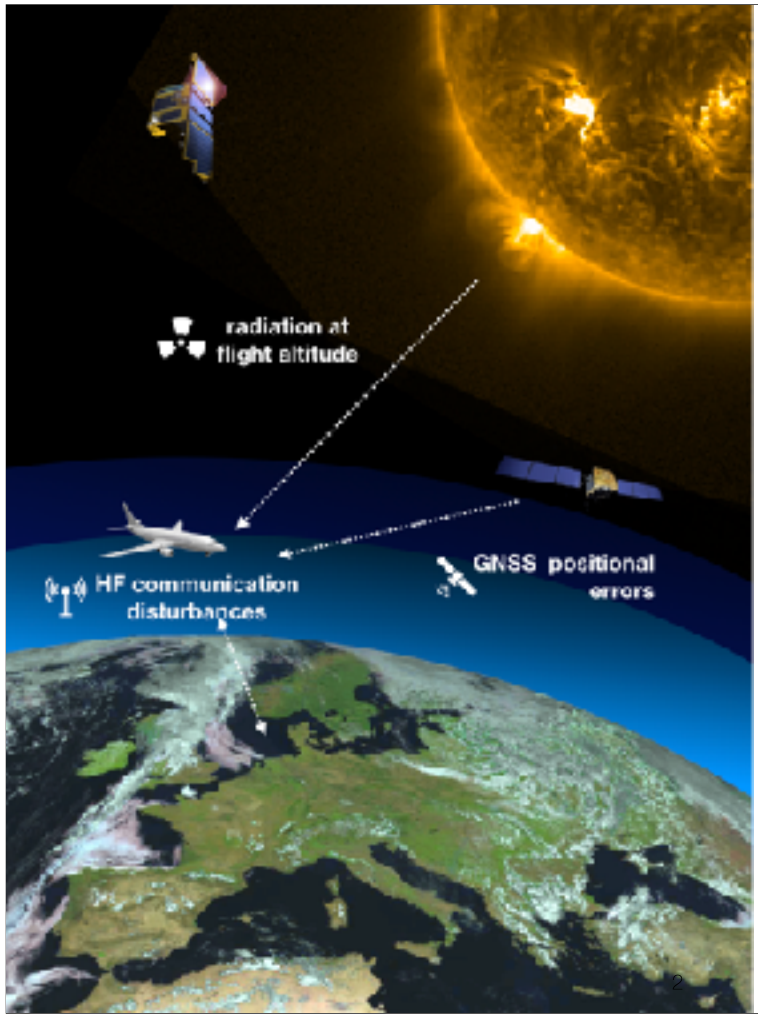
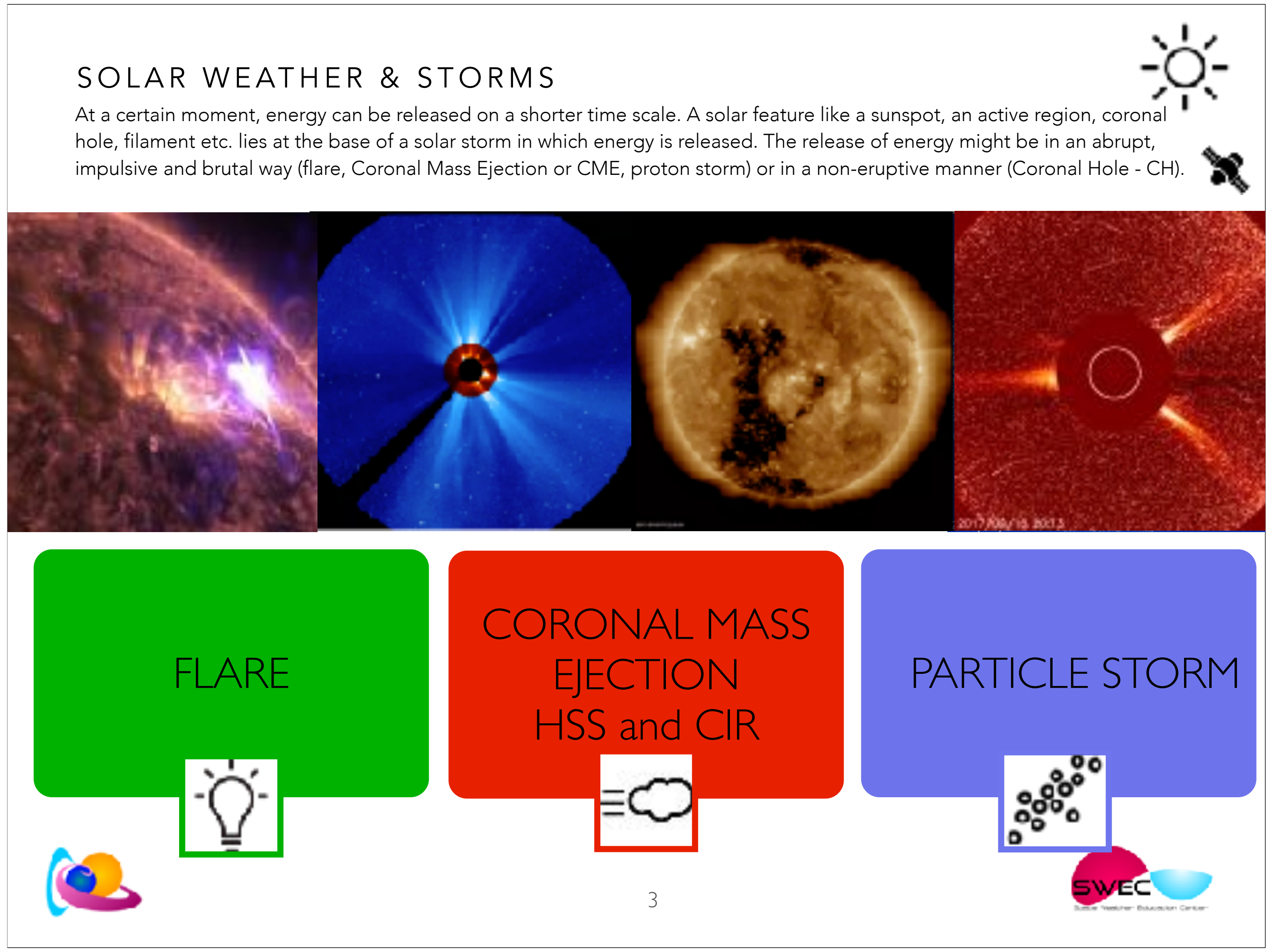
Space Weather impacts on Ionospheric wave propagation
-
Focus on GNSS and HF

Solar-Terrestrial
Centre of Excellence



Impacts on aviation

Petra Vanlommel, Tobias Verhulst,
Christophe Marqué, Ben Witvliet



Change in energy output on the scale of minutes, hours, days.

Remote sensing (seeing) – in situ (taste and touch the ambient space)

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)

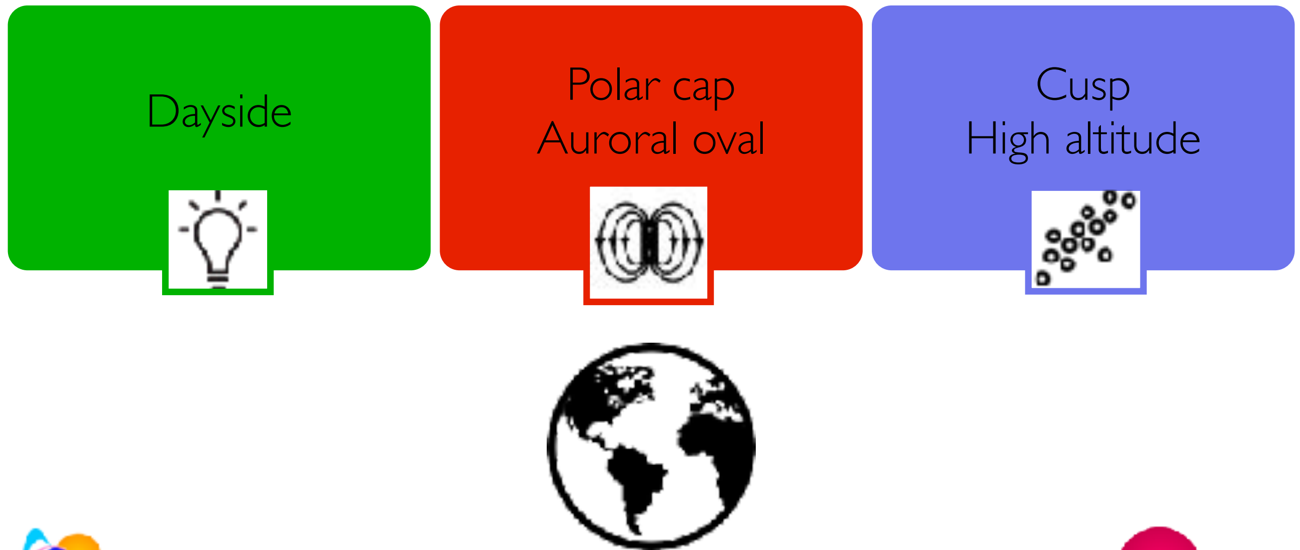
High speed stream and co-rotating interaction regions from coronal holes.
A coronal hole is a structure in the solar corona that you see as a black area in the EUV. It looks black because there is less plasma present that radiates in the EUV. The magnetic field lines are open, i.e. fan out into space. 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

Particle shower
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.

AREA OF IMPACT



Only the box on solar wind is associated with magnetic reconnection, both on the day and night side.
Particles - mainly on the day side.

Services for Aviation In 3 domains

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
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RADIATION	Moderate	Severe	Time UTC	Flags	Status	Alert	Max-3h flags	Max-3h status
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HF COM	Moderate	Severe	Time UTC	Values/Flags	Status	Alert	Max-3h values	Max-3h status
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Post-Storm Depression (PSD)	30%	50%	2020-10-12 14:15	0	QUIET		0	QUIET

…
No impact on the hardware – system itself
But on the transmission – area where the signal passes or on the signal itself

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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=
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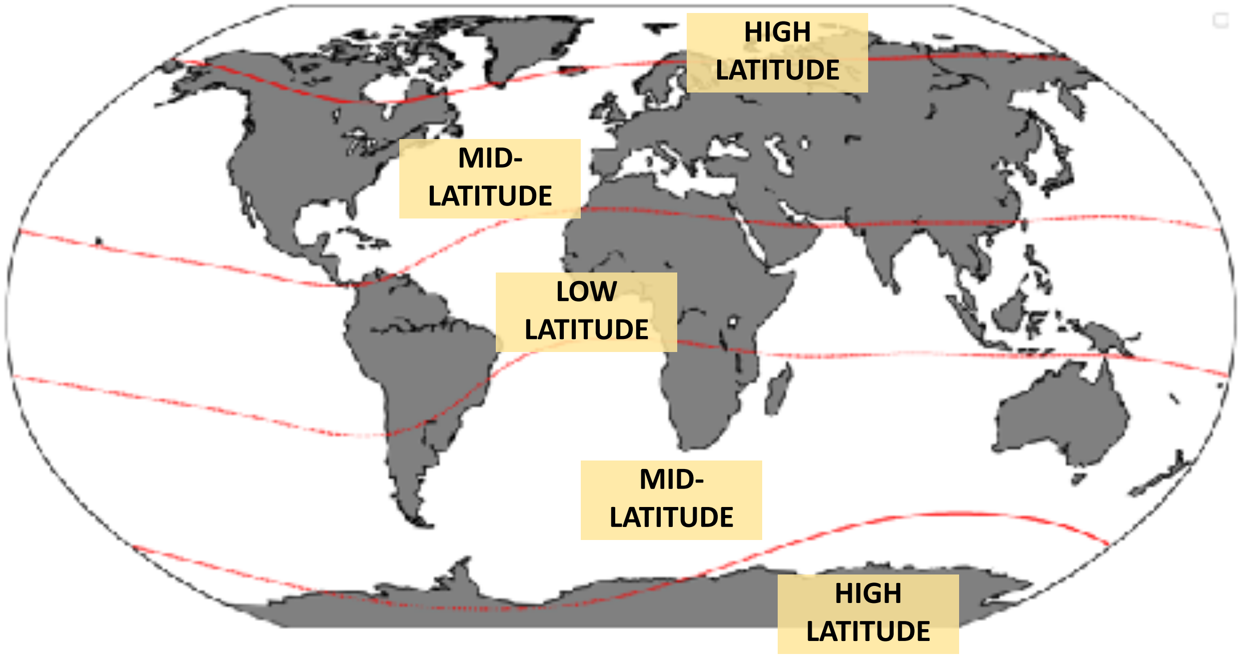
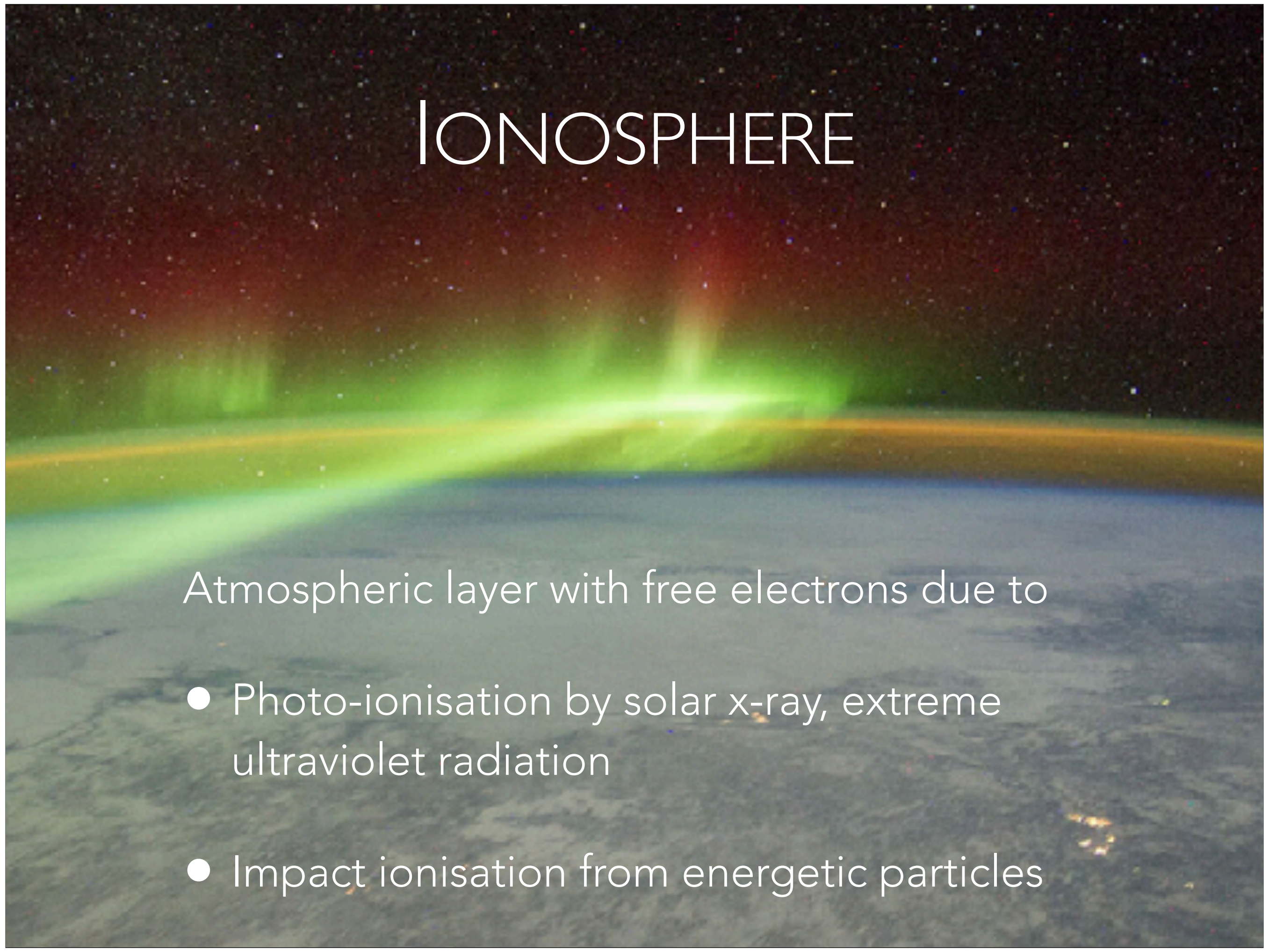
SWXC: PECASUS/SWPC/ACFJ/CRC
Type of advisory - MOD/SEV
Sequence - per domain, across centres - no combined domains
Forecast up to 24hr
Time +impacted area/NO SWX EXP/Not AVBL
Textual explanation: observed or expected impacts on technology, no details on physics, no mitigation actions

THE EARTH'S GRID SYSTEM

- Only the city of New Orleans, La., is located at the crossing of the 30th east-west line north of the Equator and the 90th north-south line west of the prime meridian.
- Lines of latitude cross lines of longitude at right angles.
- Although only a few lines of latitude and longitude are shown on globes and maps, their number is infinite.

