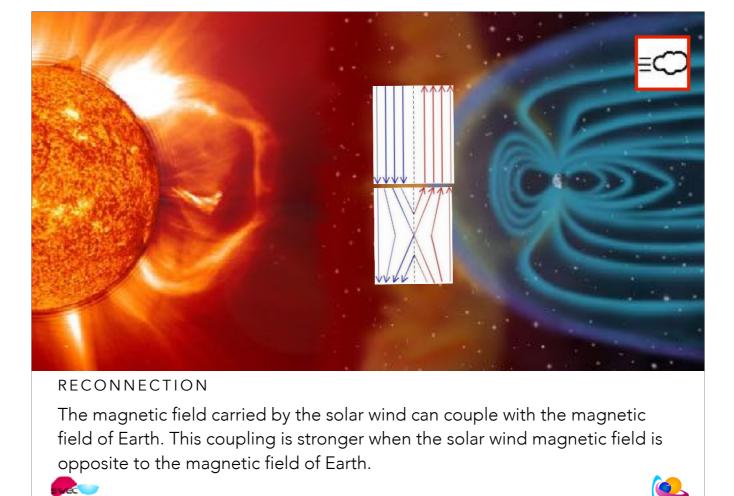
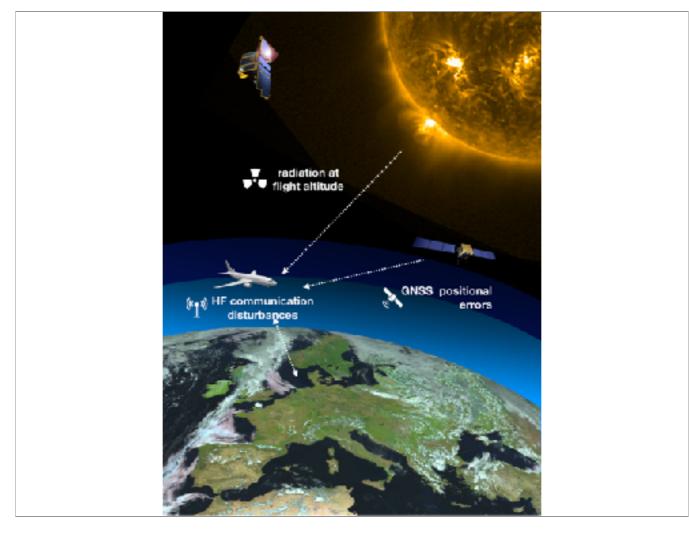
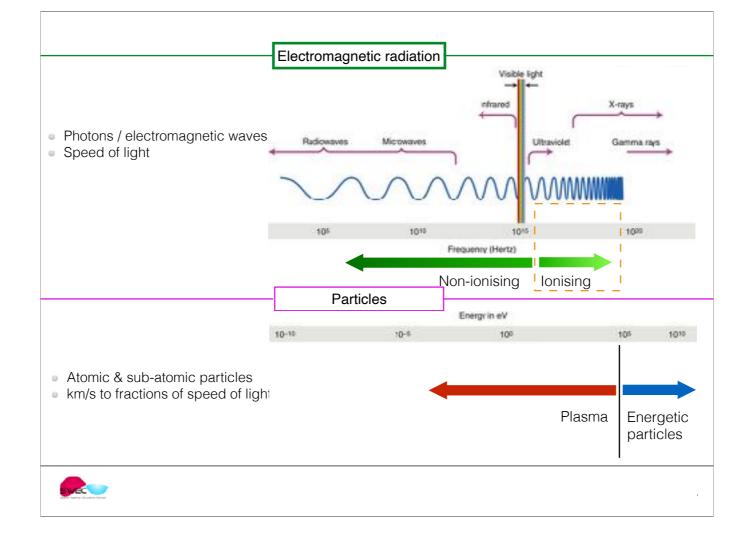


Proton flux can stay elevated for a long time - the stream of protons can be fed by a CME that keeps on pushing the particles, and this for the total transit time (1 AU)



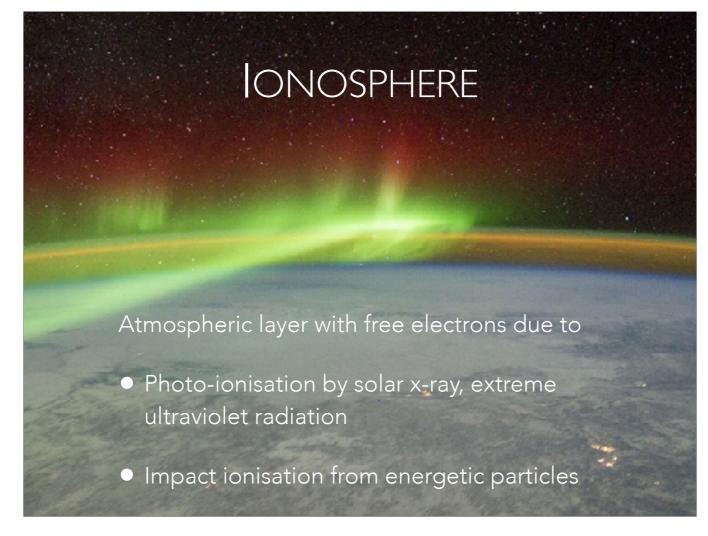
Magnetic reconnection at the magnetosphere of Earth.





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.

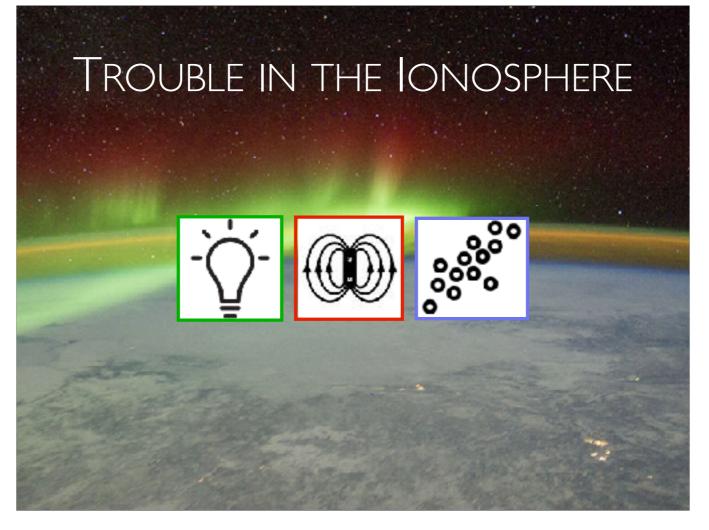
The picture shows the 'Northern Lights', seen from the International Space Station. The aurora makes the ionosphere visible to us.

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.



