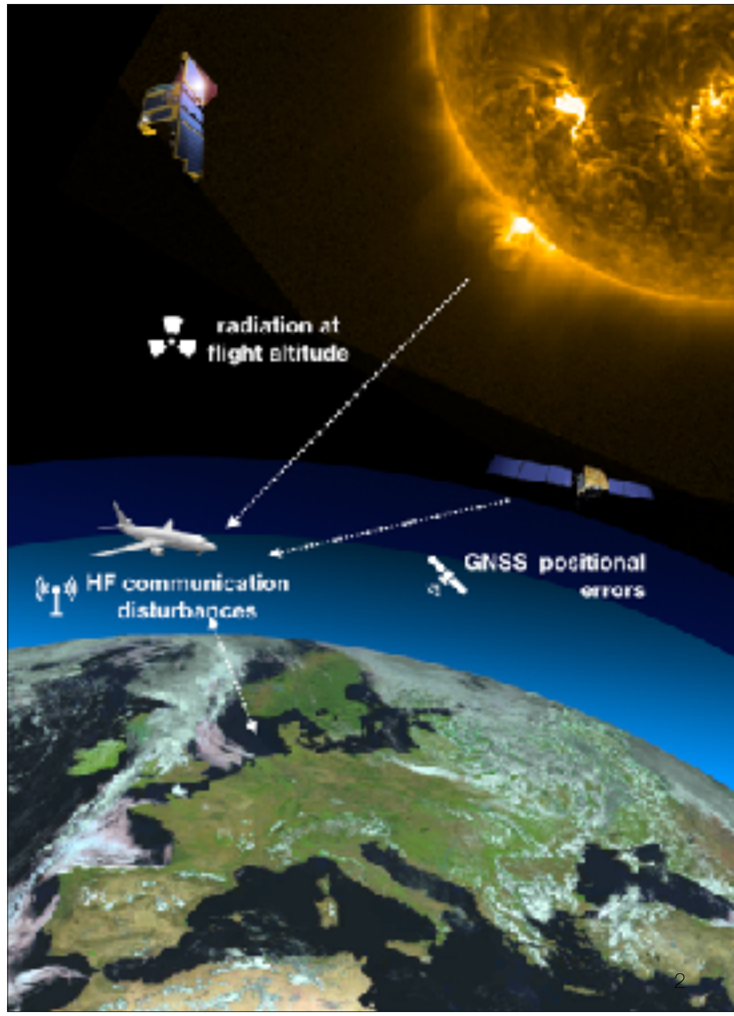
PECASUS
For civil aviation

TRAINING LEVEL 2
For MeteoWing Operators

2020

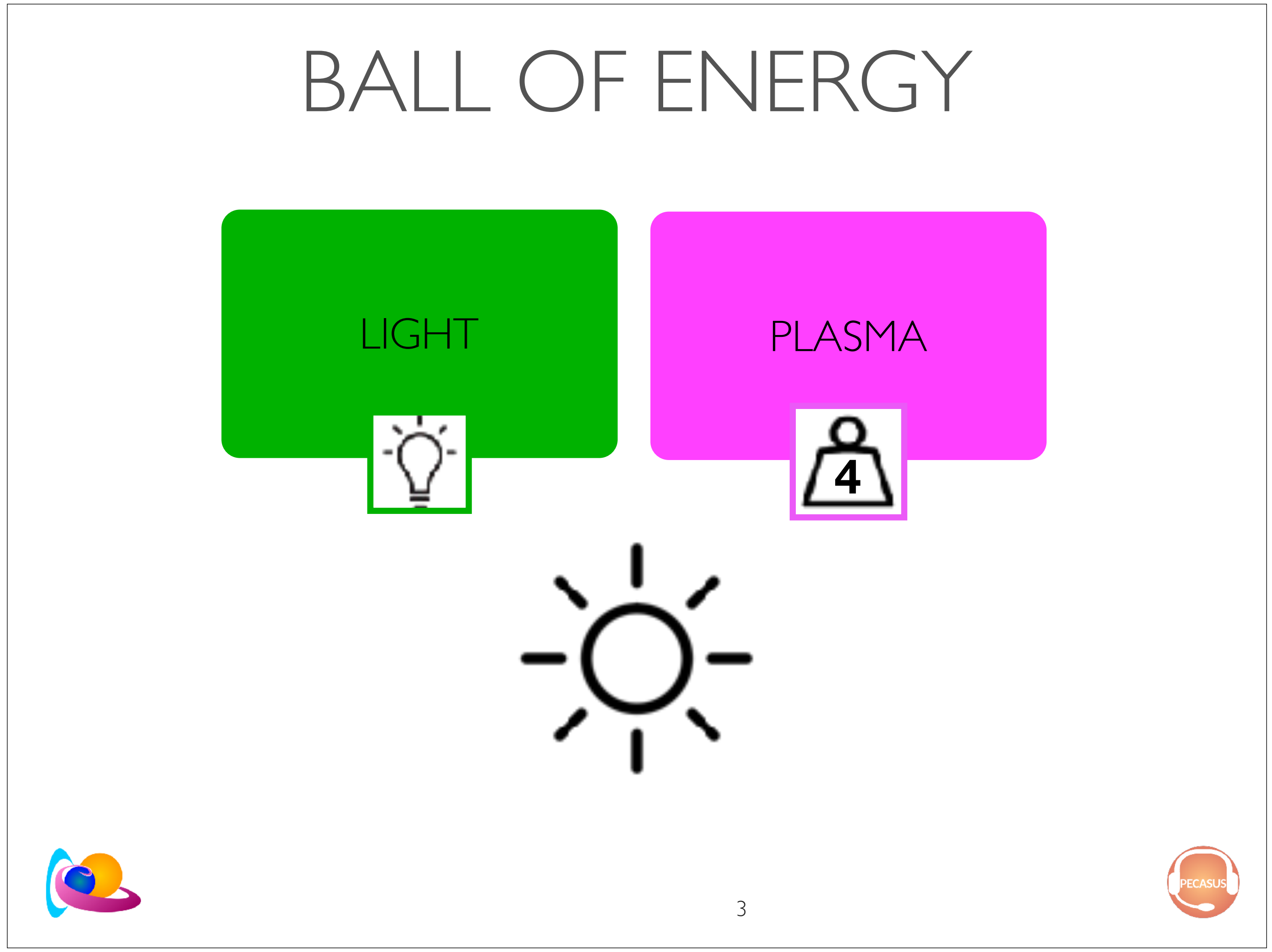


SWx for aviation

The big 3 solar events

Petra.Vanlommel@oma.be

PECASUS



4th state of matter —
The sun is a gigantic ball of energy: magnetic energy, heat, moving plasma, …
Four states of matter are observable in everyday life: solid, liquid, gas, and plasma.
Plasma is the fourth state of matter. When you have solid material and you heat it, it becomes liquid. You keep on meeting it, it becomes a gas. When you still add heat, the atoms split into ions and electrons. The gas becomes electrically conductive creating electrical and magnetic field.

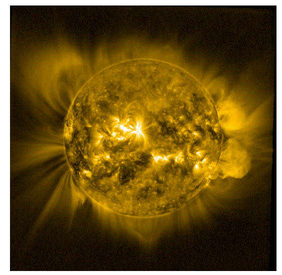
This energy is kept inside the Sun but also on its surface and in its atmosphere in magnetic structures like sunspots and magnetic loops, filaments or prominences ready to be released.

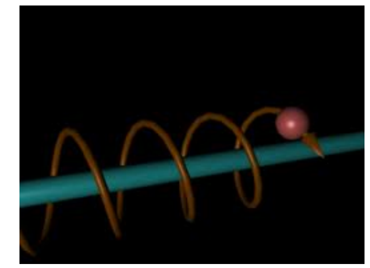
This energy is expelled, leaves the Sun to outer space in the form of electromagnetic radiation, kinetic, electric and magnetic energy.

Note: the solar plasma is hot. The plasma particles bump on each other. These collisions changes their kinetic energy. This change is emitted in the form of thermal radiation, light photons. Once these photons are at the solar surface, they can escape and move freely.
Thermal radiation is electromagnetic radiation generated by the thermal motion of charged particles in matter. You have thermal motion as soon as the temperature is above absolute zero.

SPACE CLIMATE

The sun emits continuously energy and creates a space climate that has 2 seasons: a more active and a less active. This seasonal variation is called the solar cycle and takes around 11 years.





TOTAL SOLAR IRRADIANCE

SOLAR WIND

SOLAR ENERGETIC PARTICLES

The outward flow of solar particles and magnetic fields from the Sun. Typically at 1 AU, solar wind velocities are near 375 km/s and proton and electron densities are near 5 cm−3. The total intensity of the interplanetary magnetic field is nominally 5 nT.

TSI, e.m. radiation is not linked to the IMF. It doesn't follow the magnetic field lines.
PROBA2/SWAP, the sun in the EUV.
Light/TSI is

However, plasma containing ions and electrons has to follow the magnetic field lines. Or you can also say that the magnetic field lines guide the plasma.
The solar wind plasma is glued to the IMF – or the IMF is glued to the plasma.
The plasma in the solar wind is considered as a gas, a group of particles behaving and moving in group. You don't speak about that particular particle in the solar wind, you speak about the solar wind, a whole bunch together.
Cartoon

Electrically charged particles have to follow the IMF. These electrically charged particles are considered as individuals and behave as individuals.
Cartoon

Near Earth, the IMF still controls the solar wind and its movement. Much much further away from the Sun, the IMF becomes very weak and doesn't control the solar wind anymore. But, this is not important for us. At 1AU, the IMF influences the plasma and the plasma the IMF.

About the animated gif:
Conceptual animation (not to scale) showing the sun's corona and solar wind.
Credits: NASA's Goddard Space Flight Center/Lisa Poje

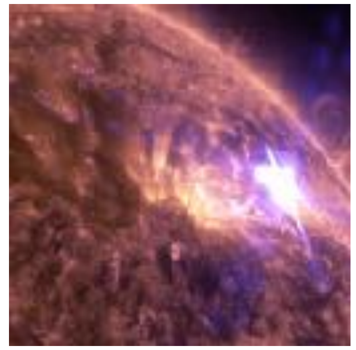
The solar wind is a continuous radial stream of solar plasma that leaves the sun and moves away from it. It fils the space between the planets with solar mass. The solar wind reaches the boundaries of the heliosphere, a magnetic shield around the Sun. In the heliosphere, the Sun sets the rules and you have solar weather. Outside the heliosphere, you have the rest of the galaxy. Earth is in the heliosphere.

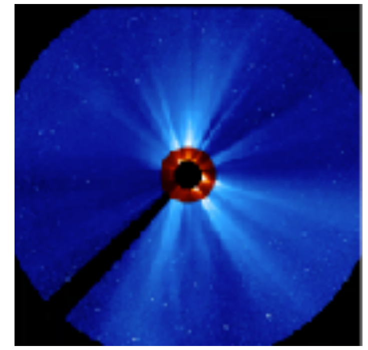
A nice movie is found on
https://www.nasa.gov/feature/goddard/2016/images-from-sun-s-edge-reveal-origins-of-solar-wind

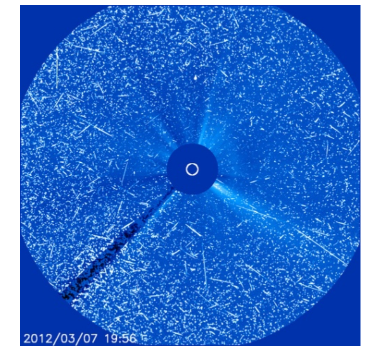
https://youtu.be/QYM2_ytkjQo

SOLAR STORMS

At a certain moment, energy might be released on a shorter time scale. Space weather is the change that occur on the Sun or in the space environment. This chance might be in an abrupt, impulsive and brutal way (flare, CME, proton storm) or in a non-eruptive manner (CH).







FLARE

CME

PARTICLE STORM

Space weather is the change of energy that occur in the space environment.

A Flare is a sudden strong increase of the solar e.m. radiation. The light flash is localised on the solar surface.
SDO/AIA

A Coronal Mass Ejection is a plasma cloud that is ejected into space. You consider it as a cloud and not as a bunch of individual particles. It is superimposed on the background solar wind. You can see a CME as a complex magnetic bag with different magnetic layers with plasma in it that travels as a tsunami through space. It can go faster/as fast as/slower than the background solar wind. When it is faster, you will see a shock in front of the cloud. This is exactly the same as the shock you see in front of a speed boat.
A CME is visible as a white cloud in corona graphic images like the one on the slide. A coronagraph is a telescope that creates an artificial eclipse and makes pictures in the visible light of the region around the sun.
SOHO/LASCO C2 (red) and LASCO C3 (blue)

A coronal hole is a structure in the solar corona that you see as a black area in the EUV. It looks black because there is less plasma present that radiates in the EUV. The magnetic field lines are open, i.e. fan out into space. There are no magnetic loops above a coronal hole. The solar wind emanating from a CH is faster compared to the usual solar wind.
SDO/AIA

A particle storm is a bunch of electrically charged particles that are accelerated in the solar atmosphere to very high velocities by a large-scale magnetic eruption often causing a CME and/or solar flare. They follow the IMF
They may impact telescopes. They are seen as white stripes and dots: this are particles that fall into the lens and blind the pixel(s). During that particular moment, the telescope can’t see anymore through the impacted pixels. You can say that the dots and stripes represent a sort of in situ measurement.

In situ means that you measure a parameter local. Remote sensing means that you look at something from a distance.

Near Earth, the IMF still controls the solar wind and its movement. If we would go much much further, the CME magnetic bag with solar plasma would be almost empty (all the solar material is spread over an immense volume) and the magnetic bag would have evaporated. But, this doesn’t matter for us. We are at 1AU and at 1AU the IMF and solar plasma make space weather in a normal way, in an extreme way.

