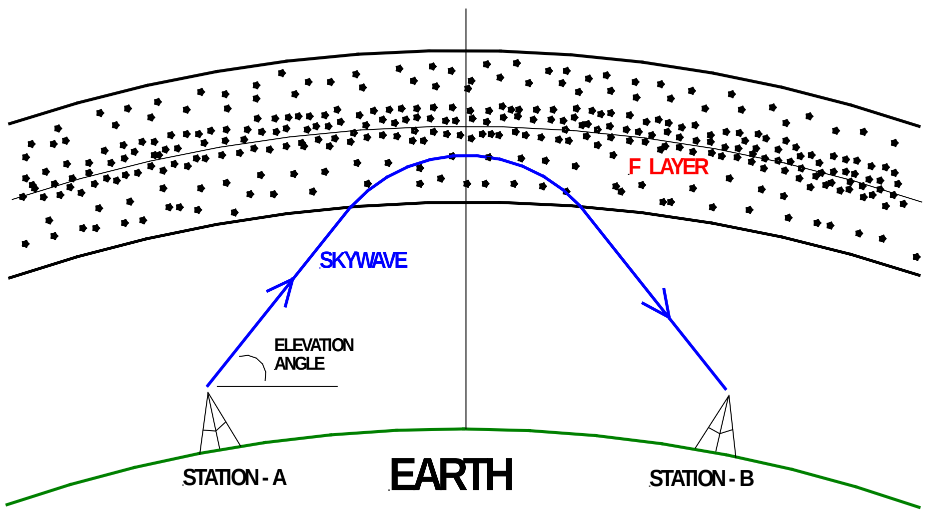
Regional and Long Distance
Skywave Communications



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1 Introduction

This is the second of a two part series studying High Frequency (HF) skywave radio communication. The two parts of the series are:

- Solar Dynamics Affecting Skywave Communications
- Regional and Long Distance Skywave Communications

The characteristics of the Earth's Ionosphere which affect HF radio communications are driven by the dynamics of the Sun. To understand the basics of skywave communications, one must first have an understanding of the Sun and the solar dynamics responsible for Earth's Ionosphere. These issues are covered in the first part of this series. This part, Part 2, looks at the characteristics of the Ionosphere which support both regional and long distance HF radio communications. With this foundation, the mechanisms of skywave propagation are discussed, including refraction, absorption, critical frequency, maximum usable frequency, maximum usable angle, skip distance, and propagation modes. Finally, the parameters used to measure the current conditions of the Sun and the Ionosphere, including Solar Flux, Boulder A and K indices, X-ray Flux, etc., are covered.

2 The Earth's Ionosphere

The Earth's magnetic field protects the atmosphere to some extent from solar winds and Coronal Mass Ejections (CMEs). However, the magnetic field provides no protection from the extreme ultra violate (EUV) and x-rays radiation from the Sun. The solar energy spectrum is shown in Figure 1. Extreme ultra violate and x-ray energy accounts for only one thousandths of a percent (10^{-3} %) of the spectrum. However, it is the extreme ultra violate and x-rays radiation that ionizes the upper atmosphere forming the Ionosphere. The Ionosphere and ozone layers protect the Earth's surface from the Sun's intense radiation. Without the Ionosphere and ozone layers, much of life on Earth could not exist.

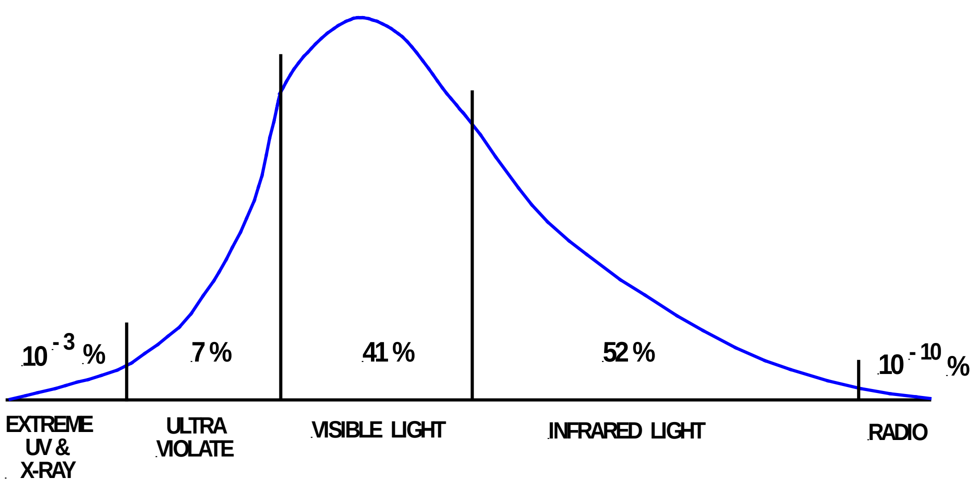


Figure 1 Solar Spectrum

The Ionosphere is formed when oxygen and nitrogen atoms in the upper atmosphere absorb the EUV radiation for the Sun. If an electron in an atom gains enough energy from the absorbed radiation, it will break free from the atom creating a free electron and a positive ion (an atom with a missing electron).

Should they collide, a positive ion and free electron will recombine to form a neutral atom. Collisions and recombination occurs readily in the lower atmosphere where the density of oxygen and nitrogen atoms are high, but at a much slower rate in the rarified upper atmosphere.

Recombination occurs continuously, but ionization can only occur in that part of the atmosphere facing the Sun. Thus the Ionosphere forms quickly in the morning, reaches maximum strength in early afternoon, and then decreases throughout the evening and night reaching its lowest (weakest) level just before sunrise the next morning.

The degree to which the Ionosphere is ionized depends on the level of extreme ultra violate and x-ray energy received from the Sun. The level of EUV and x-ray energy varies with the 11 year solar sunspot cycle as described in the first part of this series "Solar Dynamics Affecting Skywave Communications".

The EUV and x-ray energy originates primarily from bright active areas in the Sun's Chromosphere called plages. Plages are usually, but not always, associated with sunspots. They normally form before the sunspot appears and disappear after the sunspot vanishes. We think of sunspots as being the source of the energy responsible of creating the Earth's Ionosphere. However, plages are actually the source of most of the extreme ultra violate and x-ray energy responsible for the Ionosphere. Since sunspots are easy to see and plages are not. Thus, sunspots serve as markers. If there are large numbers of sunspots visible on the Sun, then there are also large numbers of plages radiating vast amounts of extreme ultra violate and x-ray energy, creating the relatively density upper Ionosphere needed for long distance HF communications. When there are few or no sunspots, there are few plages generating much less extreme ultra violate and x-ray energy, the Earth's Ionosphere weakens, and long distance HF communications is poor.

The 10.7cm Solar Radio Flux (2800 MHz radio waves emitted by the Sun) is a good indicator of probable activity on the Sun, including occurrence of sunspots, plages, flares, etc. The Solar Radio Flux is measured daily by the Dominion Radio Astrophysical Observatory of the Canadian National Research Council located at Penticton, British Columbia, Canada. The level of solar flux is measured in terms of solar flux units that range from a theoretical minimum of about 50 to numbers larger than 300. During the early part of the 11-year sunspot cycle, the flux numbers are low, but they rise and then fall again as the cycle proceeds. The Solar Radio Flux shown in Figure 2 correlates very closely to the sunspot number shown in Figure 3. These graphs are available at www.swpc.noaa.gov/SolarCycle/index.html .

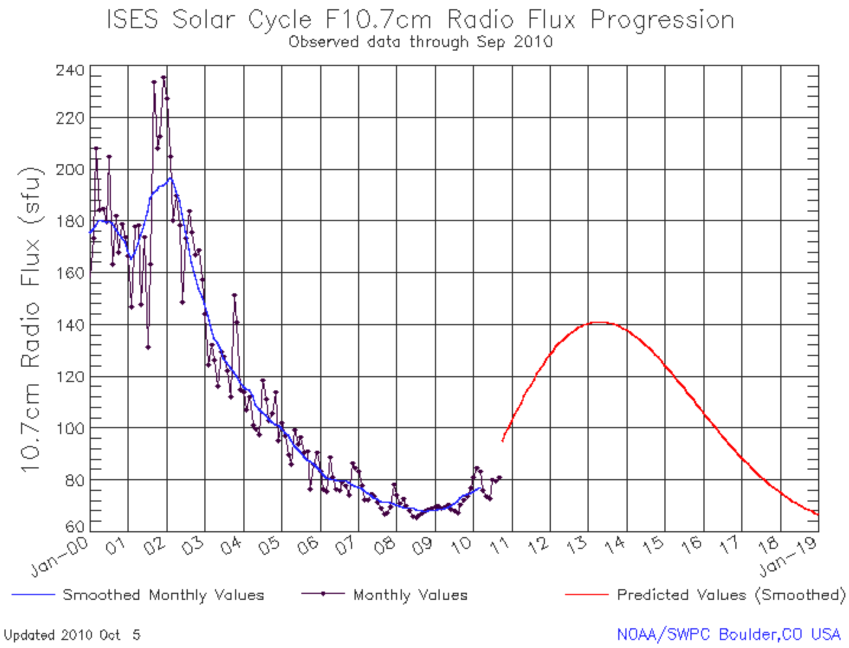


Figure 2 10.7cm Solar Radio Flux

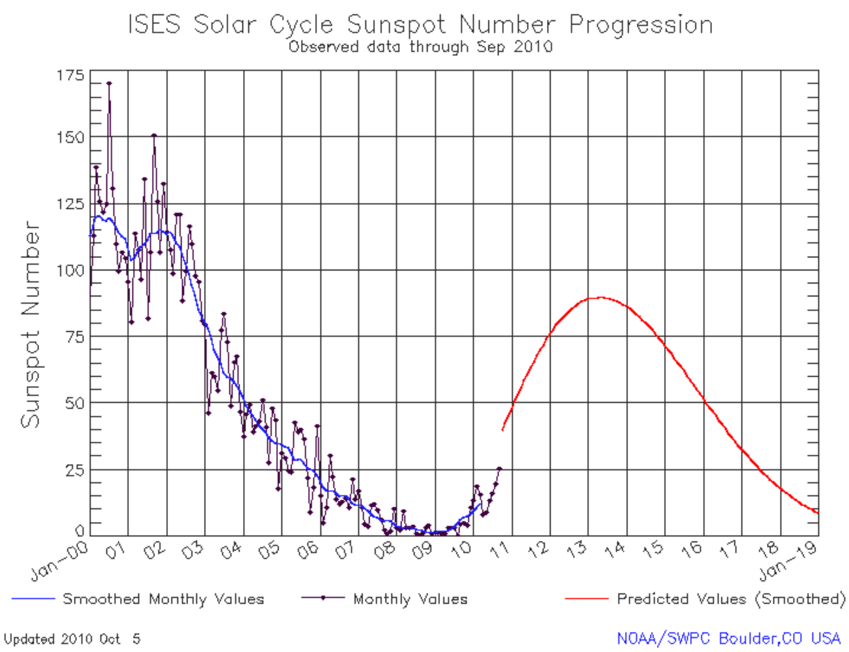


Figure 3 Solar Sunspot Number

3 Structure of the Ionosphere

When fully ionized, the Ionosphere consists of four distinct layers as shown below.

