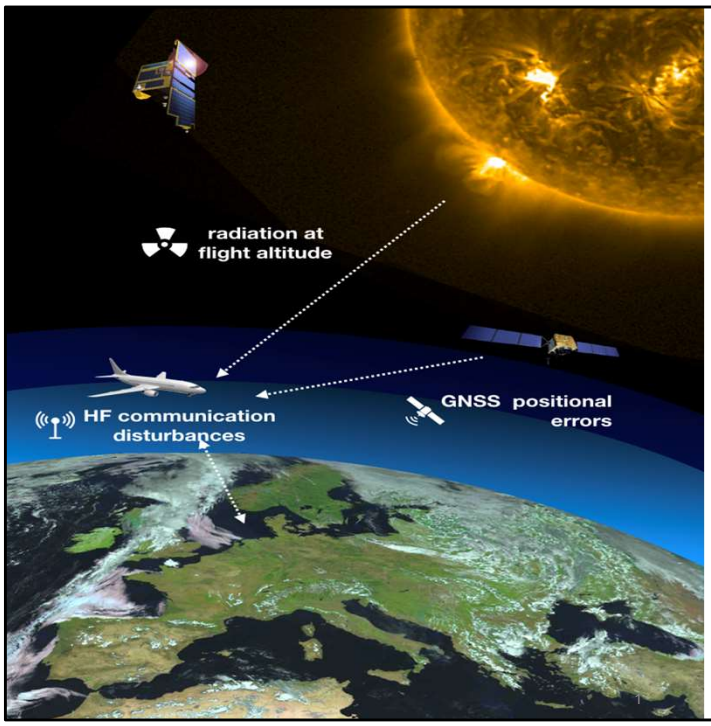


Space Weather impacts on Aviation

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.*

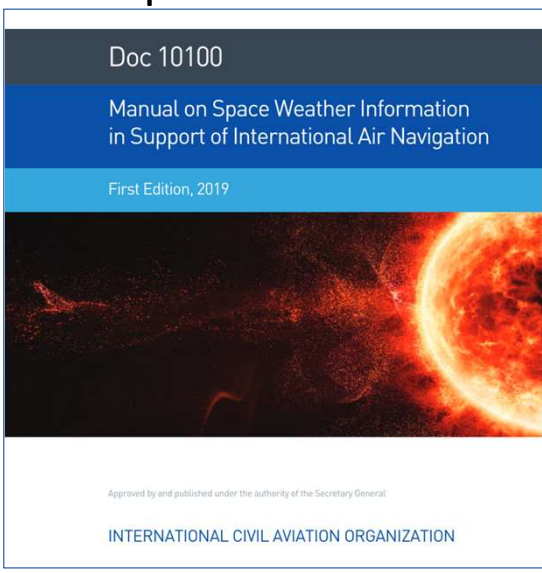
ICAO SW service

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.

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 (μSievert/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

