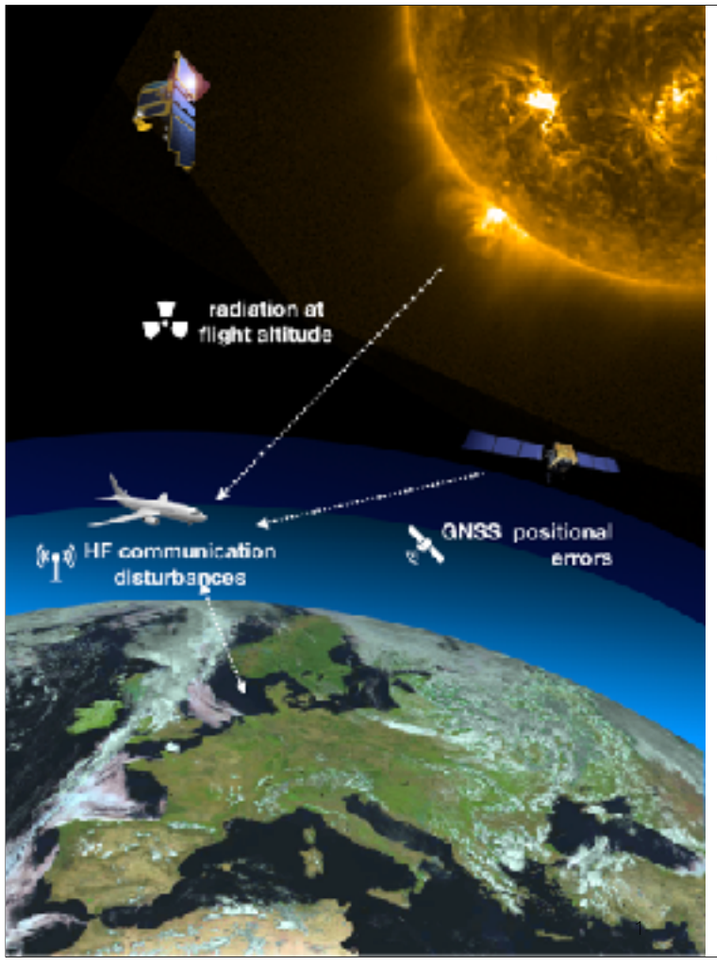


Space Weather impacts on Aviation

PECASUS advisories for ICAO

Course by the
Solar-Terrestrial Centre of Excellence

March 2024

CASE STUDY - April 23, 2023

Sunday

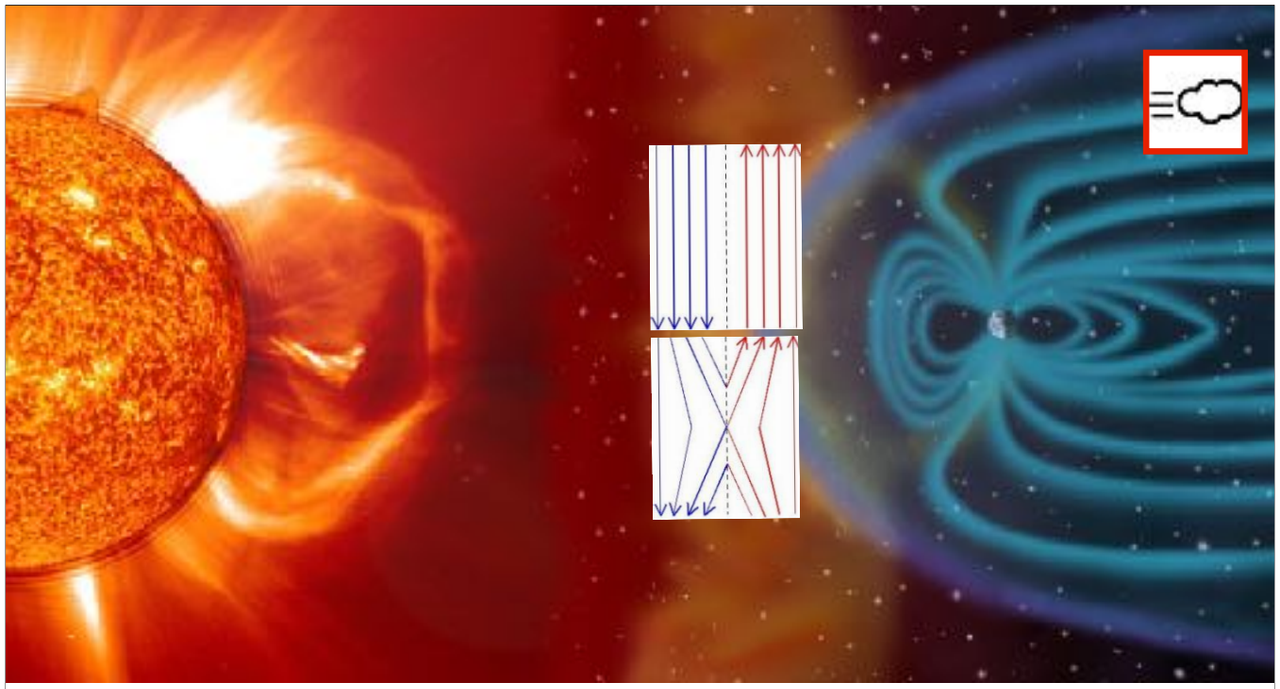
STORM SCALE

e.m. radiation
Flare
8 min
SWF/Radio Blackout
X-ray flux: A,B,C,M,X

Solar wind/plasma
Solar wind disturbance
Days
Geomagnetic storm
Kp: 0 - 9

Energetic particles
Proton Flux
hour
Solar Radiation Storm

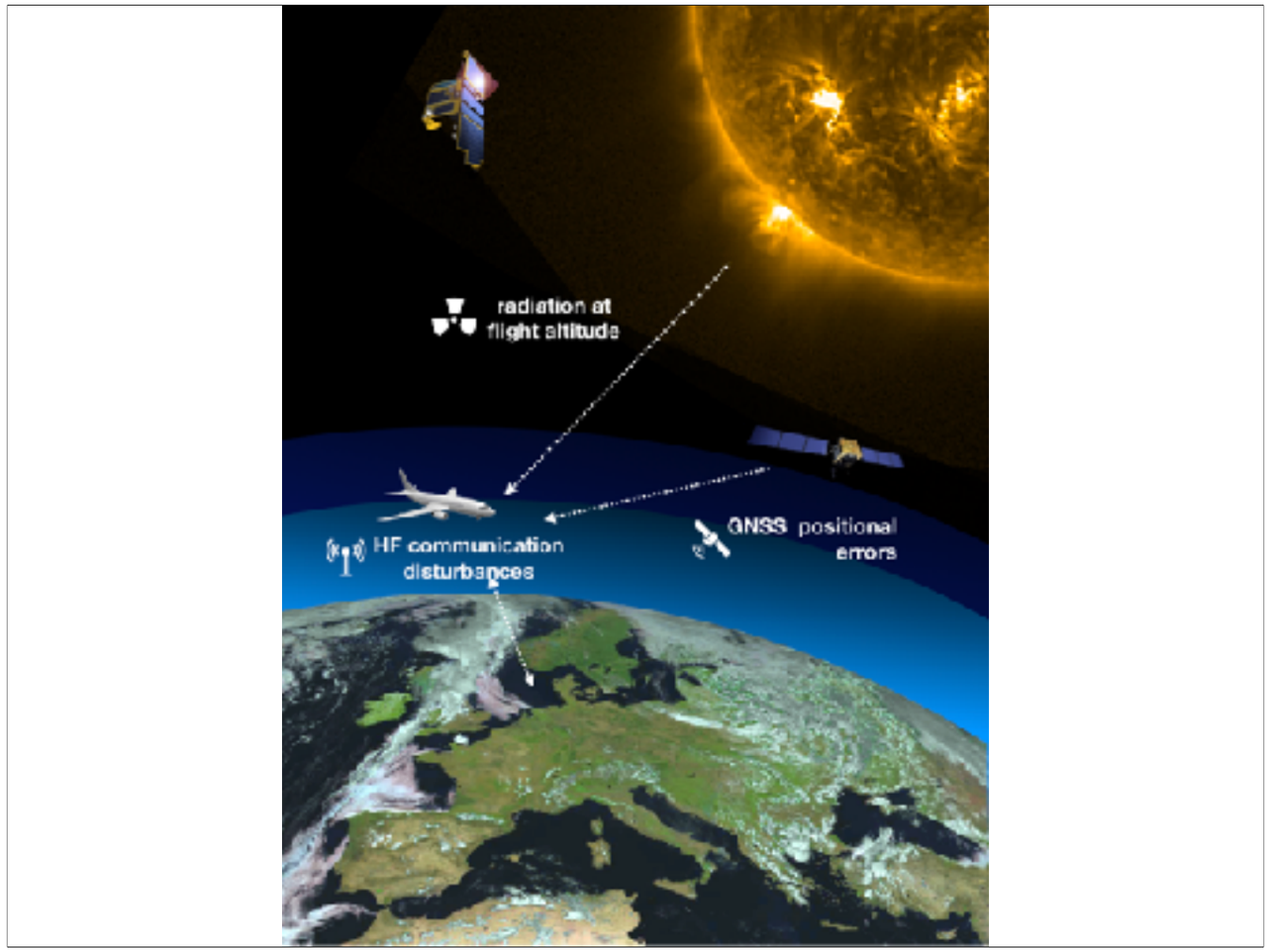
Proton flux can stay elevated for a long time - the stream of protons can be fed by a CME that keeps on pushing the particles, and this for the total transit time (1 AU)



RECONNECTION

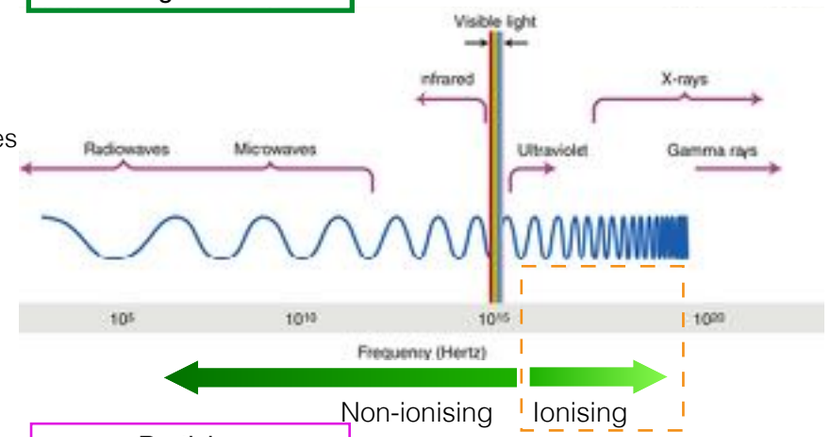
The magnetic field carried by the solar wind can couple with the magnetic field of Earth. This coupling is stronger when the solar wind magnetic field is opposite to the magnetic field of Earth.

Magnetic reconnection at the magnetosphere of Earth.


radiation at
flight altitude
HF communication
disturbances
GNSS positional
errors

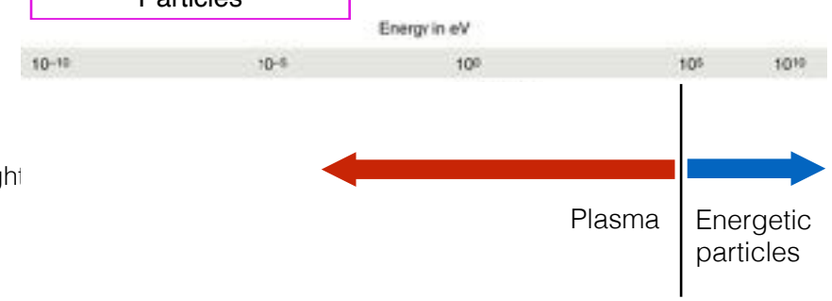
Electromagnetic radiation

- Photons / electromagnetic waves
- Speed of light



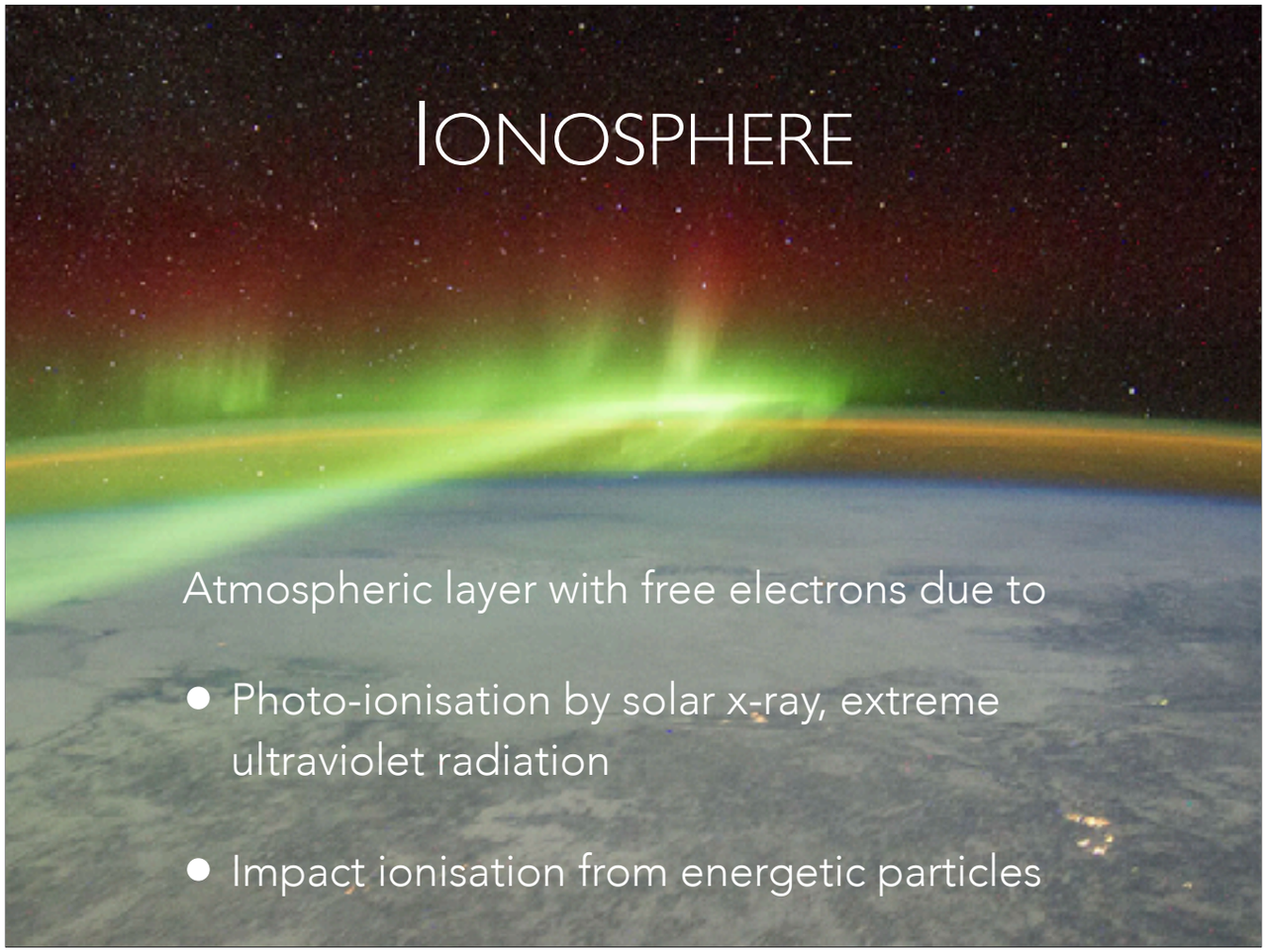
Particles

- Atomic & sub-atomic particles
- km/s to fractions of speed of light



100 kEV
Plasma in

Photo-ionisation
Impact ionisation



To understand what the ionosphere does that affects these radio waves, we must first understand what the ionosphere is.

