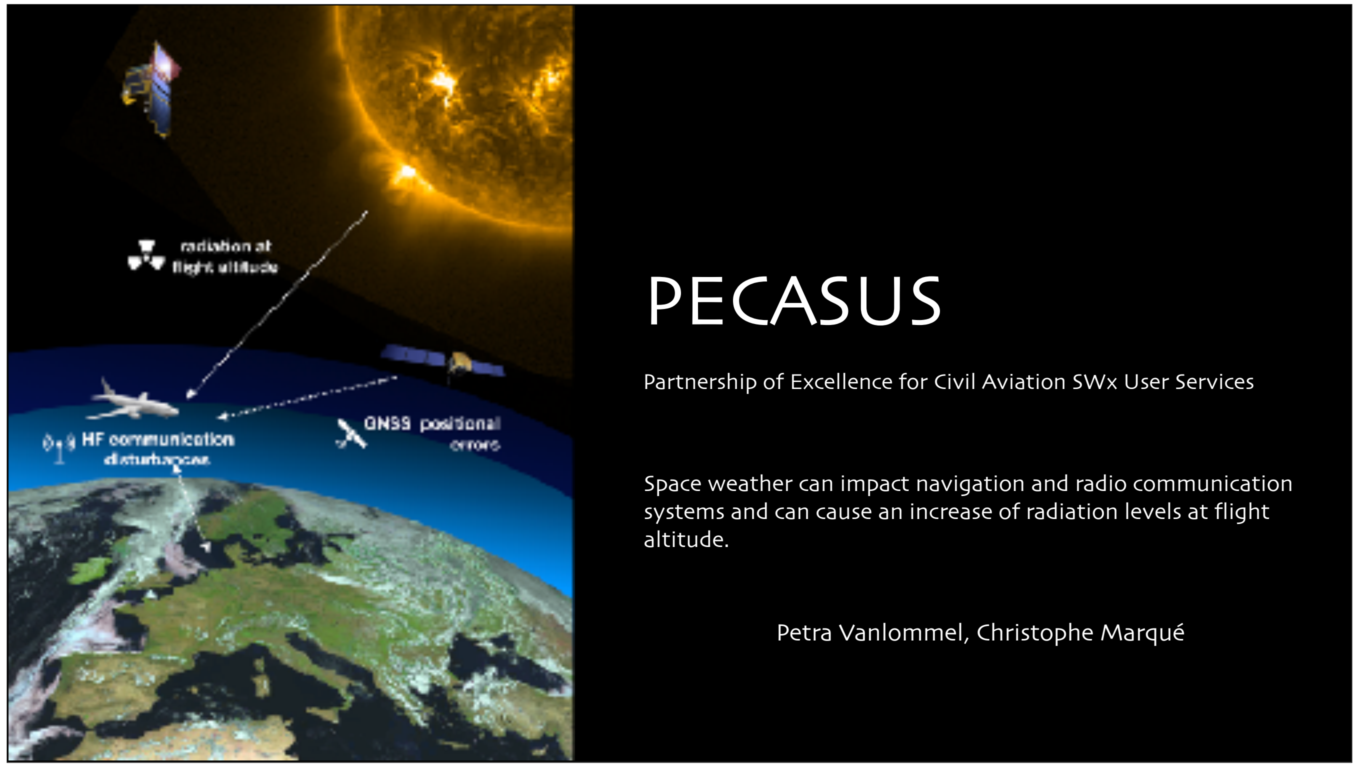

International Civil Aviation Organization
Since Nov 2019

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
<u>ICAO-compliant advisories (specified thresholds)</u>
2-week rotation scheme with SWPC, ACFJ, CR
(on duty - primary backup - secondary backup - maintenance)
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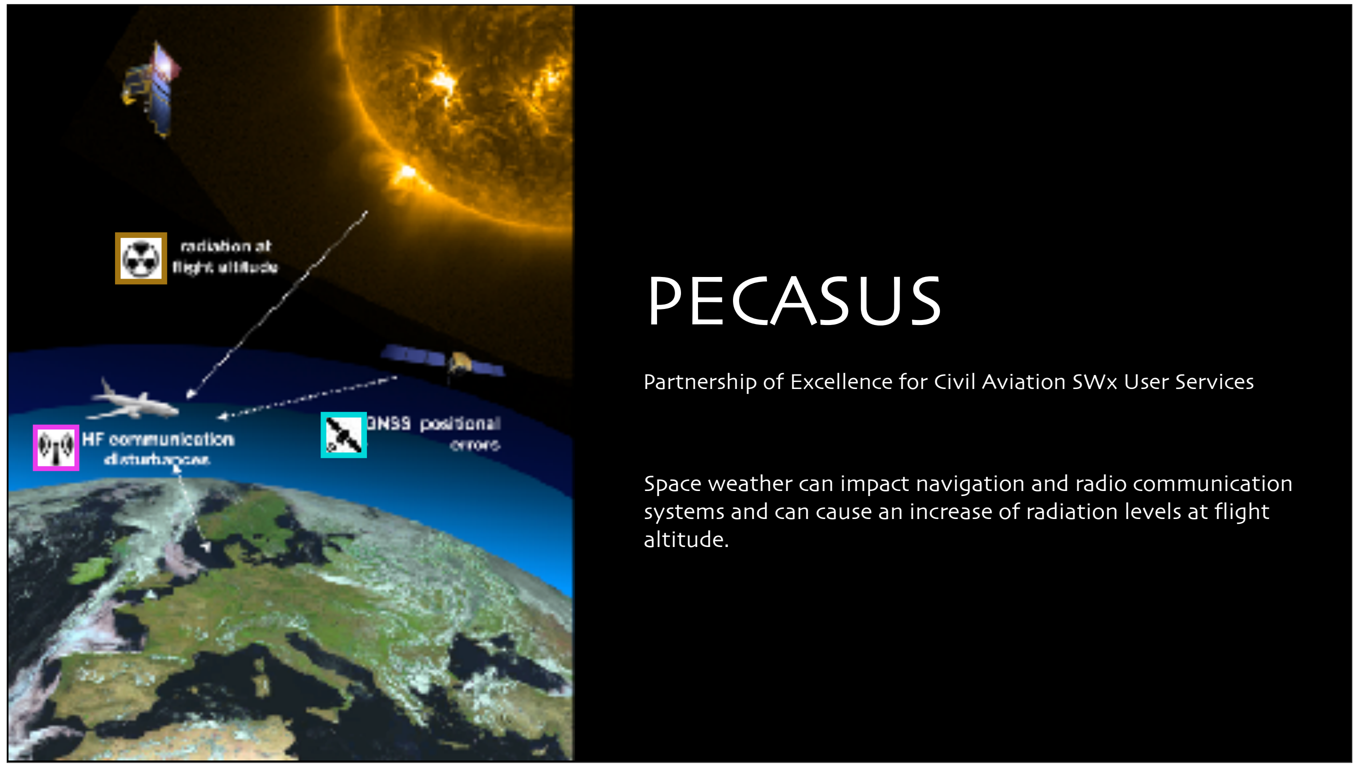

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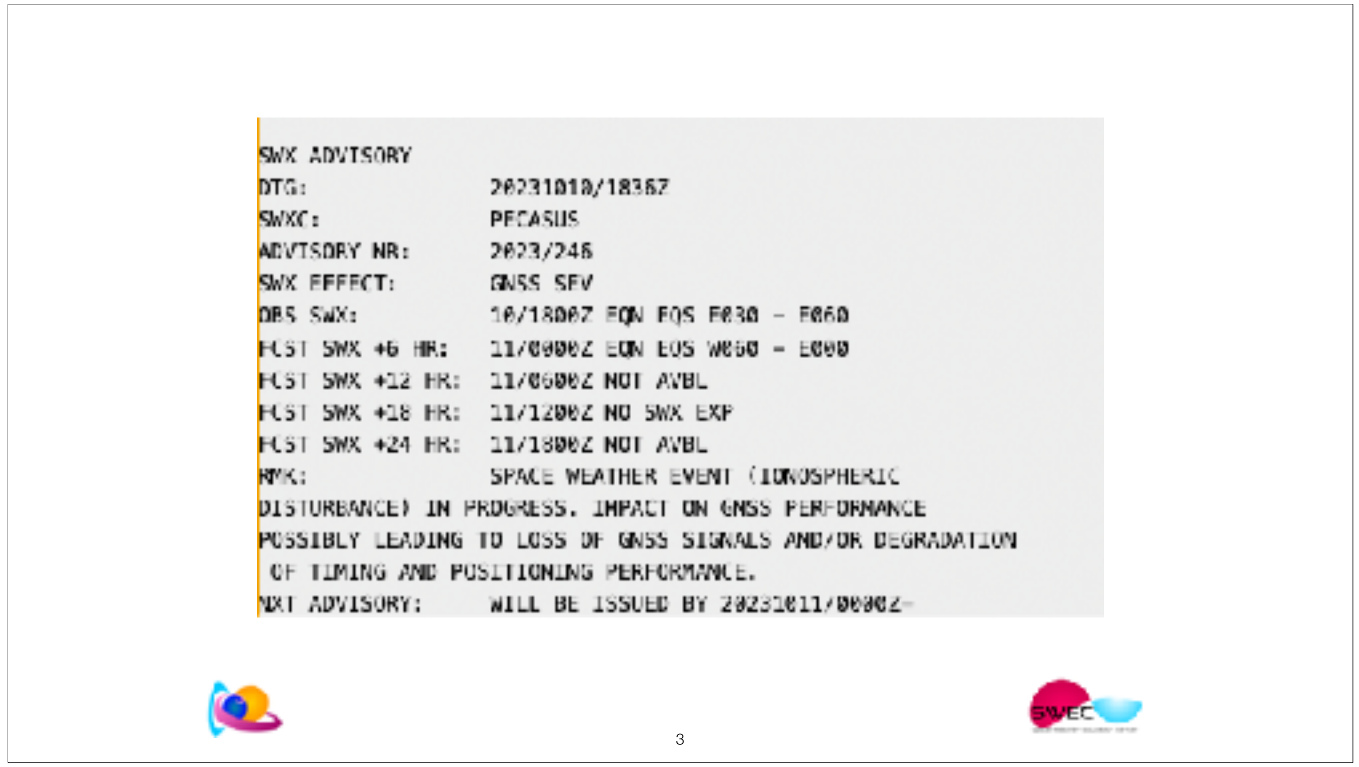
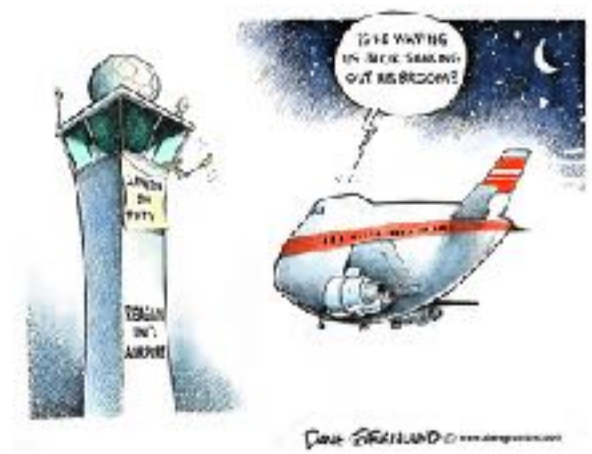
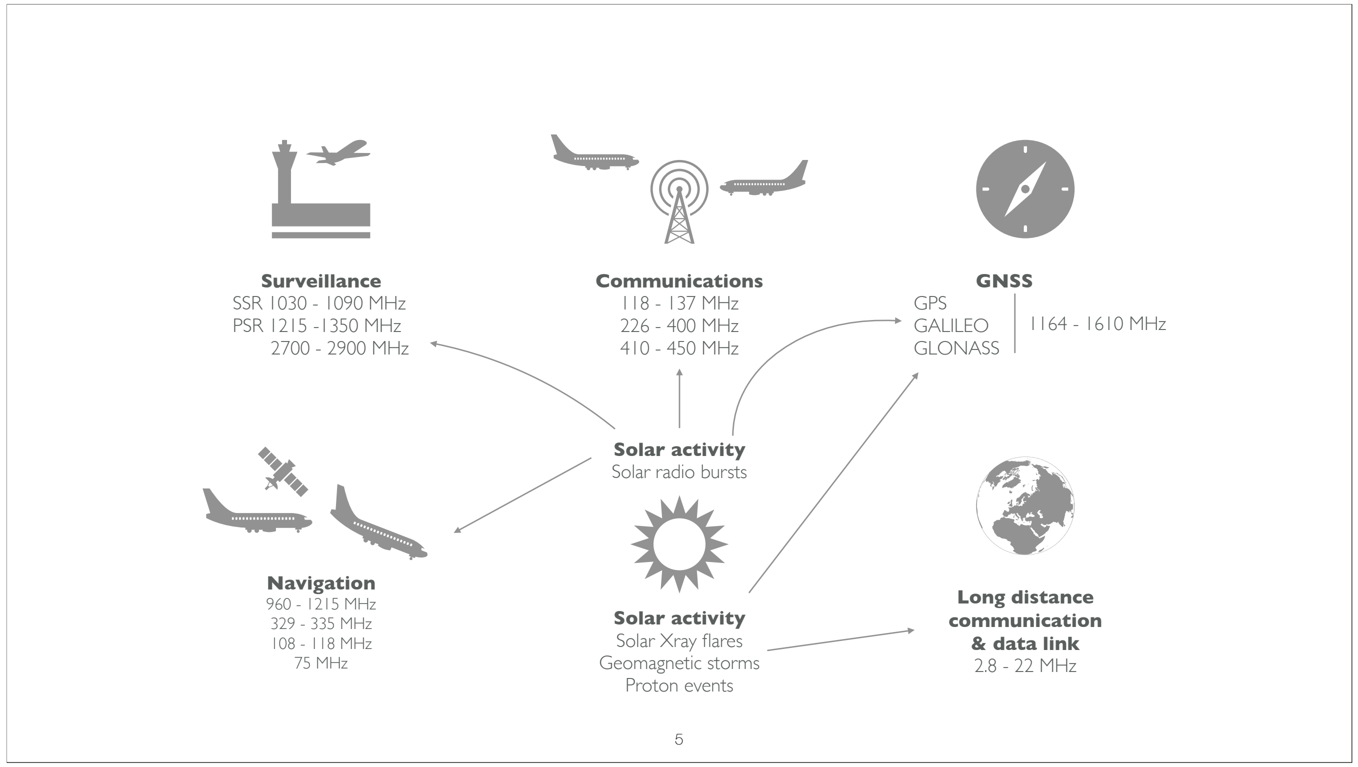


```
SWX ADVISORY
DTG:                20231010/1836Z
SWXC:               PECASUS
ADVISORY NR:        2023/246
SWX EFFECT:         GNSS SEV
OBS SWX:            10/1800Z EQN EQS E030 - E060
FCST SWX +6 HR:     11/0000Z EQN EQS W060 - E000
FCST SWX +12 HR:    11/0600Z NOT AVBL
FCST SWX +18 HR:    11/1200Z NO SWX EXP
FCST SWX +24 HR:    11/1800Z NOT AVBL
RMK:                SPACE WEATHER EVENT (IONOSPHERIC
DISTURBANCE) IN PROGRESS. IMPACT ON GNSS PERFORMANCE
POSSIBLY LEADING TO LOSS OF GNSS SIGNALS AND/OR DEGRADATION
 OF TIMING AND POSITIONING PERFORMANCE.
NXT ADVISORY:       WILL BE ISSUED BY 20231011/0000Z=
```


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





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.

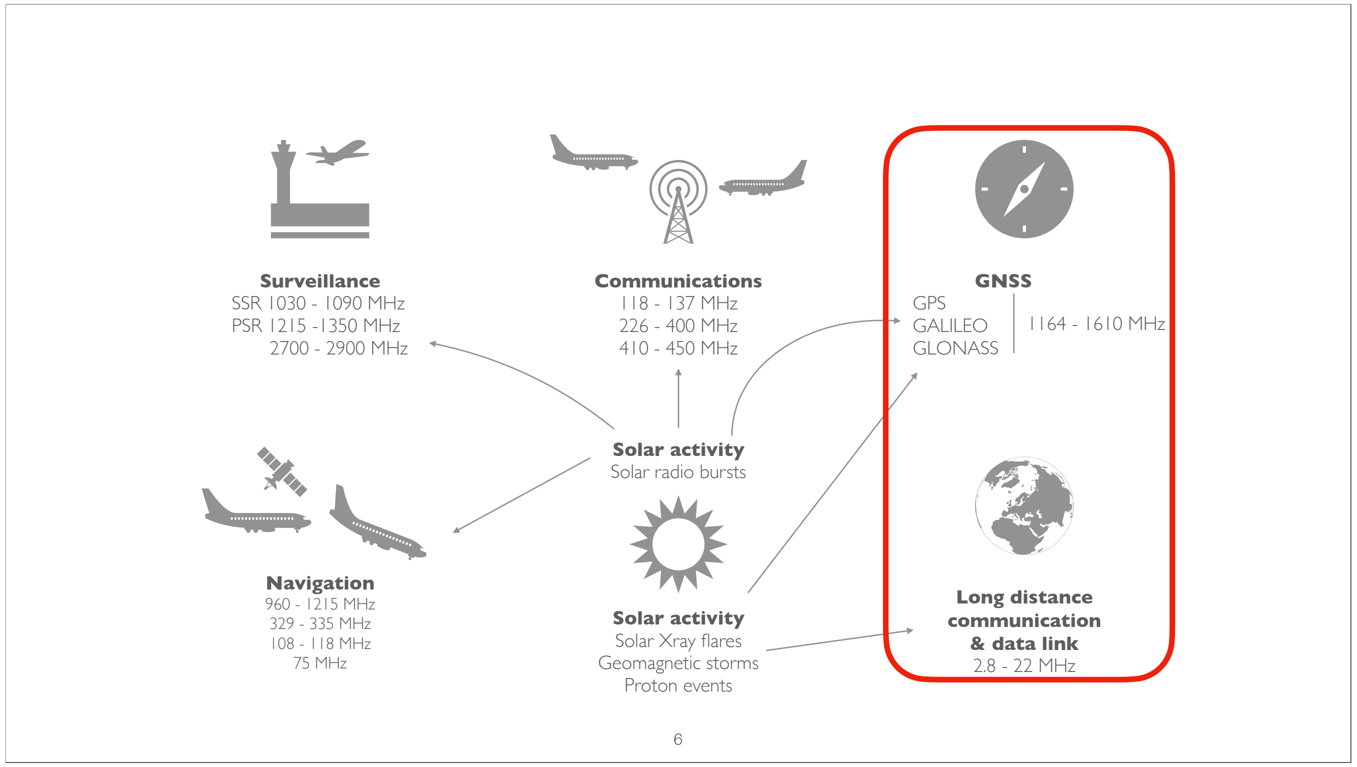
Non-cooperative systems[edit]