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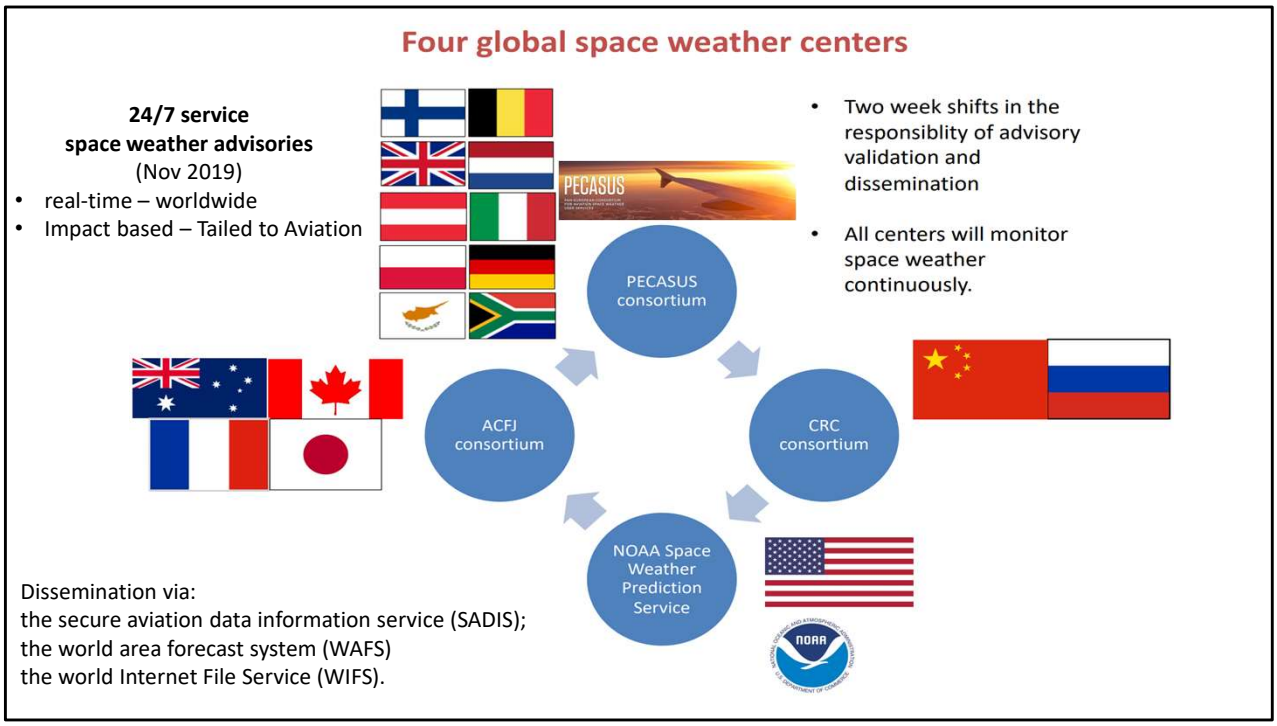
SWX ADVISORY
DTG:              20250815/0555Z
SWXC:             PECASUS
ADVISORY NR:      2025/18
NR RPLC:          2025/17
SWX EFFECT:       HF COM SEV
OBS SWX:          15/0535Z EQS W045 - E045
FCST SWX +6 HR:   15/1200Z NOT AVBL
FCST SWX +12 HR:  15/1800Z NOT AVBL
FCST SWX +18 HR:  16/0000Z NOT AVBL
FCST SWX +24 HR:  16/0600Z NOT AVBL
RMK:              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=
```

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

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 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.

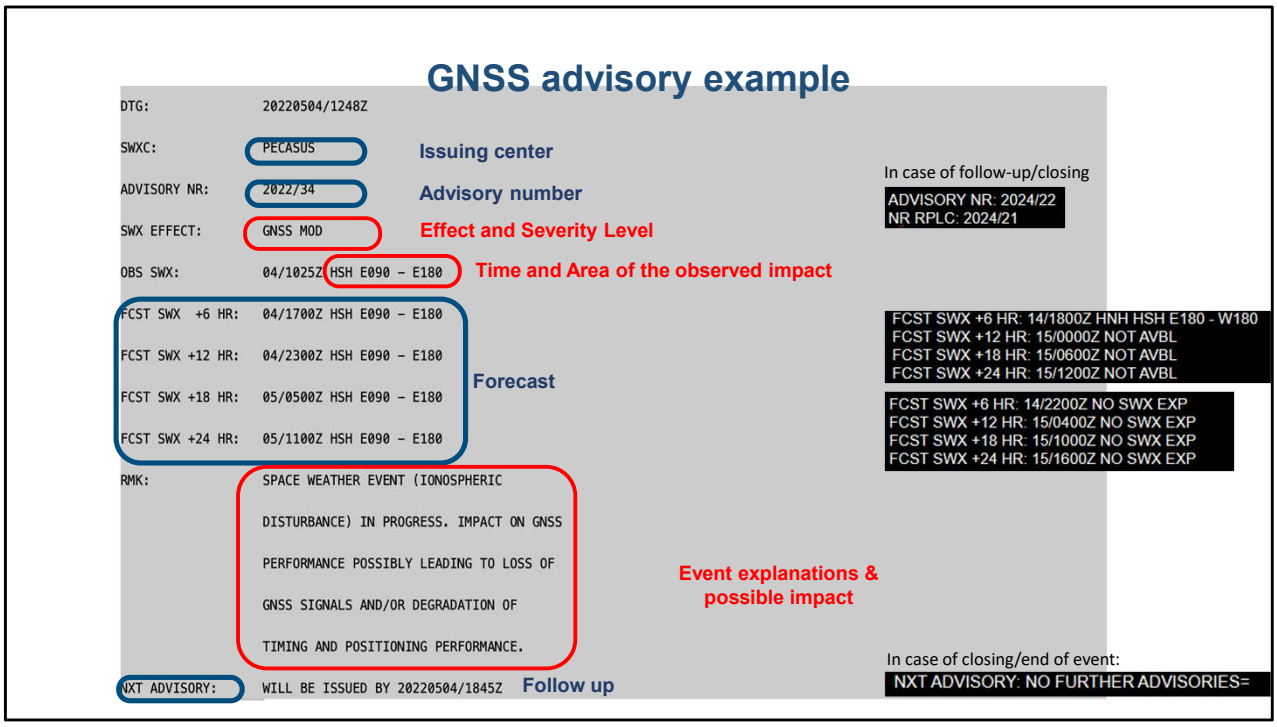
Each center has 2 weeks shift, then the responsibility is passed to the next center,
All center use the same thresholds, but slight differences in detection methods and phraseology in the “remark”- section can be observed, but from advising point of view they are equivalent.

In Belgium: Space Weather Forecaster and Operators team is part of PECASUS - consortium

www.pecasus.com:
=> Link to ICAO advisories

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.



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: this gives you the impact ~~as it explains the nature/type of the GNSS/HF COM issue, and this will help you do know if you are facing a phenomenan of minutes/hours/days. :~~
- 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.

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)

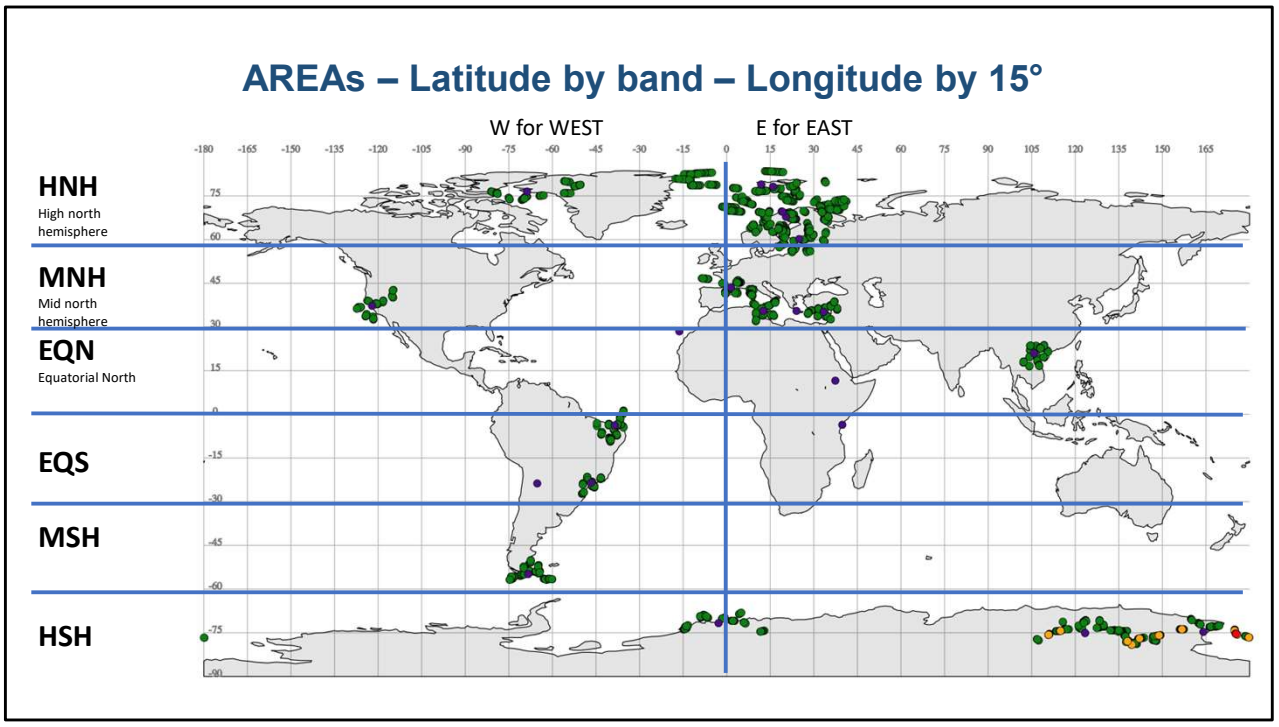
GNSS	Moderate	Severe	Time UTC	Values	Status	Alert	Max-3h values	Max-3h status
Amplitude Scintillation	0.5	0.8	2023-04-23 20:36	1.08	SEVERE		1.08	SEVERE
Phase Scintillation	0.4	0.7	2023-04-23 20:36	0.30	QUIET		1.06	SEVERE
Vertical TEC	125	175	2023-04-23 20:35	131.84	QUIET		134.83	MODERATE

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

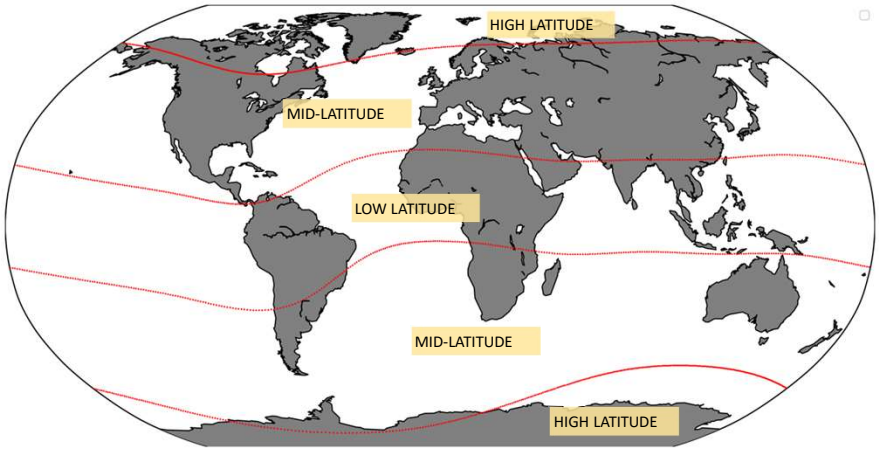
For each type of Advisory: there are two possible levels: MODERATE (here in Amber on our internal PECASUS dashboard) and

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 splitted 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°

GEOGRAPHIC - GEOMAGNETIC



AREAS for advisories are based on geographic latitude

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)

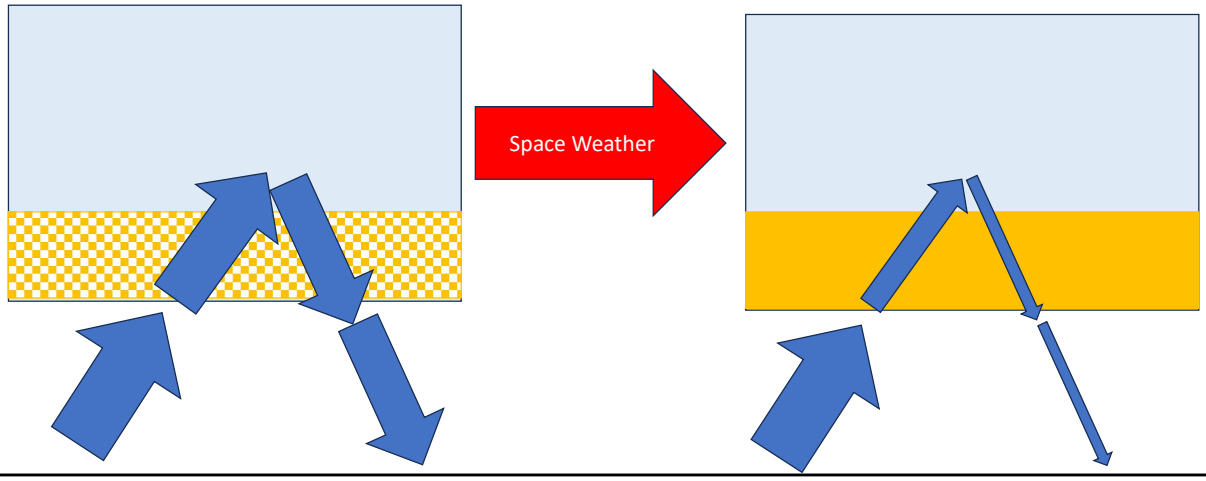
In civil aviation, HF is used for communication for transoceanic flights and over the poles. But over the ocean, there is also Satellite communication for most airplanes to communicate with ATC and Airline Operating Center. But this is not the case over the poles.

HF COM

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

Absorption increased

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



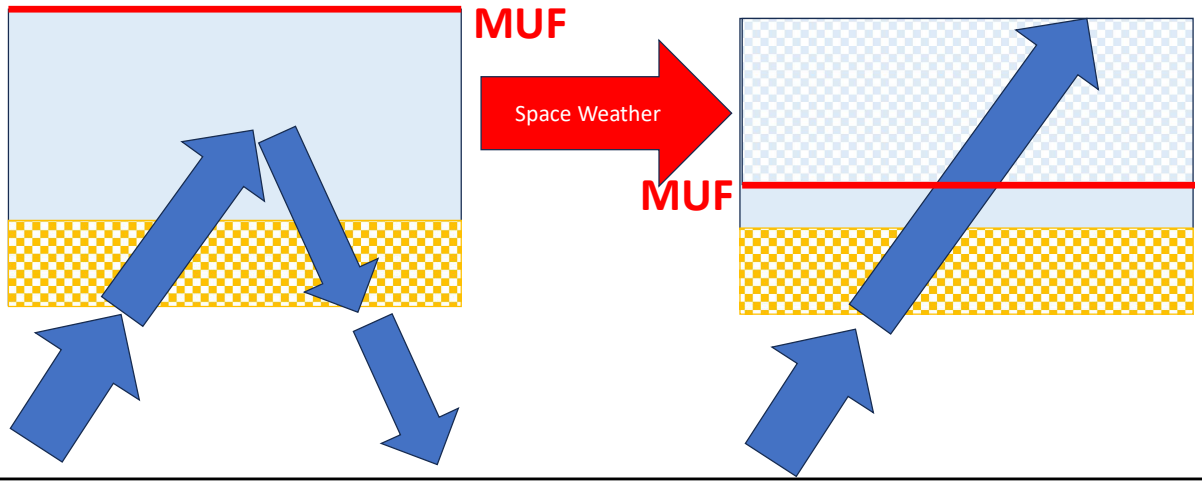
A quick reminder:
The principle of HF communication is that the radio waves are reflected in the ionosphere back to the earth.
So the ionosphere acts as a mirror.

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.

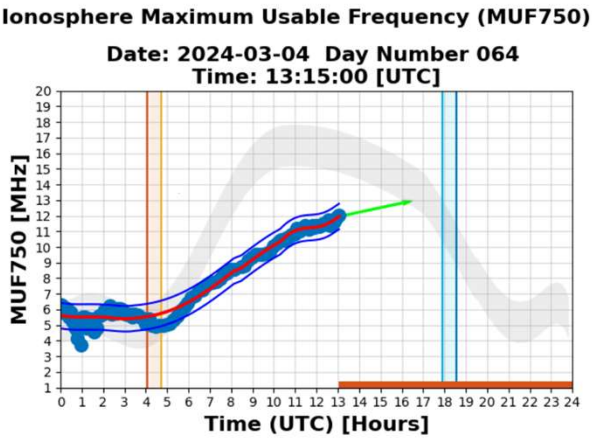


And in some cases, the ionosphere becomes less reflective (Muf depression):
The Maximum Useable Frequency is the highest HF frequency that is reflected.
So:
- Frequencies below the MUF are reflected and can be used,
- Frequencies above pass through the ionosphere and are “lost”.

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…

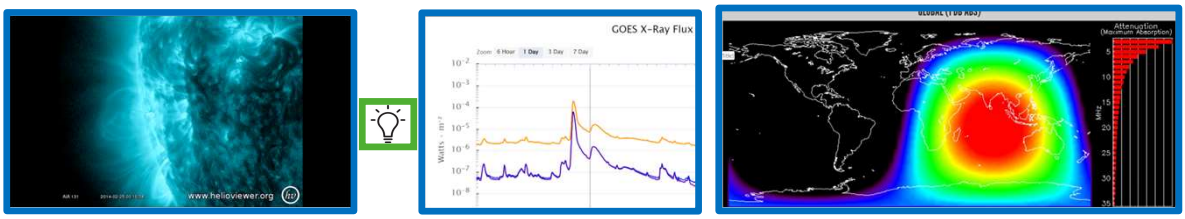
