

Space Weather impacts on Aviation

PECASUS advisories for ICAO

Course by the
Solar-Terrestrial Centre of Excellence



March 2024

Good Morning everybody,

So in the coming hour, I will explain you the advisories that we make here at PECASUS for ICAO. But I will stay at a high level, trying to give you a feel of the physics behind, but also give you a feel what they could mean to you, operationally.

Speaker notes are provided for information only: the author *assumes no responsibility or liability for any errors or omissions in the content of this presentation. The information contained in this presentation is provided on an "as is" basis with no guarantees of completeness, accuracy, usefulness or timeliness.*

ICAO SW service

But first some words about the ICAO space Weather Service itself.

ICAO SW Service - Framework & requirements

Impact Area	Parameter (Unit)	Moderate	Severe
GNSS	Amplitude scintillation S4 (dimensionless)	0.5	0.8
	Phase scintillation σ_ϕ (radians)	0.4	0.7
	Vertical TEC (TEC Unit)	125	175
Radiation	Effective dose (μ Sievert/hour)	30	80
HF	Auroral absorption (Kp)	8	9
	PCA (dB from 30 MHz riometer data)	2	5
	Solar X-ray (W/m^2) (0.1-0.8 nm)	10^{-4}	10^{-3}
	MUF (%)	30	50



ICAO

```

SWX ADVISORY
DTG: 20250815/0555Z
SWXC: PECASUS
ADVISORY NR: 2025/18
NR RPLC: 2025/17
SWX EFFECT: HF COM SEV
OBS SWX: 15/0535Z EQS W045 - E045
FCST SWX +6 HR: 15/1200Z NOT AVBL
FCST SWX +12 HR: 15/1800Z NOT AVBL
FCST SWX +18 HR: 16/0000Z NOT AVBL
FCST SWX +24 HR: 16/0600Z NOT AVBL
RMR: SPACE WEATHER EVENT (MAXIMUM USABLE
FREQUENCY DEPRESSION) IS IN PROGRESS. IMPACT ON HIGHER HF
COM FREQUENCY BANDS EXPECTED. LOWER FREQUENCY BANDS MAY BE
LESS IMPACTED.
NXT ADVISORY: WILL BE ISSUED BY 20250815/1155Z=
    
```



Approved by and published under the authority of the Secretary General

INTERNATIONAL CIVIL AVIATION ORGANIZATION

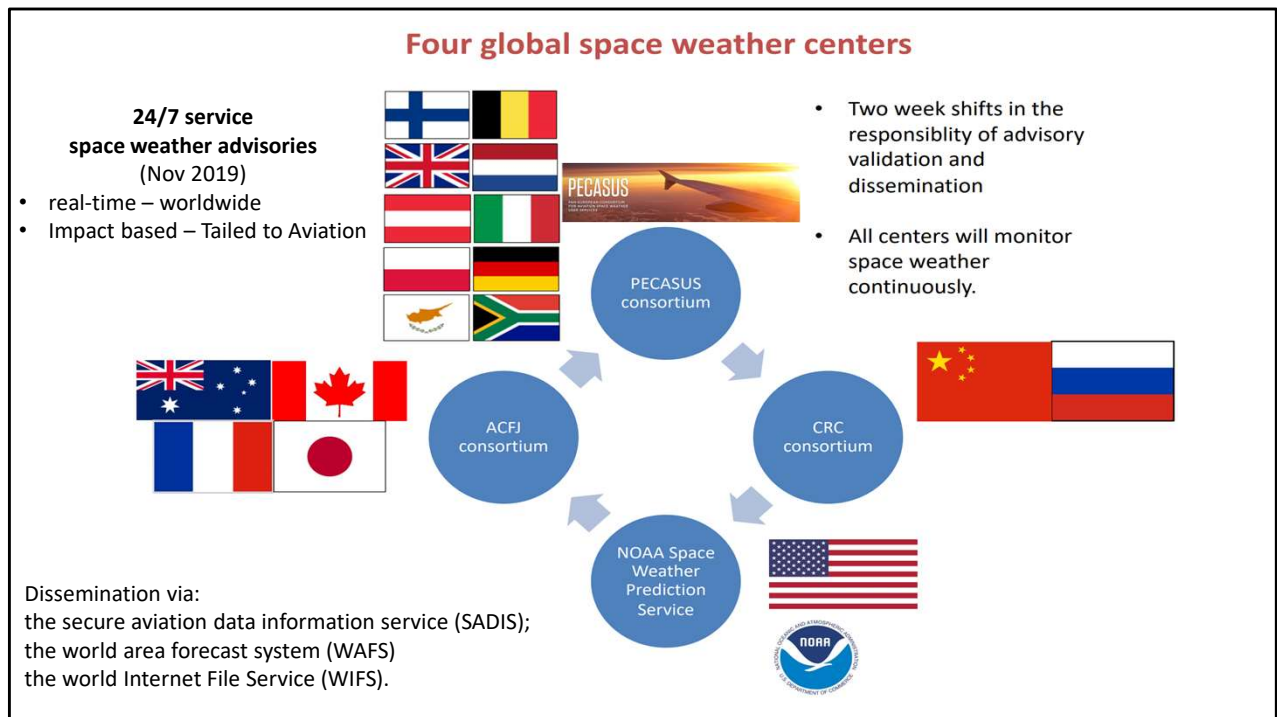
Specification

- ICAO Annex 3-Meteorological Service for International Air Navigation
- Manual on Space Weather Information in Support of International Air Navigation (ICAO Doc 10100)
- WMO message headers for SWX Advisories

It all started 5 years ago, 2019.

ICAO first worked out a clear framework of protocols and guidelines and specifications and thresholds. The references specifications see slide.

All center use the same thresholds, and we all follow the same protocols and guidelines are given in different specifications: so there is a clear frame for what we can write or not in the advisories.



So the ICAO service is a 24/7 service that provides you with real-time alerts. What is particular, is that it is impact based (not based on the solar effect) and thresholds are tailored to Aviation.

After an audit, ICAO decided to work with a network of 4 different centers/consortiums,. And we as STCE, are part of PECASUS.

Each center has 2 weeks shift, then the responsibility is passed to the next center, All center use the same thresholds, but slight differences in detection methods and phraseology in the “remark”- section can be observed, but from advising point of view they are equivalent.

Advisory – General

I will first go to some general parts of the Advisory messages and then in the following sections we will make a deep dive for every “type” of Advisory.

GNSS advisory example

DTG: 20241111/0924Z
SWXC: **PECASUS** Issuing center
ADVISORY NR: **2024/635** Advisory number
SWX EFFECT: **GNSS MOD** Effect and Severity Level
OBS SWX: 11/0912Z **HNH W015 - E030** Time & Area of the observed impact
FCST SWX +6 HR: 11/1600Z NOT AVBL Forecast
FCST SWX +12 HR: 11/2200Z NOT AVBL
FCST SWX +18 HR: 12/0400Z NOT AVBL
FCST SWX +24 HR: 12/1000Z NOT AVBL
RMK: SPACE WEATHER EVENT (IONOSPHERIC SCINTILLATION) IN PROGRESS. IMPACT ON GNSS PERFORMANCE POSSIBLY LEADING TO LOSS OF GNSS SIGNALS AND/OR DEGRADATION OF TIMING AND POSITIONING PERFORMANCE. Event explanations & possible impact
NXT ADVISORY: WILL BE ISSUED BY 20241111/1512Z= Expected update time

This is an example of an advisory: on the red fields I will come back when detailing the advisories.

- Issuing Center:
- Number: and if there is a follow-up advisory: there will be a line to say which advisory is replaced.
- Effect (GNSS/HF COM/RAD) and the severity (MODERATE or SEVERE)
- Issuing time : in Zulu time or UTC.
- Observation Time and Location:
- 4 Forecast times: it is what is expected to happen at exactly 6h later. It is not “what can happen during those 6h”. Very often it is “no forecast available” (which means we cannot predict with certainty what will happen” or “no space observed” (which means “we are sure” there will be no further effect” at T+6h).
- Remark field: - Next advisory: indicates the time of the next message (update or closure). Important is here: each advisory will be closed by a “closing advisory” stating “No further advisories”. When you read this, it means, the effect has ended.

GNSS advisory example

Example closing advisory

```
DTG:                20241111/1326Z
SWXC:               PECASUS
ADVISORY NR:        2024/636
NR RPLC:            2024/635
SWX EFFECT:         GNSS MOD
OBS SWX:            11/1322Z NO SWX EXP
FCST SWX +6 HR:     11/2000Z NOT AVBL
FCST SWX +12 HR:    12/0200Z NOT AVBL
FCST SWX +18 HR:    12/0800Z NOT AVBL
FCST SWX +24 HR:    12/1400Z NOT AVBL
RMK:                END OF GNSS (SCINTILLATION) EVENT
NXT ADVISORY:       NO FURTHER ADVISORIES=
```

So a closing advisory indicates which advisory is replaced RPLC, like any “follow up advisory” would have.

But it also states “No Swr expected” and “End of xx event” and “No further advisories”.