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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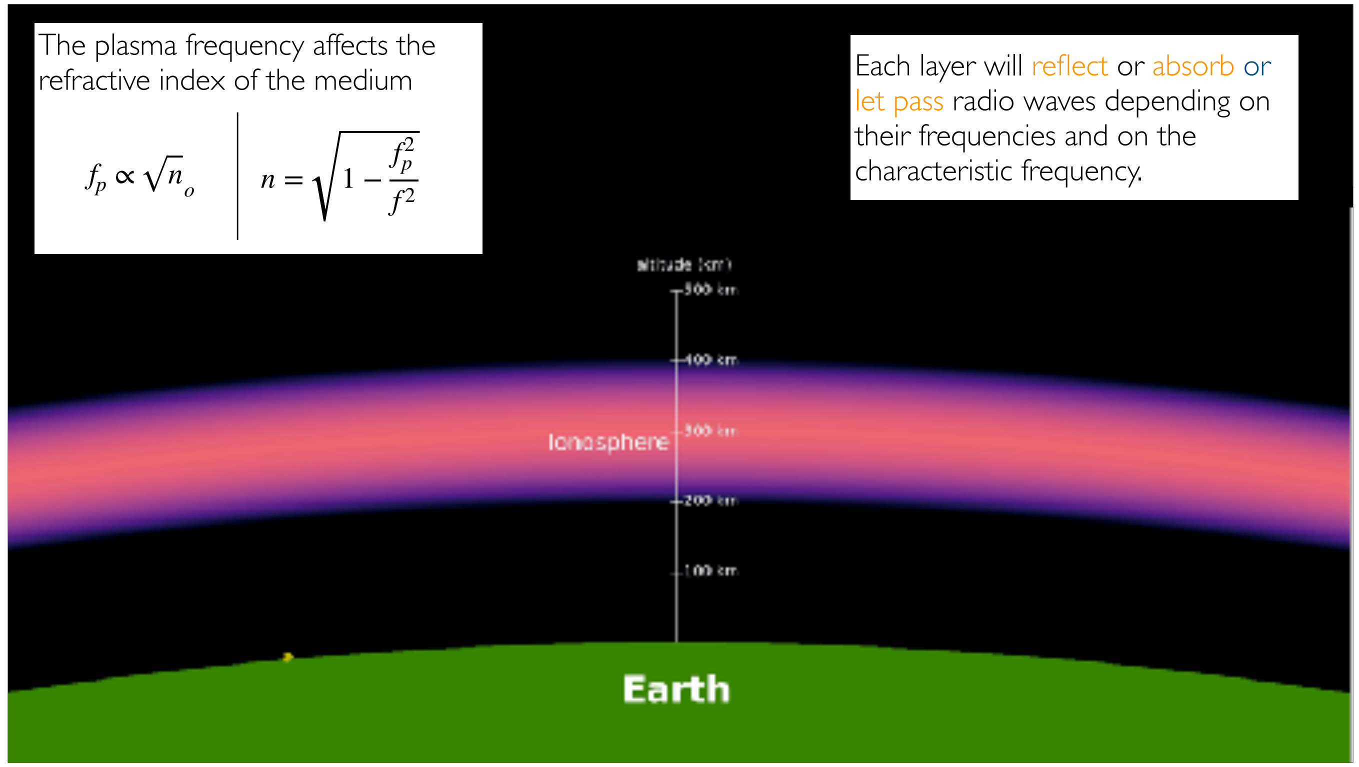


The plasma frequency is the resonant frequency of the electrons in an ionized medium.
There is a direct relation between the electron density and the plasma frequency, which can be approximated as f ≈ 8.9 Ne^1/2.

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.

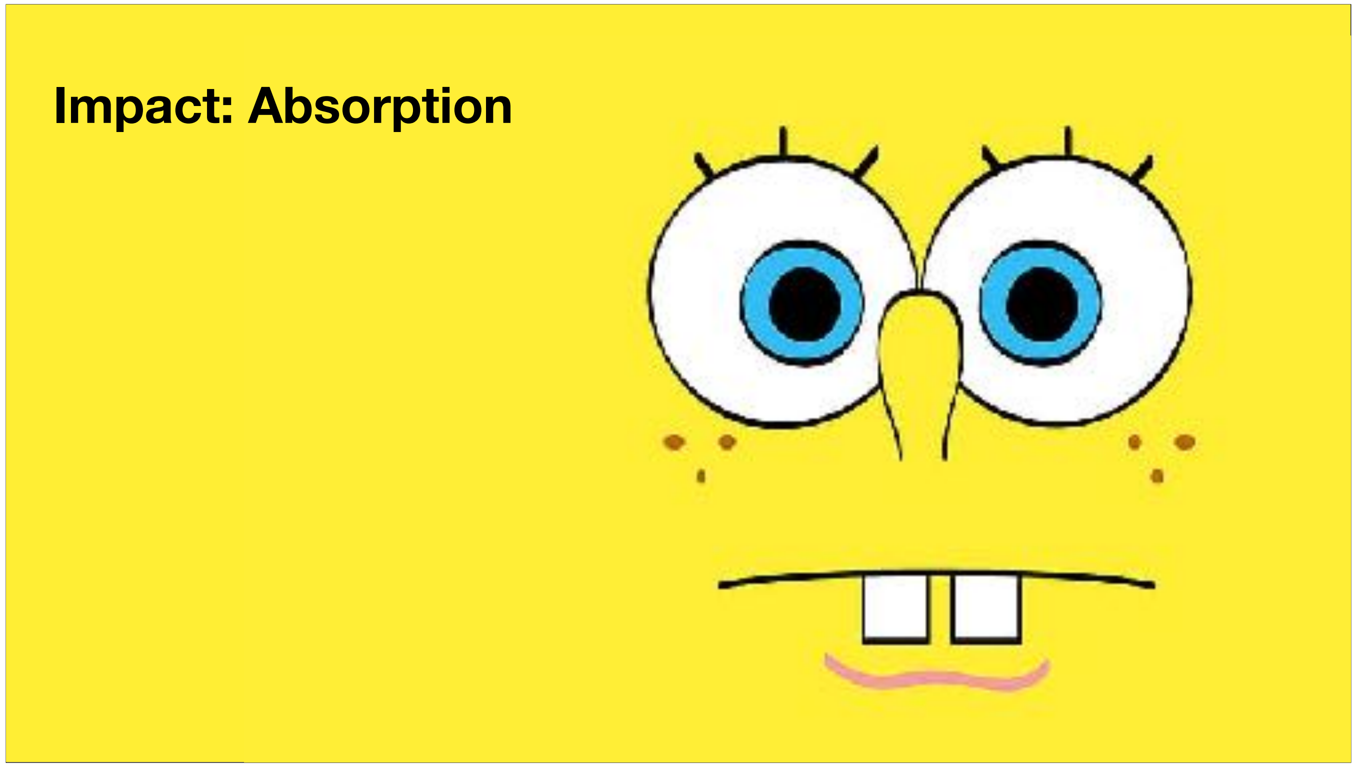
The ionosphere has the ability to reflect radio waves. If the degree of ionisation would be zero, no radio waves would be reflected and all would pass.

Reflection - binary: or it is being reflected or not
Transmission —> refraction (In physics, refraction is the redirection of a wave as it passes from one medium to another. The redirection can be caused by the wave's change in speed.) For light, refraction follows Snell's law.

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.



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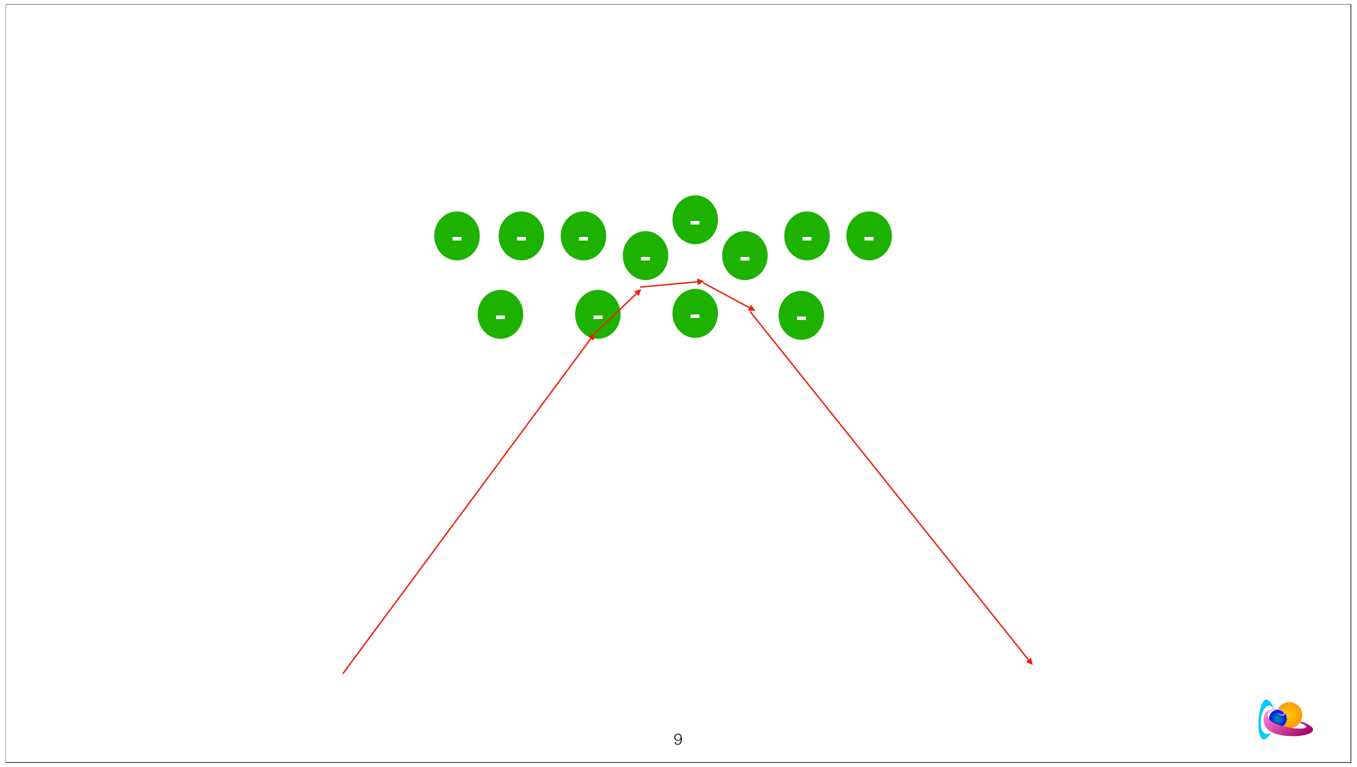
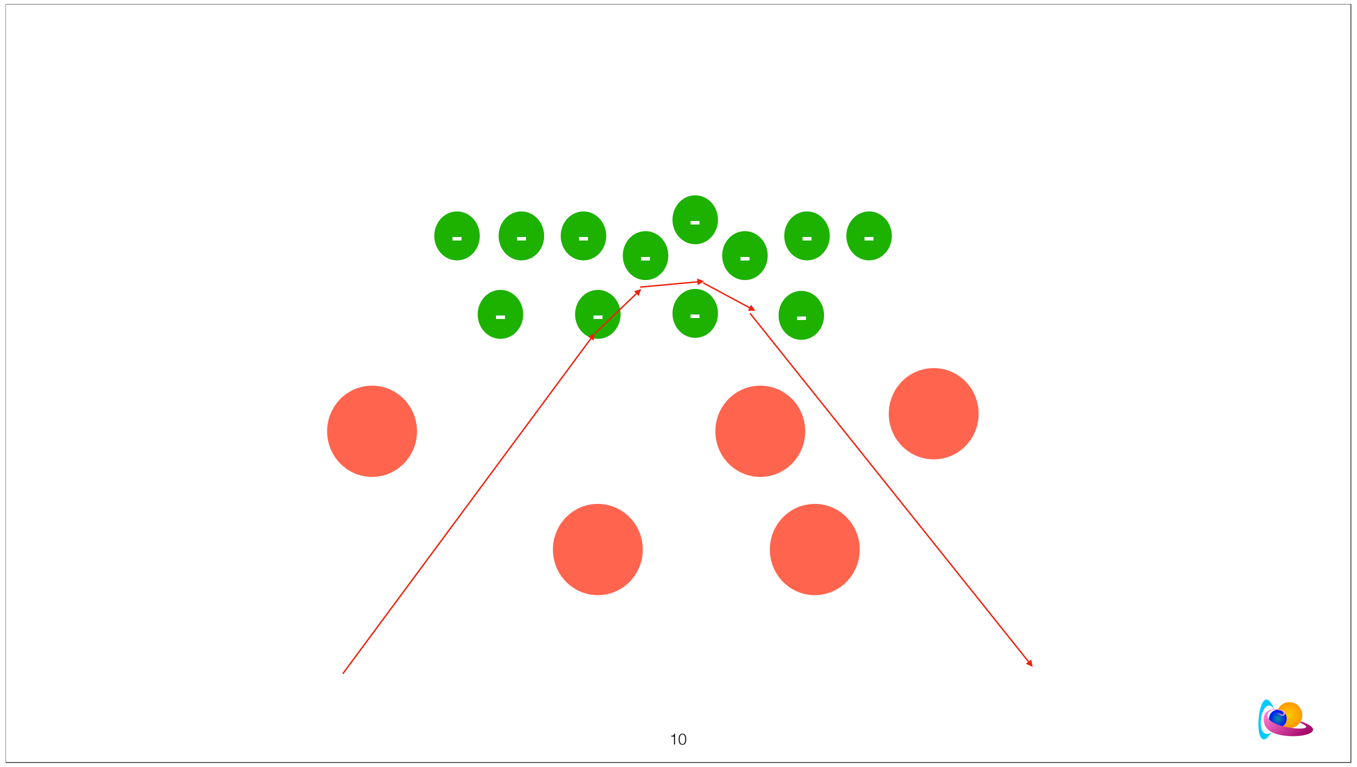
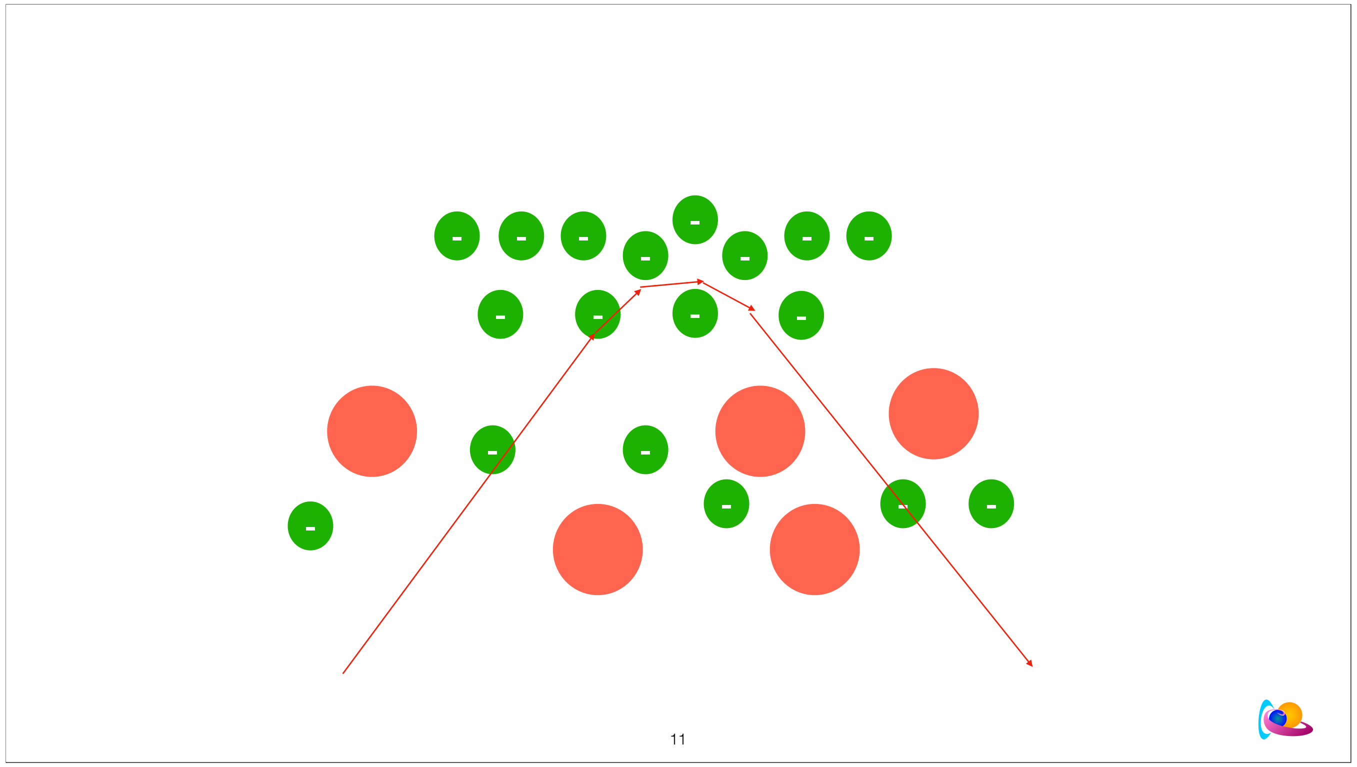


Radio wave makes the electrons move. Those moving electrons reproduce on their turn the radio signal and re-emitting it.

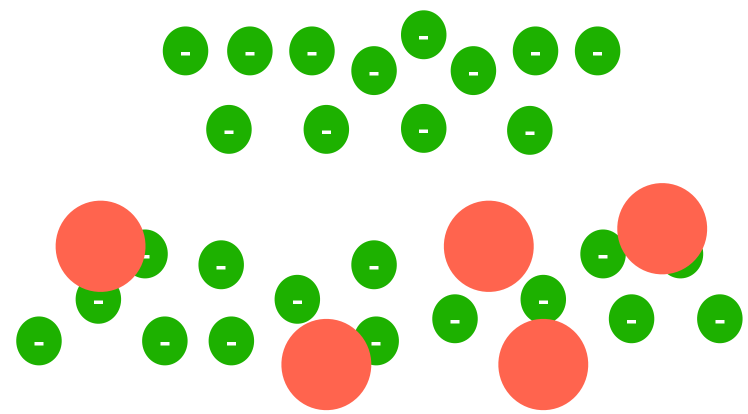
The ionosphere refracts radio waves
More refraction when higher the electron density or lower the frequency
When there are more electrons, the wave is more bent and again bent and again … until it is going down.
This is how reflection works in the ionosphere. It is a region full of magic (with a negative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



This is the D-layer during the night.
Neutrals are being present in the D-layer.