GEOGRAPHIC - GEOMAGNETIC





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

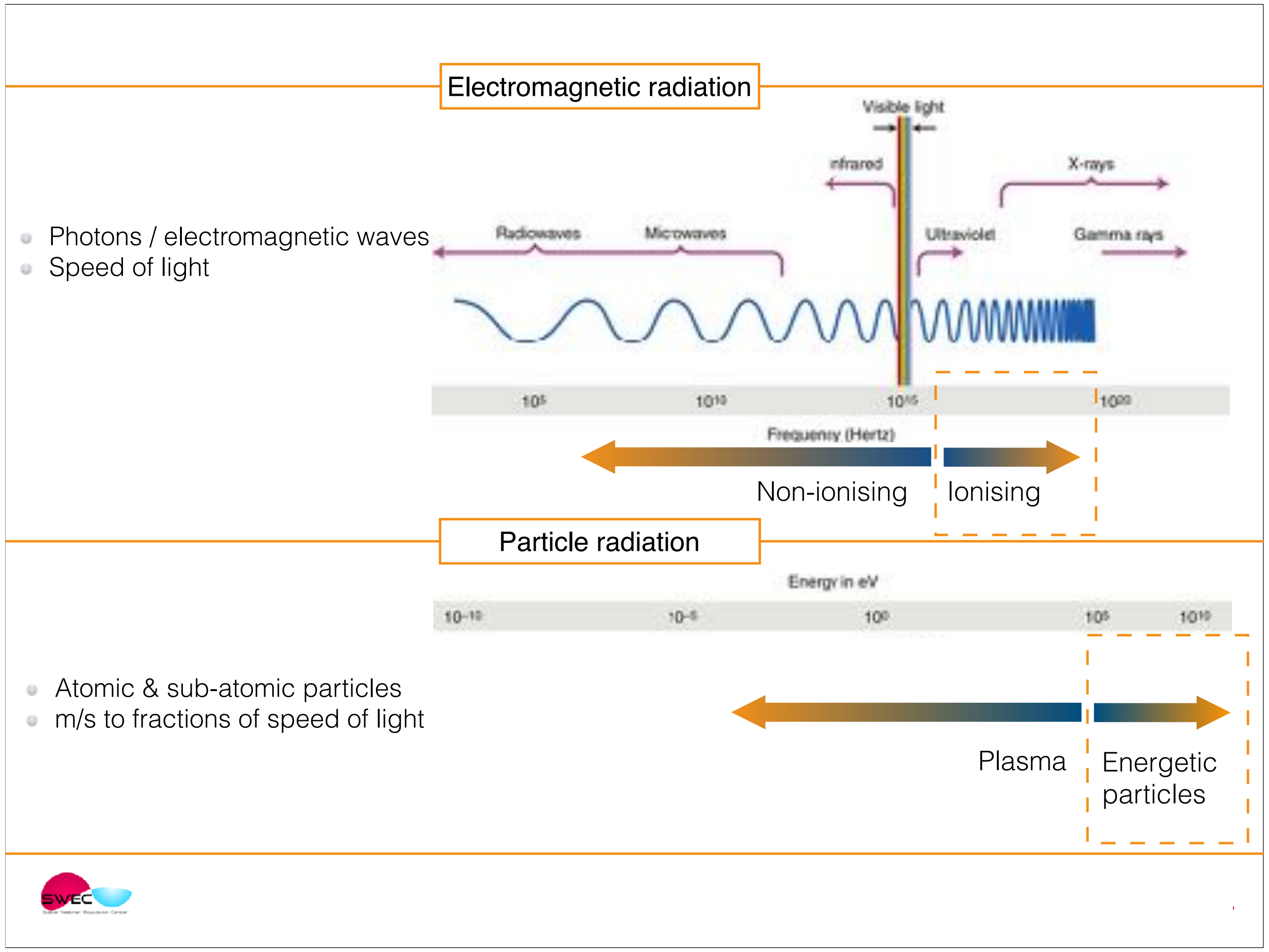
The picture shows the ‘Northern Lights’, seen from the International Space Station. The aurora makes the ionosphere visible to us.

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

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

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

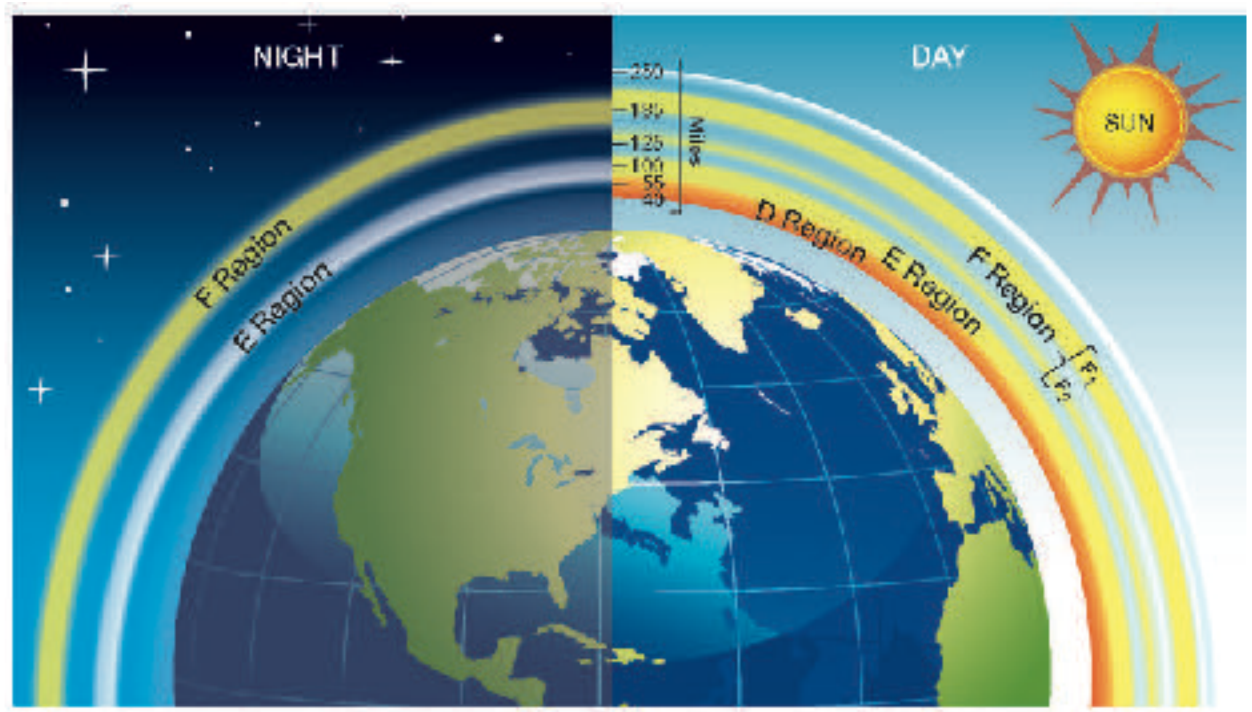
The most accurate way of measuring the ionosphere is with a ground-based ionosonde, which records data as ionograms.



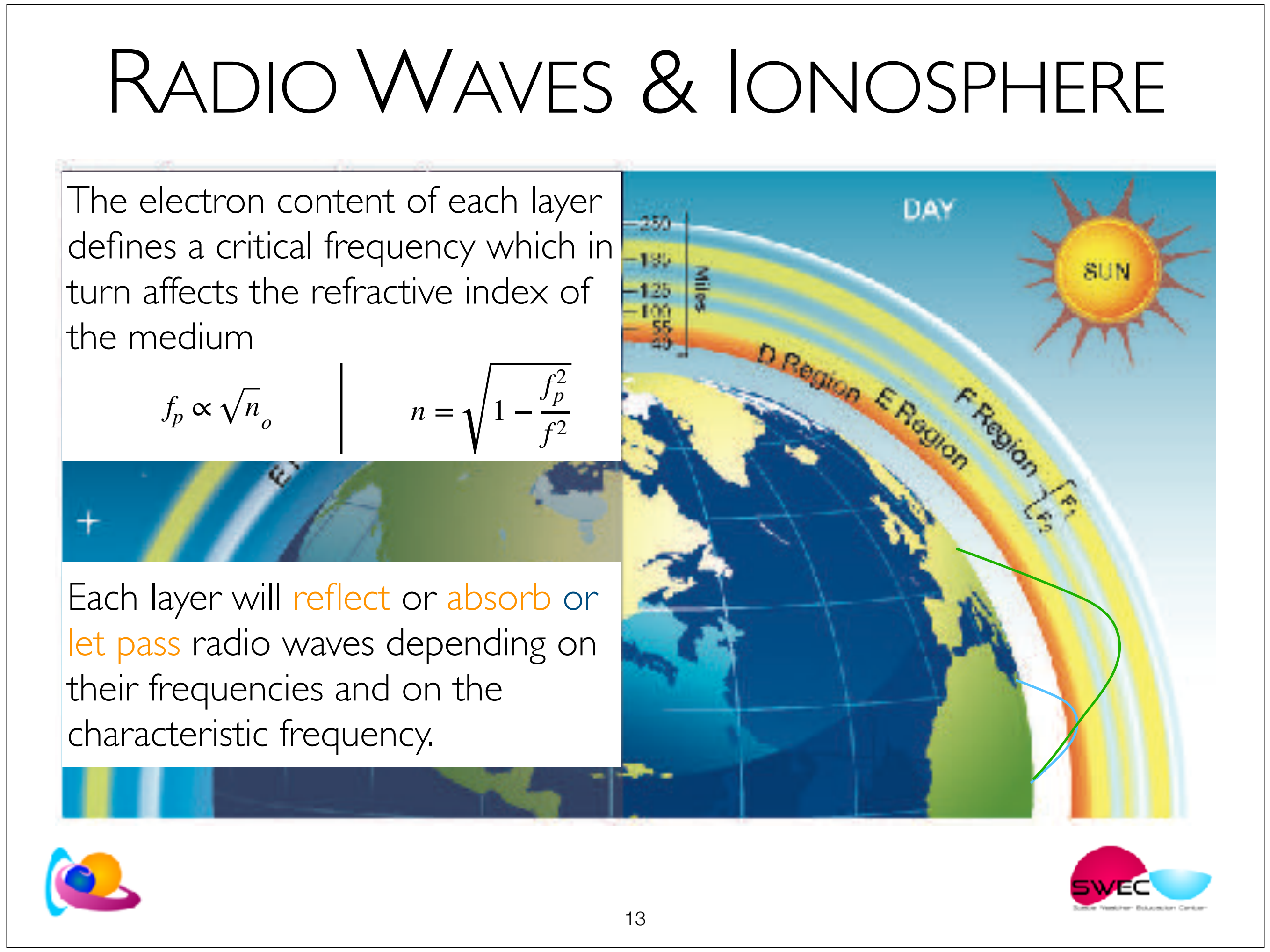
Ionizing radiation is a type of energy released by atoms that travels in the form of electromagnetic waves (gamma or X-rays) or particles (neutrons, beta or alpha). The spontaneous disintegration of atoms is called radioactivity, and the excess energy emitted is a form of ionizing radiation.

Ionizing radiation (or ionising radiation), including nuclear radiation, consists of subatomic particles or electromagnetic waves that have sufficient energy to ionize atoms or molecules by detaching electrons from them.[1] Some particles can travel up to 99% of the speed of light, and the electromagnetic waves are on the high-energy portion of the electromagnetic spectrum.

Gamma rays, X-rays, and the higher energy ultraviolet part of the electromagnetic spectrum are ionizing radiation, whereas the lower energy ultraviolet, visible light, nearly all types of laser light, infrared, microwaves, and radio waves are non-ionizing radiation. The boundary between ionizing and non-ionizing radiation in the ultraviolet area cannot be sharply defined, as different molecules and atoms ionize at different energies. The energy of ionizing radiation starts between 10 electronvolts (eV) and 33 eV.