3 Effects – RAD / HF COM / GNSS

RADIATION
effects



HF COM
effects



GNSS
effects



There are 3 Categories of Advisories:
RADIATION effects
HF COM
GNSS

2 Severity Levels – Moderate / Severe

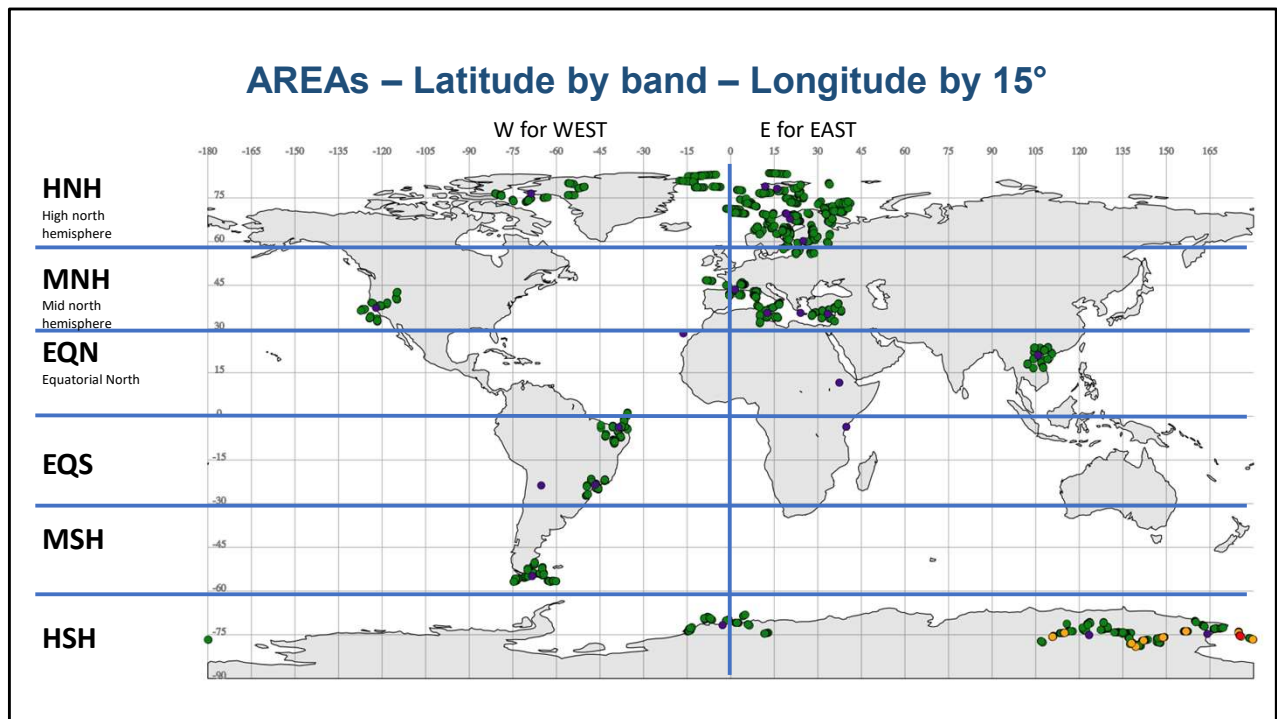
MODERATE (MOD)

SEVERE (SEV)

GNSS	Moderate	Severe	Time UTC	Values	Status	Alert	Max-3h values	Max-3h status
Amplitude Scintillation	0.5	0.8	2023-04-23 20:36	1.08	SEVERE		1.08	SEVERE
Phase Scintillation	0.4	0.7	2023-04-23 20:36	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-3h flags	Max-3h status
Effective Dose FL ≤ 460	30	80	2023-04-23 20:35	0	QUIET		0	QUIET
Effective Dose FL > 460	/	80	2023-04-23 20:35	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 20:36	8.0	MODERATE		8.0	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 20:36	< M5 flare	QUIET		< M5 flare	QUIET
Post-Storm Depression (PSD)	30%	50%	2023-04-23 20:00	2	SEVERE		2	SEVERE

For each type of Advisory: there are two possible levels: MODERATE (here in Amber on our internal PECASUS dashboard) and

The thresholds to say it is SEVERE are MODERATE are given by ICAO, and are identical for all centers.



The advisories specify also where the effect can be experienced on earth.

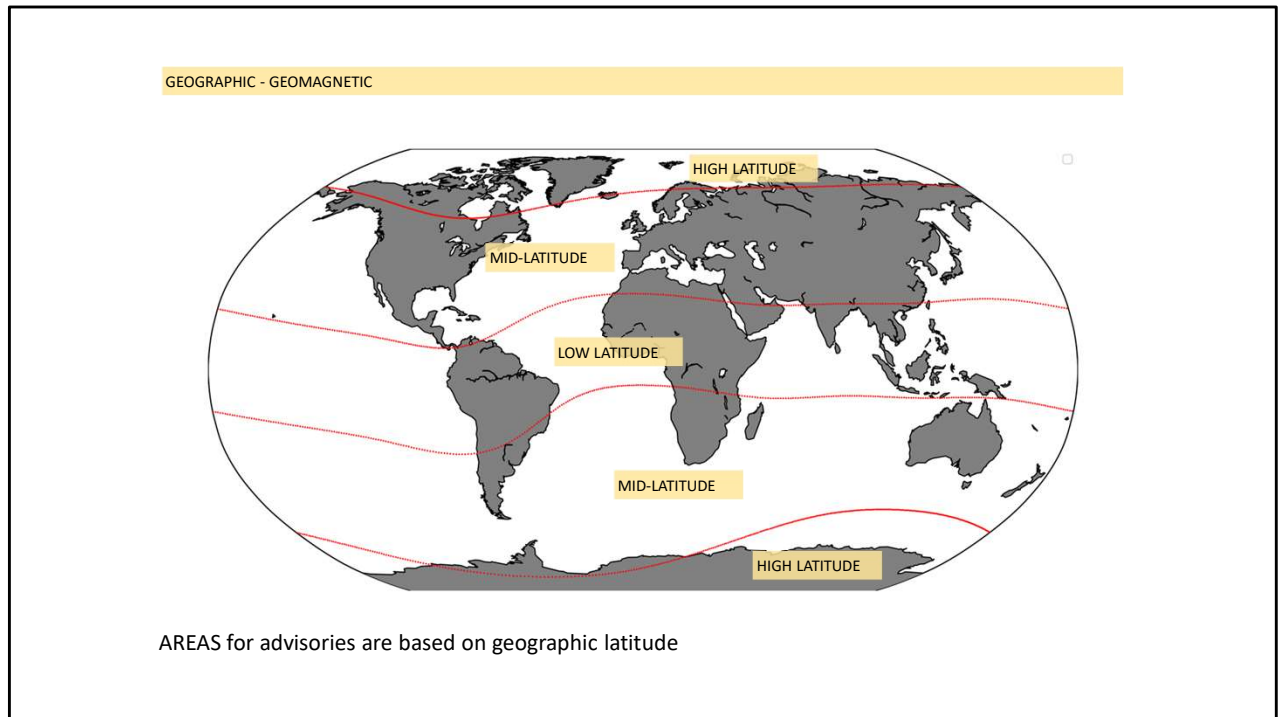
For longitude we use steps of 15° (E for EAST and W for WEST)

And in terms of latitude the earth is split in 3 latitude bands per Hemisphere per 30 degrees.

So HNH High North Hemisphere include the poles but go even lower: 60-90° North

MNH: Mid North Hemisphere: 30-60°

EQN: Equatorial North: 0-30°



So we follow the geographic latitudes, not the geomagnetic latitudes...

HF COM



The first impact I want to discuss is the impact on HF communication (3-30MHz)

In civil aviation, HF is used for communication for transoceanic flights and over the poles. But over the ocean, there is also Satellite communication for most airplanes to communicate with ATC and Airline Operating Center. But this is not the case over the poles.

HF COM

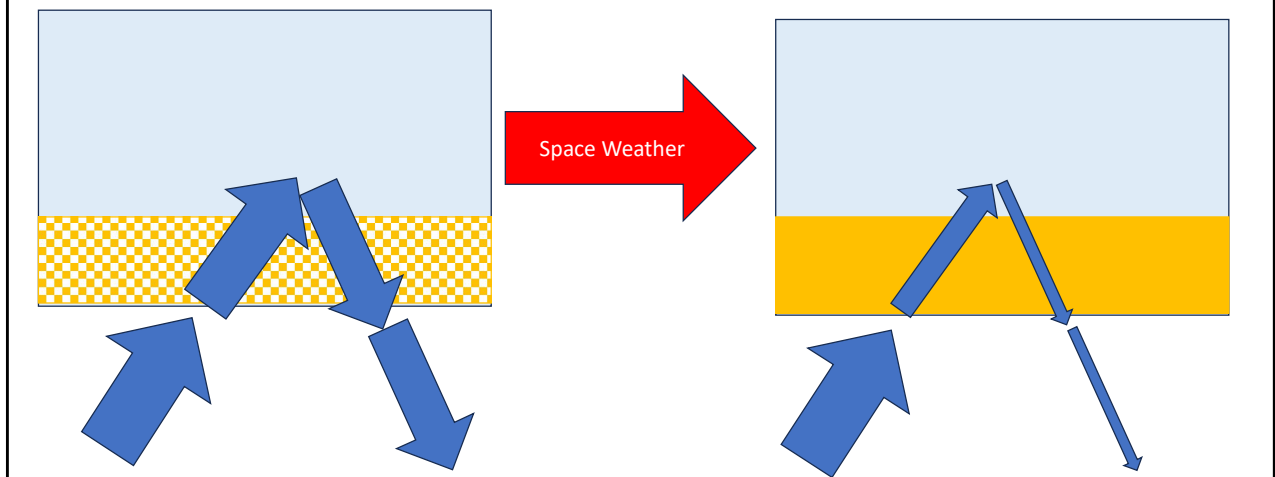
- Absorption following Solar Flare
- Polar Cap Absorption
- Auroral Absorption
- Maximum Useable Frequency Depression



There are 4 different cases for HF COM advisories: 3 are linked to Absorption and this plays first on the lower frequencies and 1 is linked to the reduction of the MUF so this plays on the highest HF frequencies.