The picture shows the ‘Northern Lights’, seen from the International Space Station. The aurora makes the ionosphere visible to us.

The ionosphere is that part of the upper atmosphere where free electrons occur in sufficient density to have an appreciable influence on the propagation of radio frequency electromagnetic waves. This ionization depends primarily on the Sun and its activity. ionospheric structures and peak densities in the ionosphere vary greatly with time (sunspot cycle, seasonally, and diurnally), with geographical location (polar, auroral zones, mid-latitudes, and equatorial regions), and with certain solar-related ionospheric disturbances.

The major part of the ionization is produced by solar X-ray and ultraviolet radiation and by corpuscular radiation from the Sun. The most noticeable effect is seen as the Earth rotates with respect to the Sun; ionization increases in the sunlit atmosphere and decreases on the shadowed side. Although the Sun is the largest contributor toward the ionization, cosmic rays make a small contribution. Any atmospheric disturbance affects the distribution of the ionization.

The ionosphere is a **dynamic system controlled by** many parameters including **acoustic motions of the atmosphere, electromagnetic emissions, and variations in the geomagnetic field**. Because of its extreme sensitivity to atmospheric changes, the ionosphere is a very sensitive monitor of atmospheric events.

The most accurate way of measuring the ionosphere is with a ground-based ionosonde, which records data as ionograms.

Trouble in the Ionosphere

To understand what the ionosphere does that affects these radio waves, we must first understand what the ionosphere is.

The picture shows the ‘Northern Lights’, seen from the International Space Station. The aurora makes the ionosphere visible to us.

The ionosphere is that part of the upper atmosphere where free electrons occur in sufficient density to have an appreciable influence on the propagation of radio frequency electromagnetic waves. This ionization depends primarily on the Sun and its activity. ionospheric structures and peak densities in the ionosphere vary greatly with time (sunspot cycle, seasonally, and diurnally), with geographical location (polar, auroral zones, mid-latitudes, and equatorial regions), and with certain solar-related ionospheric disturbances.

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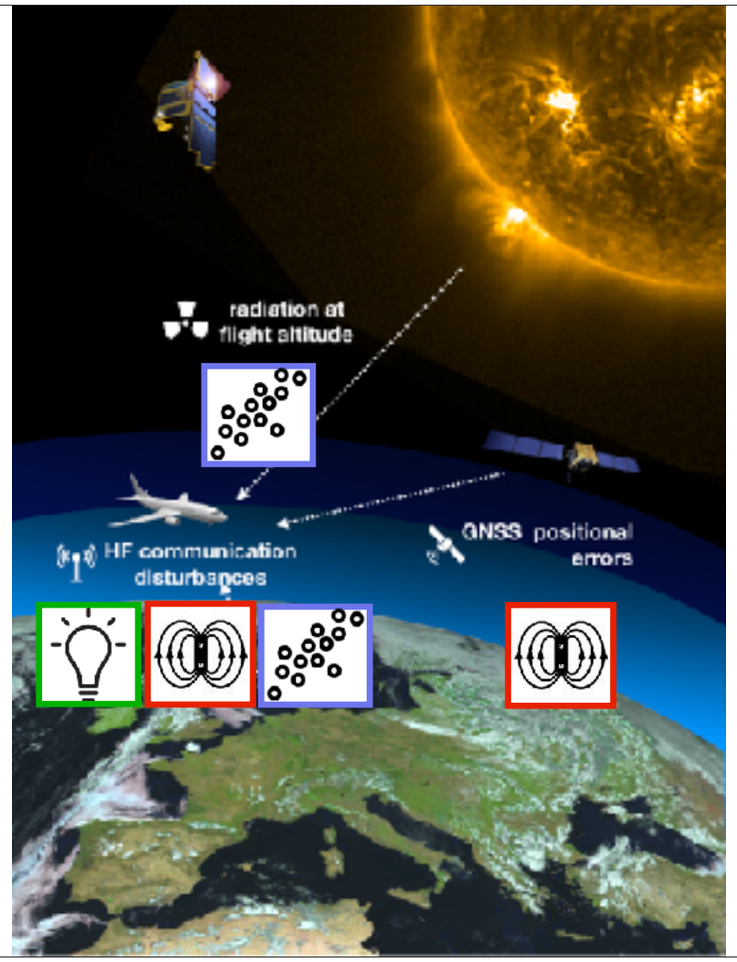
The most accurate way of measuring the ionosphere is with a ground-based ionosonde, which records data as ionograms.


radiation at
flight altitude
HF communication
disturbances
GNSS positional
errors

GNSS	Moderate	Severe	Time UTC	Values	Status	Alert	Max-3h values	Max-3h status
Amplitude Scintillation	0.5	0.8	2020-12-12 14:15	0.25	QUIET		0.35	QUIET
Phase Scintillation	0.4	0.7	2020-12-12 14:15	0.13	QUIET		0.14	QUIET
Vertical TEC	125	175	2020-12-12 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	2020-12-12 14:20	0	QUIET		0	QUIET
Effective Dose FL > 460	/	80	2020-12-12 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	2020-12-12 14:10	3.0	QUIET		3.0	QUIET
Polar Cap Absorption (PCA)	2	5	2020-12-12 14:20	0.00	QUIET		0.00	QUIET
Shortwave Fadeout (SWF)	x1.0	x10.0	2020-12-12 14:17	< M.5-flare	QUIET		< M.5-flare	QUIET
Post-Storm Depression (PSD)	30%	50%	2020-12-12 14:15	0	QUIET		0	QUIET

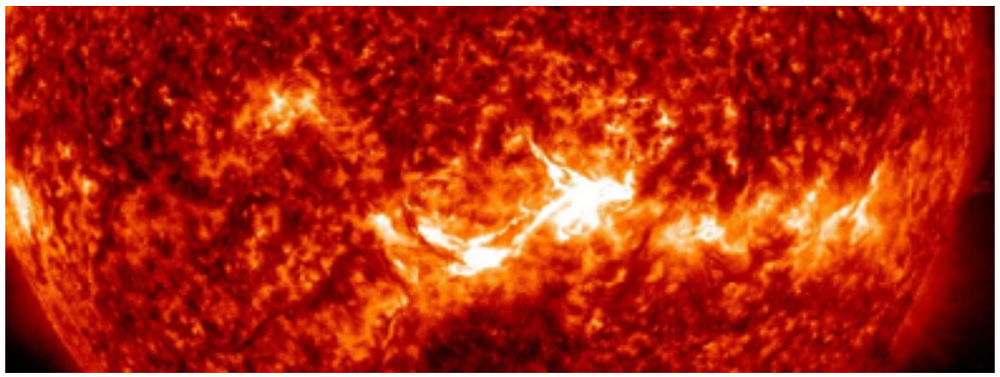
Ionosphere is needed for long distance HF communication which makes use of the reflective capability of the ionosphere. The ionosphere acts as a mirror.

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

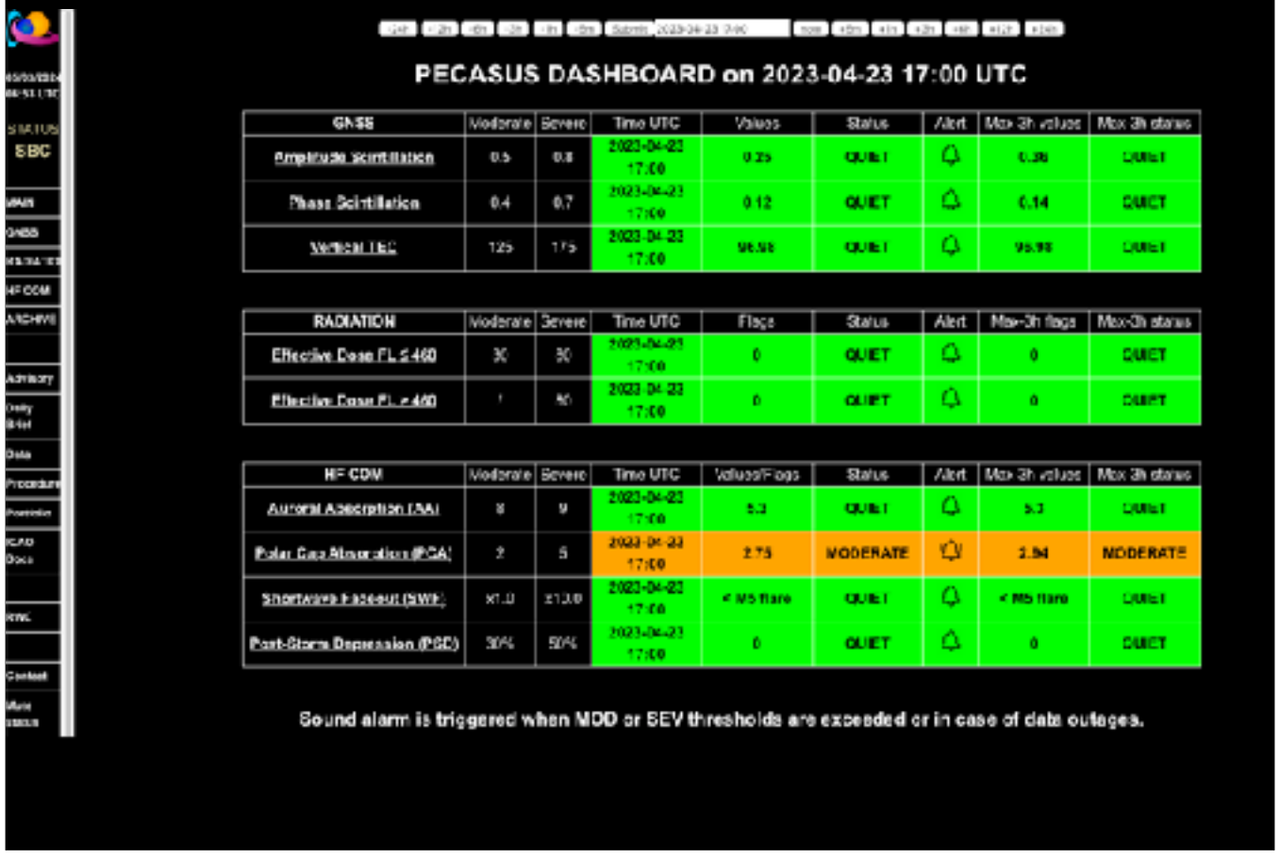
HF Com
If you have a strong radio burst in HF, your MUF might be full of solar noise and in practice not usable. But SRB are not taken into account by ICAO

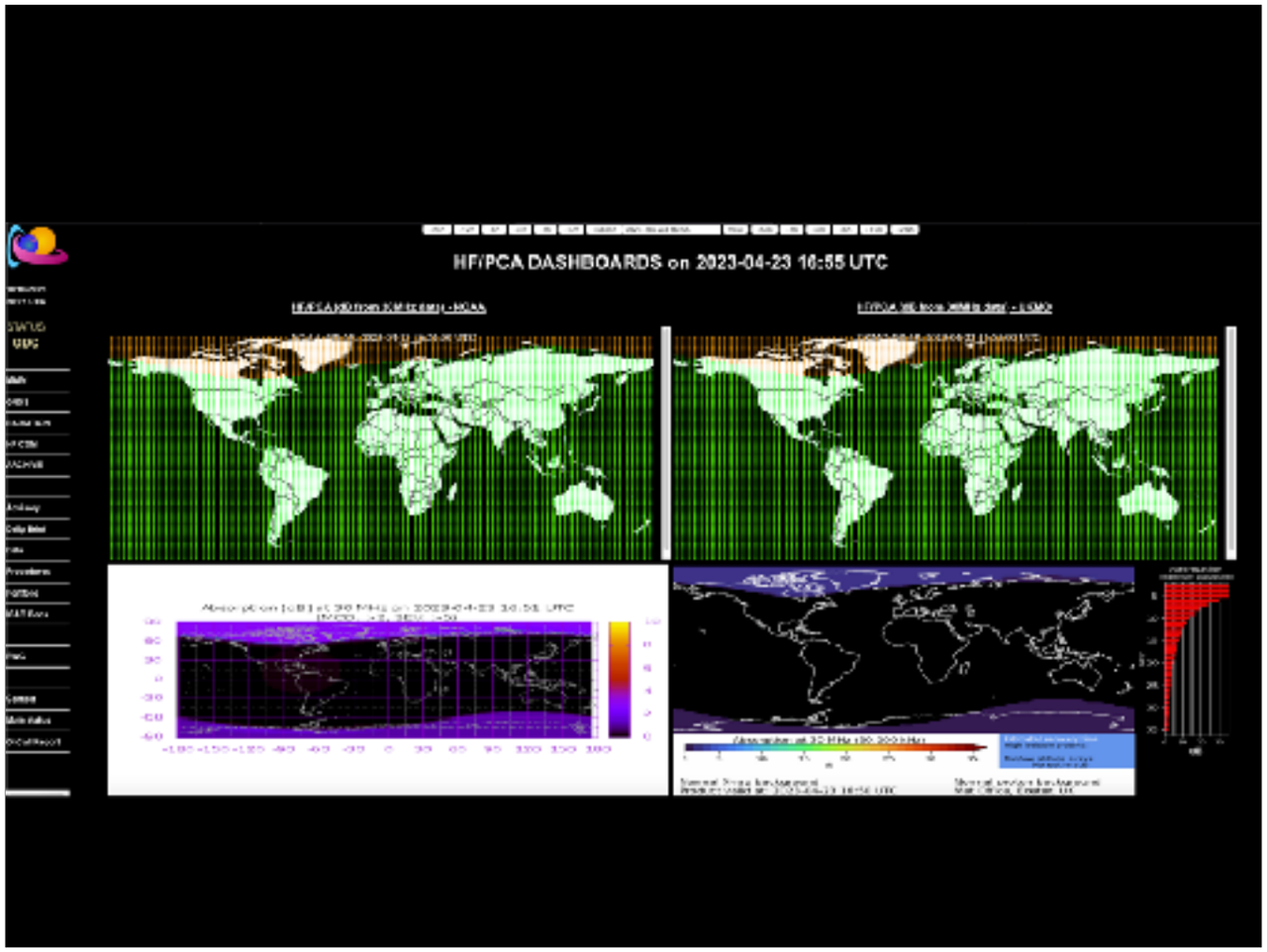
Solar and heliospheric storms impacting aviation

CASE STUDY - April 21, 2023



Elke’s case study started at April 21 with an M-flare.


