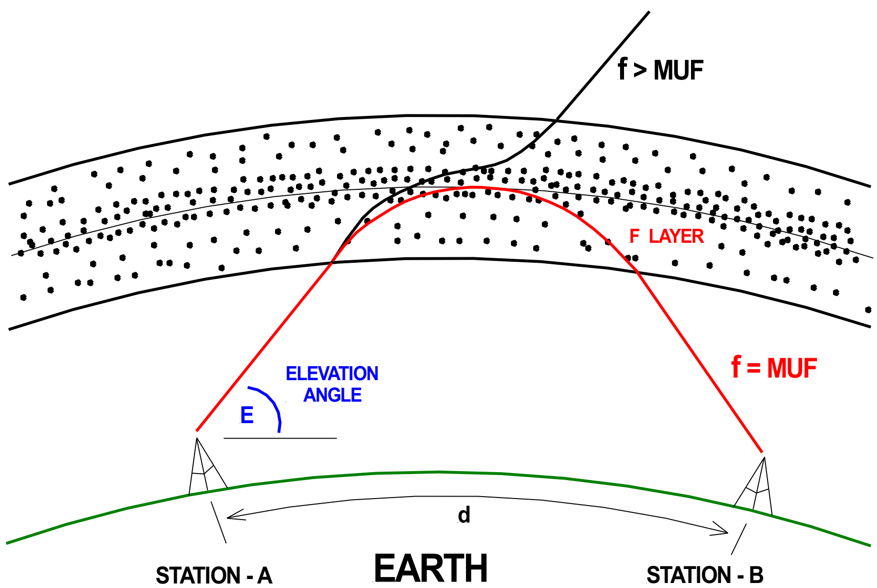
Chapter 18

Maximum Usable Frequency



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18 Maximum Usable Frequency

A radio signal travels progressively higher into the ionosphere as its frequency increases and its wavelength becomes shorter, as illustrated in Figure 1. If the frequency of the radio signal becomes high enough, it will penetrate the ionosphere and be lost to outer space as illustrated by the black 15 meter (21 MHz) trace in Figure 1. The highest frequency (shortest wavelength) signal that can be transmitted and return to Earth is the Maximum Usable Frequency (MUF). In Figure 1 the 20 meter (14 MHz) blue trace is the maximum usable frequency.

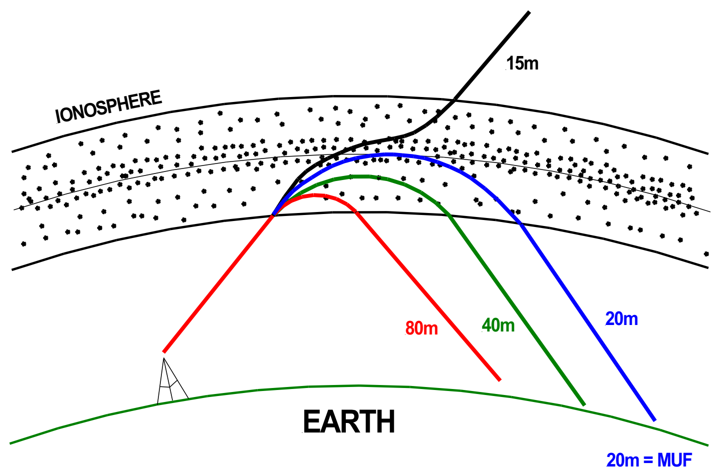


Figure 1 Signal travels higher into the ionosphere as its frequency increases (source: author)