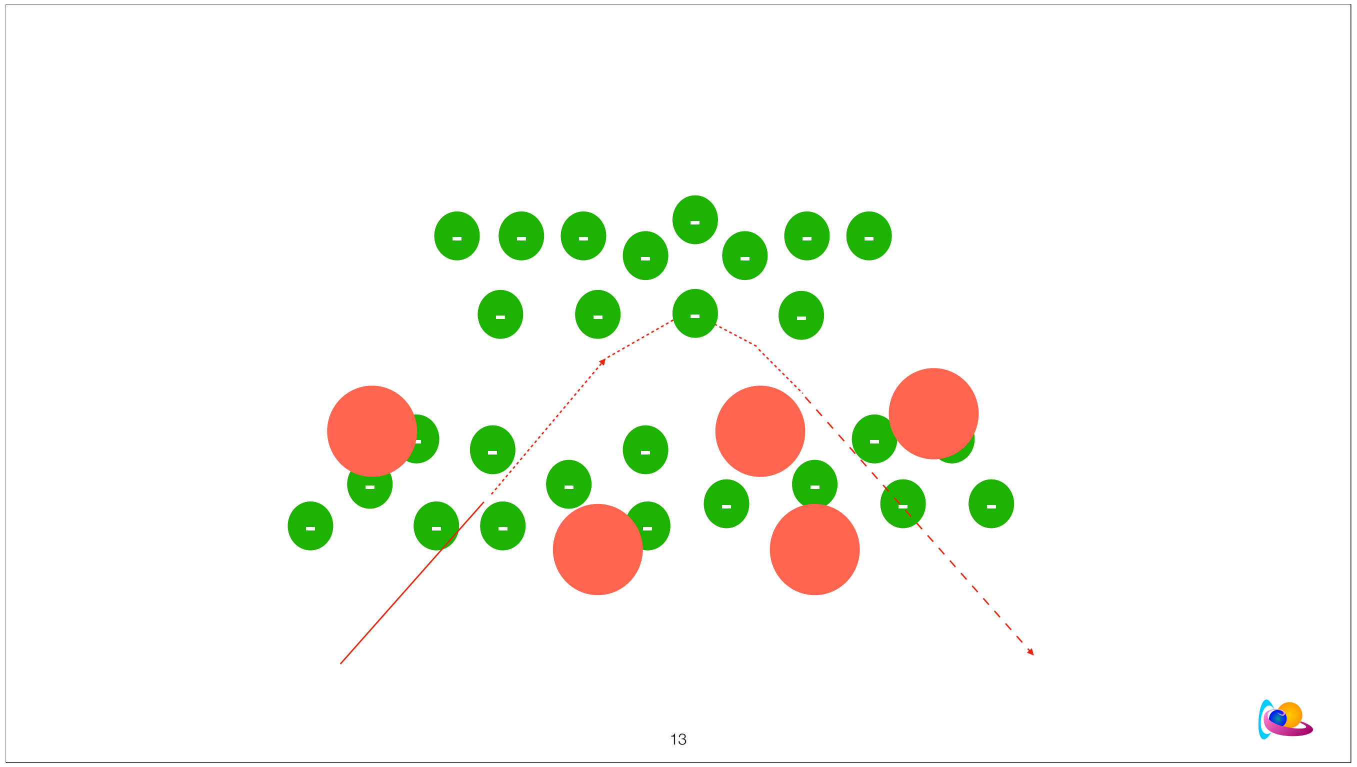


This is the D-layer during the day.
The radio wave also meets electrons in the D-layer. These electrons can’t move as much due to the neutral —> absorption.
Luckily, there are not many electrons and the absorption is minimal.



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.



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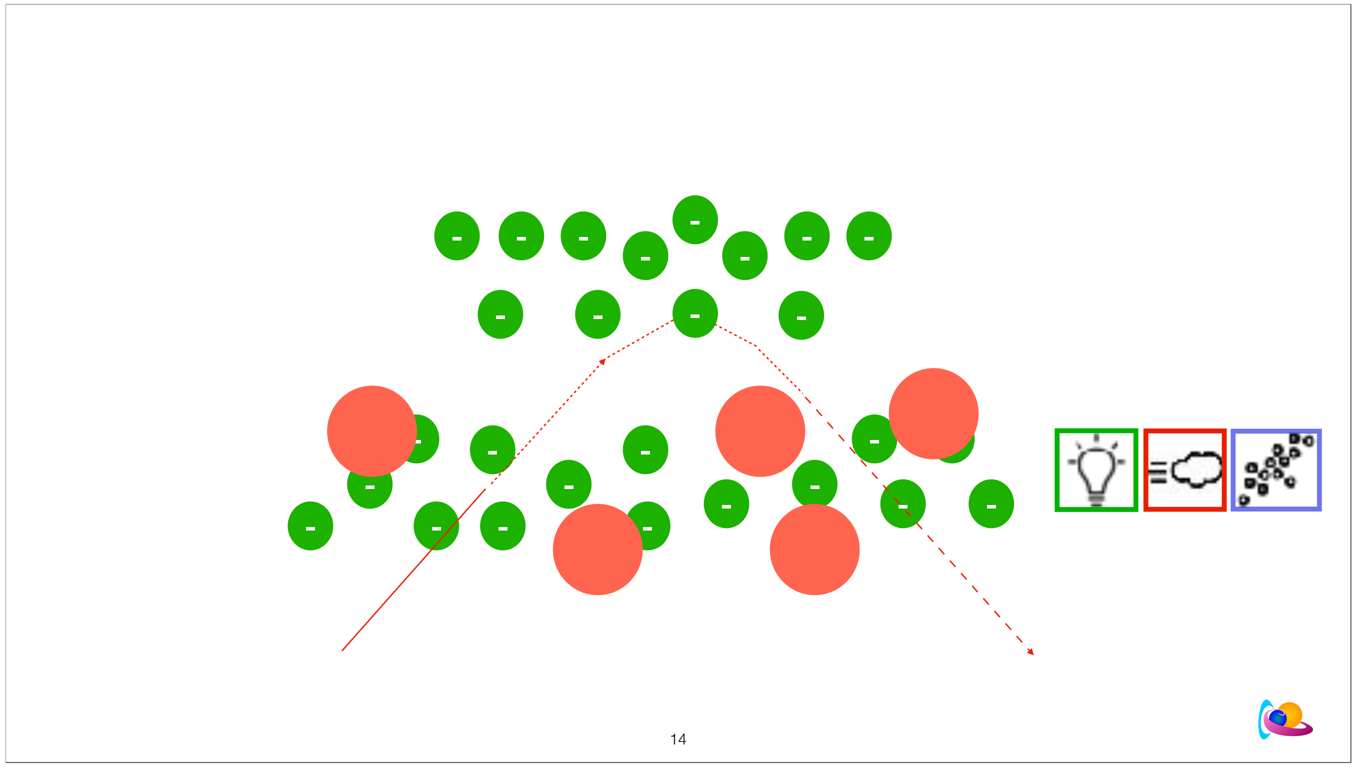
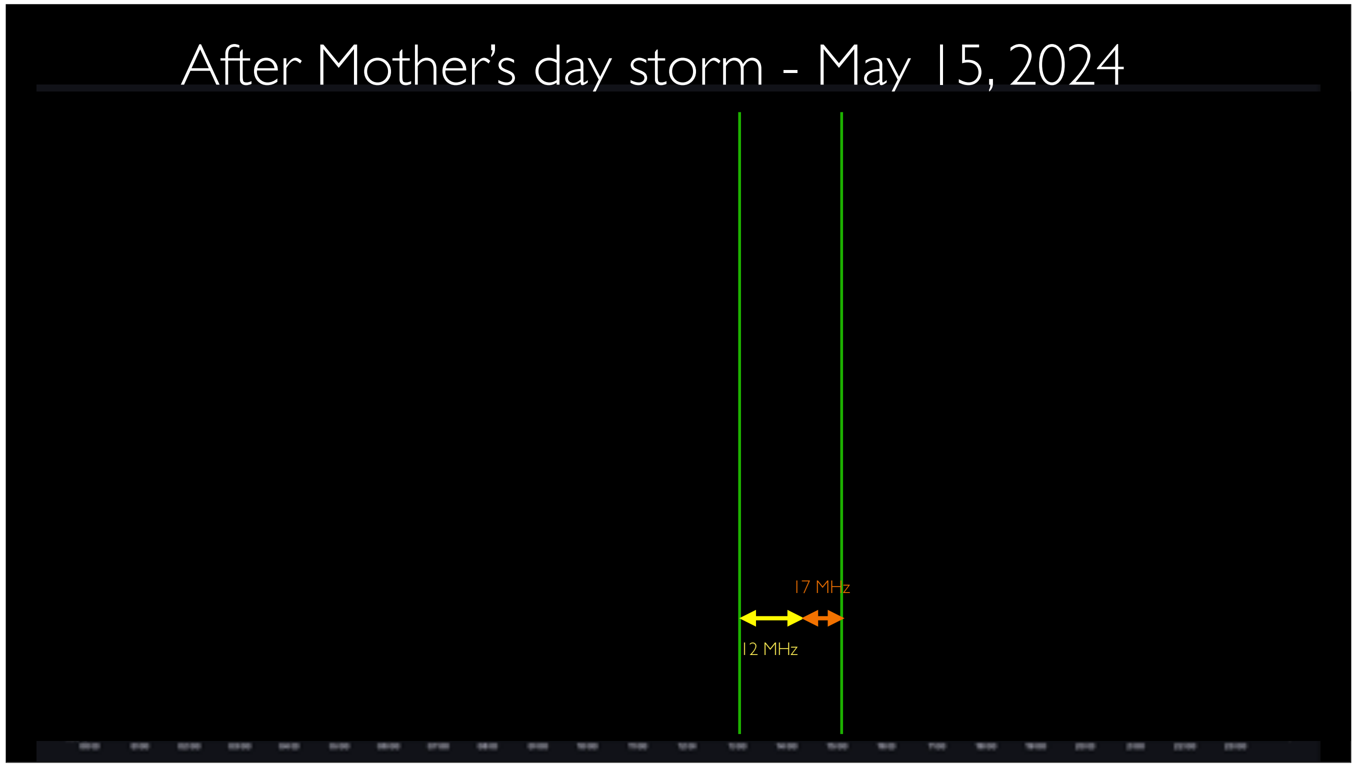


Short Wave Fadeout, auroral absorption, PCA

After Mother’s day storm - May 15, 2024

DEFENSIE

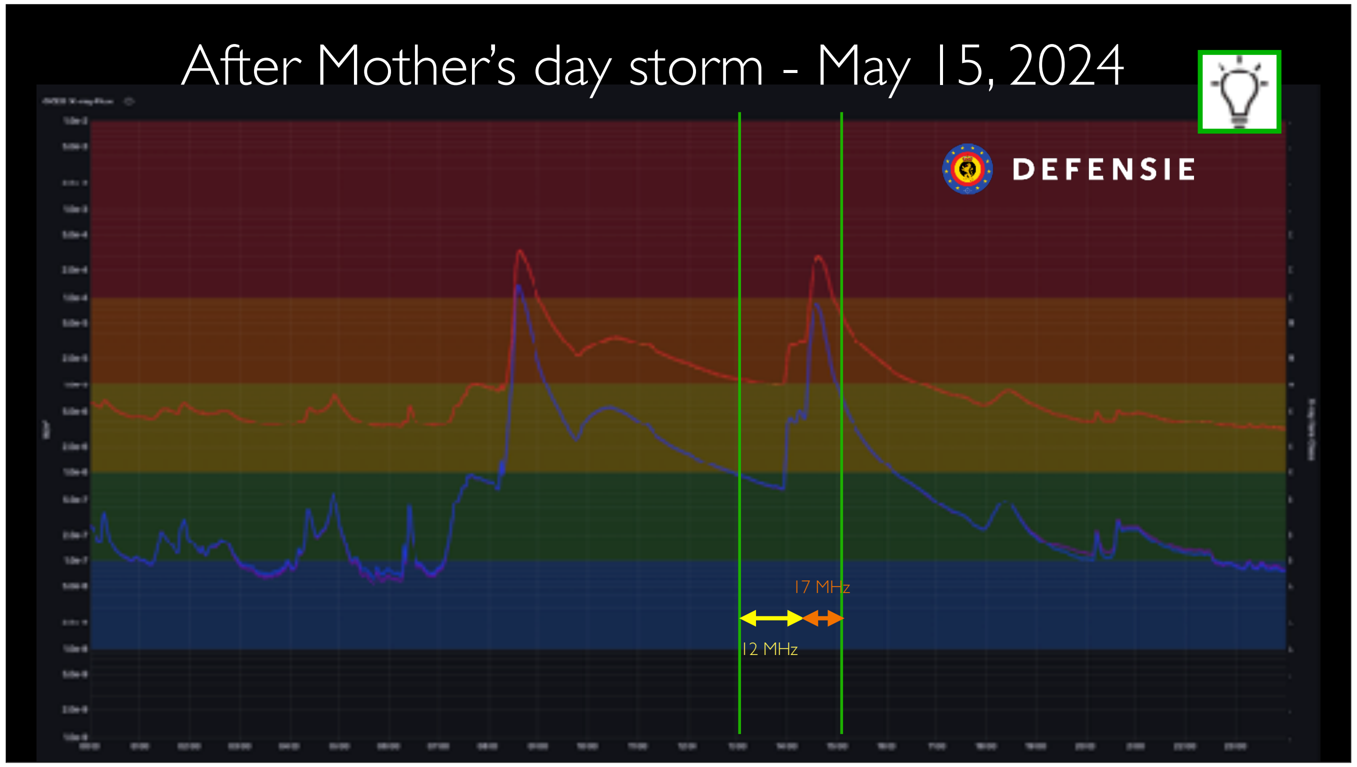
15 mei was een test tussen België en Canada.



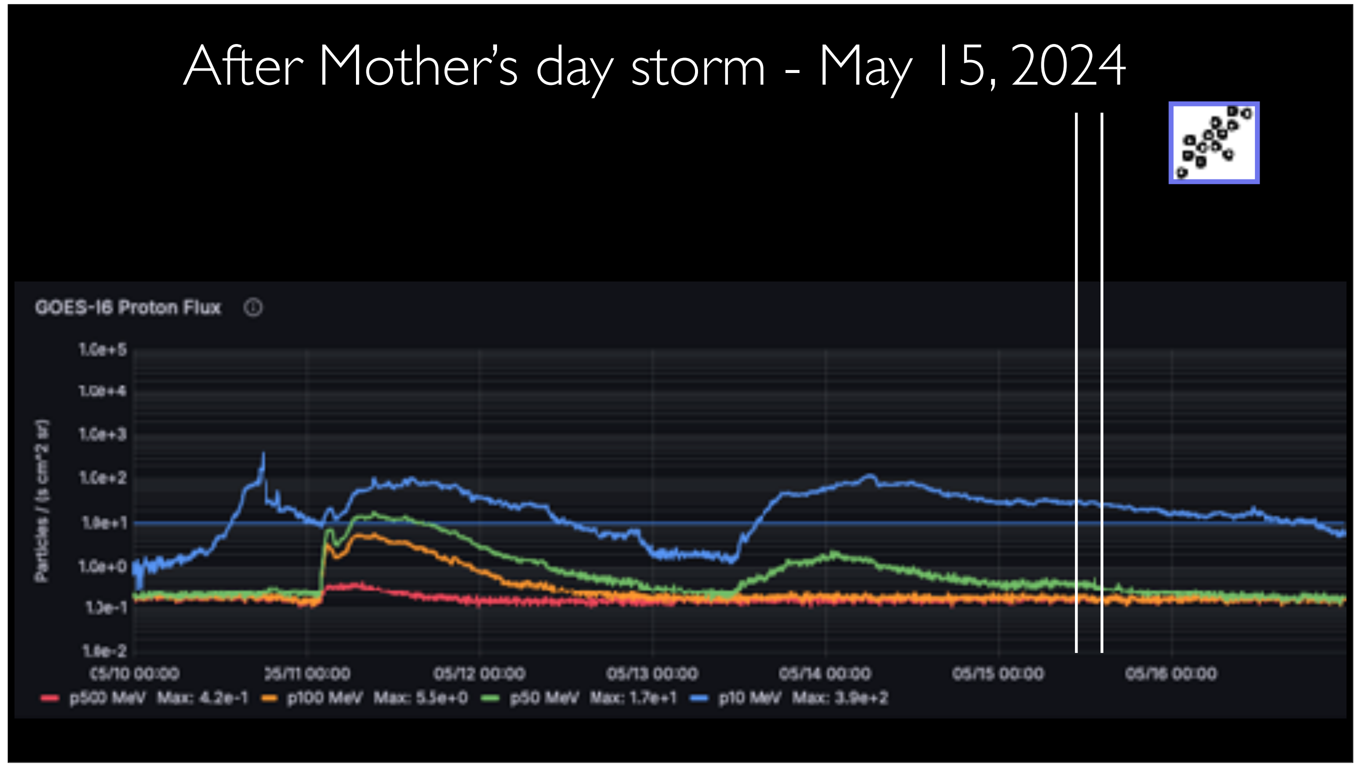
15 mei was een test tussen België en Canada.

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.



Ons antwoord: wij weten wat de oorzaak is - analyse voor de klant



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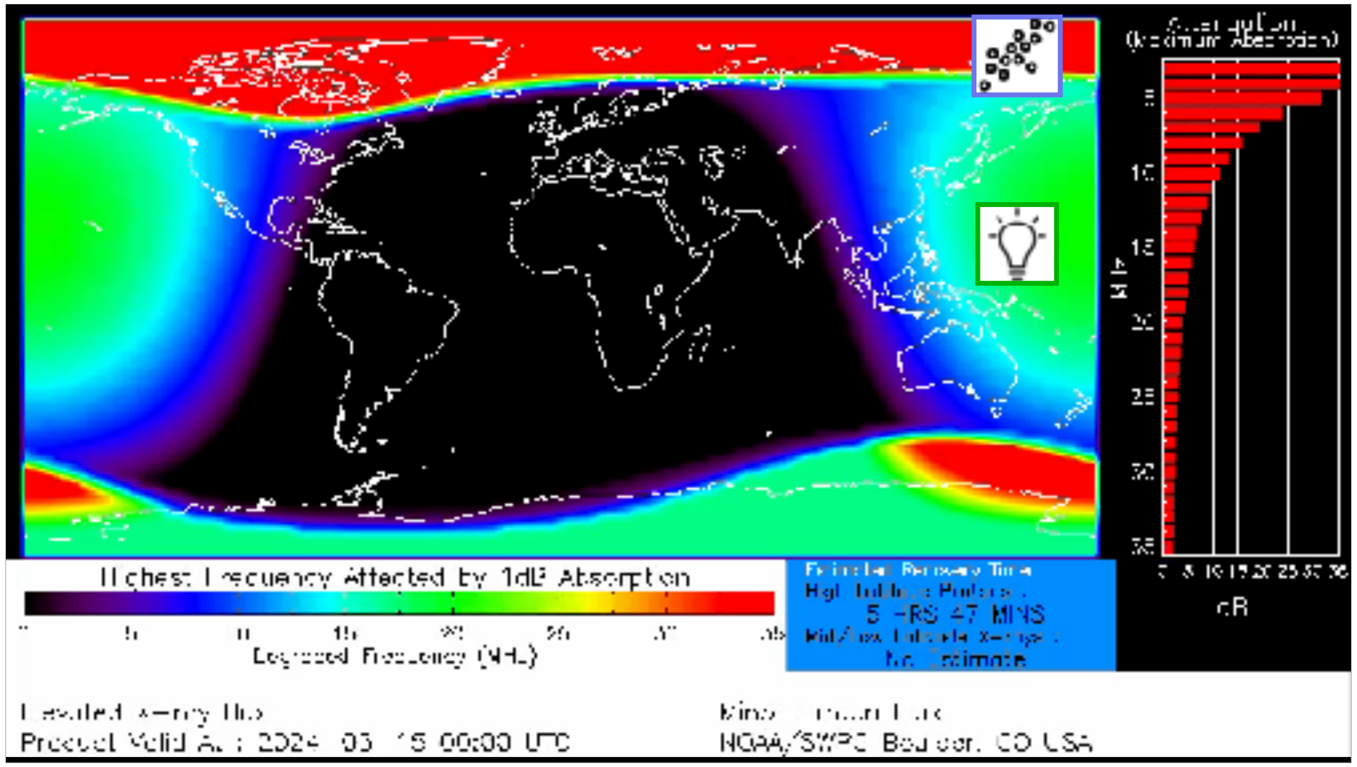