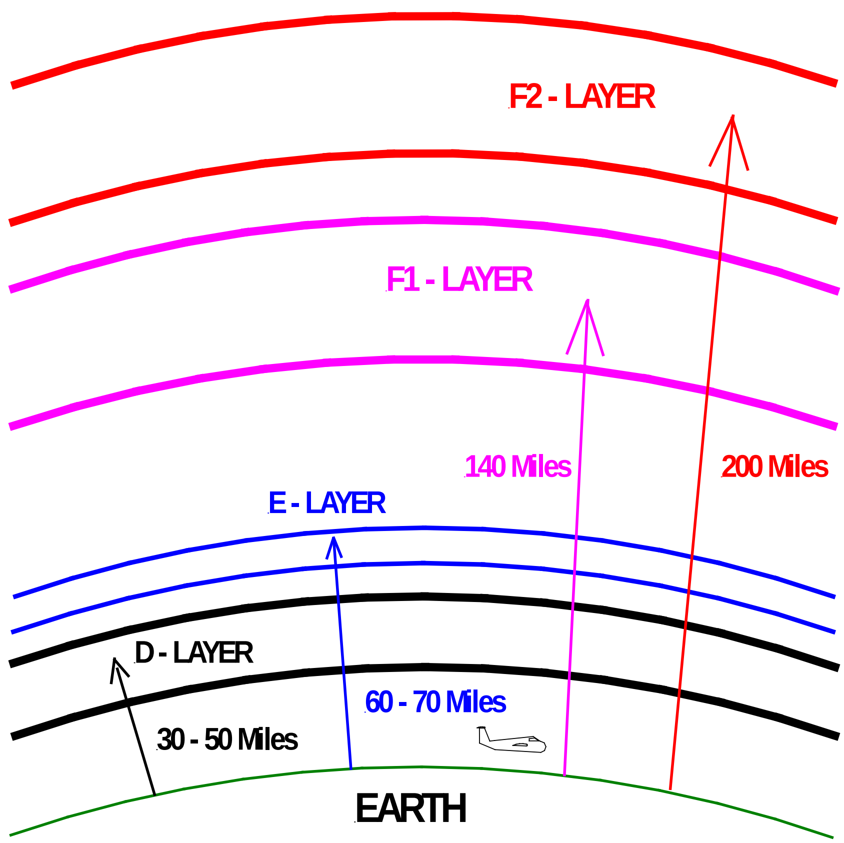


Figure 4 The Ionosphere consists of 4 layers

3.1 F Layer

The F layer is the region of the Ionosphere most responsible for HF communications. This layer is actually a very large region from about 100 to 260 miles above the Earth, depending on the season of the year, latitude, time of day and solar activity. To put the F layer in perspective, we think of the International Space Station orbiting in space above the Earth's atmosphere. Actually, the space station is orbiting in the F layer of the Ionosphere.

The F layer is ionized by extreme ultra violate energy from the Sun. Ionization reaches a maximum shortly after noon local time, and tapers off very gradually toward sunset. At this altitude, the Earth's atmosphere is so thin that ions and electrons recombine very slowly. Consequently, the F layer remains ionized throughout the night, reaching a minimum just before sunrise. After sunrise, ionization increases rapidly for the first few hours. Throughout the rest of the morning it continues to increase, but at a slower rate, reaching its maximum shortly after noontime.

During the day, the F layer splits into two parts, F1 and F2, with the central regions at altitudes of about 140 and 200 miles respectively. These altitudes vary with the season of the year. At noon in the summer the F2 layer can reach an altitude of 300 miles. At night, the two layers recombine to form a single F layer at about 180 miles above the Earth. The F1 layer does not contribute much to long distance communications. It tends to act similar to the E layer to be discussed next. The F2 layer is responsible for almost all long distance communications in the HF amateur radio bands.

3.2 E Layer

The E layer occurs at an altitude of about 60 to 70 miles above the Earth. At this height, the atmosphere is dense enough so that ionization does not last very long. This makes normal HF propagation via the E layer useful only during the day. The E layer reaches maximum ionization around midday, and by early evening the ionization level is very low.

Nighttime E and sporadic E (thin patches of extra ionization) are due to meteor bombardment, providing random opportunities for E level communications. Some sporadic E radio reflections may be due to turbulence in the normal E layer.

3.3 D Layer

The D layer is the lowest layer of the ionosphere. This layer is in a relatively dense part of the atmosphere about 30 to 50 miles above the Earth. The extreme ultra violate energy responsible for creating the F layers of the Ionosphere do not penetrate this deeply into the atmosphere. Atoms in the D layer are ionized primarily by x-rays. Ionization of the D layer will thus increase rapidly following a solar flare as the x-rays generated by the flare reach the Earth.

The ions and free electrons formed in the D layer quickly recombine to form neutral atoms. The amount of ionization in this layer varies widely depending on how much x-ray radiation hits the layer. D layer ionization is maximum around noon time. By sunset, the D layer has usually disappeared.

The D layer is ineffective in refracting (bending) HF radio signals back to Earth. The major effect the D layer has on HF communication is to absorb energy from radio waves. The amount of absorption is proportional to the amount of D level ionization. The more ionization, the more energy the radio waves lose as they pass through the D layer. Absorption is thus most pronounced at midday. D layer absorption increases rapidly following a large solar flare, disrupting HF communications for up to several hours.

4 Skywave Radio Communications

Figure 5 illustrates HF radio signals being transmitted from Station-A to Station-B through the F layer of the Ionosphere. The transmitted radio waves travel in a straight line from the Station-A antenna to the Ionosphere. However, once they enter the Ionosphere they are refracted (bent) back to Earth by their interaction with the Ionosphere’s free electrons. The ions that are also produced in forming and maintaining the Ionosphere are too massive to interact with the passing radio waves. Thus the F layer ions do not play a role in skywave radio propagation.

4.1 Refraction of Radio Waves

How does refraction work? As shown in Figure 5, the density of free electrons in the F layer is not uniform. The highest density of electrons occurs approximately in the center of the F layer with very few at the top and bottom of the layer. The density of electrons increases gradually from zero at the bottom of the F layer to a maximum at its mid point. The density then decreases from the mid point back to zero (no free electrons) at the F layer's upper boundary. The electron densities in the D and E layers act in the same way. It is this variation in electron density that causes the radio waves to be bent back to Earth.

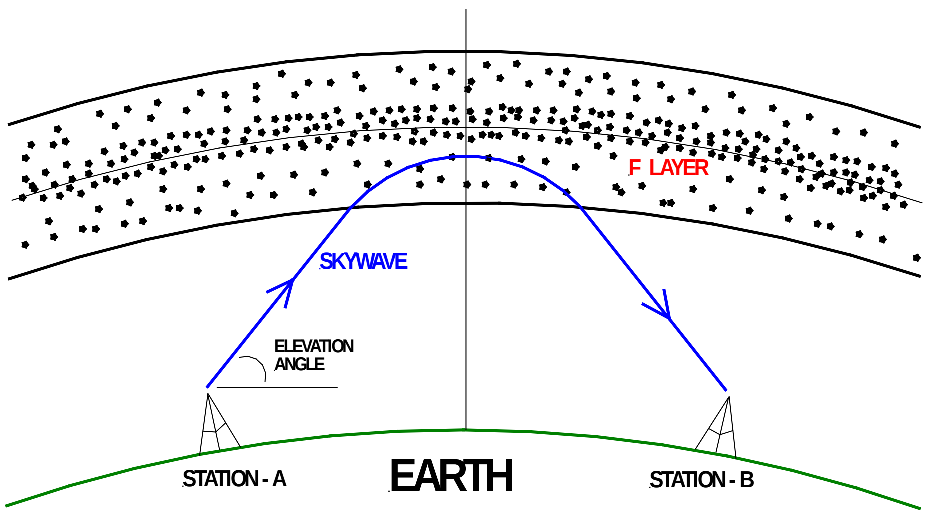


Figure 5 Skywave Propagation

As the radio wave enters the bottom of the F layer it interacts with the few free electrons there and is bent very slightly to the right. As it travels deeper into the F layer the increasing density of free electrons causes the radio wave to continue bending to the right (in a clockwise direction) at an increasing rate. At some point, the radio wave has been bent so far that it is traveling parallel to the Earth's surface. If the radio wave kept bending at an increasing rate in the clockwise direction, it would end up traveling in a tight circle of decreasing radius until it spiraled into a point and disappeared, as shown in Figure 6, never exiting from the F layer. That does not happen. As soon as the radio wave is bent ever so slightly from its path parallel to the Earth's surface back toward the Earth, something different begins to happen. The radio wave is now traveling in a direction of decreasing electron density. The decreasing density cause the radio wave to bend in the opposite direction. The radio wave straightens out, exits the bottom of the F layer and travels to Station-B as shown in Figure 5.

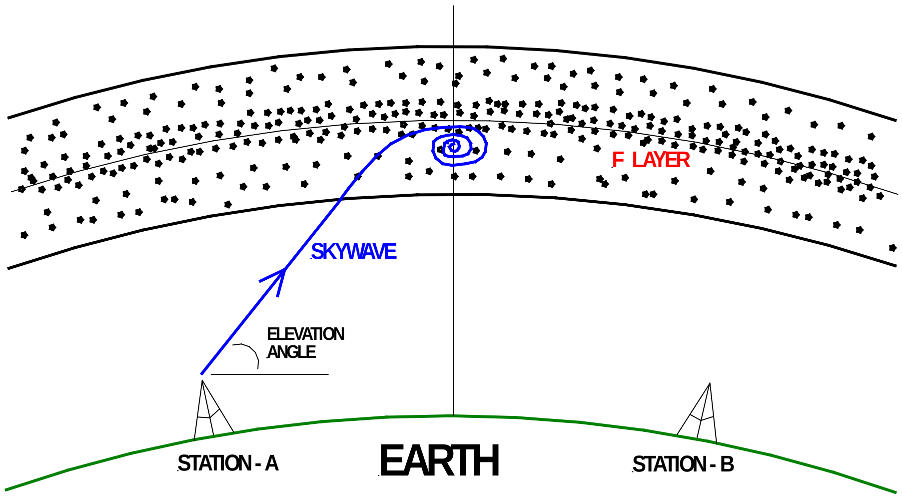


Figure 6 This does not happen

4.2 The Frequency Dependency of Refraction

Not all frequencies are refracted the same in the F layer. Low frequency signals are refracted quicker than higher frequency signals. 80 meter radio waves are refracted sooner than 40 meter radio waves. 40 meter radio waves are refracted quicker than 15 meter signals. 2 meter radio waves are not refracted at all but pass instead through the Ionosphere to outer space.

If a radio wave travels all the way to the center of the F layer without being sufficiently refracted, it will pass through the most dense part of the F layer. Once this happens, the radio wave will be traveling in a region of decreasing electron density. The radio wave will be bent in a counter clockwise direction, straighten out, and pass through the upper boundary of the F layer into outer space, as shown by frequency f 4 in Figure 7.

Why are the refraction properties of the Ionosphere frequency dependant?

To understand the answer to this question we have to look more closely at the interaction of the Ionosphere's free electrons with the passing radio waves. Some of the free electrons interact with the radio waves oscillating at the same frequency as the radio wave. The electrons absorb energy from the radio wave in the process. The oscillating electrons re-radiate their absorbed radio energy in a different direction. The sum of the original radio wave plus the waves re-radiated by the electrons create a resulting wave that is bent (refracted) from the original radio wave path.

Free electrons can easily interact and oscillate with low frequency radio waves, such as 3.9 MHz (75 meter) signals. Because the free electrons themselves are traveling at high speeds in random directions, only a small percentage of electrons are able to follow the oscillations of higher frequency radio waves, for example a 21 MHz (15 meter) signal. Radio waves at this frequency must travel further into the F layer, where the electron density is higher, to encounter enough electrons capable of interacting with its high frequency oscillations. A 147 MHz (2 meter) radio wave passes all the way through the most dense central region of the F layer without ever encountering enough electrons capable of oscillating at its very high frequency. As a result, 2 meter VHF radio waves pass through the F layer and into outer space. Radio waves at VHF and higher frequencies are thus required to communication with satellites and space probes.

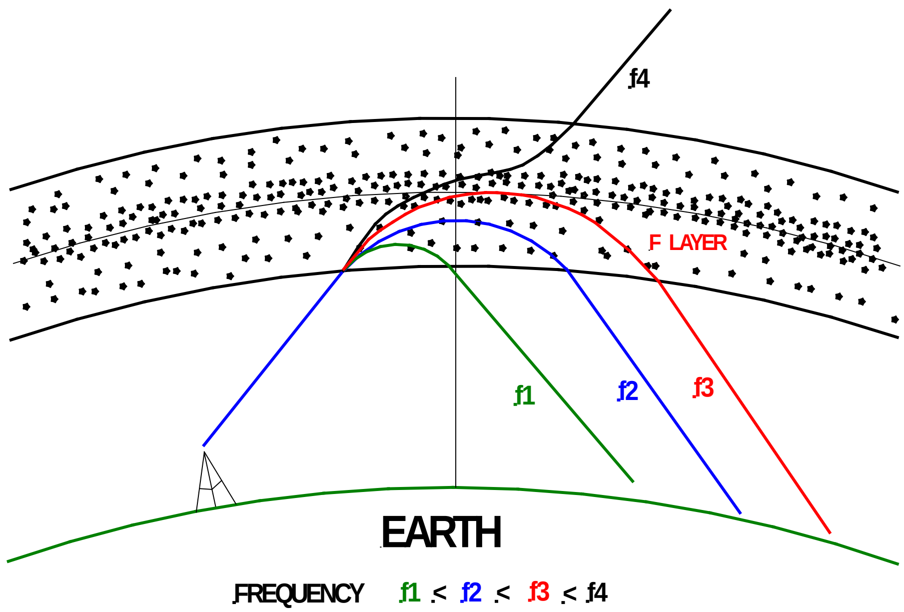


Figure 7   Frequency Dependence of Refraction

As shown in Figure 7, higher frequency HF signals travel further on a single hop (one excursion through the Ionosphere) because they are refracted from a higher point in the F layer. Thus a 10 meter signal (f3) travels further than a 15 meter signal (f2), which in turn travels further than a 20 meter signal (f1) assuming that the F layer is sufficiently ionized to support skywave communications on all three frequency bands.