SPACE WEATHER

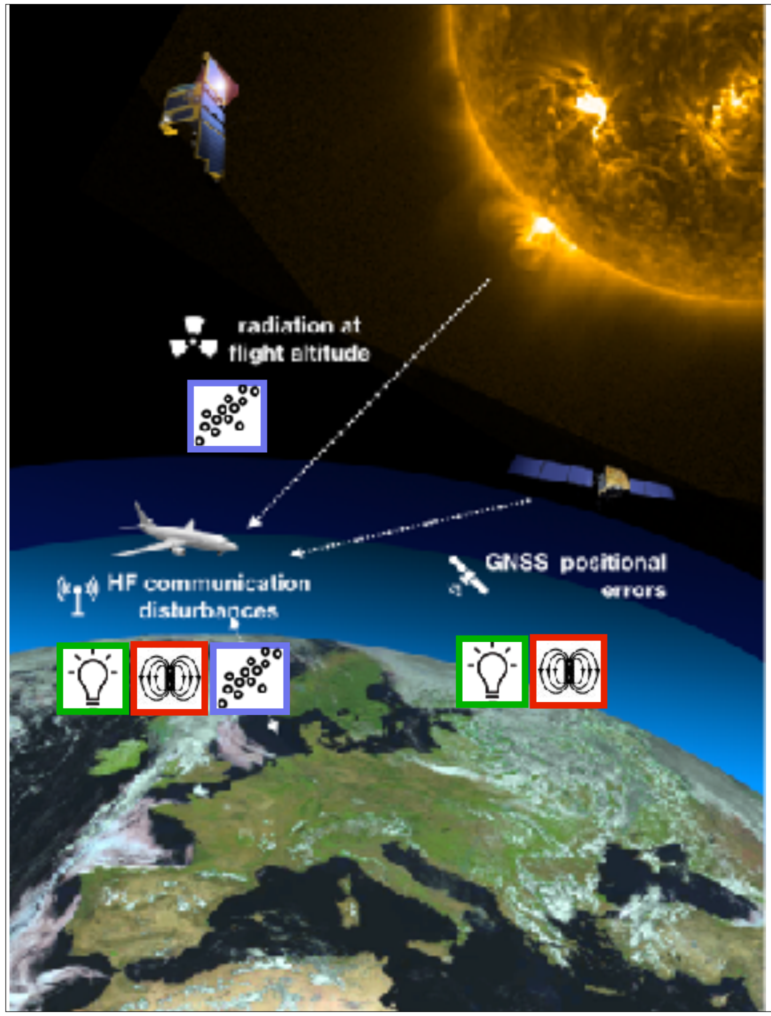
Our atmosphere and magnetosphere can respond in a dramatic way to solar storms. A solar storm can initiate space weather processes in our atmosphere and magnetosphere who can respond in a dramatic way. This impact is measured near or on Earth and results in 3 sorts of space weather storms.

Radio blackout	Geomagnetic storm	Solar radiation storm

The consequence of a solar flare is a radio black out

The consequence of a troubled solar wind, is a geomagnetic storm.

The consequence of a particle storm, is a solar radiation storm.
Not a geomagnetic storm. An individual particle doesn't carry a magnetic field that can couple or disturb the magnetic field of Earth.



SOLAR STORMS IMPACTING AVIATION

A solar storm initiates space weather processes which impact our navigation and radio communication systems and can cause an increase of radiation levels at flight altitude.

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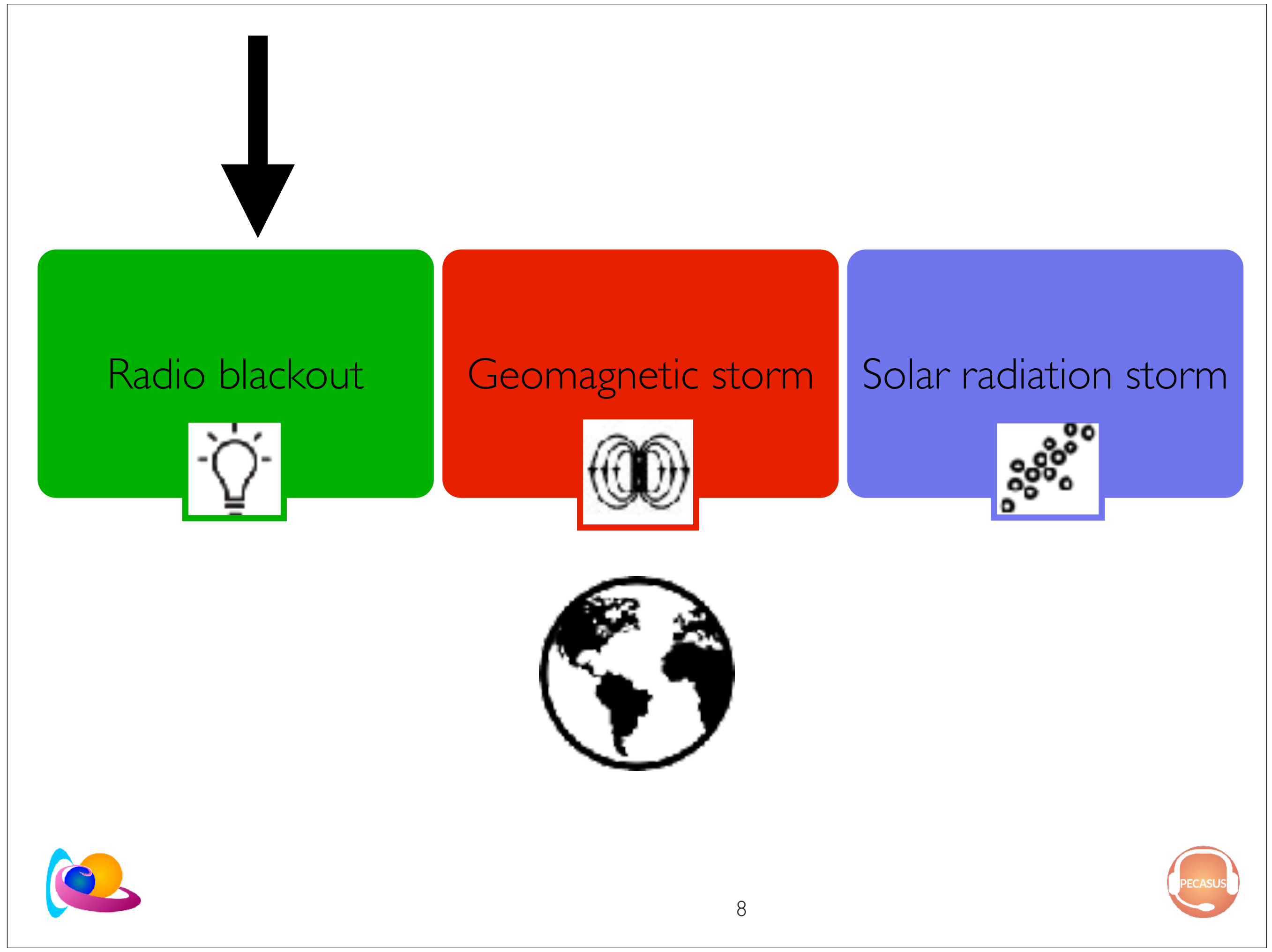

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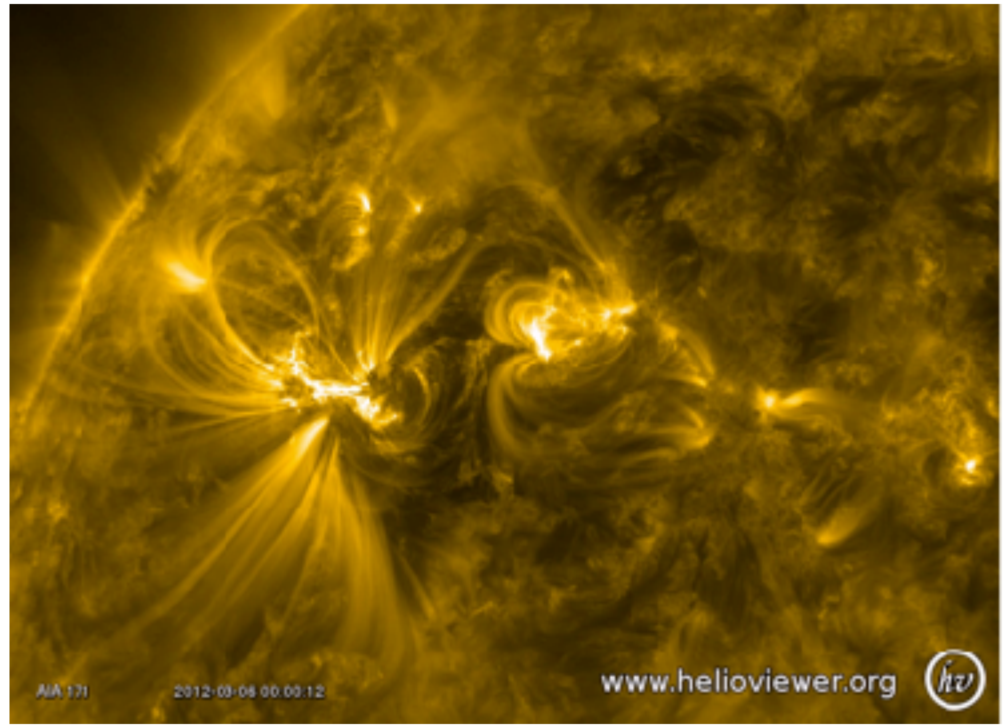
SOLAR FLARES

A flare is a light flash near an active region. A volume of plasma is suddenly heated and therefore lights up.



During a solar flare a particular plasma volume is heated. This happens in a brutal way and during a limited time. The volume is heated up to 107 K. The heating is a consequence of a fast reconnection and reorganisation of the local magnetic field.

Flare

FLARE CATEGORIES

A flare is identified by its x-ray flux. Flares are put into logaritmisch categories.

http://pecasus.stce.be/dashboards/pecaDashboard_HF.php

C1=1*10-6
C2=2*10-6
C3=3*10-6

M1=10-5=1*10*10-6=10*C1=C10
M2=2*10-5= 2*10*10-6=10*C2=C20
M3=3*10-5 = 3*10*10-6=10*C3=C30
…

X1=10-4=1*10*10-5=10*M1=M10
X2=2*10-4=2*10*10-5=10*M2=M20
…
Y1=X10
Y2=X20
Y8=X80
Y9=X90

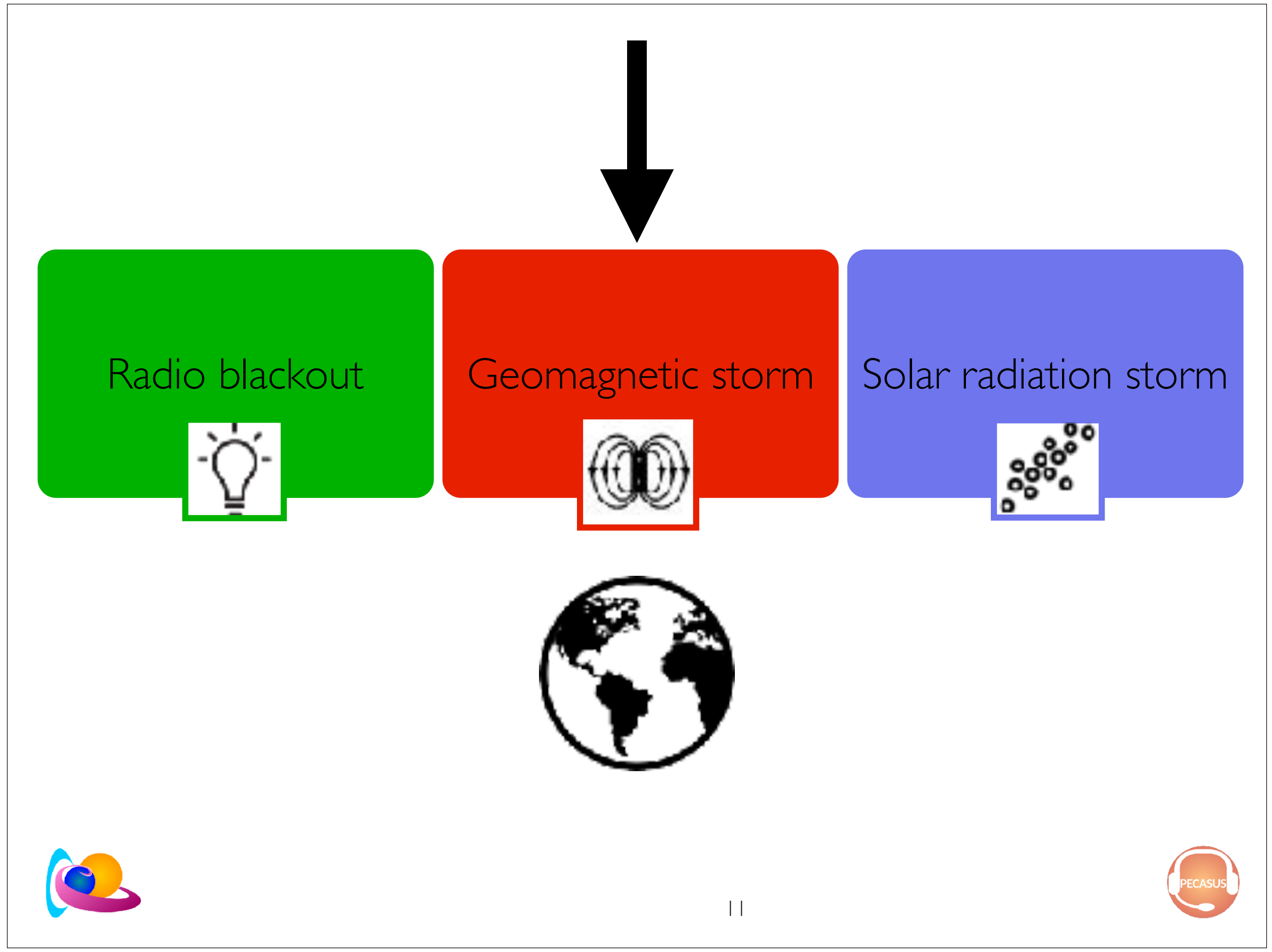
GOES satellite, geostationary
http://www.swpc.noaa.gov/products/goes-x-ray-flux

This graph was made on the fly with staff, a solar time lines viewer: http://staff.oma.be

During a flare, magnetic energy is transformed into e.m. waves.