PECASUS DASHBOARD on 2023-04-23 17:00 UTC
GNSS
Moderate
Severe
Time UTC
Values
Status
Alert
Max-3h values
Max-3h status
Amplitude Scintillation
0.5
0.8
2023-04-23 17:00
0.23
QUIET
0.36
QUIET
Phase Scintillation
0.4
0.7
2023-04-23 17:00
0.12
QUIET
0.14
QUIET
Vertical TEC
125
175
2023-04-23 17:00
QUIET
RADIATION
Moderate
Severe
Time UTC
Flags
Status
Alert
Max-3h flags
Max-3h status
Effective Dose FL ≤ 460
30
50
2023-04-23 17:00
0
QUIET
0
QUIET
Effective Dose FL > 460
1
10
2023-04-23 17:00
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
2023-04-23 17:00
5.3
QUIET
5.3
QUIET
Polar Cap Absorption (PCA)
2
5
2023-04-23 17:00
2.75
MODERATE
2.94
MODERATE
Shortwave Fadeout (SWF)
X1.0
X10.0
2023-04-23 17:00
< M5 flare
QUIET
< M5 flare
QUIET
Post-Storm Depression (PSD)
30%
50%
2023-04-23 17:00
0
QUIET
0
QUIET
Sound alarm is triggered when MOD or SEV thresholds are exceeded or in case of data outages.

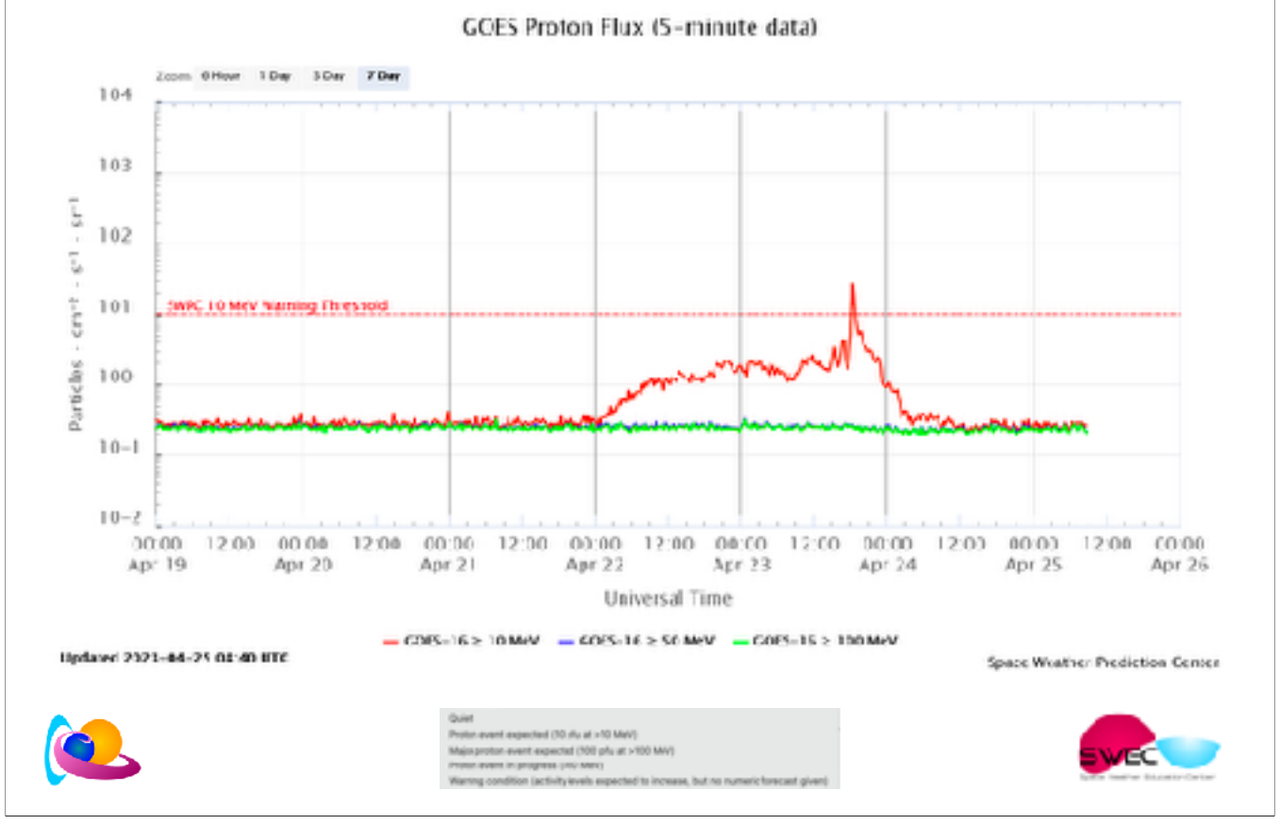


DRAP model

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

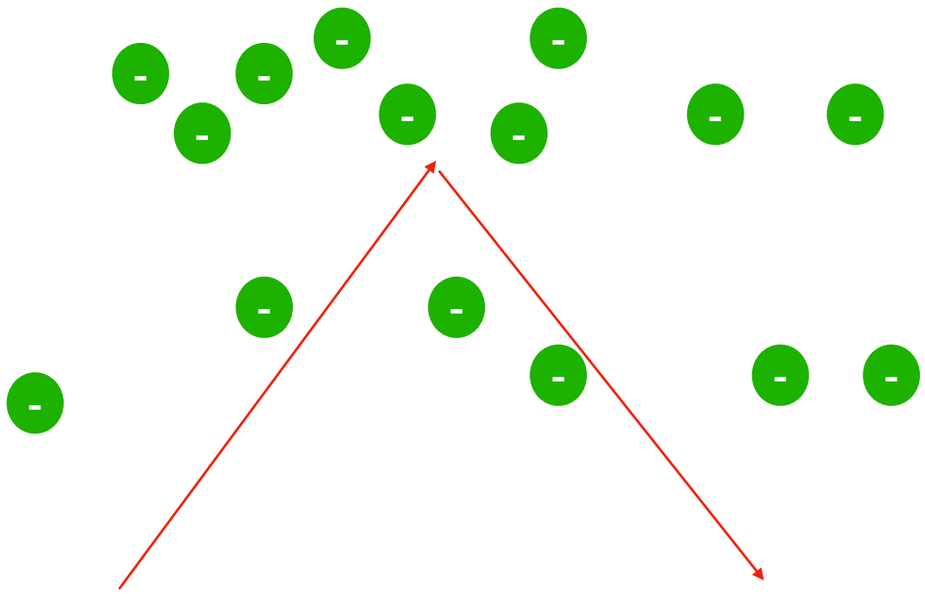
PCA - scherpe overgang - bruut over van open naar gesloten magnetische veldlijnen.
De deeltjes moeten een open route (open veldlijn) hebben om af te dalen naar de D-laag

Proton Event



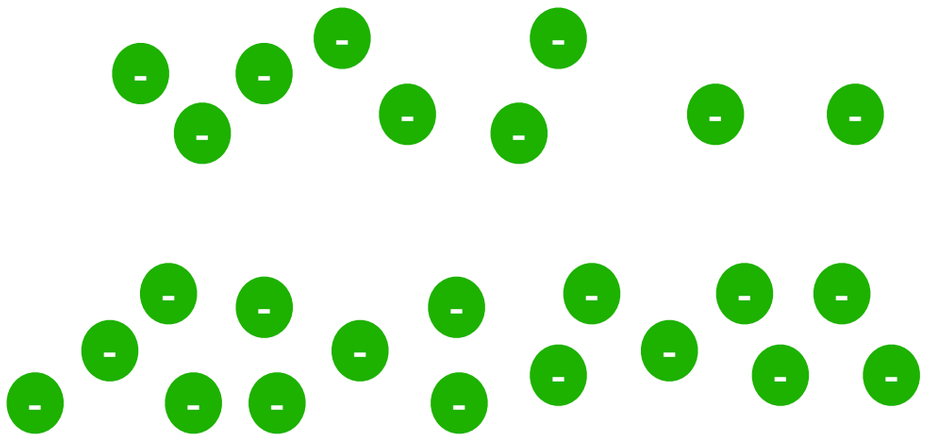
A shock was recorded in the solar wind parameters on 23 April at 17:00UTC (DSCOVR ; graph). It marked the **somewhat (a few hours) earlier-than-expected arrival of the interplanetary coronal mass ejection (ICME**). **The passage of the shock briefly drove the already enhanced greater than 10 MeV proton 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.

PCA

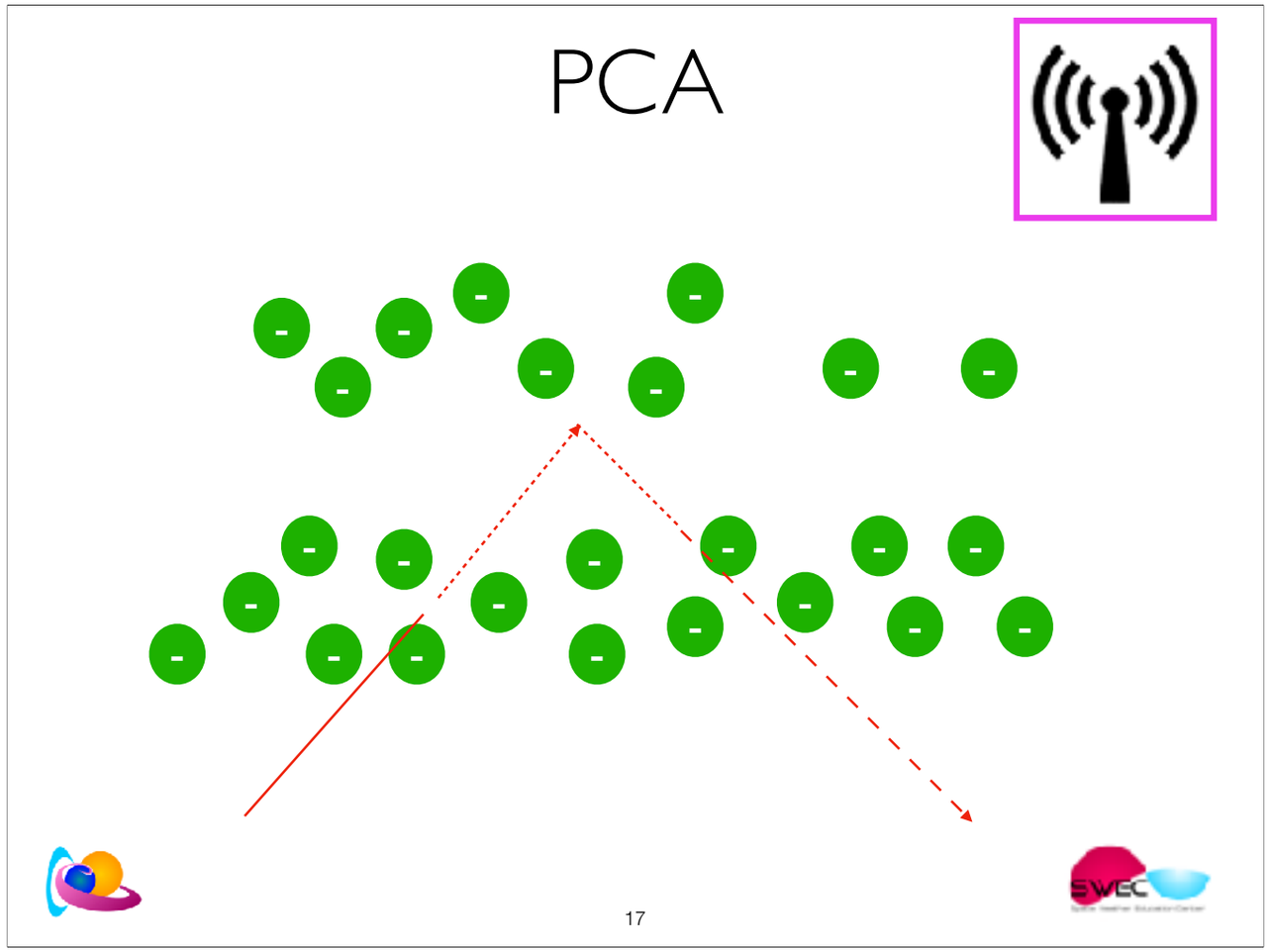


Radio wave makes the electrons move. Those moving electrons reproduce on their turn the radio signal and re-emitting it. This is how reflection works in the ionosphere. It is a region full of magic (with a negative refractive index).