Absorption increased

Lower HF frequencies are absorbed more => Use higher frequencies to re-establish HF COM.



A quick reminder:

The principle of HF communication is that the radio waves are reflected in the ionosphere back to the earth.

So the ionosphere acts as a mirror.

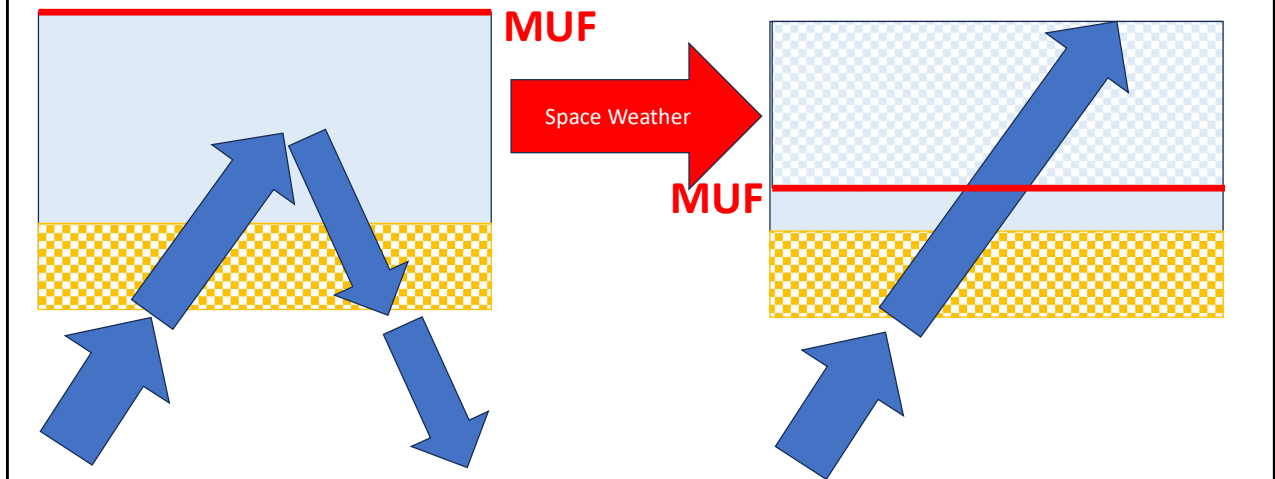
Space weather has 2 different impacts on the ionosphere, depending what happens:
Absorption and Depression

In some cases, the ionosphere becomes more Absorbing: you get less decibels in the signal. And this absorption affects more lower frequencies so operationally you need to use higher frequencies in that case.

Depression - MUF (Max Useable Freq) reduced

Maximum Useable Frequency: Maximum frequency that is reflected in the ionosphere.

Frequencies > MUF go straight through => Using lower frequencies may allow to re-establish HF COM.



And in some cases, the ionosphere becomes less reflective (Muf depression):
The Maximum Useable Frequency is the highest HF frequency that is reflected.

So:

- Frequencies below the MUF are reflected and can be used,
- Frequencies above pass through the ionosphere and are "lost".

Due to space weather, this MUF can be lower than usual, which means that and you need to reduce the frequency used to be able again to reflect the HF Signals...

Depression - MUF (Max Useable Freq) reduced

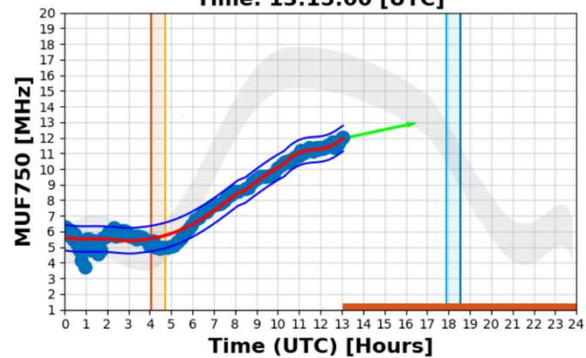
Maximum Useable Frequency: Maximum frequency that is reflected in the ionosphere.

Frequencies > MUF go straight through => Using lower frequencies may allow to re-establish HF COM.

Ionosphere Maximum Usable Frequency (MUF750)

Date: 2024-03-04 Day Number 064

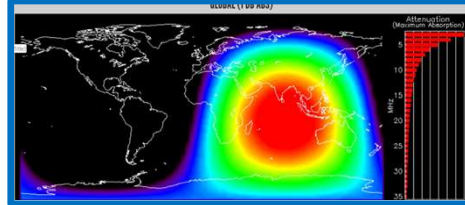
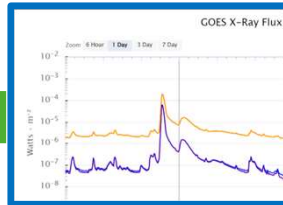
Time: 13:15:00 [UTC]



So we have today a “MUF” depression ongoing: so in the graph below, the grey line shows the “usual maximum useable frequency” on a given hours of the day (during night, it is low). So we can observe that today the MUF (blue/red dots) is clearly below the usual value.



Absorption following Solar Flare



Origin: Flare
 Sun to Earth: Minutes
 Impact duration: Minutes (for one flare)
 Impact Area: Daylight side
 Impact: Absorption: dB loss at lower HF frequencies (higher HF frequencies are less affected)

The soft X-ray flux increase will induce an excess ionization of the D layer of the ionosphere triggering an absorption of low HF frequencies (short wave fade out) at the daylight side.

The fastest but also the shortest effect on HF COM is from the solar flare.

It's relatively short as you can see in the curve (GOES X-Ray curve), in average only minutes and the impact affects the dayside only.

And the effect of the absorption is nicely seen with the D-RAP model as in this video: the red is where the absorption is highest.



Absorption following Solar Flare

DTG: 20240222/0736Z
 SWXC: PECASUS
 ADVISORY NR: 2024/39
 SWX EFFECT: HF COM MOD
 OBS SWX: 22/0637Z DAYLIGHT SIDE
 FCST SWX +6 HR: 22/1300Z NOT AVBL
 FCST SWX +12 HR: 22/1900Z NOT AVBL
 FCST SWX +18 HR: 23/0100Z NOT AVBL
 FCST SWX +24 HR: 23/0700Z 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 20240222/1237Z

MODERATE: Flares > X1
 SEVERE: Flares > X10

Duration: minutes-1h

Impact on lower HF

In the case of a Solar Flare >X1, the PECASUS team will send out a ICAO advisory.

The impacted area will indicate "DAYLIGHT SIDE"

And in the RMK section we have the following std text:

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.

So for the reader of the advisory, the importance is in the term "solar flare", which gives you an indication that the issue of this one single event is "relatively short" compared to other absorption HF COM advisories...Of course, if successive flare follow on each other, then the event duration will be longer...

The MODERATE level is triggered for a X1 flare and above.

The SEVERE level is triggered for a X10 flare are above.

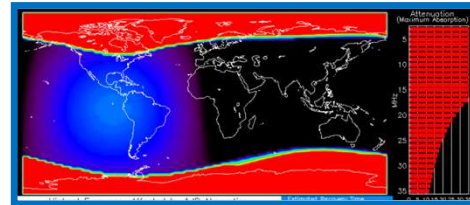
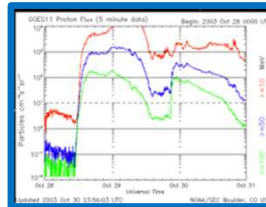
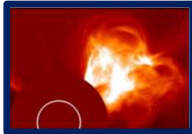
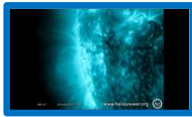
So we detect it via the GOES X-RAY flux data, not the D-RAP model.

This advisory will be typically closed after 30 min or 1h. But multiple flares may happen, then there will be several HF COM advisories/longer advisories.

Forecasting Flare timing is not yet possible: we currently only have flare probabilities for the next 24h, but these kind of forecast cannot be made in the ICAO format.



Polar Cap Absorption



Origin:	Proton event following strong X-flares/CME shock wave
Sun to Earth	Usually hours (but can be minutes)
Impact duration:	1 or 2 days
Impact Area:	High Latitude Band
Impact:	Absorption: dB loss at lower HF frequencies (higher HF frequencies are less affected)

During proton events or solar radiation storms, energetic particles from the Sun will trigger extra ionisation of the D-layer in the polar regions inducing a radio fade out, called a **Polar Cap Absorption**.

The second phenomena is what we call Polar Cap Absorption, so again an Absorption effect.

This effects takes place when after stronger flares or CME shock waves, electrically charged particles are expelled at very high speeds.

They arrive in minutes or hours to Earth but the Earth's geomagnetic fieldlines act as a shield except at the poles, where it will destabilize the ionosphere.

So this absorption effect plays at the poles.

This effect lasts on average roughly for 1 or 2 days, so it's relatively a long term effect.