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

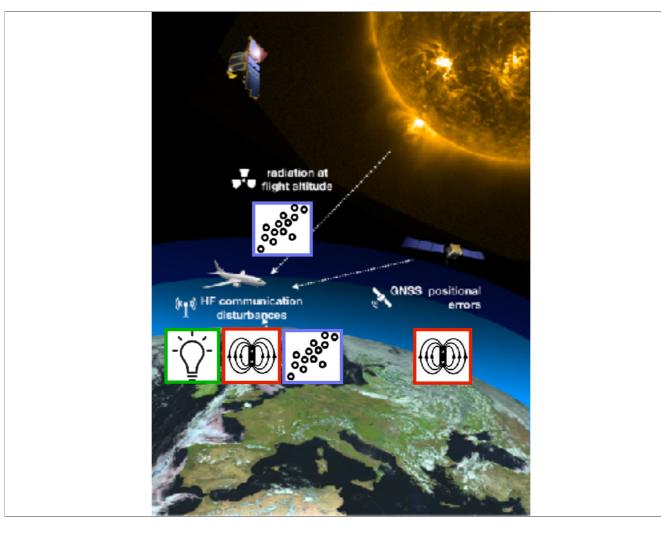
The picture shows the 'Northern Lights', seen from the International Space Station. The aurora makes the ionosphere visible to us.

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GNSS	Modera/e	Se/ere	Time UTC	Values	Statue	Alert	Nax-3P values	Max-3h status
Amplitude Scintillation	0.5	0.8	2020-10-12 14:15	0.25	QUIET	Δ	0.35	QUIET
Phase Scintillation	0.4	0.7	2020-10-12 14:15	0.13	QUIET	4	0.14	
Vertical TEC	125	175	2020-10-12 14:15	61.92	QUIET	4	61.93	QUIET
RADIATION	Modera/e	Severe	Time UTC	Flags	Status	Alert	Max-3h flags	Max-3h status
Effective Dose FLS460	30	80	2020-10-12 14:20	9	QUIET	4	•	QUIET
Effective Dose FL > 460	,	ю	2020-10-12 14:20	<u>a</u>	CUIET	۵	•	
HF COM	Modera/e	Severe	Time UTC	Values/Flags	Status	Alert	Nax-31: values	Max-3h stat
Auroral Absorption (AA)	8	9	2020-10-12 14:16	3.0	QUIET	4	3.0	
Pelar Cop Absorption (PCA)	2	5	2020-10-12 14:20	0.00	QUIET	4	0.30	
Shortwave Facecut(SWF)	x1.0	x10.0	2020-13-12 14:17	< M.5-flare	QUIET	4	< M.5-flare	
Post-Sterm Depression (FSD)	30%	50%	2020-10-12 14:15	3	QUIET	۵		

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

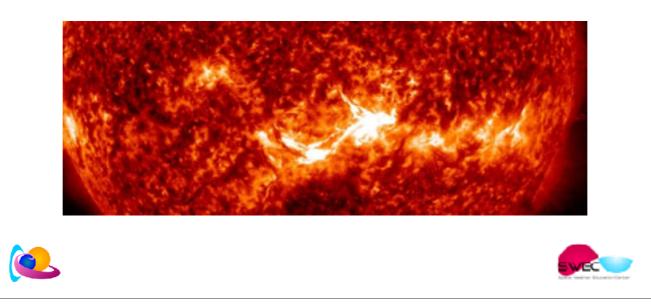
AA, PCA, SWF are absorption events - low frequencies PSD reduces the range of frequencies available - high frequencies are not available.

# **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.

### Get (2n (6n (3t (in (5n 5abm) 2023-04/23 740) non (6n (4n (42) (40) (412) (50)

# PECASUS DASHBOARD on 2023-04-23 17:00 UTC

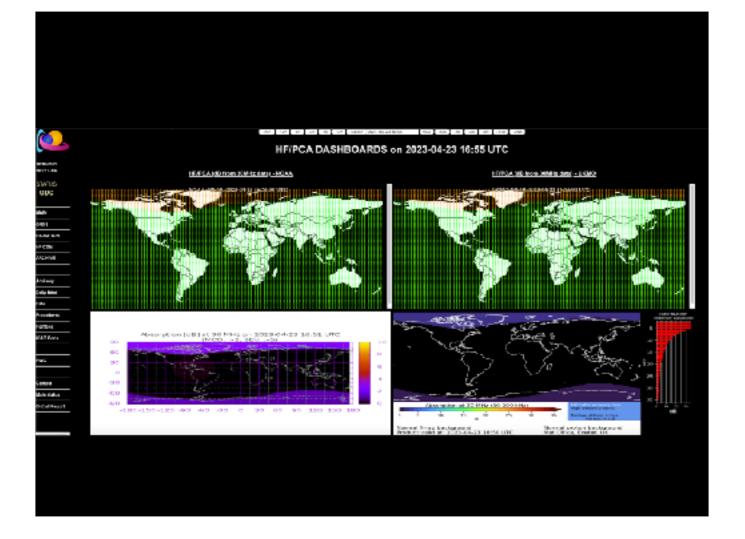
GN \$5	<b>Vioderale</b>	Severe	Time UTC	Values	Status	/Jkrt	Max 3h values	Mox 3h status
Ampiruda scintilation	0.5	0.8	2023-04-23 17:00	0.25	QUET	4	0.36	QUIET
Phase Scintillation	0.4	0.7	2023-04-23 17:00	0.12	QUET	Δ	0.14	QUICT
WHEN TEC	125	175	2023-04-23 17:00	96.98	QUET	φ	95.98	QUIET

RADIATION	Voderate	<b>Bereie</b>	Time UTC	Flaça	Status	Alert	Max-3h flags	Mex-3h atatwa
Effective Dose FL ≤ 460	30	30	2023-04-23 17:00	0	QUET	Φ	0	QUIET
Effective Cone FL # 460	•	80	2023-04-23 17:00	Ð	GUET	Φ	٥	OWET

HE COM	Vioderale	Severe	Time UTC	Values/Flags	Status	/.krt	Max 3h volues	Mox 3h status
Autoral Assorption (AA)	¥	y	2023-04-23 17:00	8.3	QUET	۵	5.3	QUIET
Polar Gaz Absorption (PCA)	2	5	2023-04-23 17:00	2.75	NODERATE	Ŵ	2.54	NODERATE
STORWARD FREEDOWL(SWF)	x1.0	213.0	2023-04-23 17:00	< N5 flare	QUET	4	< M5 flare	QUIET
Past-Starm Depension (PSC)	30%	50%	2023-04-23 17:00	0	QUET	Φ	0	OWET