4.3 D Layer Absorption

Why are radio waves absorbed in the D layer? In the F layer free electrons exist for long periods of time before finally recombining with the heavy oxygen and nitrogen ions. The free electrons have plenty of time to re-radiate the energy that they absorb from passing radio waves, allowing refraction to occur.

In the D layer, free electrons recombine with ions almost immediately. The radio energy absorbed by a free electron is passed to the ion that it recombines with instead of being re-radiated, and is thus lost. The ion is too massive to re-radiate the small amount of radio energy transferred to it by the electron.

Since electrons absorb energy from low frequency signals easier than high frequency radio waves, low frequency signals are more affected by D layer absorption. The amount of absorption is inversely proportional to the square of the frequency. That is:

$$D_{absorb} \approx \frac{1}{f^2}$$

where

D_{absorb} = the level of absorption, and
f = frequency.

During daylight hours when the D layer is present, communications at 7.050 MHz on the 40 meter band will incur 4 times more D layer absorption than a 14.100 MHz signal on the 20 meter band.

4.3.1 D Layer Absorption During a Solar Flare

The D layer is heavily ionized whenever the x-rays from a solar flare reach the Earth. When a solar flare occurs, communications will be lost first on the 80 and 40 meter frequency bands. Communications on the 30 and 20 meter bands will disappear, or at least become erratic, a few minutes later. Communications on the 15 meter and higher frequency bands may not be affected at all. Note that a flare affects communications only on that part of the Earth facing the Sun.

The following figures show what happen during a massive solar flare on September 7, 2005. Figure 8 shows the x-ray flux measured by the GOES satellites. X-ray energy from the Sun was at normal levels prior to 1700 hours UTC, 10 AM in California. At approximately 1720 UTC the solar flare hit. At the time our Auxiliary Communications Services (ACS) Area 2 team, operating from our radio room at the East County Sheriff's Station in Thousand Oaks, California, had just completed participation in the California Emergency Management Agency 40 meter net. Per our procedure, we began taking signal strength readings for WWV (Boulder, Colorado) and WWVH (Kauai, Hawaii). At 1650 UTC, just prior to the California net, we had received good WWV and WWVH readings on 5, 10, and 15 MHz. When we checked at 1720 UTC, WWV on 5 MHz was completely gone. We tuned to WWV & WWVH on 10 MHz, it was "shaky". WWV & WWVH on 15 MHz was ok. We tuned back to 10 MHz, WWV & WWVH were gone. We returned to 15 MHz, it too was now gone. Signals did not return again on these frequencies until late in the afternoon local time.

Figure 9 shows the D layer absorption an hour into the event at 1830 UTC. At that time the Sun was positioned directly over head off the west coast of Costa Rica (the Sun is the black diamond shown in Figure 9). The most intense D layer absorption occurred in the region where the Sun was directly overhead (the orange circle). California was heavily affected (the green section of the chart).

Notice that central Asia, on the opposite (night time) side of the world was not affected at all. The bar graph on the right side of Figure 9 shows the level of D layer attenuation verses frequency. At 5 MHz the attenuation was about 28 db, at 10 MHz nearly 15 db, and maybe 2 db at 20 MHz. The estimated recover time of 1 hour 17 minutes was way off. The flare lasted much longer than expected.

X-ray flux plots are available at www.swpc.noaa.gov/rt_plots/xray_1m.html and are updated every minute. D level absorption can be viewed at www.swpc.noaa.gov/ by selecting Global D-Region Absorption under Popular Pages.

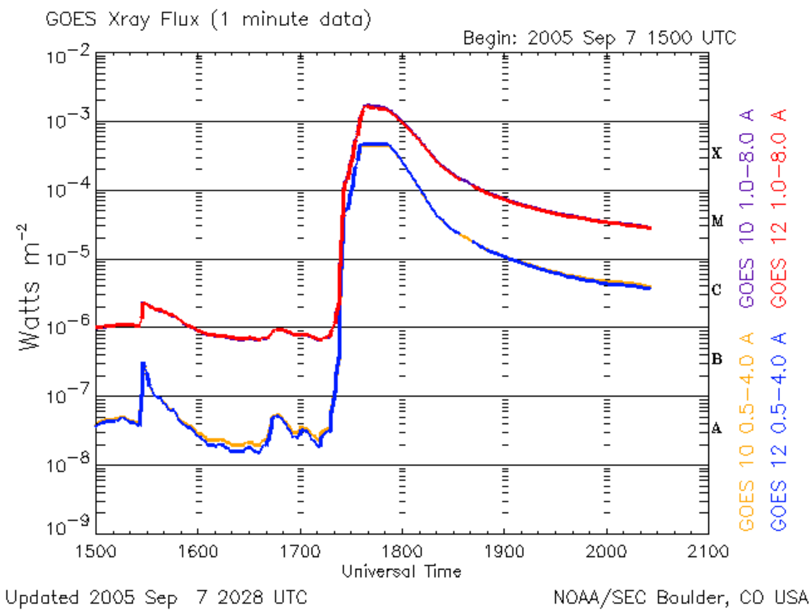


Figure 8 X-ray Flux from September 7, 2005 solar flare

Note that the X-ray Flux chart is a logarithmic graph. The x-ray flux levels in Band B are ten times that in Band A. Under quiet solar conditions, the GOES 12 display (the red curve) is in Band A or B.

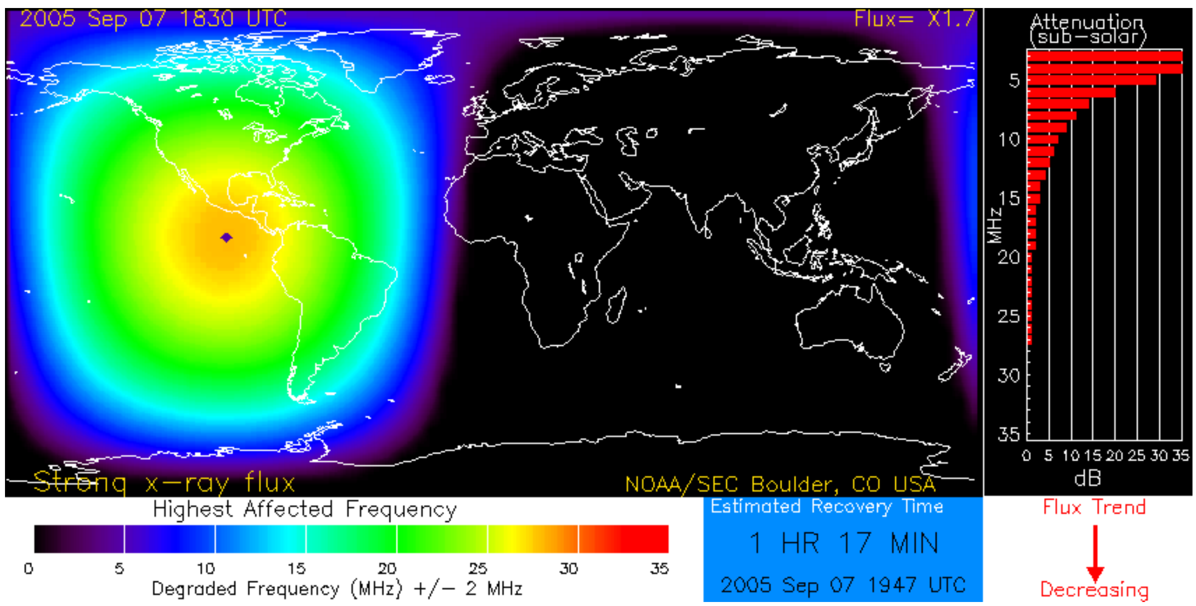


Figure 9 D layer absorption from the September 7, 2005 solar flare

The colorful display shown above only occurs when there are abnormal levels of D layer absorption, such as when a solar flare is in progress. Normally, the chart is simply a black ground with the white outline of the continents and a blank attenuation chart.

4.3.2 Gray Line DX

Communications along the gray line (the line separating night and day shown in Figure 10) is well known for its long distance DX opportunities. This is easily understood in terms of D layer absorption. The gray line represents late afternoon early evening local time when the D layer has mostly if not completely disappeared. Thus, all along the gray line there is no D layer absorption. However, the much higher F layer is still in full sunlight and highly ionized. These are excellent conditions for skywave propagation through the Ionosphere, a strong F layer and no D layer absorption. As a consequently, long distance communications along the gray line is possible on the 40 meter and higher frequency amateur radio bands. The gray line map shown below can be viewed at http://dx.qsl.net/ under the Propagation Tab. The map is updated every 5 minutes.

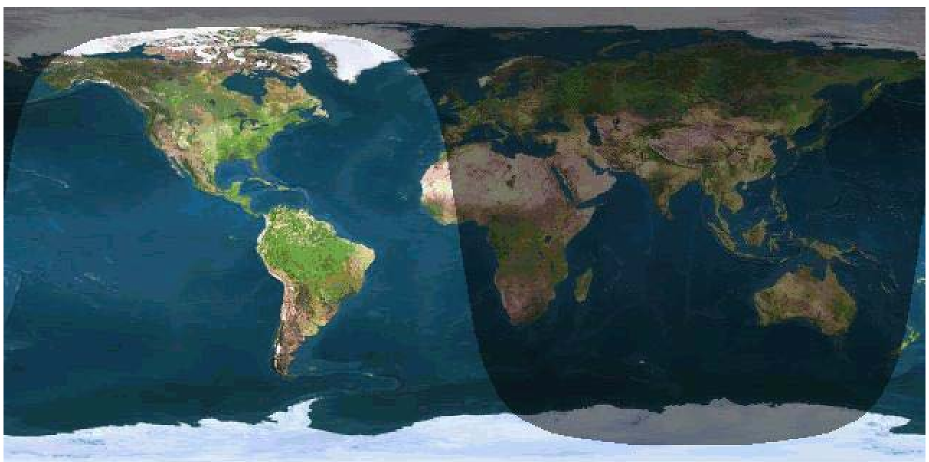


Figure 10 Gray Line

4.3.3 Low Band DX Opportunities

Long distance DX communications on the low frequency amateur radio bands (160 and 80 meters) occurs only at night. For a good low band DX contact to occur, it must be night time over the entire length of the radio circuit. The 160 and 80 meter frequency bands are the most severely affected by D level absorption. So long distance communications must occur late at night when the D layer has completely disappeared. Low frequency signals are the easiest to refract in the F layer. Fortunately, at night there is still enough ionization left in the F layer to support long distance communications at these low frequencies. Thus communications on the 160 and 80 meter amateur radio frequency bands is possible when communications on the 40 meter and higher frequency bands is no longer viable.

4.4 Critical Frequency

Critical frequency is the highest frequency radio wave that can be transmitted straight up into the Ionosphere and reflected back, as shown in Figure 11.

