Search

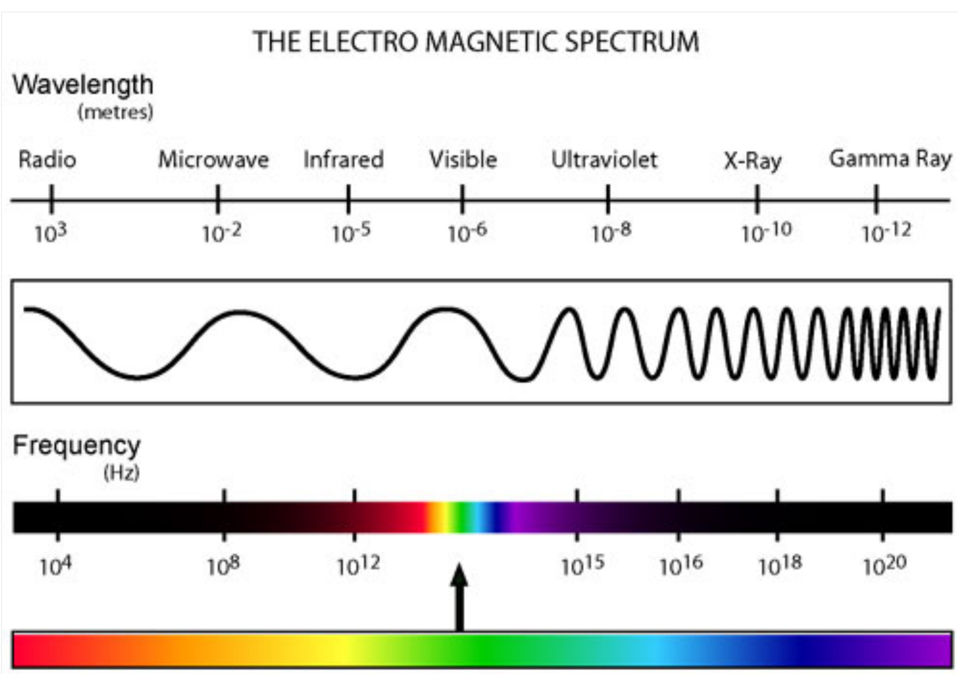
Propagation

Radio wave propagation is something that has intrigued me from the very first time I made a radio contact. In my first years on HF, I quickly found out that understanding propagation and being able to forecast propagation, would give me a substantial advantage. So in the early 90's I gathered as much information as available and started to make my own forecasts.

I wrote this article to share my knowledge with other radio amateurs, professionals and enthusiasts. It explains what radio waves are and how they propagate around Earth and how the sun affects propagation on a part of the radio spectrum.

1. Radio waves:

Radio waves are electromagnetic waves that propagate with a speed near 300,000 km/s. Electromagnetic waves have a frequency and wavelength. There are different type of waves, with high and low frequency. Even visible light is an electromagnetic wave, that has a very short wavelength. Your own eye is in fact an antenna, and you probably did not know!



Privacy - Terms

— The electromagnetic spectrum

You can calculate frequency or wavelength with these two formulas:

Frequency (MHz) = 300 / Wavelength (m).
For example a wavelength of 10m has the following frequency: 300 / 10 = 30 MHz.

Wavelength (m) = 300 / Frequency (MHz).
For example a frequency 28.495 MHz has the following wavelength: 300 / 28.495 = 10.528 m.

In the world of communication, different wavelengths or frequencies are divided into:

- LF (Low Frequency) = 0.03 – 0.3 MHz (1000 m to 10000 m band)
- MF (Middle Frequency) = 0,3 – 3 MHz (100 m to 1000 m band)
- HF (High Frequency) = 3 – 30 MHZ (10 m to 100 m band)
- VHF (Very High Frequency) = 30 – 300 MHz (1 m to 10 m band)
- UHF (Ultra High Frequency) = 300 – 3000 MHz (1 m to 10 cm band)
- SHF (Super High Frequency) = 3000 – 30000 MHz (10 cm to 1 cm band)
- EHF (Extremely High Frequency = 30000 – 300000 MHz (1 cm to 1 mm band)

By the way:

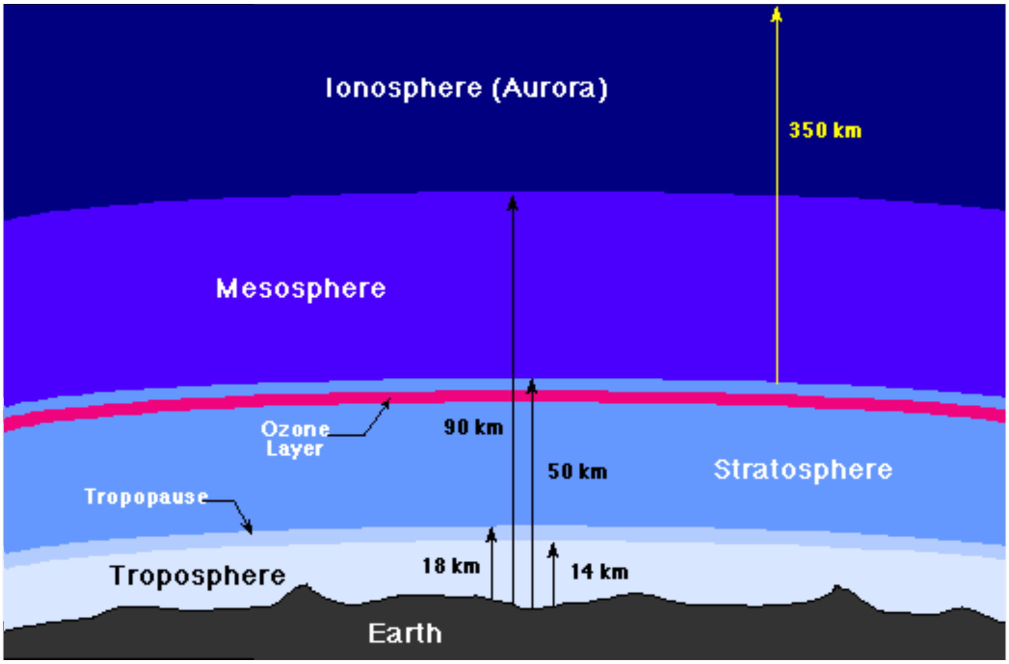
- 1000 Hz = 1 kHz
- 1000 kHz = 1 MHz
- 1000 MHz = 1 GHz

There are also differences in properties for these wavelengths. LF waves easily penetrate through dense materials like concrete, rock, soil, etc. They follow the curvature of the Earth, which makes LF ideal for long distance ground wave communication over more than 1000 km. Submarines even use VLF (Very Low Frequency) radio waves, because they can even travel right through the Earth's core!

The higher the frequency of the radiowave, the less it traales along the Earth's curvature, and the less it can penetrate dense materials. 10 m wavelength radio waves follow the Earth's curvature only little compared to 160 m.

2. Earth's atmosphere

Before we explain the physics of propagation, you must know that the Earth's atmosphere has a great influence on propagation:



— Earth's atmosphere

2a. Troposphere

The lowest part of the atmosphere is the troposphere. This part of the atmosphere holds for our weather. The troposphere ends at roughly 14 km under a small layer, the tropopause. Only the tops of large thunderstorm or supercell clouds (*Cumulonimbus Incus*) occasionally reach over 14 km, and some even push up the tropopause. The troposphere does not have great influence on HF propagation, but sometimes it extends normal 'ground wave' propagation, especially on the shorter HF wavelengths like 10 m and 12 m.

2b. Stratosphere

This part of the atmosphere does not influence HF propagation. The upper part of the stratosphere holds the ozone layer, which filters harmful ultraviolet (UV) radiation. The only clouds you find here are so called 'Noctilucent Iceclouds' which are sometimes visible after midsummer sunsets.

2c. Mesosphere

The mesosphere harbours the so called D-layer. The most lower part of the ionosphere. The D-layer absorbs HF radio waves, especially up to 10 MHz.

2d. Ionosphere

The ionosphere is very important when it comes to propagation of HF radio waves. It harbours the so called E-layer, F1-layer and F2-layer. These layers emerge under influence of ultraviolet solar radiation.

3. Three types of propagation

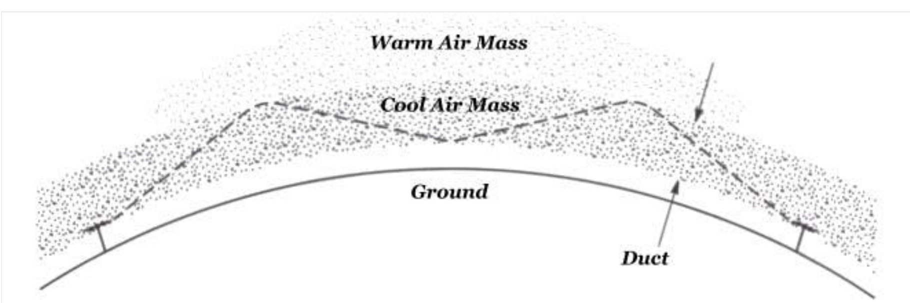
Propagation is divided in roughly three types:

3a. Ground waves

Ground waves are waves that propagate along the Earth's surface. Your favourite station on FM for example uses ground waves. How far ground waves can travel depends on the height of the antenna. That is why commercial broadcast stations on FM use large towers or are located on the highest hills and mountains. 10 m band radio waves usually travel around 30-50 km on ground wave, with the antenna at an average height of 10 m. The less obstacles the radio wave encounters, the stronger the signal will be. Ground waves over large surfaces of water travel much further than ground waves in mountainous or rural areas. Once the ground wave cannot follow the Earth's curvature anymore, it travels into the sky and into space!