Polar Cap Absorption

DTG	20240129/2359Z
SWXC	PECASUS
ADVISORY NR.	2024/4
NR. RPLC	2024/3
SWX Effect	HF COM MOD
OBS SWX	29/2348Z HNH HSH W180 - E180
FCST SWX + 6 HR	30/0600Z NO SWX EXP
FCST SWX + 12 HR	30/1200Z NO SWX EXP
FCST SWX + 18 HR	30/1800Z NO SWX EXP
FCST SWX + 24 HR	31/0000Z NO SWX EXP
RMK	SPACE WEATHER EVENT (HF COM POLAR CAP ABSORPTION) IN PROGRESS. IMPACT ON LOWER HF COM FREQUENCY BANDS EXPECTED AT HIGH LATITUDES. STRONGER IMPACT ON THE SOUTHERN POLE.
NXT ADVISORY	WILL BE ISSUED BY 20240130/0548Z=

MODERATE: Loss > dB 5 at 30MHz
SEVERE: Loss > dB 10 at 30 MHz

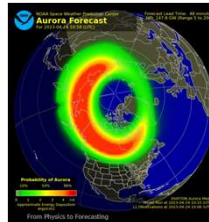
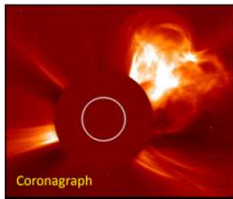
Duration: 1-2 days

Impact on lower HF

In case of Polar Cap Absorption, we will send a HF COM Advisory, almost identical to the one send for the flare. But now we mention “Polar Cap Absorption” so for the reader this is important because it hints you to expect it for roughly 1 or 2 days (not minutes as the flare)

The area will be the full north and south highest band latitude so HNH HSH

Auroral Absorption



Origin: CME hitting Earth
Sun to Earth: Around 3 days
Impact duration: 1 day
Impact Area: High Latitude Band
Impact: Absorption: dB loss at lower HF frequencies (higher HF frequencies are less affected)

. During geomagnetic storms, energetic particles will enter the polar regions of the ionosphere and trigger excess ionisation, triggering radio absorption, called an **auroral absorption**

Then the 3th effect, is again an absorption effect, but not due to the arrival of this high energy particle cloud, but due to arrival of CME (slower to arrive) that hits the Earth also via the poles.

This creates again the absorption effect at the poles, but now in the auroral oval, but for PECASUS it is similar to the poles.

This effect takes on average just 1 day or even less.

Auroral Absorption



DTG	20240129/2359Z
SWXC	PECASUS
ADVISORY NR.	2024/4
NR. RPLC	2024/3
SWX Effect	HF COM MOD
OBS SWX	29/2348Z HNH HSH W180 - E180
FCST SWX + 6 HR	30/0600Z NO SWX EXP
FCST SWX + 12 HR	30/1200Z NO SWX EXP
FCST SWX + 18 HR	30/1800Z NO SWX EXP
FCST SWX + 24 HR	31/0000Z NO SWX EXP
RMK	SPACE WEATHER EVENT (HF COM AURORAL ABSORPTION) IN PROGRESS. IMPACT ON LOWER HF COM FREQUENCY BANDS EXPECTED AT HIGH LATITUDES. EFFECT MAY EXTEND TO LOWER LATITUDES ABOVE THE AMERICASHNH HSH W180-E180
NXT ADVISORY	WILL BE ISSUED BY 20240130/0548Z=

MODERATE: > Kp 8
SEVERE: > Kp9

Duration: Roughly 1 day

Impact on lower HF

In case of Aurora Absorption, we will send a HF COM Advisory, almost identical to the one send for the PCA. But for the we mention "Auroral absorption" and you may guess it for 1 day or less.

The area will be the full north and south highest band latitude so HNH HSH

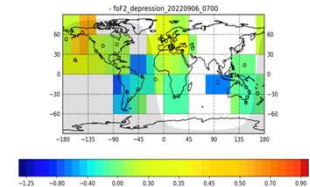
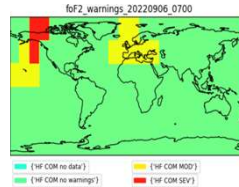
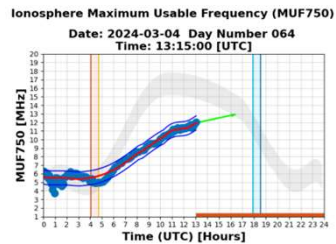
The thresholds for Moderate is when $Kp > 8$ and Severe when $Kp > 9$.

These PCA advisories are typically updated every 6h,

MUF depression



Start of MUF depression



Origin:	Re-stabilization, after CME hits Earth
Sun to Earth	Several days
Impact duration:	few days
Impact Area:	Can impact entire globe (disturbances very local and patchy and changing in time)
Impact:	Depression of the MUF : loss of highest HF frequencies

The maximum usable frequency (MUF) for a given communication path is the highest HF radio frequency that can be used for communication via reflection. In the late phases of geomagnetic storms (increased Kp), the ionosphere remains in an unsettled state, triggering disturbances in reflection capacity. The MUF varies with respect to their undisturbed values

The last effect is not an absorption effect, but the depression effect:

When there is a geomagnetic storm (created by the arrival of the CME), even if the storm does not create AA, the ionosphere can be deeply “disturbed” after the storm before it returns to normal.

This effect is however not at the poles but is observed globally, but it is very patch and varying phenomena. It is also not an absorption effect, it is the reduction of the reflecting factor namely a reduced MUF. So in this case the pilots should rather use a lower frequency

Maximum Usable Frequency (MUF) depressions usually occur after the end of the main phase of geomagnetic storms, thus they are closely associated with variations of the geomagnetic indices

It is also called Post Storm Depression, because it arrives after the end of the main phase of the geomagnetic storm

MUF depression



```
FNXX02 EFKL 141923
SWX ADVISORY
DTG:                20240914/1924Z
SWXC:               PECASUS
ADVISORY NR:       2024/240
NR RPLC:           2024/239
SWX EFFECT:        HF COM SEV
OBS SWX:           14/1921Z HNH MNH W180 - E180
FCST SWX +6 HR:    15/0200Z NOT AVBL
FCST SWX +12 HR:   15/0800Z NOT AVBL
FCST SWX +18 HR:   15/1400Z NOT AVBL
FCST SWX +24 HR:   15/2000Z 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 20240915/0121Z=
```

MODERATE: > 30 % drop of MUF
SEVERE: > 50% drop of MUF
Compared to 30 day running median foF2

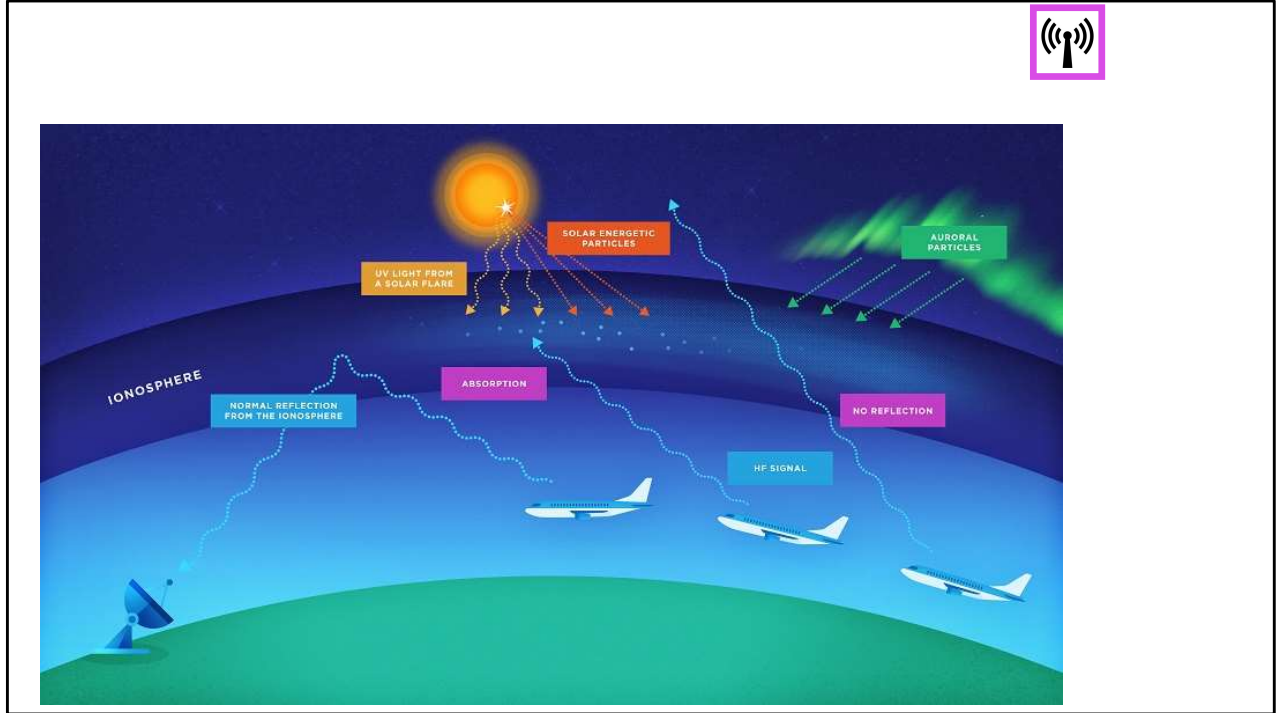
Duration: Several days
Area will be varying a lot

Impact on higher HF

In case of Post Storm depression, we will send a HF COM Advisory,
Here the importance is that you see the word Depression/MUF and saying it affects the
higher HF frequencies.