Depression - MUF (Max Useable Freq) reduced

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.



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



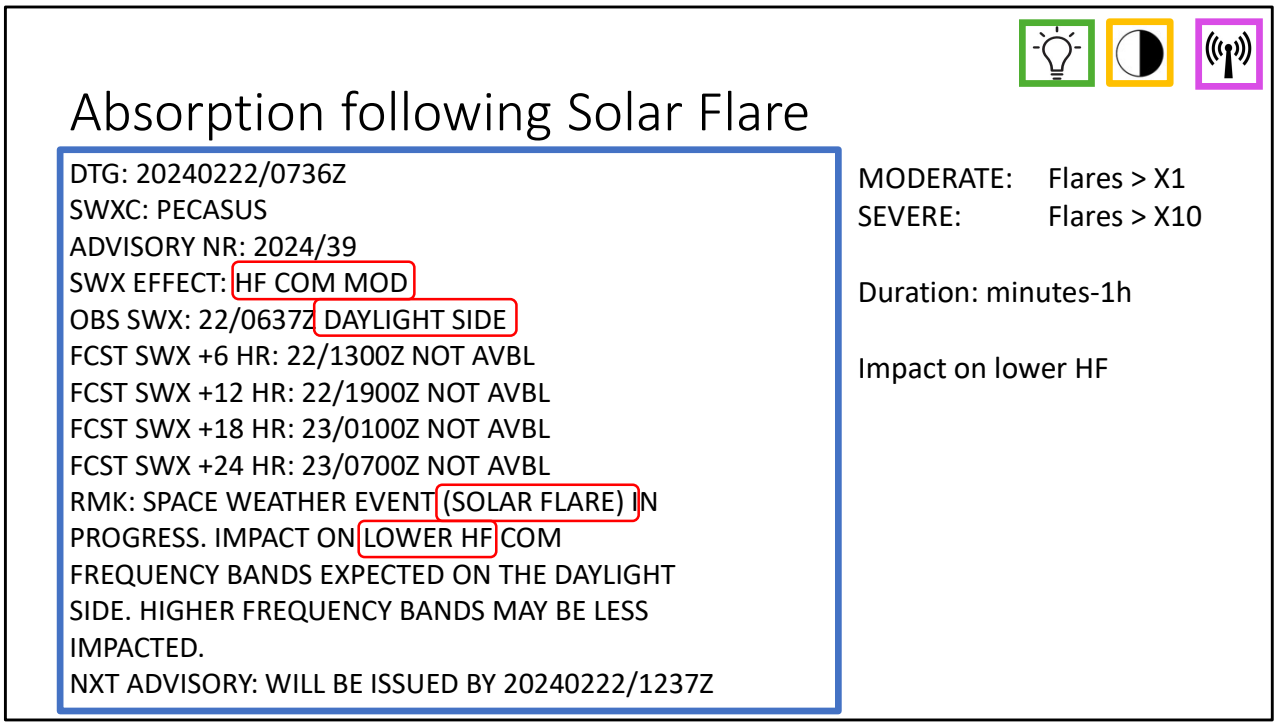
Origin:	Flare
Sun to Earth	Minutes
Impact duration:	Minutes (for one flare)
Impact Area:	Daylight side
Impact:	Absorption: dB loss at lower HF frequencies (higher HF frequencies are less affected)

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

The fasted 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 (tbc if added): the red is where the absorption is highest.



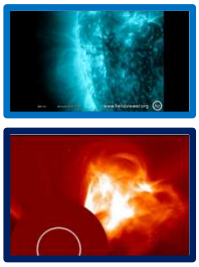
In the case of a Solar Flare >X1, the PECASUS team will send out a ICAO advisory.
The impacted area will indicate “DAYLIGHT SIDE”
And in the RMK section we have the following std text:
SPACE WEATHER EVENT (**SOLAR FLARE**) IN PROGRESS. **IMPACT ON LOWER HF** COM FREQUENCY BANDS EXPECTED ON THE **DAYLIGHT** SIDE. HIGHER FREQUENCY BANDS MAY BE LESS IMPACTED.

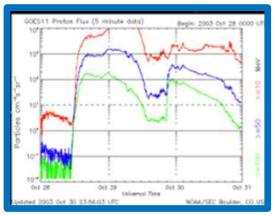
So for the reader of the advisory, the importance is in the term “solar flare”, which gives you an indication that the issue of this one single event is “relatively short” compared to other absorption HF COM advisories…Of course, if successive flare follow on eachother, then the event duration will be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

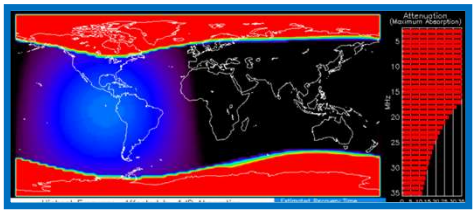
The MODERATE level is triggered for a X1 flare and above.
The SEVERE level is triggered for a X10 flare are above.
So we detect it via the GOES X-RAY flux data, not the D-RAP model.

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 expulsed 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

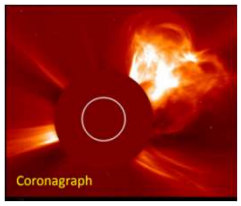
Duration: 1-2 days

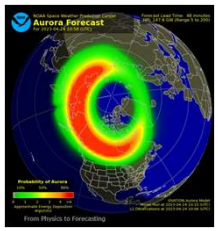
Impact on lower HF

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





High Kp (>8)

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

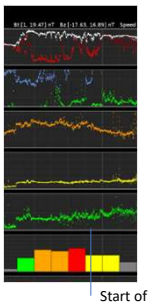
In case of Aurora Absorption, we will send a HF COM Advisory, almost identical to the one send for the PCA. But for the we mention “Auroral absorption” and you may guess it for 1 day or less.

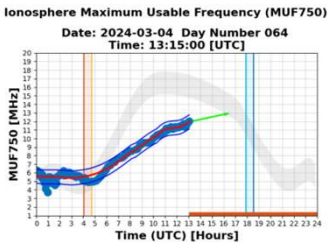
The area will be the full north and south highest band latitude so HNH HSH

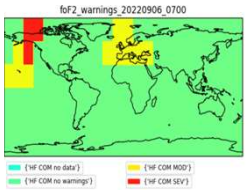
The thresholds for Moderate is when Kp> 8 and Severe when Kp> 9.

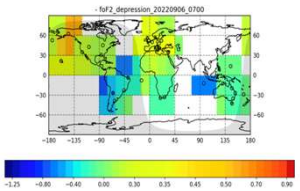
These PCA advisories are typically updated every 6h,

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

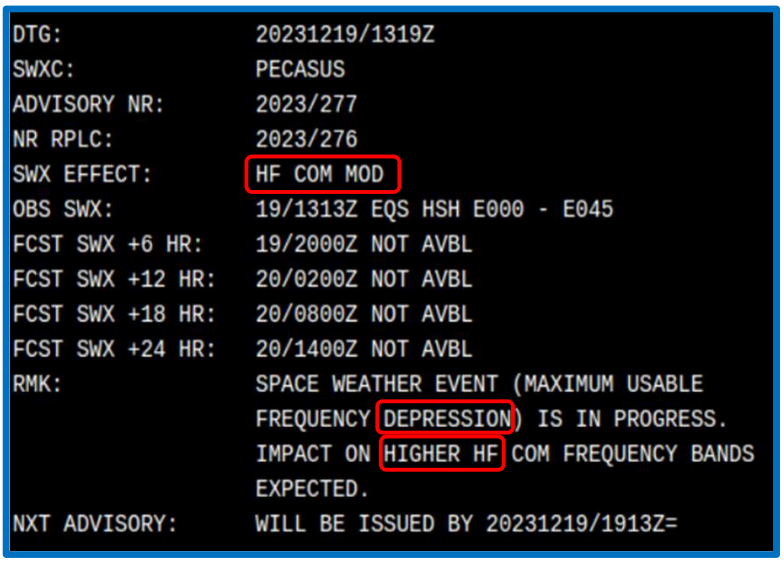
The maximum usable frequency (MUF) for a given communication path is the highest HF radio frequency that can be used for communication via reflection. In the late phases of geomagnetic storms (increased Kp), the ionosphere remains in an unsettled state, triggering disturbances in reflection capacity.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



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DTG:              20231219/1319Z
SWXC:             PECASUS
ADVISORY NR:      2023/277
NR RPLC:          2023/276
SWX EFFECT:       HF COM MOD
OBS SWX:          19/1313Z EQS HSH E000 - E045
FCST SWX +6 HR:   19/2000Z NOT AVBL
FCST SWX +12 HR:  20/0200Z NOT AVBL
FCST SWX +18 HR:  20/0800Z NOT AVBL
FCST SWX +24 HR:  20/1400Z 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 20231219/1913Z=
```