3b. Tropospheric sky waves

Sometimes ground waves travel further than theoretically possible. Distances up to 100 km and even more are possible on 10 m. This type of propagation is called Troposheric or 'Tropo'. In the troposhere, there are different layers of air, with different temperatures and different humidities. When it's windy, these layers of air mix together. But when it is not windy, different layers of air are present at different altitudes. When you are in the center of a high pressure area, weather is very quiet. In the morning, the air layer close to the ground is relatively cool and moist (sometimes visible as fog or mist), while the area above it is relatively warm and dry. The change of temperature can be easily 10 °C over just 100 m, and is called an inversion. The cold layer of air is more dense than the warm layer of air. The sharp transition between cold and warm air, a temperature inversion, refracts radio waves in VHF and UHF bands.



— A duct allows VHF and UHF radio waves to travel within

On some occasions there can be multiple inversions. Once a radio signal has been caught between two inversions, it can travel in between like traveling through a kind of tunnel. This propagation mode is called tropospheric ducting. Ducting has only been reported on VHF and UHF.

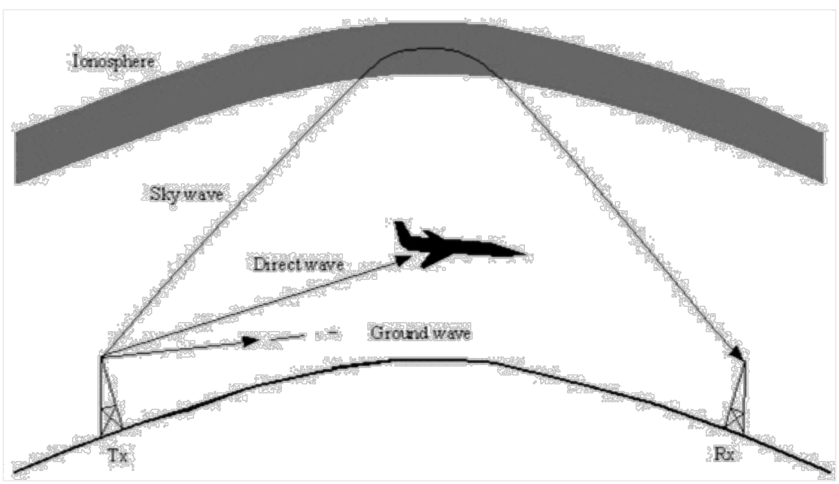
Tropo is also observed along cold fronts, where there is a very sharp transition between cold dry and warm moist air. Even in violent atmospheres like hurricanes.

Such inversions affect VHF and UHF bands most, but the higher HF bands like 10 m are also affected, however much less. On 10 m band contacts have been made over 350 km on a day with paths across stationary high pressure area, and no reports of any ionospheric propagation at all on the same day.

Good tropo predictions can be found at William Hepburn's Worldwide Tropospheric Ducting Forecast.

3c. Ionospheric sky waves

Radio waves can travel far distances because they can be reflected to the Earth's ionosphere. Such a reflection is called a 'hop'. The radio wave that is being reflected by the ionosphere can travel back to Earth under the right angle. It bounces off the Earth' s surface back up again into the ionosphere. There it will be reflected down again. Multiple bounces and reflections is called 'multi hop' propagation.



— Radio waves bended by the ionosphere

4. The Ionosphere

The ionosphere is a thin layer of air. It is called ionosphere because it is formed by ions. Ions are charged particles that appear under the influence of solar radiation (ultraviolet and X-rays). These ions have the capability to bend or reflect a radiowave. That capability depends on the density of ions, the more ions the stronger the reflection. The maximum frequency that the ionosphere can reflect is called the MUF or Maximum Usable Frequency.

We read earlier that the ionosphere consists out of four layers:

- **D-layer:** only absorbs radio waves, especially under 4-5 MHz. Appears very fast after sunrise, and disappears almost immediately during sunset.
- **E-Layer:** reflects radio waves up to 5 MHz, radio waves above 5 MHz are absorbed, but less than in the D-layer. Appears shortly after sunrise, and disappears shortly after sunset.
- **F1-layer:** reflects radio waves up to 10 MHz. Appears shortly after sunrise and after sunset it merges with the F2-layer to become the F-layer.
- **F2-layer:** reflects radio waves up to 50 MHz (occasionally MUF's of 70 MHz have been reported). Appears after sunrise and disappears shortly and after sunset it merges with the F2-layer to become the F-layer. Is stronger in the winter than in the summer, due to seasonal effects.

As you can see the F2-layer is the most important one for us, it reflects our HF radio waves along great distances, and at nighttime the F-layer does the same.

5. Solar Activity

You now know that the ionosphere appears under the influence of solar radiation, mainly ultraviolet (UV) and X-ray. This solar radiation varies under the influence of:

5a. Sunspots and Solar Flux

Sunspots are dark spots on the sun's surface which are significantly cooler thans their surroundings. You can compare a sunspot with the crater of an active volcano. Sunspots produce the intense radiation which causes ionization of the ionosphere. The index for this radiation is called the Solar Flux and is measured at 2800 MHz. The higher this Solar Flux, the higher the level of ionization. The lowest possible Solar Flux is just under 64 (no sunspot regions), and the highest numbers go well into 200. Conditions on 10 m band generally come alive on all latitudes, when the solar flux index passes the 100 number.