This will indicate you that potentially for the next few days the MUF will be varying and that
several advisories with different areas will be triggered.

Radio operators are advised to use lower frequencies



In summary: There are 2 different impacts on the HF COM due to Solar Weather:

- 1) Absorption, namely which will impact stronger the lowest HF frequencies.
- 2) Loss of reflexion (depression of MUF), which will impact first the highest HF Frequencies.

HF COM



Illustrative image (Eye catcher)	Effect on Aviation	Affected Area	ROM of Duration
	Absorption following Solar Flare	Dayside	Minutes to several hours
	Polar Cap Absorption	Poles	Several hours to several days
	Auroral Absorption		1 to several days
	Post Storm Depression	Anywhere (erratic)	Several Days (min 4 days)

For Information

GNSS

- Amplitude and Phase Scintillations
- Increased VTEC



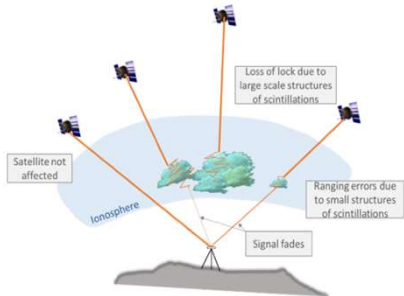
So until now we discussed the HF COM impact.
The Second impact is the GNSS.

GNSS signals is not like the HF COM signals that need reflection:
GNSS Signals pass (and need to pass through) the ionosphere to reach the receiver.

Space weather can disturb the ionosphere, which will disturb the GNSS signal:
- small scale irregularities lead to Amplitude or Phase scintillation of the wave
- large scale irregularities (like VTEC increase), impacts the speed and path of the wave.

But for a user point of view both lead to the same effect:
LOSS OF GNSS SIGNALS AND/OR DEGRADATION OF TIMING AND POSITIONING
PERFORMANCE

Ionospheric irregularities



Research on-going on Space Weather impact on ionospheric irregularities:

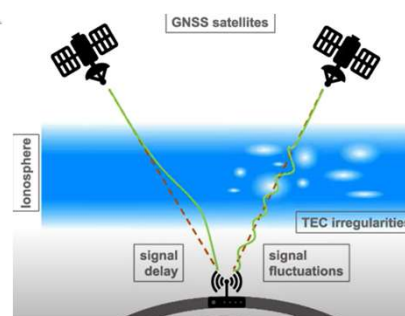
- Seasonal effect (Position Earth on ellipse)
- Solar cycle effect (More during Solar Max)
- CME arrival / Geomagnetic storm?

Impact on Signal:

- Amplitude scintillation
- Phase scintillation
- Speed/path (increased VTEC)

Impact for user:

- GNSS loss, and/or
- Reduced performance in timing and position

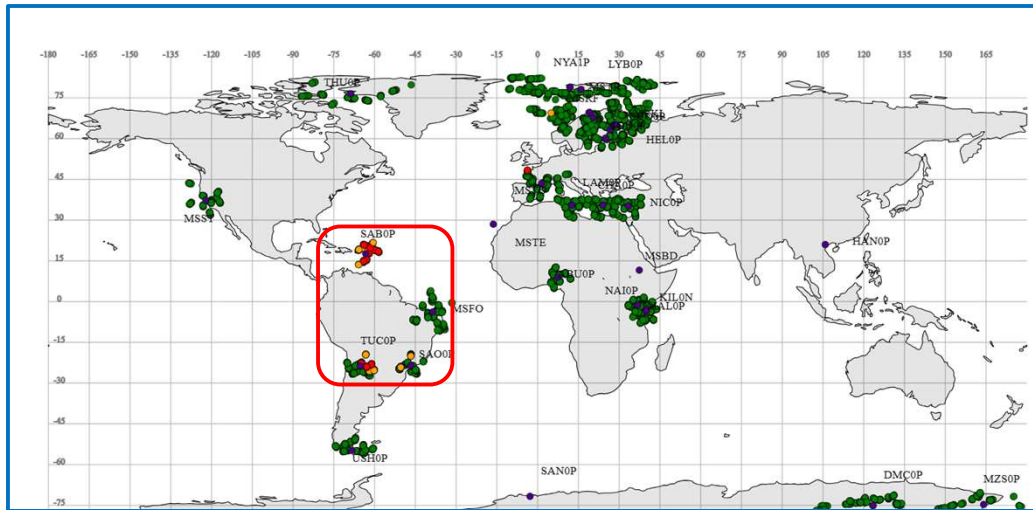


So what is scintillation:

If the GNSS signal has to go through small scale irregularities in the ionosphere (typically differences in electron density), it results in scattered waves (different speed/amplitude) This is what we call “scintillation” of the signal:

As a consequence, positioning errors can be introduced in satellite navigation.

How do we detect scintillation?

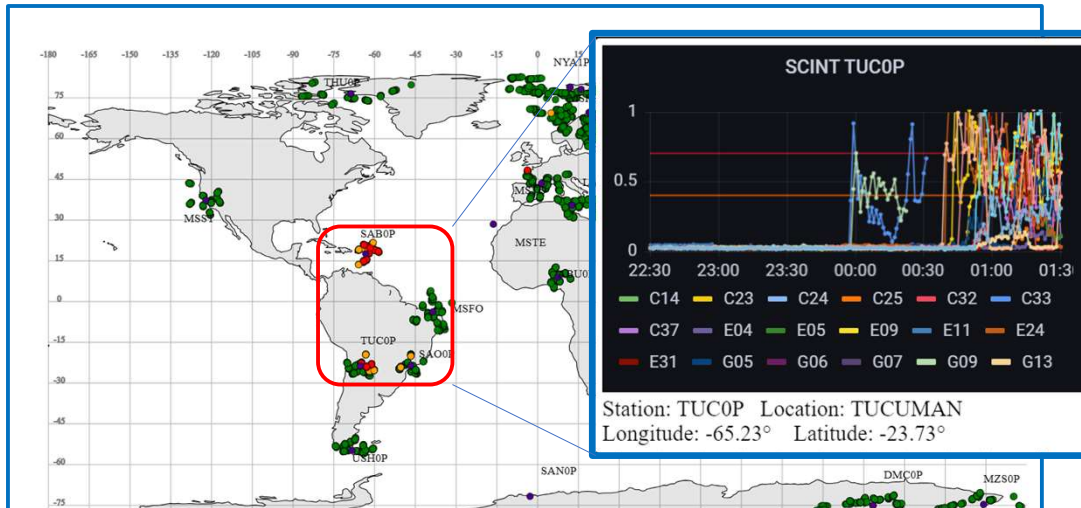


How do we detect scintillation?

We have different receivers in the world who continuously receive data from all GNSS satellites, including AS/PS index? the phase scintillation and amplitude scintillation which one of the main triggers for Scintillation advisories. But we are indeed limited by the number of receivers from which we get the data: large gaps.

So when there is scintillation the signal goes like this;

How do we detect scintillation?

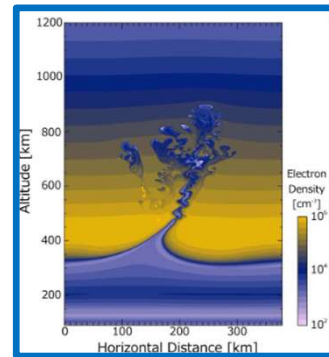
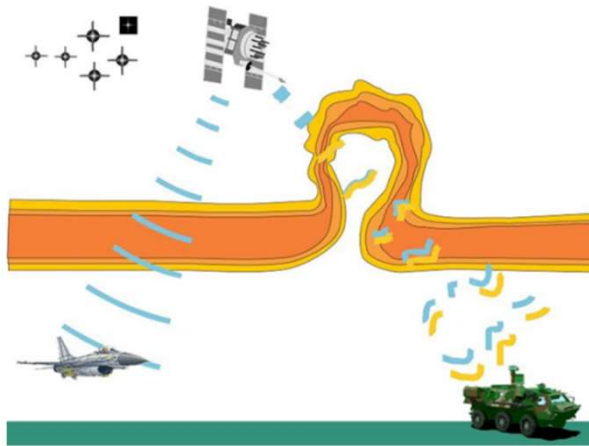


How do we detect scintillation?

We have different receivers in the world who continuously receive data from all GNSS satellites (C14-G13 in the image), including S4 and sigma Phi (the phase scintillation and amplitude scintillation) which are the parameters to monitor to send Scintillation advisories. But we are indeed limited by the number of receivers from which we get the data.