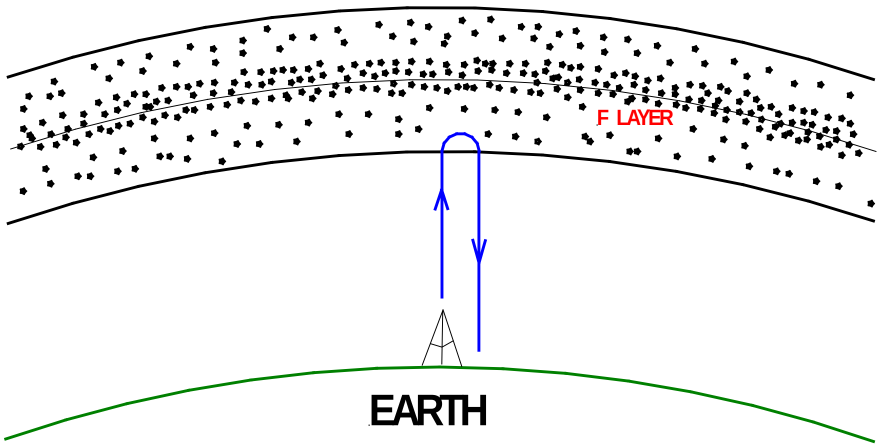


Figure 11   Critical Frequency

Critical frequency varies with the sunspot cycle, seasonally, with the latitude of the transmitting station, and throughout the day in accordance with the level of F layer ionization. The critical frequency is at its lowest level just before sunrise. During sunspot minimum, the critical frequency may drop to as low as 1 to 2 MHz. The critical frequency increases rapidly following sunrise, reaching a maximum shortly after noon local time. Within the continental United States, noon time critical frequency may only be around 5 MHz during sunspot minimum and as high as 14 MHz during sunspot maximum. In the equatorial zones, the critical frequency will be much higher.

A global map showing the critical frequency contours world wide, and updated hourly, is distributed on the internet by the Australian Government IPS Radio and Space Services, www.ips.gov.au/HF_Systems/6/5 . An example of the map is shown in Figure 12 for 1900 UTC on October 13, 2010. The color code key for the map is shown in its upper left hand corner. For this particular map, all of California and most of central United States is in the blue band, meaning that the critical frequency above California at the time the map was issued was 6 MHz. Notice that the critical frequency above the Caribbean is 11 MHz and the critical frequency over north central Asia, where it was still night, is 2 to 3 MHz.

Governments and other organizations world wide make vertical sounds of the Ionosphere F layer over their locations several times an hour. This sounding data is sent to Australian Radio and Space Services who then process the data, creates and distributes the maps.

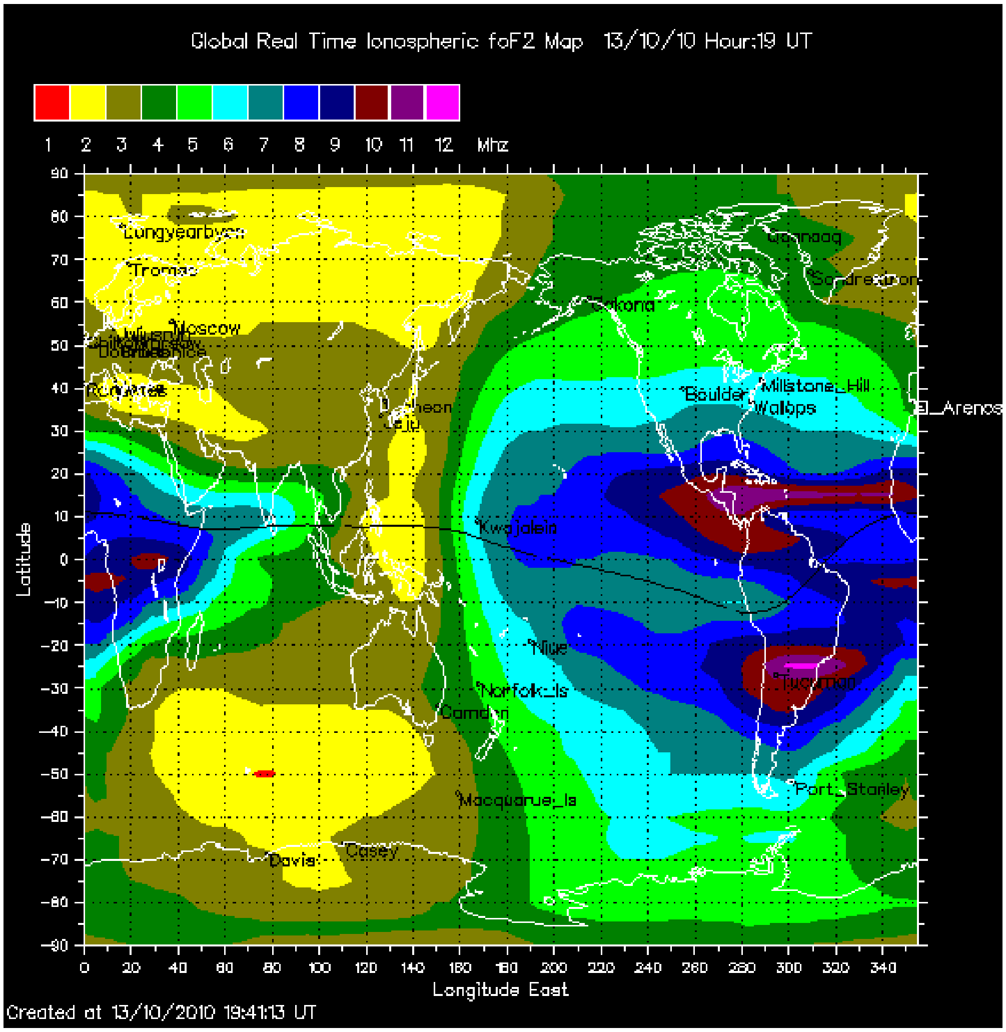


Figure 12 World Wide Critical Frequency Map

4.5 Maximum Usable Frequency

Maximum Usable Frequency (MUF) is the highest frequency that can be used to communicate between two locations. All frequencies lower than the MUF can also, potentially, be used for communications between the two sites as shown in Figure 13.

There is also a lowest usable frequency. All frequencies below the lowest usable frequency are absorbed by the D layer and thus can not be used for communications. Sometimes during periods of sunspot minimum, the lowest usable frequency can be higher than the Maximum Usable Frequency. When this occurs, no communications between the two sites is possible. Regional communications occasionally runs into this problem during day time nets when sunspot activity is at a minimum. For example, communications on 40 meters (7.230 MHz) between stations participating in the net are very poor with some stations unable to be heard. The Maximum Usable Frequency for some of the stations is below the net frequency. The net switches to 75 meters (3.960 MHz) in an attempt to achieve better communications. The 75 meter frequency is below the Maximum Usable Frequency for all participating stations, and should thus be a good choice. However, all signals on the 75 meter band are being absorbed by the D layer, so no communications is possible there either.

Maximum Usable Frequency is equal to:

$$MUF = \frac{f_c}{\sin\alpha}$$

where

f_c = the critical frequency at the time of the communications, and
α = the elevation angle of the signal radiating from the transmit antenna relative to ground.

For a signal transmitted straight up $\alpha = 90^\circ$ and $\sin\alpha = 1$. In this case, MUF = f_c, as it should. As the angle α decrease, the value of $\sin\alpha$ becomes smaller (less than 1) causing MUF to be greater than f_c .

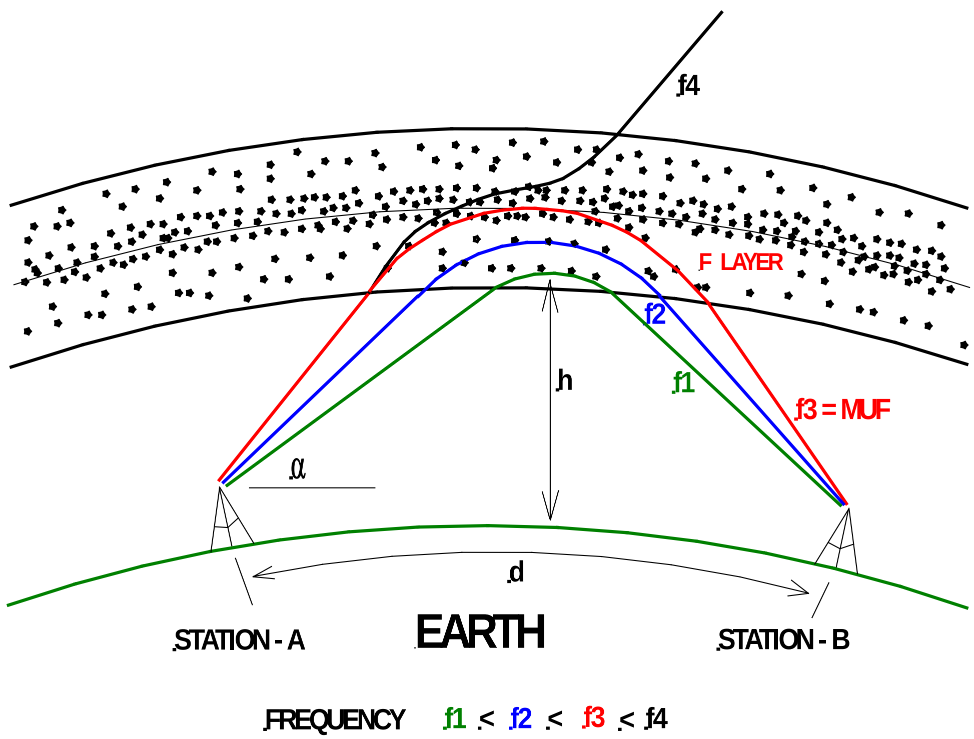


Figure 13 Maximum Usable Frequency

The MUF is different for each communications path. That is, for a given time of day, the MUF for a communications circuit from Los Angeles to Denver will be different from the MUF for a circuit between Los Angeles and San Diego.

The angle α depends on the distance "d" between the two communicating sites and the height "h" at which the signal is refracted in the Ionosphere. Specifically

$$\sin \alpha = \frac{h}{\sqrt{(d/2)^2 + h^2}}$$

A 10 meter signal will penetrate further into the Ionosphere before being refracted than a 20 meter signal. Thus the height h_{10} for the 10 meter radio wave will be greater than h_{20} for the 20 meter signal. This means that α for the 10 meter transmission will be greater than for 20 meter communications, as shown in Figure 13.

The distance from Los Angeles to Denver is approximately 1025 miles. If the refraction point in the F layer is assumed to be 200 miles, then $\alpha = 21^o$. Assuming the critical frequency at the time of the transmission is 9 MHz, the Maximum Usable Frequency for this communications path is 25 MHz. A 15 meter communications circuit between Los Angeles and Denver is viable since the MUF is greater than the 21.3 MHz frequency probably used for the 15 meter transmission.

A double hop signal transmitted at an angle of 40 degrees could also be used to communicate from Los Angeles to Denver as shown in Figure 14.

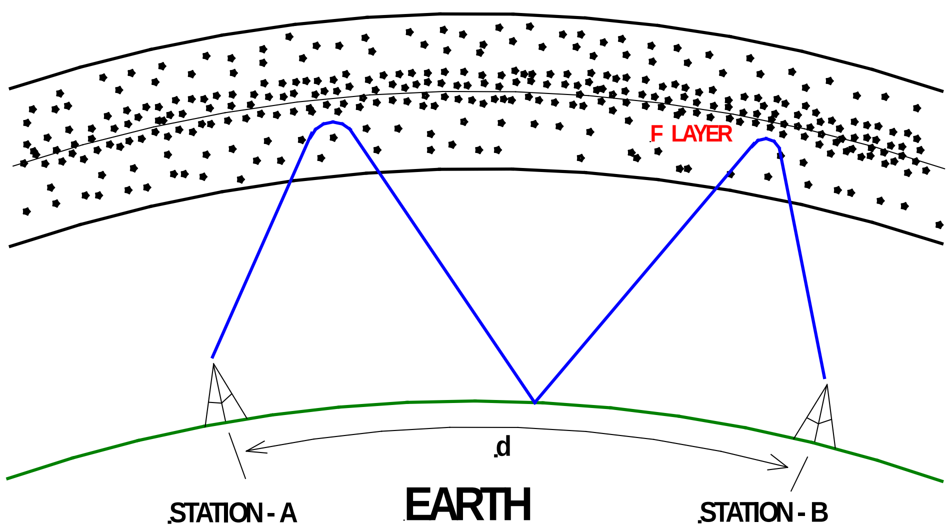


Figure 14 A Double Hop Transmission.