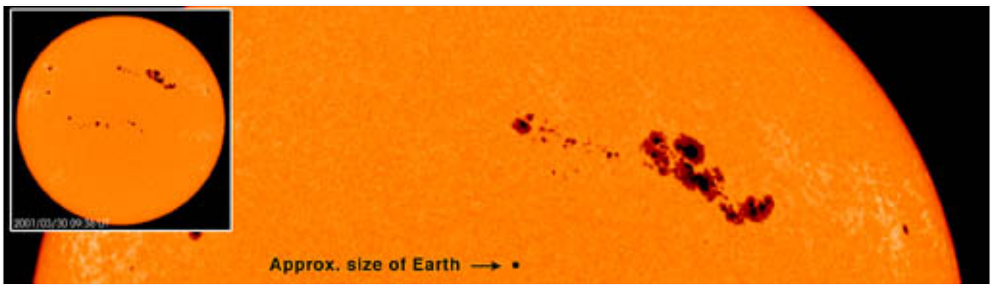
Sunspots are classified by their magnetic complexity. The more complex the magnetic configuration, the more active they are producing lots of radiation and all kind of other events like solar flares and CME's. Magnetic configuration is classified as:

Classification:	Magnetic configuration:
Plage	Spotless region
Alpha	Simple
Beta	Medium

Gamma	Complex
Delta	Very complex

Up to date Solar Flux data is daily available on the Spaceweather Canada website.

In the picture below you can see many sunspots, and just above the middle, the largest sunspot ever recorded in modern history. These sunspots are clustered together in so called sunspot regions. The active regions are assigned a number when they appear on the sun's surface.



— Active sunspot 9393 was the largest seen in many years and appeared in 2001 during Solar Cycle 23.

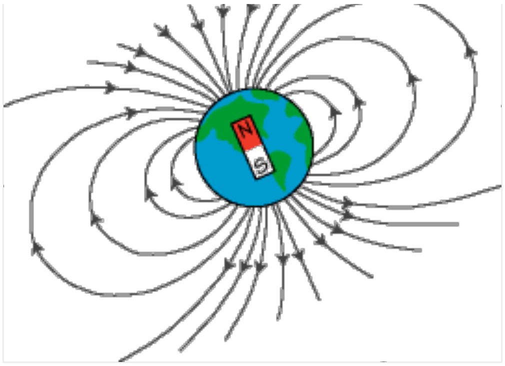
5b. Solar Wind

The solar wind is a constant stream of charged particles which flows form the sun into our solar system. Solar wind can reach speeds up to 1000 km per second.

5c. EGF (Earth's Geomagnetic Field)

Our planet has a core of mainly pure iron. The remarkable thing about iron is when you rotate it, it produces a magnetic field like in the picture below. This magnetic field protects the Earth from charged particles that travel with the solar wind. When solar wind speed is very low, the EGF is quiet, but when the solar wind's speed is very high, the EGF becomes unsettled to active, and in some occasions we even talk about a solar wind storm. The EGF is very important for the production of a stable ionosphere. A quiet EGF means a stable ionosphere, with relative high MUF's. An active or stormy EGF means unstable propagation with a relative low MUF.

The EGF is strongest around the equator and weakest on the north pole and south pole, as you can see in the picture below.



— Earth's Geomagnetic Field

5d. Solar Flares

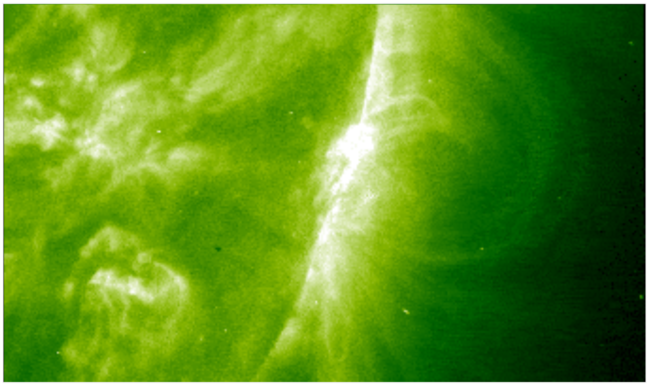
When groups of sunspots are active, they are likely to produces solar flares. These solar flares are like volcanic eruptions with large flames shooting millions of kilometers into space, like in the pictures below. These solar flares produce a lot of radiation, like X-ray which causes the D-layer to grow stronger. Usually after a large solar flare, propagation blacks out, because of very high absorption of the D-layer. Solar Flares also cause and ejection of large masses of charged particles, which is called a Coronal Mass Ejection (CME). The strength of a solar flare is measured from C-class followed by a number, up to M-class and X-class. M-class and X-class flares are likely to produce a radio blackout. A-level means very low levels of X-ray radiation.