PCA



The incoming solar energetic particles ionise the D-layer.



D-region - ionisation of this regions causes absorption instead of reflection
Radio wave comes into the ionosphere, the electrons absorb the energy of the incoming radio wave and start moving. These moving electrons produce/reemit on their turn the radio signal. This is how reflection works.
In the D-layer is the neutral density high. The electrons are not free to move around. The electron still absorb the energy of the incoming radio wave, but they can’t move. So, the electrons can’t re-emit the total absorbed energy but simply convert it into heat.

D-region: the electron absorbs and reemits, but the neutral gas makes the electrons to dissipate the absorbed energy in the form of heat.

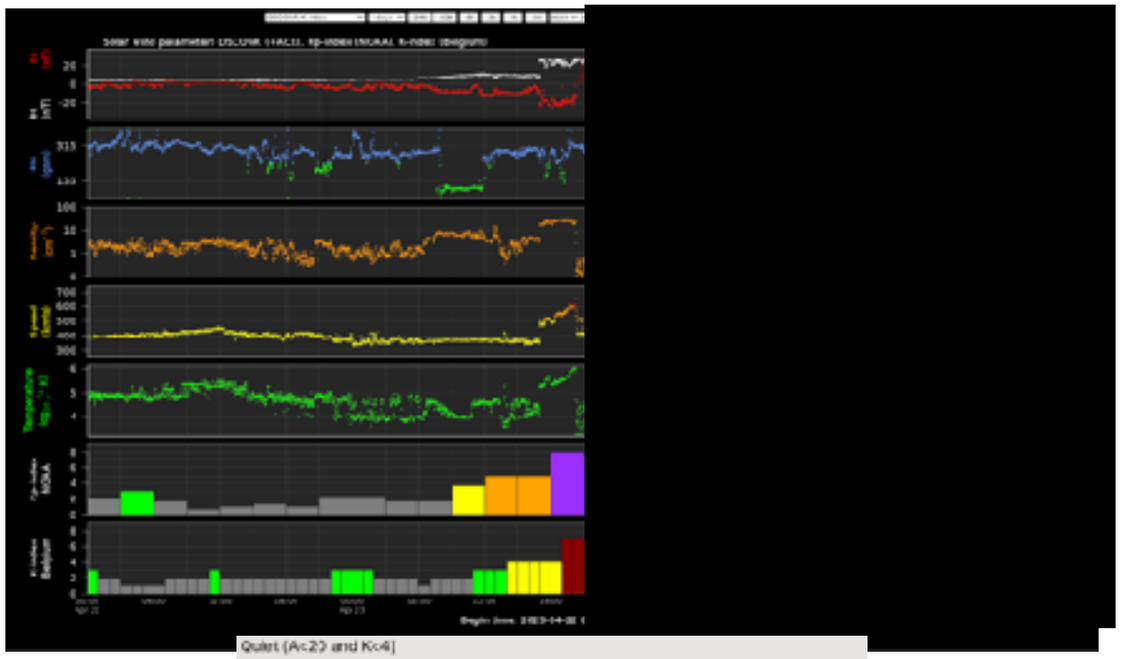
```
SWX ADVISORY
DTG:              20230423/1706Z
SWXC:             PECASUS
ADVISORY NR:      2023/59
SWX EFFECT:       HF COM MOD
OBS SWX:          23/1655Z HNH W150 - E000
FCST SWX +6 HR:   23/2300Z NOT AVBL
FCST SWX +12 HR:  24/0500Z NOT AVBL
FCST SWX +18 HR:  24/1100Z NOT AVBL
FCST SWX +24 HR:  24/1700Z 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


PECASUS DASHBOARD on 2023-04-23 18:50 UTC
Sound alarm is triggered when MOD or SEV thresholds are exceeded or in case of data outages.

Focus on AA

CME arrival



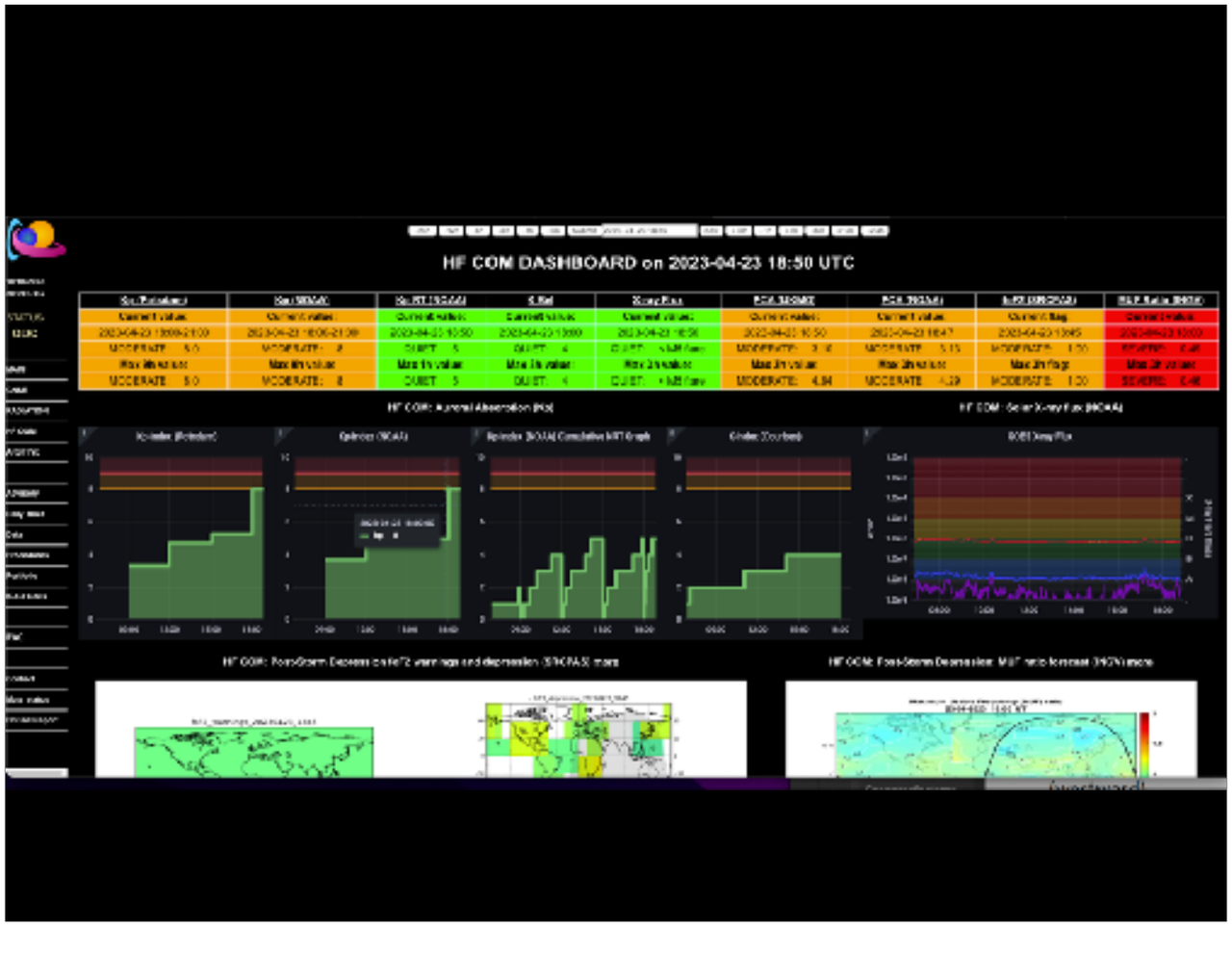
Quiet (A<20 and K<4)
Active conditions expected (A>=20 or K=4)
Minor storm expected (A>=30 or K=5)
Moderate (ISES: Major) magstorm expected (A>=50 or K=6)
Major (ISES: Severe) magstorm expected (A>=100 or K>=7)
Warning condition (activity levels expected to increase, but no numeric forecast given)

Geomagnetic Storm because of a CME arrival!

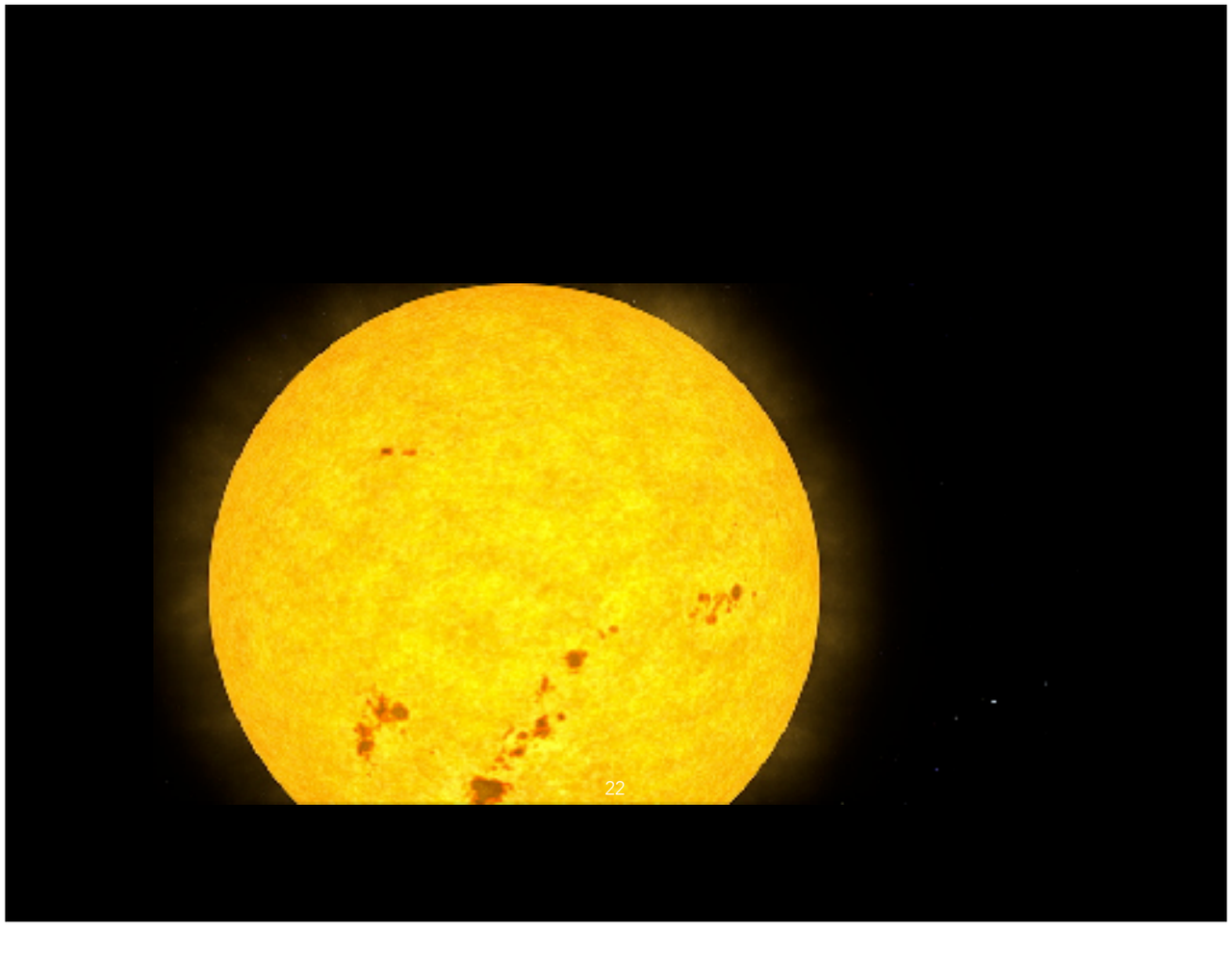
The satellite DSCOVR in a point 1 hour upstream of the earth, which means that it takes the solar wind 1 hour to reach the Earth, 'saw' the cloud passing and measured a jump on **April 23, 17UT** as seen in the top panel of the graph below. The cloud induced a **severe geomagnetic storm on the planetary 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.

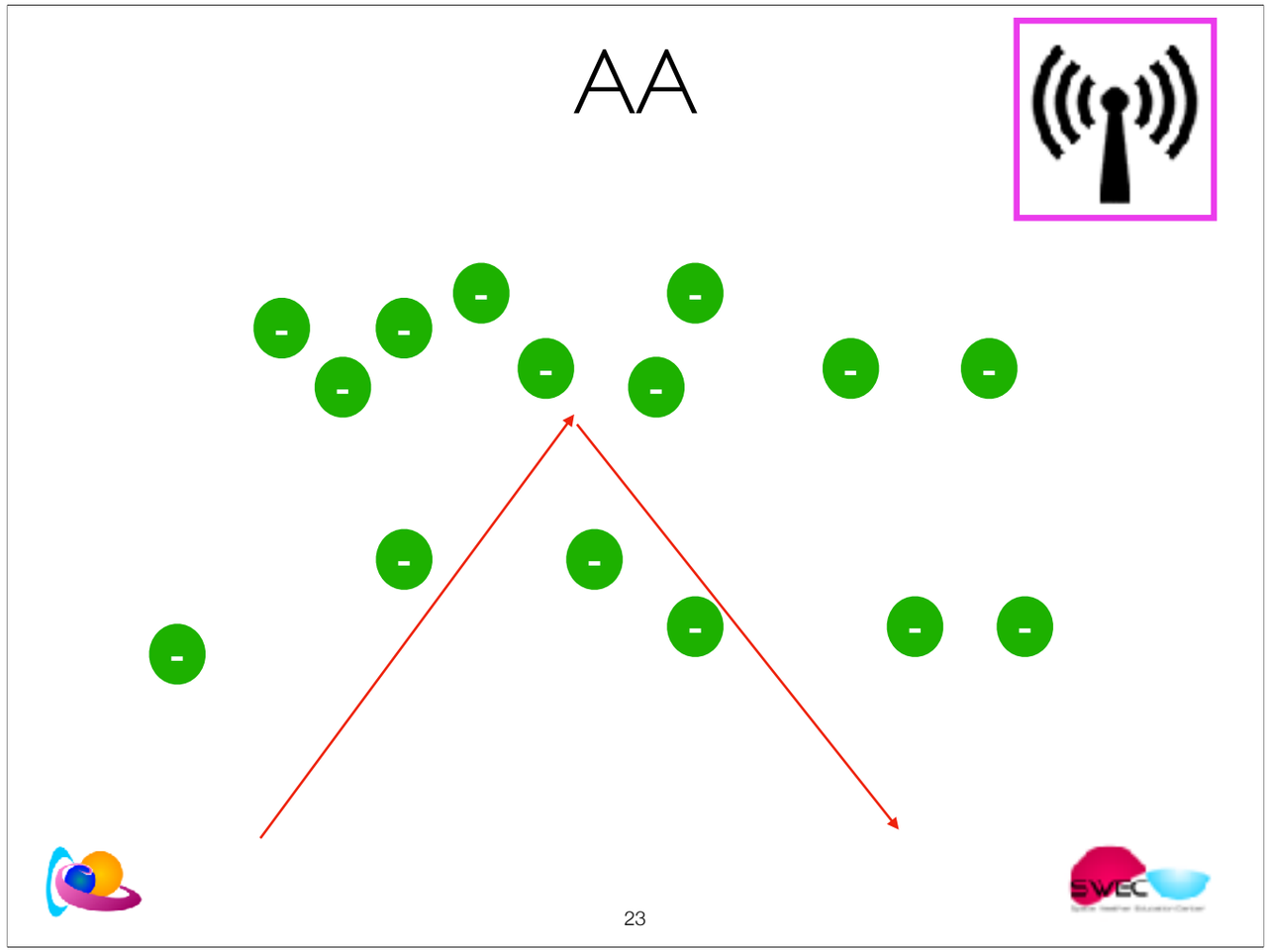
Solar wind speed jumped from 360 to 475 km/s, then gradually further increased to values near 700 km/s by 21:00UTC. Bz, the north-south component of the interplanetary magnetic field, showed 2 prolonged periods of negative values: during the 17-20UTC interval, when its value was at a fairly stable -24 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.



Kp is a 3 hour index. Normally, we should wait 3 hours to see if it really reaches 8. The operator made an assessment: 'It will'.



This is how auroral absorption works: precipitating electrons from the tail induce extra ionisation of the D-layer.
Those electrons have no direct solar origin. They are present in the plasmasphere and get an energy boost from the magnetic reconnection in the tail.



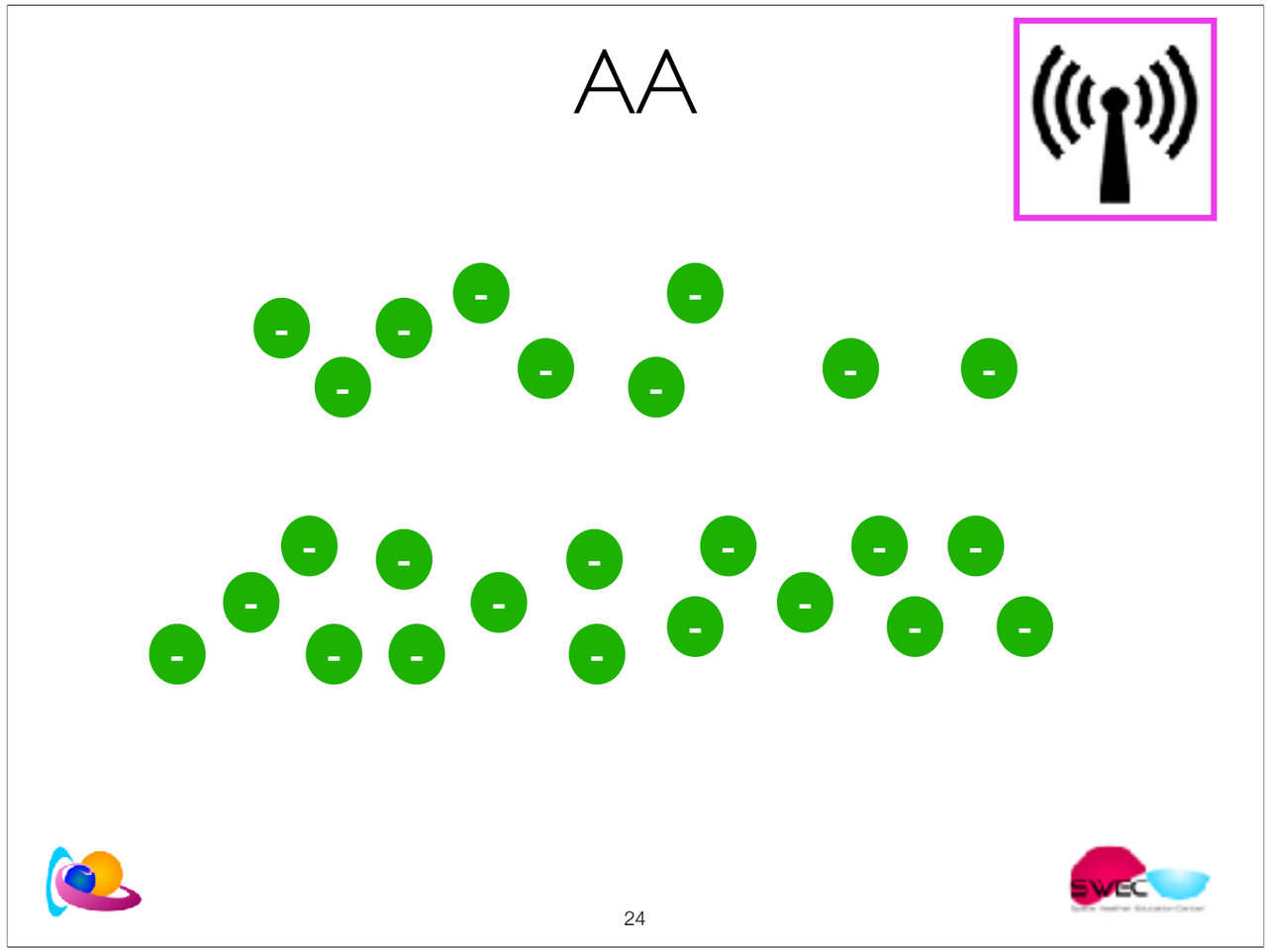
D-region - ionisation of this regions causes absorption instead of reflection

Radio golf komt in in de ionosfeer en doet de electronen bewegen. De bewegende electronen produceren op hun beurt het radio signaal. Zo werkt reflectie.
In de D-laag is de neutrale dichtheid hoog. De electronen zijn niet vrij om te bewegen en zenden geen radiosignaal uit maar de geabsorbeerde energie wordt omgezet in warmte.

D-region: the electron absorbs and reemits, but the neutral gas makes the electrons to dissipate the absorbed energy in the form of heat.

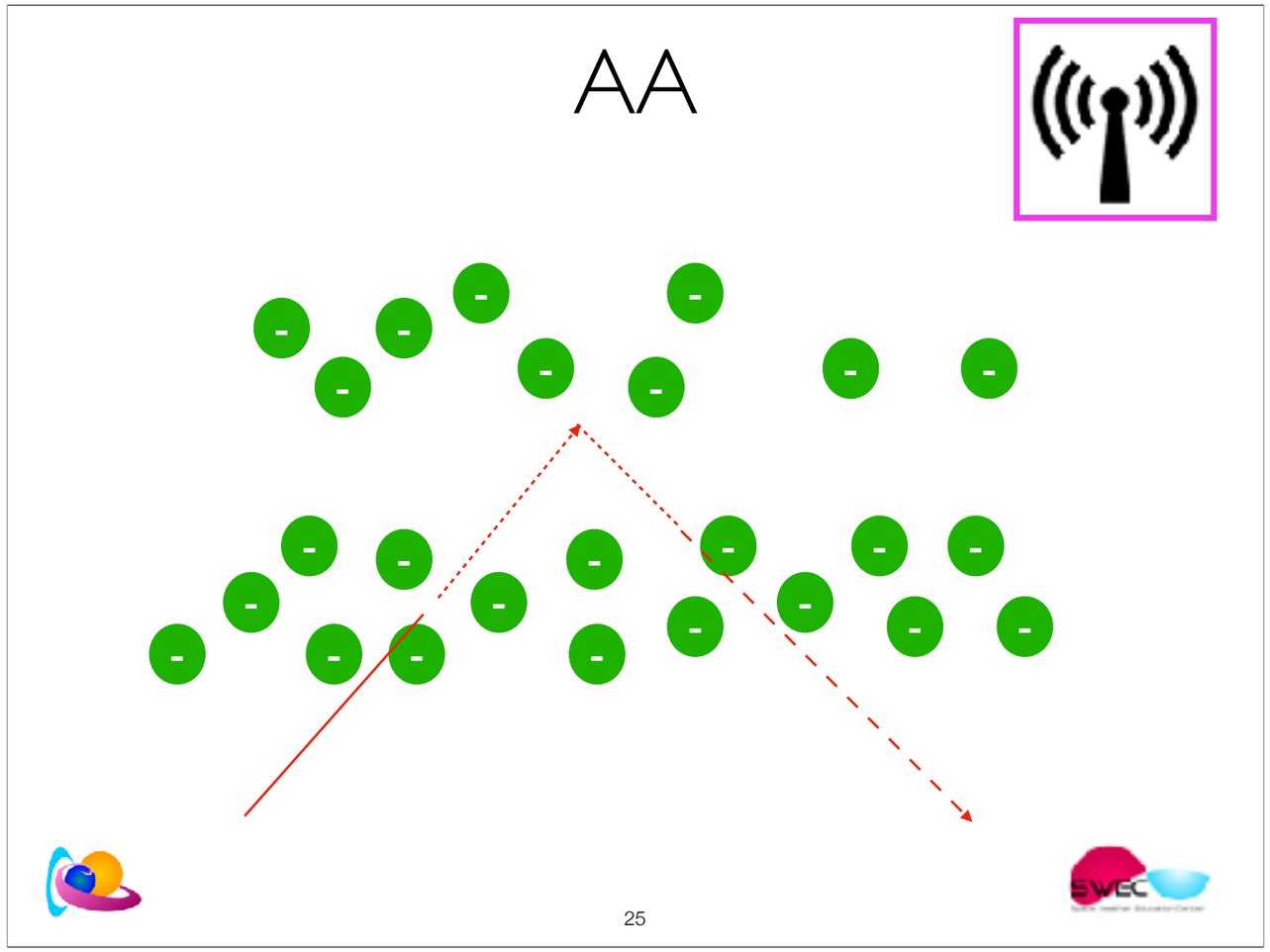
PCA - scherpe overgang - bruut over van open naar gesloten magnetische veldlijnen.

De deeltjes moeten een open route (open veldlijn) hebben om af te dalen naar de D-laag



The incoming precipitating electrons ionise the D-layer in the morning/night sector

During auroral displays, the **precipitating electrons** can enhance other layers of the ionosphere and have similar disrupting and blocking effects on radio communication. This occurs mostly **on the morning/night side of the polar regions of Earth where the aurora is most intense and most frequent.**



MOD from 8- onwards
NH and SH together

The Kp index is an indicator of the high-energy electrons intrusion in the lowest ionosphere layer D.

D-region - ionisation of this regions causes absorption instead of reflection
Radio wave comes into the ionosphere, the electrons absorb the energy of the incoming radio wave and start moving. These moving electrons produce/reemit on their turn the radio signal. This is how reflection works.
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De deeltjes moeten een open route (open veldlijn) hebben om af te dalen naar de D-laag