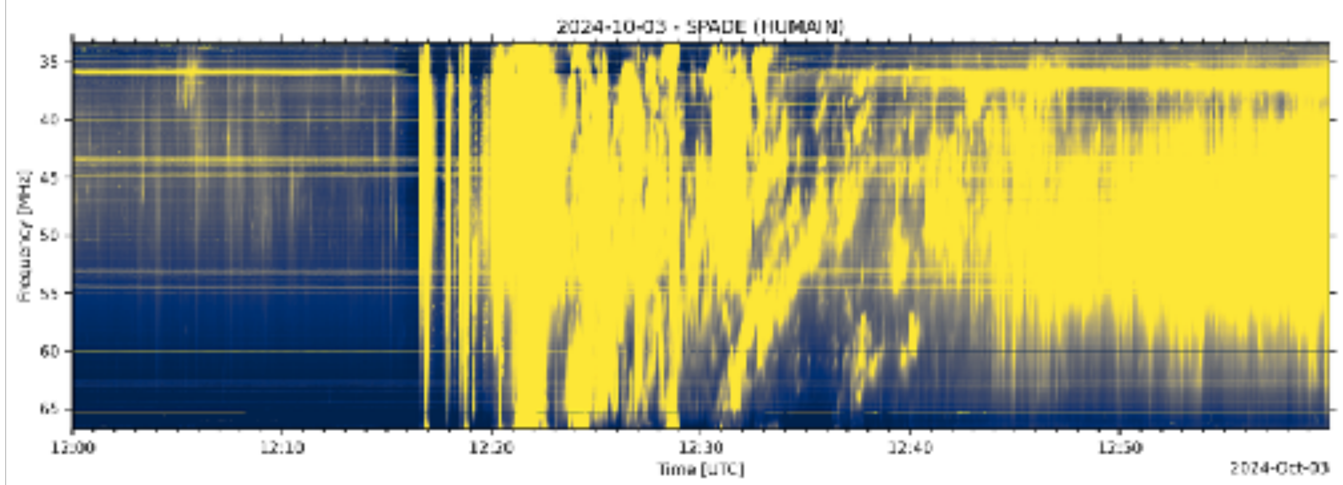
Flare
Solar energetic particles
Causing absorption of radio waves
DRAP model - D region absorption predictions

Antonio - Ingineer- expert

SPADE

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

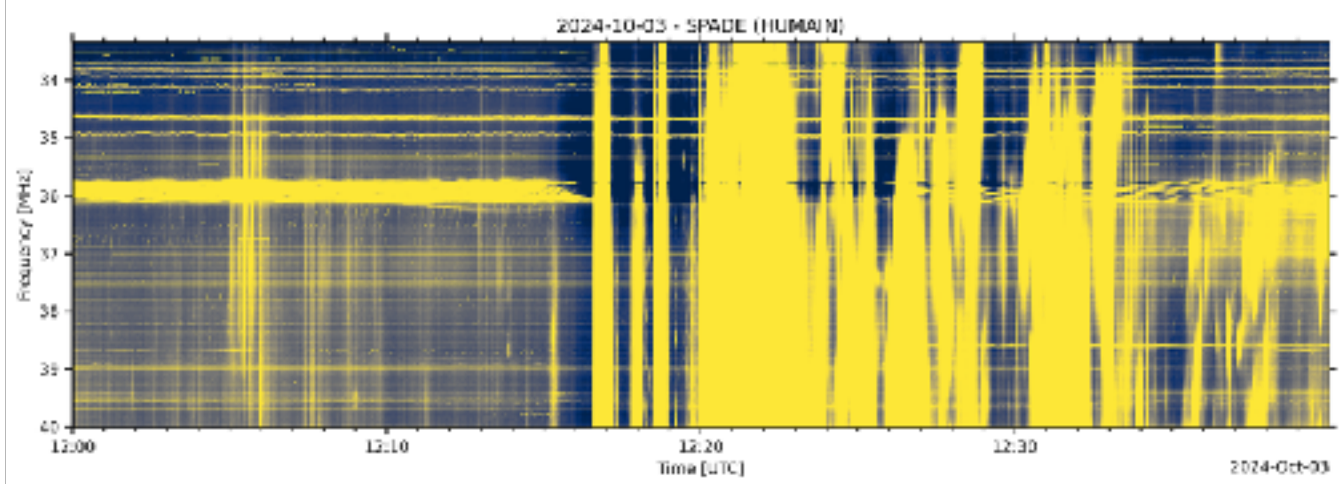
Solar Radio Station in Humain



X9.9 flare - 12:08 - 12:18 - 12:27
—> absorption in HF due to X-rays + SRB (adds noise)

Horizontal lines: selfmade interference at 40, 50, 60 MHz
36 MHz - terrestrial beacon - is being absorbed —> background is little bit darker

SRB: At the right type IV



Zoom
36 MHz line - stops when it is being absorbed.

SRB
type III (three lines)
Type II

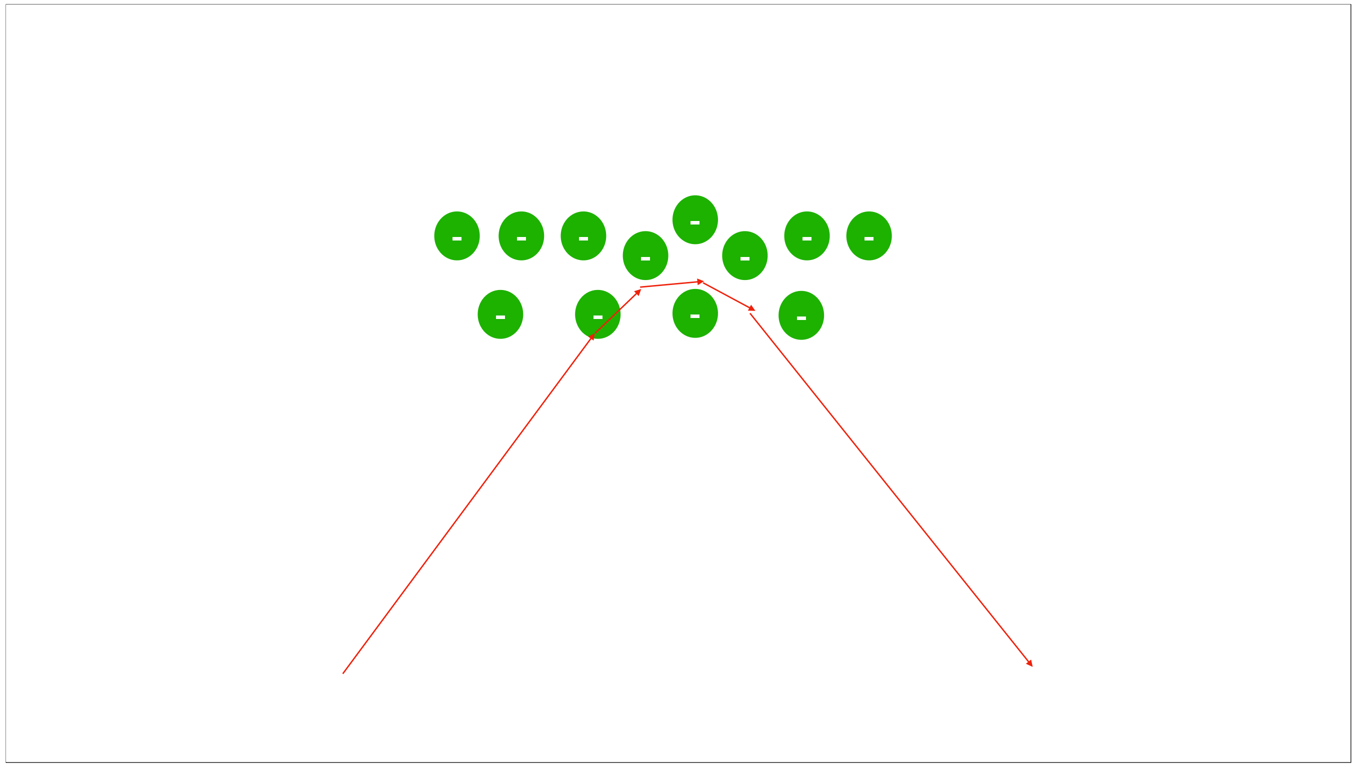
Data is also a product

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

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

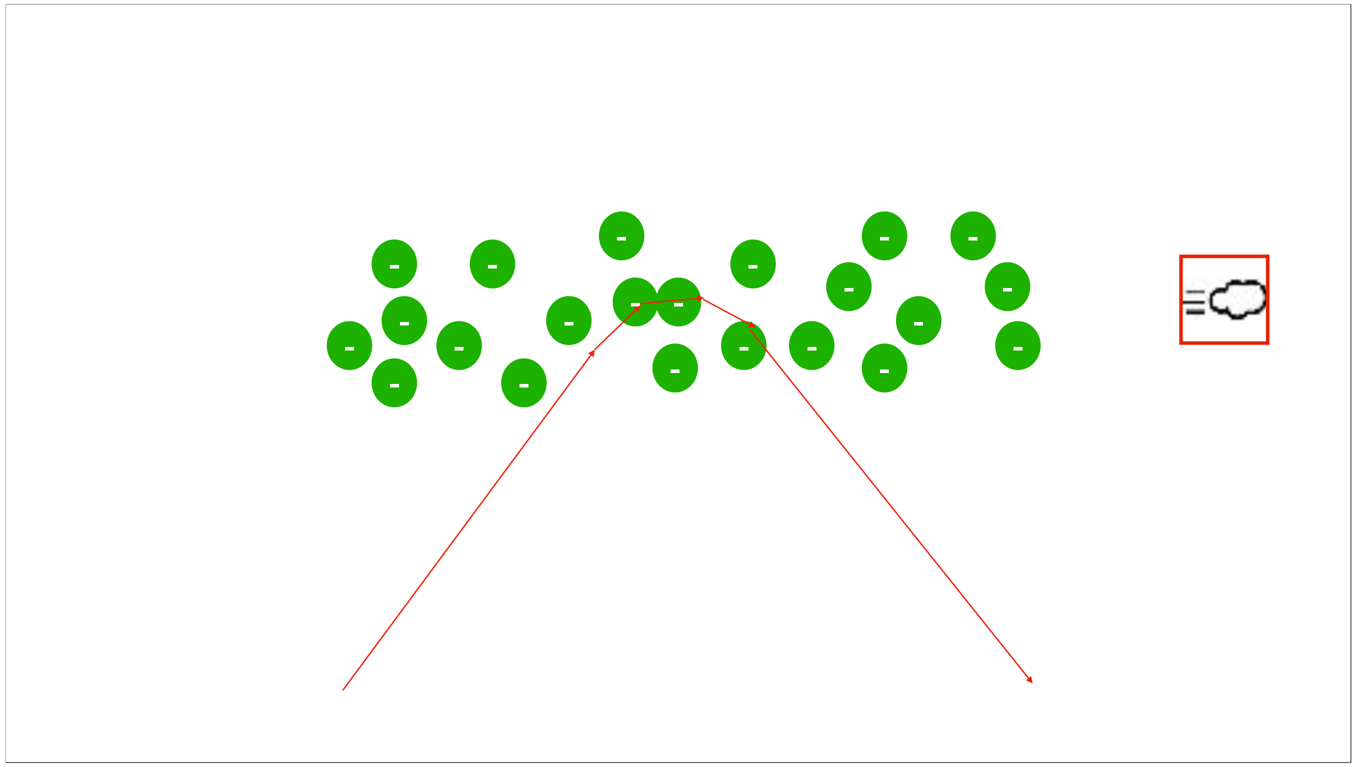
Impact: decrease of MUF

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



The ionosphere can reflect waves

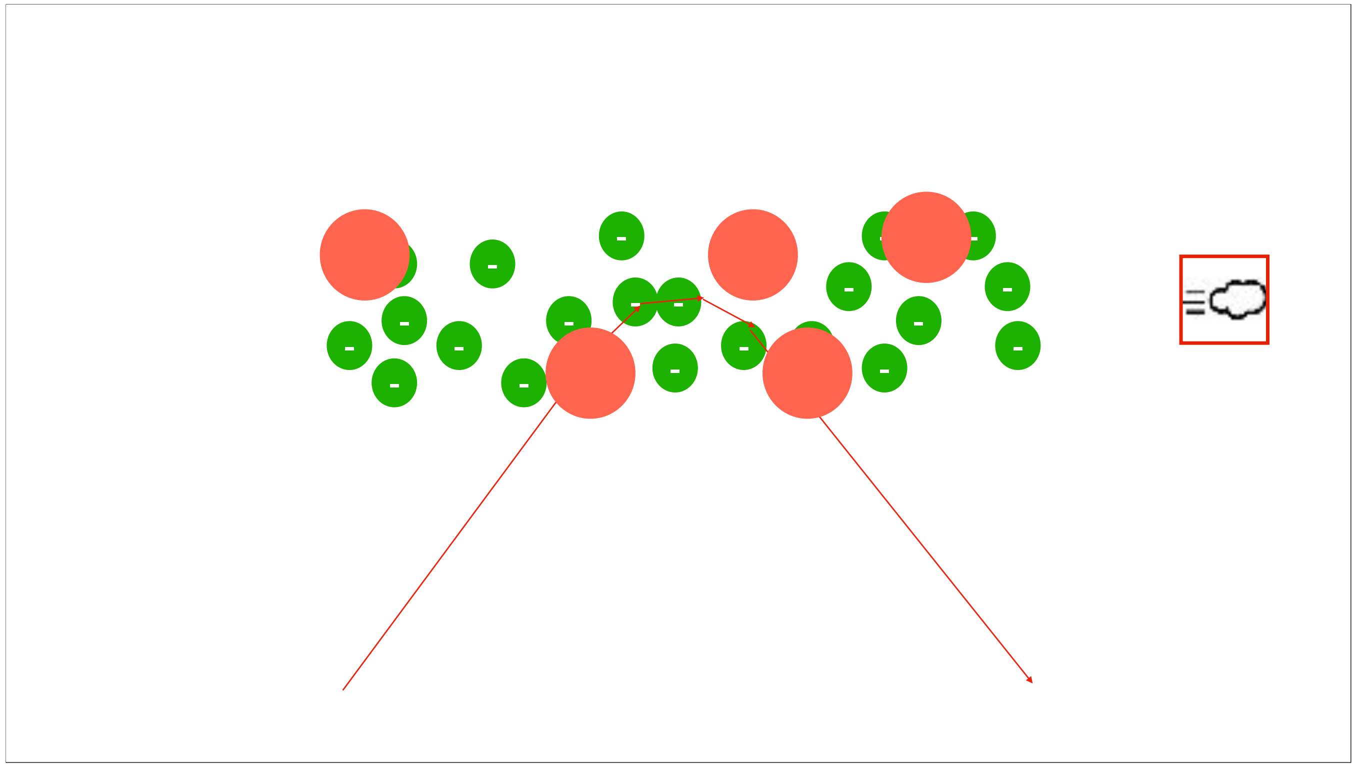
When the ionosphere is not ionised, which waves are being reflected?
As soon as the ionisation increases, waves under the MUF are being reflected.
The higher the ionisation, the higher the MUF.



Increase of electrons - positive phase of the storm - VTEC increases
increase is due to Drift of plasma across B = upward flow
Better HF communication because more waves are being reflected.
Also waves with a higher freq are being reflected. MUF increases

The most significant disturbances to the ionosphere result from solar events (CMEs, CIRs), propagating through the solar wind and interacting with the magnetosphere.

1 Energy injected into the ionosphere, mainly at high latitude.
2 As a result, the auroral oval expands in height and width
3 This causes large scale movement of plasma towards the equator.
4 Drift along the magnetic field lines cause the ionosphere 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").



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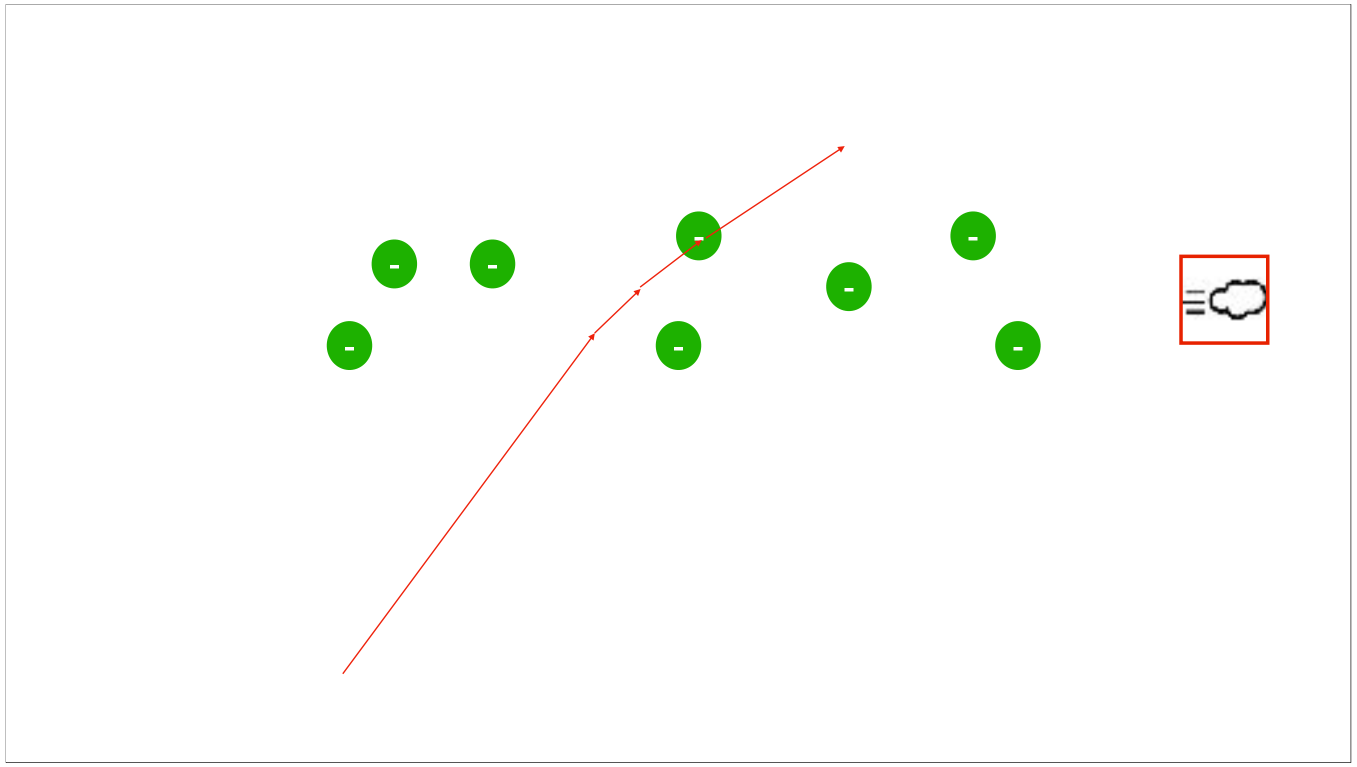