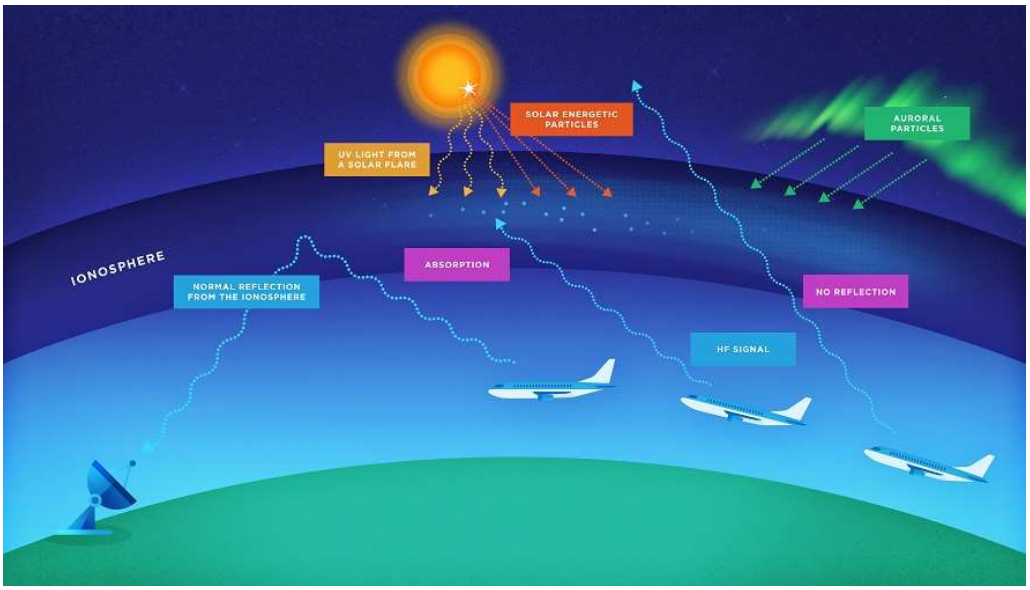
MODERATE: > 30 % drop of MUF
SEVERE: > 50% drop of MUF
Compared to 30 day running median foF2