```
SWX ADVISORY
DTG:              20230423/1957Z
SWXC:             PECASUS
ADVISORY NR:      2023/61
NR RPLC:          2023/60
SWX EFFECT:       HF COM MOD
OBS SWX:          23/1950Z HNH HSH W180 - E180
FCST SWX +6 HR:   24/0200Z NOT AVBL
FCST SWX +12 HR:  24/0800Z NOT AVBL
FCST SWX +18 HR:  24/1400Z NOT AVBL
FCST SWX +24 HR:  24/2000Z NOT AVBL
RMK:              SPACE WEATHER EVENT (HF COM AURORAL
ABSORPTION) IN PROGRESS. IMPACT ON LOWER HF COM FREQUENCY
BANDS EXPECTED AT HIGH LATITUDES.
NXT ADVISORY:     WILL BE ISSUED BY 20230424/0150Z=
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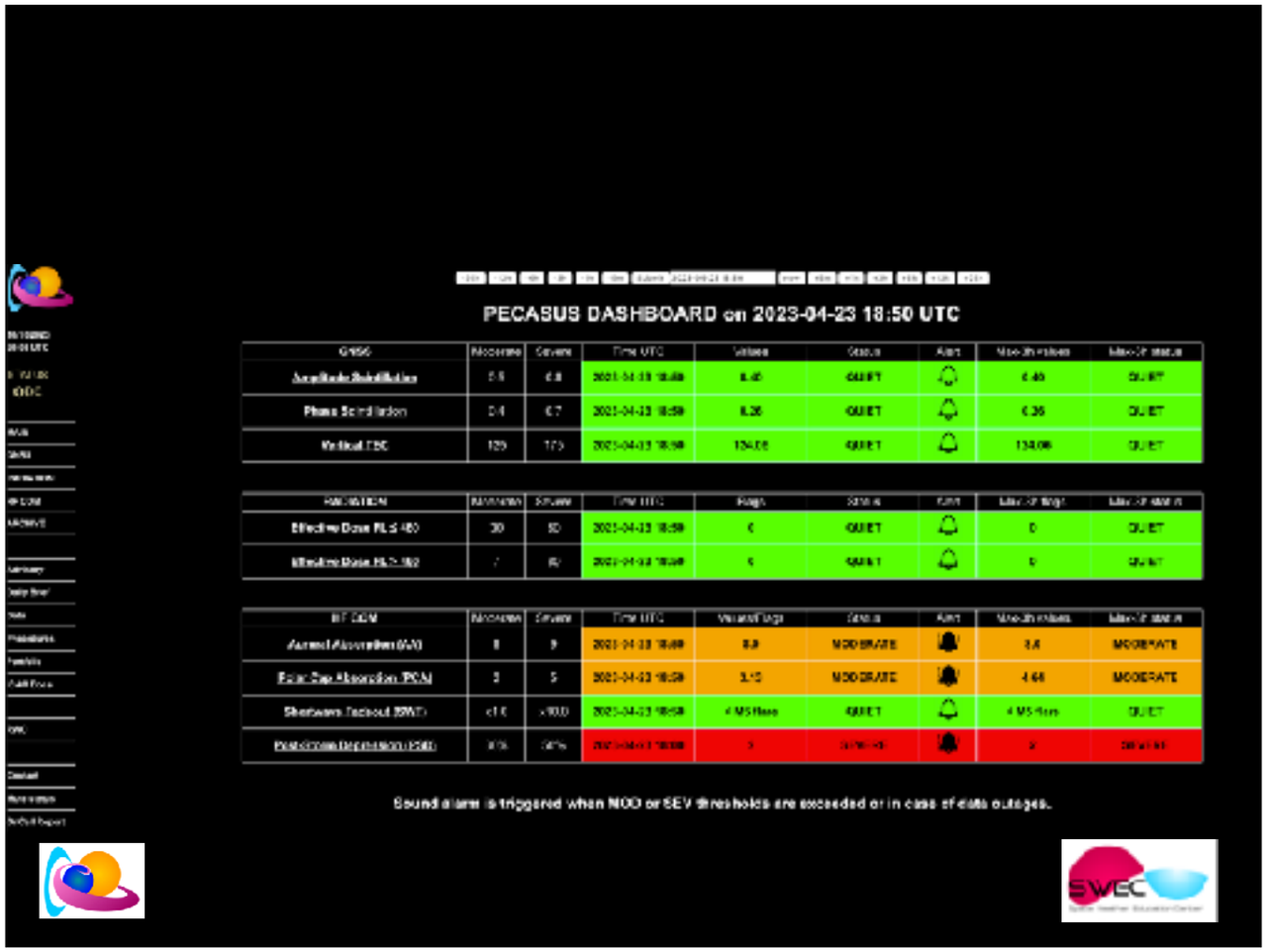
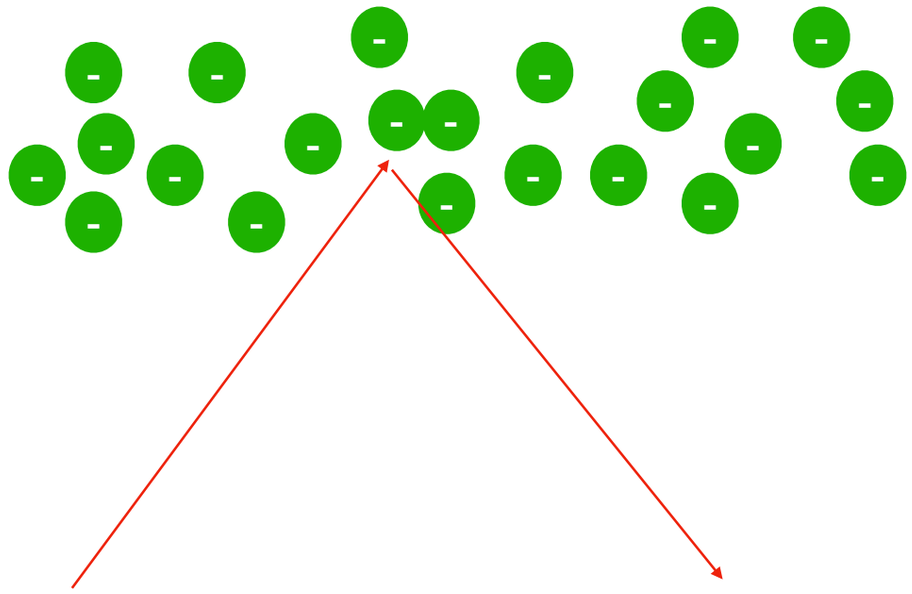