GOES measures the full disk e.m. radiation (Energy per second per square meter) in a particular X-ray wavelength every minute. The more intense, the higher the curve.

Flares are put into X-ray flux categories. The X-ray flux is measured by GOES (meteo-satellites of NOAA). The classes are based on the enlargement factor of the X-flux in the spectral range 1 to 8 Å – logarithmic. This enlargement factor can go up to 10 000, typically between 10 and 100.



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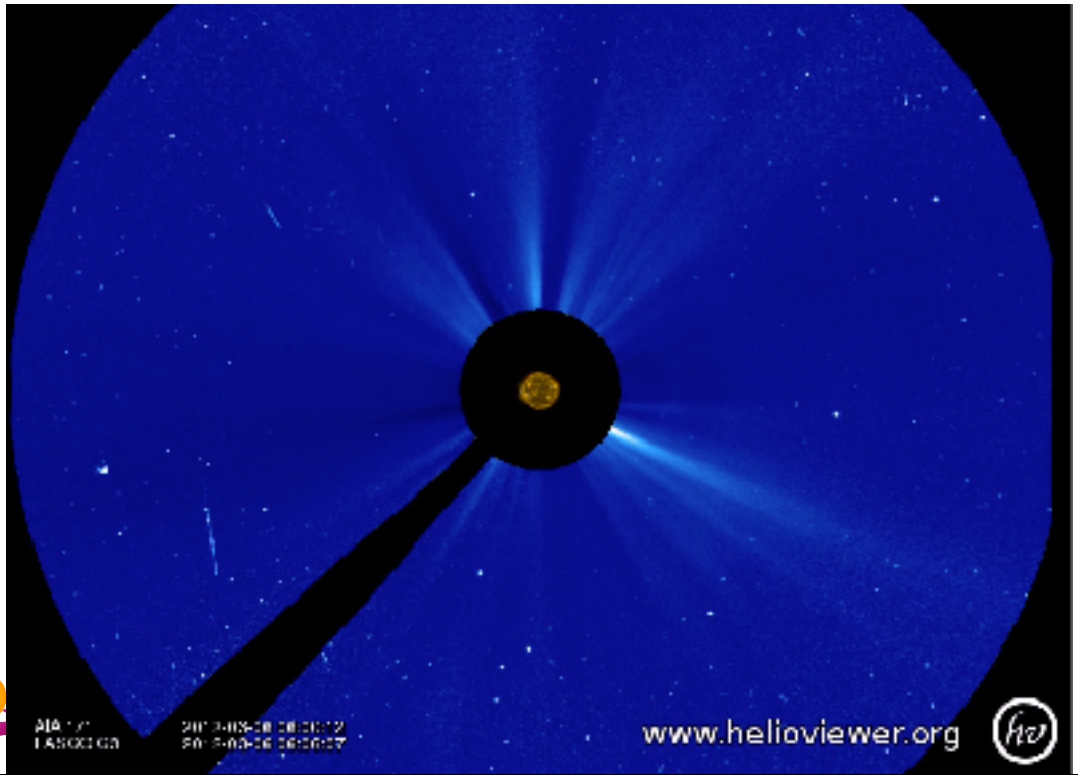
SOLAR STORMS

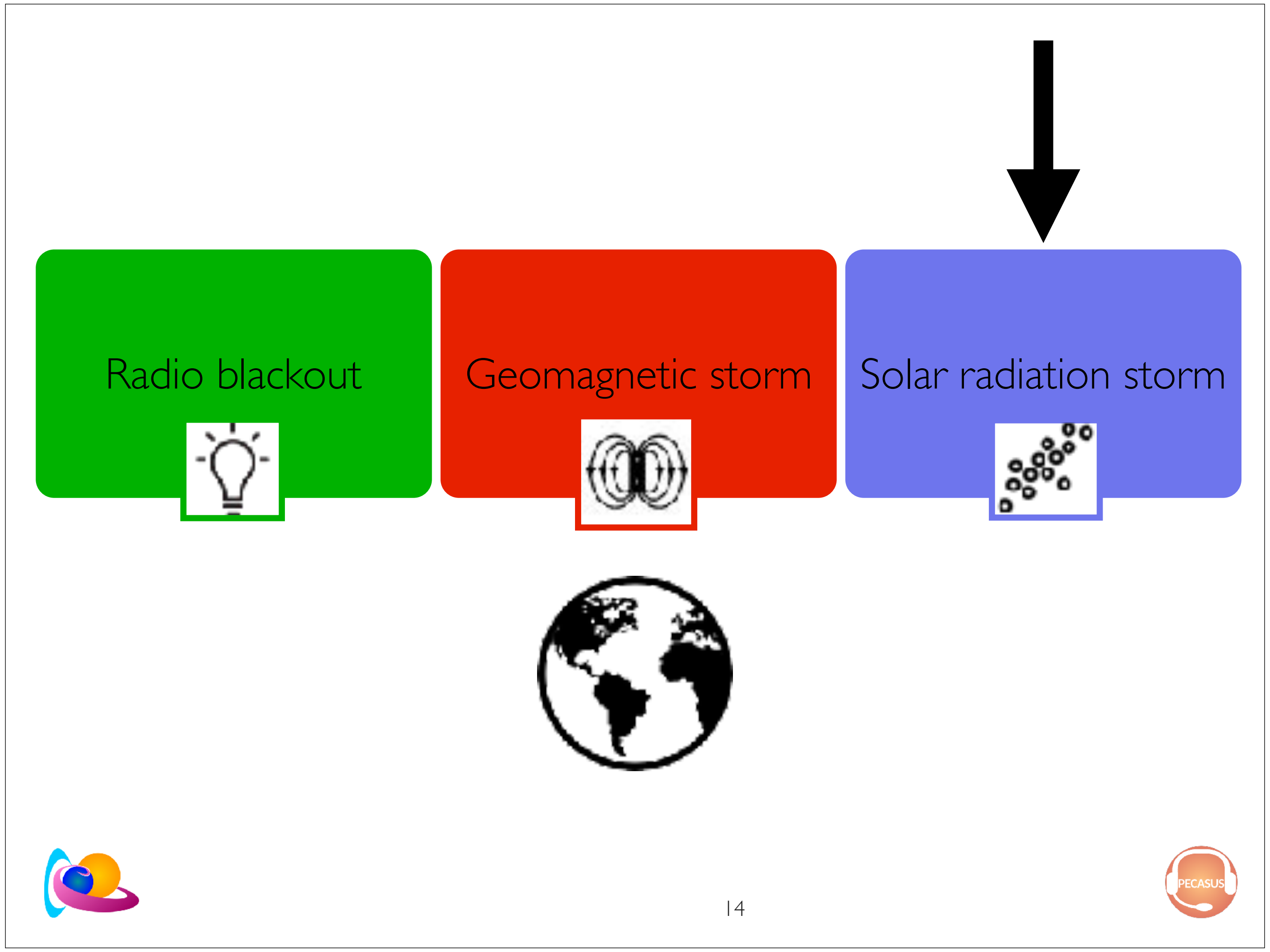
A solar cloud hurling through space. Solar particles hit the coronagraph.



GEOMAGNETIC STORM

The effect of a geomagnetic storm depends on how strong the geomagnetic field is disturbed. This is described by an index Kp. This is an index that describes the conditions of the geomagnetic field at planetary level.

http://pecasus.stce.be/dashboards/pecaDashboard_HF.php



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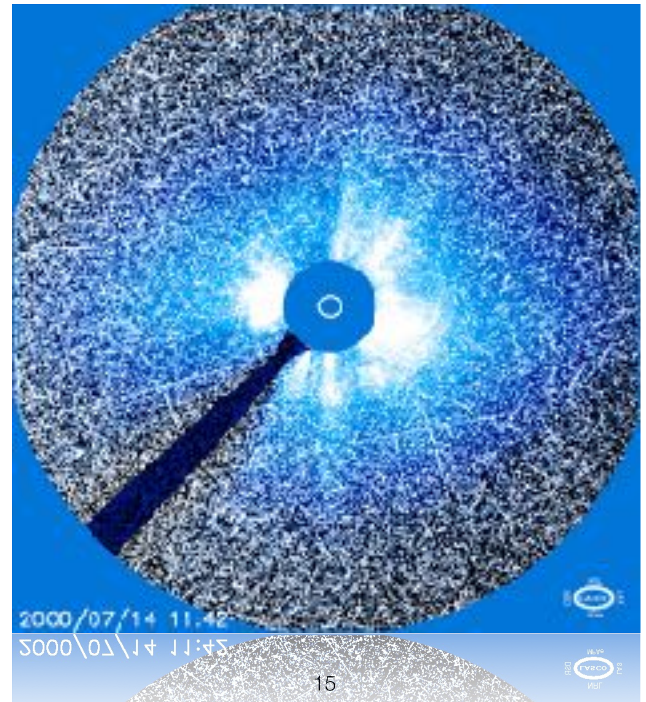
SOLAR ENERGETIC PARTICLES

Solar energetic particles hit the lasco-detector onboard of the spacecraft SOHO which is located at the L1 point, 1 hour upstream of Earth.



JF, 2020

15

Steradiaal is een dimensieloze eenheid, de 3D versie van de 2D radiaal.

Radiaal is de eenheid voor hoek en legt de link tussen hoek en een booglengte.
De radiaal is de SI-eenheid voor hoek. Eén radiaal is gedefinieerd als de grootte van een middelpuntshoek van een cirkel waarvan de lengte van de boog gelijk is aan de lengte van de straal (radius).

Steradiaal is de eenheid voor ruimtehoek en legt de link tussen ruimtehoek en boloppervlak.
Wanneer men op een boloppervlak met een straal van 1 m een figuur (van willekeurige vorm) tekent met een oppervlakte van 1 m^2, heeft deze figuur (vanuit het middelpunt van de bol) een ruimtehoek van 1 steradiaal.

In het geval van een cirkel
Booglengte = hoek * straal
SI eenheid van lengte is meter.
Met hoek in radiaal, dimensieloos
De hoek van een hele cirkel is 2*pi, de omtrek van een cirkel met straal r is 2*pi*r

In het geval van een sfeer
Boloppervlak = ruimtehoek * straal^2
SI eenheid van oppervlak is m^2
Met ruimtehoek in steradiaal, dimensieloos
De ruimtehoek van een hele sfeer is 4*pi, het oppervlak van een sfeer met straal r is 4*pi*r^2

Het woord rad of sr wordt veelal niet vermeld: 180 graden komt overeen met pi rad, men zegt gewoon pi.
Hetzelfde voor steradiaal: in de definitie voor proton flux kan je het woord steradiaal weglaten.

Flux is ‘iets’ doorheen een oppervlak - alles in SI eenheden.
bv magnetische flux: aantal veldlijnen die doorheen een oppervlak prikken.
Als het ‘iets’ beweegt, vloeit, spreek je over die grootheid per seconde doorheen oppervlak, een debiet.
Bv debiet van een rivier : volume water dat per seconde doorheen m^2-oppervlak vloeit.

Het woord steradiaal staat er niet bij omdat de proton flux niet perse isotoop hoeft te zijn.
Het staat erbij omdat de proton-flux een richting heeft, je neemt alle protonen die in de ‘kegel' zitten gedefinieerd door de ruimtehoek (let op: je hebt alleen een echte kegel als de ‘doorsnede' van je ruimtehoek met een bol een cirkel is - weet niet goed hoe ik dit duidelijk moet zeggen). De punt van de kegel is de zon.

Dat de punt van de kegel de zon is, moet je kaderen in de betekenis van het woord flux. Want er kunnen evengoed protonen op het meetinstrument invallen die niet uit de kegel komen met punt op de zon. In LASCO beelden zie je soms strepen naast de witte stippen die protonen voorstellen. De strepen zijn protonen die langs de detector ‘scheren' en een hele rits pixels aandoen.

Vanuit de wiskunde:
Voor een flux heb je een vector-veld nodig: magnetische flux, stroom (snelheidsveld), ….
Het is de component loodrecht op je oppervlak die bijdraagt tot de flux, de component evenwijdig met het oppervlak draagt niet bij tot de flux. ‘Schuin onder een invalshoek theta_1’ definieert dan weer een andere kegel dan ‘schuin onder een invalshoek theta_2’. Je moet dus de component nemen loodrecht op je oppervlak en die component definieert een kegel met als punt de zon.