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

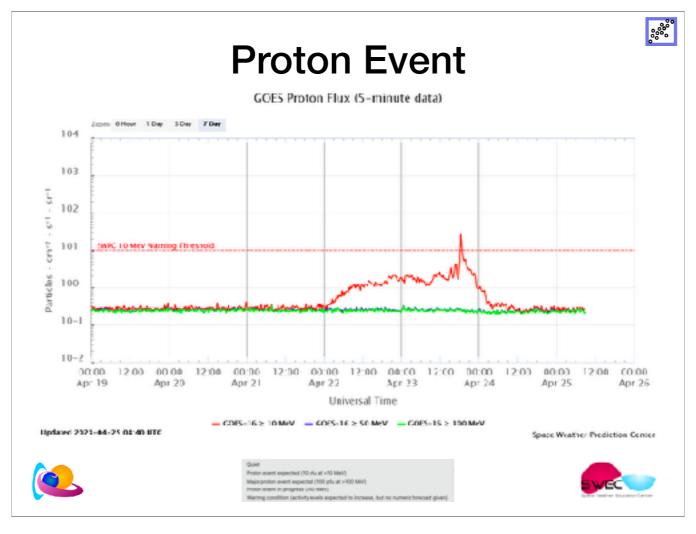
Ancervie Anc



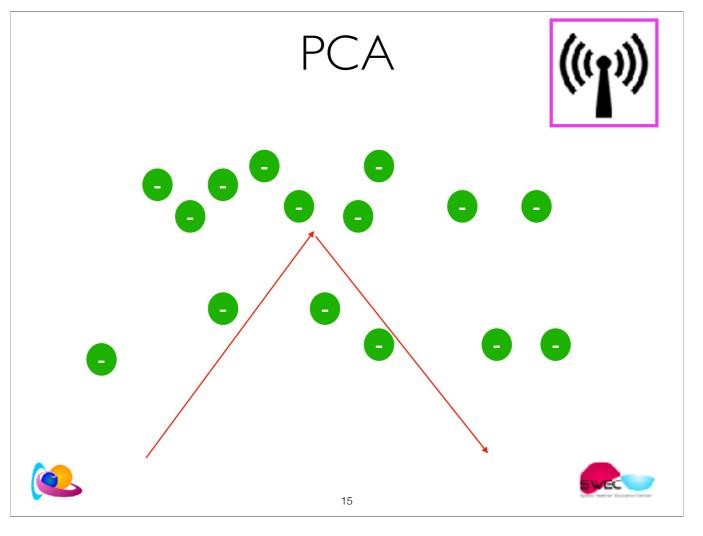
DRAP model

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

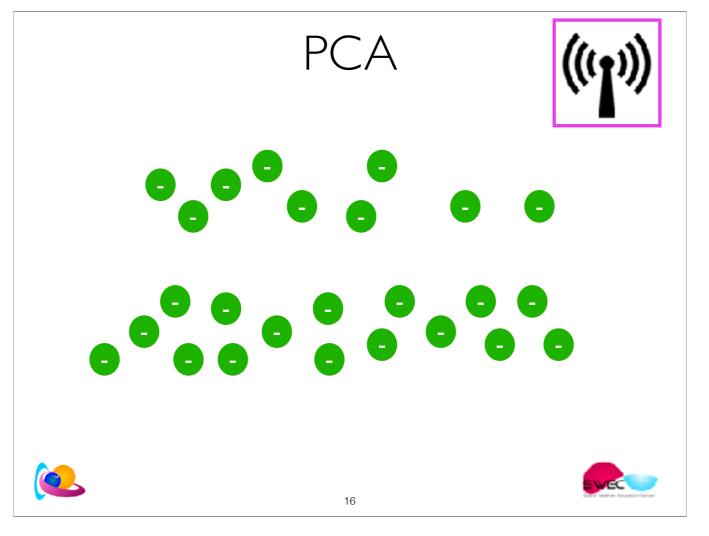
PCA - scherpe overgang - bruut over van open naar gesloten magnetische veldlijnen. De deeltjes moeten een open route (open veldlijn) hebben om af te dalen naar de D-laag



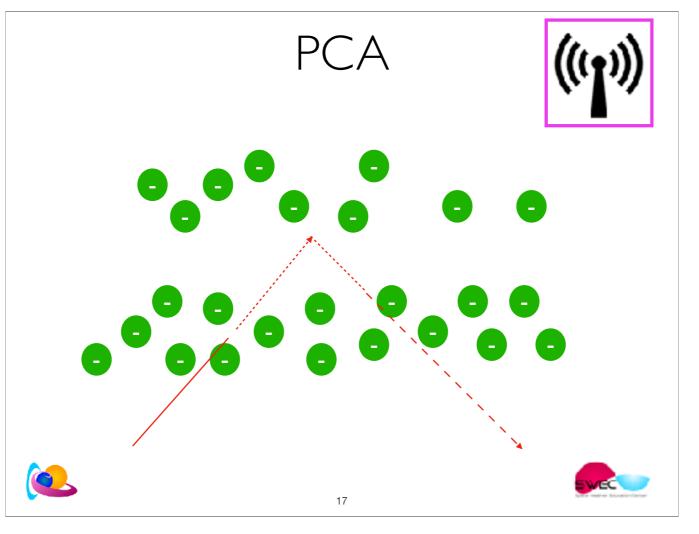
A shock was recorded in the solar wind parameters on 23 April at 17:00UTC (DSCOVR; graph). It marked the **somewhat (a few hours) earlier-than-expected arrival of the interplanetary coronal mass ejection (ICME)**. The passage of the shock briefly drove the already enhanced greater than 10 MeV proton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



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).



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	
	ABSCRPTION) IN PR	OGRESS. IMPACT ON LOWER HF COM FREQUENCY	
	BANDS EXPECTED AT	HIGH LATITUDES.	
	NXT ADVISORY:	WILL BE ISSUED BY 20230423/2255Z=	
<b>(</b>		18	EVEC

18

Should have been: HNH + HSH W180-E180

#### 100 100 100 10 10 10 10 100 1000 001000 000 100 100 100 100 100 100 100

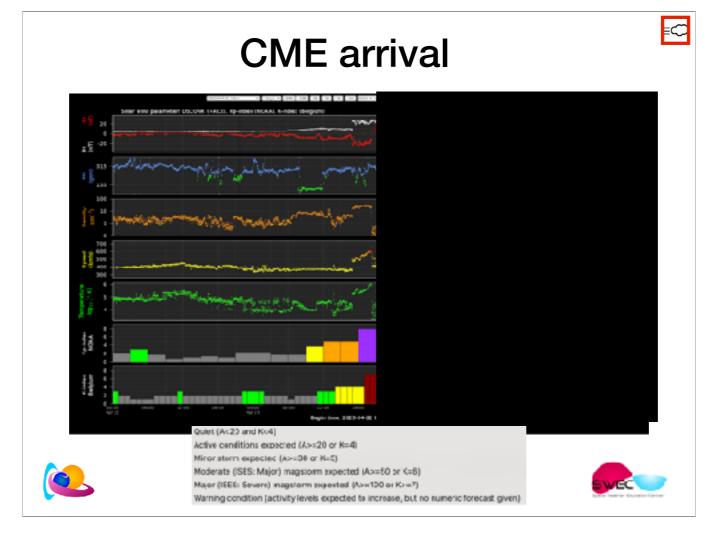
# PECASUS DASHBOARD on 2023-04-23 18:50 UTC