Neutrals are being transported to the F2 layer. This is the second, negative phase of the storm - more electron are being eaten by neutrals.
Less electrons, the MUF decreases —> less frequencies available for HF com
Higher freq radio waves pass through
<u>—> mid-latitude</u>

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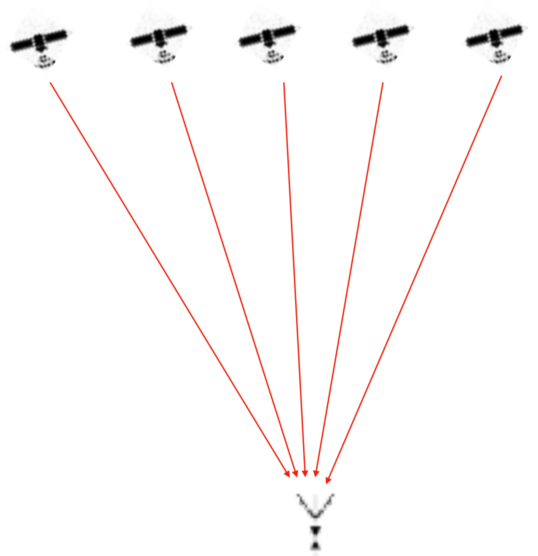
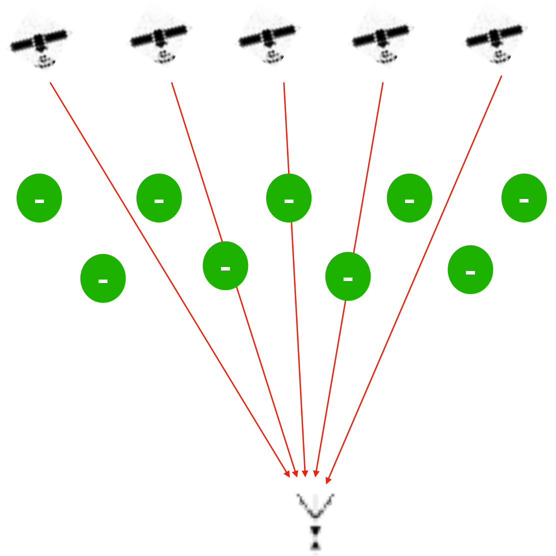
Impact: Scintillation

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

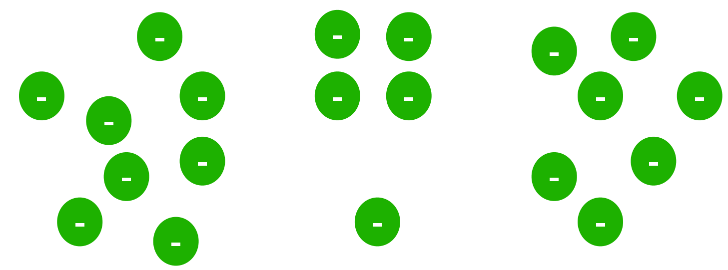


no ionosphere - or an ionosphere that behaves as expected

No refraction
No diffraction
The waves nicely reach the receiver without meeting another wave.



Even with an ionosphere that behaves, it is OK.



Strong gradients

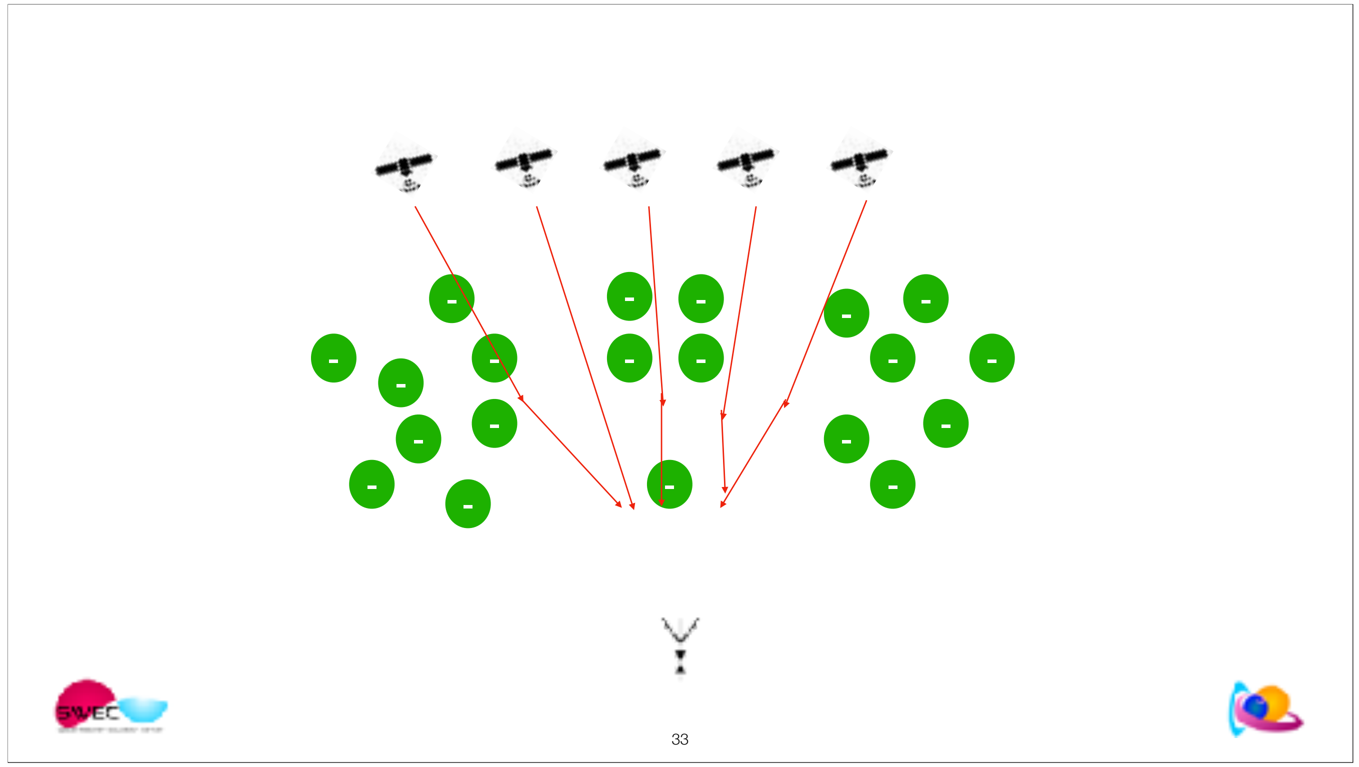
Due to space weather, small scale irregularities exist in the ionosphere.

Landscape of electrons - dense regions and less dense regions

Localised

Due to

- Post-sunset Plasma Bubbles at lower latitudes
- Precipitating particles in the auroral oval - the auroral oval itself
- Patches in the polar caps due to neutral wind dragging the plasma along
- Travelling ionospheric disturbances



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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

1. Post-sunset Plasma Bubbles (decreased ionisation) at lower latitudes
2. Structures (increased ionisation) in the auroral oval
3. Patches (increased ionisation) in the polar caps
4. Travelling ionospheric disturbances

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

Equatorial induced anomoly allows the plasma bubbels to rise

The four mechanisms that give rise to scintillation are

- Plasma bubbles (in the lower latitudes)
- Precipitating particles (auroral oval)
- Patches 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

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

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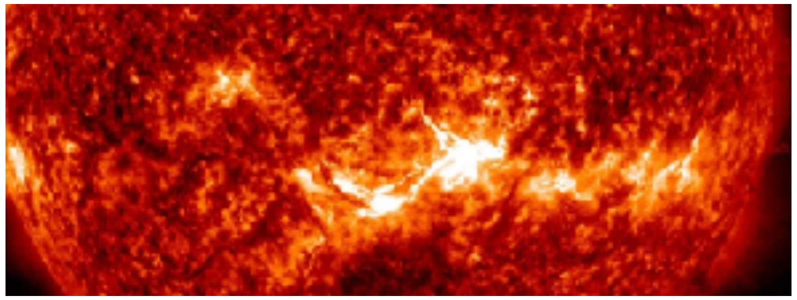
Solar and heliospheric storms impacting aviation

CASE STUDY - April 23, 2023



GNSS	Moderate	Severe	Time UTC	Values	Status	Alert	Max-3h values	Max-3h status
Amplitude Scintillation	0.5	0.8	2020-10-12 14:14	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	[illegible]	80	2020-10-12 14:20	0	QUIET		0	QUIET

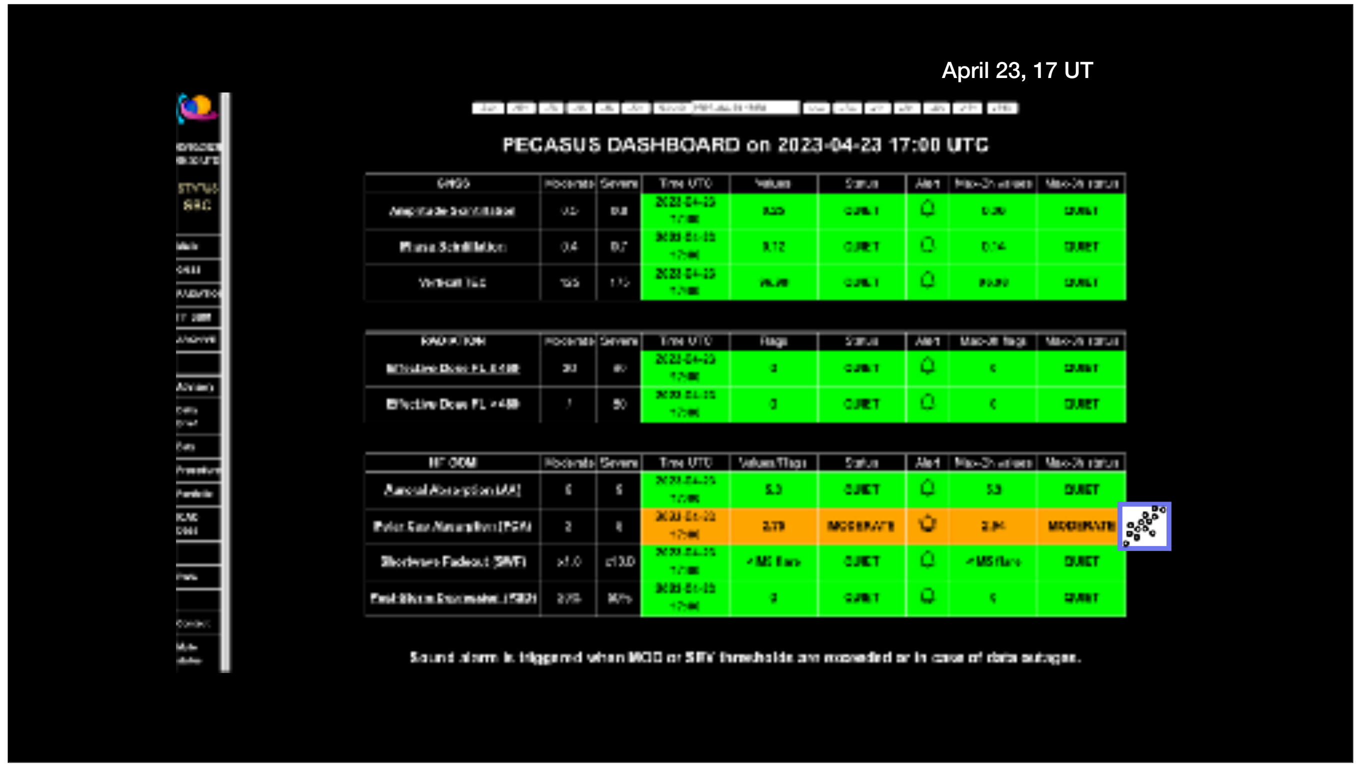
HF COM	Moderate	Severe	Time UTC	Values/Flags	Status	Alert	Max-3h values	Max-3h status
Auroral Absorption (AA)	8	9	2020-10-12 14:16	3.0	QUIET		3.0	QUIET
Polar Cap Absorption (PCA)	2	5	2020-10-12 14:20	0.08	QUIET		0.00	QUIET
Shortwave Fadeout (SWF)	x1.0	x10.0	2020-10-12 14:17	< M.5-flare	QUIET		< M.5-flare	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.

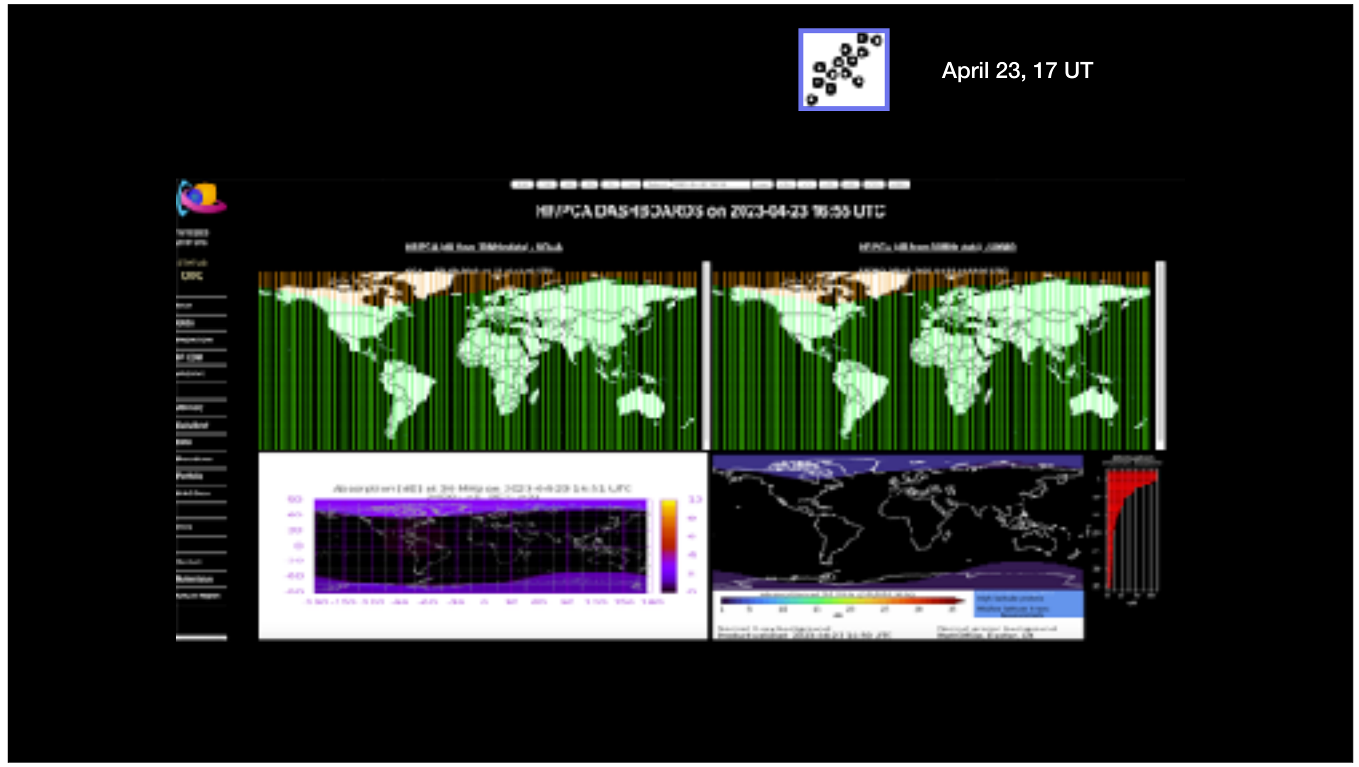
AA, PCA, SWF are absorption events – low frequencies
PSD reduces the range of frequencies available – high frequencies are not available.

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.


April 23, 17 UT
PECASUS DASHBOARD on 2023-04-23 17:00 UTC
Sound alarm is triggered when MOD or SEV thresholds are exceeded or in case of data outages.