Focus on Post Storm Depression

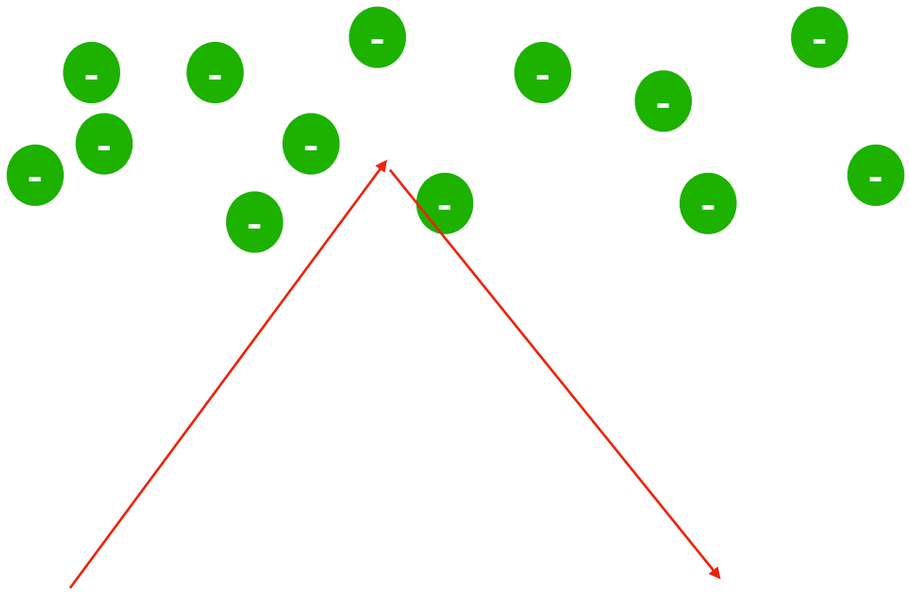
PSD



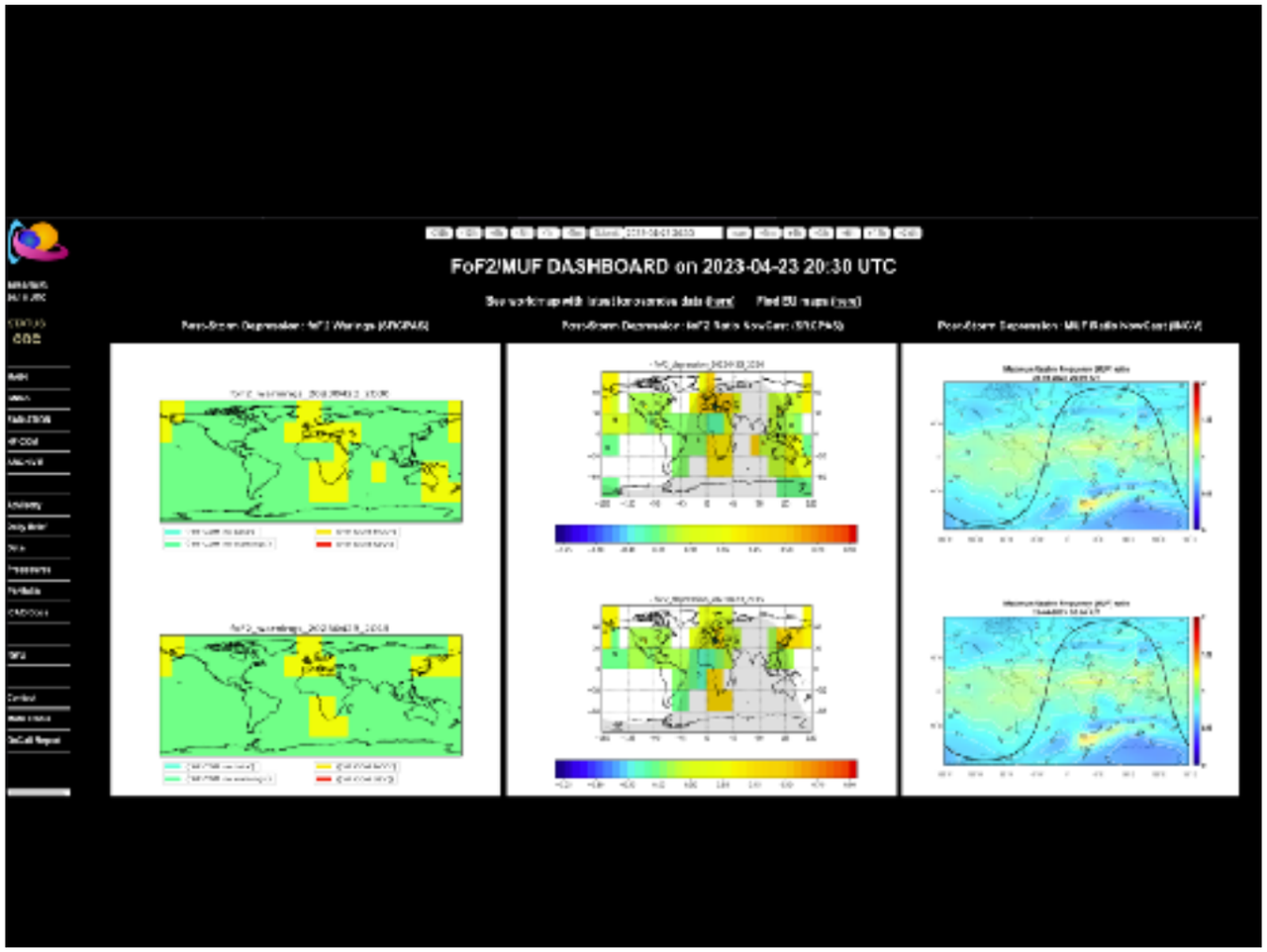
The ionosphere can reflect waves

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.