Now the chance for a solar flare, depends on the magnetic configuration of the sunspot group:

Classification:	Flaring probability:
Plage	None
Alpha	B-Class
Beta	Up to low M-class
Gamma	Up to low X-class
Delta	Up to extreme large X-class

The magnetic configuration is important. For example, a sunspot group or region with a 5 spot count in Delta-class can produce much more and bigger solar flares, than a 30 spot count group in Beta-class!

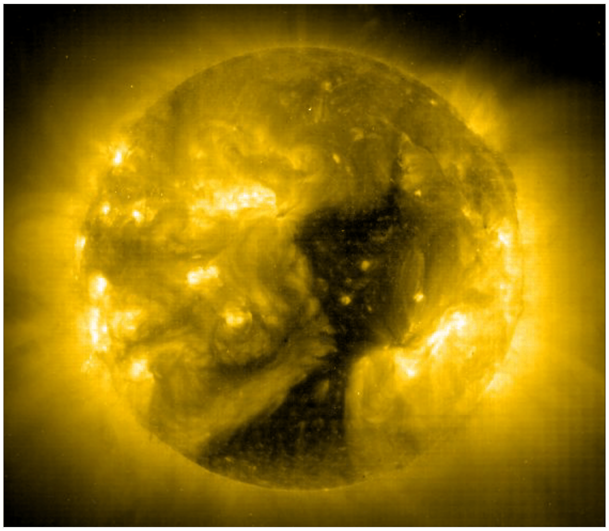
Solar Flares can even be heard on your own radio, especially the larger X-class flares, but also C-class flares that spit out lots of radiation. You can hear the level of background static rise for a short period, as the radiation reaches Earth.



— Animation of the largest solar flare. X28 class, ever recorded

5e. Coronal Holes

that is a a hole through the sun's outer shell (the corona). Coronal holes are always there, and they always produces a stream of charged particles. When a coronal hole faces Earth, it's stream is likely to hit the EGF within 1-5 days, and push solar wind speeds up to 600-700 km/s, bringing the K-index to active or storm levels. The black area in the picture below is a very large coronal hole.



— The dark area is a hole in the sun's corona (atmosphere)

5f. CME (Coronal Mass Ejection):

With every solar flare the sun spits out a vast cloud of charged particles. This coronal mass ejections can speed up the solar wind up to 1000 km/s. Coronal mass ejections are immense clouds of charged particles, which travel very fast. They usually follow a solar flare within 72 hours after the eruption (like lava which flows form a volcanic eruption).

Very fast moving CME's travel to Earth within 24 hours. A CME is likely to hit Earth when the sunspot region which produced the CME, is directed to Earth. When a full halo CME is reported, it is directed to Earth. A partial halo means it is directed partial to Earth.

Watch closely around 2003/10/28 when a series large full halo CME's knocks out the SOHO satellites instruments. On 2003/11/04 (19:54 hours) you can see the largest CME ever seen, being ejected from the right side of the sun, a partial halo. A full halo would have sparked Aurora even at tropical latitudes.