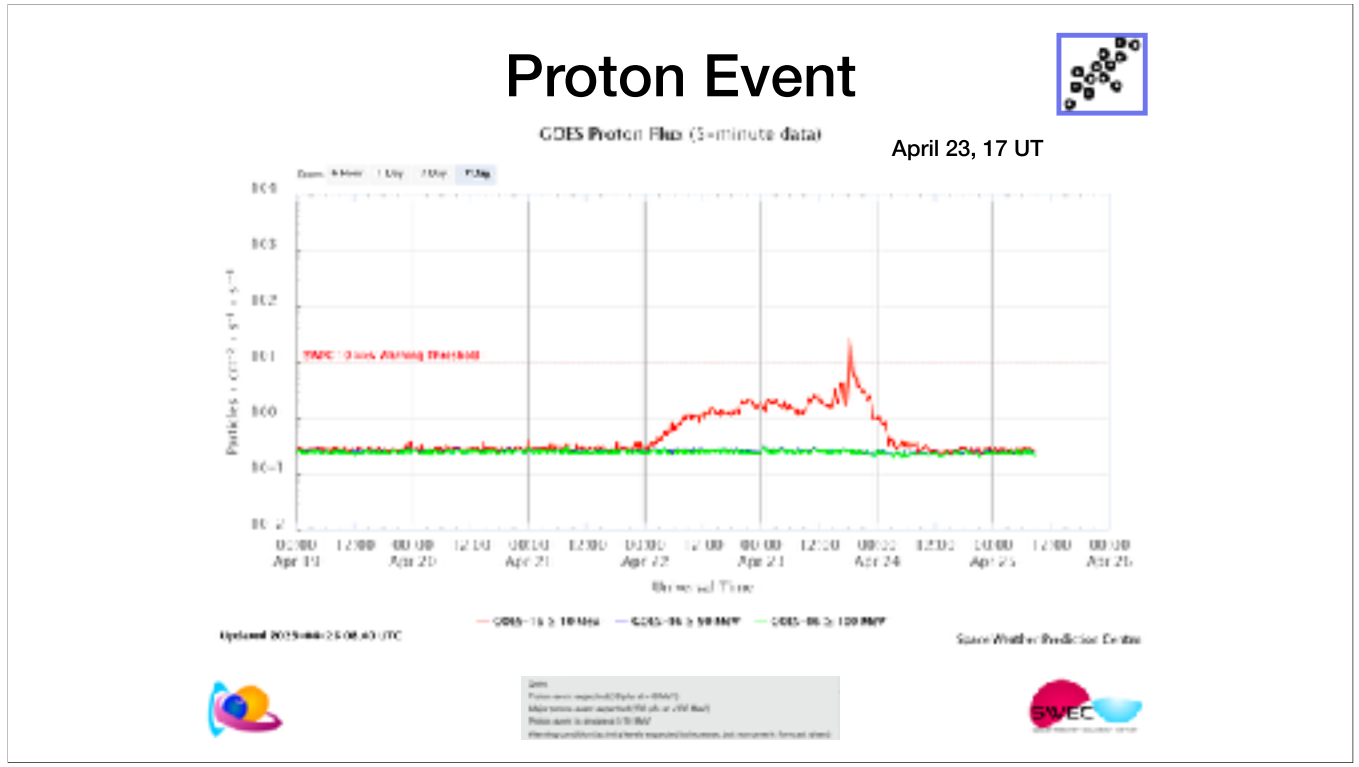
19LT —> 17 UTC



DRAP model

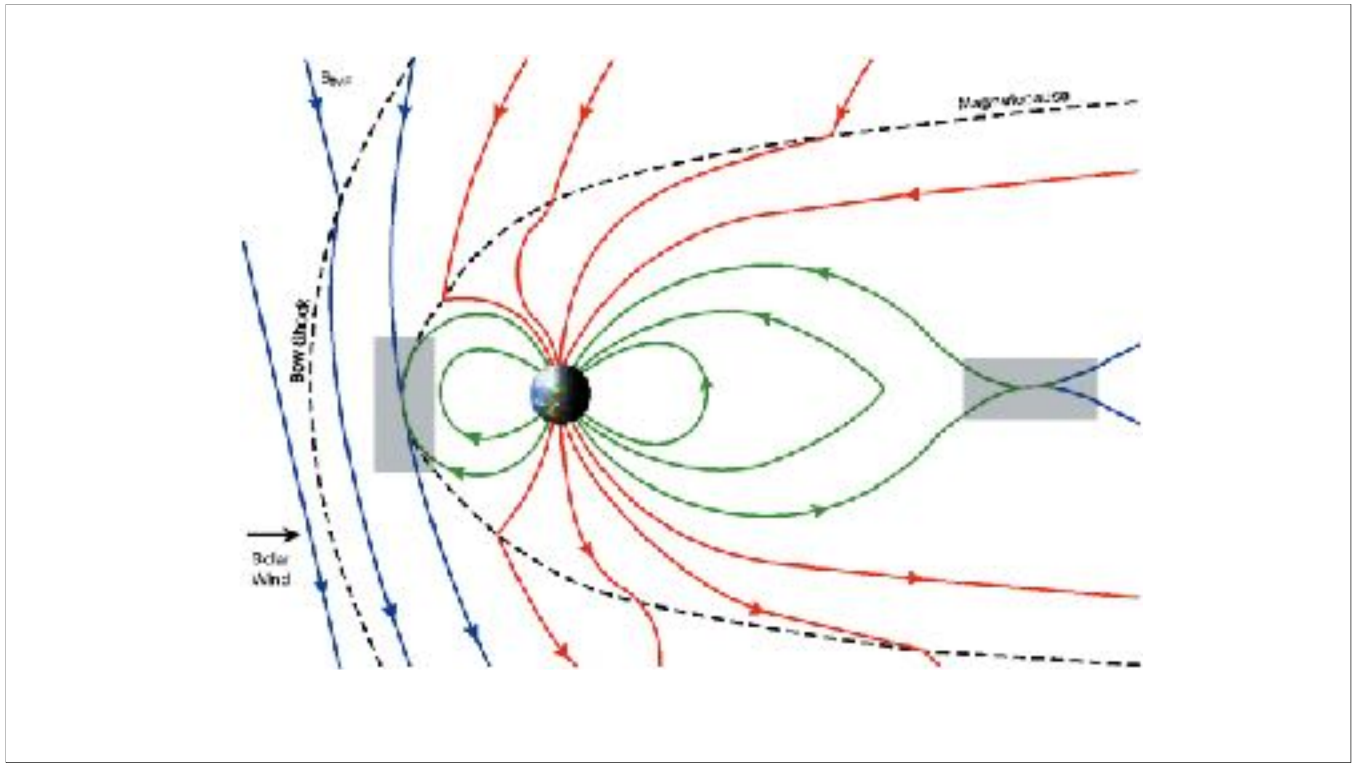
D-Region Absorption Predictions
Map giving info on spatial extend and which frequencies are impacted

PCA - scherpe overgang van open naar gesloten magnetische veldlijnen.
De deeltjes moeten een open route (open veldlijn) hebben om af te dalen naar de D-laag



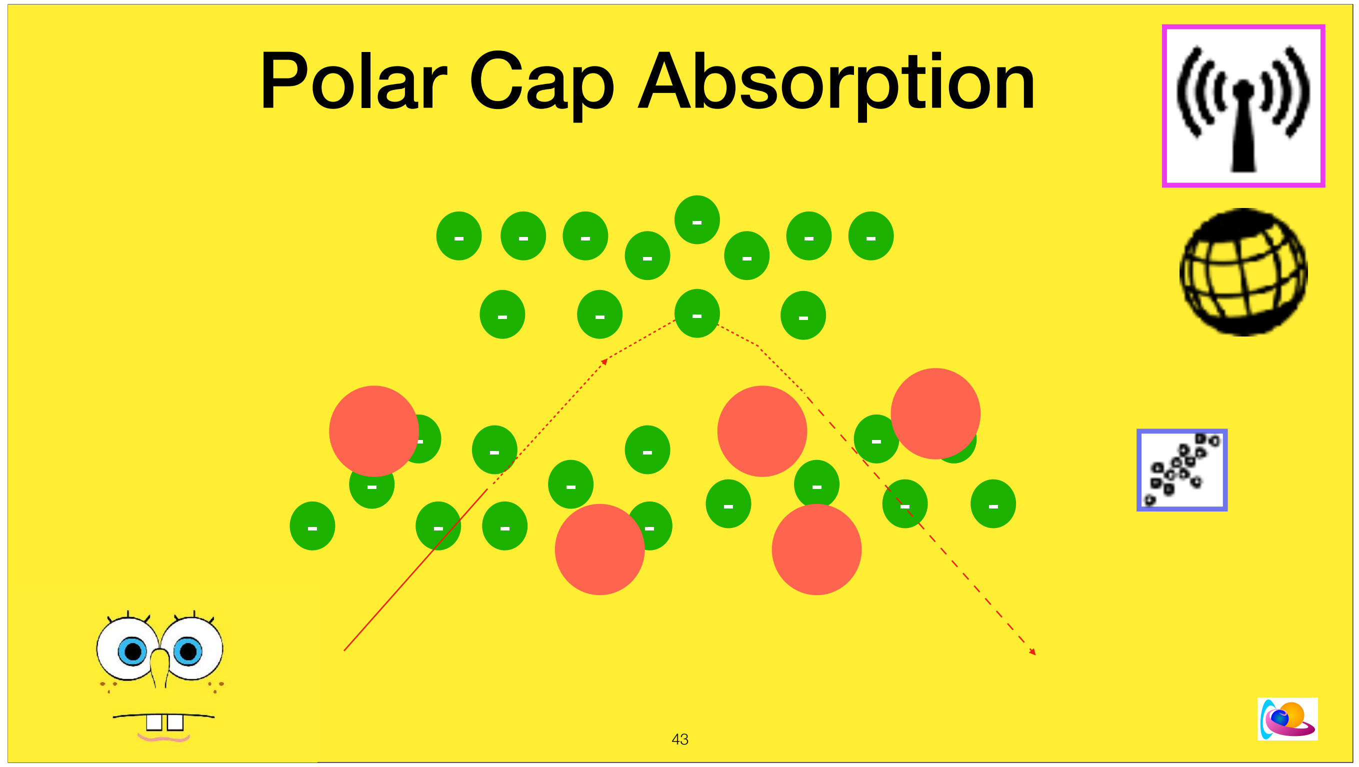
A shock was recorded in the solar wind parameters on 23 April at 17:00UTC (DSCOVR ; graph). It marked the **somewhat (a few hours) earlier-than-expected arrival of the interplanetary coronal mass ejection (ICME)**. **The passage of the shock briefly drove the already enhanced greater than 10 MeV proton flux finally above the proton event threshold (10 pfu)**, with a maximum of 26 pfu recorded at 18:20UTC (graph underneath). This is called an Energetic Storm Particles event (ESP), and originates from the acceleration of charged particles by a fast, usually ICME-driven shock in interplanetary space (e.g. Ameri et al. 2023). The proton flux drops sharply after the **shock** passage, as was the case here.

Shock pushes



This is why the transition between the impacted area and the undisturbed area is abrupt: a 'sharp' transition area (plasmasheet - see next slide)
The solar energetic particles catch up with a magnetic field line of the earths magnetosphere and gyrate down towards the polar regions.
They mainly drop in in the area with open magnetic field lines (red).

Plasma sheet: area between open and closed magnetic fields



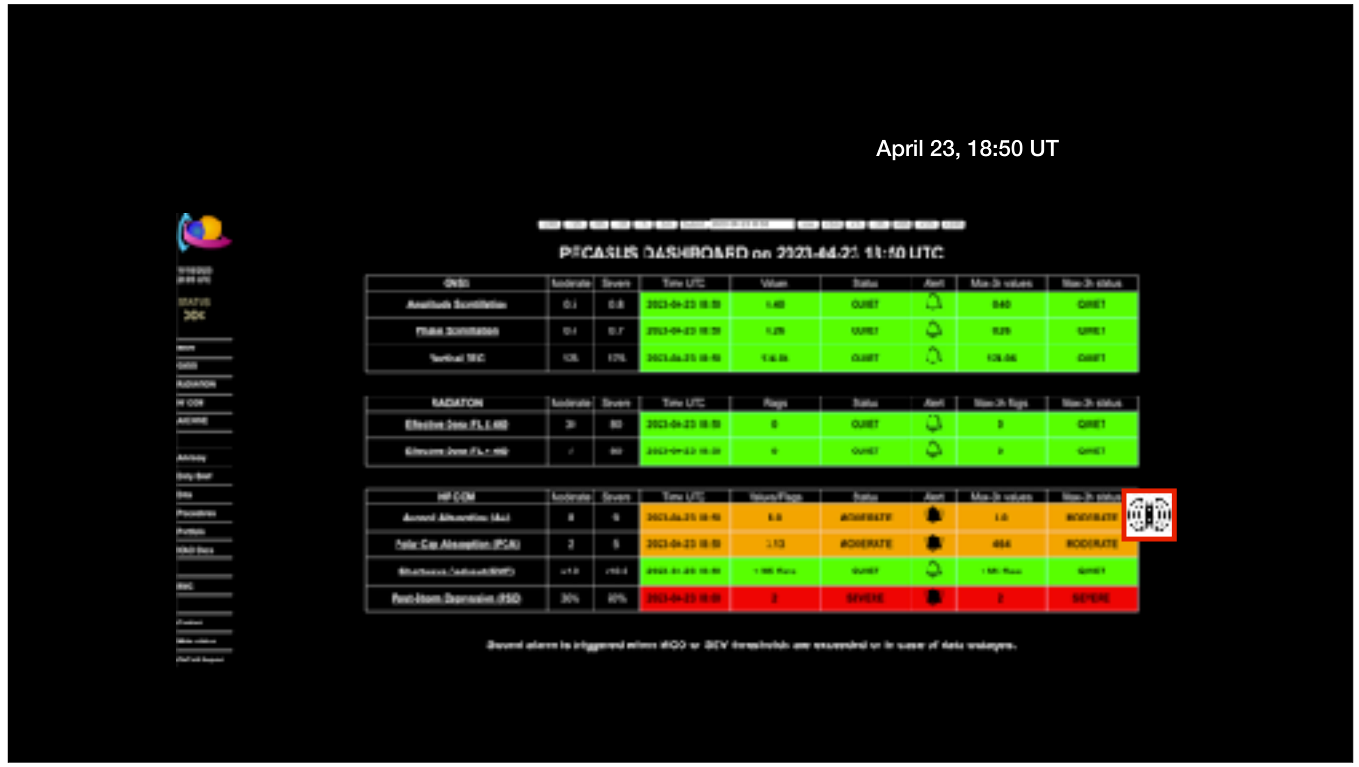
Extra ionisation in the D-layer where big fat neutrals are present limiting the movement of the electrons.

April 23, 17:06 UT

```
SWX ADVISORY
DTG:                20230423/1706Z
SWXC:               PECASUS
ADVISORY NR:        2023/59
SWX EFFECT:         HF COM MOD
OBS SWX:            23/1655Z HNH W150 - E000
FCST SWX +6 HR:     23/2300Z NOT AVBL
FCST SWX +12 HR:    24/0500Z NOT AVBL
FCST SWX +18 HR:    24/1100Z NOT AVBL
FCST SWX +24 HR:    24/1700Z NOT AVBL
RMK:                SPACE WEATHER EVENT (HF COM POLAR CAP
ABSORPTION) IN PROGRESS. IMPACT ON LOWER HF COM FREQUENCY
BANDS EXPECTED AT HIGH LATITUDES.
NXT ADVISORY:       WILL BE ISSUED BY 20230423/2255Z=
```

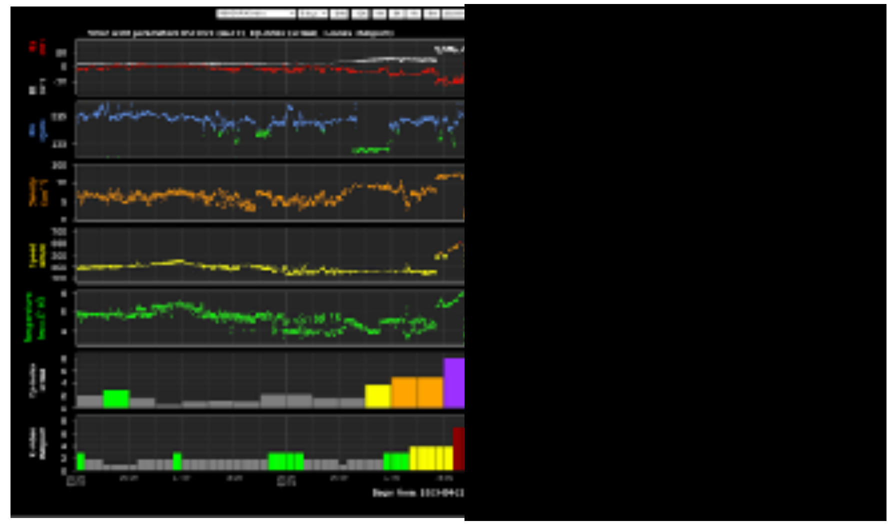

Should have been: HNH + HSH W180-E180


April 23, 17:06 UTC
WEEE-WOOO-WEEE-WOOO-WEEE-WOOO!



>1 hour later, it began
Passed Kp 6, leading to PSD but first focus on AA

CME arrival

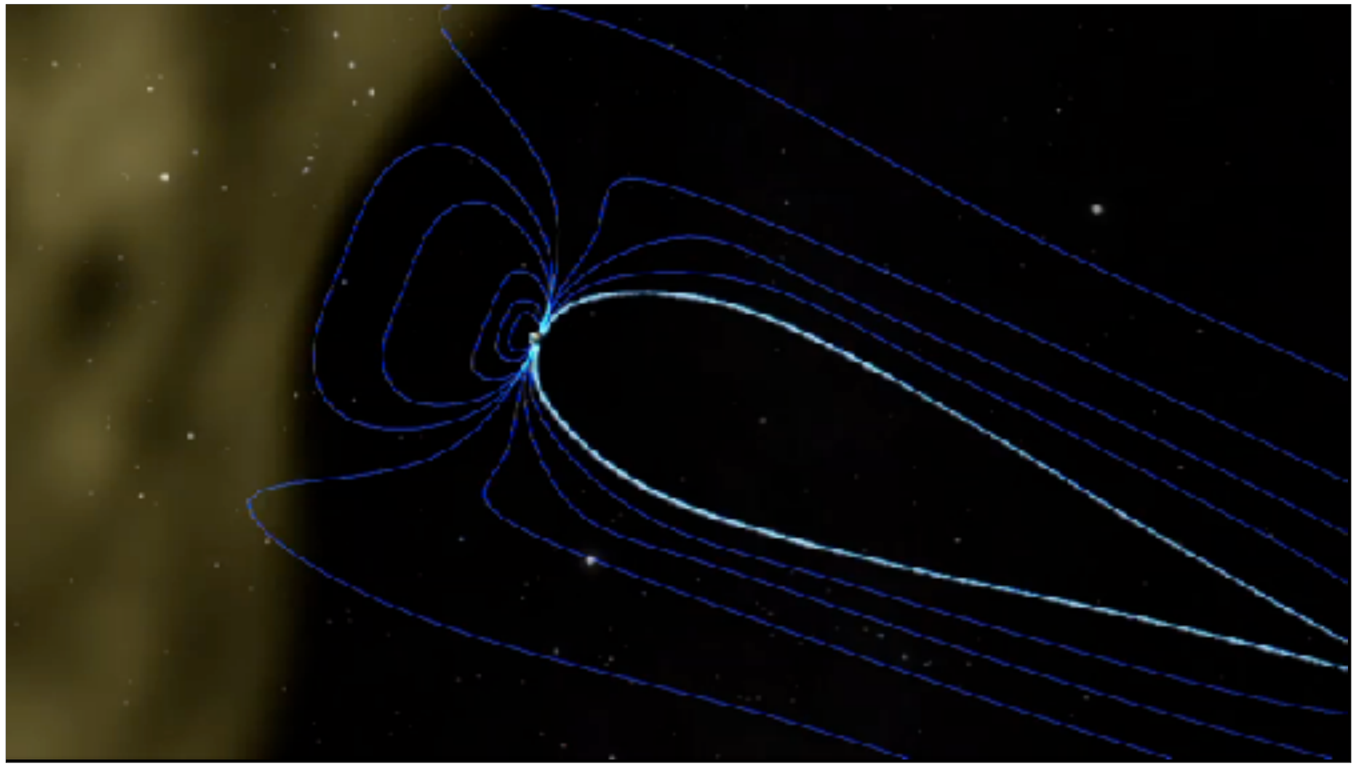


Geomagnetic Storm because of a CME arrival!