PSD



Less electrons, the MUF decreases —> less frequencies available for HF com



Areas of PSD —> where there are stations.

```
FNXX02 EFKL 232029

SWX ADVISORY
DTG:              20230423/2029Z
SWXC:             PECASUS
ADVISORY NR:      2023/62
SWX EFFECT:       HF COM MOD
OBS SWX:          23/2021Z FQS MSH E000 - E045
FCST SWX +6 HR:   24/0300Z NOT AVBL
FCST SWX +12 HR:  24/0900Z NOT AVBL
FCST SWX +18 HR:  24/1500Z NOT AVBL
FCST SWX +24 HR:  24/2100Z NOT AVBL
RMK:              SPACE WEATHER EVENT (MAXIMUM USABLE
FREQUENCY DEPRESSION) IS IN PROGRESS. IMPACT ON HIGHER HF
COM FREQUENCY BANDS EXPECTED.
NXT ADVISORY:     WILL BE ISSUED BY 20230424/0221Z=
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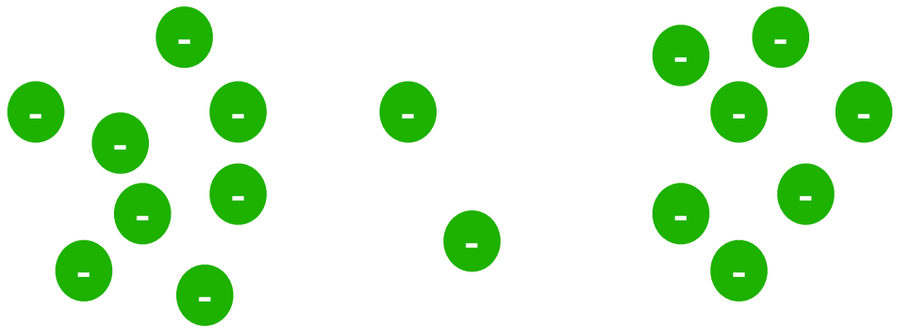
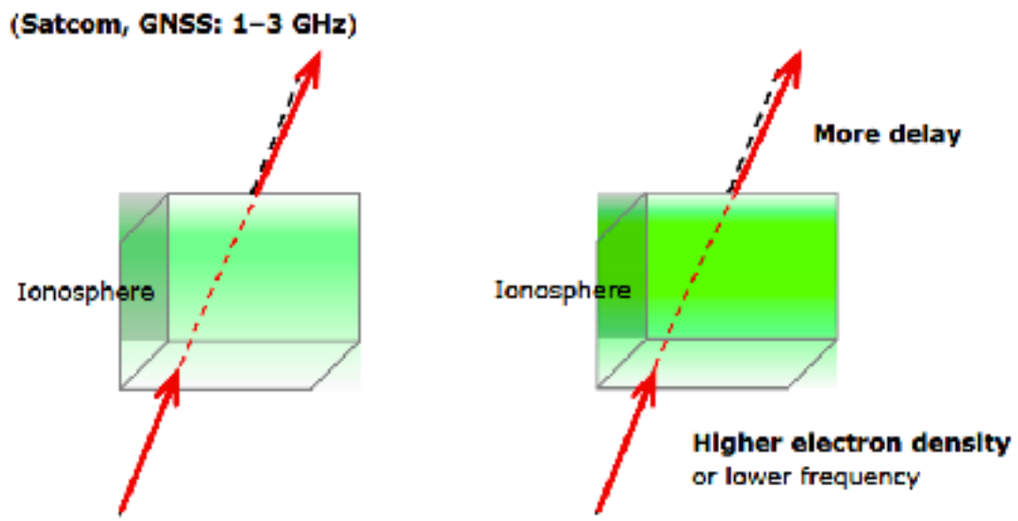
New telephone call
focus on AS

SCINTILLATION



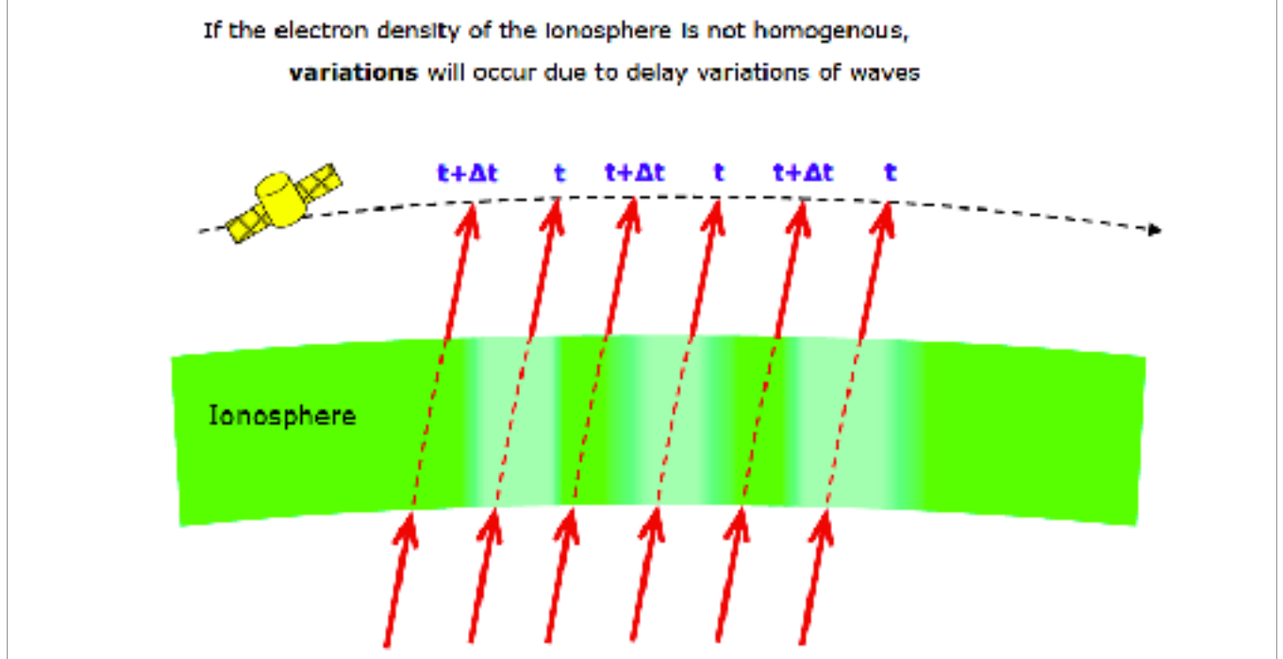
Due to space weather, small scale irregularities exist in the ionosphere.
Landscape of electrons - dense regions and less dense regions
Localised

When waves pass through, they are more or less refracted/delayed.



When a wave pass through, it is more or less delayed depending on the local electron density

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.

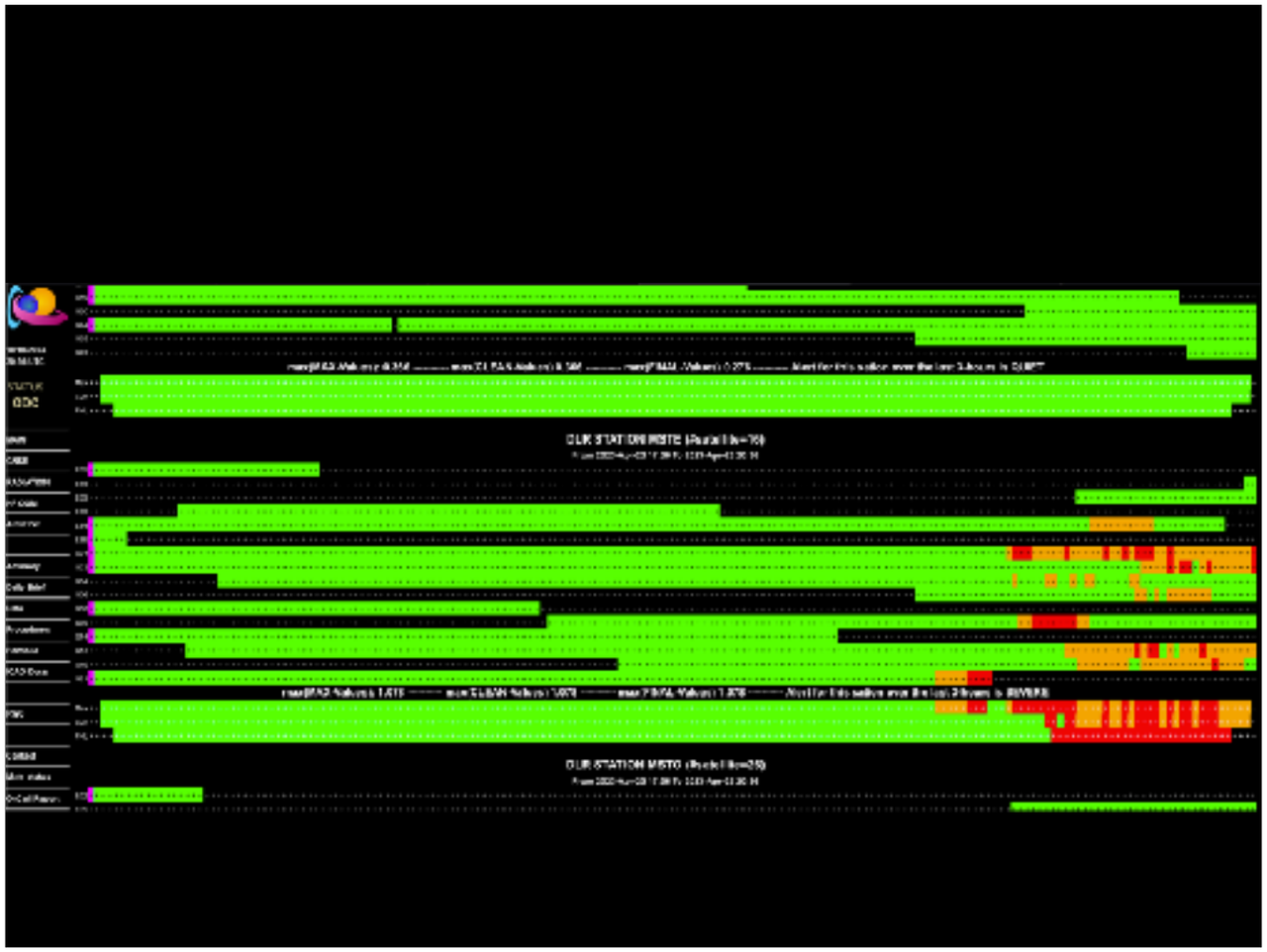


So far, we assumed a stable and predictable ionosphere. That is not always the case. At high frequencies, were there is only a little refraction, the delay imposed on radio waves may still be important. When – either due to the movement of the satellite or due to traveling ionospheric disturbances - 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.

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.


Amplitude scintillation map based on IPP positions at 2025-04-23 20:36

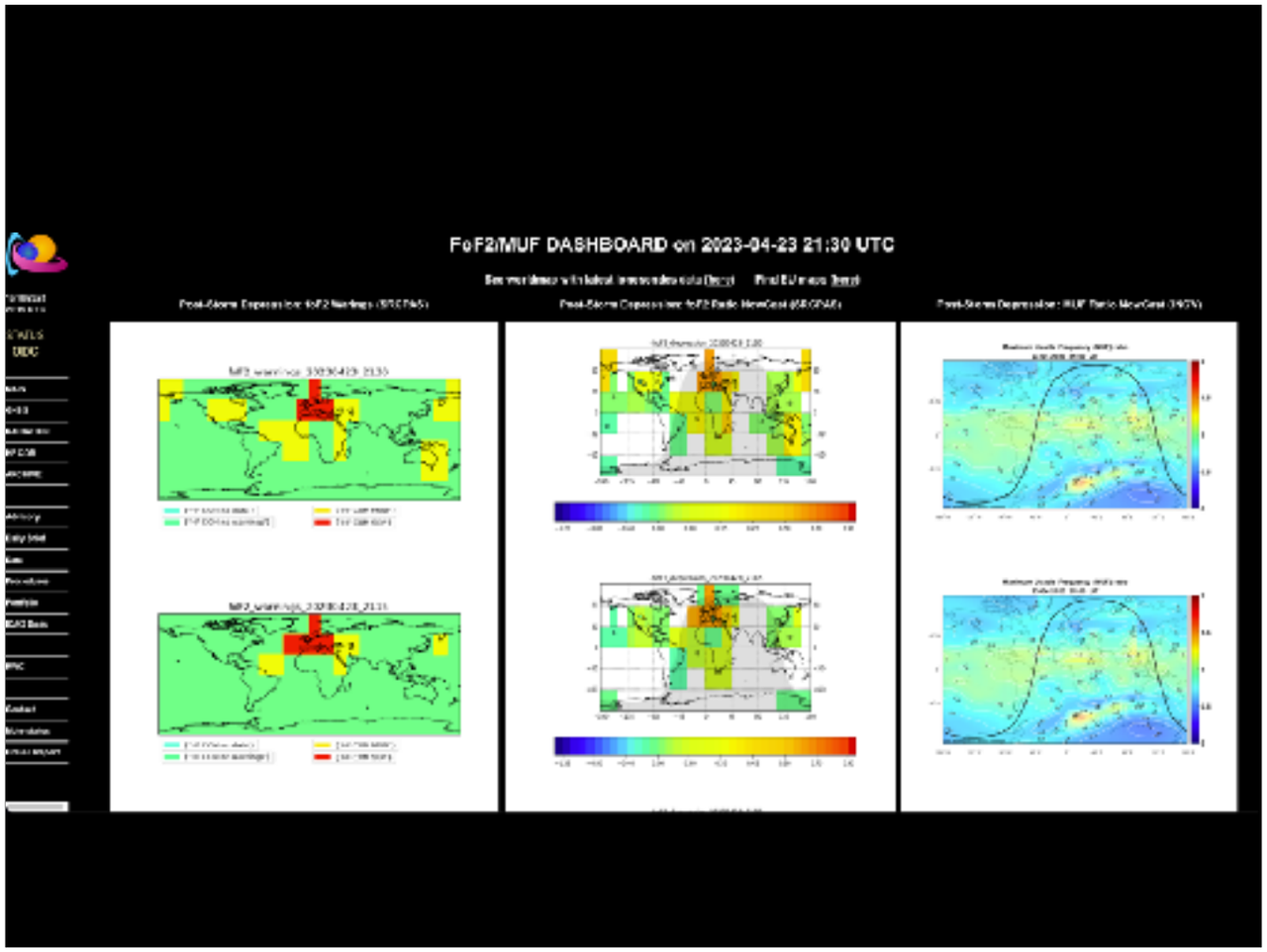


Link between a station and satellites
A cross is one minute.

```
SWX ADVISORY
DTG:              20230423/2036Z
SWXC:             PECASUS
ADVISORY NR:      2023/141
SWX EFFECT:       GNSS SEV
OBS SWX:          23/2029Z EQN W030 - E000
FCST SWX +6 HR:   24/0300Z NOT AVBL
FCST SWX +12 HR:  24/0900Z NOT AVBL
FCST SWX +18 HR:  24/1500Z NOT AVBL
FCST SWX +24 HR:  24/2100Z 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 20230424/0229Z=
```


PECASUS DASHBOARD on 2023-04-23 20:36 UTC
Sound alarm is triggered when MOD or SEV thresholds are exceeded/or in case of data outages.

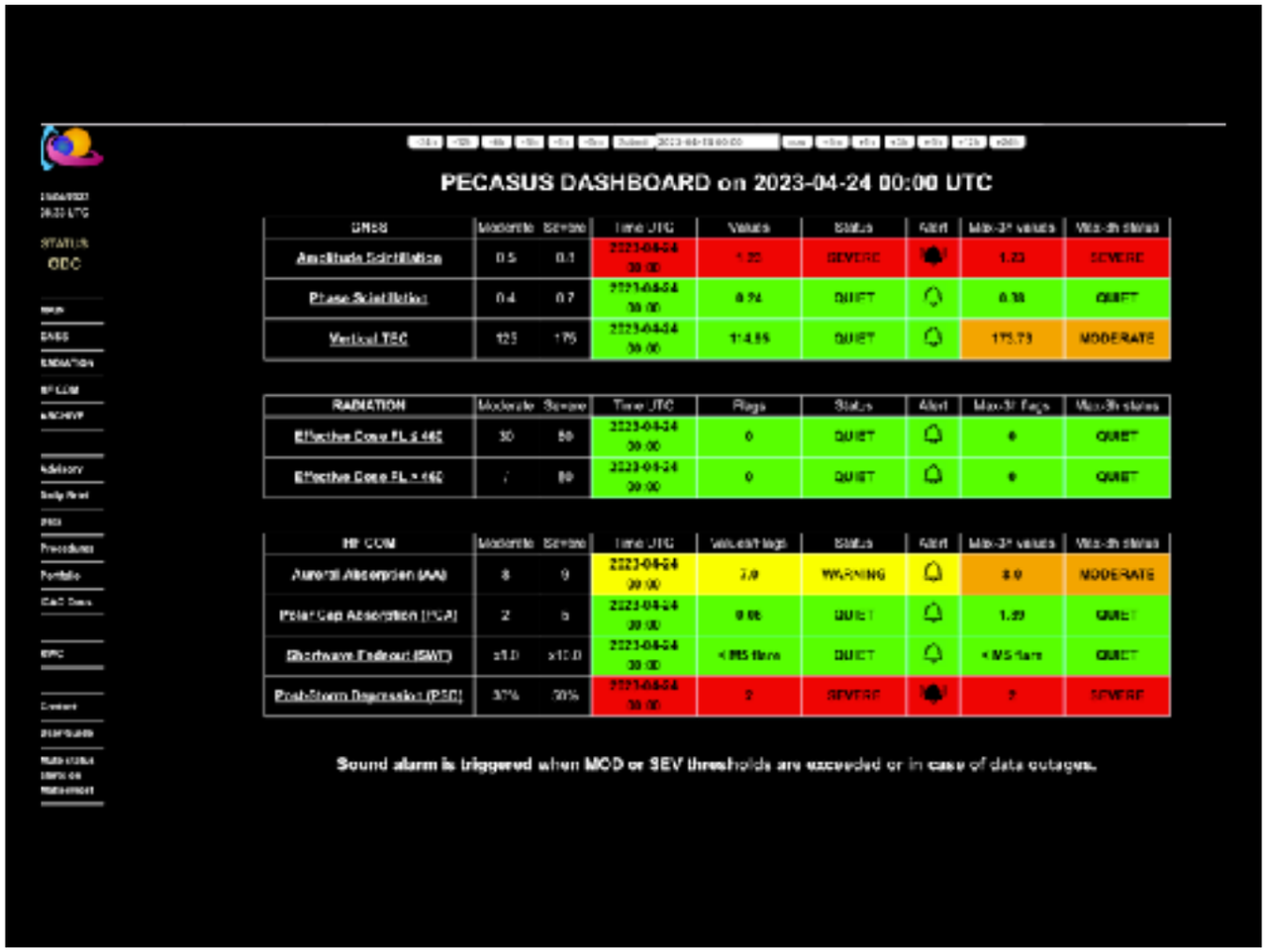
Back to PSD



Update of the advisory: for the whole globe
The regions were jumping around. A sign that all areas were troubled.