G456	Nocerse	Severe	Firm VTC	Vition .	Otabum	Alet	No-3h-sheet	Max-OF status
Acquitade Solutification	5.5	¢.8	2021-02-03 10-68	1.0	00.87	4	6.40	QUET
Phone Scintillation	D/4	67	2023-04-33 (8:59	1.2	00181	4	C36	OUET
Vertical TSC	125	175	2023-04-03 18:59	124.06	40.61	4	134.08	quer
PADIATION	Manager	Struete	Day UTS	Even A	Same e	6.04	Marc 37 Bogs	May Stream a
Effective Dose PL 5 480	30	so	2025-04-03 18:59	. C.	OUIET	4	D	OUET
Effective Dose HL > 182	1	R	2023-04-03 18:58		QUET	4	¢.	quer
HF COM	NACAUMA	(mane	Dime UTC	Velantings	(4%).B	Alent .	NAME IN COMMAN	Marshit statut
Annual Alexandren 640	•	3	2023-04-03 18-69	13	NOOSMATE		8.6	MODERATE
Fois: Cap Absorption (PCA)	3	5	3023-04-63 18:59	1/0	NOD GRATE	۲	161	MODERATE
Sherberry Tachout (SWT)	c1.0	×10.0	2023-04-02 10:50	4 MSHare	40101	4	4 WS from	QUET
Post-Groun Depth-sion (2005)	305	31%	2010-00-00 TROOT		armont.	۰		any sec

Sound alarm is triggered when NOD or SEV thresholds are exceeded or in case of data outlages.

No control No control

Focus on AA



Geomagnetic Storm because of a CME arrival!

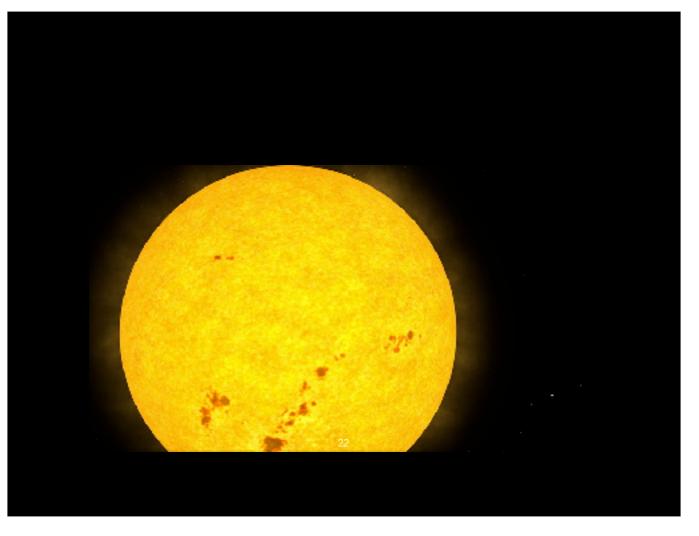
The satellite DSCOVR in a point 1 hour upstream of the earth, which means that it takes the solar wind 1 hour to reach the Earth, 'saw' the cloud passing and measured a jump on April 23, 17UT as seen in the top panel of the graph below. The cloud induced a severe geomagnetic storm on the planetary level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

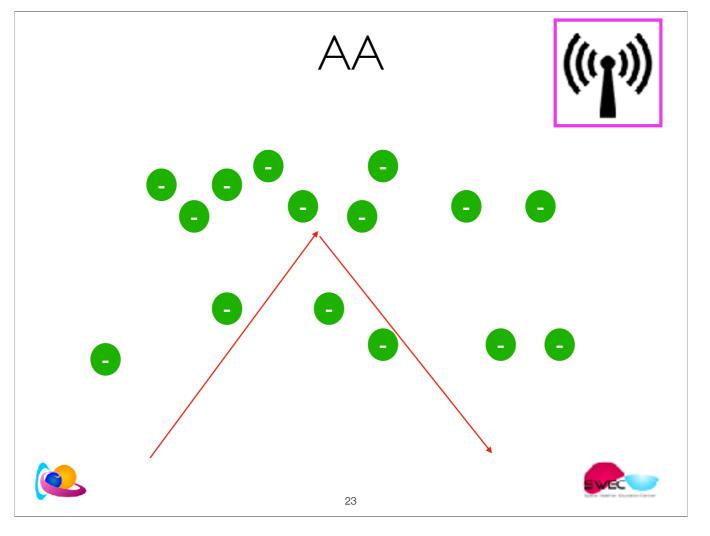


Kp is a 3 hour index. Normally, we should wait 3 hours to see if it really reaches 8. The operator made an assessment: 'It will'.



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.



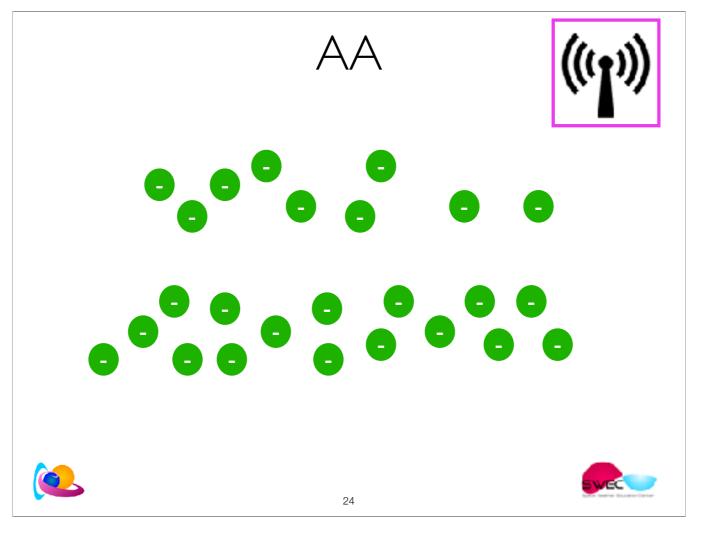
D-region - ionisation of this regions causes absorption instead of reflection

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.

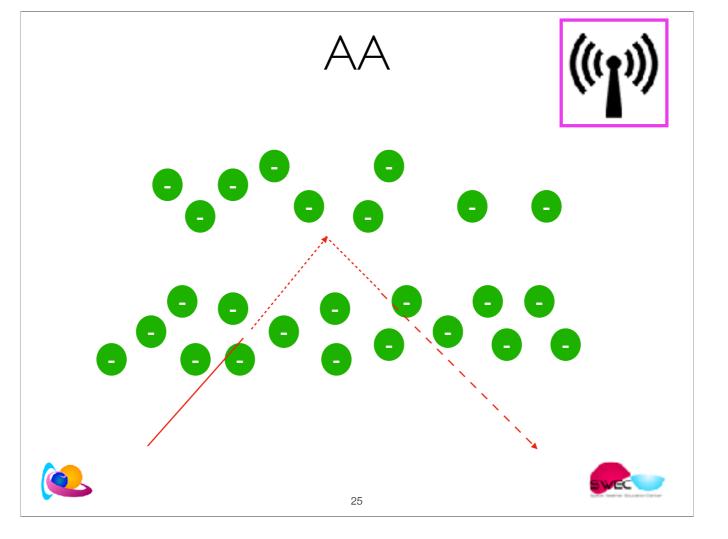
PCA - scherpe overgang - bruut over van open naar gesloten magnetische veldlijnen.