In this case, the transmitted signal will refract from the Ionosphere, return to Earth 512 miles from Los Angeles, reflect from the Earth's surface, travel back up into the Ionosphere where it will be refracted a second time and finally arrive at Denver. The Maximum Usable Frequency for this double hop path is 14.5 MHz, again assuming a critical frequency of 9 MHz. In this case, 20 meters is the highest usable amateur radio band for double hop communications between Los Angeles and Denver. The single hop path will produce a stronger signal at Denver because it will incur lower losses than the double hop path. Using the information presented here, transmission to Denver via the single hop path can be guaranteed using the 17 and 15 meter bands. If 20 meters is used, signals may propagate to Denver via the single hop path, or the double hop path, or both. This could lead to undesirable multipath interference. Thus, the best choice for communicating with Denver is to select one of the higher frequency bands that supports only the single hop propagation mode.

At the same time, and under the same conditions, the Maximum Usable Frequency for single hop communications with San Diego (125 miles from Los Angeles with a required elevation angle of 72^o) is 9.45 MHz. Thus 40 meters is the highest frequency band that can be used for communications with San Diego under the given conditions.

4.6 Maximum Usable Angle

Maximum Usable Angle (MUA) is the highest elevation angle α that a signal of a given frequency (or in a given frequency band) can be transmitted and be refracted to Earth. The Maximum Usable Angle is derived by solving the Maximum Usable Frequency equation for α, in this case α_{max}.

$$\mathrm{MUA} = \alpha_{max} = \sin^{-1}\left[(f_c / f_b) \text{ or } (1 \text{ if } f_c \geq f_b)\right]$$

where

f_c = the critical frequency, and
f_b = the center frequency of the particular amateur radio band of interest.

Any signal, in the given frequency band, transmitted at an elevation angle $\alpha \leq \alpha_{max}$ will also be refracted back to Earth. However, a signal transmitted at an angle $\alpha > \alpha_{max}$ will pass through the Ionosphere and be lost to outer space. For example, if the critical frequency is 9 MHz, the Maximum Usable Angle for the 40 meter band (7.2 MHz) is 90^o. That is, for this critical frequency all signals transmitted in the 40 meter frequency band will be refracted to Earth regardless of the elevation angle, including signals transmitted straight up. However, if the critical frequency is 5 MHz, the MUA for signals transmitted in the 40 meter band is 44^o. At this critical frequency, any 40 meter signals transmitted at an elevation angle greater than 44^o will be lost to outer space.

The Maximum Usable Angle is important when operating regional HF communications circuits utilizing the Near Vertical Incident Skywave (NVIS) mode of transmission. Regional HF communications is often needed for emergency communications work when disaster relief organizations want to communicate with near by cities capable of sending personnel, equipment, and supplies to aid in recovery efforts. Regional HF communications may be the only way of communicating with these cities during a natural disaster if they are beyond the reach of local VHF and UHF repeaters.

4.7 Skip Distance

A skywave signal transmitted at a low elevation angle α, Ray-1, travels a considerable distance as shown in Figure 15.

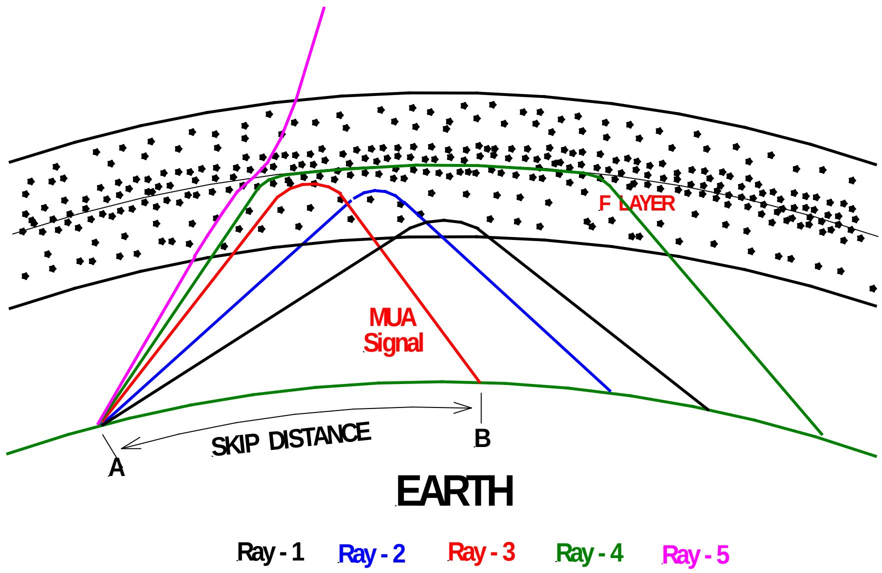


Figure 15 Skip Distance

Increasing the elevation angle, without changing frequency, shortens the transmission path to that of Ray-2. A signal transmitted at the Maximum Usable Angle will travel the shortest distance, Ray-3. Increasing the elevation just a little further causes the transmission distance to again increase (Ray-4). Increasing the angle any further will cause the signal to pass through the Ionosphere to outer space (Ray-5). The difference in elevation angle between Ray-4 and Ray-5 is very slight. Attempting to use Ray-4 to achieve very long hops is very unreliable and erratic. It can, however, sometimes occur when operating near the Maximum Usable Angle, even though it was not intended.

The distance from A to B is defined as the skip distance. Stations within the skip distance (within the skip zone) can not be heard by or communicate with either site A or B via normal skywave propagation. These locations are “skipped over” because communications with them would require a higher elevation angle α than can be supported by Ionospheric conditions at the time, that is an elevation angle greater than the Maximum Usable Angle. Stations within about 60 miles of A (depending on terrain) can sometimes hear the transmissions of A via ground level propagation modes, and Station A can hear them. Under some conditions, stations within the skip zone can also hear and be heard by Station A as the result of back scatter. The same occurs with stations in the skip zone close to Station B. Ground level and back scatter propagation modes are discussed in the following subsections.

The skip distance D_s is roughly equal to:

$$D_s = \frac{2h}{\tan\alpha}$$

where

h = the height of the signal refraction point in the Ionosphere, a
α = the signal elevation angle.

Because of the Earth's curvature, and other factors, the skip distance is actually a little long than given by the above equation.

4.7.1 Line of Sight HF Communications

We often forget that line of sight communications is also possible with HF radio signals. While most of the energy from HF antennas is radiated upward into the Ionosphere, a small part of the energy is also radiated out horizontally. Vertical antennas, including the antennas on vehicles equipped with HF mobile equipment, do have a significant near horizontal component. The horizontally radiated energy propagates very similar to VHF and UHF transmissions. It follows straight line of sight paths, the height of the transmitting station relative to surrounding terrain matters, and the HF signals reflect off large objects, particularly mountains, as shown in Figure 16. The length of HF radio waves are much longer than those of VHF and UHF signals, so one would expect the reflection properties of HF signals to be quite different from those of VHF / UHF. That could be quite important in some situations. In mountainous terrain where there are no VHF or UHF repeaters, radio equipped vehicles may have better success communicating with one another using HF reflected line of sight communications than with VHF or UHF line of sight communications. Of course, the opposite could also be true. It depends on the location.

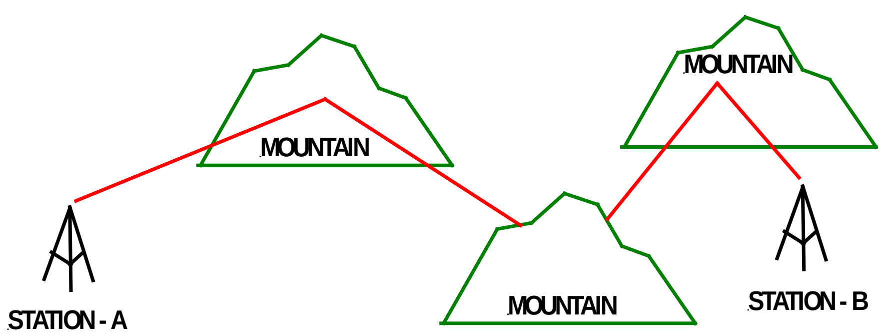


Figure 16 Line of Sight HF Communications

The annual Sea to Summit bike ride, supported each year by the Ventura County ACS/ARES group, begins near the Pacific Ocean and winds its way through the mountains of the northern Ventura County back country to Mount Pinos at 7,000 feet. There are no VHF or UHF repeaters in the area, so the ACS/ARES team normally positions portable repeaters on two mountain tops to provide radio coverage for the bike ride. Portable HF radios stations were positioned along the course one year to see if HF Near Vertical Incident Communications (NVIS) could supplement VHF / UHF communications, particularly in some of the deeper canyon areas. The experiment was successful. HF communications worked out quite well. One of the puzzles was that an HF equipped mobile unit was also achieving excellent HF results. A mobile unit with a vertical HF antenna should not be capable of NVIS communications. Later it was discovered that the critical frequency on the day of the bike ride was too low to support NVIS communications. It turned out that the successful HF communications was the result of the HF signals reflecting off the canyon walls and high mountains in the area. While the communications paths for this experiment were extremely short in terms of what we normally think of for HF communications, the experience has provided another very useful tool in conducting emergency radio communications is this back country of Ventura County.

In areas where mountains are present, reflected line of sight propagation may also account for communications with stations in the skip zone that one would not expect to hear. Horizontal HF signals reflect sideways off the sides of mountains just as well as skywave signals reflect vertically off the "Earth" on multi-hop propagation paths. While line of sight HF communications is of no use for long distance communications, it can be very important for close in regional emergency communications work.

4.7.2 F Layer Back Scatter

Another propagation mode that can account for stations in the skip zone being heard is F layer back scatter. Back scatter occurs when part of the energy from a skywave signal scatters back toward the transmitting sight from a distant skywave ground reflection point as shown in Figure 17. Signals often back scatter from ocean reflection points.

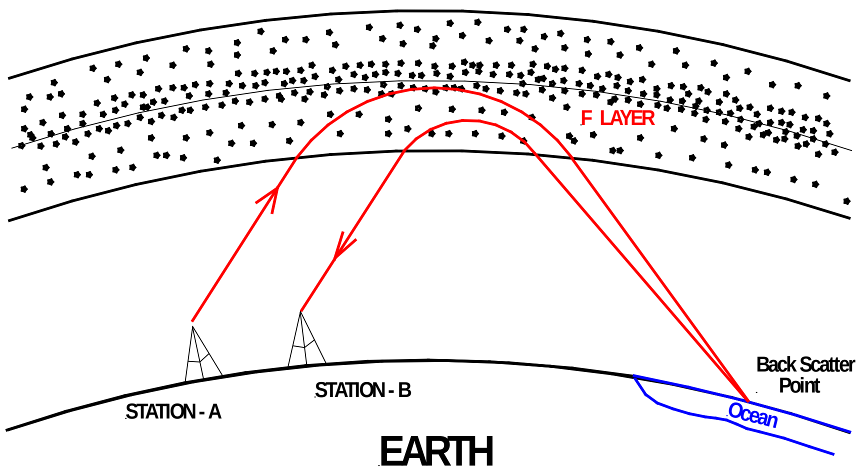


Figure 17 HF Back Scatter

4.8 Long Distance DX Communications

Considerable loss in signal strength occurs with each hop through the Ionosphere due to ground reflection and Ionospheric losses. Ground reflection losses along can be 1 – 3db per hop. Delivering a strong signal to the receiving site is achieved in part by minimizing the number of hops needed to get there. This is accomplished by transmitting at the lowest elevation angle possible.

This concept is illustrated in Figure 18 for a one hop path and a two hop circuit. The elevation angle α for the one hop circuit is considerable less than that for the two hop path.