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.

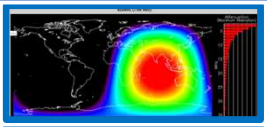
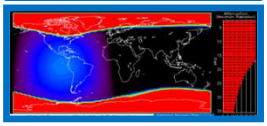
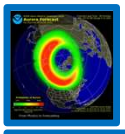
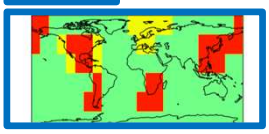
Radio operators are advised to use lower frequencies



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	Loss of LOWEST HF	Dayside	Minutes to several hours
	Polar Cap Absorption		Poles	Several hours to several days
	Auroral Absorption			1 to several days
	Post Storm Depression	MUF reduced Loss of HIGHEST HF	Anywhere (erratic)	Several Days (min 4 days)

For Information

GNSS

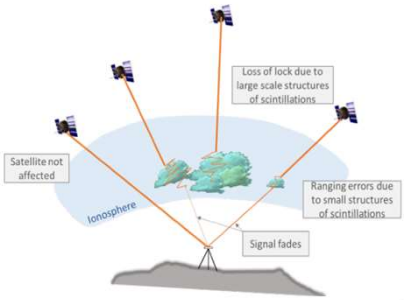
So until now we discussed the HF COM impact.
The Second impact is the GNSS.

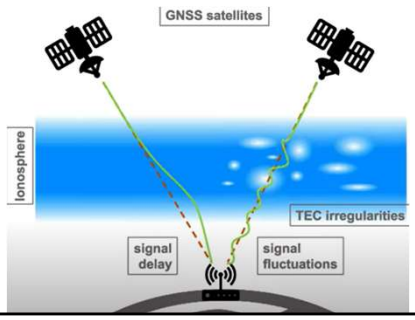
GNSS signals is not like the HF COM signals that need reflection:
GNSS Signals pass (and need to pass through) the ionosphere to reach the receiver.

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





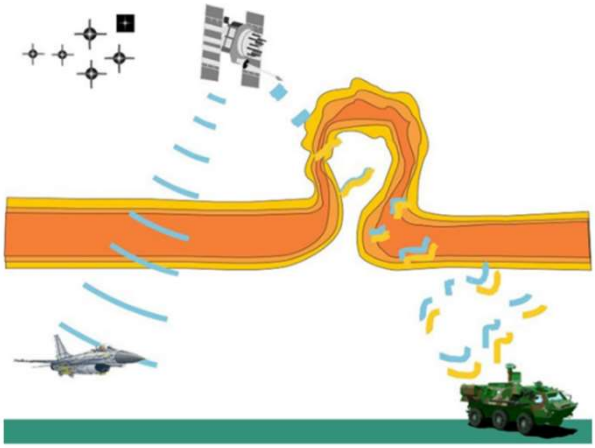
Research on-going on Space Weather impact on ionospheric irregularities:
- Seasonal effect (Position Earth on ellipse)
- Solar cycle effect (More during Solar Max)
- CME arrival / Geomagnetic storm?

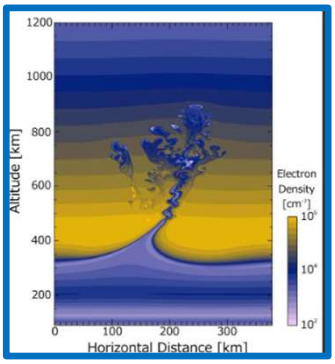
Impact on Signal:
- Amplitude scintillation
- Phase scintillation
- Speed/path (increased VTEC)

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.

Scintillation – Equatorial “bubbles”

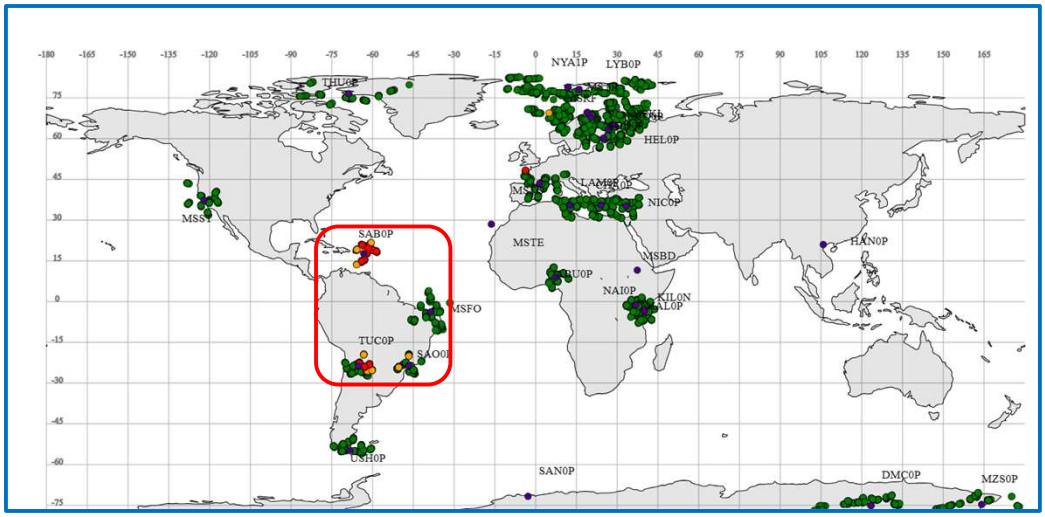




At the equator at local sunset => Area will move with the Day/Night line
Strength/frequency is seasonal (non- eruptive space weather)
Duration : 2-3 hours locally