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

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SWX ADVISORY	
DTG:	20230423/19572
SWXC:	PECASUS
ADVISORY NR:	2023/61
NR RPLC:	2023/60
SWX EFFECT:	HF COM MOD
OBS SWX:	23/19502 HNH HSH W180 - E180
FCST SWX +6 HR:	24/0200Z NOT AVBL
FCST SWX +12 HR:	24/0800Z NOT AVBL
FCST SWX +18 HR:	24/14802 NDT AVBL
FCST SWX +24 HR:	24/2000Z NOT AVBL
RPK:	SPACE WEATHER EVENT (HF COM AURORAL
ABSORPTION) IN PRO	OGRESS. IMPACT ON LOWER HE COM FREQUENCY
BANDS EXPECTED AT	HIGH LATITUDES.
NXT ADVISORY:	WILL BE ISSUED BY 20230424/0150Z=



PECASUS DASHBOARD on 2023-04-23 18:50 UTC

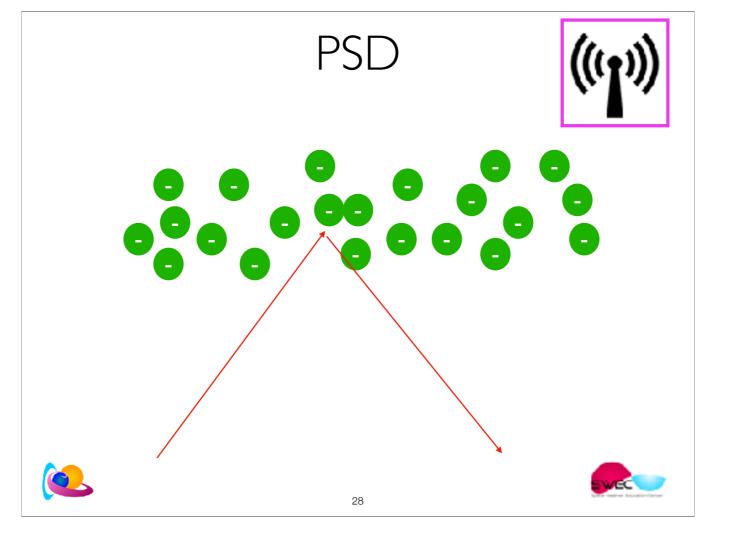
6456	Nocerse	Severe	Time VTC	Vitiese	Otadum	Aist	No-3h-states	Max-Of-status
An pittade Solutification	5.8	¢.8	2021-02-08 18-68	LØ	01187	4	6.45	0.07
Phone Scind laders	D/4	67	2023-04-33 (8:59	1.3	QUET	4	C35	OUET
Vertical FBC	125	179	2023-04-03 18:50	154.08	40.61	4	134.06	quer
RADIATION	Monora	\$7.ee	DAM HTS	Raga	Strill is	6.04	Mar.37 Wegs	Line Strategy of
Billiochine Dove PL ≤ 480	30	so	2023-04-03 18:59	e	QUET	4	D	OUET
Window Dote PLP- 182	1	R	2023-04-03 18:58		QUAT	4	¢.	quar
HF COM	Nocean	(mare	THE UT C	VERNENGE	(410.0	Aint	NAME IN COMMON	March and a
Aanual Aksemption (AA)	•	,	2023-04-03 18:69	- 10	NOOSMATE		8.6	MODERATE
Four Cap Absorption (PCA)	3	5	3023-04-63 18:59	1/0	NOD DRATE	۲	161	MODERATE
Sherways Faceout (SWT)	c1.0	×10.0	2023-04-02 10:50	4 MS flave	40101	4	4.95.505	OUET
Post-Stream Depression (1990)	305	ars	80.000 mm		areas	۰.		DEVENT