Both GNSS and HF com use radio waves —> how do radio waves behave in an ionised medium



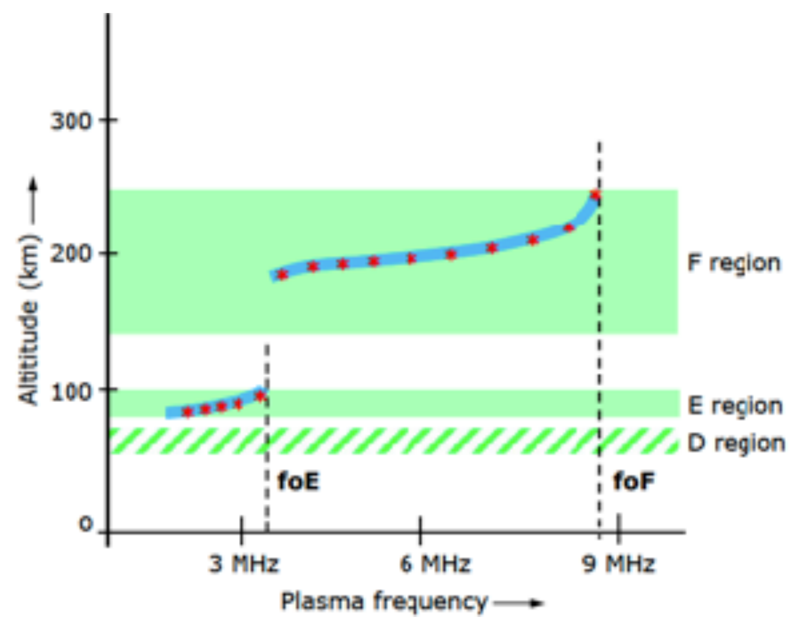
Both GNSS and HF com use radio waves —> how do radio waves behave in an ionised medium

n0, electron content —> critical frequency f0F2 or fp or characteristic frequency—> refractive index
n=c/v
v=c —> n=1
V<c —> n>1

A qualitative understanding of how an electromagnetic wave propagates through the ionosphere can be obtained by recalling geometric optics. **Since the ionosphere is a plasma, it can be shown that the refractive index is less than unity.** Hence, the electromagnetic "ray" is bent away from the normal rather than toward the normal as would be indicated when the refractive index is greater than unity. It can also be shown that the refractive index of a plasma, and hence the ionosphere, is frequency-dependent, see Dispersion (optics).[24]

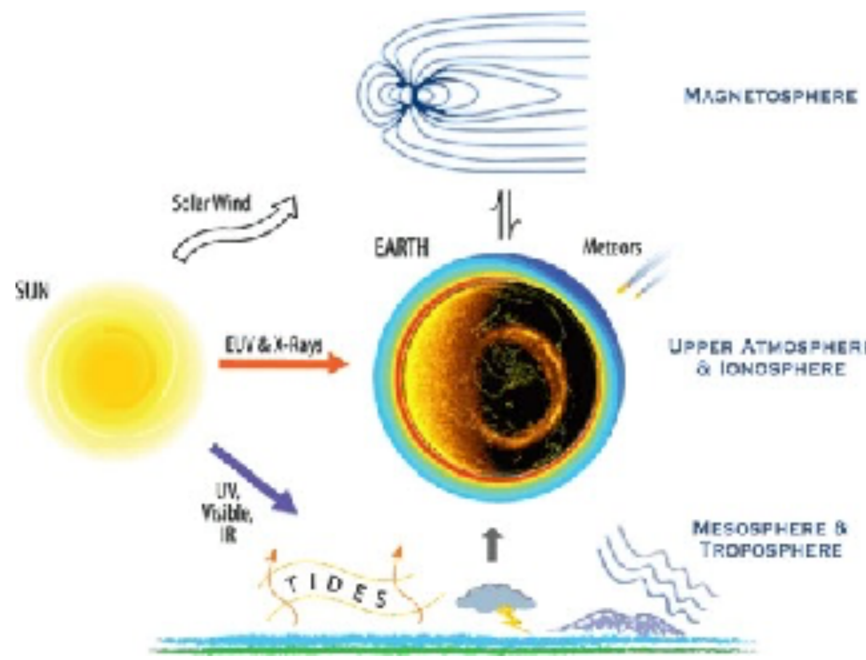
In physics, <u>refraction is the change in direction</u> of a wave passing from one medium to another or from a gradual change in the medium.

f>fp—> passes through ionosphere
f< fp —> reflected by ionosphere —



The plasma frequency varies with height. Because of the typical form of the chapman profile, we have layers in the ionosphere and each layer has a critical frequency (foE, for). Radio waves below the critical frequency are reflected in that specific layer, above can pass through that specific layer.

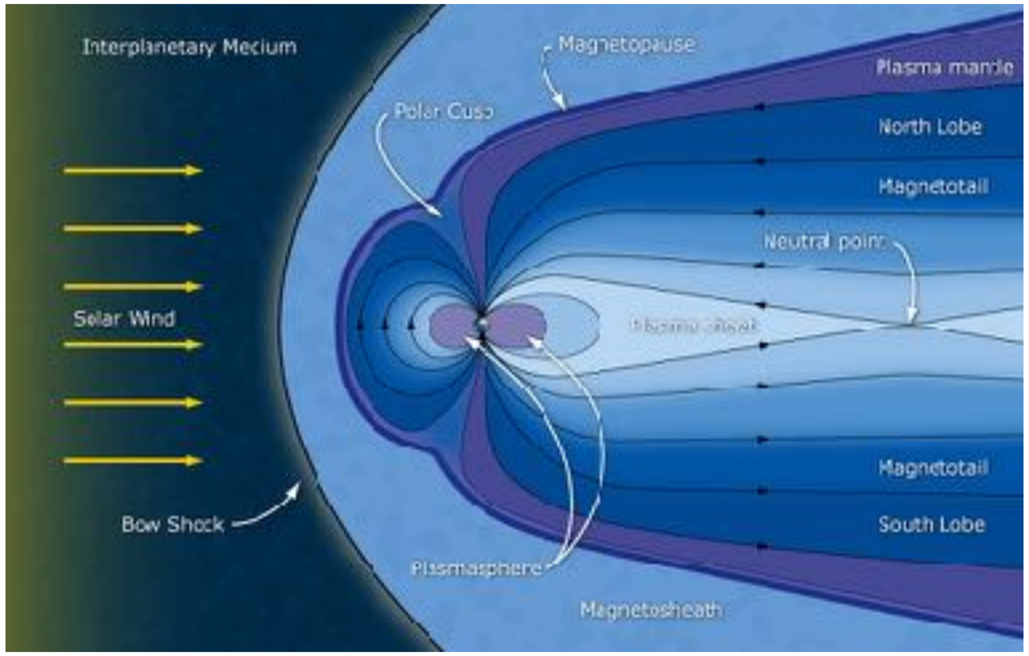
WHICH EXTERNAL SOURCES IMPACT THE IONOSPHERE?



impacts that make the ionosphere variable.

https://doi.org/10.1007/s11214-012-9872-6
In order to illustrate the context of the near-earth plasma within the larger sun-earth system, we depict the main pathways by which energy and momentum are deposited and exchanged within the earth's upper atmosphere in Fig. 1. Here, one path shows how the sun directly influences the upper atmosphere via EUV and X-ray radiation, both via heating of the neutral atmosphere, which results in its expansion, and also via photo-ionization of a small fraction of this same neutral gas which thereby re-generates the ionosphere throughout the day. A second path shows how solar wind processes, including plasma flow with embedded interplanetary magnetic fields, interact with the magnetosphere to drive large-scale electric fields, currents, and energetic particles that subsequently interact with the underlying upper atmosphere/ionosphere. Such solar wind/magnetospheric input impacts the near-earth plasma primarily at high latitudes, although it may dramatically influence all latitudes during periods of magnetic storms. Although the globally averaged energy input by the solar wind/magnetosphere is not as high as the total solar photon irradiance, its impact in the upper atmosphere is nonetheless quite significant, and locally it can be the dominant energy source. The diagram in Fig. 1 also includes a sketch showing that the upper atmosphere is also influenced by energy and momentum sources from below, namely from electrical discharges in the troposphere (lightning) and mesosphere (e.g., sprites), as well as via upward-propagating tides, planetary waves, and gravity waves. Such sources have profound effects on the characteristics of the mid- and low-latitude ionosphere in particular. The energy source that heats and sets in motion the lower and middle atmosphere is, again, solar radiation, but in this case, its ultraviolet, visible, and infrared wavelengths.

Magnetosphere-ionosphere coupling



The solar wind is a magnetized plasma. It encounters the environment of the Earth, which also turns out to be a magnetized plasma. Indeed, the Earth has an internal magnetic field. That field is produced in the Earth's interior. It is changing slowly. (The magnetic poles move with a speed of about 10 km/year.)

The magnetosphere is the region around Earth that is dominated by the geomagnetic field. The magnetospheric plasma originates in part in the ionosphere; the rest is captured solar wind material.

Magnetosphere is a highly dynamical system
https://www.researchgate.net/figure/Structure-of-Earth-magnetosphere-with-magnetopotentials-in-blue-inner-radiation-belt-in_fig3_351130787
Structure of Earth magnetosphere with magnetopotentials in blue, inner radiation belt in green, and outer radiation belt in red.

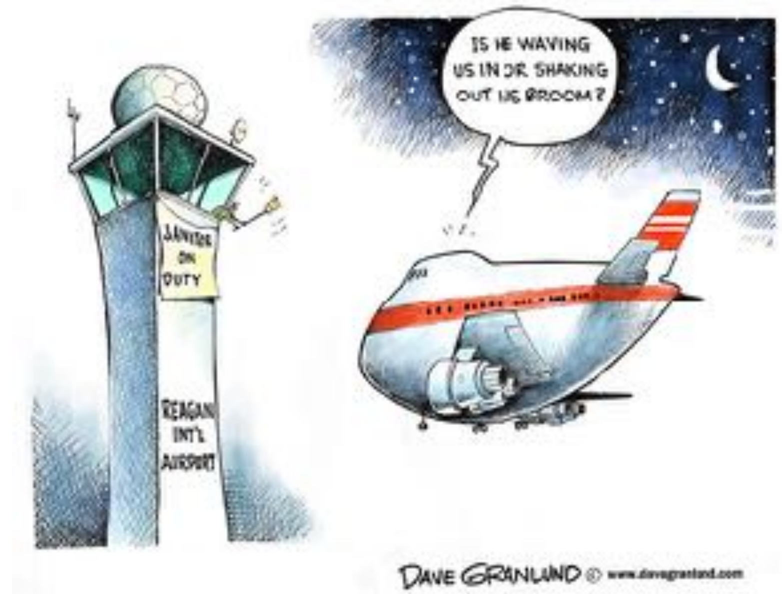
The magnetosphere consists of a (1) bow shock, where the solar wind (the stream of protons from the Sun) is slowed; (2) the magnetosheath behind the bow shock that contains thermalized solar plasma; (3) the magnetopause, where the thermalized solar plasma pressure is balanced by the plasma pressure generated by the magnetosphere; (4) the magnetotail, where the magnetic field is stretched out by the solar wind behind the dipole; and (5) the plasmasphere, where plasma is trapped by the magnetic field. The radiation belts are formed in the plasmasphere of the Earth's magnetosphere.

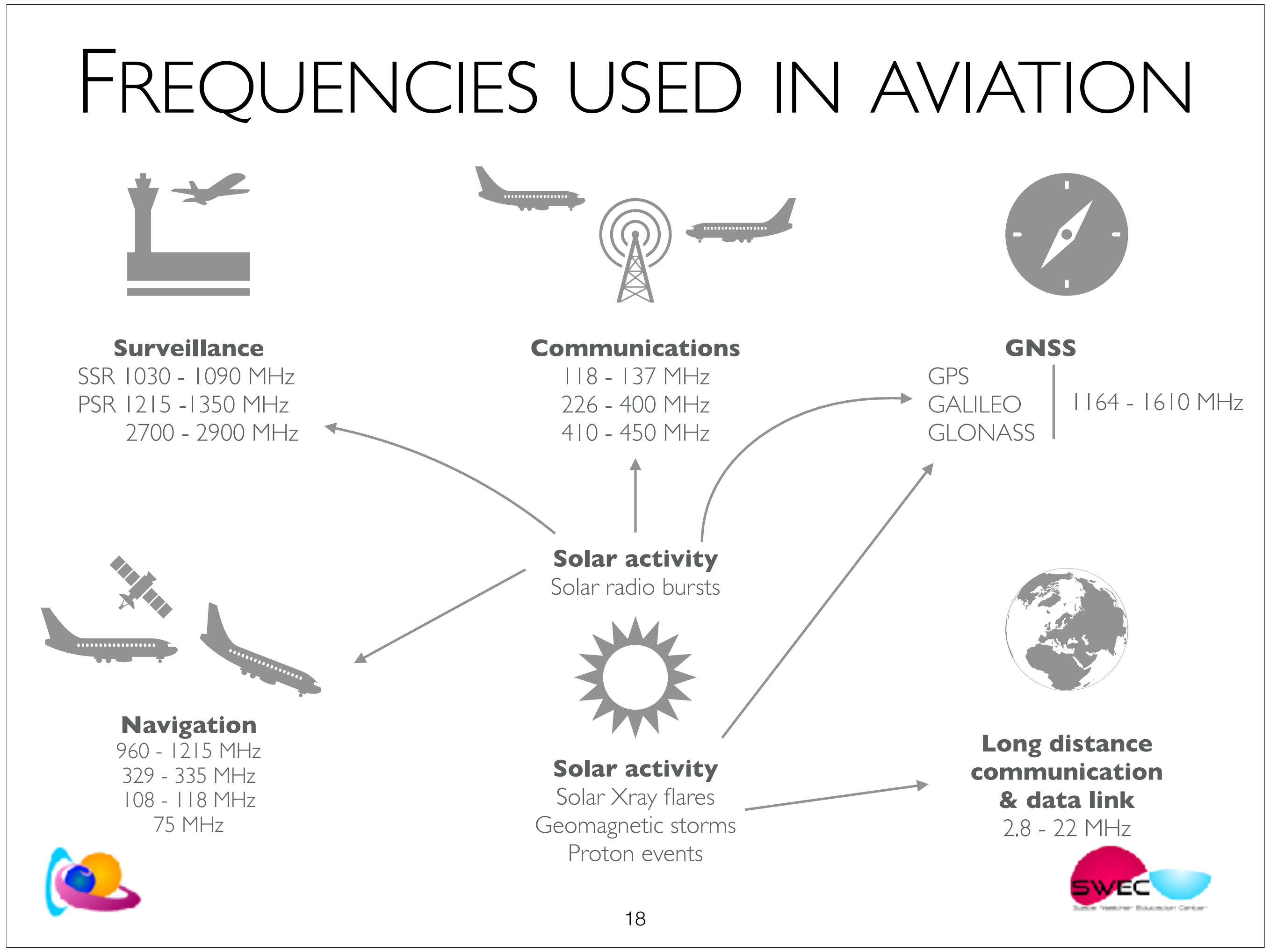
When the plasma up above is caused to move, magnetic field lines communicate this motion down to the ionosphere as if they were pieces of string tying the different plasma regions together.

Charged particles can move rather freely along field lines and therefore are good electric conductors. Electric currents flow along the field lines and connect magnetosphere and ionosphere. Therefore every electric feature in the magnetosphere has an "image" in the ionosphere, and conversely. We identify the following regions:

- Magnetopause ↔ footpoints of the cusps
- Tail lobes ↔ polar caps
- Plasma sheet ↔ auroral oval
- Plasmasphere ↔ ionosphere at low latitude

Frequencies used in aviation





<u>Long Distance Communication & data link</u>

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.