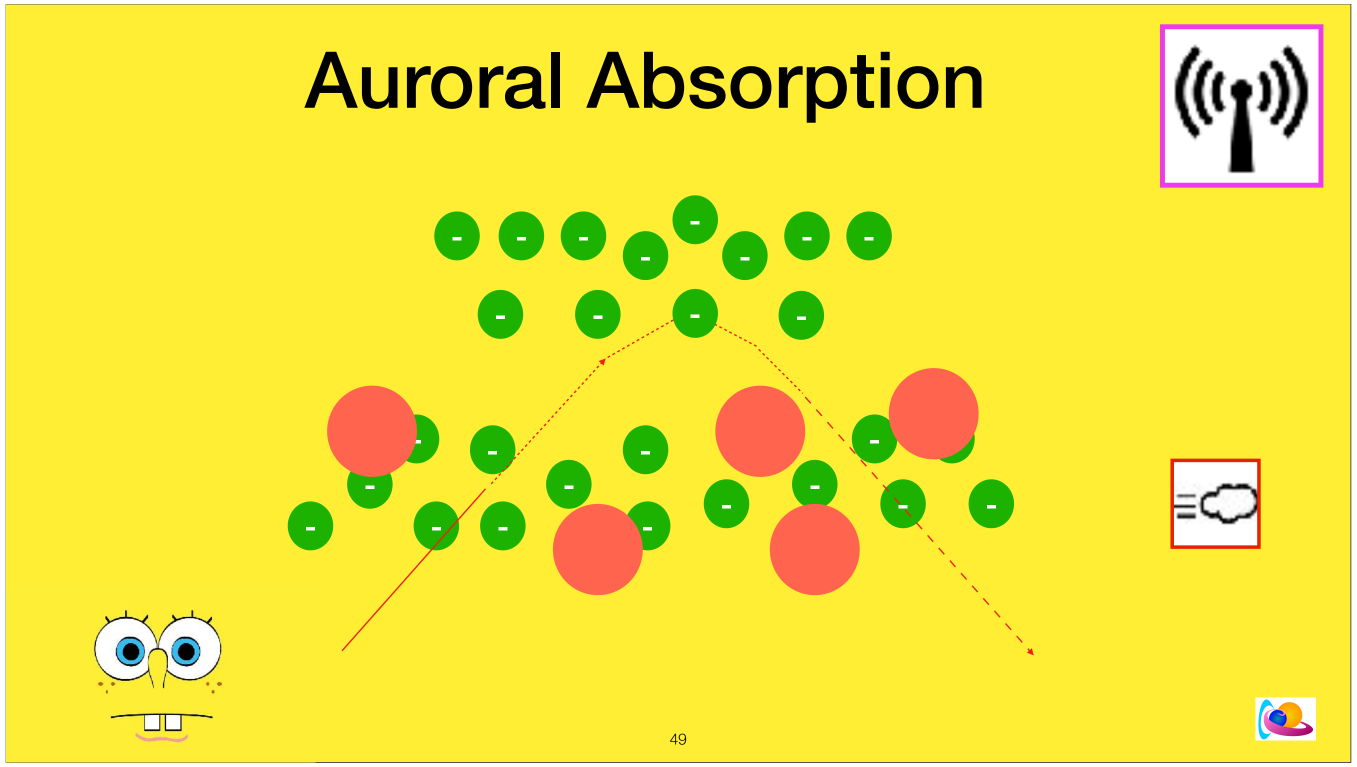
The cloud induced a **severe geomagnetic storm on the planetary level** (purple rectangles in the 6th panel)) and a **moderate geomagnetic storm locally** in Belgium (dark red rectangles in the 7th panel).

These graphs show (from top to bottom): the outward component of the magnetic field, the total magnetic field, the direction of the magnetic field, the density of the solar wind, the velocity of the solar wind, the temperature of the solar wind, The planetary K-index and the Local K-index for Belgium.

Solar wind speed jumped from 360 to 475 km/s, then gradually further increased to values near 700 km/s by 21:00UTC. Bz, the north-south component of the interplanetary magnetic field, showed 2 prolonged periods of negative values: during the 17-20UTC interval, when its value was at a fairly stable -24 nT, and again on 24 April during the 01-09UTC interval when Bz evolved from -33 nT to -9 nT. The Bz value of -33 nT was the lowest since the 7 September 2017 storm (also -33 nT). For even more negative Bz, we have to go back all the way to the Solstice storm of 22 June 2015 when it reached values of -39 nT.



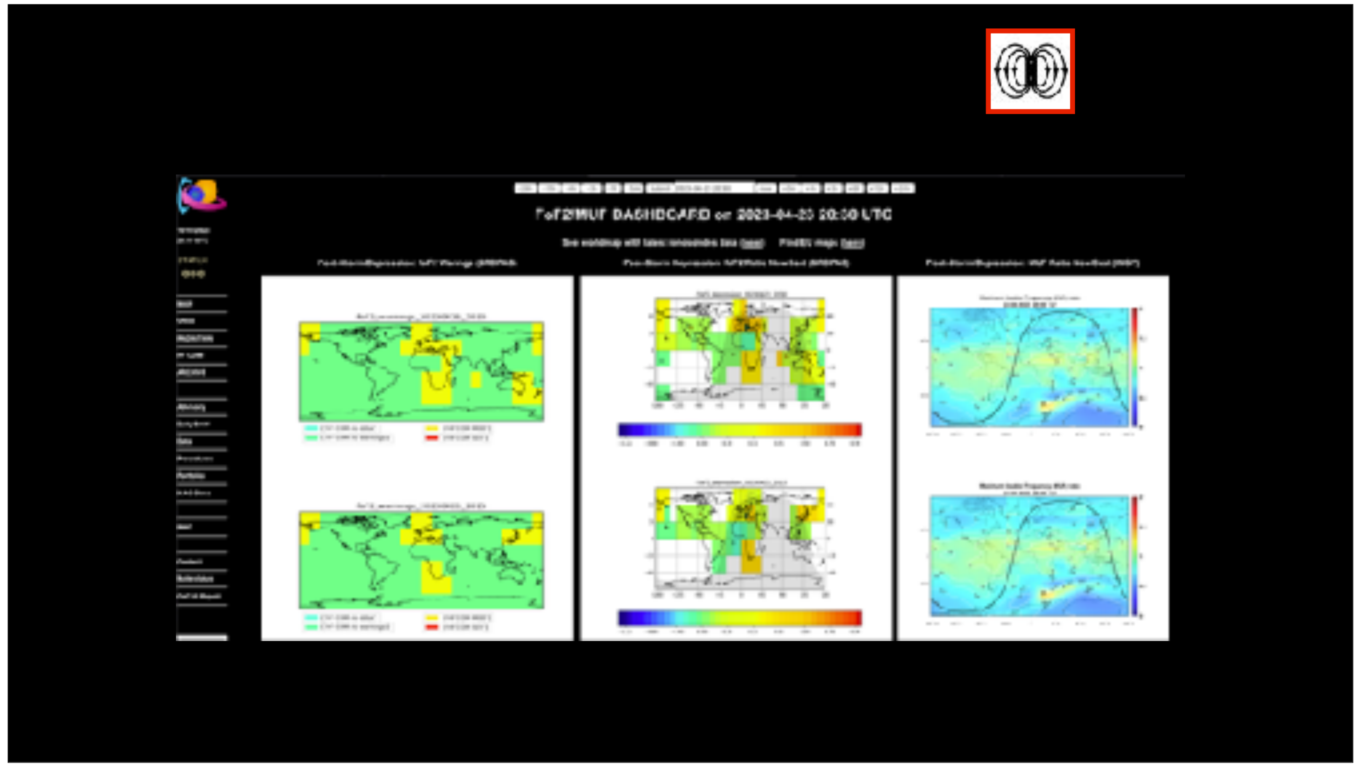
Precipitating electrons coming from the tail



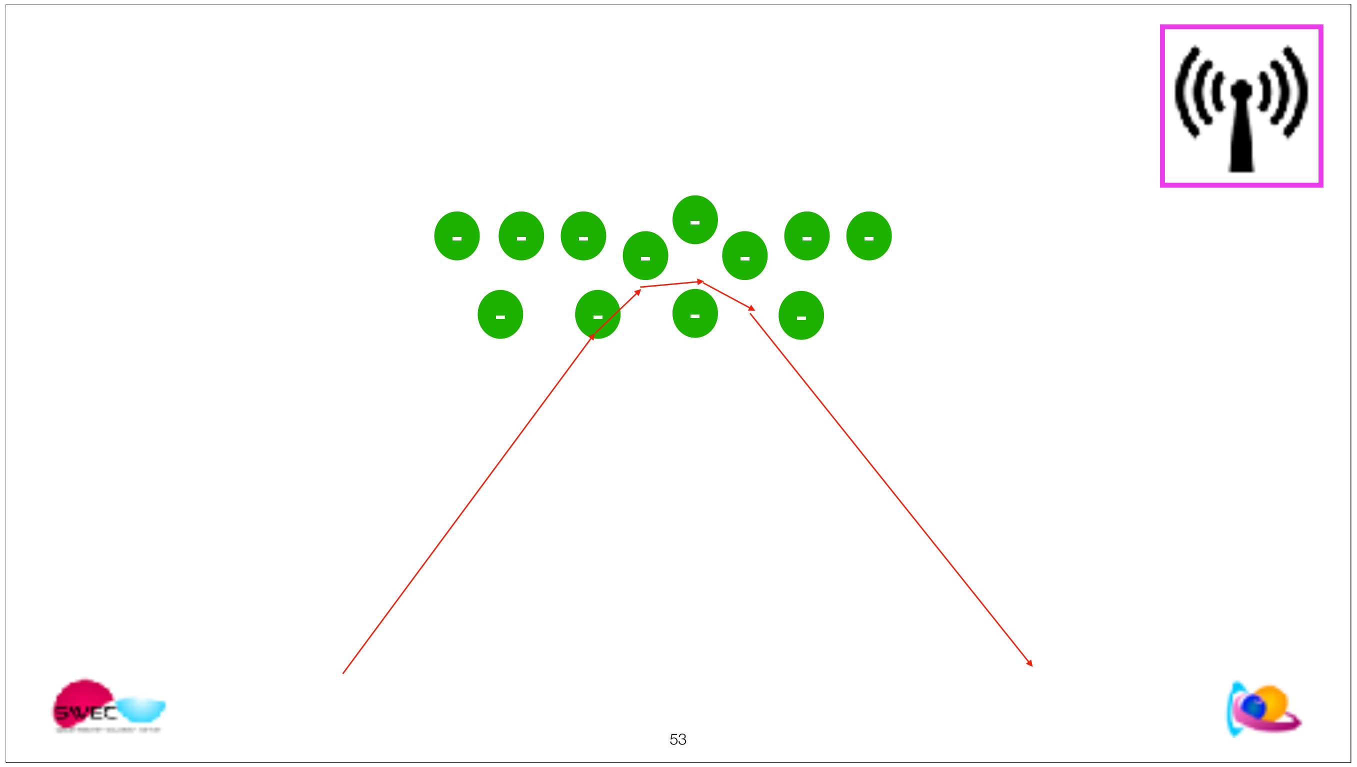
Short Wave Fadeout, auroral absorption, PCA


April 23, 19:57 UTC
WEEE-WOOO-WEEE-
WOOO-WEEE-WOOO!

Focus on Post Storm Depression

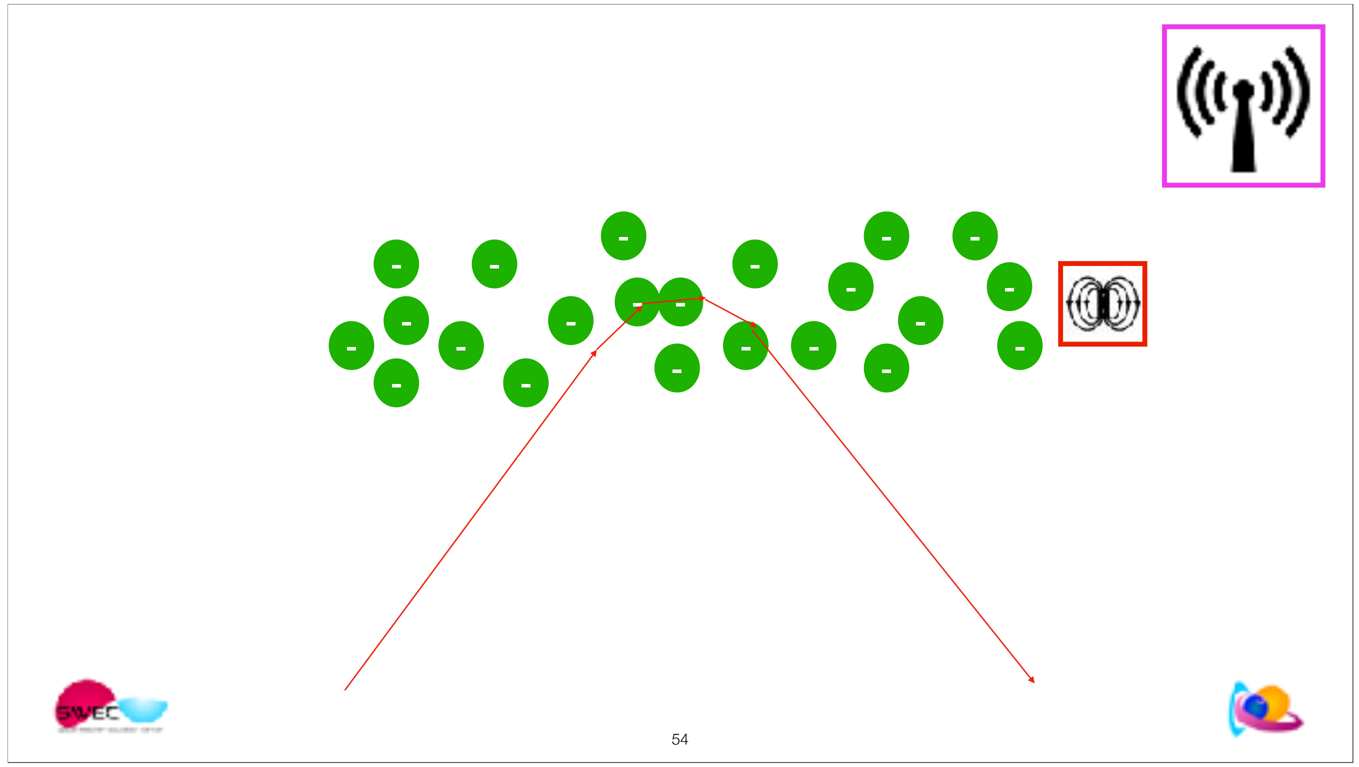


Areas of PSD —> where there are stations.



The ionosphere can reflect waves

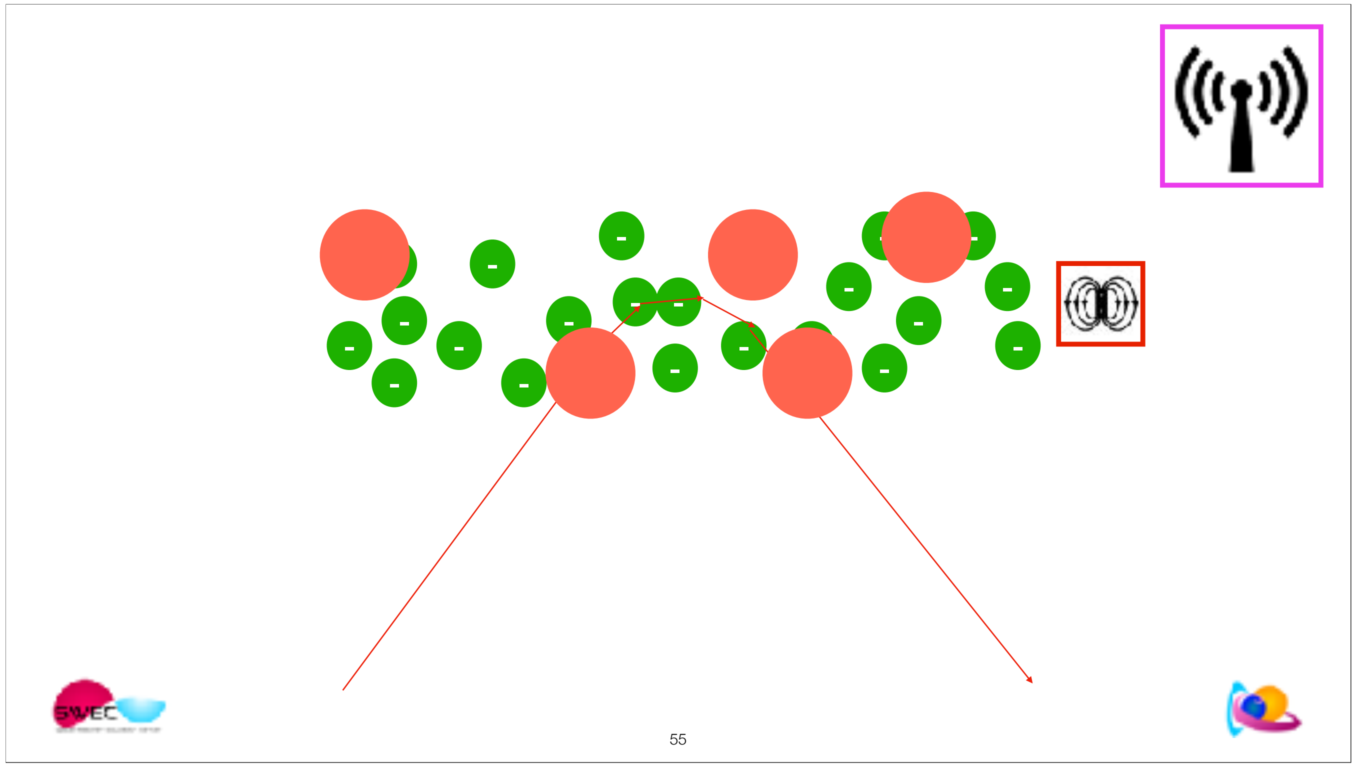
When the ionosphere is not ionised, which waves are being reflected?
As soon as the ionisation increases, waves under the MUF are being reflected.
The higher the ionisation, the higher the MUF.



Increase of electrons - positive phase of the storm - VTEC increases
increase is due to Drift of plasma across B = upward flow
Better HF communication because more waves are being reflected.
Also waves with a higher freq are being reflected. MUF increases

The most significant disturbances to the ionosphere result from solar events (CMEs, CIRs), propagating through the solar wind and interacting with the magnetosphere.

1 Energy injected into the ionosphere, mainly at high latitude.
2 As a result, the auroral oval expands in height and width
3 This causes large scale movement of plasma towards the equator.
4 Drift along the magnetic field lines cause the ionosphere to move up, which can increase electron density (“positive storm phase”).
5 Finally, upwelling of N_2 causes increased recombination, leading to a depletion of ionisation (“negative storm phase”).