So when there is scintillation the signal goes like this;

Scintillation – Equatorial “bubbles”



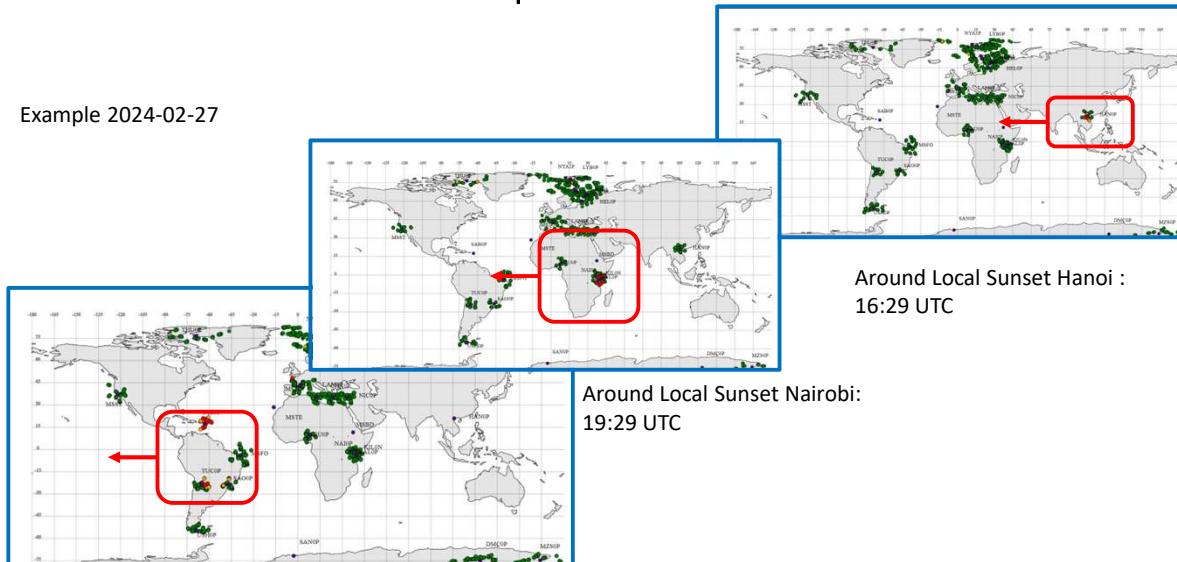
At the equator at local sunset => Area will move with the Day/Night line
Strength/frequency is seasonal (non- eruptive space weather)
Duration : 2-3 hours locally

Scintillation is very often observed at the equator, more precisely at the local sunset. We know that at the local sunset at the equator so called plasma bubbles are created, which have a electron density that strongly varies. So as shown in the image: a wave going through a “standard ionosphere” will be well passed, but a wave encountering on it’s path a big varying density will be disturbed/scintillated.

GNSS scintillation – Equatorial “bubbles”



Example 2024-02-27



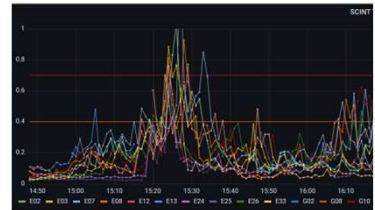
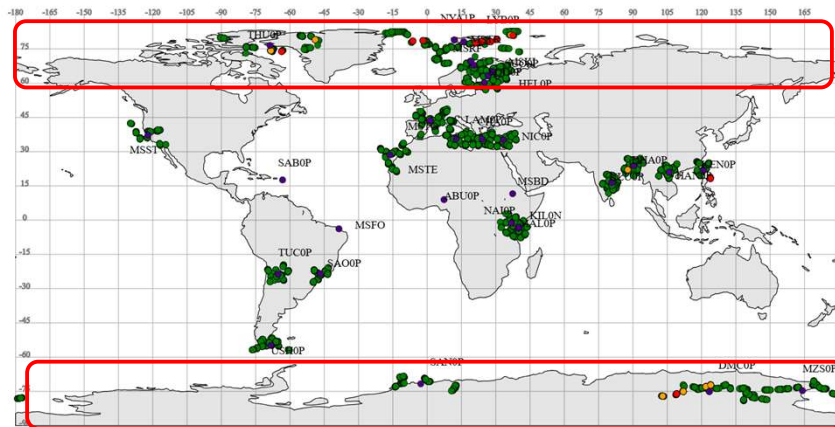
In the detections, you can nicely follow the observed scintillations by the receivers, following the day/night line.

The take roughly 3 hours, per station, but of course this can vary

And we see them currently every night, but strongest (most frequent) at South America.

It is not clear to us if the aircraft (systems) are disturbed by this scintillation, as we do not have feedback from in service.

GNSS scintillation at high latitude



Example of Oct 10 2024
CME arrival at 14h45

Scintillation at poles following due to geomagnetic storm
Duration Hours-1 day

The second area where we typically see scintillation is at the polar areas. Here, the scintillation is caused by the disturbances in the ionosphere following geomagnetic storm (ie CME arrival). As explained before, the effects of the CME is always stronger at the poles as there is not the shield of the earth magnetic field lines. The effects here last typically hours/day

GNSS Advisory for scintillation

FNXX01 EFLK 112216

SWX ADVISORY

DTG: 20241111/2217Z

SWXC: PECASUS

ADVISORY NR: 2024/639

SWX EFFECT: GNSS SEV

OBS SWX: 11/2207Z EQN W030 - E000

FCST SWX +6 HR: 12/0500Z NOT AVBL

FCST SWX +12 HR: 12/1100Z NOT AVBL

FCST SWX +18 HR: 12/1700Z NOT AVBL

FCST SWX +24 HR: 12/2300Z NOT AVBL

RMK: SPACE WEATHER EVENT (IONOSPHERIC

SCINTILLATION) 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 20241112/0407Z=

MODERATE:

>0.4 Sigma-Phi (Phase) or

>0.5 S4 (Amplitude)

SEVERE:

>0.7 Sigma-Phi (Phase) or

>0.8 S4 (Amplitude)

This is a typical advisory for scintillation.

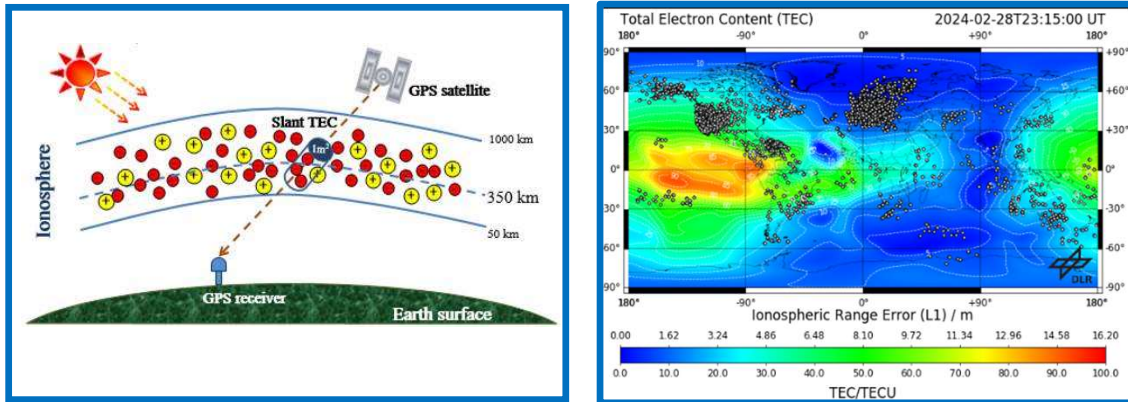
More specifically this is typical for the plasma bubbles: The area EQN EQS indicates the Equatorial region.

For these advisories, if the Longitude zone also corresponds to the local sunset at time of observation, you can “guess” we are observing the effects of plasma bubbles and therefore “expect” that the following “sunset”-regions will be subsequently impacted as the night/day-line progresses.

We observe these type of scintillations almost every night currently in solar maximum.

If the area would indicate HNH or HSH then it is a different: it will stay a few hours then it is expected to disappear.

VTEC increase



We also monitor the ionosphere itself (based on the VTEC- parameter), as the VTEC Change in the path and velocity.

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, which quantifies the refractive index.

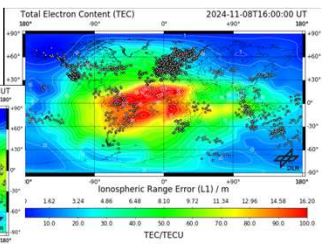
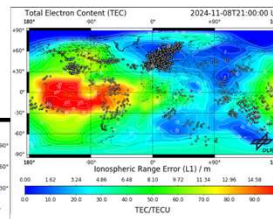
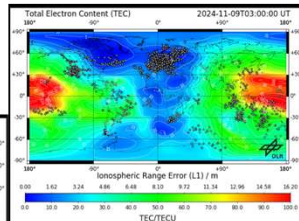
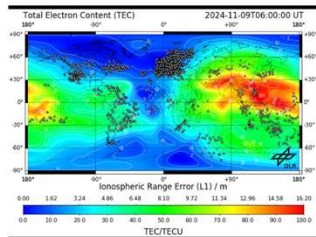
The GPS receivers usually take into account the refractive index of a “standard ionosphere” (Klobuchar model), but they do not take into account the rapid deviations from this standard ionosphere.

You can see in the image that the TEC is not the same everywhere: there is always an area where the VTEC is higher than the rest of the globe, usually around the equator

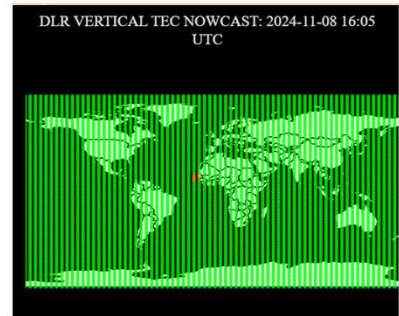
VTEC increase

Example 11 Nov 2024

No eruptive Solar Weather ongoing but high F10.7



Our dashboard

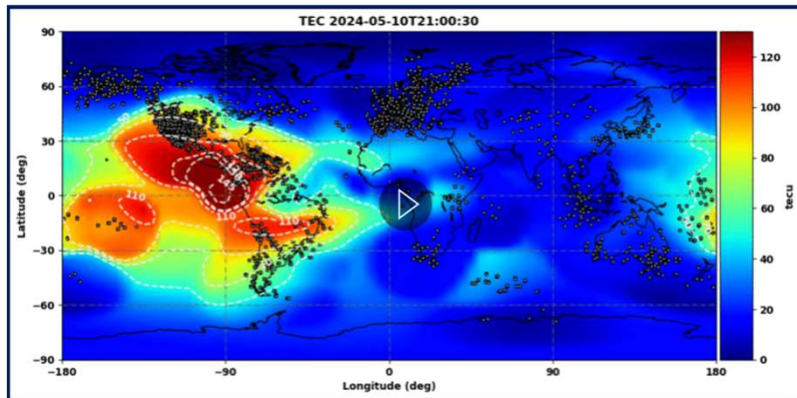


And this area of “higher VTEC” will be observed more westwards as the day goes on (similar as to the plasma bubbles, the area with higher VTEC evolves with the rotation of the earth.)