Looked at from a different perspective, longer wavelength 80 meter (3.5 MHz) signals are bent (refracted) back to Earth lower in the ionosphere than shorter wavelength 20 meter (14 MHz) signals. The reason for this is that the ionosphere's index of refraction is wavelength dependent. This same wavelength dispersion phenomena causes sunlight to be split into its rainbow of colors when refracting through a glass prism. In Figure 2 short wavelength blue light is bent more than long wavelength red light. This is just the opposite of what happens in the ionosphere. Long wavelength 80 meter signals are bent more in the ionosphere than shorter 20 meter signals. The reason for this difference is variations in the index of refraction. The index of refraction in the vacuum of free space is 1.0. The index of refraction for transparent material such as plastics, glass, etc. is greater than one, typically 1.3 or higher. The index of refraction for air is just slightly more than one. For most practical purposes the refraction index of air and free space are considered the same, that is equal to 1.0. However, in a plasma containing positively charged ions and negative electrons, such as the ionosphere, the index of refraction is less than 1. Consequently, long wavelength signals are bent more in a plasma.

Notice in Figure 1 that short wavelength signals travel further than long wavelength signals. The 20 meter MUF signal travels the furthest, considerably further than the 80 meter signal. The reason for this is that short wavelength signals travel higher into the ionosphere before refracting back to Earth resulting in longer distances.

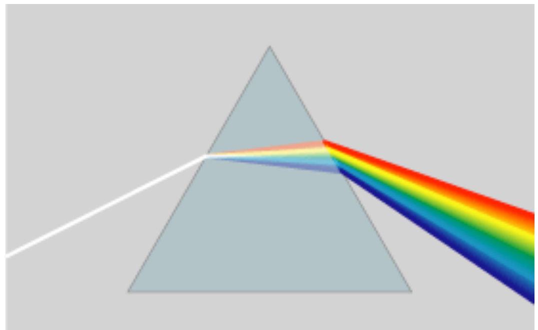


Figure 2 Sunlight refracting through a glass prism (source: Wikipedia)

18.1 Advantages of Operating at the Maximum Usable Frequency

Communicating at the maximum usable frequency is beneficial for a number of reasons including:

- Obtaining the best long distance DX communications,
- Minimizing D Layer absorption, and
- Reducing multi-path interference problems

18.1.1 Long Distance Communications

Multiple hops through the ionosphere are required for long distance communications as illustrated in Figure 3. With each hop the strength of the propagating signal decreases due to:

- Energy lost (absorbed) in each pass through the ionosphere's D region, and
- Ground losses with each reflection from the Earth's surface.

Ground losses range from 0.5 db for reflections from the ocean to around 3 db for reflections from poorly conducting ground.

Long distance communications typically consists of 3 to 4 hops. Under ideal conditions, 5 to 6 hops may be possible particularly over the ocean. Usually, however, more than 4 hops result in signals which are too weak to be received. Consequently, long distance communications depends on each hop being as long as possible which means operating at the maximum usable frequency.

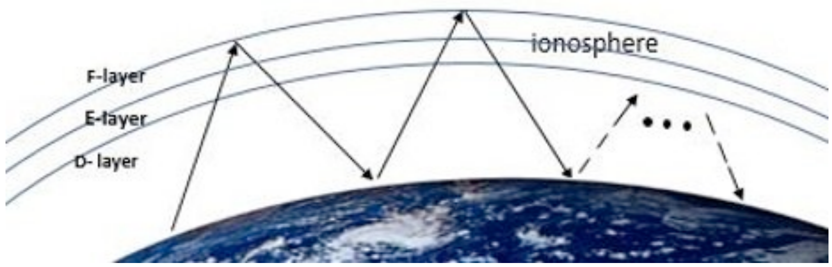


Figure 3 Multi-hop long distance DX communications (source: ResearchGate)

18.1.2 Anatomy of Absorption

Radio waves are absorbed as they pass through the ionosphere. Free electrons absorb energy from passing radio waves causing the electrons to vibrate at the radio wave frequency. The vibrating electrons reradiating the absorbed radio energy resulting in little radio energy being lost in the ionosphere's E and F regions.