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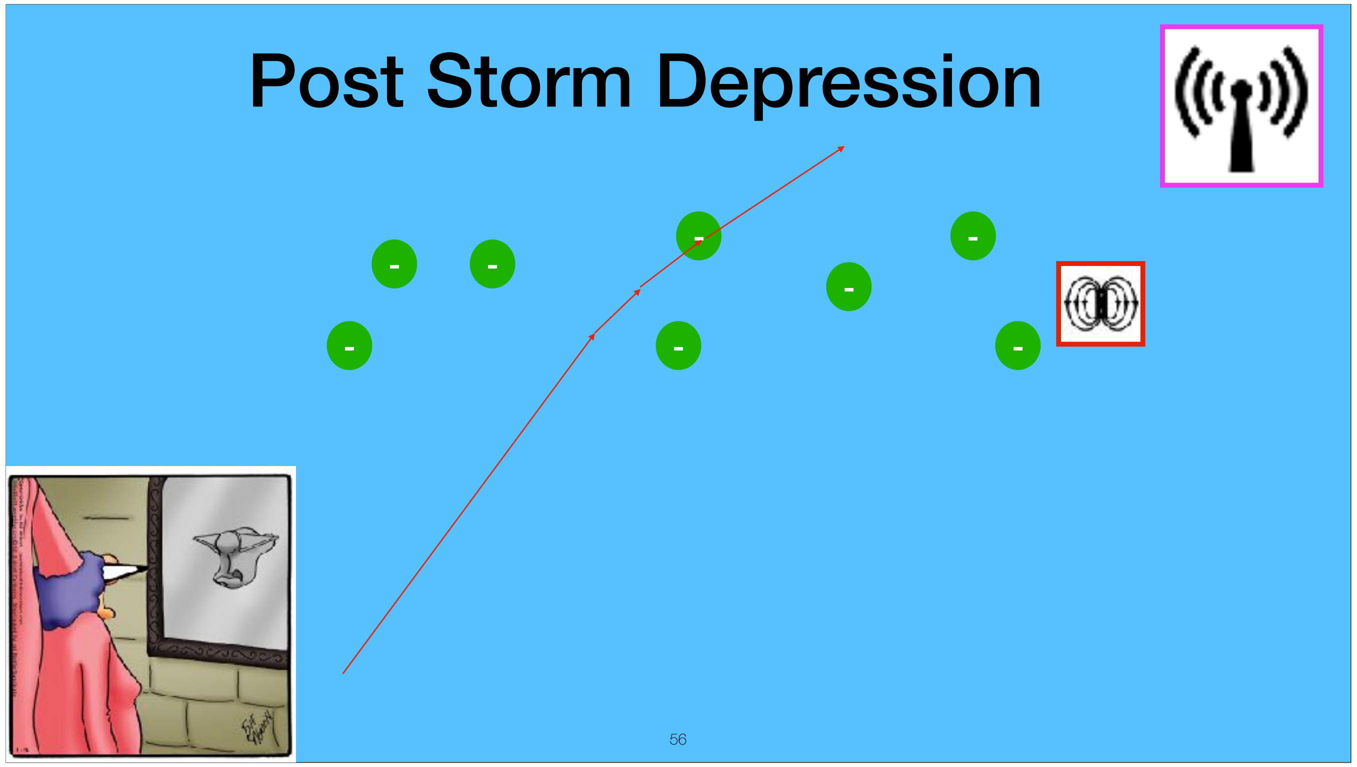

Neutrals are being transported to the F2 layer. This is the second, negative phase of the storm - more electron are being eaten by neutrals.
Less electrons, the MUF decreases —> less frequencies available for HF com
Higher freq radio waves pass through
<u>—> mid-latitude</u>

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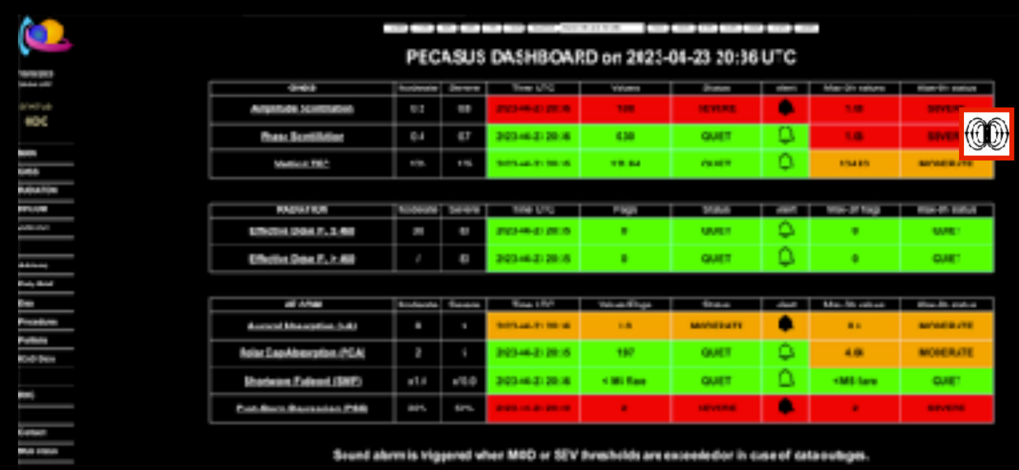
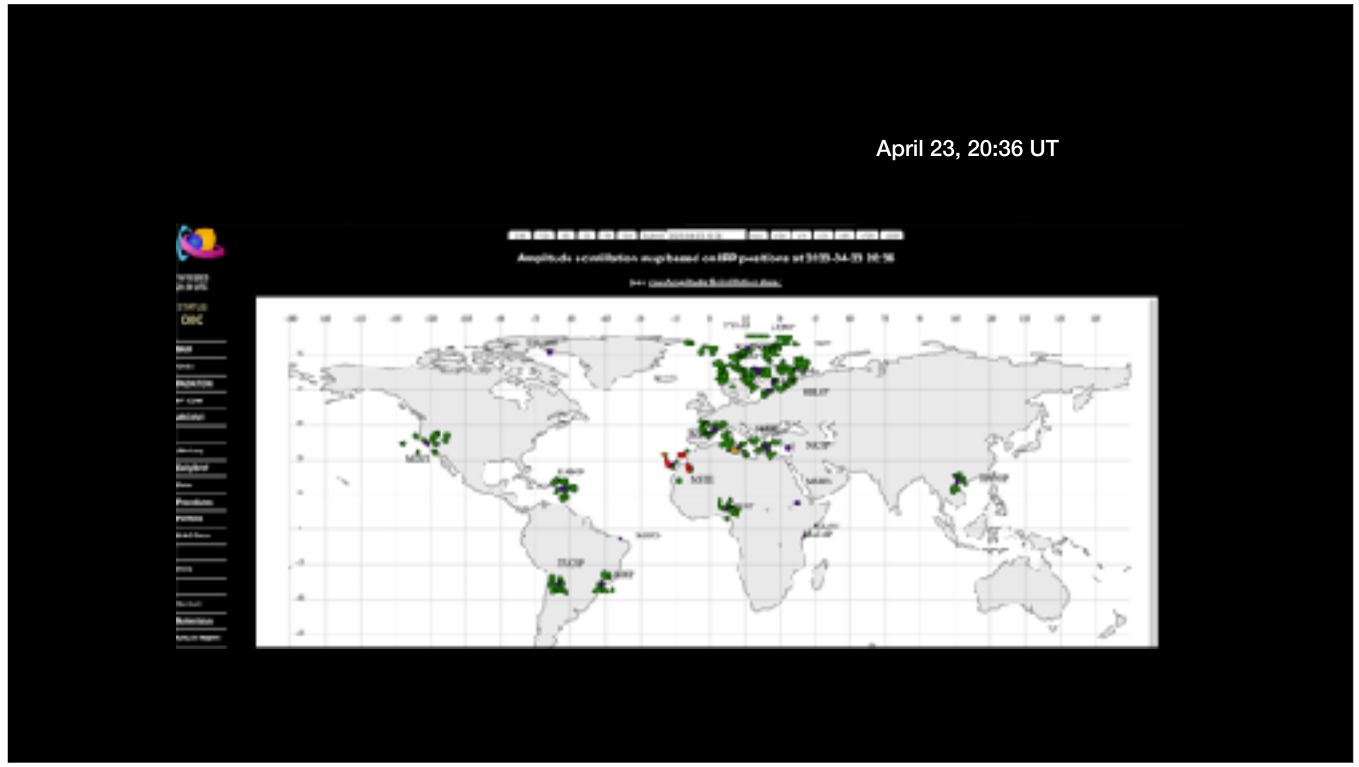
April 23, 20:29 UTC
WEEE-WOOO-WEEE-
WOOO-WEEE-WOOO!

April 23, 20:36 UT



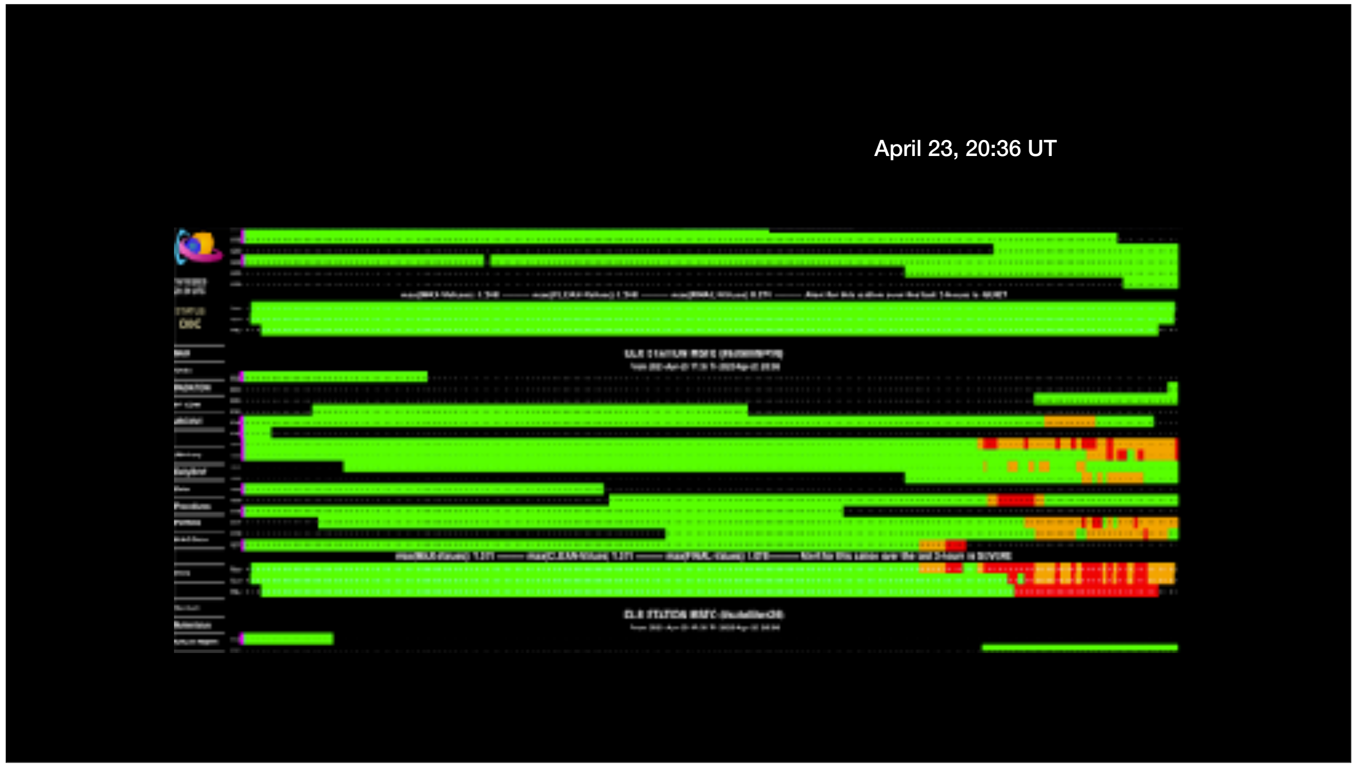
New telephone call
focus on AS



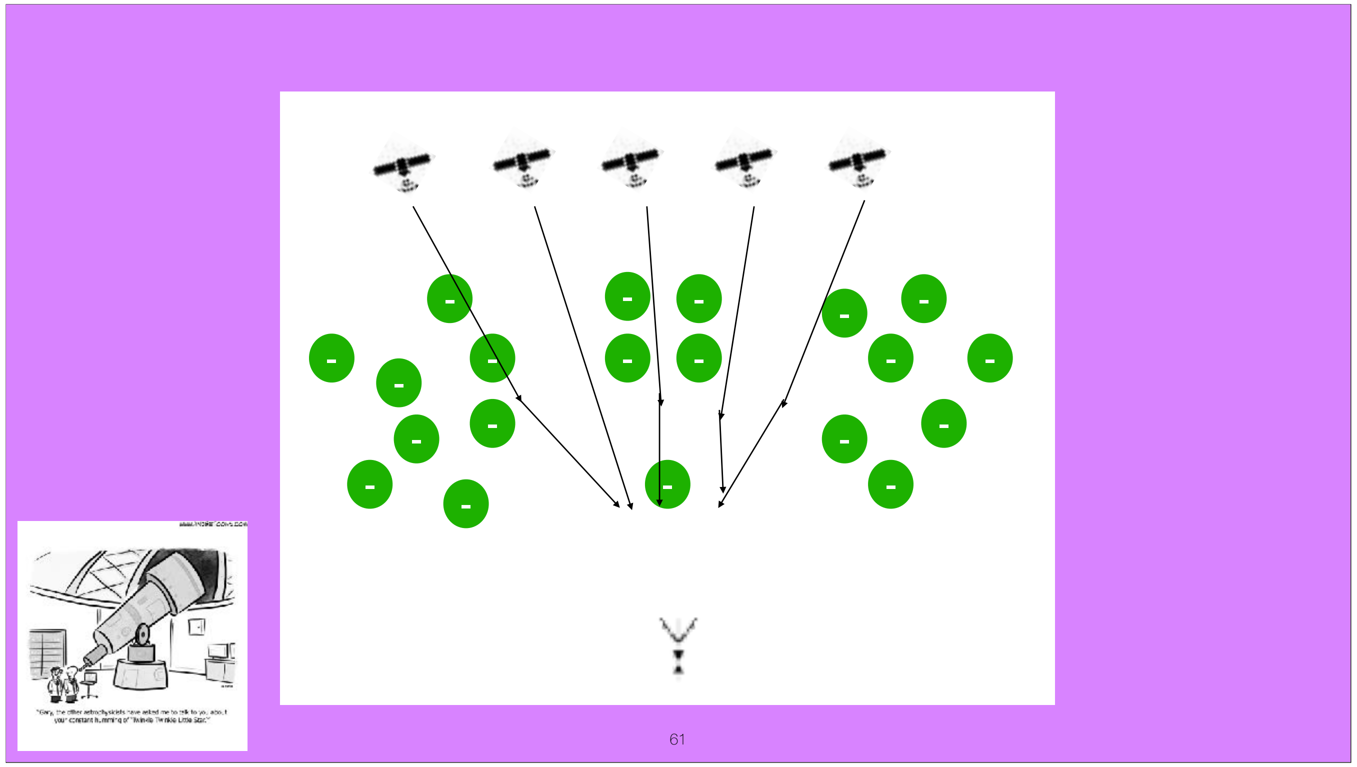
The four mechanisms that give rise to scintillation are

- Plasma bubbles (in the lower latitudes)
- Precipitating particles (auroral oval)
- Patches 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.



Link between a station and satellites
A cross is one minute.



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.


April 23, 20:36 UTC
WEEE-WOOO-WEEE-
WOOO-WEEE-WOOO!

You made it until the end of this presentation!
Well done.

The PECASUS operator on duty at that time was not done yet. Trouble in the ionosphere continues until 4 days after Kp=6

BIS slides

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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
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Post-Storm Depression (PSD)	30%	50%	2020-10-12 14:15	0	QUIET		0	QUIET

Micro = 10^-6
Sieverts = J/kg
Effective dose = Micro Sievert / hour

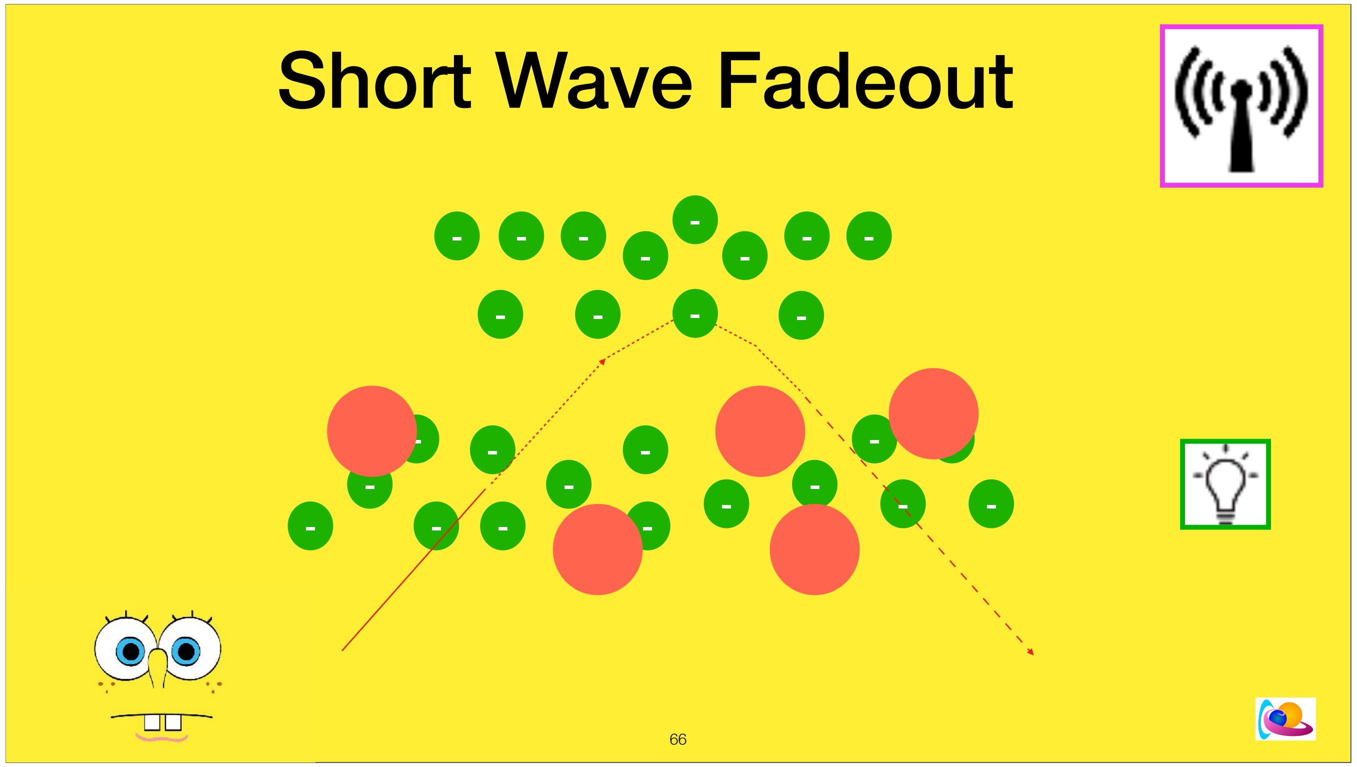
Whole body cancer risk -

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

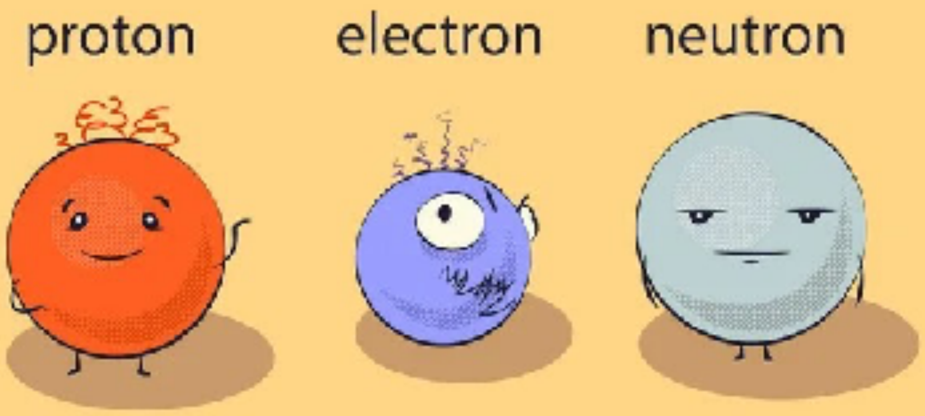
Similar, Solar Radio Bursts can impact also GNSS by adding noise.



Short Wave Fadeout, auroral absorption, PCA


WEEE-WOOO-WEEE-
WOOO-WEEE-WOOO!

Biological impact




WEEE-WOOO-WEEE-
WOOO-WEEE-WOOO!