And sometimes the VTEC in this higher zone becomes so high that it passes the threshold for advisories (it may be eg just a very small area of this bigger area of high VTEC, that is above the thresholds)

VTEC increase

Example 10 May 2024 – Impact of the Geomagnetic Storm – increased VTEC



High VTEC typically happens when a geomagnetic storm arrives, like in this example of the 10th of May geomagnetic storm. But there are also periods of high VTEC that are not directly linked to geomagnetic storms (probably linked to periods to high F10.7)

GNSS Advisory for VTEC

FNXX01 EFKL 051517

SWX ADVISORY

DTG: 20241105/1515Z

SWXC: PECASUS

ADVISORY NR: 2024/588

SWX EFFECT: GNSS MOD

OBS SWX: 05/1513Z EQN W010 - E015

FCST SWX +6 HR: 05/2200Z NOT AVBL

FCST SWX +12 HR: 06/0400Z NOT AVBL

FCST SWX +18 HR: 06/1000Z NOT AVBL

FCST SWX +24 HR: 06/1600Z NOT AVBL

RMK: SPACE WEATHER EVENT (IONOSPHERIC
DISTURBANCE RELATED TO VTEC) 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 20241105/2113Z=

MODERATE:

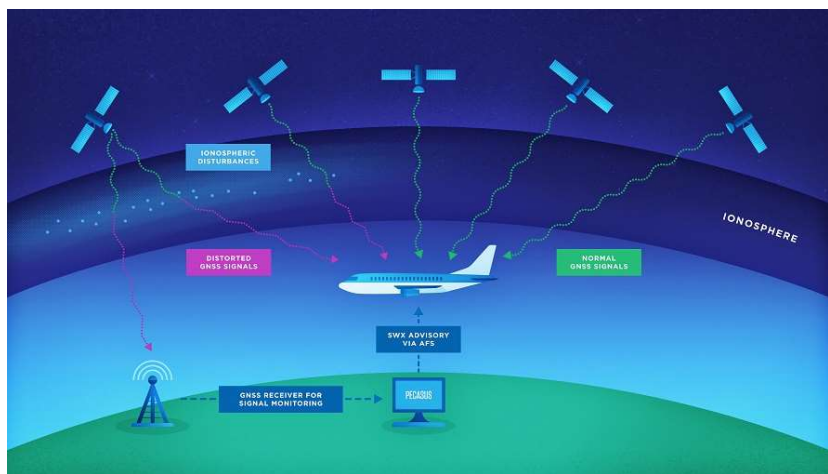
>125 TECU (VTEC)

SEVERE:

>175 TECU (VTEC)

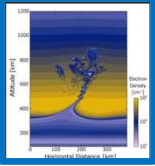
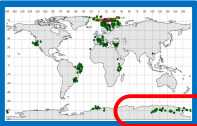
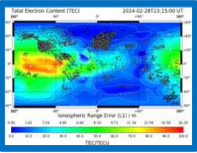
This is a typical advisory for vtec.

The area for high VTEC is also typically the Equatorial region.



GNSS



Illustrative image (Eye catcher)	Sun to Earth	Effect on Aviation	Affected Area	ROM of Duration
	No eruptive space weather trigger	GNSS Loss and/or Position Error	Equator at local sunset Follows day/nightline	Few hours (start at sunset)
	3 days (Science ongoing)		Poles	Few hours
	(Science ongoing)		To be studied	Few hours

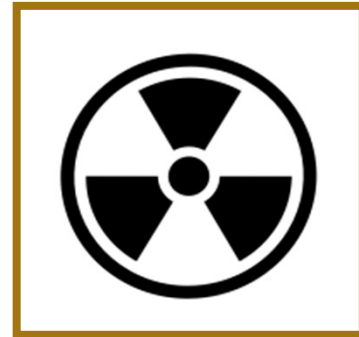
RAD



The following impact is Radiation.

RAD

- Galactic Cosmic Rays (GCR) - always
- Extreme strong Proton Event (GLE) - rare



COMMON: Stronger impact at higher Flight Levels
Stronger impact at higher latitude (towards poles)

The radiation environment at aviation altitudes is shaped by two aspects :
1) mainly by Galactic Cosmic Radiation (GCR), which is always there and
2) occasionally, by (extreme) strong Solar Radiation Storm (SEP - Solar Energetic Particles),

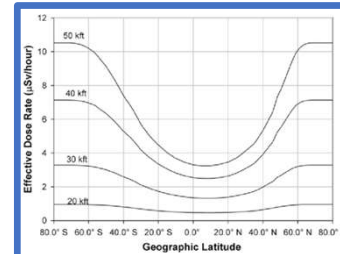
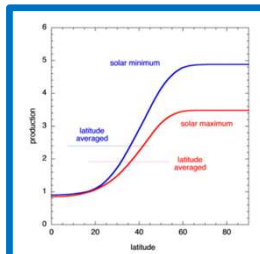
Both phenomena are basically very high energetic particles coming from the galactic background or from the sun respectively, that travel to earth. The particles travel along earth's magnetic field lines, collide with air molecules and produce showers of secondary particles in the atmosphere.

- On the one hand: These particles are weakened (slowed and absorbed) and ultimately stopped by passing through the atmosphere of the earth:
=> so as a consequence: radiation effect is higher at higher FL than at the ground.
- On the other hand: The earth's near-horizontal magnetic field acts as a shield in the equatorial and mid-latitude regions. But in the polar regions however, where the magnetic fieldlines are closer to vertical, these energetic particles can cascade down to lower altitudes or even reach the ground.
=> so as a consequence: radiation effect is higher closer than the poles.

Galactic Cosmic Rays – Radiation is always there



Galactic Cosmic Rays



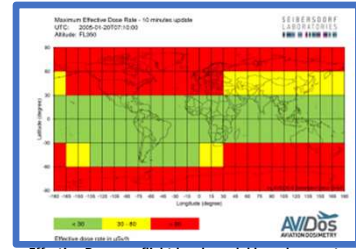
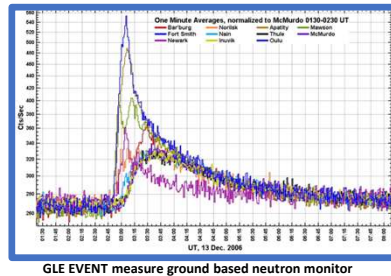
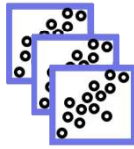
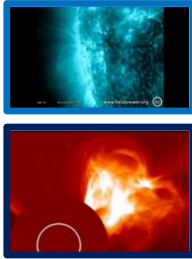
Graphs for illustration (accuracy of values not checked)

Origin: Galactic Cosmic Rays
 Sun to Earth: N/A
 Impact duration: Always there
 Impact Area: Polar Area more impacted & higher FL more impacted
 Impact: Effective dose always below ICAO advisory levels (Effective dose higher at solar Minimum)

So just as recap: GCR are : higher during solar minimum, higher at higher FL, higher at higher Latitude.

But always lower then ICAO advisory levels

Strong Proton event – Increased radiation at high latitude & FL



Origin: Extreme strong Proton event following strong X-flares/CME shock wave
 Sun to Earth: Minutes to Hours
 Impact duration: few hours
 Impact Area: Polar Area more impacted & higher FL more impacted
 Impact: Increased effective dose

During a strong Solar Radiation Storm, a Ground Level Enhancement (GLEs) may occur.
 A GLE is sudden increase in the radiation intensity recorded by ground based detectors (neutron-monitors).

On top of this GCR that is always there, there can be occasionally additional high-energy particles, that are released during solar eruptive events such as strong flare or a CME Shock wave. We call this a Proton Event.

In the majority of the Proton Events do not significantly increase the effective dose at FL.

But in rare cases, these particles that *bombard our atmosphere*, create secondary particles that are 'seen' by neutron monitors at ground level.

We call that a GLE (Ground Level Enhancement)

In this specific case, the impact on the effective dose in FL is not negligible compared to the Galactic Cosmic Ray.