The D layer is different. The density of neutral atoms and molecules is far greater in the D region than anywhere else in the ionosphere. Due to this high density, electrons recombine with ions so quickly in the D region that they do not have time to reradiate their absorbed radio wave energy. Instead, the absorbed energy is dissipated as heat in D layer.

D layer absorption is inversely proportional to frequency squared according to the equation

$$\text{Absorption} \propto \frac{1}{f^2}$$

Absorption on 40 meters is 1/4 that on 80 meters, while absorption on 20 meters is only 1/16 that on 80. D layer absorption on 15 meters is insignificant.

To avoid absorption, we want to operate at the highest frequency possible, that is at the MUF. This means operating on 20 through 10 meters during the day. MUF drops at night as the ionosphere's critical frequency declines making 20 through 10 meter communications difficult. However, the D layer disappears at night allowing long-distance communications on 80 and 40 meters. Propagation conditions for 80 and 40 meters are illustrated in Figure 4. The D layer is fully developed during the day heavily absorbing 80 and 40 meter signals. At night propagation conditions on 80 and 40 are good since the D layer (brown band in Figure 4) is no longer present.

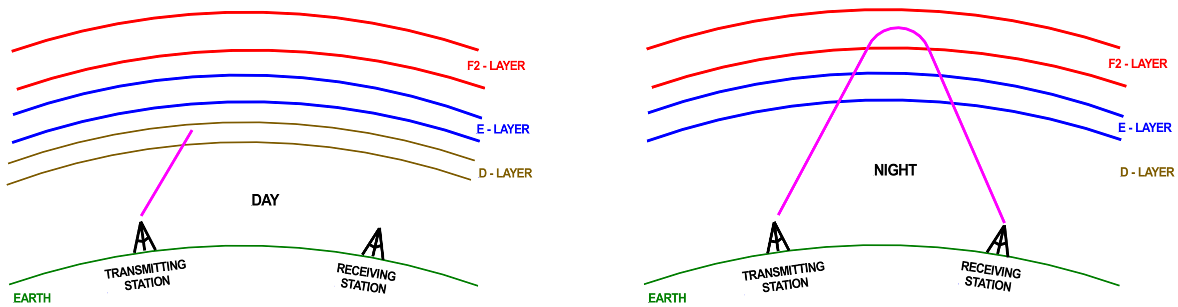


Figure 4 Day vs night propagation on 40 and 80 meters (source: author)

18.1.3 Multi-path Interference Problems

Communications between Los Angeles and Denver on 40 meters, a distance of 830 miles, often occurs by both single hop and double hop propagation. The double hop path (blue trace in Figure 5) is much longer than the single hop path (red trace) causing it to be received out of phase with the single hop signal. Destructive interference between the out of phase single and double hop signals can seriously weaken and distort LA to Denver communications.

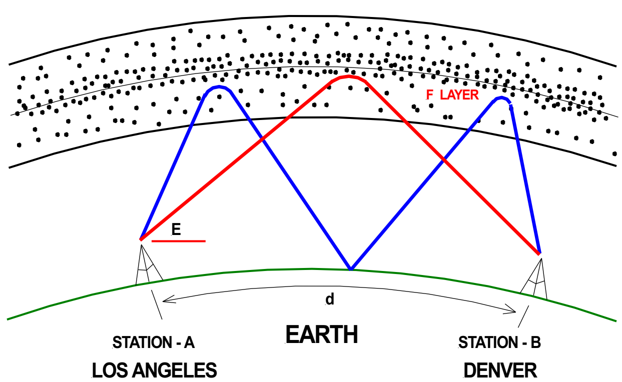


Figure 5 Multi-path propagation between Los Angles and Denver (source: author)

By moving to a higher frequency, for example 20 meters, the high elevation angle path penetrates the ionosphere and disappears into outer space as illustrated by the blue trace in Figure 6. The lower angle red single hop path is the only path remaining eliminating multi-path interference.

Operating at the highest possible frequency (MUF) often solves multi-path problems.