<u>Navigation</u>

<u>https://en.wikipedia.org/wiki/Air_navigation</u>

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

<u>Communication</u>

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]

<u>Navigation</u>

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]

<u>Surveillance</u>

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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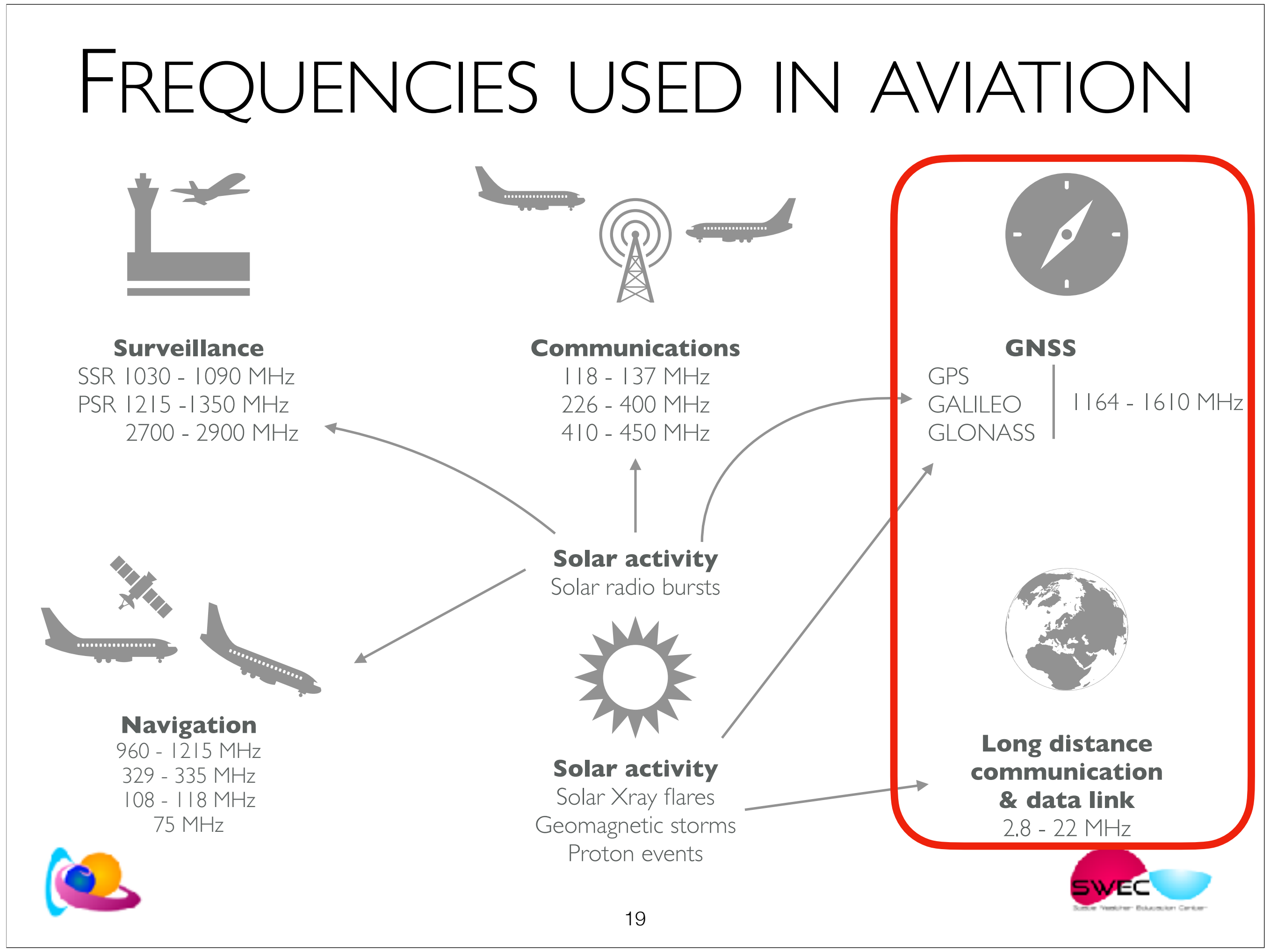
https://www.swpc.noaa.gov/impacts/hf-radio-communications

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.



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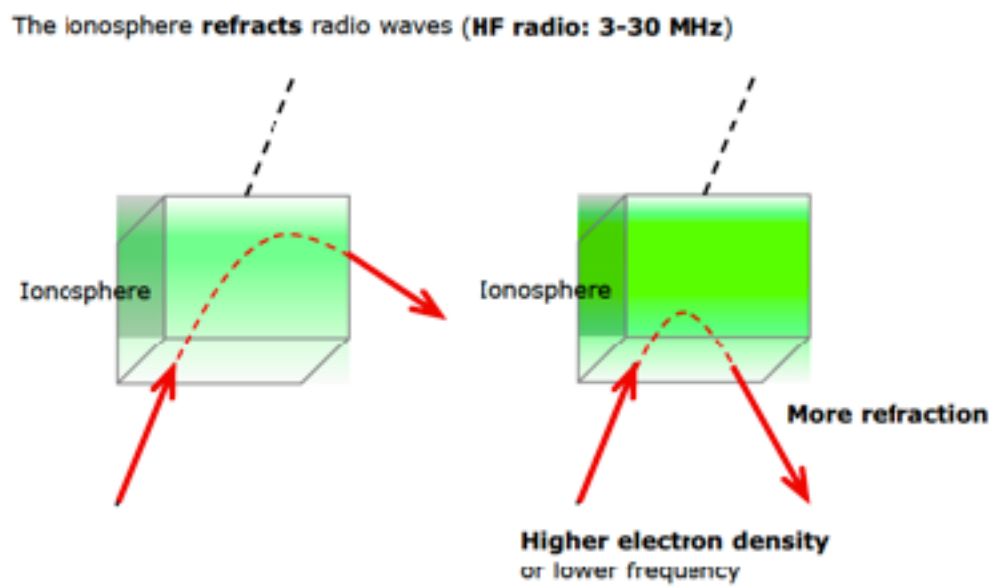
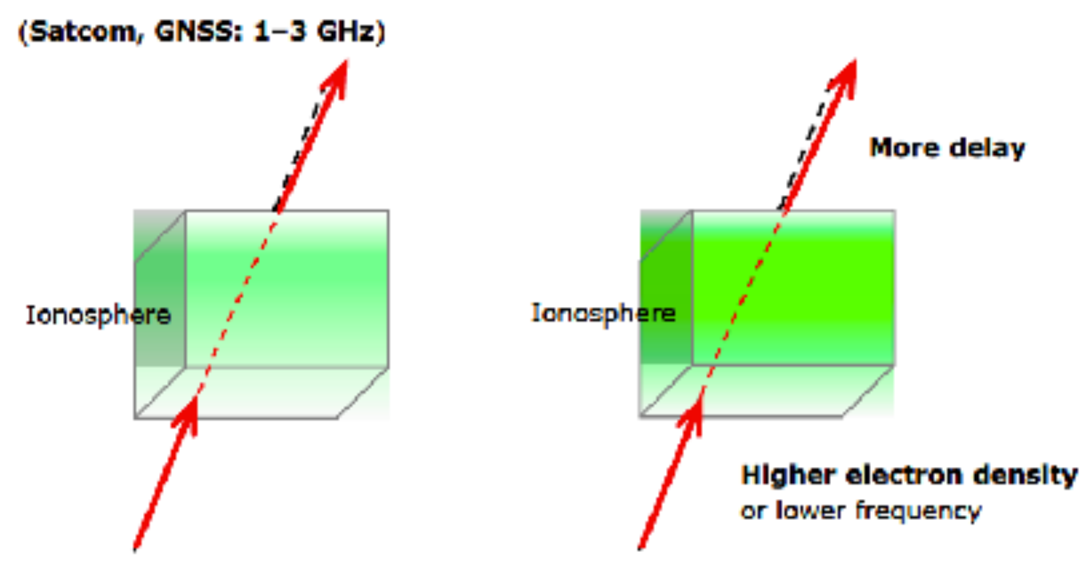


we look at HF radio
We have seen that vertical waves at frequencies below the maximum plasma frequency are reflected. But also waves that enter the ionosphere at an angle will be bent back to earth, up to approximately 3x the maximum plasma frequency. Typically, these frequencies are below 30 MHz. On rare occasions frequencies up to 150 MHz are reflected.



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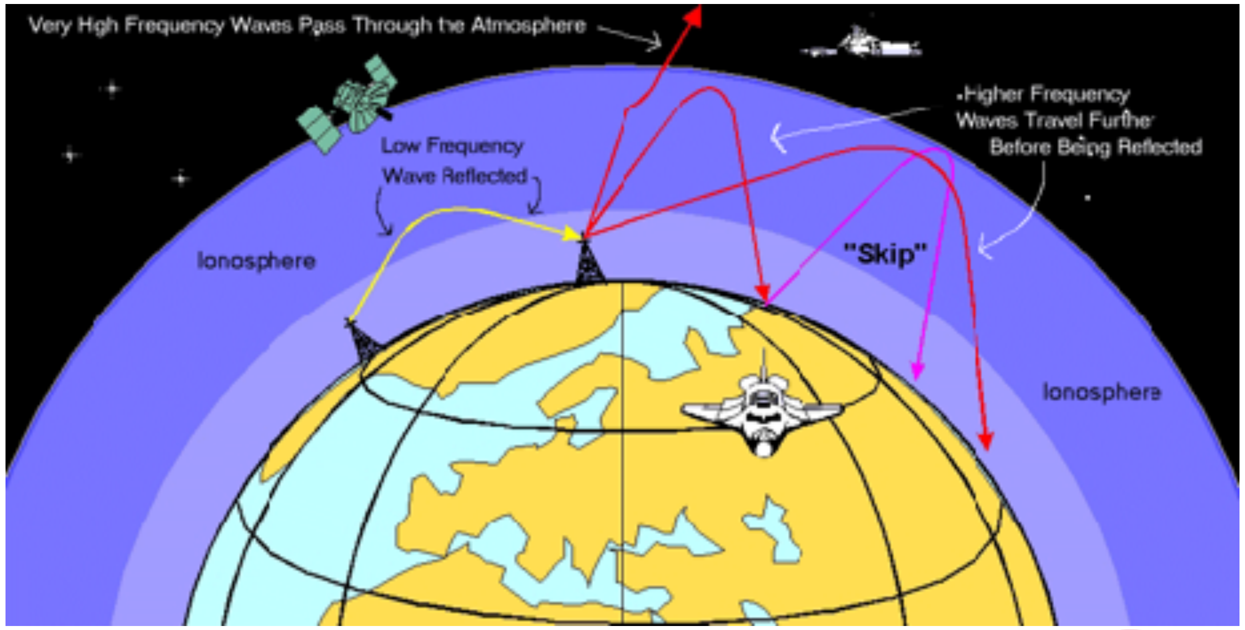
At still higher frequencies, the radio waves do not longer deviate much from a straight line, just a little bit. However, there is still a delay, which depends on (again) the electron density and the frequency.
The examples are all shown with signals going upward, but the explanations also hold for downward signals.

RADIO WAVES & IONOSPHERE

The ionosphere is the key-layer for HF communication and GNSS performance: or radio waves are reflected at, or pass through the ionosphere. The reflection is used for long distance communications.

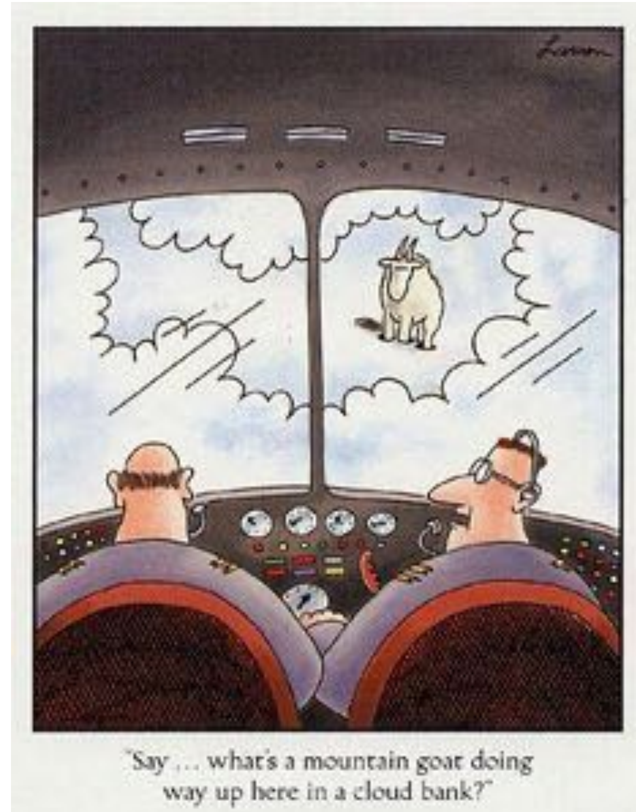


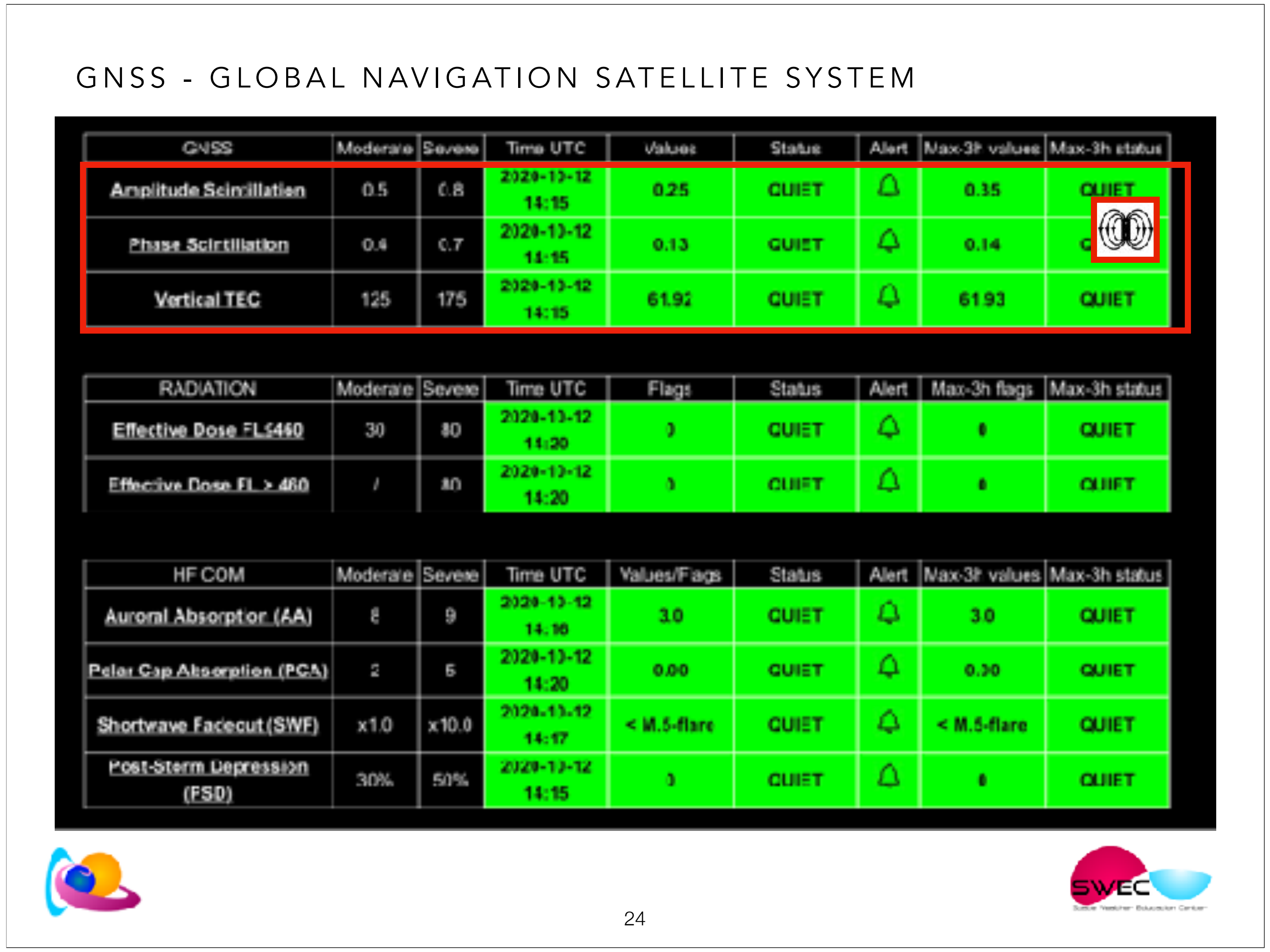
The ionosphere has the ability to reflect radio waves. If the degree of ionisation would be zero, no radio waves would be reflected and all would pass.

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

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

PECASUS DASHBOARDS





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

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

One of the largest sources of error in Positioning Navigation and Timing (PNT) signals from GNSS satellites is due to the passage of the satellite signal through the relatively dense electron environment of the upper atmosphere. These errors are compensated for by GPS receivers that use an ionospheric delay correction model. During ionospheric storms, or periods where the ionosphere deviates significantly from normal conditions, these models may be inadequate and lead to uncorrected positioning errors. Precision navigation systems that autocorrect for the ionosphere, such as differential GPS, or GPS augmentation systems such as the Satellite-Based Augmentation System (SBAS) or Ground-Based Augmentation System (GBAS) are still susceptible to errors during severe ionospheric storms. GNSS positioning is also susceptible to interference from solar radio bursts in the ultra-high-frequency (UHF) range, leading to significant loss of satellite tracking for up to tens of minutes in severe cases.