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



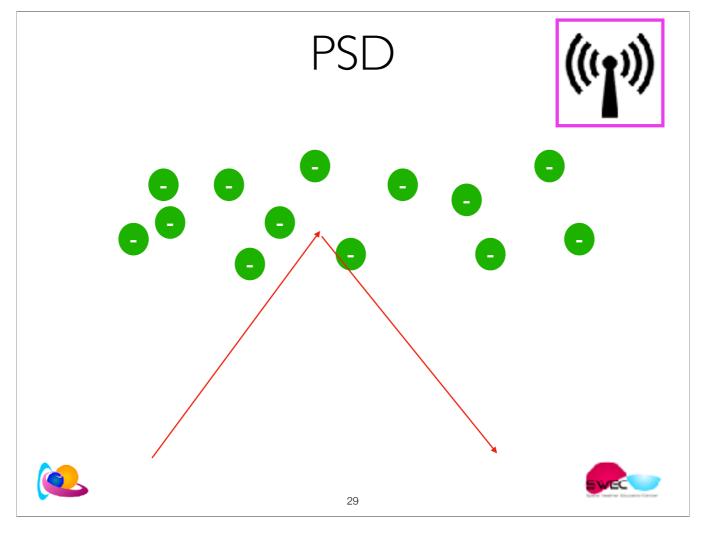
Kissen Ki

Focus on Post Storm Depression

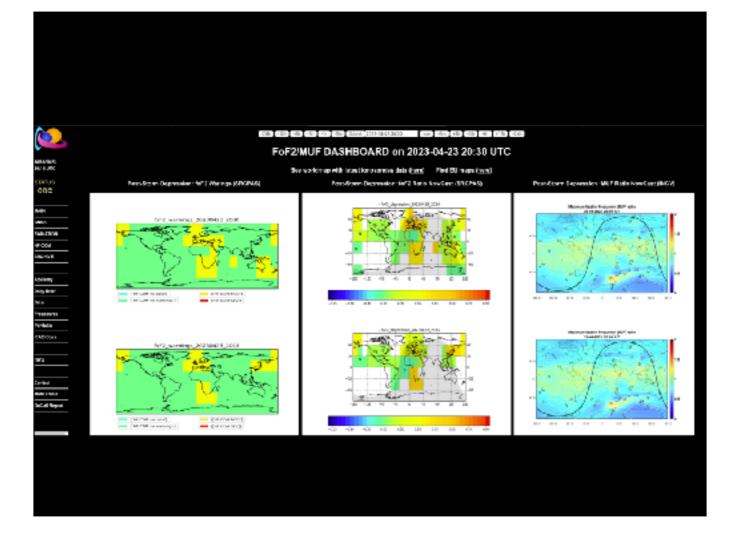


The ionosphere can reflect waves

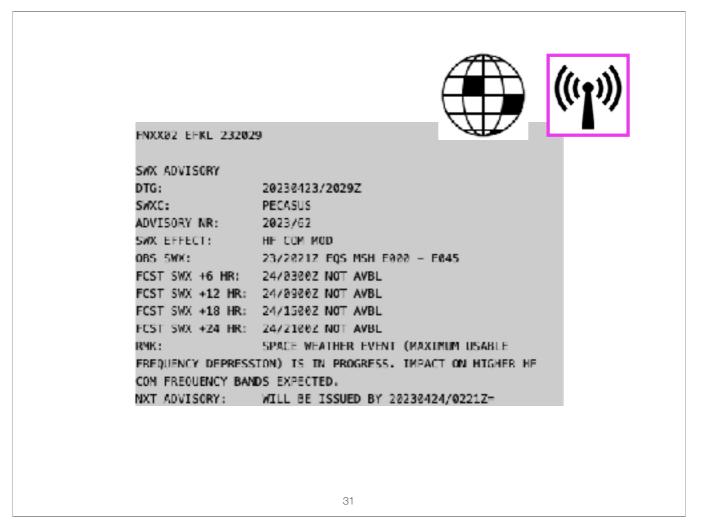
When the ionosphere is not ionised, which waves are being reflected? As soon as the ionisation increases, waves under the MUF are being reflected. The higher the ionisation, the higher the MUF.



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



Areas of PSD —> where there are stations.



#### -ce -72 -46 -76 -46 -3444 22360623234 - cou -46 -46 -72 -46 -726 -734

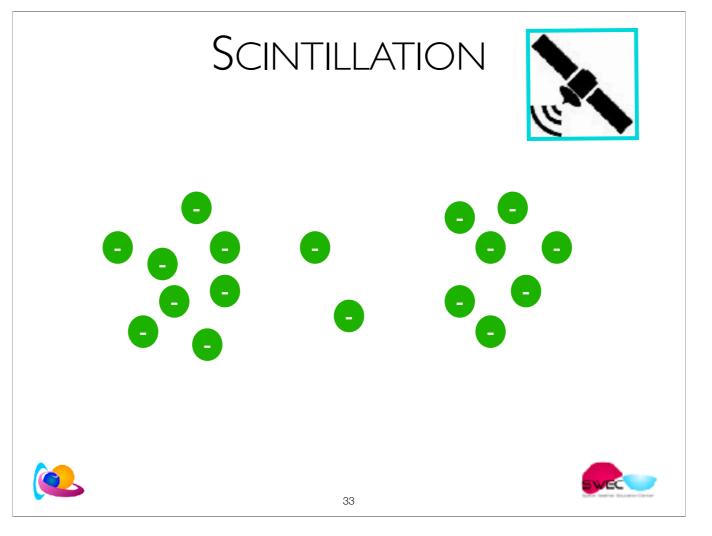
PECASUS DASHBOARD on 2023-04-23 20:36 UTC

PECA303 DA3HBOARD 01 2023-04-23 20:30 010											
Moderate	2010	Time UFC	SARLOS	5501.9	4964	Marcel values	No-Instas				
2.5	63	2023-04-25 28 26	122	SEVEN	۰	1.08	SEVENE				
3.4	4.7	2023-04-25 38:38	8.30	QUIET	Φ	1.06	SEVERE				
129	1/5	812346425 38.35	131.84	QUET	4	194,83	NOCERCIE				
Maderole	Severe.	Time UFC	Maya	Skius	Alat	Max.31 flags	Non-Bhoulas				
24	- 760	2003-06-21 98:35		QUET	\$	1.1	QUET				
r	8	2023-84-25 08:25		QUICT	φ.		QUIET				
Moderne	Severe	Title+ UFC	Virial-STage	501.0	Alet	Max-Of Versee	No-35 Care				
8	3	2023-04-25-28-36	8.6	MODERATE		- 10	NOCENATE				
х	3	2023-04-05 38.35	1.91	QUET	4	4.94	ROSEROE				
<b>x</b> : 0	210.0	2013-06-21 98:35	4365300	QUET	\$	4.05.000	QUET				
20%	58%	2023-04-25 78:00	2	SEVEN.	۰	2	sevent				
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Additional Additional

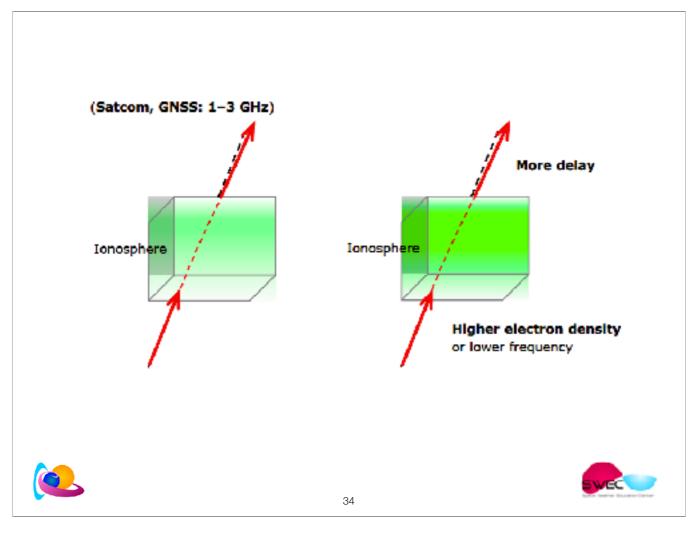
Bound alarm is triggered when NOD or SEV thresholds are exceeded or in case of data outages.

New telephone call focus on AS



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

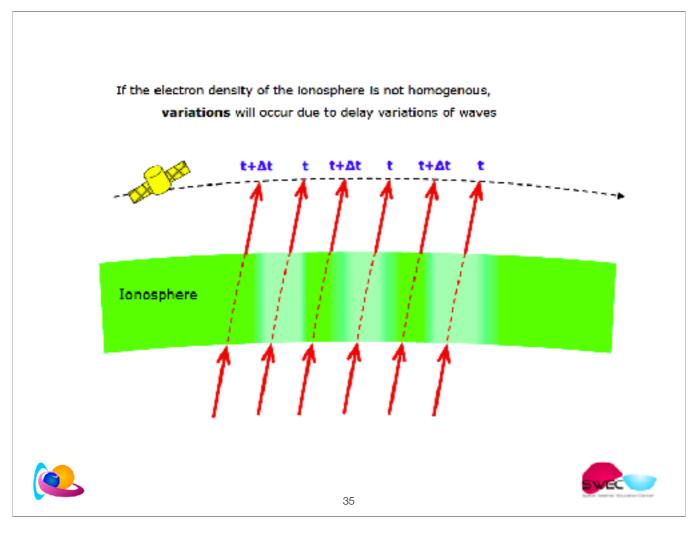
When waves pass through, they are more or less refracted/delayed.