Thus far we have discussed the transmitted signal as if it were a single very thin ray of energy. It of course is not. Figure 19 shows the vertical radiation pattern for a half wave horizontal dipole antenna. The elevation angle α of maximum radiation from the antenna is approximately 30^o. This is the angle normally used in calculating the hop distance for an antenna. However, the antenna radiates a considerable amount of energy at its -3db point which occurs at an angle of 15^o. A signal radiated at 15^o will require fewer hops and suffer less loss on a long distance circuit than signals

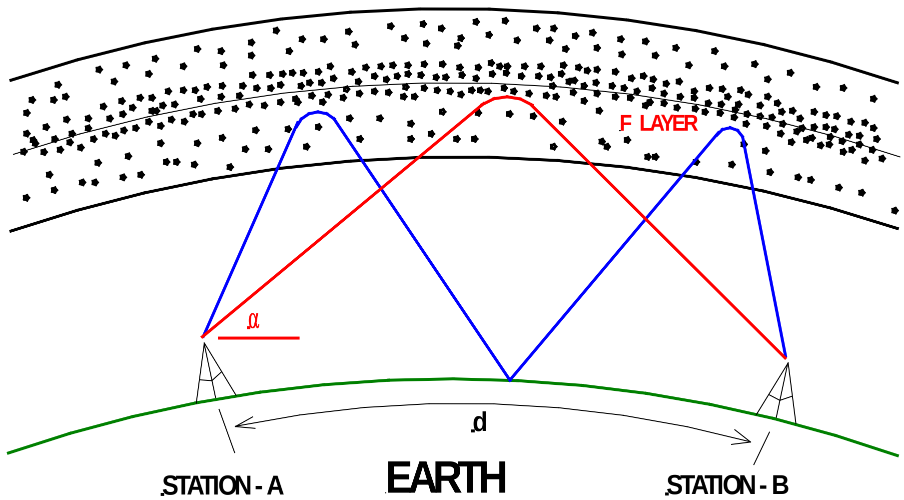


Figure 18 Elevation Angle vs Skip Distance

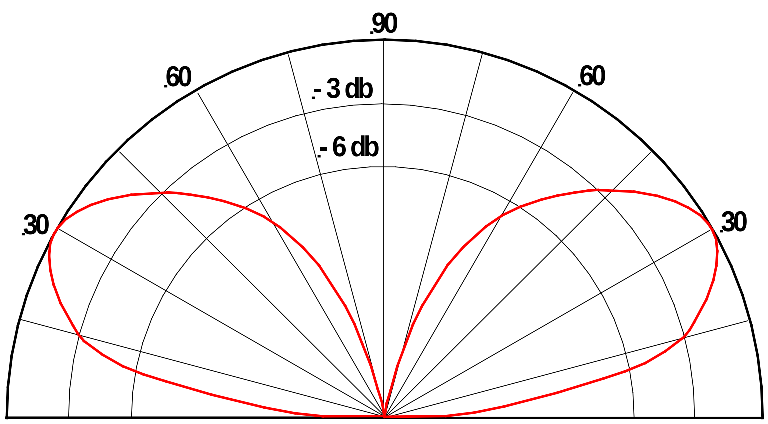


Figure 19 Half wave horizontal dipole, ½ wavelength above ground

radiated at 30^o. If that part of the signal radiated at 15^o requires three fewer hops, it will be the stronger signal upon arriving at the receiver, even though it initially began at a 3 db deficit. It may in fact be the only part of the antenna's radiated energy that actually arrives at the distant receiving site.

The radiation pattern shown in Figure 19 is achieved by installing the antenna a half wavelength above ground, its optimum height for long distance DX communications.

A vertical is the other popular antenna used for long distance DX communications. Its vertical radiation pattern is shown in Figure 20.

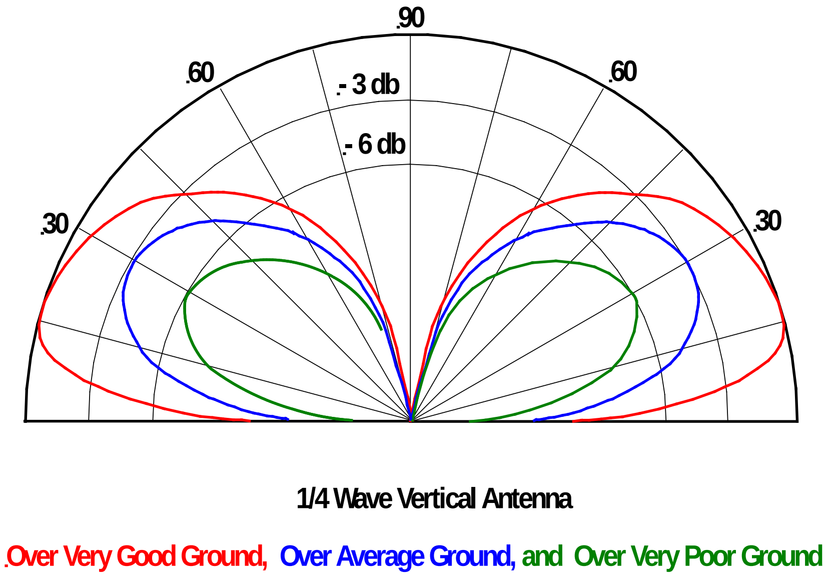


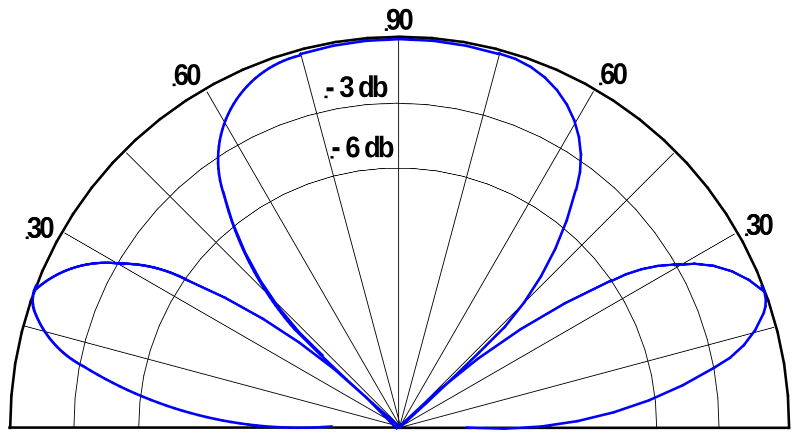
Figure 20 Vertical Antenna Radiation Patterns

A vertical antenna installed on very good moist ground, such as rich farm land, has a lower elevation angle than a horizontal 1/2 wave dipole antenna. With an elevation angle of 15^o, a vertical antenna is an excellent choice of a long distance antenna. The problem with a vertical antenna is that its performance is seriously affected by the condition of the ground on which it is mounted. For average ground (typical suburban communities), and very poor ground conditions (desert locations), a vertical antenna actually performs worse than a horizontal 1/2 wave dipole antenna. That is, its elevation angle is the same as that of a dipole but its radiated energy is over 3db less than the dipole.

A horizontal 1/2 wave antenna also has its problems as shown in Figure 21 and Figure 22.

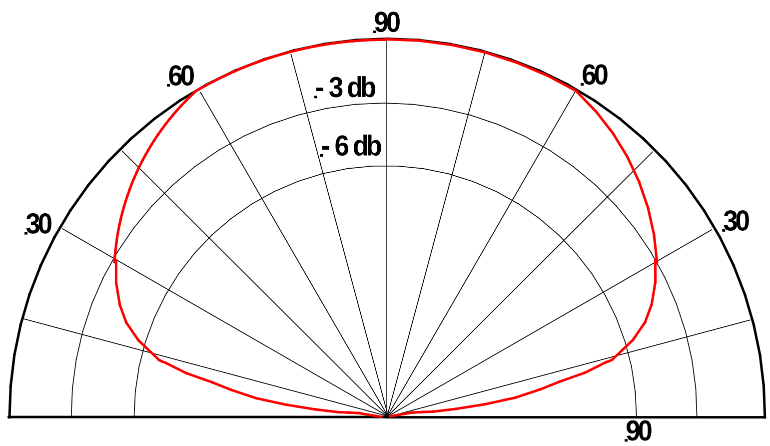
The antenna has high angle radiation lobes if it is installed too low or too high, that is installed less than 1/4 wavelength or more that 3/4 wavelengths above ground. These high angle radiation lobes are of no value for long distance communications. They simply degrade the antenna's performance. A horizontal dipole antenna installed 3/8 to 5/8 wavelengths above ground usually provides excellent long distance communications results. A half wavelength above ground is the most desirable height. Inverted V antennas have radiation patterns similar to those of horizontal dipoles provided the apex angle between the sloping wires is more than 90^o and the center of the antenna is the same height as the horizontal antenna. An Inverted V becomes a horizontal dipole if its apex angle is increased to 180^o.

The chart below shows the respective heights for 160 through 10 meter horizontal dipole antennas.



1/2 Wave Dipole Antenna 3/4 Wavelenght Above Ground

Figure 21



NVIS 1/2 Wave Dipole 1/4 Wavelenth Above Ground

Figure 22

	Height Above Ground (feet)		
Frequency Band	**3/8 Wavelength**	**1/2 Wavelength**	**5/8 Wavelength**
160 m	194.3	259.1	323.8
80 m	98.4	131.2	164.1
40 m	51.6	68.8	86.1
30 m	36.5	48.6	60.8
20 m	26.1	34.8	43.5
17 m	20.4	27.2	33.9
15 m	17.4	23.2	28.9
12 m	14.8	19.7	24.7
10 m	12.7	16.9	21.2

Table 1

Good DX dipoles for 160 and 80 meters must be installed too high to be practical (259 and 131 feet respectively). A vertical is the only practical long distance antenna for these two bands. 40 and 30 meters are the transition bands. Dipoles for these two bands, at 69 and 49 feet, are practical but probably more expensive than a vertical antenna covering the same frequency range. For 20 through 10 meters, dipole antennas are generally less expensive, easier to install, and perform better than vertical antennas. The exception of course are situations in which space is so limited that a vertical antenna is the only available choice.

4.9 Regional and NVIS Communications

For regional emergency HF communications one would like the smallest skip zone possible, ideally no skip zone at all, so that everyone can hear the sending site's transmissions. For example, a station located in Thousand Oaks, California would ideally like to communicate with all Emergency Operation Centers (EOCs) in Southern California including Los Angeles (about 45 miles south east of Thousand Oaks), Irvine, San Diego, San Bernardino, etc., as well as EOCs in Central and Northern California including San Francisco and Sacramento. These short hops require transmissions at high elevation angles. For example, the elevation angle for transmissions from Thousand Oaks to Los Angeles is about 77^{o}. The purpose of Near Vertical Incident Skywave (NVIS) antennas is to provide the needed high angle transmissions. While the antenna shown in Figure 22 is a poor DX antenna, it is an ideal NVIS antenna for regional emergency communications. A vertical antenna, with its inherently low radiation angle and long skip distance, is a poor choice for regional communications.

However, NVIS communications is possible only if the Ionosphere will support it. In the example used above, 40 meter NVIS communications is not possible when the critical frequency is 5 MHz or less. At that critical frequency the 40 meter Maximum Usable Angle is 44^{o}. Under these conditions the skip zone is about 370 miles. The closest stations that Thousand Oaks could contact would be San Francisco and Sacramento. Stations in Southern California would not be able to hear Thousand Oaks via skywave propagation and visa versa.

The Thousand Oaks ACS/ARES Area 2 team has had considerable experience with this problem as part of its participation in the California EMA Wednesday 40 meter nets. For this net, the team utilizes a 100 watt transceiver working into an NVIS 40 meter Inverted V antenna 30 feet above the ground. Government agencies, including FEMA, CALTrans, National Weather Service, Military MARS stations, and Emergency Operations Centers (EOCs) from throughout California participate in this weekly net. As a part of its on going study of regional communications, the Area 2 team records how well net control copies each site, how well each site copies net control, and how well each site is received in Thousand Oaks. This information is correlated with the critical frequency at the time of the net, the solar x-ray flux, 10.7cm solar flux, and the Boulder A and K indices. The Area 2 team can easily copy all stations on the net when the critical frequency is 7 MHz and above. Under these conditions all stations are received so well that the net is almost like a local 2 meter FM net. When the critical frequency is in the range of 6.5 MHz, reception of stations in Southern California is poor, some stations not heard at all. If the critical frequency drops below 6 MHz, it is nearly impossible to copy any Southern California stations. Stations on a line from San Francisco to Lake Tahoe can nearly always be received well if the critical frequency is above 5 MHz. Communications along this line is achieved with a single hop at an elevation angle of approximately 42^{o}. The Maximum Usable Angle for these sites, approximately 400 miles from Thousand Oaks, at a critical frequency of 5 MHz, is about 46^{o} . Communications with stations in Northern California is usually quite good under most conditions, but not as good as that along the San Francisco to Tahoe line. At low critical frequencies, higher elevation angle double hop circuits from Northern California have a more difficult time reaching Thousand Oaks than lower angle single hop paths.

Net control for the Wednesday net alternates between Sacramento and San Bernardino. At low critical frequencies, stations in Southern California have a very difficult time trying to copy net control when located in San Bernardino. Relay stations at Tahoe and Burney (near Redding) usually must relay check-ins from Southern California to net control in San Bernardino. Similarly, under low critical frequency conditions stations in Central and Northern California have a difficult, if not impossible, time trying to copy net control when located in Sacramento. In contrast, Southern California stations can copy Sacramento well and serve as relays stations for the Central and Northern California sites.