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.

https://www.swpc.noaa.gov/phenomena/solar-radiation-storm

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Solar Radiation Storms cause several impacts near Earth. When energetic protons collide with satellites or humans in space, they can penetrate deep into the object that they collide with and cause damage to electronic circuits or biological DNA. During the more extreme Solar Radiation Storms, passengers and crew in high flying aircraft at high latitudes may be exposed to radiation risk. **Also, when the energetic protons collide with the atmosphere, they ionize the atoms and molecules thus creating free electrons.** These electrons create a layer near the bottom of the ionosphere that can absorb High Frequency (HF) radio waves making radio communication difficult or impossible.

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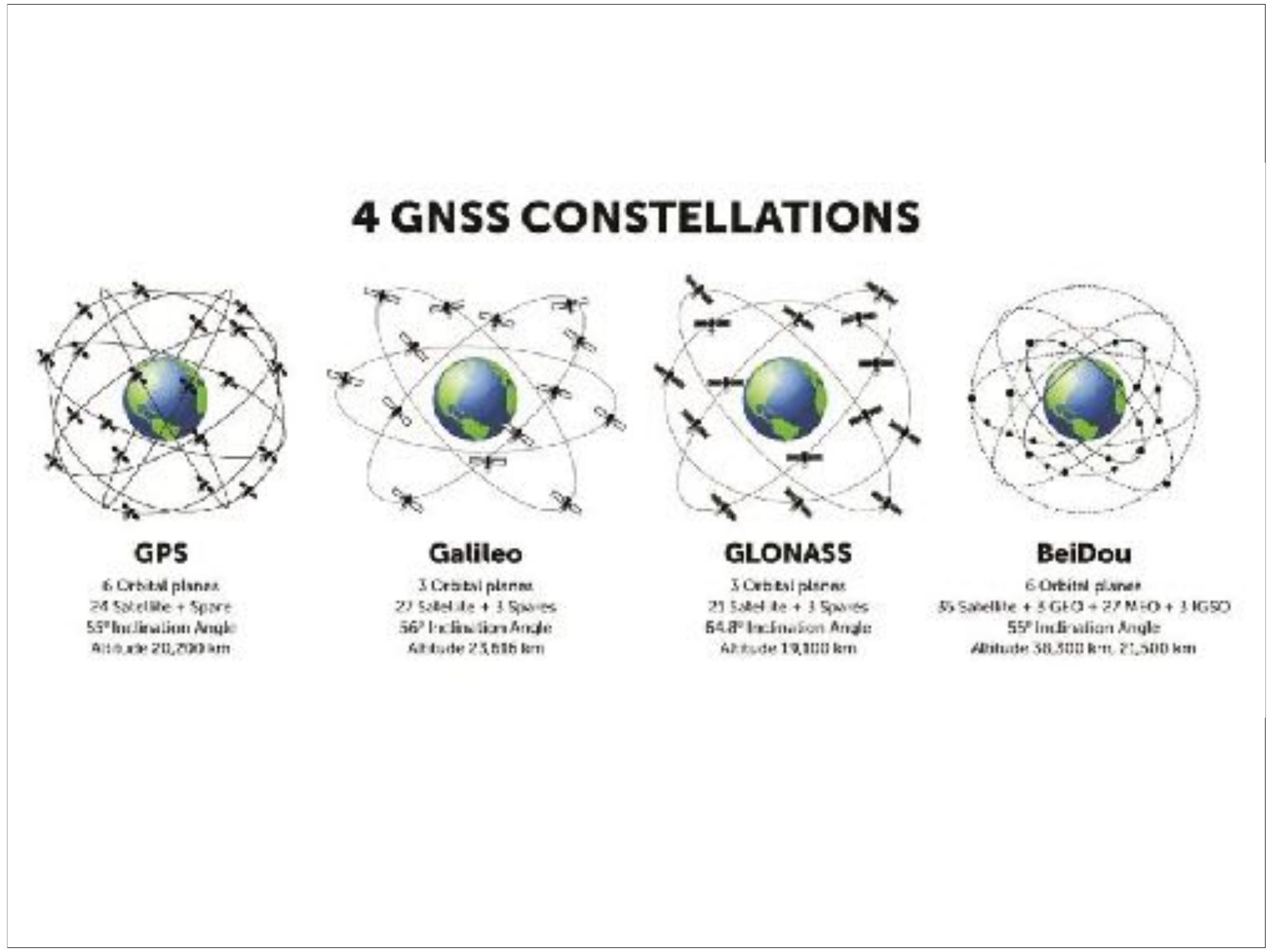


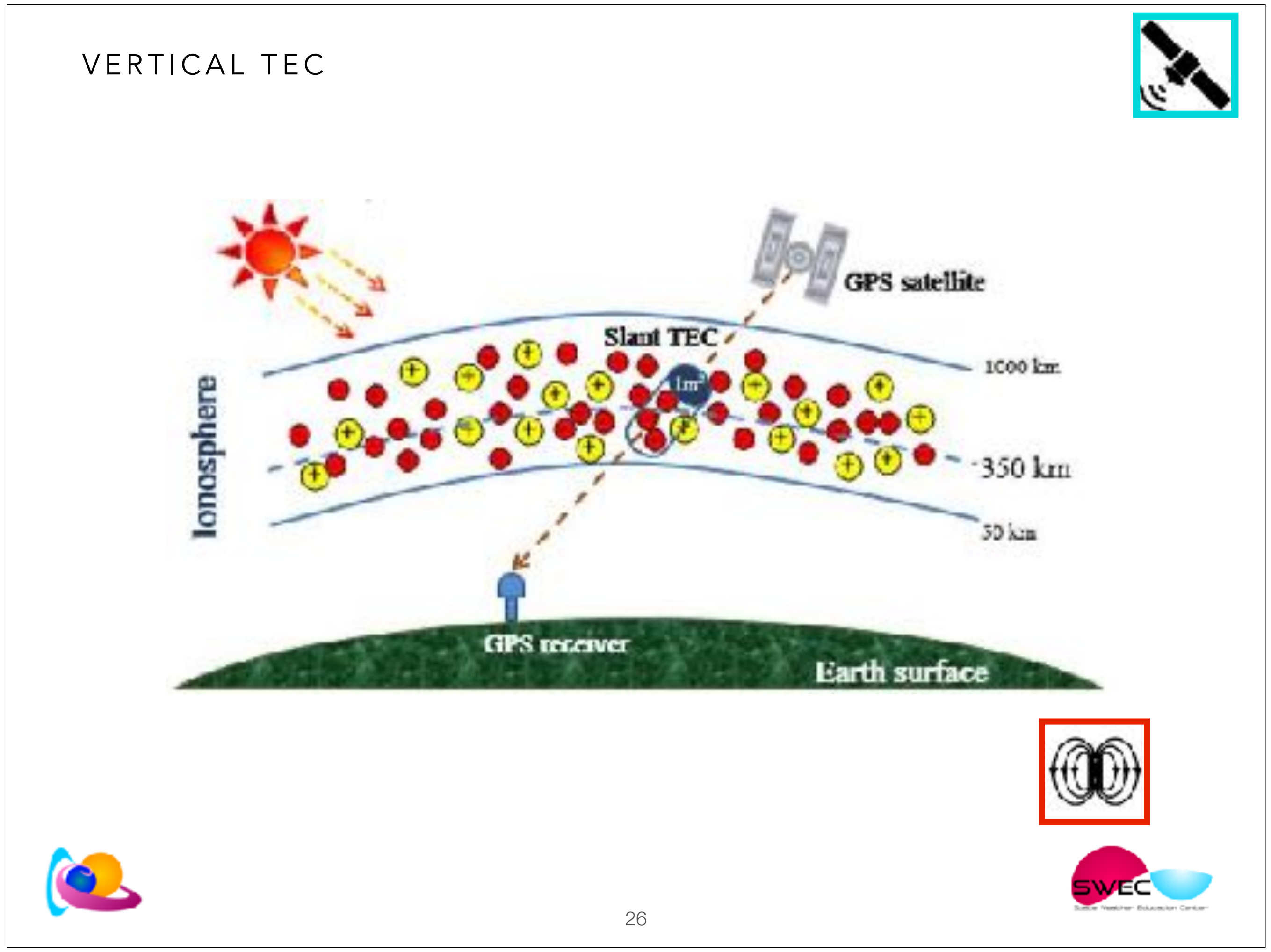
GNSS satellites : MEO - Medium Earth Orbit
Galileo 23616 km - in the outer radiation belt

GNSS satellites are placed in a medium Earth orbit (MEO) of around 20,000 km which means they circle the earth approximately every 12 hours.

Impact on the satellite itself
Impact on the area where the signal has to pass - ionosphere
Mimic the signal —> SRB

GPS: VS
Galileo: EU
GLONASS: Rusia
Beidou: China
Global systems

Low power signal with very high frequency —> need for LOS



Change in the path and velocity.

VTEC defines the refractive index. In physics, refraction is the change in direction of a wave passing from one medium to another or from a gradual change in the medium.

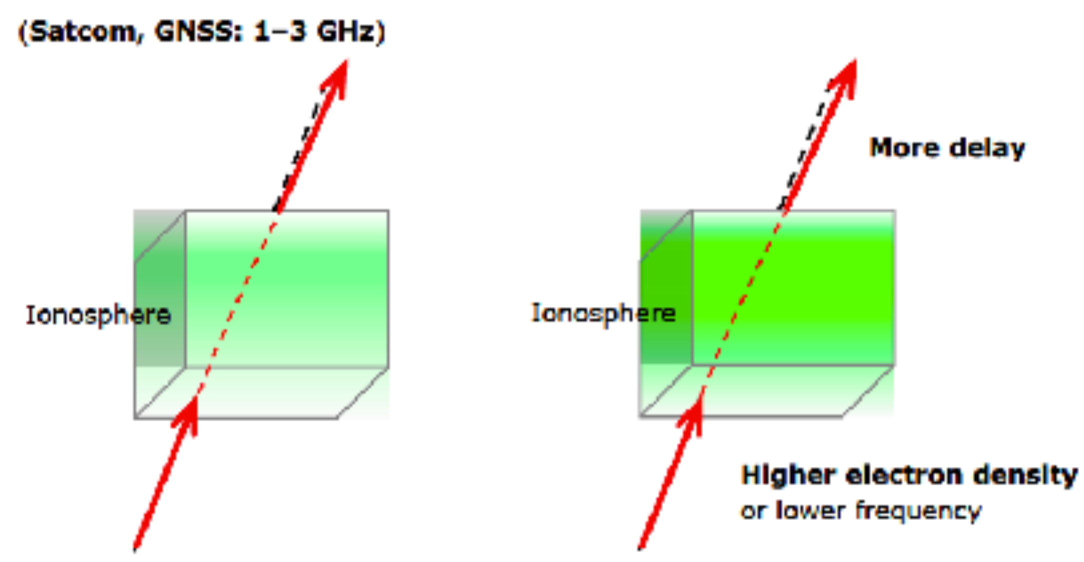
http://www.trimbleionoinfo.com/Library/IonosphericEffects.htm
Ionospheric Signal Delay
An important descriptive quantity in describing the effect of the ionosphere on the GNSS signal is the total electron content (or TEC). TEC is the total number of electrons present along a path between the satellite 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

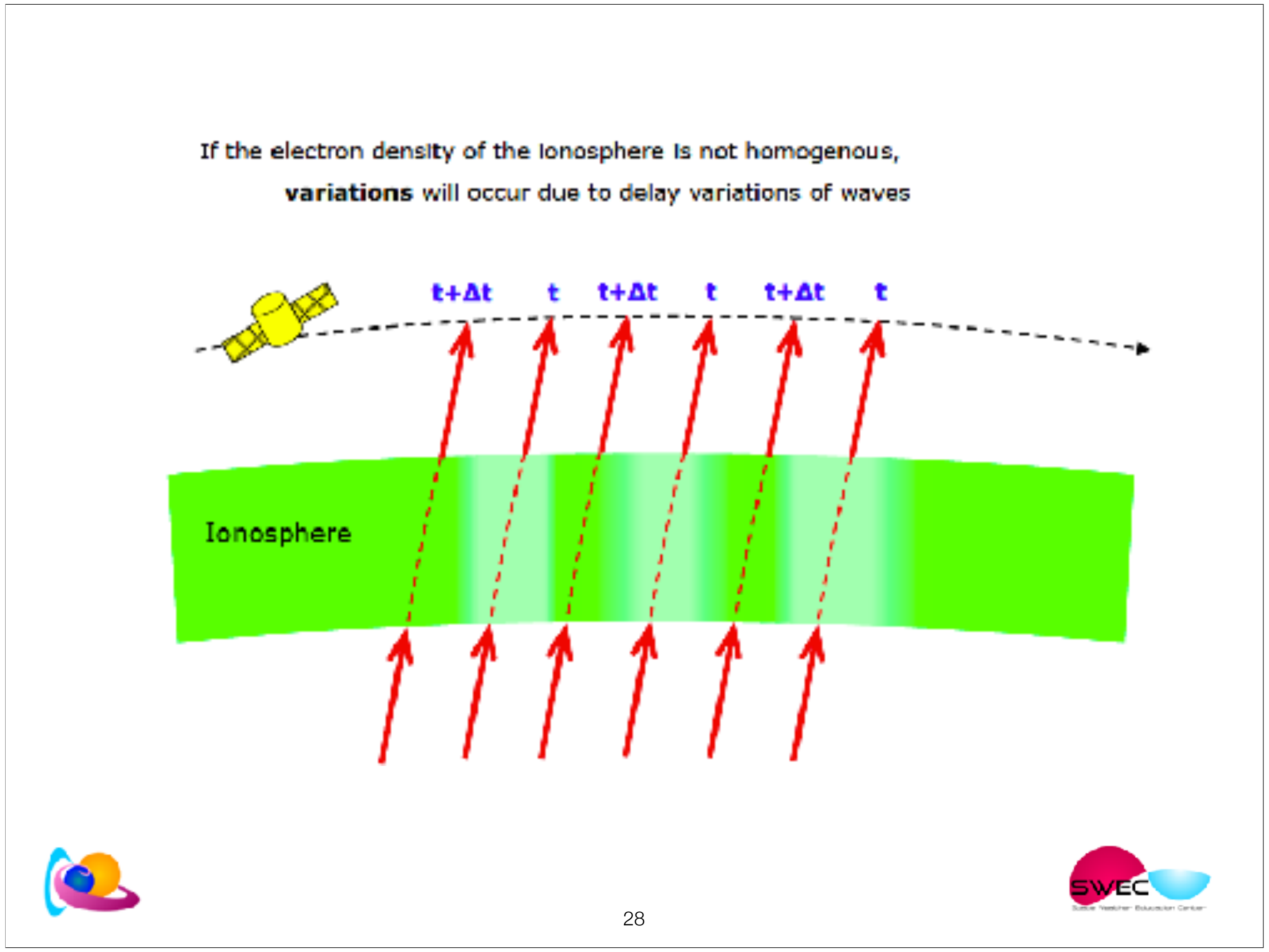
lower atmosphere. The TEC will therefore depend on local time, latitude, longitude, season, geomagnetic conditions, solar cycle and activity, and troposphere conditions. The propagation of radio waves is affected by the ionosphere. The velocity of radio waves changes when the signal passes through the 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



At still higher frequencies, the radio waves do not longer deviate much from a straight line, just a little bit. However, there is still a delay, which depends on (again) the electron density and the frequency.