SOLAR RADIATION STORM

The GOES satellite literally counts the protons with a particular energy that pass the instrument. These protons link to the magnetic field of Earth and circle down to the atmosphere at the poles.

http://pecasus.stce.be/dashboards/pecaDashboard_RADIATION.php

JF, 2020

PECASUS

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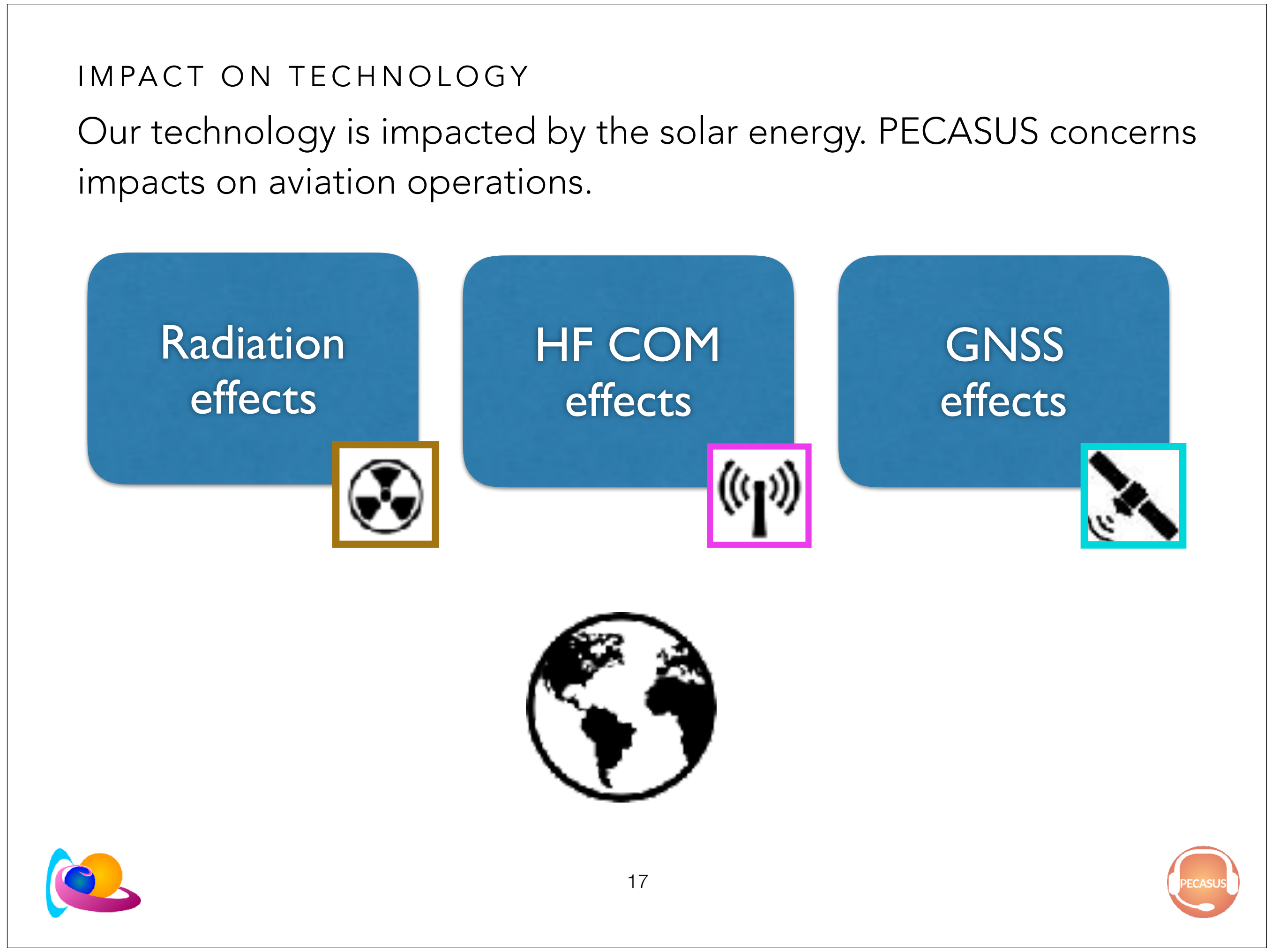


Monitoring & forecasting space weather should result in 3 advisory messages.

NOTAM = NOtice To AirMen

Radiation exposure at flight levels
High Frequency radio communication
GNSS-based navigation and surveillance

Note: for geomagnetic storm
If an event were strong enough to produce moderate degradation in the equatorial regions, it would likely be severe in the middle and high regions. In this case, there would be two advisories issued, one for the severe event affecting HNH, HSN, MNH and MSH and a second advisory for the moderate event affecting EQN and EQS.

Note for Radiation storm
Solar radiation may be severe above a certain altitude and moderate below. This requires 2 advisories.

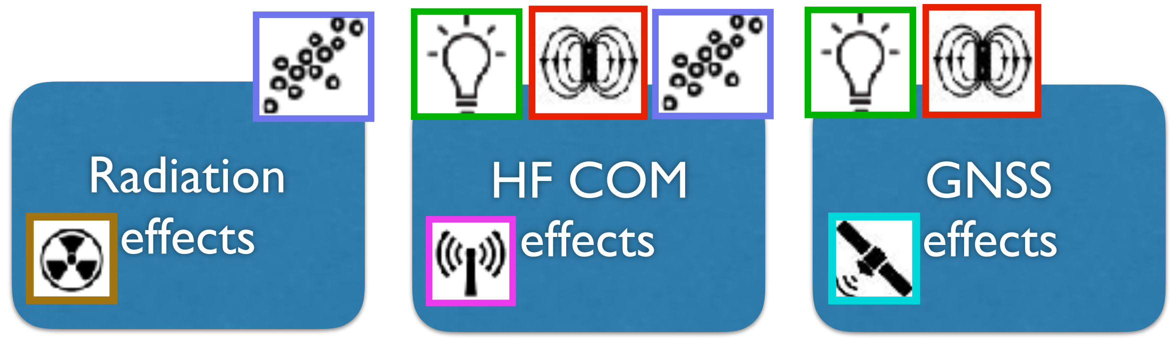
HF COM
https://en.wikipedia.org/wiki/High_frequency
High frequency (HF) is the ITU designation[1] for the range of radio frequency electromagnetic waves (radio waves) between 3 and 30 megahertz (MHz). It is also known as the decameter band or decameter wave as its wavelengths range from one to ten decameters (ten to one hundred metres). Frequencies immediately below HF are denoted medium frequency (MF), while the next band of higher frequencies is known as the very high frequency (VHF) band. The HF band is a major part of the shortwave band of frequencies, so communication at these frequencies is often called shortwave radio. Because radio waves in this band can be reflected back to Earth by the ionosphere layer in the atmosphere – a method known as "skip" or "skywave" propagation – **these**

frequencies are suitable for long-distance communication across intercontinental distances and for mountainous terrains which prevent line-of-sight communications.[2] The band is used by international shortwave broadcasting stations (2.31–25.82 MHz), aviation communication, government time stations, weather stations, amateur radio and citizens band services, among other uses.

https://www.swpc.noaa.gov/impacts/hf-radio-communications
Space weather impacts radio communication in a number of ways. At frequencies in the 1 to 30 mega Hertz range (known as “High Frequency” or HF radio), the changes in ionospheric density and structure modify the transmission path and even block transmission of HF radio signals completely. These frequencies are used by amateur (ham) radio operators and many industries such as commercial airlines. They are also used by a number of government agencies such as the Federal Emergency Management Agency and the Department of Defense.

IMPACT OF THE BIG 4

Nevertheless, our technology is impacted. PECASUS concerns impacts on aviation operations.



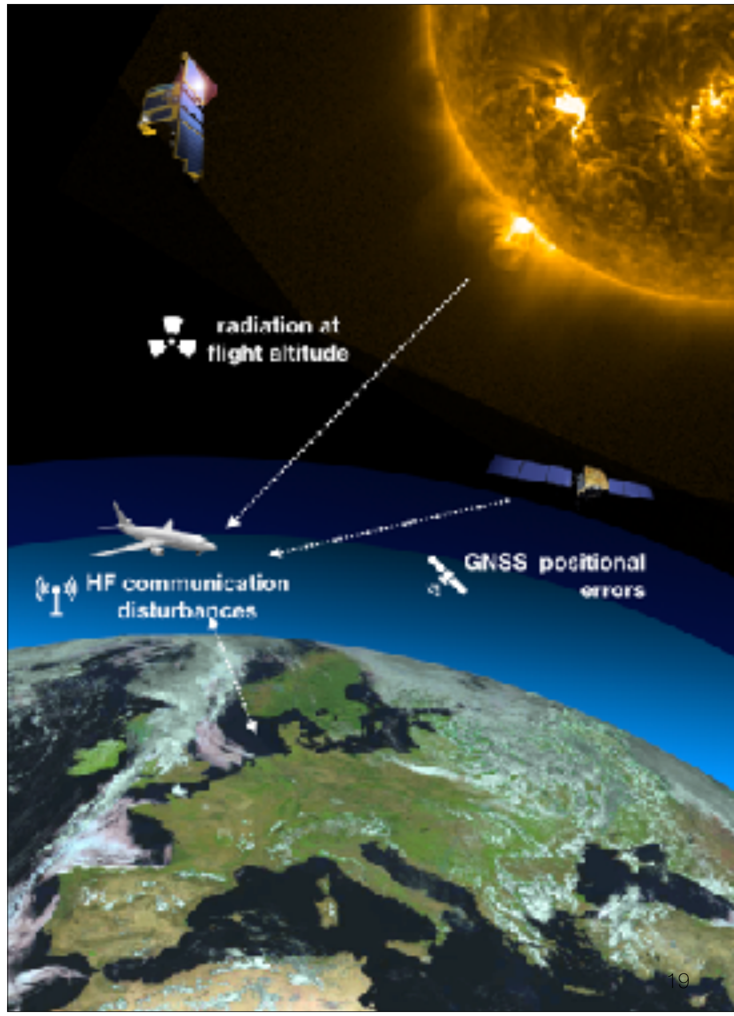
Monitoring & forecasting space weather should result in 3 advisory messages.

These messages are called ‘NOTAM’ = NOtice To AirMen

Radiation exposure at flight levels concerns increased exposure to radiation

High Frequency radio communication concerns propagation & absorption of radio waves

GNSS-based navigation and surveillance concerns the degradation of the performance of satellite navigation systems.



Storm parameters

Thresholds

Petra.Vanlommel@oma.be

IONOSPHERE

Atmospheric layer with free electrons.

Ionization by solar x-ray and ultraviolet radiation and particle radiation.

https://www.ngdc.noaa.gov/stp/iono/ionointro.html

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.

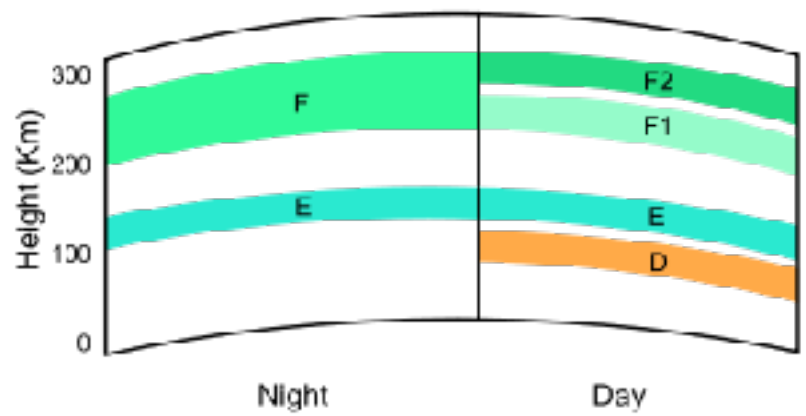
The ionosphere is a **dynamic system controlled by** many parameters including **acoustic motions of the atmosphere, electromagnetic emissions, and variations in the geomagnetic field**. Because of its extreme sensitivity to atmospheric changes, the ionosphere is a very sensitive monitor of atmospheric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

In some circles it is thought that there is persuasive evidence of an ionospheric precursor to large earthquakes that can be used a predictor. Besides the obvious acoustic waves generated before and during an earthquake, a part of the preparation process of large earthquakes is the generation of electromagnetic emissions (EMEs). These EMEs have been detected in the ionosphere up to six days prior to a large earthquake, such as with the May 1960, Chilean 8.3 earthquake.

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

RADIO WAVES AND IONOSPHERE

The electron content of each layer defines a characteristic frequency which in turn affects the refractive index of the medium. Each layer will reflect or absorb radio waves depending on their frequencies. The reflection is used for long distance communications

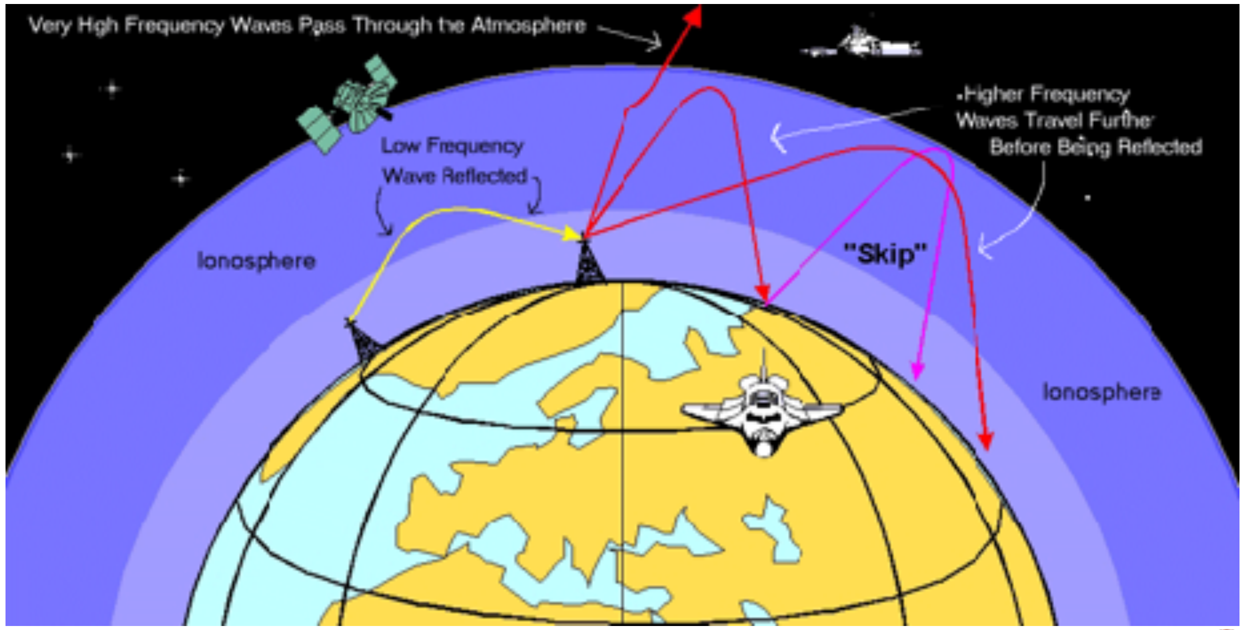


The ionosphere (/aɪˈɒnəˌsfɪər/[1][2]) is the ionized part of Earth's upper atmosphere, from about 60 km (37 mi) to 1,000 km (620 mi) altitude, a region that includes the thermosphere and parts of the mesosphere and exosphere. The ionosphere is ionized by solar radiation. It plays an important role in atmospheric electricity and forms the inner edge of the magnetosphere. It has practical importance because, among other functions, it influences radio propagation to distant places on the Earth.[3]

The Total Electron Content (TEC) is the integrated total number of electrons present along a path between a radio transmitter and receiver.

RADIO WAVES & IONOSPHERE

The ionosphere seems to be the key-layer for HF communication and GNSS performance: or radio waves are reflected at, or pass through the ionosphere.