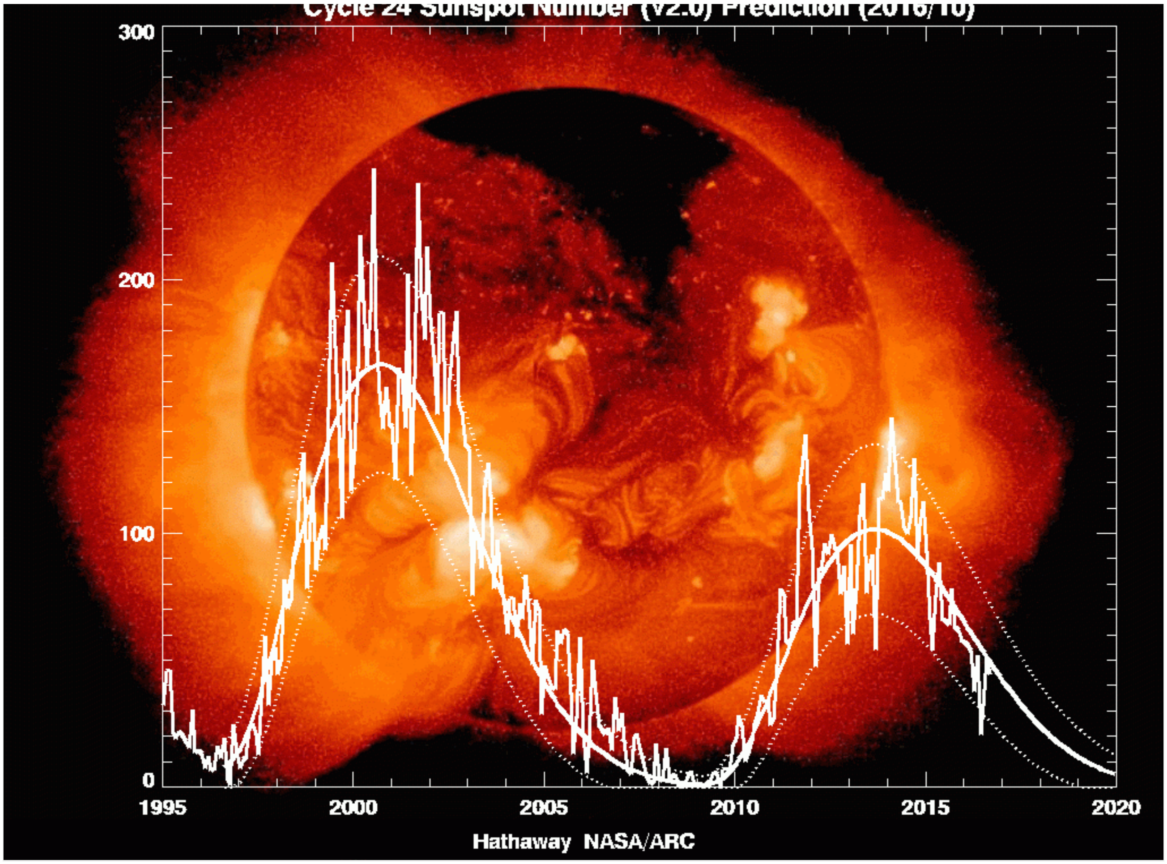
5g. The 27-day cycle

While Earth needs 1 day to rotate around its axis, the Sun needs 27 days. That means that active sunspots that appear on certain days, are likely to return there 27 days later. It can be that the sunspots developed into more active regions in those 27 days, but it could be that they decayed entirely. But 27 days is a cycle that you van take into account when preparing your own propagation forecast.

5h. The sunspot cycle

Solar activity is never at at a static level. It follows an average 11 year cycle, called the sunspot cycle or solar cycle. On the peak of this cycle, the number of sunspots can reach well over 100, with solar flux numbers reaching over 200. In between those peaks, solar activity can be very low, with not a single sunspot for months and daily solar fluxes under 70.

In April 2000 Solar Cycle 23 peaked with a smoothed sunspot number of 120. Cycle 24 started late 2007 and peaked at the end of 2013. It was less intense than Cycle 23 and 22.



— Sunspot Cycle 23 and 24 progression.

5i. The Earth's seasons

As normal weather changes by the season, propagation changes as well. Like with normal weather, temperatures at the equator remain at the same level during the year, but temperature differences between summer and winter increase as you go more northwards or southwards. Same happens with propagation, but the other way around! The MUF of the F2 layer is higher in winter than in summer. One cause is that more intense and longer sunshine in the summer gives the D-layer more strength to absorb HF waves. Due to other complex atmospheric influences, ions in the F2 layer tend do "dissolve" more quickly in the summer than in the winter. That allows winter MUF to reach higher levels than summer MUF.

6. Solar activity and the effects on HF propagation:

We saw in paragraph 5, that X-ray and UV radiation shape the ionosphere and that charged particles influence the EGF. Those factors strongly affect the ionization process and so propagation.

6a. Solar flares

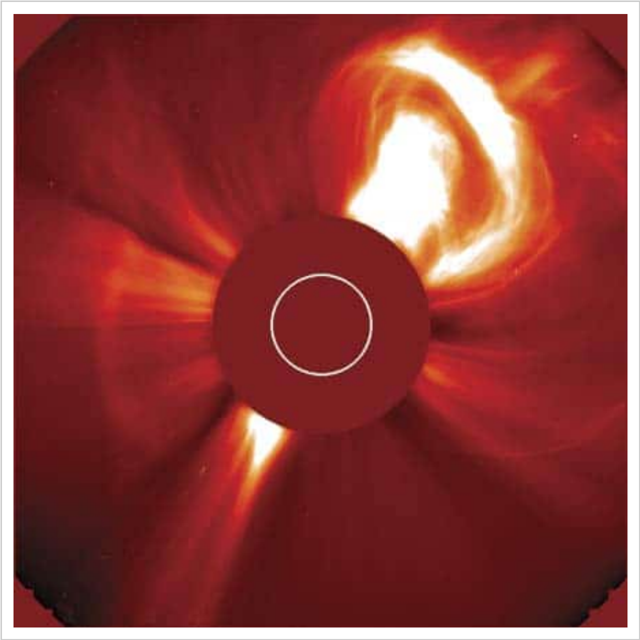
Solar flares produce large amounts of X-ray radiation, causing radio blackouts. But those flares can also intensify ionization in the F2-layer for a short period, with unstable and fast and deep QSB (fading).

6b. Coronal holes

Coronal holes produce streams of energized particles which “press” down the EGF. The EGF itself is weakest around the poles, so stormy conditions are most noticeable around the polar areas. Large streams can enter Earth’s atmosphere on the poles, and collision with gases like oxygen and nitrogen produces the Northern Lights or Aurora.