The examples are all shown with signals going upward, but the explanations also hold for downward signals.



So far, we assumed a stable and predictable ionosphere. That is not always the case. At high frequencies, were there is only a little refraction, the delay imposed on radio waves may still be important. When – either due to the movement of the satellite or due to traveling ionospheric disturbances - the radio signals travel through dense and underdens sections of the ionosphere, a variation in path delay will occur. As a result, a satellite moving about or through an inhomogeneous ionosphere will receive the signal, but with rapid variations superimposed on it.

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

The examples are all shown with signals going upward, but the explanations also hold for downward signals. The upward case is easier to draw and explain without resorting to more complex animations.

IONOSPHERIC SCINTILLATION

What

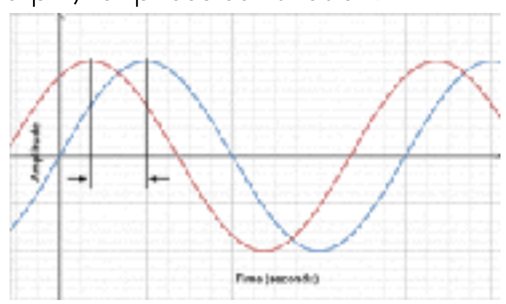
Ionospheric scintillation is the rapid modification of radio waves caused by small scale structures in the ionosphere. Scintillation of radio waves impacts the power and phase of the radio signal. Scintillation is caused by small-scale (tens of meters to tens of km) structures in the ionospheric electron density along the signal path and is the result of interference of refracted and/or diffracted (scattered) waves.

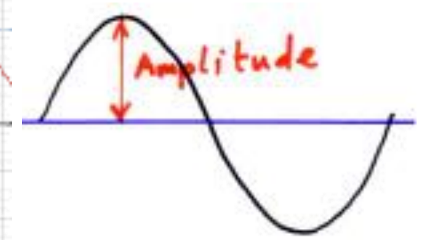
Consequences

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.

What to monitor

Scintillation is usually quantified by two indexes: S4 for amplitude scintillation and σϕ (sigma-phi) for phase scintillation.





Measured by a receiver

———————-

NO change of path or speed — NO Refraction

————-

S4 is a normalised standard deviation of C/NO = carrier-to-noise ratio

The S4 index is defined as the normalized ratio of the standard deviation of signal intensity fluctuations to the mean signal intensity

S4^2=(<I^2>-<I>^2)/<I>^2

—————

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.

——

induced 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.

****

Ionospheric scintillation is the rapid fluctuation of the power and/or phase of radio signals passing through the ionosphere. Scintillation occurs when a radio frequency signal, up to a few gigahertz (GHz), passes through a region of small-scale irregularities in the ionospheric electron density. The effect can be compared to the twinkling of stars as their light passes through the earth's atmosphere.
Scintillation occurs primarily in the equatorial region of the earth (+/- 20° latitude) between dusk and midnight. This is due to large electron density depletions known as Equatorial Plasma Bubbles in the ionosphere above those areas. Scintillation can also occur in high-latitude regions. Scintillation effects are most significant in L-band SATCOM and SATNAV applications where GHz-frequency signals travel through the ionosphere. For SATNAV, the rapid signal fluctuations impede the ability of GNSS receivers to track signals from individual GNSS satellites. This results in fewer satellites available for positioning and reduces positioning accuracy. In the worst-case scenario, scintillation can result in a complete loss of GNSS positioning for up to tens of minutes. For SATCOM, scintillation can result in reduced signal-to-noise ratio and poor communication quality.

Scintillation mechanisms

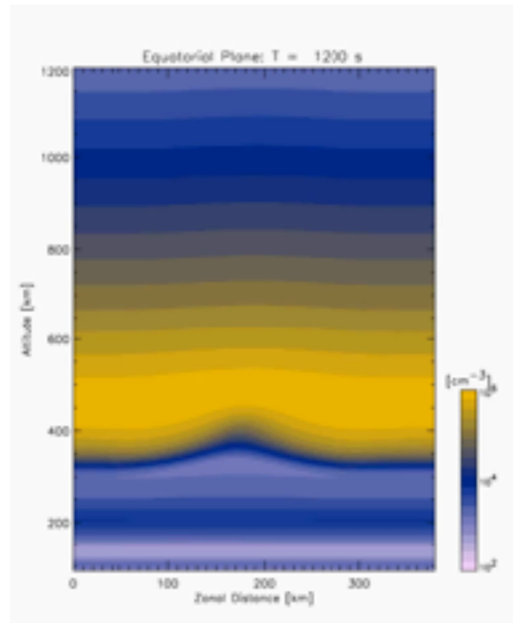
1. Post-sunset Plasma Bubbles at lower latitudes
2. Structures in the auroral oval
3. Patches in the polar caps
4. Travelling ionospheric disturbances

The four mechanisms that give rise to scintillation are

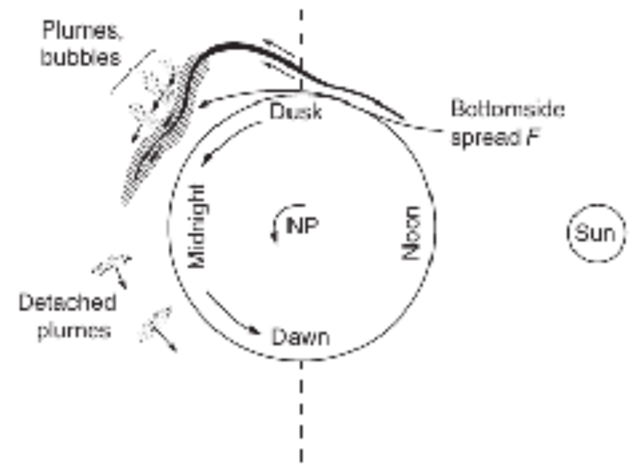
- Plasma bubbles (in the lower latitudes)
- Precipitating particles (auroral oval)
- Patches in the polar caps
- Travelling ionospheric disturbances

All three happen more or less depending on the circumstances, but plasma bubbles happen most of the days.

Scintillation mechanism 1: equatorial plasma bubbles



https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014JA020708

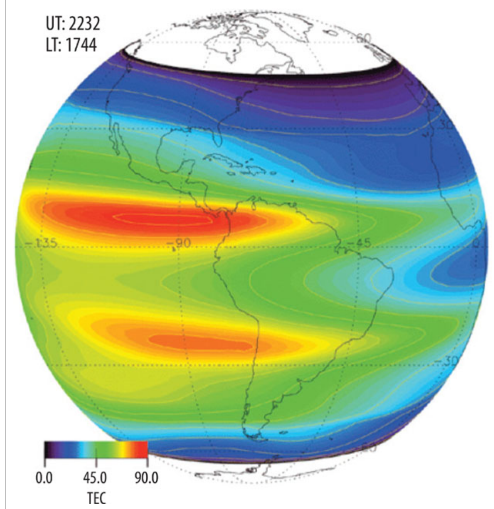


Post sunset - solar cycle dependent

Empty bubbles
Rise up and come in a region with more plasma
Move to the east, towards midnight

Plasma bubbles are formed at Rayleigh–Taylor instabilities when the lower ionosphere rapidly recombines **after dusk, creating very strong electron density gradients**. They form below hmF2 and **rise to over 700 km, while drifting eastward.**

Large gradient due to Equatorial ionisation anomaly



Pfaff, 2012, The Near-Earth Plasma Environment

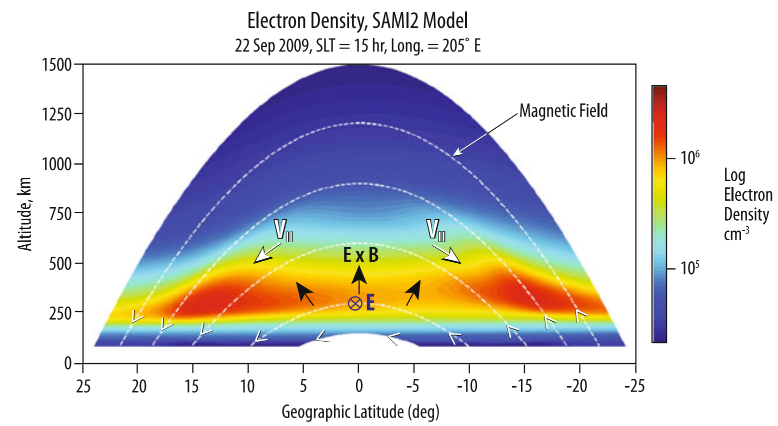
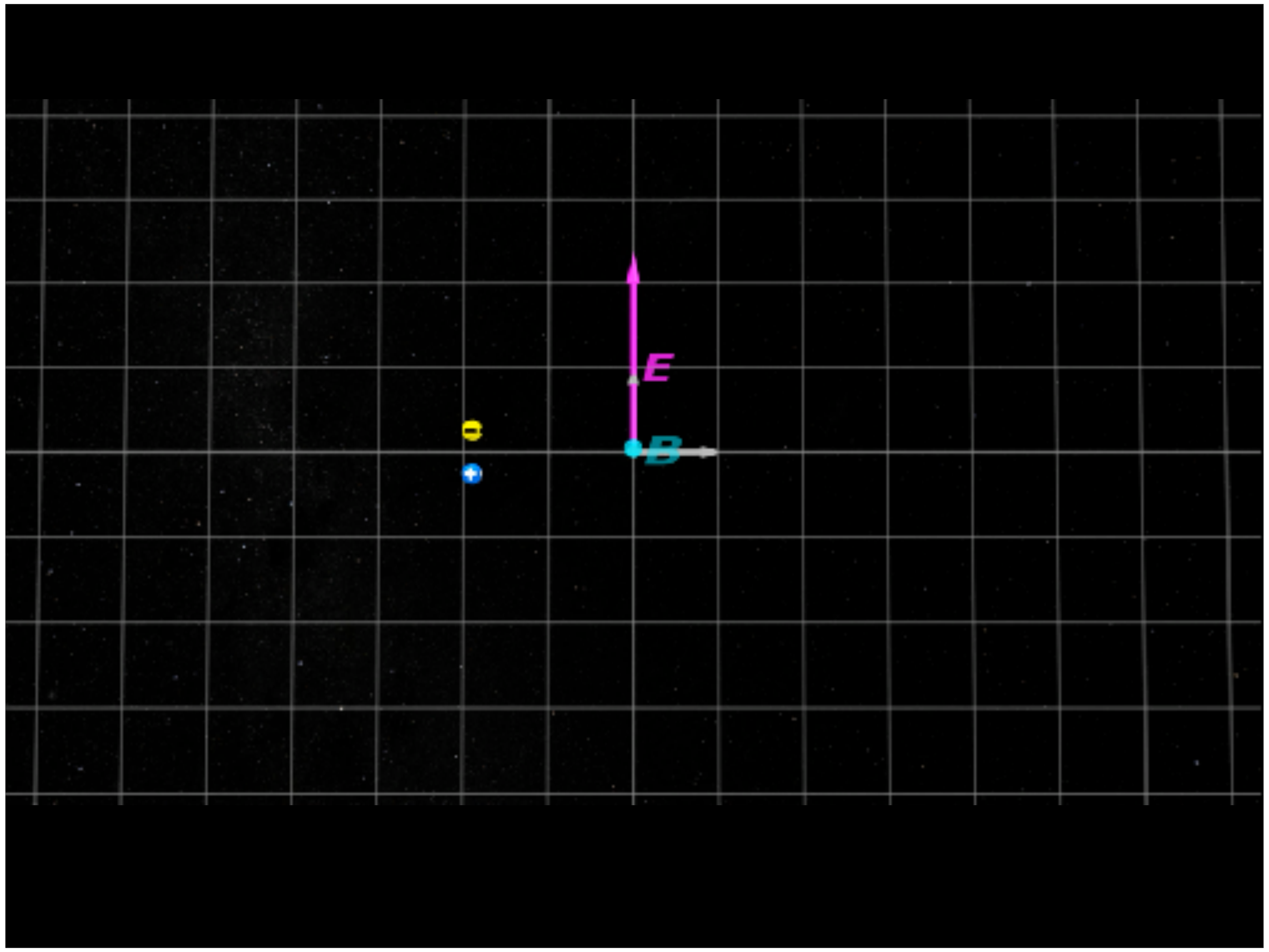


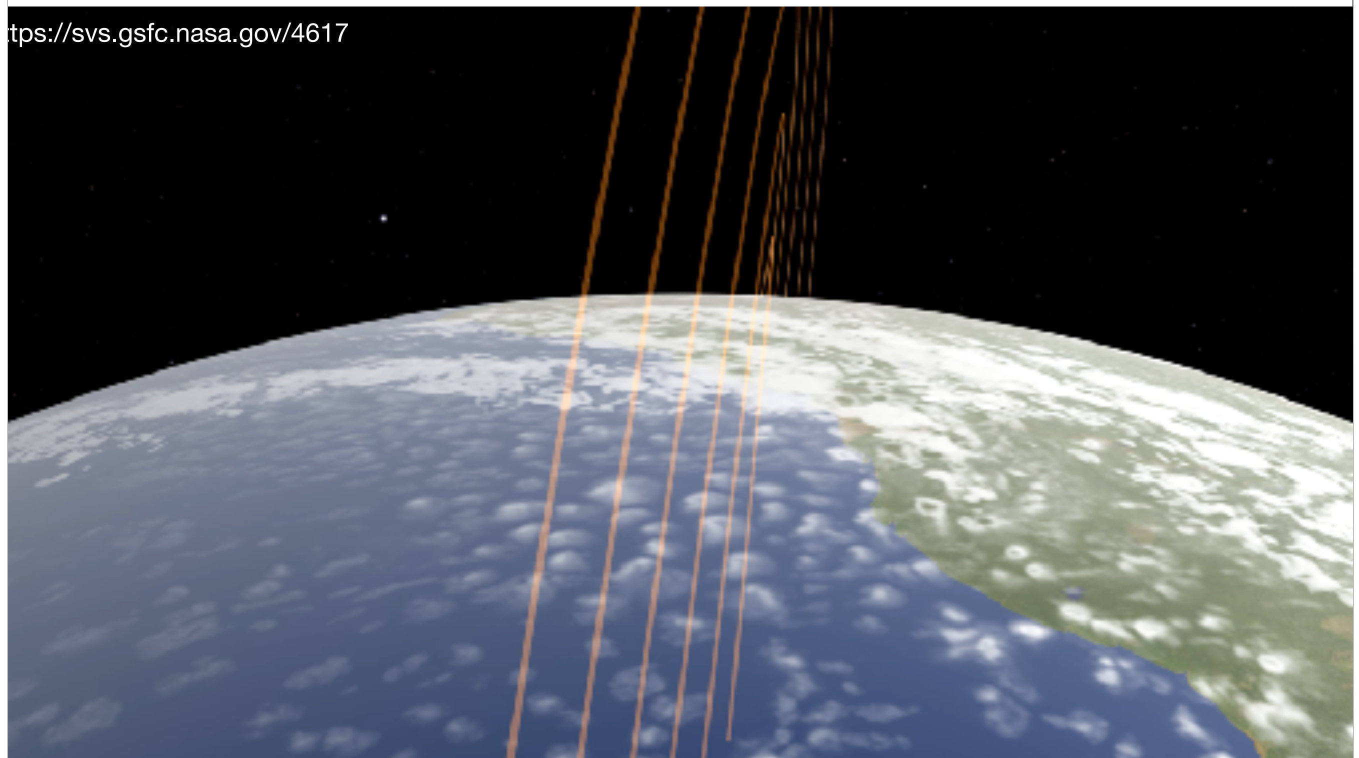
Fig. 19 SAMI2 model calculations versus latitude and altitude of the plasma density for 1500 SLT at 205° East. The upward **E** × **B** drift at the magnetic equator is driven by the eastward electric field, and there is subsequent flow downward along the magnetic field lines

De **reden voor deze grote gradient is juist de extra ionisatie in de EIA**. Moest in de figuren op deze slide over EIA de dichtheid niet groter worden dan groen, dan zouden er geen instabiliteiten zijn en dus ook geen bubbels (en dus ook geen scintillatie).