This experience is an excellent example of skip distance and the problems encountered in regional communications under low critical frequency conditions. At a critical frequency of 6.5 MHz, the Maximum Usable Angle is about 64^o with a 170 mile skip zone. Under these conditions the closest 40 meter stations that Thousand Oaks should be able to hear are San Luis Obispo and Fresno to the north and marginally San Diego to the south. These results are very close to what the Thousand Oaks team has experienced.

4.10 Portable HF Field Communications

The discussions of long distance and regional HF communications has a considerable impact on the installation and operation of portable HF stations in the field, such as during the annual ARRL Field Day held each year in late June and for HF field emergency communications work.

Horizontal antennas installed less than 3/8 wavelengths above ground will have a high elevation NVIS radiation pattern like the one shown in Figure 22. NVIS, if it is desired at all, works well only if the critical frequency is above the operating frequency. Even during sunspot maximums, the critical frequency is rarely above 14 MHz. That means that nearly all of the energy radiated by a 20 meter horizontal antenna will be transmitted straight up to outer space if the antenna is installed less than 3/8 wavelength above ground. The same is true for a yagi antenna installed too close to the ground. If the antenna can not be installed above this height, then a vertical antenna would be a better choice.

Emergency field sites are interested in good quality regional communications. 80 and 40 meter NVIS Inverted V antennas installed on a portable tip up 20 to 30 foot pole are generally easy to erect and operate very well. In fact a dual band 80 – 40 meter antenna system consisting of two Inverted Vs at right angles to each other fed by a single coax cable works very well, in addition to the antenna legs serving as the four “guy wires” supporting the vertical pole.

4.11 An Interesting Antenna System

A very good, inexpensive, easy to install HF antenna system can be built with a single 30 foot center pole and four Inverted V antennas covering 80, 40, 20, and 15 meters. At 30 feet, the 80 meter antenna is 1/8 wavelength above ground and the 40 meter antenna is about 1/4 wavelength above ground, forming two good NVIS antennas for regional communications. As shown in Figure 22, the -3db point for the 40 meter antenna will be about 30°, providing communications over much of the United States as well as excellent regional communications. The 20 meter antenna will be 0.43 wavelengths above ground providing excellent long distance DX communications as will the 15 meter antenna at 5/8 wavelength above ground.

5 Propagation Modes

Propagation paths through the Ionosphere can be quite complex, and uncontrollable. Figures 23 – 26 illustrate some of the many variations.

Figure 23 shows three possible single hop variations, a single hop from the F layer (identified as a 1F hop), a single hop in the E layer (1E) and a single hop from a sporadic E zone (1Es). The obvious problem is that the transmitting site was expecting the relative long hop provided by the 1F propagation mode, but got the shorter 1E hop instead. The single 1E hop will not reach the intended receiving site. Multiple E hops will be needed to arrive at the receiving site, incurring more propagation losses than would have occurred with the 1F path. Even more complex propagation modes are shown in Figures 25 and 26.

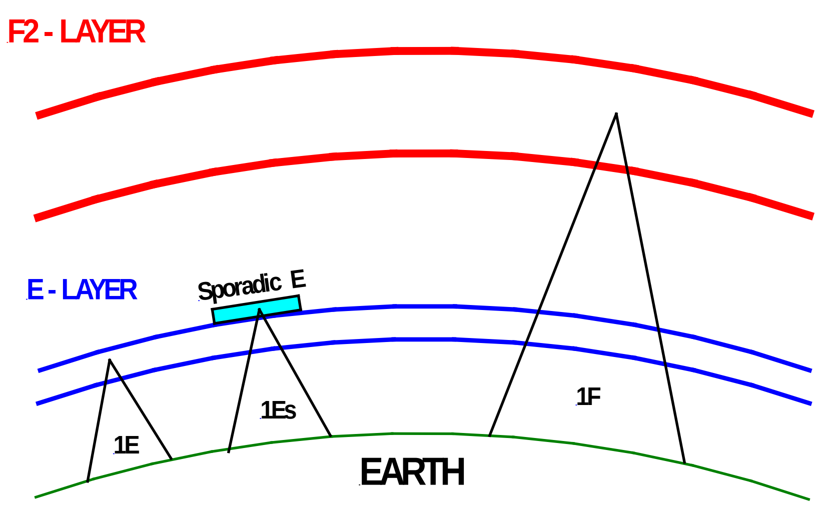


Figure 23 Single Hop Propagation Modes

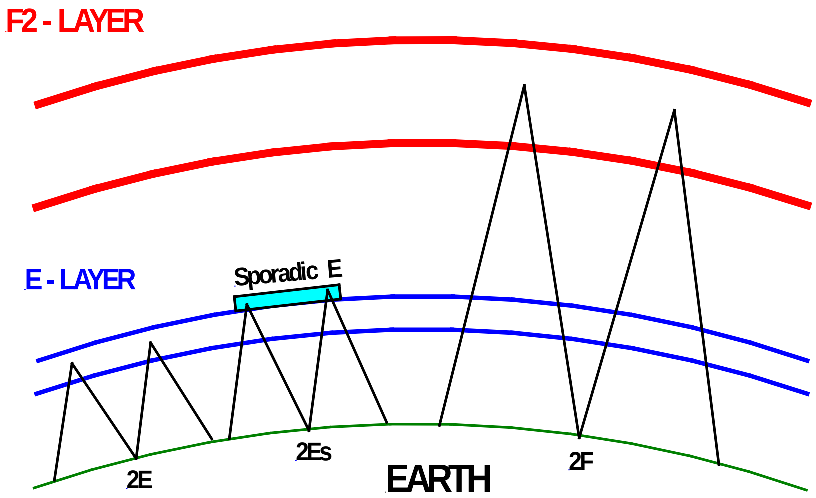


Figure 24 Double Hop Propagation Modes

These various propagation modes add to the variability of HF communications. There is generally no way for the transmitting and receiving sites to know exactly what paths were followed by the signal in traveling between the two sites. Worse yet, the paths followed could be continuously changing.

The level of ionization within the D, E, and F layers is not constant either, but can change from minute to minute, changing the height of refraction, propagation mode, skip distances, and the amount of signal attenuation. All of these conditions contribute to signal fading.

One solution to multiple propagation modes it to operate near the Maximum Usable Frequency. Single and multiple hops through the F layer are often the only propagation mode supported by the Ionosphere when operating near the Maximum Usable Frequency. Of course, operating too close

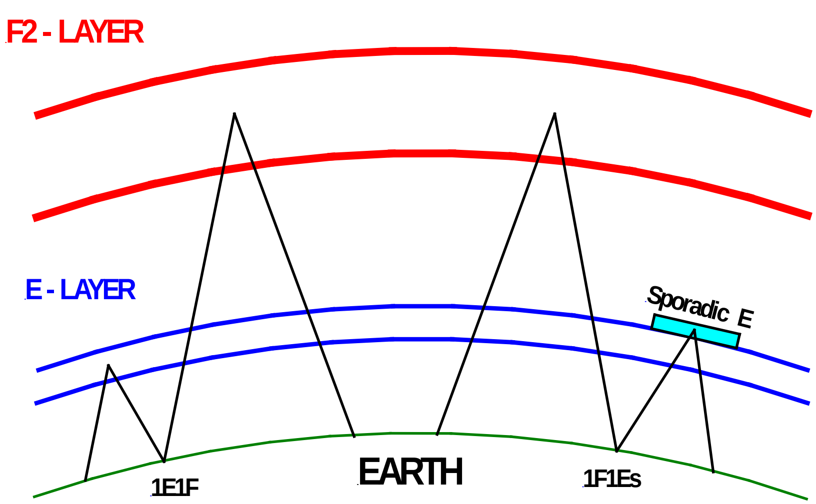


Figure 25 Double Hop Mixed Modes

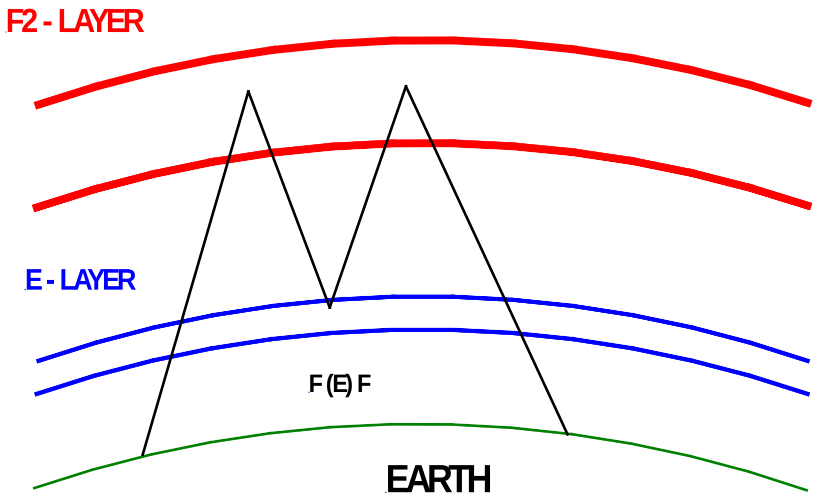


Figure 26 Another Double Hop Mixed Mode Variation

to the MUF can have its own problems. A turbulent F layer can often cause the MUF to randomly drop below the selected operating frequency.

6 Interesting Long Distance Propagation Modes.

Some interesting and useful long distance propagation modes are shown in Figures 27 through 29.

6.1 Long Distance Chordal Mode Propagation

This propagation mode involves multiple refractions from the F layer without any ground reflections. High signal strengths are achieved at the receiving site since signals do not pass repeatedly through the D layer and do not suffer any ground reflection losses. This mode is possible at dawn and sunset and occurs at transmission elevation angles of about 22 – 24^{o}.

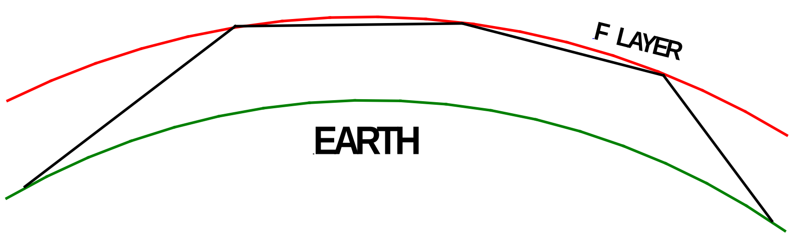


Figure 27 Long Distance Chordal Mode Propagations

6.2 Transequatorial Propagation (TEP)

This propagation mode is the result of a fountain effect within the F layer on both sides of the magnetic equator. The Earth's eastward electric field and north-south magnetic field causes Ionospheric electrons over the magnetic equator to drift upward. As a result, upward tilted concentrations of electrons form at latitudes of 10 to 20^{o}. An FF propagation mode results as signals refract off one electron concentration, propagate across to the other, and then refract back to Earth. This phenomena occurs most frequently during solar maximum and during the equinoxes.

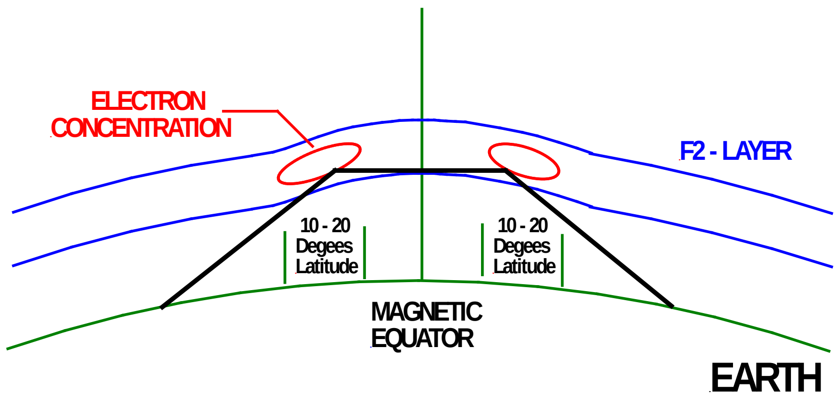


Figure 28 Transequatorial Propagation (TEP)

6.3 Long Distance F Layer - Sporadic E Propagation Mode

Sporadic E layers regularly occur in the day time equatorial Ionosphere in a band about 5^{o} on either side of the Magnetic Equator. Very low elevation angle signals often refract off the sporadic E layer, skim above the Earth's surface and refract off the F layer creating very long transmission paths.