6c. CME’s

Same as Coronal Holes only with a more intense effect. CME’s have caused satellites, power grids and communications on Earth to go dead because of the intense bombardments with charged particles. Back in the 90’s a giant CME caused a part of the North American power grid to go down. During such a CME the currents that flow through the atmosphere at high and polar latitudes exceed 1,000,000 (one million) Ampere!



7. Extraordinary propagation

Next to the ‘common’ types of propagation, there are also some very special types of propagation. Some predictable and some unpredictable. Some are very spectacular.

7a. Sporadic-E (Es)

Every year around mid summer (May-August) and mid winter (December-January) short skip propagation turns up with distances form 500-1800 km. Remarkable about this propagation is that it can turn up in only 15 minutes, and disappear just as fast. Also signal levels can be very high. On the CB band (27 MHz or 11 m) for example, you can hear low power stations from other areas between 500-1800 km with only 4 watts in FM with quite impressive signals. QSO’s with toy walkie talkies on the CB band have been made over more than 1000 km.

The layer in the ionosphere responsible for this is called the Es-layer (Es = sporadic-E). This layer floats at the same altitude as the normal E-layer, somewhere between 80-150 km. Scientists still do not know what makes the Es-layer appear and disappear, but it is surely not influenced by solar radiation.

We do know that Es is at it’s best during a sunspot minimum, because it turns op more regular with a quiet EGF. Studies on this type of propagation learned us, that Es shows up mostly in the late morning and early evening, but can show up at any time, even at night. The MUF of the Es-layer can reach up to the VHF band, with recorded QSO’s signals at 200 MHz. Amateurs in the 6 m (50 MHz) 4 m (70 MHz) and 2m (144 MHz) band use Es to cover distances well over 2000 km. In multihop occasions, even double the distance.

I remember a summer holiday in Portugal, when we received Dutch FM stations in the 88-108 MHz VHF broadcast band for several days in a row.

7b. Backscatter

Normally you would expect HF radio signals to be reflected forwards in the ionosphere, but there is a propagation mode where signals are being reflected back from the surface after a first hop. The modulation of the station you are hearing via backscatter, has a specific ‘sound’. It sounds hollow like talking through a large tube and sometimes even a short echo is heard.

Backscatter signals are not very strong, usually not more than an S1 to S5. But in some occasions backscatter can be as strong as S9. About 100 Watts and a directional antenna are minimal requirements to produce a usable backscatter signal. Backscatter is best on the higher HF bands like 15 m to 10 m, but can also be observed on 6 m (50 MHz). Backscatter occurs mostly when the MUF of the ionosphere is well above 28 MHz, and the reflection from the ionosphere is strong.

Working via backscatter allows you to work stations within the so called blind zone (the area which is too far away for ground waves and to nearby for ionospheric waves, usually between ± 50-500 km). To work backscatter, both stations need to point their antenna to more or less the same point about 1000-4000 km away. For example, if a station from Belgium wants to work a station from England, they could point their antenna’s both in the direction of the Azores, or any other direction that produces the loudest signals.

Backscatter is a typical F2-layer propagation mode but is also observed with Es-layer propagation.

7c. Aurora

When a CME or Coronal Hole stream hits Earth’s atmosphere it cannot penetrate at equatorial regions, lower and middle latitudes. The Earth’s magnetic field lines are strong there. They push the energized particles towards the polar regions where the magnetic field is weaker. When they enter the polar atmosphere, they collide with the different gases there. You will see it as Northern Lights or Aurora, like neon gas in a tube is lighted up by bombarding the neon gas with charged particles.

Aurora ‘clouds’ are extremely intense ionized. They reflect radio waves up to the UHF band. Aurora clouds do not float horizontally like the normal D-, E-, and F-layers do. Instead they are hanging more like curtains (like in the picture below). This allows you to use Aurora like backscatter.

Because Aurora only appears around the polar regions, you need to direct your antenna to the North Pole or South Pole (whatever is nearest). The area coverable via aurora ranges up to 2000 km. Working Aurora on HF means having needs a good set of ears. The very fast and strong QSB make the signal almost unreadable! Like someone is talking with a soar throat, or talking behind a spinning wheel or fan.

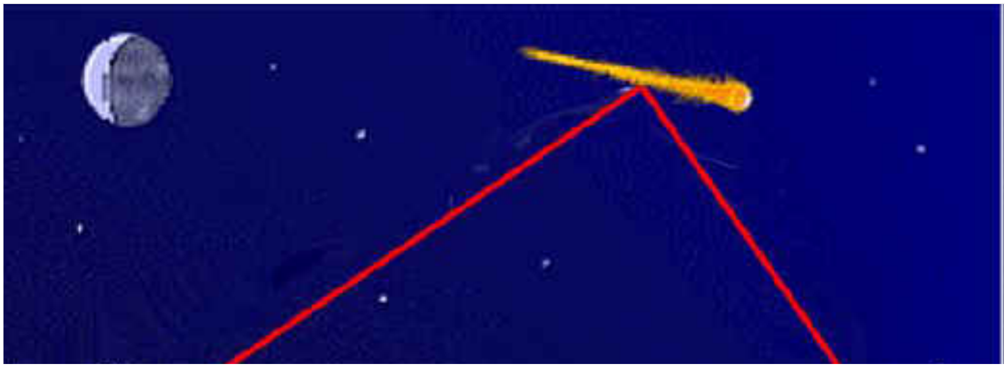
Aurora works best on the higher HF bands on SSB.