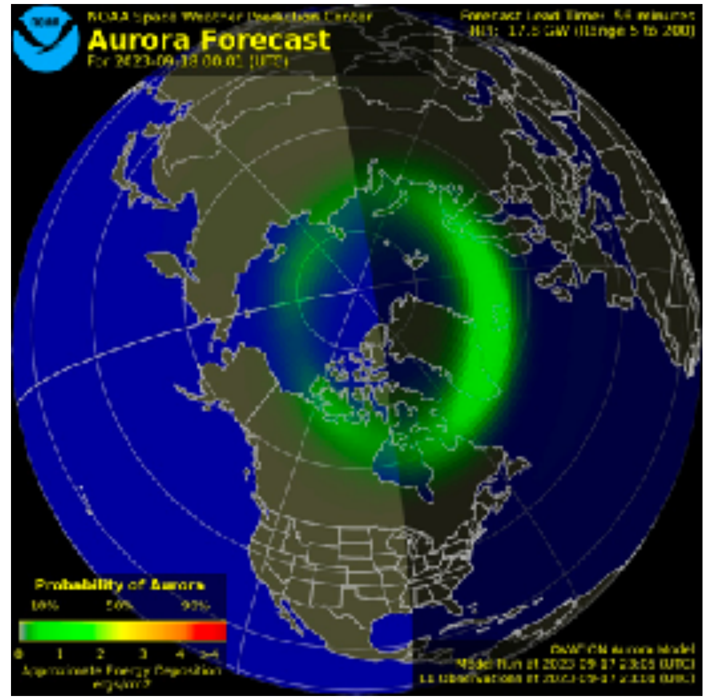
1 Thermospheric wind creates dynamo E, eastward during day-time.
2 This causes ExB drift upwards.
3 This plasma then diffuses along the field lines away from the equator.
4 equatorial anomaly or Appleton anomaly

The vertical drift in the F-region after sunset is a characteristic of the low latitude ionosphere, whose intensity exhibits seasonal and solar cycle dependence.—> largest near the equinoxes at solar maximum.


E
B


tps://svs.gsfc.nasa.gov/4617

Scintillation mechanism 2: auroral oval structures

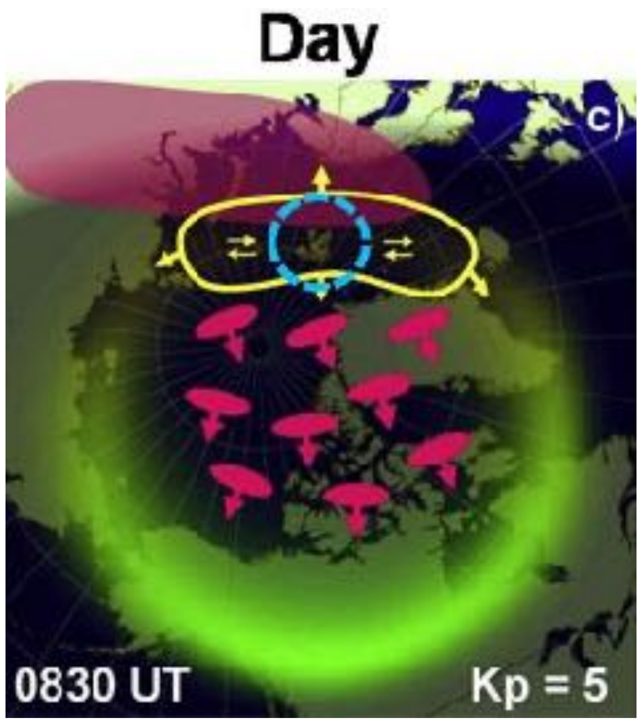


High latitude ionosphere

Defining feature: Auroral oval: magnetic field lines connecting to the plasma sheet. This allows for particles to precipitate, producing a complicated current system in the auroral ionosphere.

Precipitating particles
—> come towards Earth from the reconnection areas in the plasmasheet
—> follow the magnetic field form sheets
—> typical form of auroras.
—> small scale irregularities
—> induces scintillation
—> example auroral clutter: aurora acts as a echo

Scintillation mechanism 3: Polar Cap Patches



High latitude ionosphere

This phenomenon is linked to the orientation of the Bz component of the IMF

In the polar cap, magnetic field lines are open, connected to the interplanetary field.

PCP are plasma blobs that form during geomagnetic storms
Polar cap patches are islands of high-density ionospheric plasma in the F-region ionosphere surrounded by plasma that is half or less than half as dense as the patch.

Polar cap patches are regions of enhanced plasma density in the ionospheric F region inside the polar cap, i.e., poleward of the auroral oval. The plasma density of polar cap patches is more than twice that of the background. Polar cap patches are convected over the magnetic poles from the dayside towards nightside. While travelling they are subject to instabilities (e.g., gradient drift instability), and thereby become structured. The resulting plasma irregularities can have negative consequences on the communication with satellites - they lead to scintillations of satellite signals and influence the reliability of Global Navigation Satellite Systems

Mechanism 4: Traveling ionospheric disturbances during a geomagnetic storm

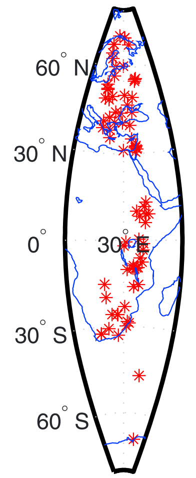


Figure 5. Map of GNSS receiver locations used for the generation of the TID estimation shown in Figure 4.

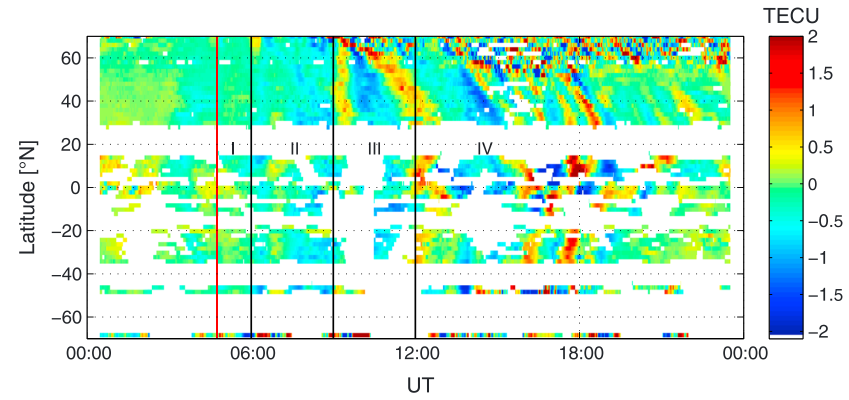
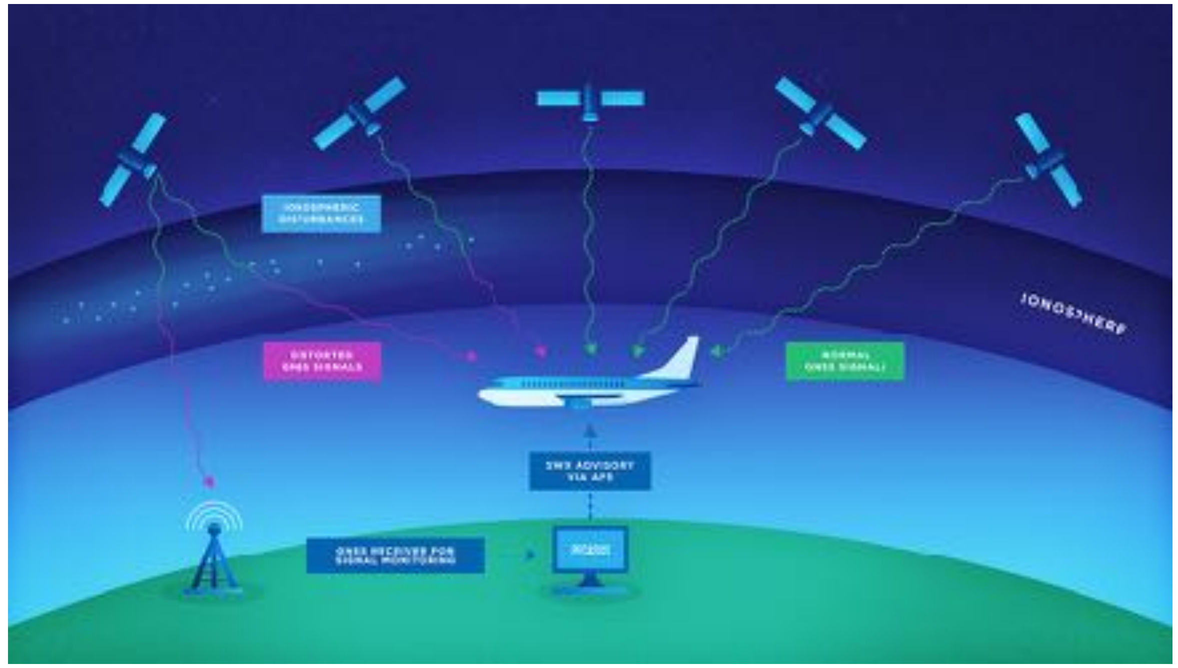


Figure 4. Illustration of TID amplitudes generated from GNSS data along the European-African sector with about 30°E center longitude during the 17 March 2015 storm. The red line indicates storm onset at 04:45 UT, and the solid black lines show the shift between the different phases of storm.

Borries et al., 2016, http://doi.wiley.com/10.1002/2016JA023178

Such disturbances can be produced by a wide range of drivers, including geomagnetic storms, but also disturbances propagating from the lower atmosphere (e.g. due to typhoons, earthquakes, etc.), or even artificial sources (major explosions, rocket launches,...).



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 and the path 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.

HF COM

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	QUIET
Vertical TEC	125	175	2020-10-12 14:15	61.92	QUIET		61.93	QUIET

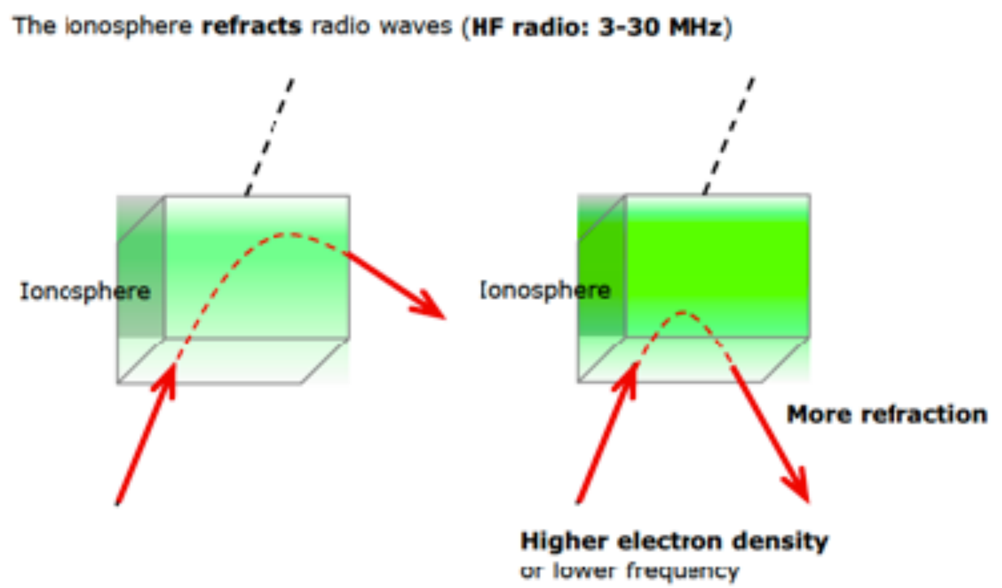
RADIATION	Moderate	Severe	Time UTC	Flags	Status	Alert	Max-3h flags	Max-3h status
Effective Dose FL≤460	30	80	2020-10-12 14:20	0	QUIET		0	QUIET
Effective Dose FL > 460	/	80	2020-10-12 14:20	0	QUIET		0	QUIET

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

AA, PCA, SWF are absorption events
PSD reduces the range of frequencies available.

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



The ionosphere refracts radio waves
More refraction when
higher the electron density
Or
lower the frequency

we look at HF radio
We have seen that vertical waves at frequencies below the maximum plasma frequency are reflected. But also waves that enter the ionosphere at an angle will be bent back to earth, up to approximately up to approximately 3x the maximum plasma frequency. Typically, these frequencies are below 30 MHz. On rare occasions frequencies up to 150 MHz are reflected.

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.

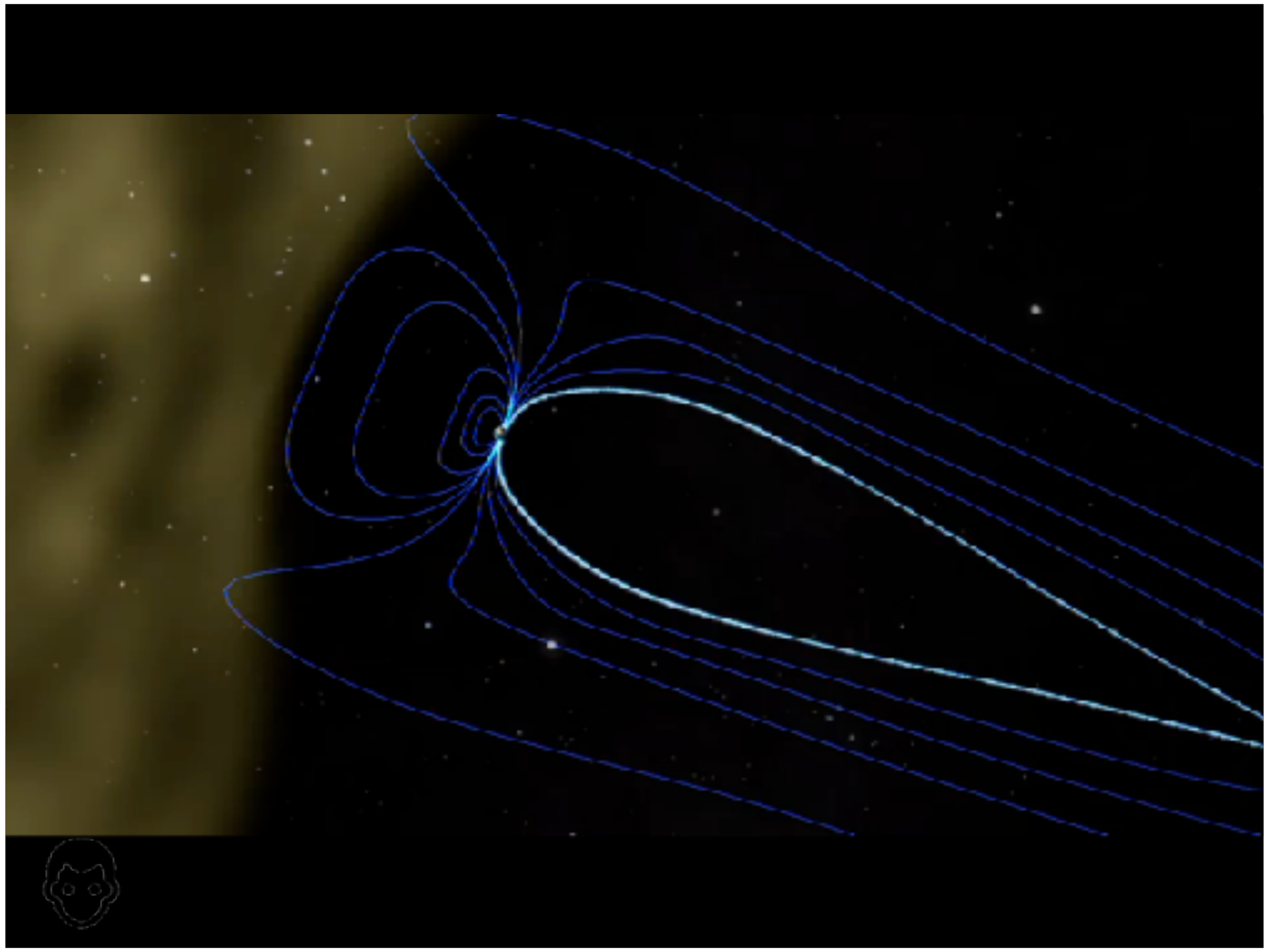
What?	Strong geomagnetic storms Kp>8
Consequences	radio fade out in both polar region
What to monitor	Kp indices

MOD from 8- onwards
NH and SH together
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.**

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

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2000RS002550
The high variability of radio wave propagation in the polar regions is especially challenging to geophysicists and radio engineers. Propagation effects include polar cap absorption (PCA), which lasts for one to several days following solar proton events, and auroral absorption, which occurs almost all the time and varies on shorter timescales. Except when a PCA event is ongoing, auroral absorption is the most significant effect on high-latitude propagation. Auroral absorption occurs primarily in the D region of the Earth's ionosphere, where electron-neutral collisions dissipate the energy of electromagnetic waves passing through the medium. The collision frequency depends on electron density, which in the nighttime auroral D region is provided primarily by electron impact ionization by auroral electrons, leading to a close correlation between the absorption and auroral activity.