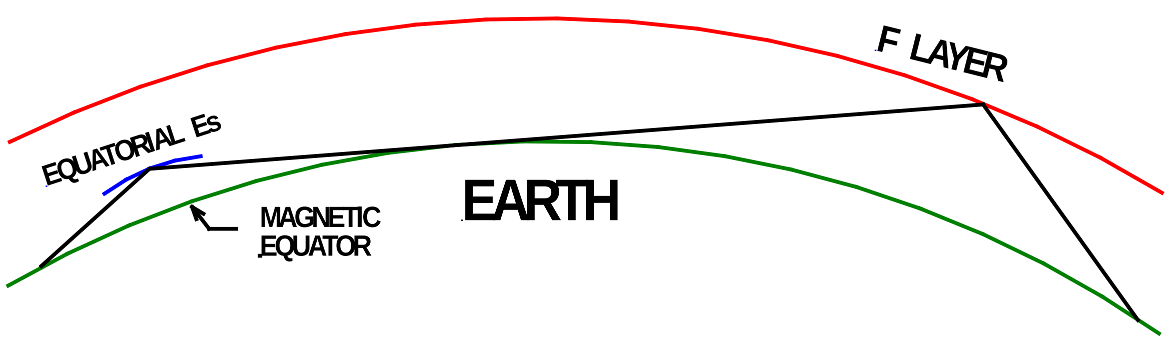


Figure 29 Long Distance 1Es 1F Propagation Mode

7 Disturbances In The Ionosphere

Disturbances in the Ionosphere are generally the result of charged particles from the Sun, resulting from solar flares, Coronal Mass Ejections (CMEs), and solar winds, impacting the Earth's magnetic field and upper atmosphere.

7.1 Geomagnetic Storms

The impact of the charged particles with the Earth's magnetic field creates disturbances in the field called geomagnetic storms.

HF communications will improve when the geomagnetic field is quiet, and worsen during a geomagnetic storm. A geomagnetic storm causes the F layer to become unstable, fragment, and even seem to disappear. Storm conditions are more severe in the higher latitudes of both hemispheres than in the equatorial zones. Storms are the most severe in the regions around the Earth's magnetic poles since the charged particles are drawn to the poles by the Earth's magnetic field. As a result, signal paths that traverse the polar regions will be more affected by geomagnetic storms than signal paths that cross the equator.

The condition of the geomagnetic field is measured in terms of A and K indices in accordance with the following table:

A	K	Geomagnetic Field
0 - 3	0	Quiet
4 - 6	1	Quiet to unsettled
7 - 14	2	Unsettled
15 - 47	3 – 4	Active
48 - 79	5	Minor storm
80 - 131	6	Major storm
132 - 207	7	Severe storm
208 - 400	8 - 9	Very major storm

Table 2

The A and K indices are a measurement of the behavior of the magnetic field in and around the earth. The K index uses a scale from 0 to 9 to measure the change in the horizontal component of the geomagnetic field. A new value for the K index is determined every 3 hours based on magnetometer measurements made at the Table Mountain Observatory north of Boulder, Colorado. The A index is a daily value on a scale from 0 to 400 to express the range of disturbance of the geomagnetic field. It is obtained by converting and averaging the day's eight, 3 hour K index values. An estimate of the A index is released at 2100 UTC, based on 7 measurements and 1 estimated value. At 0000 UTC, the final value of the A index, consisting entirely of known measurements is distributed with the word "estimated" dropped from the announcement. Daily A and 3 hour K values, as well as 10.7 cm Solar Radio Flux readings, can be obtained at www.swpc.noaa.gov/alerts/solar_indices.html .

7.2 Auroral Oval

The Earth's magnetic field deflects the charged particles arriving from the Sun causing them to spiral along the magnetic field lines toward the Earth's north and south magnetic poles. As a consequence, these particles have little impact on the Earth's equatorial Ionosphere. However, the affect in northern and southern upper latitudes is much different. The Earth's magnetic field carries these charged particles deep into the Earth's atmosphere in and around the north and south magnetic poles. One can think of the north and south magnetic poles as the Earth's garbage pails for this in coming debris from the Sun.

The northern hemisphere aurora borealis (northern lights) and southern hemisphere aurora australis are the result of the in coming particles colliding with the atmosphere's oxygen and nitrogen atoms at an altitude of about 60 to 70 miles above the Earth (approximately in the E region of the Ionosphere).

The interaction of the in coming particles with the Ionosphere create the northern and southern hemisphere auroral ovals. The northern hemisphere auroral oval is shown in Figure 30. The current condition of the northern auroral oval is available at www.swpc.noaa.gov/pmap/pmapN.html .

This plot shows the current extent and position of the auroral oval in the northern hemisphere, extrapolated from measurements taken during the most recent polar pass of the NOAA POES satellite.

The red arrow in the plot, that looks like a clock hand, points toward the noon meridian.

The statistical pattern depicting the auroral oval is appropriate to the auroral activity level determined from the power flux observed during the most recent polar satellite pass. The power fluxes in the statistical pattern are color coded on a scale from 0 to 10 ergs/cm^2 sec according to the color bar on the right. The pattern has been oriented with respect to the underlying geographic map using the current universal time, updated every ten minutes.

This presentation provides an estimate of the location, extent, and intensity of aurora on a global basis. For example, the presentation gives a guide to the possibility that the aurora is located near a given location in the northern hemisphere under the conditions that existed at the time of the most recent polar satellite pass.

The auroral oval is fixed with respect to the Sun, with the Earth rotating about its geographic poles beneath the oval. The most intense part of the oval occurs over the night portion of the Earth. The red arrow in the lower left hand corner of Figure 30 is pointing in the direction of noon when this picture was captured at 22:13 UTC on October 16, 2010.

All levels of the Ionosphere are disrupted in the most intense region of the auroral oval. The high concentrations of in coming positive ions accelerates the recombination process in the F layer, lowering the concentration of free electrons and causing a significant drop in the critical frequency and maximum usable frequency through the area. Increased ionization of the E layer can cause undesirable Es-F propagation modes throughout the polar region. Heavy ionization of the D layer occurs as the in coming particles penetrate deep into the atmosphere. The ionization is often sufficient to absorb all radio waves propagating through the region. In addition, the lateral change in F layer ionization near the outer edge of the auroral oval can cause radio signals to be diffracted horizontally, as well as vertically, causing signals to deviate from their great circle path. That is, radio propagation from California to Norway could be bent in the region of the auroral oval and end up being received instead in France.

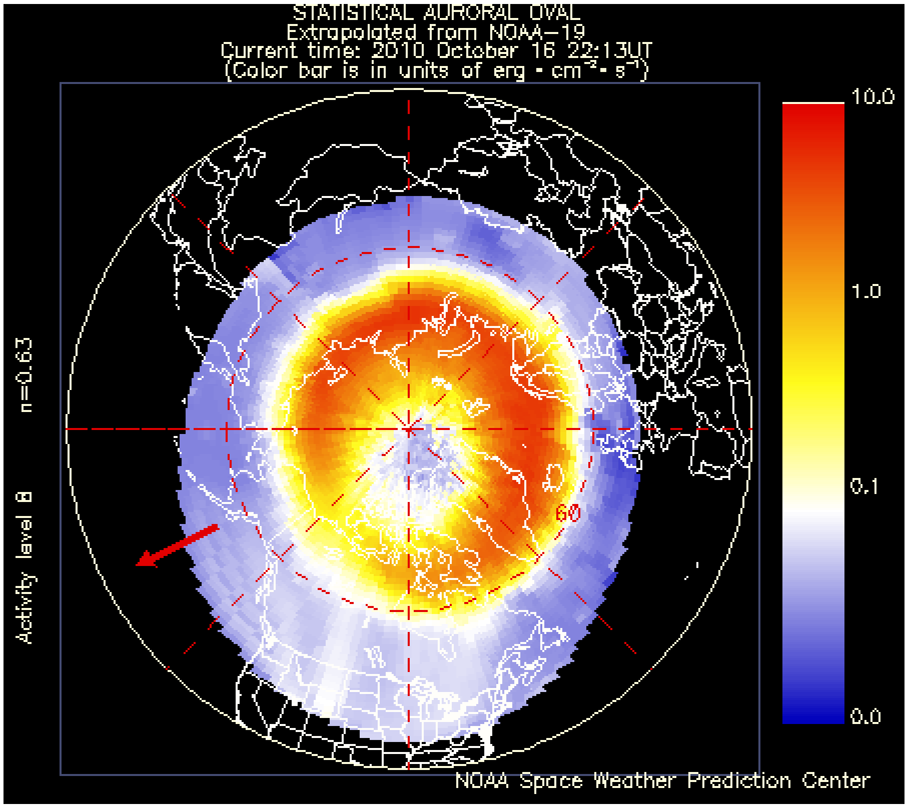


Figure 30 Northern Hemisphere Auroral Oval

The combination of these Ionospheric conditions can make HF communications over the pole very difficult, if not impossible, during periods of severe auroral disturbances, like the one shown in Figure 30. Based on the intensity of the auroral oval shown in Figure 30, one would guess that the Ionosphere is seriously impacted over northern Europe and Asia. The auroral oval shown in Figure 30 occurred three hours following a significant solar flare, shown in Figure 31, that occurred at approximately 1915 UTC.

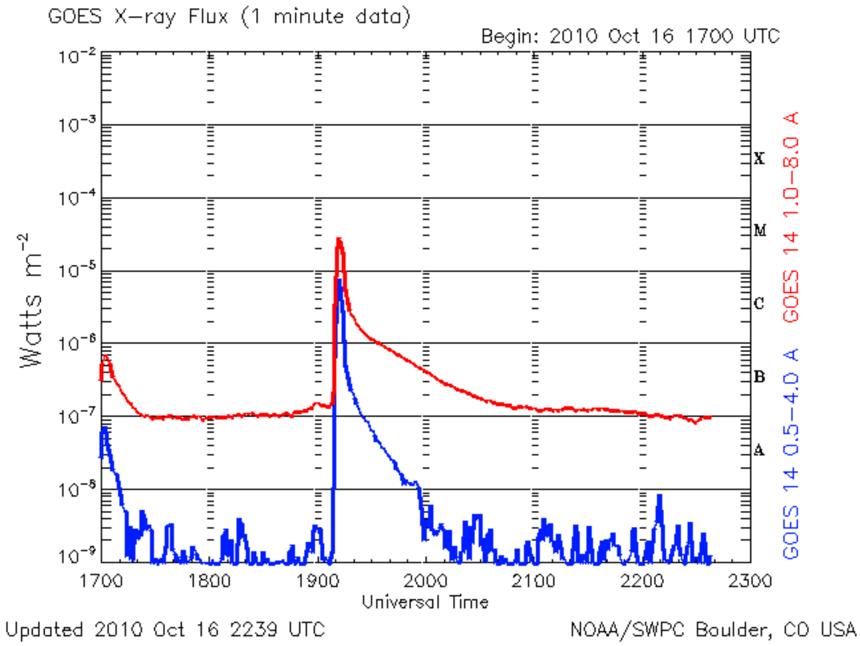


Figure 31 Solar Flare Occurring on October 16, 2010

8 Summary Of Important Web Sites

Solar Cycle and 10.7cm Solar Radio Flux: www.swpc.noaa.gov/SolarCycle/index.html .

Solar X-ray Flux: www.swpc.noaa.gov/rt_plots/xray_1m.html

D layer absorption: Can be viewed at www.swpc.noaa.gov/ by selecting Global D-Region Absorption under Popular Pages.

Critical Frequency: www.ips.gov.au/HF_Systems/6/5

A and K indices plus 10.7cm Solar Radio Flux: www.swpc.noaa.gov/alerts/solar_indices.html

Northern Hemisphere Auroral Oval: www.swpc.noaa.gov/pmap/pmapN.html

Gray Line Map: http://dx.qsl.net/

References

1. Ionospheric Radio, Kenneth Davies, Peter Peregrinus Ltd. London, United Kingdom, 1990.

2. The Ionosphere: Communications, Surveillance, and Direction Finding, Leo F. McNamara, Krieger Publishing Company, 1991.

3. Low-Band Dxing, John Devoldere, ARRL Inc., 2005