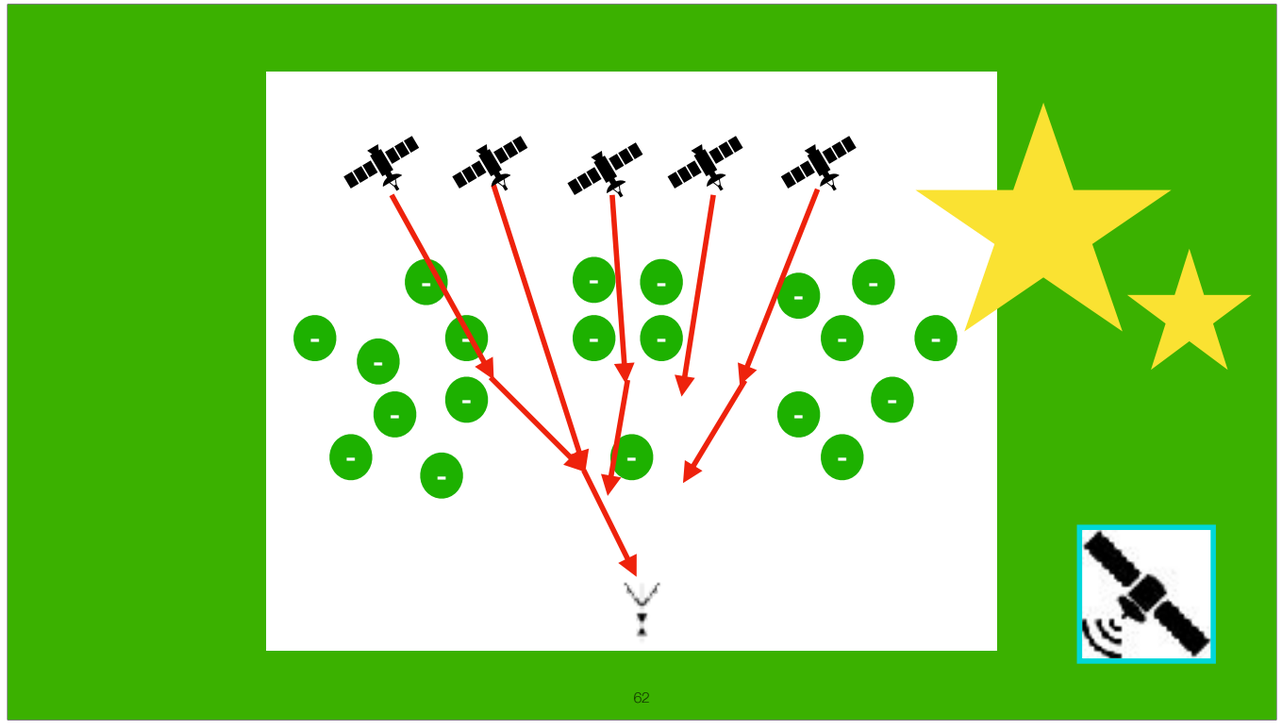
No refraction
No diffraction: bend around an obstacle or pass through an opening
The waves nicely reach the receiver without meeting another wave.



Even with an ionosphere that behaves, it is OK.
Their wavelength is small, so, the electrons don’t need much space



Strong gradients
Due to space weather, small scale irregularities exist in the ionosphere.
Landscape of electrons - dense regions and less dense regions
Localised



Due to space weather, small scale irregularities exist in the ionosphere.
Landscape of electrons - dense regions and less dense regions
Localised
REFRACTION
When a wave enters another medium, its speed is different. The wave is redirected as it passes from one medium to another —> delay
DIFFRACTION
A wave bends around the corner of an obstacle.
—> refracted and diffracted waves interfere —> As a result, the receiver sees a twinkling signal, i.e. the signal with rapid variations superimposed on it.

Regions of scintillation:
- Polar caps — solar energetic particles
- Auroral oval - trapped particles from the plasma sheet
- Equatorial region - equatorial ionisation anomaly - plasma bubbles - Rayleigh Taylor instability

The result is the same, the cause of the density irregularity is different.

SCINTILLATION MECHANISMS



Post-sunset at the Equator

Auroral structures

Polar patches

Travelling ionospheric disturbances

Scintillation is caused by small-scale (tens of meters to tens of km) structures in the ionospheric electron density

Equatorial induced anomaly allows the plasma bubbels to rise
The four mechanisms that give rise to scintillation are

- Post-sunset Plasma bubbles - decreased ionisation - in the lower latitudes
- Auroral structures - increased ionisation - in the auroral oval
- Patches - increased ionisation - in the polar caps
- Travelling ionospheric disturbances

All three happen more or less depending on the circumstances, but plasma bubbles happen most of the days.