```
SWX ADVISORY
DTG:              20230423/2126Z
SWXC:             PECASUS
ADVISORY NR:      2023/63
NR RPLC:          2023/62
SWX EFFECT:       HF COM SEV
OBS SWX:          23/2108Z MNH HSH MNH MSH EQN EQS
WI8M - EI8M
FCST SWX +6 HR:   24/0400Z NOT AVBL
FCST SWX +12 HR:  24/1000Z NOT AVBL
FCST SWX +18 HR:  24/1600Z NOT AVBL
FCST SWX +24 HR:  24/2200Z NOT AVBL
RMK:              SPACE WEATHER EVENT (MAXIMUM USABLE
FREQUENCY DEPRESSION) IS IN PROGRESS. IMPACT ON HIGHER HF
COM FREQUENCY BANDS EXPECTED.
NXT ADVISORY:     WILL BE ISSUED BY 20230424/0308Z=
```

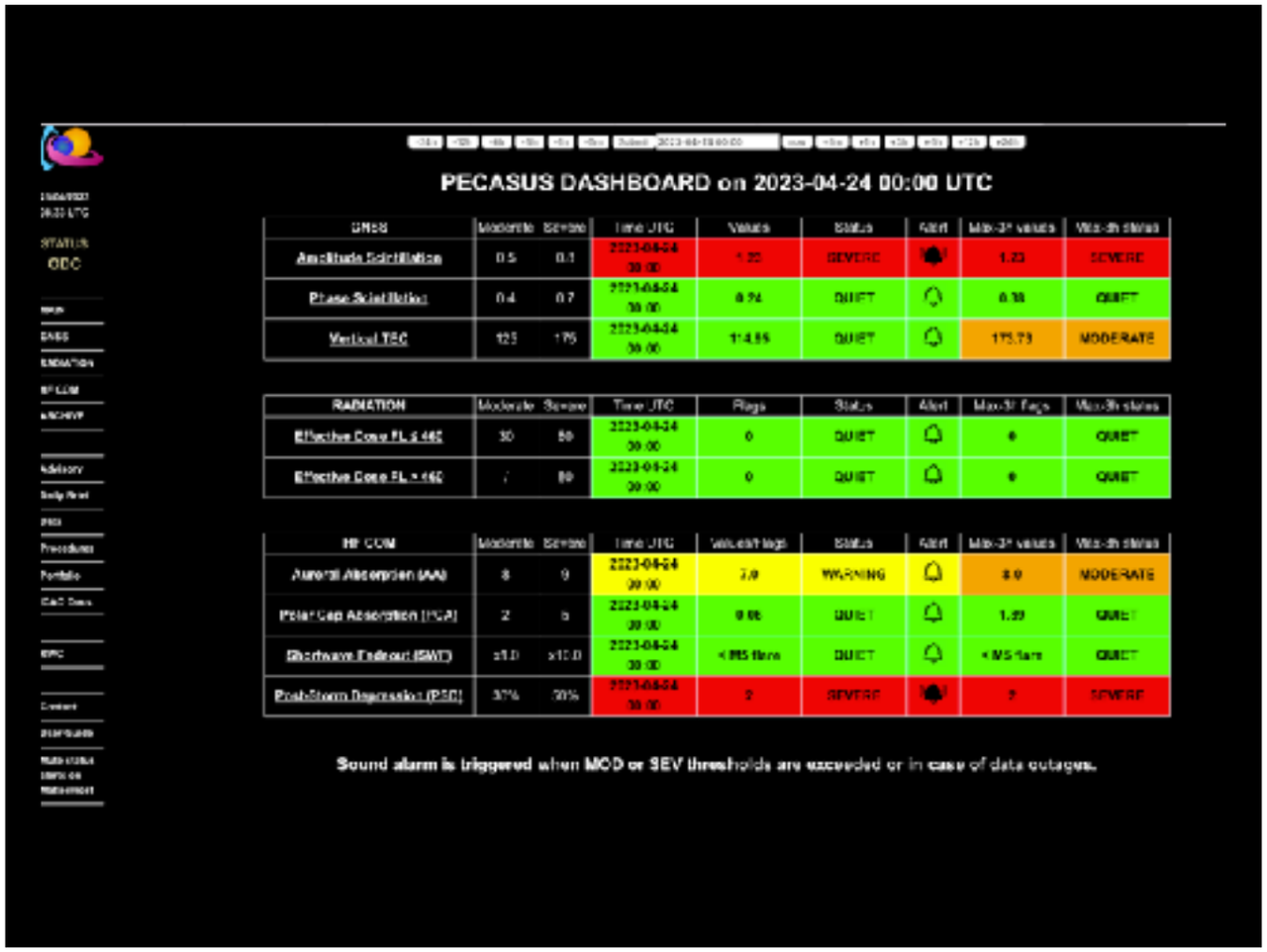

Update of the advisory: for the whole globe



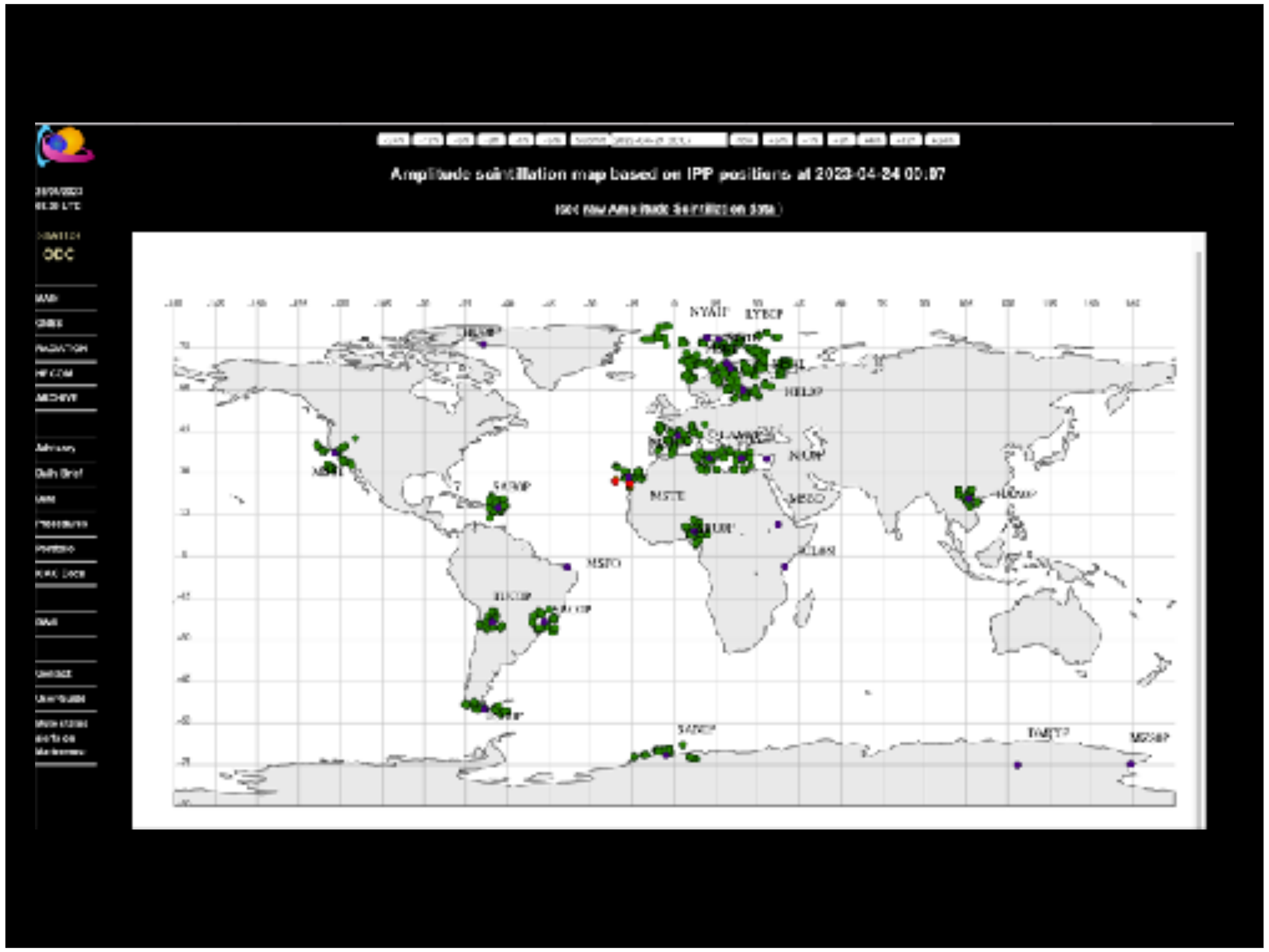
AA has finished.

```
000051801

FNXX02 EFKL 232343

SWX ADVISORY
DTG:              20230423/2344Z
SWXC:             PECASUS
ADVISORY NR:      2023/64
NR RPLC:          2023/61
SWX EFFECT:       HF COM MOD
OBS SWX:          23/2329Z NO SWX EXP
FCST SWX +6 HR:   24/0600Z NO SWX EXP
FCST SWX +12 HR:  24/1200Z NO SWX EXP
FCST SWX +18 HR:  24/1800Z NO SWX EXP
FCST SWX +24 HR:  25/0000Z NO SWX EXP
RMK:              SPACE WEATHER EVENT (HF COM AURORAL
ABSORPTION/POLAR CAP ABSORPTION) HAS ENDED.
NXT ADVISORY:     NO FURTHER ADVISORIES=
```

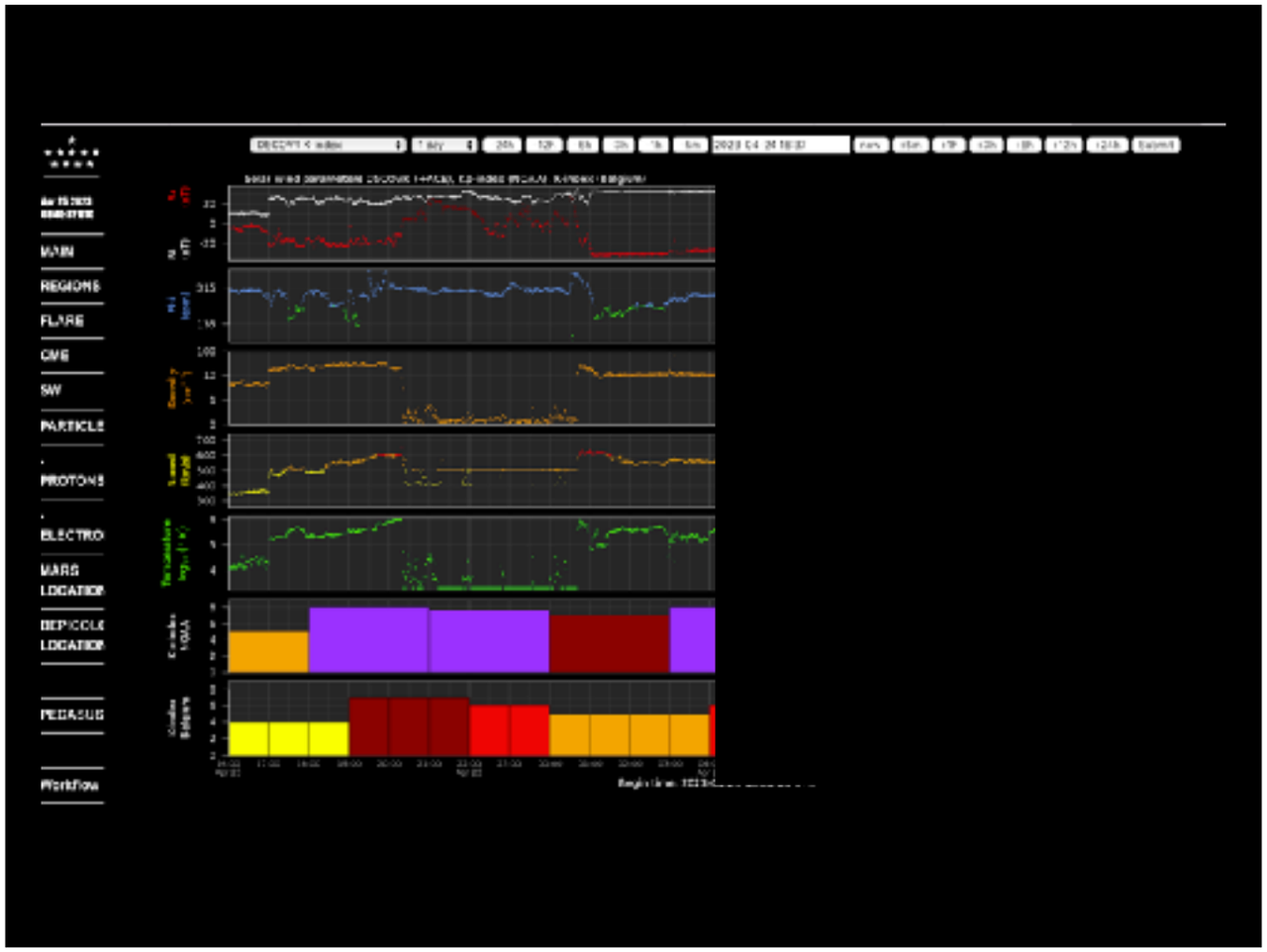

End the advisory


PECASUS DASHBOARD on 2023-04-24 00:00 UTC
SCINTILLATION
Amplitude Scintillation
Phase Scintillation
Vertical TEC
RADIATION
Effective Dose FL ≤ 450
Effective Dose FL > 450
HF COM
Auroral Absorption (AA)
Polar Cap Absorption (PCA)
Shortwave Fadeout (SWF)
ProbStorm Degradation (PSD)
Sound alarm is triggered when MOD or SEV thresholds are exceeded or in case of data outages.

Back to AS


Amplitude scintillation map based on IPP positions at 2023-04-24 00:07


max[MAX-Values]: 0.417 -------- max[CLEAN-Values]: 0.417 -------- max[FINAL-Values]: 0.133 -------- Alert for this station over the last 3-hours is: QUIET
DLR STATION MSTE (Isaellite=19)
max[MAX-Values]: 1.275 -------- max[CLEAN-Values]: 1.227 -------- max[FINAL-Values]: 0.227 -------- Alert for this station over the last 3-hours is: SEVERE
DLR STATION MSTO (Isaellite=29)



again AA.

And it went on and on.

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 continued until 4 days after Kp=6