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.

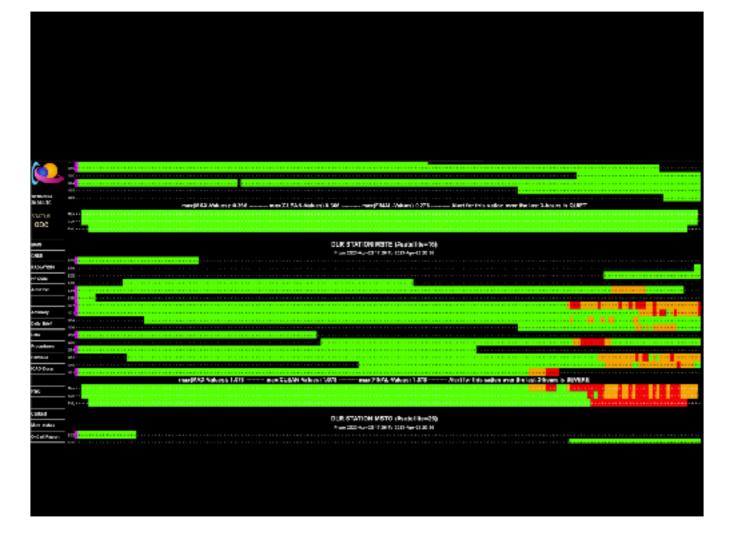


So far, we assumed a stable and predictable ionosphere. That is not always the case. At high frequencies, were there is only a little refraction, the delay imposed on radio waves may still be important. When – either due to the movement of the satellite or due to traveling ionospheric disturbances -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

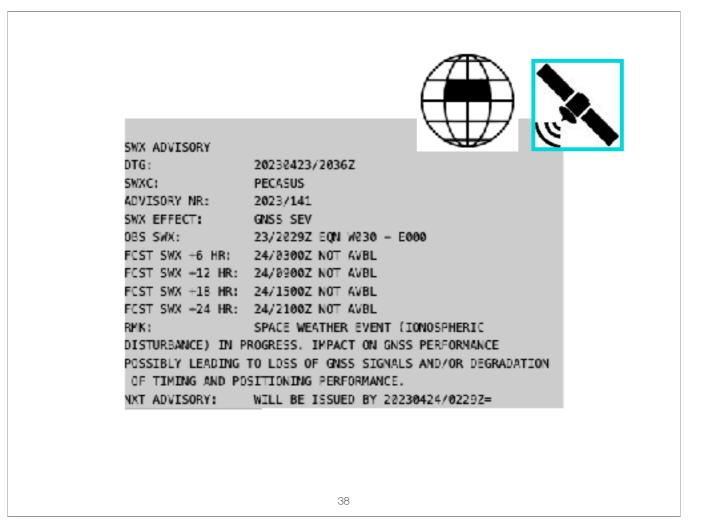
Depending on the severity of these variations, the receiver may loss signal lock.

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.





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



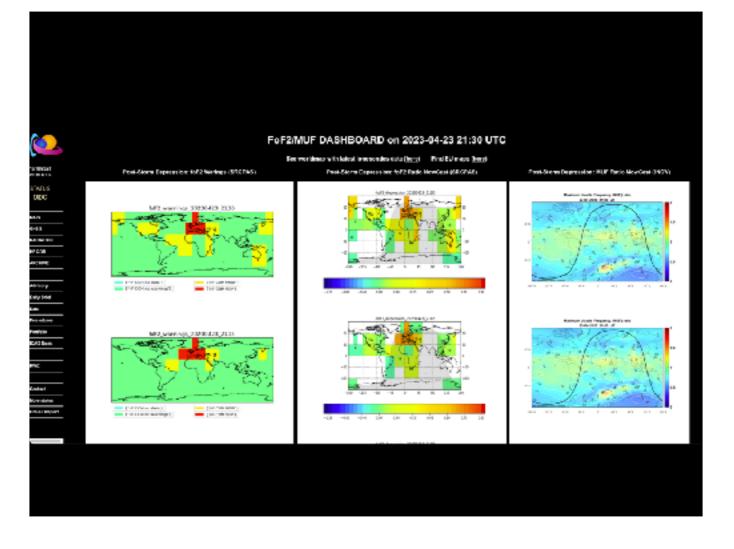
PECASUS DASHBOARD on 2023-04-23 20:36 UTC

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Bound alarm is triggered when NOD or 8EV 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.

		(((•)))
20230423/2126Z PECASUS		
2023/63		
2023/62		
HF COM SEV		
23/21987 HMH HSH MMM	I MSH FON FOS	

ADVISORY NR:	2023/63
NR BPLC:	2023/62
SWX EFFECT:	HF COM SEV
OB5 SWX:	23/2108Z HNH HSH MNH MSH EQN EQS
W180 - E180	
FCST SWX +6 HR:	24/0400Z NOT AVBL
FCST SWX +12 HR:	24/1000Z NOT AVBL
FCST SWX +18 HR:	24/1600Z NUT AVBL
FCST SWX +24 HR:	24/2200Z NOT AVBL
RMK:	SPACE WEATHER EVENT (MAXIMUM USABLE
FREQUENCY DEPRESSI	ION) IS IN PROGRESS. IMPACT ON HIGHER HE
COM FREQUENCY BAND	DS EXPECTED.
NXT ADVISORY:	WILL BE ISSUED BY 20230424/0308Z=

SWX ADVISORY

DTG:

SWXC:

Update of the advisory: for the whole globe

# PECASUS DASHBOARD on 2023-04-24 00:00 UTC

CM58	Madarella	82736	Time UTC	Values	Satus	SIER	Max-32 years	West-shistories
Amalitude Scintillation	0.5	0.4	2123-04-54	1.22	SEVERC	-	1.23	SEVERE
Phase Sciet listion	04	0.7	2223-04-54 00:00	8.74	QUIET	0	0.38	QUIET
Vertical TEC	125	175	2123-04-34 09:00	1:4.95	QUIET	۵	175.73	NODERATE

RADIATION	Moderate	31-20	Time UTC	Rigs	Status	Alert	Max-31 Fags	Max-3h status
Effective Cose FL 5 440	30	50	2123-04-24 09:00	0	QUIET	4	•	QUET
Effective Doce FL = 160	1.	10	2123-04-24 09:00	0	QUIET	۵	•	QUIET

HECON	Madarella	86+38	Time UTG	Velues 1 logs	Status -	54E ft	Mitrid? Vetes	West-th shares
Auroral Alecorption (AA)	*	9	2123-04-24 09:00	7.0	WARNING	۵	8.0	NODERATE
Polar Cap Absorption (PCA)	2	ä	2123-04-24 09:00	0.06	QUIET	Φ	1.39	QUET
Shartware Enderse: (SWT)	21.0	x10.0	2023-04-54 00:00	< MS films	DUICT	4	< NS fam	QUET
Post-Storm Depression (PSD)	37%	50%	2121-04-54	2	SEVERE	<b>.</b>	2	SEVERE

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

SIGNATION SECTION STATUS ODC STATUS ODC EADS EADATON BELOW Addisory Salig-Feet PRO Description PRO Description

AA has finished.