GLE's are rare (a few per solar cycle)

Strong Proton event – Increased radiation at high latitude & FL



DTG	20240129/2359Z
SWXC	PECASUS
ADVISORY NR.	2024/4
NR. RPLC	2024/3
SWX Effect	RAD SEV
OBS SWX	29/2348Z HNH HSH W180 - E180 ABV FL370
FCST SWX + 6 HR	30/0600Z NO SWX EXP
FCST SWX + 12 HR	30/1200Z NO SWX EXP
FCST SWX + 18 HR	30/1800Z NO SWX EXP
FCST SWX + 24 HR	31/0000Z NO SWX EXP
RMK	SPACE WEATHER EVENT (SOLAR RADIATION STORM) IN PROGRESS. MODELS INDICATE SIGNIFICANTLY INCREASED RADIATION LEVELS AT SPECIFIED FLs. EXPECTED TO BE OF SHORT DURATION
NXT ADVISORY	WILL BE ISSUED BY 20240130/0548Z=

MODERATE: 30 microSv/h N/A (for FL>460)

SEVERE: 80 microSv/h

Duration: less than 6h

In terms of ICAO advisories:

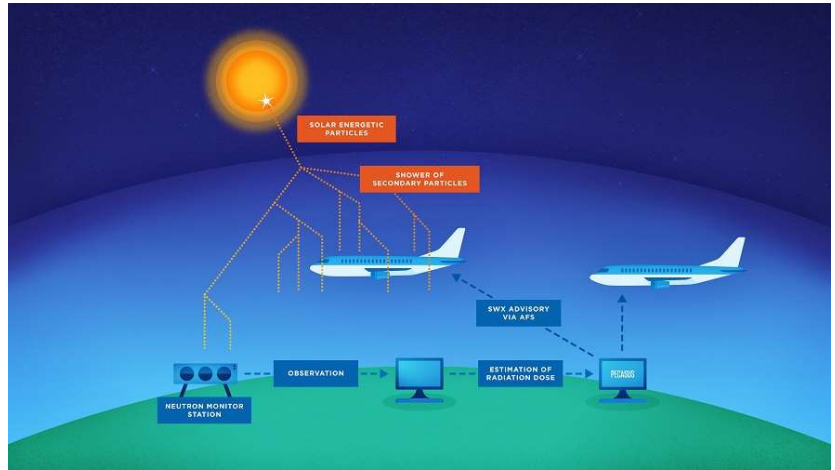
For normal FL of Commercial aviation, the thresholds are set for MOD to 30 microSV/h and for SEVERE to 80 microSV/h.

These levels are indeed very high and are therefore crossed rarely: there hasn't been any RAD advisory send since the start of the ICAO Space Weather network in Nov 2019.

In the observed Area, we will specify the entire longitude band, and specify the FL starting from which the thresholds is passed. Obviously, HNH and HSH will be impacted first/more (at lower altitudes).

In the remarque section: for severe there is the additional indication that it is expected to be short

Strictly speaking, if you want reduce the effect of radiation you should descend to lower FL or re-route to lower latitudes. But operationally speaking, it is up to the operators to judge how they want to address this case, as it might not be safe and one needs to consider that you may face a HF COM loss at the poles at the same time.



RAD



Illustrative image (Eye catcher)	Effect on Aviation	Affected Area	ROM of Duration	
	Galactic Cosmic Rays	Effective dose	Poles High FL	Always
	GLE	Effective dose increased	Poles High FL	Few hours

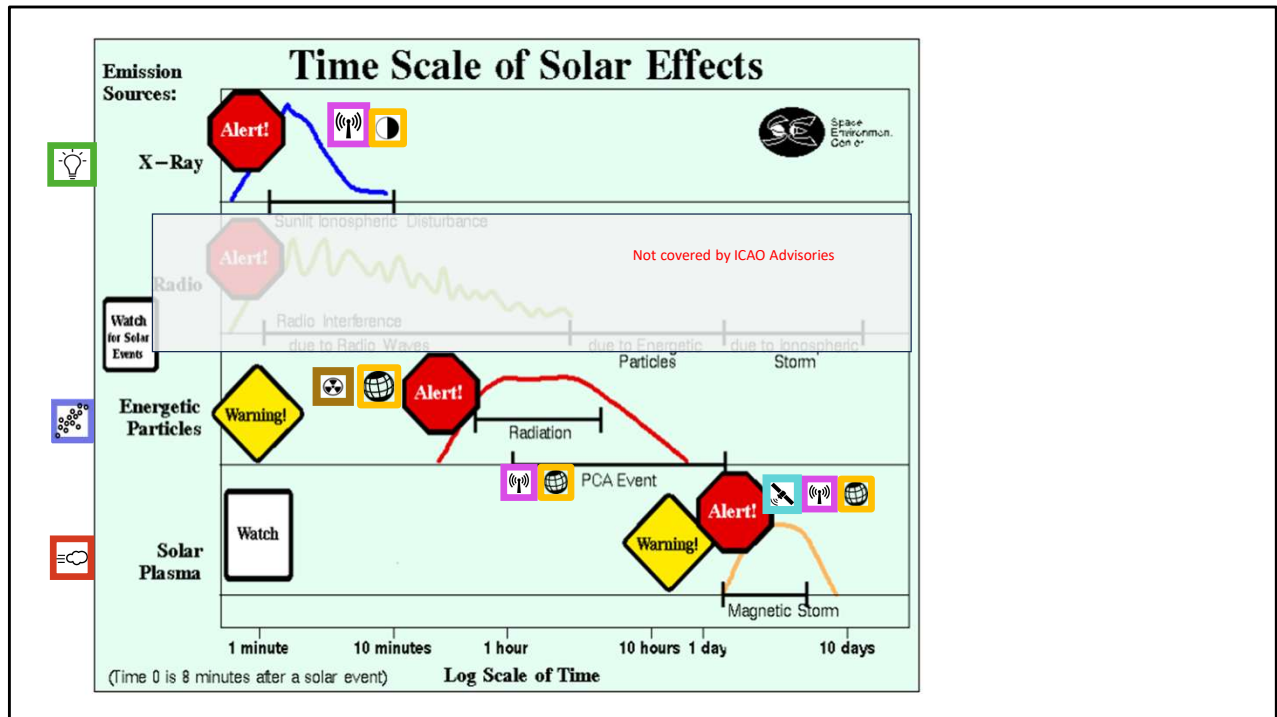
For your information

RAD



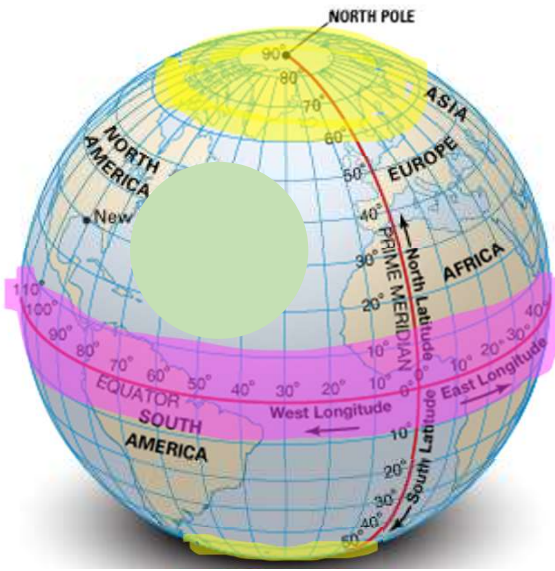
Illustrative image (Eye catcher)	Sun to Earth	Effect on Aviation	Affected Area	ROM of Duration
	Galactic Cosmic Rays	continue	Effective dose Poles High FL	Always (background level)
	GLE	Min to hours	Effective dose increased Poles High FL	Few hours

For your information



I put here on the graph the events in chronological order, with an indication when they happen and how long they last.
 Attention Logarithmic time scale!

This is a schoolbook-event, and in real time things will happen differently (not all effects present eg), but it helps for a high level view...



RAD



GNSS - Scintillation



HF COM Polar Cap Absorption
Aurora Absorption



GNSS - Scintillation at sunset



HF COM - Absorption following
Solar Flare



HF COM - MUF depression

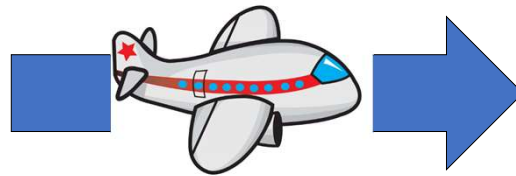
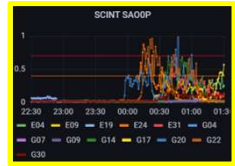
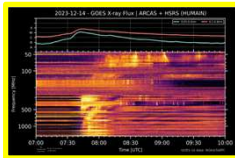
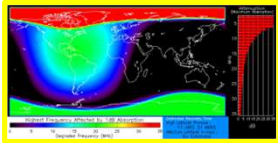
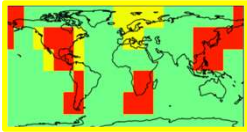
FUTUR WORK

FUTUR WORK

- Scientific research improvement:
 - More data: stations for measurements to fill in the gap
 - Better models: scientific development for models with higher accuracy
 - Need your feedback: from airlines/manufacturers/ATC on actual observed/measured effects on board of the aircraft to finetune triggering of advisories

- ICAO framework improvements - discussion ongoing:
 - More flexibility in the format?
 - Possibility to add more flexible forecast?

- On end-user site:
 - Reflect on/Develop decision-making guidelines or support in case of Space Weather Advisories
 - Provide feedback on observed/not observed effects to finetune advisories.



Interesting periods:
May 10-15 2024
Okt 10-14 Okt 2024

To:
elisabeth.dom@oma.be
yana.maneva@oma.be

CONCLUSION



24/7 Space Weather Advisories

Real Time ★ Worldwide ★ Impact based ★ tailored to Aviation

So in conclusion: We have a operative service at Pecasus, provided 24h/7days Space Weather advisories in Real time, worldwide based on the specific impact seen Aviation.

We hope these helps you in your operations.