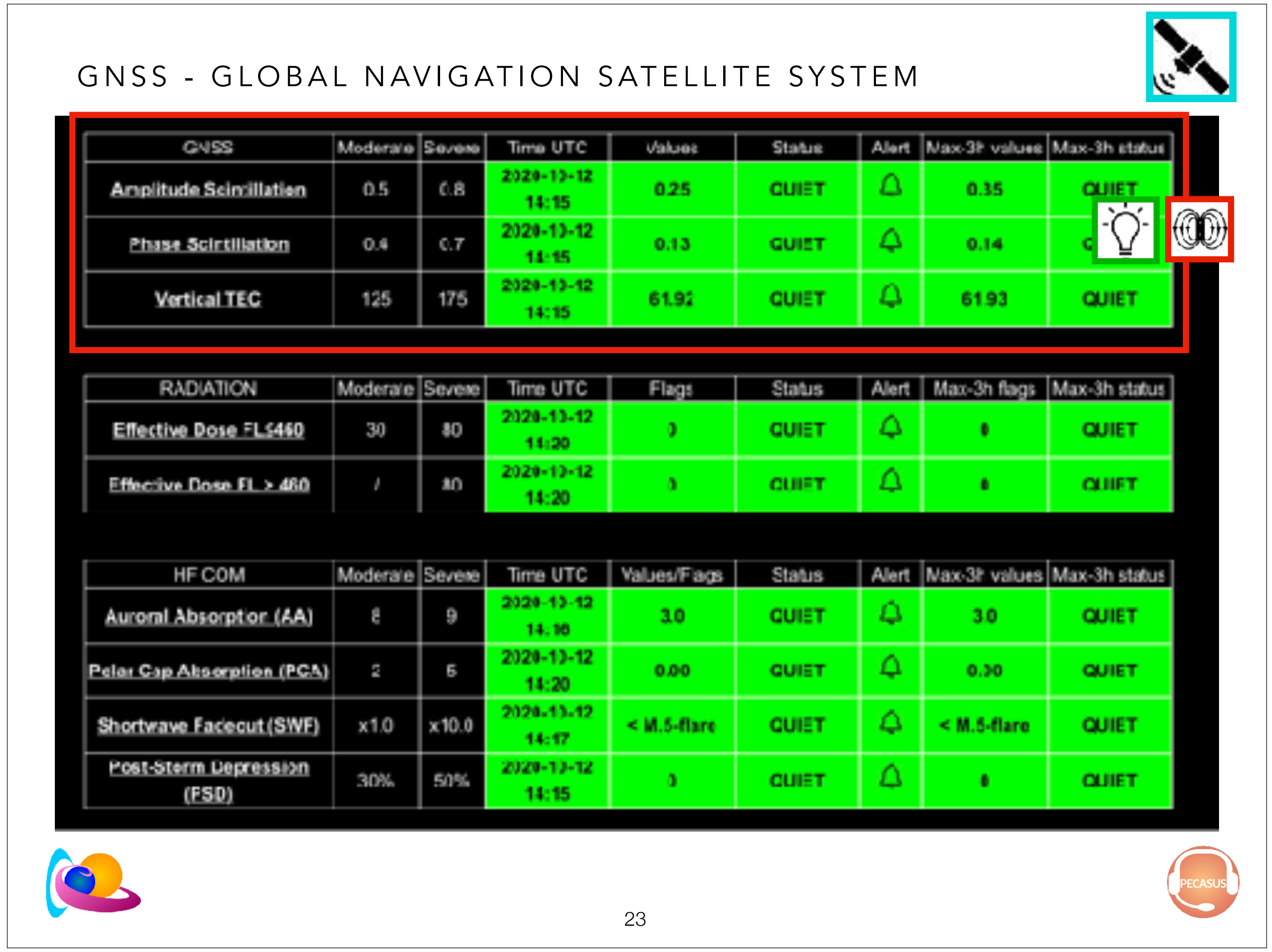


The ionosphere has the ability to reflect radio waves. If the degree of ionisation would be zero, no radio waves would be reflected and all would pass.

Ionisation can change over time.
Ionisation is not the same everywhere.

HF goes through
LF are reflected

During the night, the ionisation decreases – the skill to reflect drops.
—> also LF goes through —> Maximum Usable Frequency, MUF decreases.



GNSS	Moderate	Severe	Time UTC	Values	Status	Alert	Max-3h values	Max-3h status
Amplitude Scintillation	0.5	0.8	2020-10-12 14:15	0.25	QUIET		0.35	QUIET
Phase Scintillation	0.4	0.7	2020-10-12 14:15	0.13	QUIET		0.14	[illegible]
Vertical TEC	125	175	2020-10-12 14:15	61.92	QUIET		61.93	QUIET

RADIATION	Moderate	Severe	Time UTC	Flags	Status	Alert	Max-3h flags	Max-3h status
Effective Dose FL≤460	30	80	2020-10-12 14:20	0	QUIET		0	QUIET
Effective Dose FL > 460	/	80	2020-10-12 14:20	0	QUIET		0	QUIET

HF COM	Moderate	Severe	Time UTC	Values/Flags	Status	Alert	Max-3h values	Max-3h status
Auroral Absorption (AA)	8	9	2020-10-12 14:16	3.0	QUIET		3.0	QUIET
Polar Cap Absorption (PCA)	2	5	2020-10-12 14:20	0.00	QUIET		0.00	QUIET
Shortwave Fadeout (SWF)	x1.0	x10.0	2020-10-12 14:17	< M.5-flare	QUIET		< M.5-flare	QUIET
Post-Storm Depression (PSD)	30%	50%	2020-10-12 14:15	0	QUIET		0	QUIET

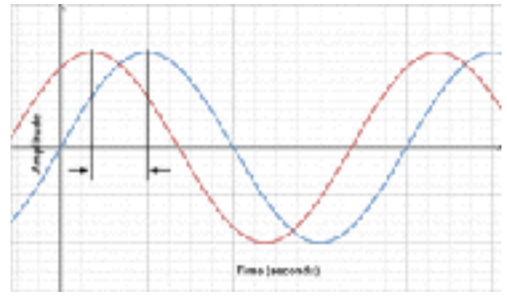
Ionosphere is not needed, it's an inconvenient layer where the satellite signal has to go through.

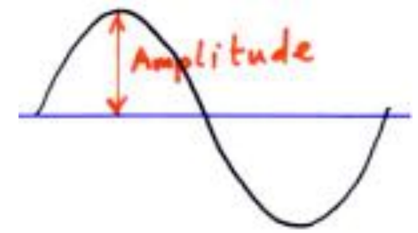
https://www.swpc.noaa.gov/impacts/space-weather-and-gps-systems

There are several ways in which space weather impacts GPS function. GPS radio signals travel from the satellite to the receiver on the ground, passing through the Earth's ionosphere. The charged plasma of the ionosphere bends the path of the GPS radio signal similar to the way a lens bends the path of light. **In the absence of space weather, GPS systems compensate for the "average" or "quiet" ionosphere, using a model to calculate its effect on the accuracy of the positioning information.** But when the ionosphere is disturbed by a space weather event, the models are no longer accurate and the receivers are unable to calculate an accurate position based on the satellites overhead.

In calm conditions, single frequency GPS systems can provide position information with an accuracy of a meter or less. During a severe space weather storm, these errors can increase to tens of meters or more. Dual frequency GPS systems can provide position information accurate to a few centimeters. In this case the two different GPS signals are used to better characterize the ionosphere and remove its impact on the position calculation. But when the ionosphere becomes highly disturbed, the GPS receiver cannot lock on the satellite signal and position information becomes inaccurate.

IONOSPHERIC SCINTILLATION





rapid modification of radio waves caused by small scale structures in the ionosphere.

Loss of lock
——
the phase of a periodic function F of some real variable t is the relative value of that variable within the span of each full period.

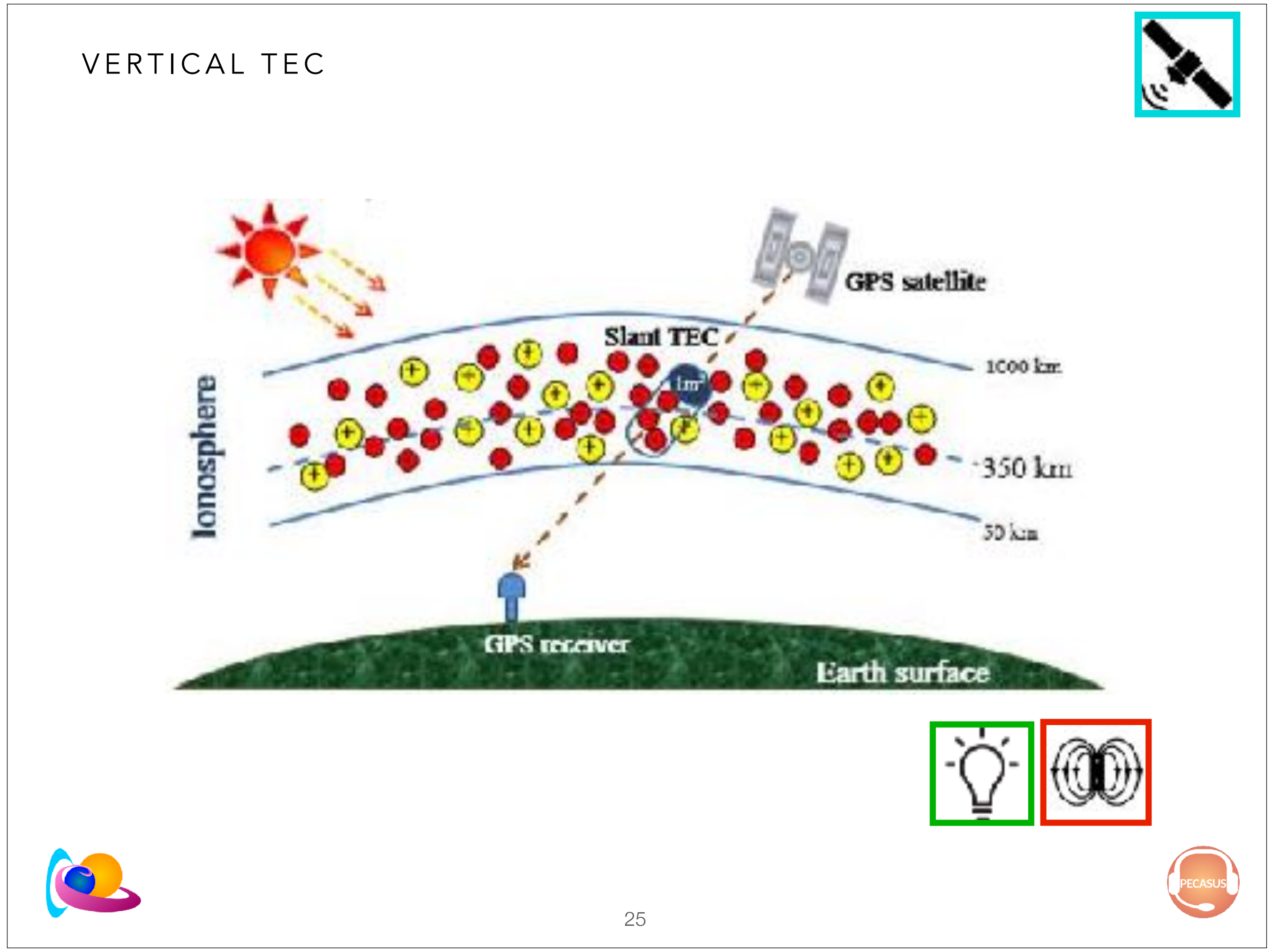
The phase is typically expressed as an angle ϕ(t), in such a scale that it varies by one full turn as the variable t goes through each period (and F(t) goes through each complete cycle). Thus, if the phase is expressed in degrees, it will increase by 360° as t increases by one period. If it is expressed in radians, the same increase in t will increase the phase by
2 π.
——
Can be induced by solar flare, by geomagnetic storm
——
Scintillation involves fluctuation in the phase and amplitude of GNSS signals. In extreme cases, scintillation can cause loss of signal tracking (i.e. cycle slips). It is important to note that the effects of scintillation are not removed by dual-frequency observations. Trimble has setup a global ionospheric scintillation sounding network, which detects scintillation effects and is able to give up to date warning information on scintillation effects in different parts of the world.

Typically scintillation occurs in equatorial regions after sunset for several hours. In polar regions, scintillation can occur at any time. Mid-latitude regions are sometimes affected by Travelling Ionospheric Disturbances (TIDs). A map showing the current ionospheric scintillation activity can be found here http://www.trimbleionoinfo.com/Images.svc/SCINTI
——-
https://www.swpc.noaa.gov/phenomena/ionospheric-scintillation

Ionospheric scintillation is the rapid modification of radio waves caused by small scale structures in the ionosphere. Severe scintillation conditions can prevent a GPS receiver from locking on to the signal and can make it impossible to calculate a position. Less severe scintillation conditions can reduce the accuracy and the confidence of positioning results.