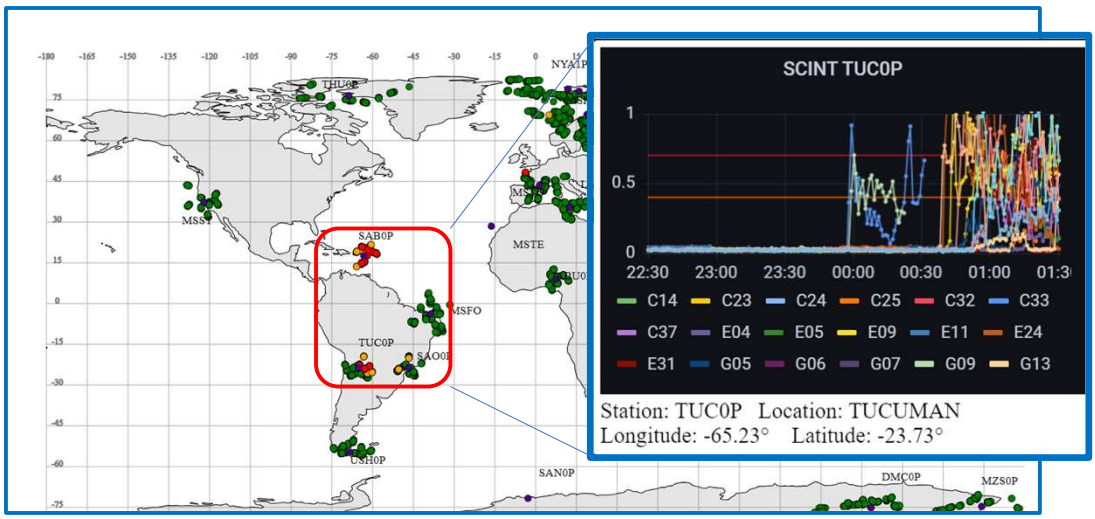
Scintillation is very often observed at the equator, more precisely at the local sunset. We know that at the local sunset at the equator so called plasma bubbles are created, which have a electron density that strongly varies. So as shown in the image: a wave going through a “standard ionosphere” will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

How do we detect scintillation?



How do we detect scintilation?
We have different receivers in the world who continuously receive data from all GNSS satelites, including AS/PS index? the phase scintillation and amplitude scintillation which one of the main triggers for Scintilation advisories. But we are indeed limited by the number of receivers from which we get the datea: large gaps.
So when there is scintillation the signal goes like this;

How do we detect scintillation?



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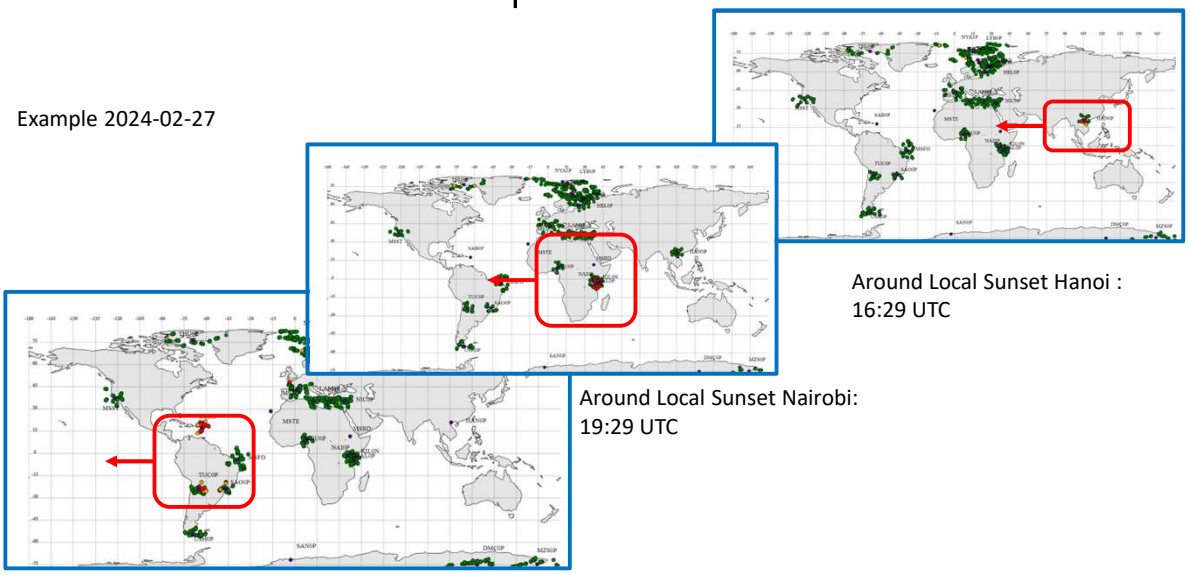
GNSS scintillation – Equatorial “bubbles”

Example 2024-02-27



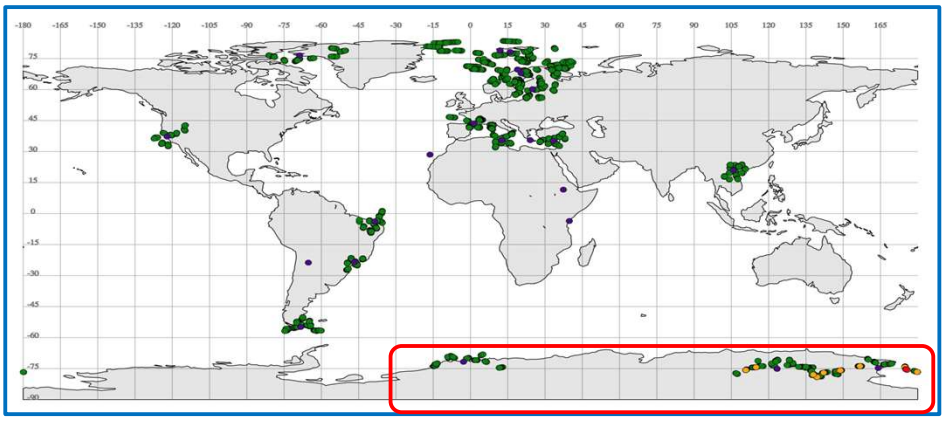
Around Local Sunset Hanoi : 16:29 UTC

Around Local Sunset Nairobi: 19:29 UTC

Around Local Sunset Sao Paulo: 01:29 UTC

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 scintilation, as we do not have feedback from in service.