Precipitating particles
—> come towards Earth from the reconnection areas in the plasmasheet
—> follow the magnetic field form sheets
—> typical form of auroras.
—> small scale irregularities
—> induces scintillation
—> example auroral clutter: aurora acts as a echo

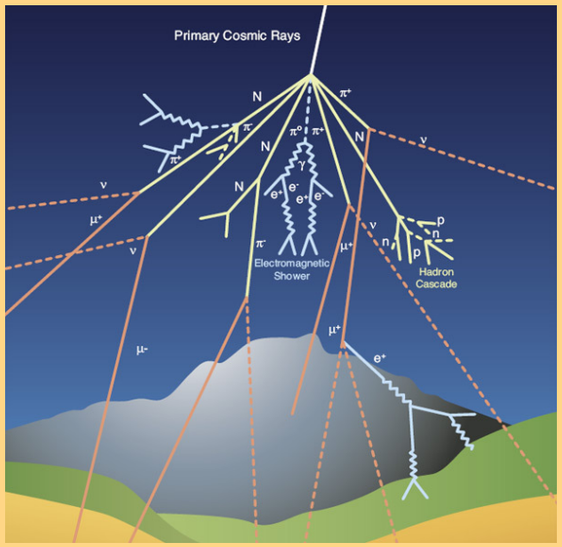
Radiation



Biological impact due to particle radiation

Solar X-rays and gamma-rays do not impact civil aviation - Why?

Radiation









Biological impact
Open magnetic field lines

Solar X-rays and gamma-rays are also ionising but do not impact civil aviation.

Why?

~~Impact: Solar Radio Burst~~



Solar radio bursts are produced by non thermal electrons accelerated during eruptive events of all magnitudes
For frequencies (f) below ~ 1 GHz, the dominant emission is called plasma emission, where energetic electrons trigger local plasma oscillations which are then converted into E. M. Radiations

Jamming

GNSS	Moderate	Severe	Time UTC	Values	Status	Alert	Max-3h values	Max-3h status
Amplitude Scintillation	0.5	0.8	2020-10-12 14:15	0.25	QUIET		0.35	QUIET
Phase Scintillation	0.4	0.7	2020-10-12 14:15	0.13	QUIET		0.14	QUIET
Vertical TEC	125	175	2020-10-12 14:15	61.92	QUIET		61.93	QUIET

RADIATION	Moderate	Severe	Time UTC	Flags	Status	Alert	Max-3h flags	Max-3h status
Effective Dose FL≤460	30	80	2020-10-12 14:20	0	QUIET		0	QUIET
Effective Dose FL > 460	1	80	2020-10-12 14:20	0	QUIET		0	QUIET

HF COM	Moderate	Severe	Time UTC	Values/Flags	Status	Alert	Max-3h values	Max-3h status
Auroral Absorption (AA)	6	9	2020-10-12 14:15	3.0	QUIET		3.0	QUIET
Polar Cap Absorption (PCA)	2	5	2020-10-12 14:20	0.00	QUIET		0.00	QUIET
Shortwave Fadeout (SWF)	x1.0	x10.0	2020-10-12 14:17	< M.5-flare	QUIET		< M.5-flare	QUIET
Post-Storm Depression (PSD)	30%	50%	2020-10-12 14:15	0	QUIET		0	QUIET

Ionosphere is needed for long distance HF communication which makes use of the reflective capability of the ionosphere. The ionosphere acts as a mirror.

AA, PCA, SWF are absorption events - low frequencies
PSD reduces the range of frequencies available - high frequencies are not available.

HF Com
If you have a strong radio burst in HF, your MUF might be full of solar noise and in practice not usable. But SRB are not taken into account by ICAO

Similar, Solar Radio Bursts can impact also GNSS by adding noise.

PECASUS DASHBOARD on 2023-04-23 20:36 UTC

GNSS	Moderate	Severe	Time UTC	Values	Status	Alert	Max-2h values	Max-2h status
Amplitude Scintillation	0.5	0.8	2023-04-23 20:35	1.68	SEVERE	🔔	1.68	SEVERE
Phase Scintillation	0.4	0.7	2023-04-23 20:35	0.30	QUIET	🔔	1.06	SEVERE
Vertical TEC	125	175	2023-04-23 20:35	131.84	QUIET	🔔	134.83	MODERATE

RADIATION	Moderate	Severe	Time UTC	Flags	Status	Alert	Max-2h flags	Max-2h status
Effective Dose (FL ≤ 460)	30	60	2023-04-23 20:35	0	QUIET	🔔	0	QUIET
Effective Dose (FL > 460)	7	60	2023-04-23 20:35	0	QUIET	🔔	0	QUIET

HF COM	Moderate	Severe	Time UTC	Values/Flags	Status	Alert	Max-2h values	Max-2h status
Auroral Absorption (AA)	0	3	2023-04-23 20:30	0.6	MODERATE	🔔	0.9	MODERATE
Polar Cap Absorption (PCA)	2	5	2023-04-23 20:35	1.97	QUIET	🔔	4.64	MODERATE
Shortwave Fadeout (SWF)	x1.0	x10.0	2023-04-23 20:35	< M5 flare	QUIET	🔔	< M5 flare	QUIET
Post-Storm Depression (PSD)	30%	50%	2023-04-23 20:30	2	SEVERE	🔔	2	SEVERE

Sound alarm is triggered when MOD or SEV thresholds are exceeded or in case of data outages.