Scintillation of radio waves impacts the power and phase of the radio signal. Scintillation is caused by small-scale (tens of meters to tens of km) structure in the ionospheric electron density along the signal path and is the result of interference of refracted and/or diffracted (scattered) waves. Scintillation is usually quantified by two indexes: S4 for amplitude scintillation and σφ (sigma-phi) for phase scintillation. The indexes reflect the **variability of the signal over a period of time,** usually one minute. Scintillation is more prevalent at low and high latitudes, but mid-latitudes, such as the United States, experience scintillation much less frequently. Scintillation is a strong function of local time, season, geomagnetic activity, and solar cycle but it also influenced by waves propagating from the lower atmosphere.

https://www.sws.bom.gov.au/Satellite/6/3



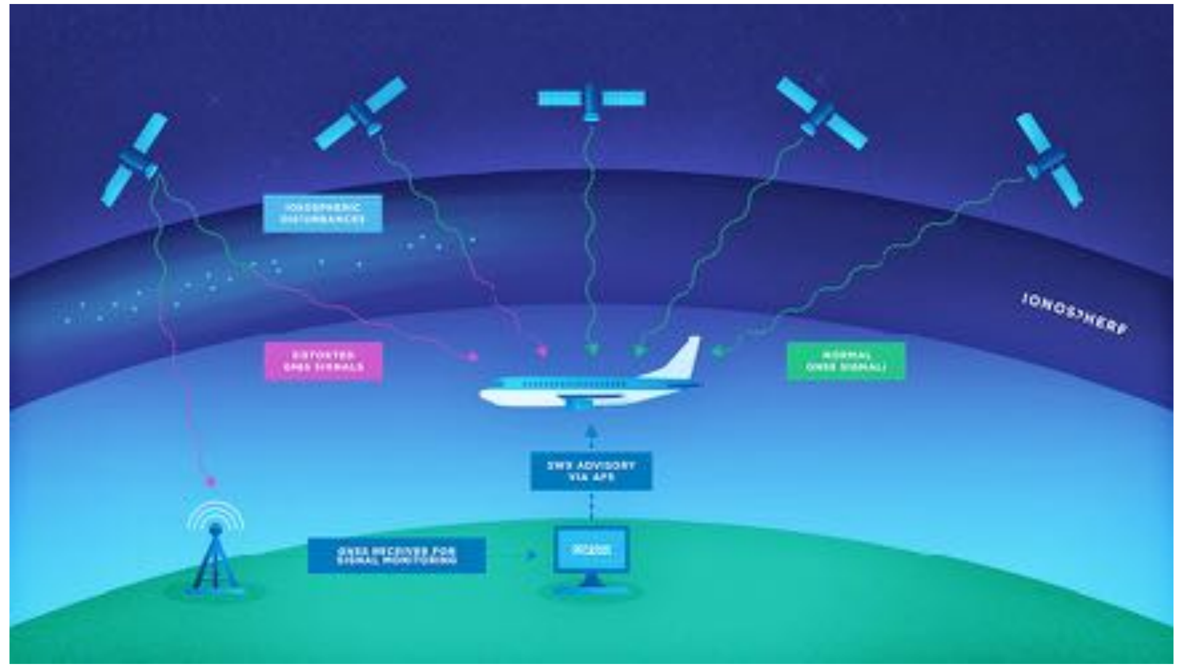
Change in the path and velocity

http://www.trimbleionoinfo.com/Library/IonosphericEffects.htm
Ionospheric Signal Delay
An important descriptive quantity in describing the effect of the ionosphere on the GNSS signal is the total electron content (or TEC). 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, where 1016 electrons/m^2 = 1 TEC unit (TECU).

The relationship between TECU and the group delay of a GNSS signal is described in the first approximation by

https://www.swpc.noaa.gov/impacts/space-weather-and-gps-systems
Geomagnetic storms create large disturbances in the ionosphere. The currents and energy introduced by a geomagnetic storm enhance the ionosphere and increase the total height-integrated number of ionospheric electrons, or the Total Electron Count (TEC). GPS systems cannot correctly model this dynamic enhancement and errors are introduced into the position calculations. This usually occurs at high latitudes, though major storms can produce large TEC enhancements at mid-latitudes as well.
——
https://www.swpc.noaa.gov/phenomena/total-electron-content
The TEC in the ionosphere is modified by changing solar Extreme Ultra-Violet radiation, geomagnetic storms, and the atmospheric waves that propagate up from the lower atmosphere. The TEC will therefore depend on local time, latitude, longitude, season, geomagnetic conditions, solar cycle and activity, and troposphere conditions. The propagation of radio waves is affected by the ionosphere. The velocity of radio waves changes when the signal passes through the electrons in the ionosphere. The total delay suffered by a radio wave propagating through the ionosphere depends both on the frequency of the radio wave and the TEC between the transmitter and the receiver. At some frequencies the radio waves pass through the ionosphere. At other frequencies, the waves are reflected by the ionosphere.

The change in the path and velocity of radio waves in the ionosphere has a big impact on the accuracy of satellite navigation systems such as GPS/GNSS. Neglecting changes in the ionosphere TEC can introduce tens of meters of error in the position calculations. The Global Positioning System (GPS), the US part of GNSS, uses an empirical model of the ionosphere, the Klobuchar model, to calculate and remove part of the positioning error caused by the ionosphere when single frequency GPS receivers are used. When conditions deviate from those predicted by the Klobuchar model, GPS/GNSS systems will have larger positioning errors. I



The ionosphere plays also a crucial role in satellite navigation. The signal sent by the satellite has to pass through the ionosphere to reach the receiver. Solar storms can introduce small scale structures in the ionosphere. When the signal encounters these obstacles, its amplitude and phase can alter very rapidly. Similarly, when the number of electrons in the ionosphere increases dramatically due to a solar storm, positioning errors are introduced in satellite navigation.

Solar wind disturbances and solar flares can create structures of tens of meters to tens of kms in the ionosphere. These structures form obstacles for the satellite signals that pass through the ionosphere. A radio wave can undergo rapid modification in its amplitude or phase. Scintillation can prevent a receiver from locking on to the signal and as such make it impossible to calculate its position.

The velocity of radio waves changes when the signal passes through the electrons in the ionosphere. The total delay suffered by a radio wave propagating through the ionosphere depends both on the frequency of the radio wave and the TEC between the transmitter and the receiver. At some frequencies the radio waves pass through the ionosphere. At other frequencies, the waves are reflected by the ionosphere.

RADIATION

GNSS	Moderate	Severe	Time UTC	Values	Status	Alert	Max-3h values	Max-3h status
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Vertical TEC	125	175	2020-12-12 14:15	61.92	QUIET		61.93	QUIET

RADIATION	Moderate	Severe	Time UTC	Flags	Status	Alert	Max-3h flags	Max-3h status
Effective Dose FL≤460	30	80	2020-12-12 14:20	0	QUIET		0	QUIET
Effective Dose FL > 460	/	80	2020-12-12 14:20	0	QUIET		0	QUIET

HF COM	Moderate	Severe	Time UTC	Values/Flags	Status	Alert	Max-3h values	Max-3h status
Auroral Absorption (AA)	8	9	2020-12-12 14:16	3.0	QUIET		3.0	QUIET
Polar Cap Absorption (PCA)	2	5	2020-12-12 14:20	0.00	QUIET		0.30	QUIET
Shortwave Fadeout (SWF)	x1.0	x10.0	2020-12-12 14:17	< M.5-flare	QUIET		< M.5-flare	QUIET
Post-Storm Depression (PSD)	30%	50%	2020-12-12 14:15	0	QUIET		0	QUIET

PECASUS

Micro = 10^-6
Sieverts = J/kg

Effective dose takes the sort of radiation into account, the human body, the tissue and the organs being radiated and tells you what the effect is at the end.

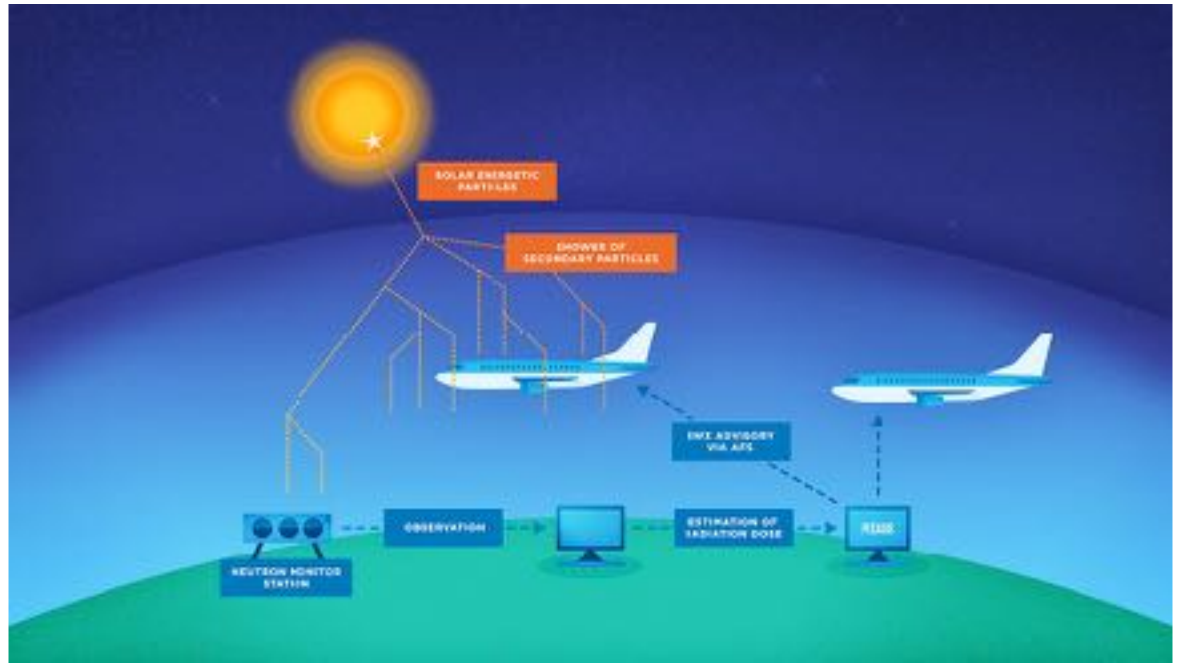
It says something about the chance, probability to develop cancer.

It is not about dropping death because of a sudden increase of radiation. This is the absorbed dose.

Effective dose is a dose quantity in the International Commission on Radiological Protection (ICRP) system of radiological protection.[1]

It is the tissue-weighted sum of the equivalent doses in all specified tissues and organs of the human body and represents the stochastic health risk to the whole body, which is the probability of cancer induction and genetic effects, of low levels of ionising radiation.[2][3] It takes into account the type of radiation and the nature of each organ or tissue being irradiated, and enables summation of organ doses due to varying levels and types of radiation, both internal and external, to produce an overall calculated effective dose.

The SI unit for effective dose is the sievert (Sv) which represents a 5.5% chance of developing cancer.[4] The effective dose is not intended as a measure of deterministic health effects, which is the severity of acute tissue damage that is certain to happen, that is measured by the quantity absorbed dose.[5]



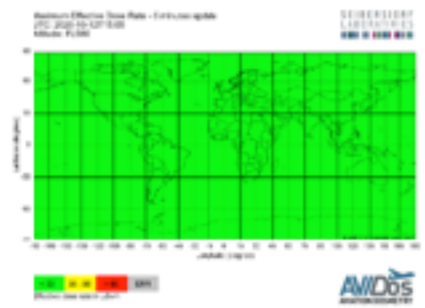
During solar storms, solar particles like protons can suddenly be accelerated, heading into space at great speed. When they arrive at Earth, these energetic particles can penetrate the atmosphere at the magnetic poles. They bombard atmospheric particles and create a shower of particles possibly reaching the Earth's surface. When this happens, crew and passengers onboard airplanes are more vulnerable to this harmful radiation. The effect is stronger at high altitudes and latitudes.

Neutron monitors are detectors on the Earth surface that measure Galactic Cosmic Rays (GCR). This is the background radiation from outside the heliosphere. The variation of GCR is negligible when it comes to human health. During a strong Solar Radiation Storm, energetic particles bombard our atmosphere and create secondary particles that are 'seen' by neutron monitors. When more than 3 stations measure an increase in radiation, we determine it as a Ground Level Event which also implies an extra dose of radiation on airplanes in flight. The impact depends on altitude and latitude: the higher the altitude and/or latitude, the stronger the impact.

RADIATION -$\mu Sv/h$

During a strong Solar Radiation Storm, a Ground Level Enhancement (GLEs) may occur. A GLE is sudden increase in the cosmic ray intensity recorded by ground based detectors. Radiation at FLV in particular latitude bands will increase.

What?	Strong Solar Radiation Storm
Consequences	Increased radiation
What to monitor	micro-Sieverts/hour



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HF COM

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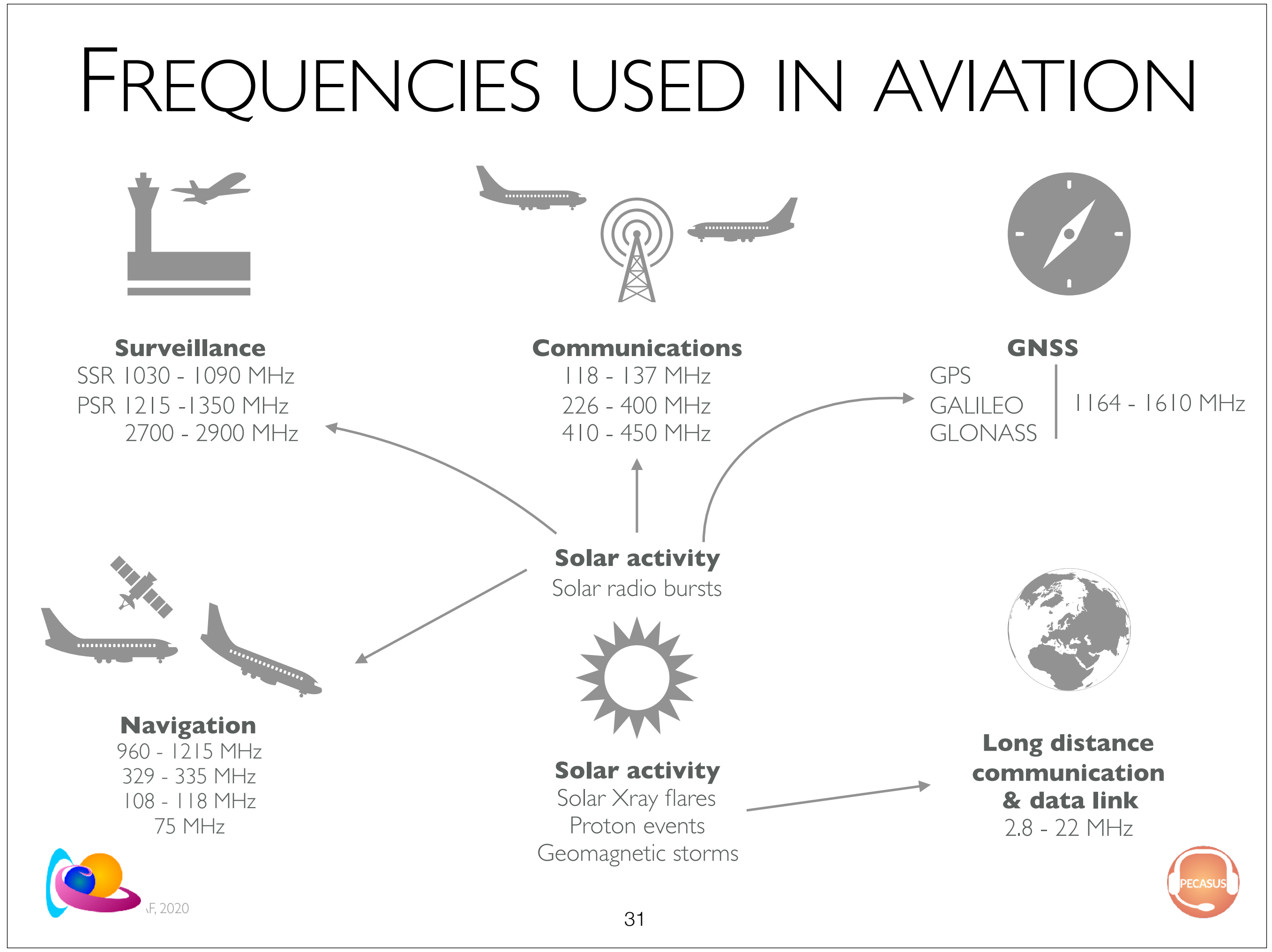
Post-Storm Depression (PSD)	30%	50%	2020-10-12 14:15	0	QUIET		0	QUIET

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



Long Distance Communication & data link
In aviation, **HF communication** systems are required for all trans-oceanic flights. These systems incorporate frequencies down to 2 MHz to include the 2182 kHz international distress and calling channel.