— Aurora band observed from ISS

You do need to be at higher latitudes to work Aurora propagation. The higher the latitude you are at, the more often you can work Aurora. Aurora appears when the K-index hits 3-4 when you live close near the magnetic North Pole or South Pole. But for locations like London, UK and Berlin, Germany, the K-index needs to be 8 or more for aurora to be actually visible. But once you see it, the sky seems like it's on fire.

7d. Meteor scatter

Meteor scatter is another remarkable propagation mode is meteor scatter. Meteors are tiny rocks, or dust particles that enter Earth's atmosphere at a high altitude (±100 km) at very high speeds (> 5000 m/s). Because of these very high speeds, these meteors burn up because due to friction in Earth's atmosphere. When disintegrating, the heat is so intense that ionization of the surrounding air takes place. Ionization can be so strong, that the ionized band of air bends radio waves up to 500 MHz, but also the higher relative quiet HF bands like 10 m and 12 m. The distances for meteor scatter can range from 400-1800 km for 10 m and 12 m, and the openings can last from a second up to a few minutes, with very strong QSB.



— Meteor Scatter propagation

Meteor scatter takes place in annual periods of meteor showers. All have their own name. Here are some important dates for meteor showers which appear annually:

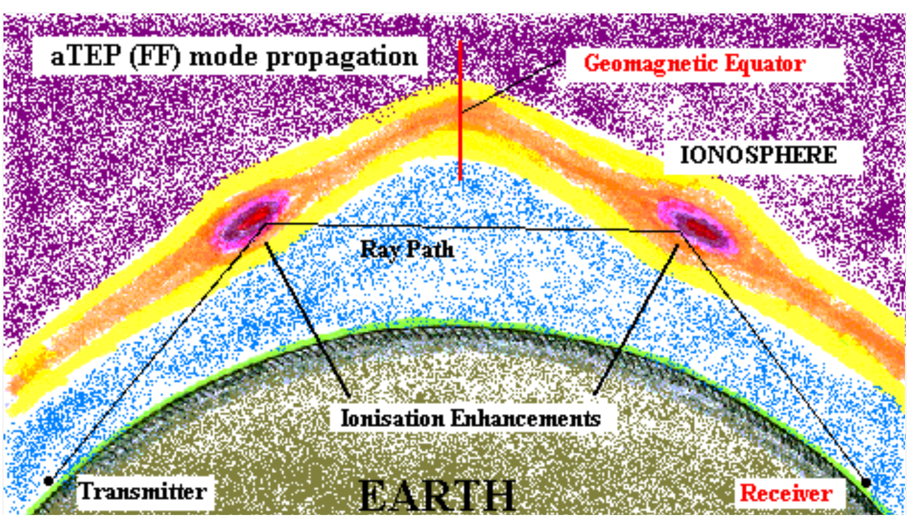
- 3 January: Quadrantids
- 1 August: Perseids
- 21 October: Orionids
- 18 November: Leonids
- 14 December: Geminids

Meteor showers tend to peak in the late winter evening into the night and early summer evening into the early morning.

7e. TEP (trans Equatorial Propagation)

The Earth's magnetic poles are not at the same location as the exact North Pole and South Pole, but are located over 1000 km from the geographic poles. Therefore the magnetic equator does not run straight like the normal equator.

On each side of the magnetic equator the intense sunshine and the Earth magnetic field lines cause extreme ionization there. As a result the F2-layer extends upwards in the atmosphere up to 500 km and higher. Because of this very high altitude and the high level of ionization, a TEP signal is reflected twice against the ionosphere and can take a signal with a single hop over 6000 km, into the VHF range, and in a single occasion even up to 500 MHz. You can see how the TEP mode can exist in the picture below.



— TEP – Trans Equatorial Propagation

TEP usually peaks between late afternoon and late evening. Signals tend to become stronger during the evening, but with more and sometimes extreme QSB.

7f. FAI (Field Aligned Irregularities)

Field Aligned Irregularities is the most unpredictable propagation mode. It appears at the same altitude as the E-layer, when ions are being driven together by the EGF, into a small cloud of ions (from several meters in length and width, up to several kilometers). At a certain point the density is high enough, to set a MUF that reaches over 200 MHz. It could appear at any time of the day. Enabling very short openings, with mostly strong signals. Usually the signals have strong QSB. FAI openings last seconds up to minutes.

There is much more to explain about propagation, but I like to keep things not too complicated. If you want to know more, Google or sent me a message via Twitter or find my email address on QRZ.com.

73 de PA9X Jean-Paul