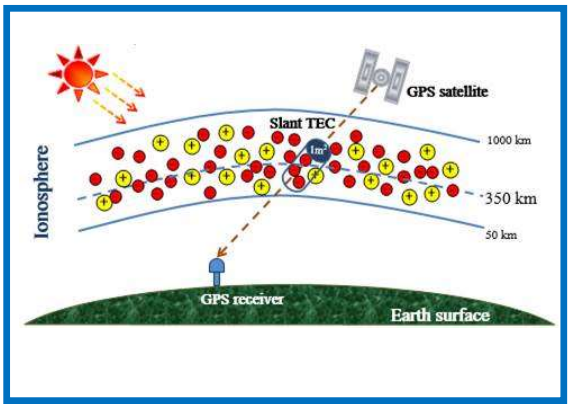
GNSS scintillation at high latitude

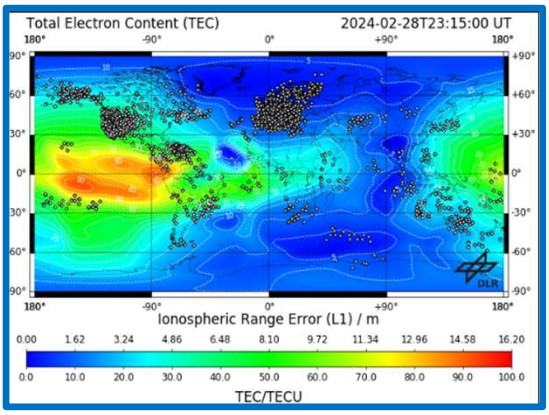


At the poles – due to geomagnetic storm
Duration Hours-1 day

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

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.