Navigation
https://en.wikipedia.org/wiki/Air_navigation
The basic principles of air navigation are identical to general navigation, which includes the process of planning, recording, and controlling the movement of a craft from one place to another.

https://en.wikipedia.org/wiki/Communication,_navigation_and_surveillance
Communication
Communication, i.e. aviation communication, refers to radio communication between two or more aircraft, or the exchange of data or verbal information between aircraft and air traffic control.[2] For continental airspace, VHF (civil) and UHF (military) systems are used whereas for oceanic areas, high frequency systems and SATCOMs are used.[3]

Navigation
Navigation, i.e. air navigation, refers to the process of planning, recording, and controlling the movement of an aircraft from one place to another by providing accurate, reliable and seamless position determination capability.[2][4]

Surveillance

Surveillance systems are used by air traffic control to determine the position of aircraft. There are two types of surveillance systems:

Cooperative systems[edit]

Cooperative systems (a.k.a. dependent surveillance): Under this form of surveillance, systems on the ground (such as SSR) communicate with equipment (such as transponders) on board the aircraft to determine the position and other details of the aircraft. Aircraft information, which may include position from GNSS or other means is determined on board and then transmitted to ATC in response to interrogation.[2][3] Other cooperative systems such as ADS-B rely on aircraft transmitting their position and other information without interrogation from the ground.

Non-cooperative systems[edit]

Non-cooperative systems (a.k.a. independent surveillance): Under this form of surveillance, systems on the ground (such as PSR) are able to locate the aircraft and measure its position from the ground by transmitting pulses of radio waves which reflect off the aircraft's hull.[2][3]

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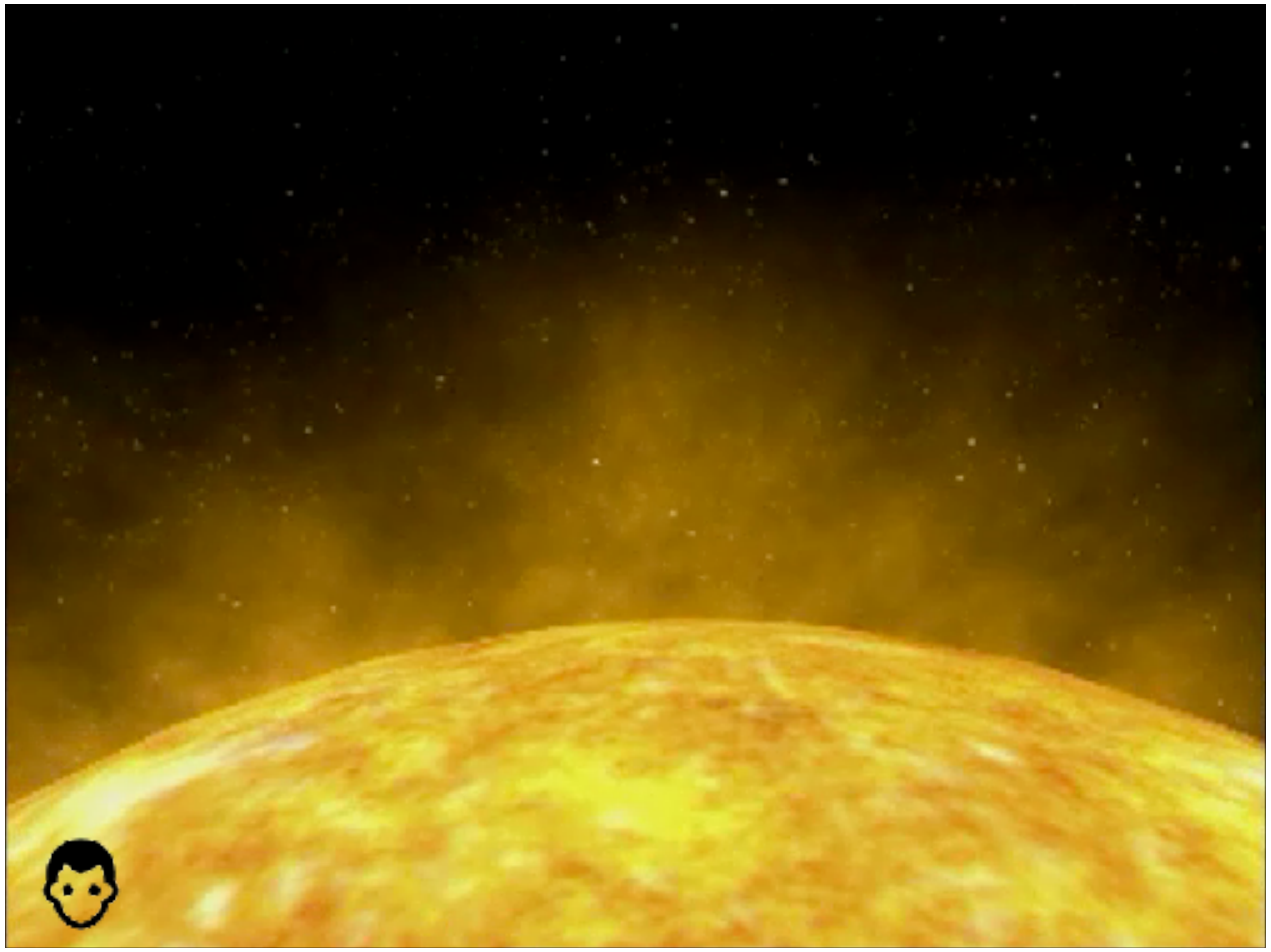
https://www.swpc.noaa.gov/impacts/hf-radio-communications
Space weather impacts radio communication in a number of ways. At frequencies in the 1 to 30 mega Hertz range (known as “High Frequency” or HF radio), the changes in ionospheric density and structure modify the transmission path and even block transmission of HF radio signals completely. These frequencies are used by amateur (ham) radio operators and many industries such as commercial airlines. They are also used by a number of government agencies such as the Federal Emergency Management Agency and the Department of Defense.

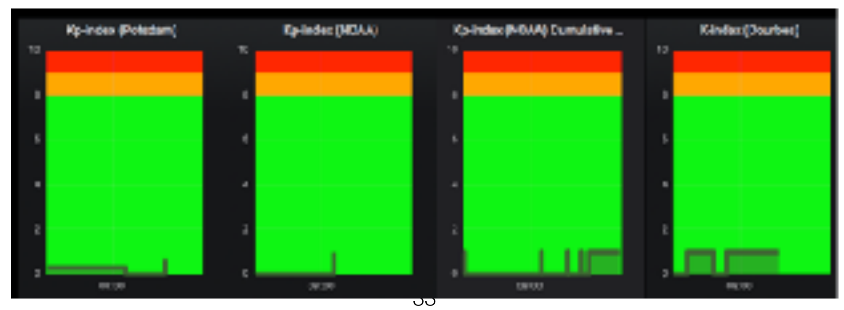


Precipitating electrons coming from the tail

AURORAL ABSORPTION - KP

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

What?	Strong geomagnetic storms Kp>8
Consequences	radio fade out in both polar region
What to monitor	Kp indices



Energetic precipitation on the morning 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 night side of the polar regions of Earth where the aurora is most intense and most frequent.**

Polar Cap Absorption

During proton events or solar radiation storms, high energy protons from the Sun will trigger extra ionisation of the D-layer in the polar ionosphere inducing a radio fade out, called a Polar Cap Absorption.

What?	Solar radiation storm
Consequences	radio fade out in both polar regions
What to monitor	Riometer data D-RAP model Absorption >2 dB

http://pecasus.stce.be/dashboards/pecaDashboard_HF_PCA.php?&time=2020-10-12+15:06

Attenuation = verzwakking

10 * log (P1/P2) met P1 in en P2 out —– log (P1/P2)=y —> P1/P2=10^y

1dB attenuation -> out = in
10dB attenuation —> out = 10 keer minder sterk - P2 = 10^-1 P1
20 dB attenuation —> out =100 keer minder sterk - P2 = 10^-2 P1
30 dB attenuation —> out = 1000 keer minder sterk - P2 = 10^-3 P1

1dB attenuation -> in = out
2,3,4,5,6,7,8,9
10dB attenuation —> in = 10 keer sterker dan out - P1 = 10^1 P2
20,30,40,50,60,70,80,90
20 dB attenuation —> in = 100 keer sterker dan out - P1 = 10^2
200,300,
30 dB attenuation —> in = 1000 keer sterker dan out - P1 = 10^3

A condition in the polar ionosphere where HF and VHF radio waves are absorbed and LF and VLF radio waves are reflected at lower altitudes than normal. PCA events usually originate from major solar storms that launch energetic protons that reach our outer atmosphere quickly and cause excess ionization that distorts the normal refractive properties of the polar ionosphere.

Radio waves are reflected at the F2 layer. The radio waves pass through the D-layer where they can be absorbed.
>2dB for 30 Mhz

https://www.oulu.fi/sgoenglish/node/19549
Riometer (Relative ionospheric opacity meter) **measures cosmic radio noise absorption** (CNA) in the D-region of ionosphere. Frequencies used for the measurement are reserved for the military communication, so time to time local transmitters can saturate the receiver. One of the strongest radio sources on the sky is Cygnus α.

Instrument

Receiver system consists three main parts: the receiver antenna, riometer radio and datalogging system.

Receiver radio

SGO uses analogical La Jolla riometers. The riometer measures the signal received from the antenna by compasating the signal. Compasation voltage is measured. During the absorption the signal level drops from the quiet time level. Active flares in the Sun can be seen as spikes in the signal. This is more common during the high solar activity.

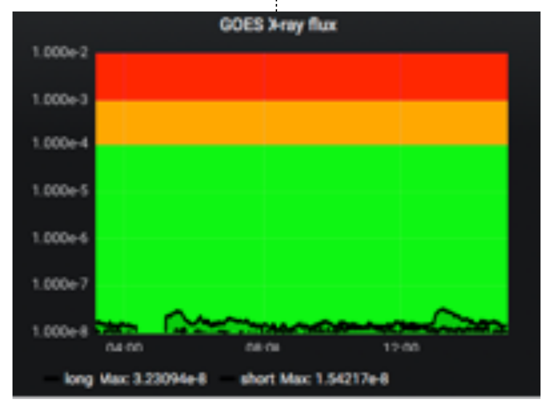
Receiver antenna

Today SGO uses dual half-wavelength dipole antenna for the receiver. These are used to form 60 ° wide beam towards zenith of the sky.

SHORT WAVE FADE OUT

The soft Xray flux increase will induce an excess ionisation of the D layer triggering an absorption of low HF frequencies (fade out).

What?	Strong flares (>X1)
Consequences	radio fade out in the Sun-lit hemisphere
What to monitor	GOES soft Xray flux



35

advise: higher HF might be less impacted

http://www.astro.gla.ac.uk/users/eduard/cesra/?p=2198&utm_source=dlvr.it&utm_medium=facebook

Both Figure 1 and Figure 2 show how quickly and dramatically a solar flare can impact HF communications. Radio blackouts are particularly difficult because they are generally impossible to predict. Since the flare X-ray energy travels at the speed of light, we can only know the flare has occurred once it has already arrived. Fortunately, the recombination time of the D region is relatively fast, and communications can resume within just a few hours. Also, solar flares primarily affect only the dayside ionosphere; Frissell et al. (2019) shows a corresponding figure to Figure 2 that shows United States communications were barely affected by the flares because the US was on the dawn flank.

POST STORM DEPRESSIONS

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 ionospheric storms, the ionosphere remains in an unsettled state, triggering disturbances in long range radio communications. The MUF varies with respect to their undisturbed values.

What?	ionospheric disturbances
Consequences	Global radio communication troubles
What to monitor	$\frac{MUF}{median_{30days}(f_oF_2)}$ % decrease

MUF is lower during night, but doesn’t fade away because the reflective capability of the ionosphere is not gone over 1 night.

foF2=vertical signal
https://www.sws.bom.gov.au/HF_Systems/6/5
A feature of the ionosphere is its ability to reflect radio waves. However, only radio waves within a certain frequency range will be reflected and this range varies with a number of factors.

The most widely used instrument for ionospheric measurement is the ionosonde. The ionosonde is essentially a high frequency radar which sends short pulses of radio energy into the ionosphere. If the radio frequency is not too high, the pulses are reflected back to earth.
——————

In the late phases of magnetic storms, the ionosphere remains in an unsettled state, triggering disturbances in long range radio communications. The MUF and the critical frequency vary with respect to their undisturbed values.