RXX02 EFKL 232343	i de la companya de l
WX ADVISORY	
	20238423/2344Z
SWXC:	PECASUS
NOVISORY NR:	2923/64
IR RPLC:	2023/61
SWX EFFECT:	HE CON MOD
DBS SWX:	23/23297 NO SWX EXP
FCST SWX +6 HR:	24/0600Z NO SWX EXP
FCST_SWX_+12_HR: 0	24/1200Z NO 5WX EXP
FCST SWX +18 HR: 0	24/1800Z NO 5WX EXP
FCST SWX +24 HR: 0	2570890Z NO SWX EXP
ачк: :	SPACE WEATHER EVENT (HE COM AURORAL
and the second	AP ABSORPTION) HAS ENDED.
ABSORPTION/POLAR_C	AF ABSUMPTIONS DAS ENDED.

End the advisory

# PECASUS DASHBOARD on 2023-04-24 00:00 UTC

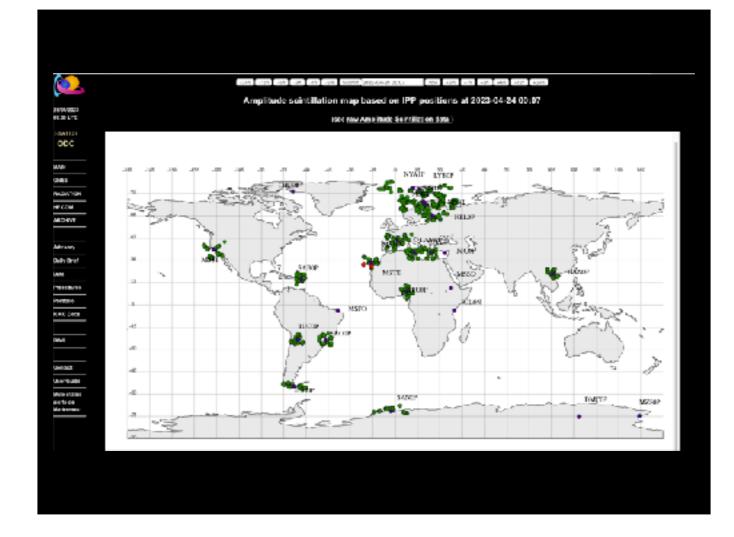
CM58	Madarella	82+36	Time UTG	Values	Satus	SIER	Max-32 years	Vice-th stores
Amalitude Ssintillation	0.5	0.3	2123-04-64	1.22	SEVERC	-	1.23	SEVERE
Phase Sciet listion	04	0.7	2023-04-54 00:00	8.74	QUIET	0	0.38	QUIET
Mertical TEC	125	175	2123-04-34 09.00	114,95	DUIET	۵.	175.79	NODERATE

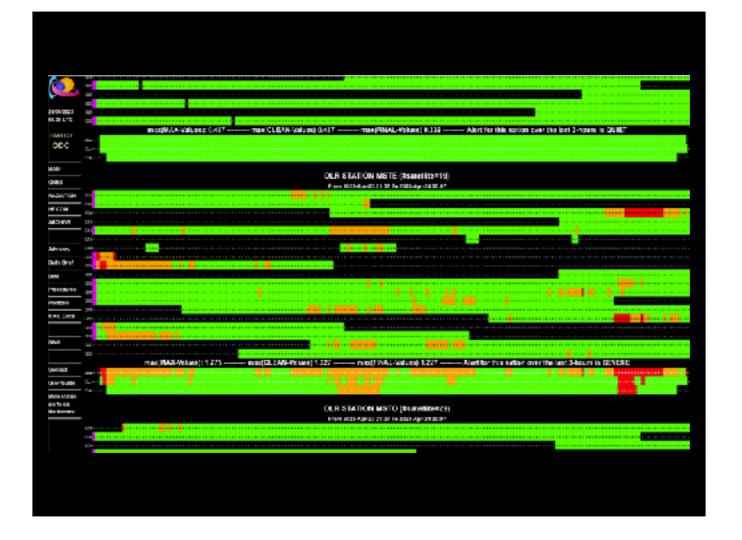
RADIATION	Moderate	30-210	Time UTC	Rigs	Status	4/61	Max-31 Reps	Max-3h status
Effective Cose FL 5 440	30	50	2023-04-24 09:00	0	QUIET	٥	•	QUET
Effective Doce FL = 160	1	10	2023-04-24 00:00	0	QUIET	۵	•	QUIET

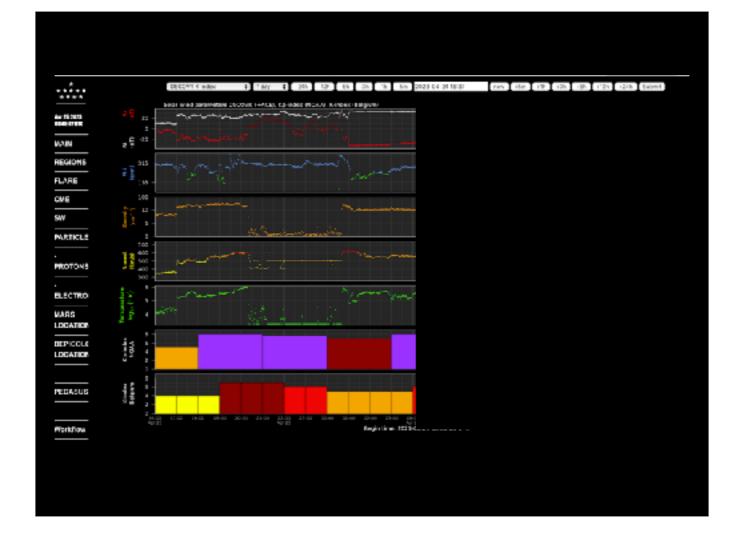
HP COM	Madarella	827310	Time UTC	Velues 1 logs	Sale is	5 Erf	Max-32 vetups	Vice-th stores
Auroral Alecorption (AA)	*	9	2123-04-24 09:00	7.0	WARNING	۵	8.0	NODERATE
Polar Cap Absorption (PCA)	2	b.	2123-04-24 09:00	0.06	QUIET	Φ	1.39	QUET
Shartware Enderse: (SWT)	21.0	x10.0	2023-04-54 00:00	< MS films	DUICT	Φ	<ns fam<="" th=""><th>QUIET</th></ns>	QUIET
Post-Storm Depression (PSD)	37%	30%	2121-04-54	2	SEVERC	<b>10</b> 1	7	SEVERE

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

Addisory Add







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