GNSS Scintillation Advisory

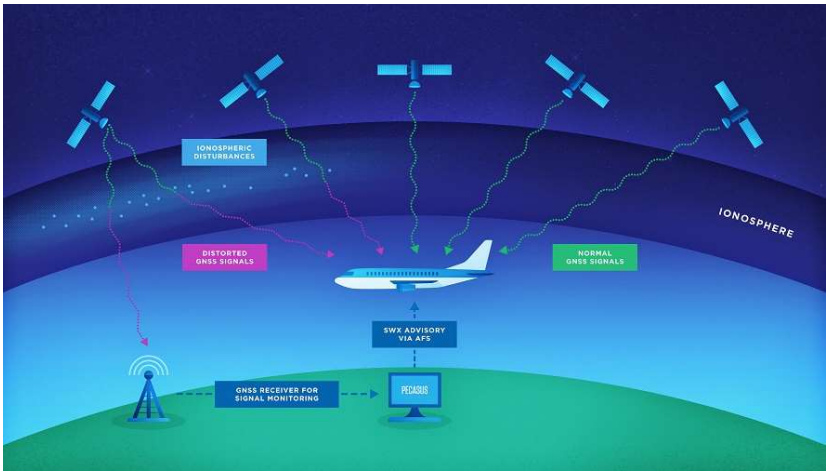
```
SWX ADVISORY
DTG:              20231010/1836Z
SWXC:             PECASUS
ADVISORY NR:      2023/246
SWX EFFECT:       GNSS SEV
OBS SWX:          10/1800Z EQN EQS E030 - E060
FCST SWX +6 HR:   11/0000Z EQN EQS W060 - E000
FCST SWX +12 HR:  11/0600Z NOT AVBL
FCST SWX +18 HR:  11/1200Z NO SWX EXP
FCST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

MODERATE:
>0.4 Sigma-Phi (Phase) or
>0.5 S4 (Amplitude)
>125 TECU (VTEC)

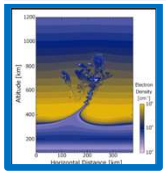
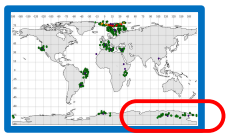
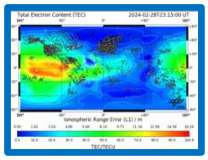
SEVERE:
>0.7 Sigma-Phi (Phase) or
>0.8 S4 (Amplitude)
>175 TECU (VTEC)

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 therefor “expect” that the following “sunset”-regions will be subsequently impacted as the night/day-line progresses.
We observe these type of scintillations every night.

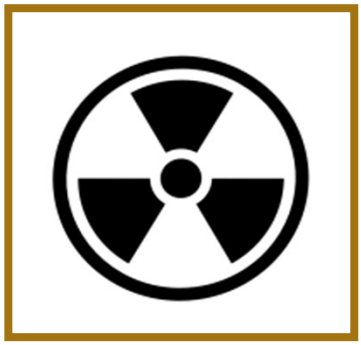
If the area would indicate HNH or HSH then it is a different: it will stay a few hours then it is expected to disappear.


IONOSPHERIC DISTURBANCES
IONOSPHERE
DISTORTED GNSS SIGNALS
NORMAL GNSS SIGNALS
SWX ADVISORY VIA AFS
GNSS RECEIVER FOR SIGNAL MONITORING
PEGASUS

GNSS

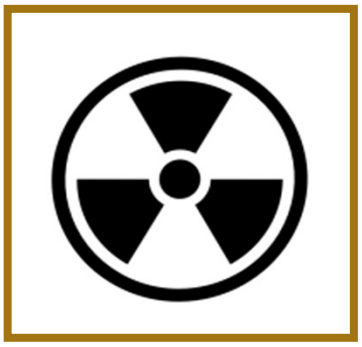
Illustrative image (Eye catcher)	Effect on Aviation	Affected Area	ROM of Duration
  	GNSS Loss and/or Position Error	Equator at local sunset Follows day/nightline Poles To be studied	Few hours (start at sunset) Few hours Few hours

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)

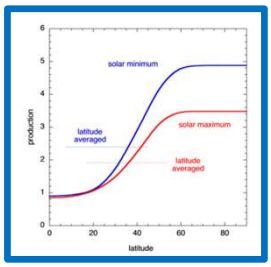
The radiation environment at aviation altitudes is shaped by two aspects :
1) mainly by Galactic Cosmic Radiation (GCR), which is always there and
2) occasionally, by (extreme) strong Solar Radiation Storm (SEP - Solar Energetic Particles),

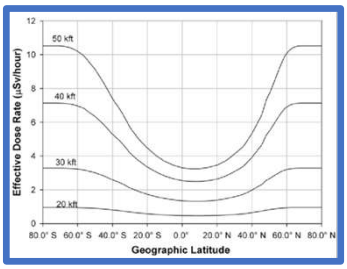
Both phenomena are basically very high energetic particles coming from the galactic background or from the sun respectively, that travel to earth.
The particles travel along earth's magnetic field lines, collide with air molecules and produce showers of secondary particles in the atmosphere.

- On the on 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, there 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 ….

Galaxtic Cosmic Rays



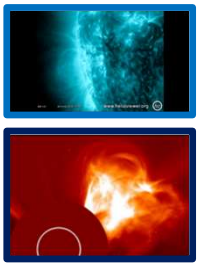


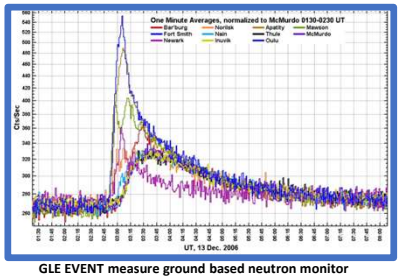
Graphs for illustration (accuracy of values not checked)

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)

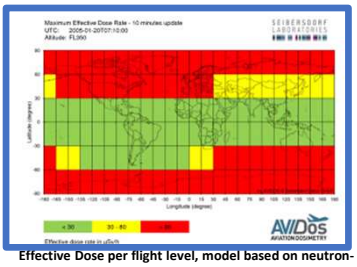
So just as recap: GCR are : higher during solar minimum, higher at higher FL, higher at higher Lattitude.
But always lower then ICAO advisory levels

Strong Proton event – Increased radiation at high latitude & FL





GLE EVENT measure ground based neutron monitor



Effective Dose per flight level, model based on neutron-monitor input

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.

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

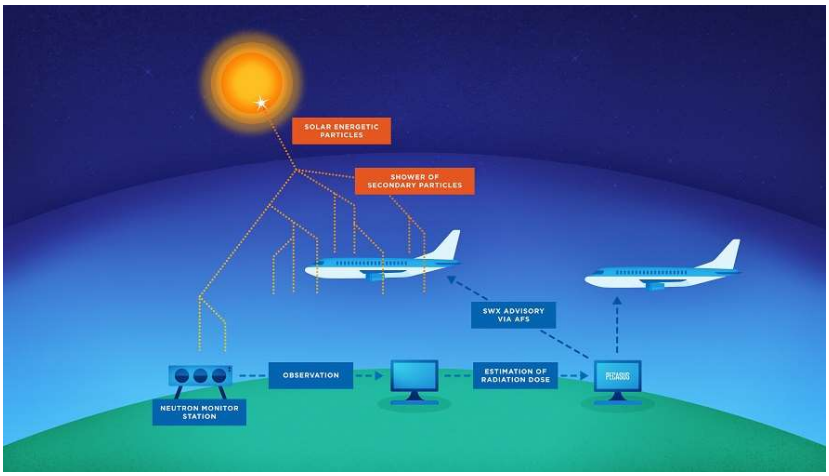
Duration: less then 6h

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.

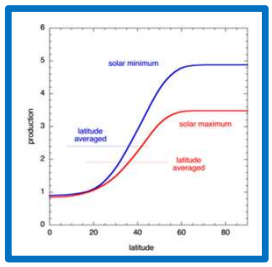
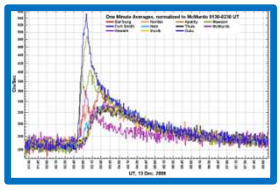
In the observed Area, we will specify the entire longitude band, and specify the FL starting from which the thresholds is passed. Obviously, HNH and HSH will be impacted first/more (at lower altitudes).

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

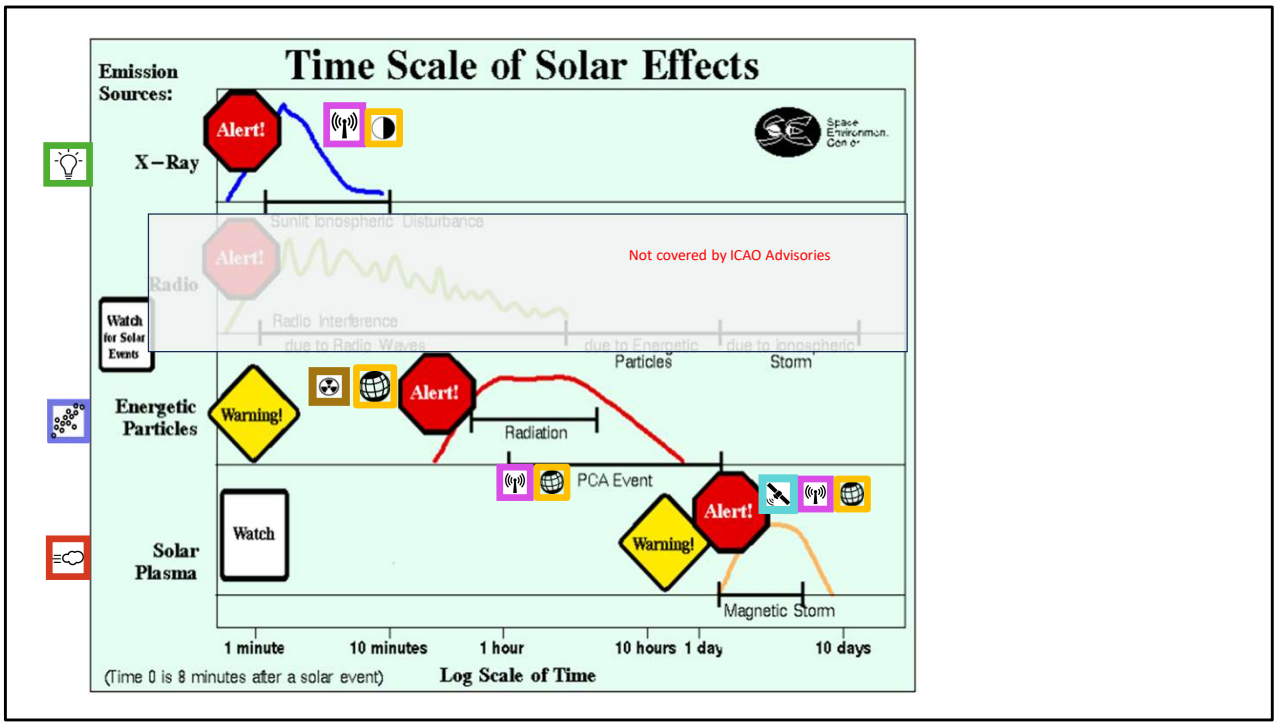
Strictly speaking, if you want reduce the effect of radiation you should descend to lower FL or re-route to lower latitudes. But operationally speaking, it is up to the operators to judge how they want to address this case, as it might not be safe and one needs to consider that you may face a HF COM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


SOLAR ENERGETIC PARTICLES
SHOWER OF SECONDARY PARTICLES
SWX ADVISORY VIA AFS
NEUTRON MONITOR STATION
OBSERVATION
ESTIMATION OF RADIATION DOSE
PEGASUS

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



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 - Scintilation

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.

Space Weather Impact on Polar Operations		
Condition	**Scale**	**Restrictions**
Radio blackout	1 to 5 (R1 – R5)	No restrictions
Solar radiation	1 & 2 (S1 – S2)	No restrictions
	3 (S3)	Require Polar operations to be conducted at or below FL310
	4 & 5 (S4 – S5)	Require non-polar operations when the predictive percentage is 60% or above. Require Polar operations to be conducted at or below FL310 if the predictive percentage is below 60%
Geomagnetic storms	1 & 2 (G1 – G2)	No restrictions
	3 and above (G3 – G5)	Require a non-polar operations (due to possible navigation errors) when the predictive percentage is 60% or above. No restrictions if the predictive percentage is below 60%

Operational Considerations

Dispatch monitor current and forecast weather reports. The following action will take place if space weather exceeds certain criteria:

1. During pre-planning, if defined criteria are exceeded, flight routings are adjusted as necessary.
2. If the forecast or actual conditions exceed the recommended limits and the aircraft is more than 60 minutes from the entry point to the Polar Region, the dispatcher will forward the information and assist the flight crew with available options. This may include alternative flight levels or routing.
3. Reroutes may not be possible for flights within 60 minutes of the Polar Region. Continuation will then be at the Captain's discretion and flight dispatch will provide any assistance required.

Storm Scales

Storm	Scale	
Geomagnetic	G1, G2	FLY
	G3, G4, G5	NO FLY (ABERI, RAMEL, DEVID)
Solar Radiation	S1, S2	FLY
	S3, S4, S5	NO FLY
Radio Blackout	R1, R2	FLY
	R3, R4, R5	NO FLY

Found on Internet: may be outdated.

Operational decision table for polar routes, still based on NOAA scales

CONCLUSION

24/7 Space Weather Advisories

Real Time ★ Worldwide ★ Impact based ★ tailered 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.