Precipitating electrons coming from the tail

POLAR CAP ABSORPTION

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.

What?	Solar radiation storm
Consequences	radio fade out in both polar regions
What to monitor	Absorption >2 dB

Riometer data
D-RAP model

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

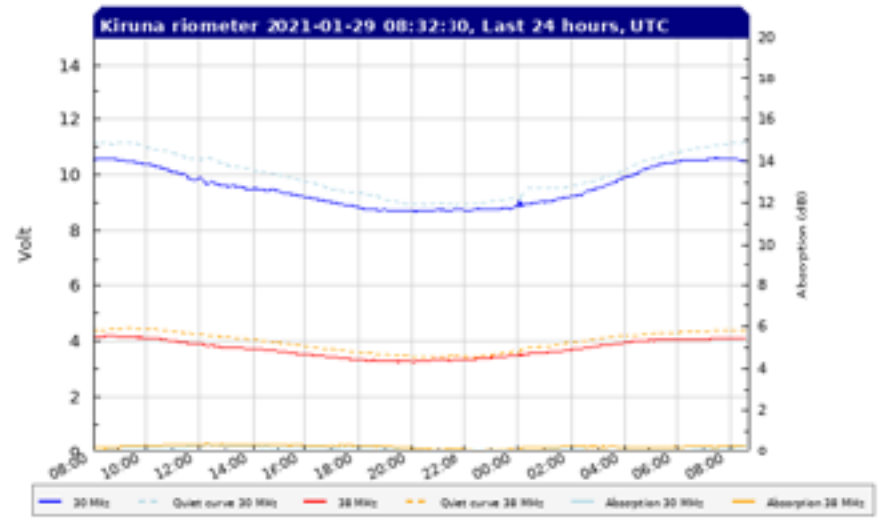
1dB attenuation -> out = in
10dB attenuation —> out = 10 times less strong - P2 = 10^-1 P1
20 dB attenuation —> out =100 times less strong - P2 = 10^-2 P1
30 dB attenuation —> out = 1000 times less strong - P2 = 10^-3 P1

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

PCA - RIOMETERS



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

A **riometer** is an instrument used to quantify the amount of electromagnetic-wave ionospheric absorption in the atmosphere.
"opacity" of the ionosphere to radio noise emanating from cosmic origin.

In the **absence of any ionospheric disturbance**, 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).

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.

Kiruna riometer: http://www2.irf.se/riographs/rtkirplot2_rio_filtered_24.png

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.

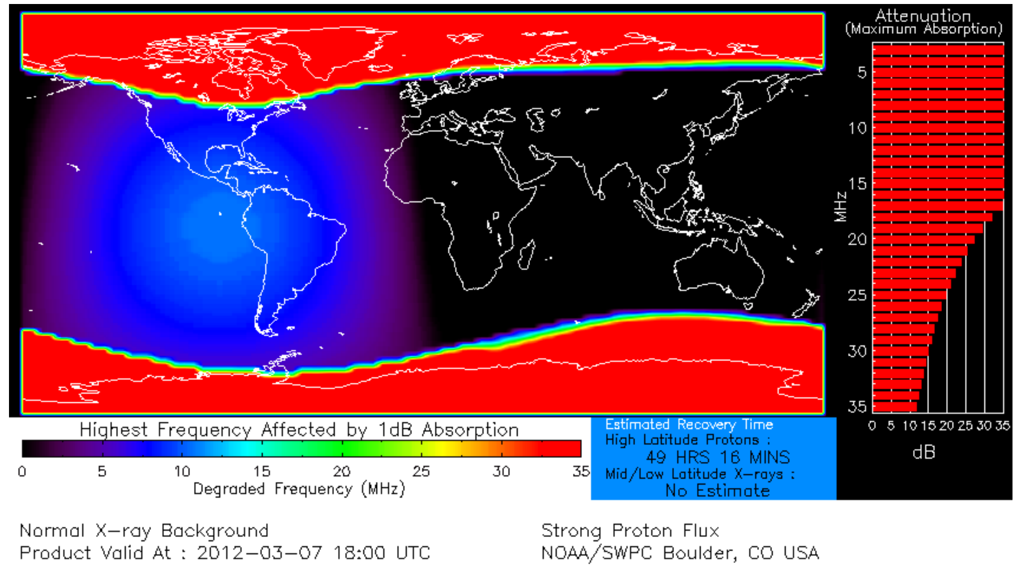
How is the riometer used scientifically?

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.

PCA - D-RAP MODEL

Conditions in the D-region of the ionosphere have a dramatic effect on HF communications. The global D-Region Absorption Predictions (D-RAP) depicts the D-region at high latitudes where it is driven by particles as well as low latitudes, where photons cause the prompt changes.



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

HF radio communication
Another type of space weather, the Radiation Storm caused by energetic solar protons, can also disrupt HF radio communication. The protons are guided by Earth's magnetic field such that they collide with the upper atmosphere near the north and south poles. The fast-moving protons have an affect similar to the x-ray photons and create an enhanced D-Layer thus blocking HF radio communication at high latitudes.

https://www.swpc.noaa.gov/products/d-region-absorption-predictions-d-rap
D-region absorption product addresses the operational impact of the solar X-ray flux and SEP events on HF radio communication. Long-range communications using high frequency (HF) radio waves (3 - 30 MHz) depend on reflection of the signals in the ionosphere. Radio waves are typically reflected near the peak of the F2 layer (~300 km altitude), but along the path to the F2 peak and back the radio wave signal suffers attenuation due to absorption by the intervening ionosphere.

The D-Region Absorption Prediction model is used as guidance to understand the HF radio degradation and blackouts this can cause.
Conditions in the D-region of the ionosphere have a dramatic effect on high frequency (HF) communications and low frequency (LF) navigation systems. The global D-Region Absorption Predictions (D-RAP) depicts the D-region at high latitudes where it is driven by particles as well as low latitudes, where photons cause the prompt changes. This product merges all latitudes using appropriate displays, and is useful to customers from a broad base that includes emergency management, aviation and maritime users.

The D-Region Absorption Map is composed of four dynamic components: a global map of the highest frequency affected by absorption of 1 dB due to either solar X-ray flux or SEP events or a combination of both, an attenuation bar graph, status messages, and an estimated recovery clock. All of the components update continuously, driven by one-minute GOES X-ray flux data and by five-minute GOES proton flux data. To complement the global frequency map, polar projection maps of the highest frequency affected by absorption of 10 dB due to primarily to SEP events are also available by clicking on the North Pole and South Pole links. The Tabular Values link displays numeric values of the frequency map in 5-degree latitude and 15-degree longitude increments. A more complete discussion of the product can be found in the Global D-Region Absorption Prediction documentation.

https://www.swpc.noaa.gov/content/global-d-region-absorption-prediction-documentation

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

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

https://www.swpc.noaa.gov/products/goes-x-ray-flux

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	$\frac{MUF}{median_{30days}(f_o F_2)}$ % decrease

Electron density: increase, followed by depletion

Positieve fase van een storm gaat met een toename van elektronen gepaard. Die worden vanuit de plasmasheet geïnjecteerd? (Precipitating electrons, auroral particles)

In de negatieve fase krijgen we te maken met electron depletion omwille van het opwellend neutraal gas waardoor de electronen recombineren.

Vanwaar komt dat opwellend gas? En welke recombinatie is dit? Je hebt dat toen op het bord geschreven maar het was weggeveegd voor ik het had overgeschreven.

Ja en Nee: De concepten 'positieve' en 'negatieve' storm verwijzen vooral naar wat in middel latitudes gebeurd, niet de oval zelf. Maar de storm in de middel latitudes wordt wel aangedreven door wat in de oval gebeurd.

Positieve storm

stap 1: injectie van energie in de oval, inderdaad door inkomende deeltjes van de plasma sheet.
stap 2: oval warmt op en zet uit, wat plasma naar de middel latitudes drijft.
stap 3: plasma dat van de polen richting evenaar wordt gedreven stijgt naar hogere hoogten, omdat het de niet-horizontale veldlijnen volgt. —> zorgt voor injectie van electronen
stap 4: op deze grotere hoogte is de neutrale dichtheid lager, waardoor de recombinatie trager gaat. Electronen recombineren niet.

De positieve storm (mid-latitude) is dus niet rechtstreeks het gevolg van extra elektronen die hier terecht komen (middel latitudes hebben immers geen directe verbinding met de plasma sheet) maar van de tragere recombinatie op grotere hoogte.

Een belangrijk, fundamenteel aspect van de aeronomie is dat de directe recombinatie
$O^+ + e \rightarrow O$
een heel trage reactie is.

Negatieve storm

Recombinatie gebeurd eerder doordat een O+ een elektron opneemt van een neutrale molecule, die dan positief wordt en wel snel recombineert met een vrij elektron. Bv:
$O^+ + N_2 \rightarrow O + N_2^+$ gevolgd door $N_2^+ + e \rightarrow N_2$
gaat veel sneller dan directe recombinatie, ook al zijn er twee stappen nodig. Recombinatie snelheid hangt dus eerst en vooral af van de omringende, neutrale dichtheid.

In de stappen hierboven beschreven is er dus nog een ander aspect: het neutrale gas warmt ook op door de injectie van extra energie. Hierdoor zullen de moleculaire, neutrale gassen (vooral N_2 en O_2) grotere hoogtes bereiken (waar normaal vooral atomaire O en H voorkomen). De toename van N_2 (en O_2) op de hoogte van de F2 laag zorgen dan voor extra recombinatie, wat de negatieve fase van de storm veroorzaakt.

— — — — — — — —

foF2= critical frequency

n0 = electron content
—————————-

Ionosonde: 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.

https://en.wikipedia.org/wiki/Ionosonde
An ionosonde consists of:

- A high frequency (HF) radio transmitter, automatically tunable over a wide range. Typically the frequency coverage is 0.5–23 MHz or 1–40 MHz, though normally sweeps are confined to approximately 1.6–12 MHz.
- A tracking HF receiver which can automatically track the frequency of the transmitter.
- An antenna with a suitable radiation pattern, which transmits well vertically upwards and is efficient over the whole frequency range used.

Digital control and data analysis circuits.
The transmitter sweeps all or part of the HF frequency range, transmitting short pulses. These pulses are reflected at various layers of the ionosphere, at heights of 100–400 km (60 to 250 miles), and their echos are received by the receiver and analyzed by the control system. The result is displayed in the form of an ionogram, a graph of reflection height (actually time between transmission and reception of pulse) versus carrier frequency.

An ionosonde is used for finding the optimum operation frequencies for broadcasts or two-way communications in the high frequency range.
—————————

1- MUF/median 30 days —> negative when MUF increases, 0 wanneer het zoals verwacht is, positive when MUF is decreased

It is negative when MUF> median

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.

——————

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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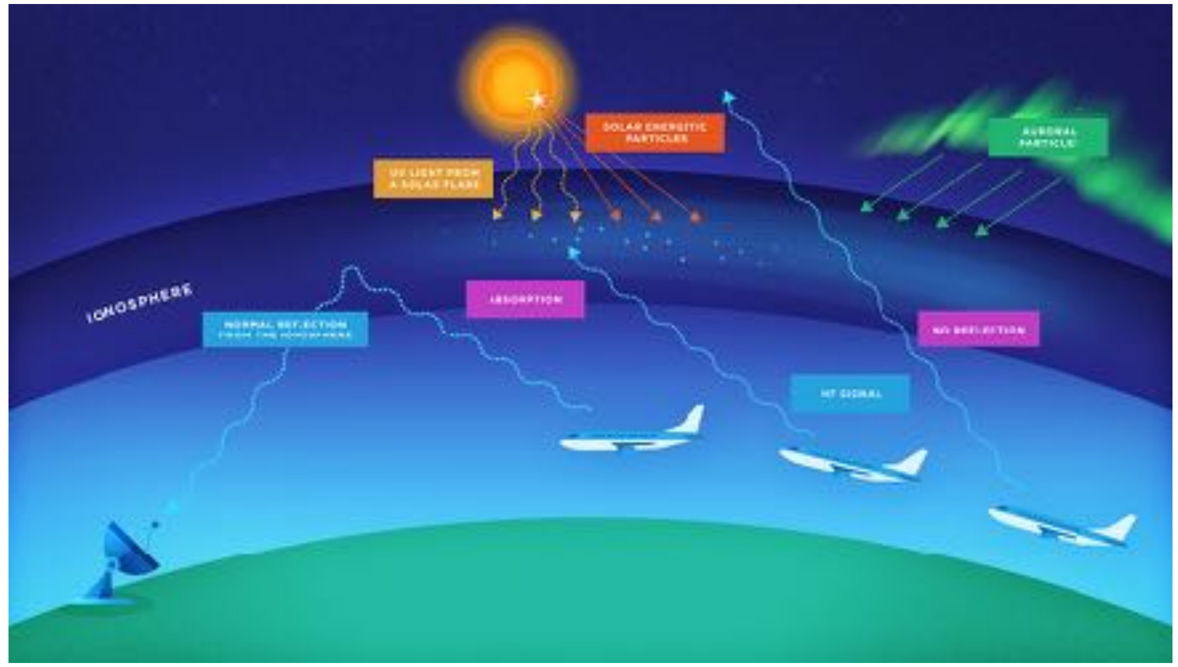

AA - auroral absorption - precipitating electrons - F-layer
PCA - protons trigger extra ionisation - D-layer
Flare - extra ionisation - D-layer
PSD - ionospheric storm

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.