The maximum usable frequency (MUF) for a given communication path is the highest HF radio frequency that can be used for communication via reflection. A depression of the MUF prohibits aircraft from accessing the highest frequencies normally available.

In radio transmission maximum usable frequency (MUF) is the highest radio frequency that can be used for transmission between two points via reflection from the ionosphere (skywave or "skip" propagation) at a specified time, independent of transmitter power. This index is especially useful in regard to shortwave transmissions.

In shortwave radio communication, a major mode of long distance propagation is for the radio waves to reflect off the ionized layers of the atmosphere and return diagonally back to Earth. In this way radio waves can travel beyond the horizon, around the curve of the Earth. However the refractive index of the ionosphere decreases with increasing frequency, so there is an upper limit to the frequency which can be used. Above this frequency the radio waves are not reflected by the ionosphere but are transmitted through it into space.

The ionization of the atmosphere varies with time of day and season as well as with solar conditions, so the upper frequency limit for skywave communication varies on an hourly basis. MUF is a median frequency, defined as the highest frequency at which skywave communication is possible 50% of the days in a month, as opposed to the lowest usable high frequency (LUF) which is the frequency at which communication is possible 90% of the days, and the Frequency of optimum transmission (FOT).

Typically the MUF is a predicted number. Given the maximum observed frequency (MOF) for a mode on each day of the month at a given hour, the MUF is the highest frequency for which an ionospheric communications path is predicted on 50% of the days of the month.

On a given day, communications may or may not succeed at the MUF. Commonly, the optimal operating frequency for a given path is estimated at 80 to 90% of the MUF. As a rule of thumb the MUF is approximately 3 times the critical frequency.[1]

MUF=critical frequency/cos θ[2]

where the critical frequency is the highest frequency reflected for a signal propagating directly upward and Θ is the angle of incidence.[3]

advise: lower frequencies might be less impacted
—-
https://en.wikipedia.org/wiki/High_frequency
The dominant means of long-distance communication in this band is skywave ("skip") propagation, in which radio waves directed at an angle into the sky refract back to Earth from layers of ionized atoms in the ionosphere.[3] By this method HF radio waves can travel beyond the horizon, around the curve of the Earth, and can be received at intercontinental distances. However, suitability of this portion of the spectrum for such communication varies greatly with a complex combination of factors:

Sunlight/darkness at site of transmission and reception
Transmitter/receiver proximity to solar terminator
Season
Sunspot cycle
Solar activity
Polar aurora
At any point in time, for a given "skip" communication path between two points, the frequencies at which communication is possible are specified by these parameters

Maximum usable frequency (MUF)
Lowest usable high frequency (LUF) and a
Frequency of optimum transmission (FOT)
The maximum usable frequency regularly drops below 10 MHz in darkness during the winter months, while in summer during daylight it can easily surpass 30 MHz. It depends on the angle of incidence of the waves; it is lowest when the waves are directed straight upwards, and is higher with less acute angles. This means that at longer distances, where the waves graze the ionosphere at a very blunt angle, the MUF may be much higher. The lowest usable frequency depends on the absorption in the lower layer of the ionosphere (the D-layer). This absorption is stronger at low frequencies and is also stronger with increased solar activity (for example in daylight); total absorption often occurs at frequencies below 5 MHz during the daytime. The result of these two factors is that the usable spectrum shifts towards the lower frequencies and into the Medium Frequency (MF) range during winter nights, while on a day in full summer the higher frequencies tend to be more usable, often into the lower VHF range.[citation needed]

When all factors are at their optimum, worldwide communication is possible on HF. At many other times it is possible to make contact across and between continents or oceans. At worst, when a band is "dead", no communication beyond the limited groundwave paths is possible no matter what powers, antennas or other technologies are brought to bear. When a transcontinental or worldwide path is open on a particular frequency, digital, SSB and Morse code communication is possible using surprisingly low transmission powers, often of the order of milliwatts, provided suitable antennas are in use at both ends and that there is little or no man-made or natural interference.[4] On such an open band, interference originating over a wide area affects many potential users. These issues are significant to military, safety[5] and amateur radio users of the HF bands.

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A riometer (commonly relative ionospheric opacity meter, although originally: Relative Ionospheric Opacity Meter for Extra-Terrestrial Emissions of Radio noise[1]) is an instrument used to quantify the amount of electromagnetic-wave ionospheric absorption in the atmosphere.[2] As the name implies, a riometer measures the "opacity" of the ionosphere to radio noise emanating from cosmic origin. In the absence of any ionospheric absorption, this radio noise, averaged over a sufficiently long period of time, forms a quiet-day curve. Increased ionization in the ionosphere will cause absorption of radio signals (both terrestrial and extraterrestrial), and a departure from the quiet-day curve. The difference between the quiet-day curve and the riometer signal is an indicator of the amount of absorption, and is measured in decibels. Riometers are generally passive radio antenna operating in the VHF radio frequency range (~30-40 MHz). Electromagnetic radiation of that frequency is typically Galactic synchrotron radiation and is absorbed in the Earth's D region of the ionosphere.

Rioters are put on the ground

https://web.archive.org/web/20130404234726/http://www.haarp.alaska.edu/haarp/Rio.html
What is a riometer?

A riometer is a passive scientific instrument used to observe ionospheric absorption, particularly absorption at altitudes less than 110 km caused by electron precipitation. The word riometer stands for Relative Ionospheric Opacity Meter
How does a Riometer Work?

Riometers measure the strength of radio noise originating from stars or galaxies and arriving at the earth after passing through the ionosphere. The sky is filled with stars and galaxies that emit a broad spectrum of radio noise and the noise is strong enough to be picked up using sensitive receiving equipment. Because some regions of the sky are noiser than others, this noise varies on a predictable basis as the Earth rotates. Although noise due to stars or galaxies may change over very long time frames, it is constant enough to be considered a repeatable function of Local Sidereal Time.
Depending on the amount of ionization present, radio signals passing through the ionosphere may suffer losses (or become weaker) in a process called absorption. Imagine the ionosphere as a set of louvers. If it is disturbed, the louvers close and signals arriving from outside of the earth's vicinity do not pass through very well. If the ionosphere is "quiet," the louvers are open fully and signals pass through easily.

If there were no sources of absorption in the earth's atmosphere, the cosmic noise measured by the riometer would be exactly the same at corresponding times during each successive Sidereal day. The "Quiet Day Curve" is this expected, or "no-absorption" diurnal noise level. (In this context,"quiet" means that the ionosphere is undisturbed by solar events.) Any difference between the actual measurement and the Quiet Day Curve is attributed to ionospheric absorption.

The riometer uses a sensitive receiver which is typically tuned to a frequency near the lower end of the Very High Frequency (VHF) region. The frequency is chosen to be high enough that radio waver are not reflected by the ionosphere but pass through it. At the same time, ionospheric absorption gets less as the frequency is increased, so the frequency should not be too high if good measurement resolution is desired. Traditionally, frequencies in the 21 to 40 MHz range have been used. A large number of riometers world wide including the one at HAARP use a common frequency, 30 MHz.

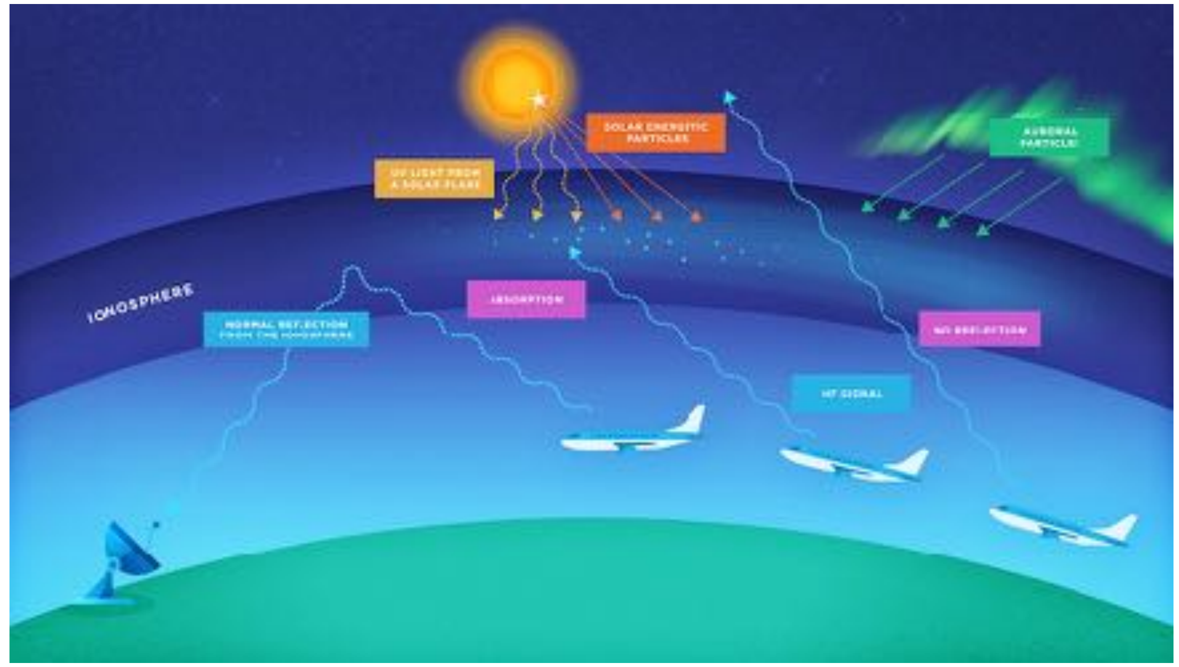
The riometer is intended to measure the ionospheric absorption directly above its location. Medium to high gain antennas pointed at the zenith are used. Such antennas also suppress interfering, man made radio signals that may propagate into the location at low angles.

In operation, the riometer listens to the background cosmic radio noise throughout the day. If that noise is the same as the expected (or quiet day curve) noise, we know that it is not being affected by the ionosphere before it reaches the earth's surface. If the received noise is less than the quiet day curve, we know the ionosphere has absorbed some of the noise signal. The riometer uses a conversion algorithm to calculate an estimate of the amount of absorption thus observed. A simple relation can be used to determine the amount of absorption that would be caused at other frequencies.

How is the riometer used scientifically?

Riometers are most sensitive to ionospheric absorption occurring at altitudes between 50 and 110 km. Absorption at these altitudes can be caused in several ways. During daylight hours, for example, the sun causes ionization in the "D layer" at altitudes near 80 km. This ionization occurs each day throughout the year and is a predictable function of the sun's zenith angle. This regular and periodic absorption is accounted for in the "quiet day curve."
Another type of absorption event is caused by high energy electrons precipitating into the earth's atmosphere from the magnetosphere as a result of a disturbance in the solar wind, for example. The altitude to which these particles penetrate depends on their initial energy. Auroral precipitation, commonly observed at high latitudes, produces absorption at altitudes of 90 - 100 km. Riometers are capable of observing auroral precipitation events that would not necessarily be visible optically.

Absorption events shown by riometers are very frequently (but not always) associated with poor HF sky-wave propagation conditions. When the sun is above the horizon, an energetic solar flare will cause nearly instantaneous increases in the ionization of the D and E layers, producing an abrupt short wave fade-out. Riometers will clearly indicate these transient events that are common during the active portion of the solar cycle.



AA - auroral absorption - precipitating electrons - F-layer
PCA - protons trigger extra ionisation - D-layer
Flare - extra ionisation - D-layer
PSD - ionospheric storm

The ionosphere is a layer at the top of our atmosphere which is ionised due to sunlight (at ultraviolet and x-ray wavelengths). Because the layer is ionised, it has the ability to reflect HF radio waves allowing long distance radio communication, which is crucial for aviation. HF radio waves have frequencies between 3 and 30 MHz.
However, during solar storms, extra energy is deposited into the ionosphere, introducing additional ionisation and irregularities. HF radio waves can be absorbed or reflected in unforeseen ways, causing a radio communication failure. This malfunctioning can happen near the Earth's poles or on the day-light side of the Earth, depending on the sort of solar storm and associated energy input.

A geomagnetic storm disturbs the Earth's magnetic field allowing an increased transport of energy from the magnetotail towards the auroral zones. Typically, a geomagnetic storm is more intense at higher latitudes.
Solar energetic protons can penetrate the Earth at the magnetic poles and cause extra ionisation making radio communication impossible for hours and days. A so-called Polar Cap Absorption is localised near the Earth's magnetic poles and depends on latitude and impacts the lower frequencies of the HF band.
During a solar flare, extra ionising solar radiation indents on the ionosphere on the day-side of Earth and impacts HF communication. The impact of a solar flare lasts as long as the flare, ranging from minutes to hours.
These three space weather storms impact the ionosphere. These impacts are labelled as an 'ionospheric storm' and result in a Post Storm Depression. The parameter used describes in percentages how much the frequency usable for HF radio communication is lowered.

GNSS	Moderate	Severe	Time UTC	Values	Status	Alert	Max-3h values	Max-3h status
Amplitude Scintillation	0.5	0.8	2020-10-12 14:15	0.25	QUIET		0.35	QUIET
Phase Scintillation	0.4	0.7	2020-10-12 14:15	0.13	QUIET		0.14	
Vertical TEC	125	175	2020-10-12 14:15	61.92	QUIET		61.93	QUIET

RADIATION	Moderate	Severe	Time UTC	Flags	Status	Alert	Max-3h flags	Max-3h status
Effective Dose FL≤460	30	80	2020-10-12 14:20	0	QUIET		0	QUIET
Effective Dose FL > 460	/	80	2020-10-12 14:20	0	QUIET		0	QUIET

HF COM	Moderate	Severe	Time UTC	Values/Flags	Status	Alert	Max-3h values	Max-3h status
Auroral Absorption (AA)	8	9	2020-10-12 14:16	3.0	QUIET		3.0	QUIET
Polar Cap Absorption (PCA)	2	5	2020-10-12 14:20	0.00	QUIET		0.00	QUIET
Shortwave Fadeout (SWF)	x1.0	x10.0	2020-10-12 14:17	< M.5-flare	QUIET		< M.5-flare	QUIET
Post-Storm Depression (PSD)	30%	50%	2020-10-12 14:15	0	QUIET		0	QUIET