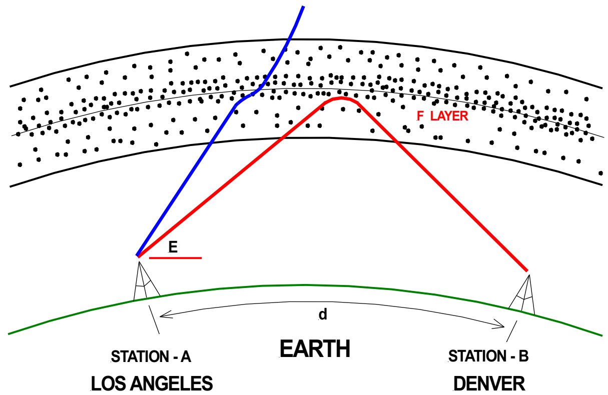


Figure 6 Solving the multi-path problem between Los Angles and Denver (source: author)

18.2 Calculating MUF

Mathematically, maximum usable frequency is a function of the ionosphere's critical frequency at the center of the first hop and the transmitted signal's elevation angle. In equation form

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

where

- MUF = Maximum Usable Frequency,
- f_c = The ionosphere's Critical Frequency, and
- E = Elevation angle of the signal radiating from the transmitting antenna

18.2.1 Critical Frequency

As discussed earlier, Critical Frequency f_c is the highest frequency signal that can be transmitted straight up and reflected back down to Earth (blue trace in Figure 7). All signals lower in frequency than f_c will also be reflected back to Earth. But, signals higher in frequency transmitted straight up will penetrate the ionosphere and be lost to outer space illustrated by the brown trace in Figure 7.

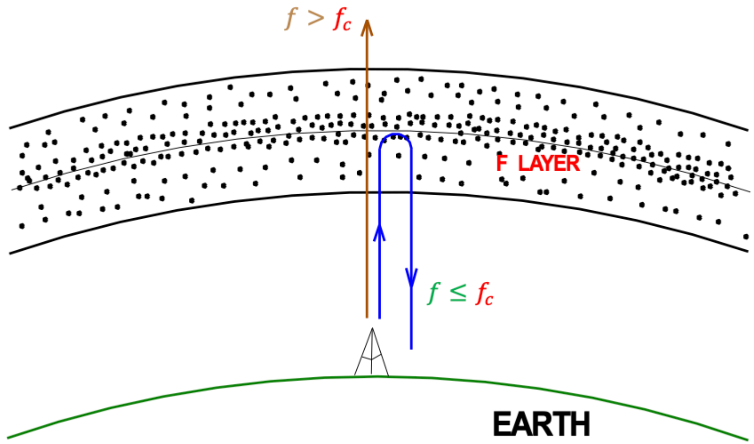


Figure 7 Critical frequency (source: author)

Critical frequency varies throughout the day as the Earth rotates, seasonally as the Earth's upper atmosphere changes, and with the 11-year solar cycle as Extreme Ultra-Violate (EUV) and X-ray radiation from the Sun changes.

Figure 8 shows the diurnal and seasonal variations in critical frequencies during solar maximum. Figure 9 shows the solar minimum variations.

F2 critical frequency is at its lowest level just before sunrise. It then rises quickly throughout the morning as photoionization resumes. Around noon F2 critical frequency levels off as photoionization and electron-ion recombination reach equilibrium. Later in the afternoon F2 critical frequency declines as photoionization decreases and then disappears altogether at night. The diurnal pattern is slightly different during solar minimum with the peak in F2 critical frequency actually occurring shortly before sunset.

Contrary to what would be expected, F2 critical frequencies in the winter are higher than during summer, despite the fact that the Sun is lower in the sky in the winter. This is known as the seasonal anomaly. In the winter cooler temperatures in the upper atmosphere retard electron – ion recombination resulting in higher electron densities and critical frequencies than expected.

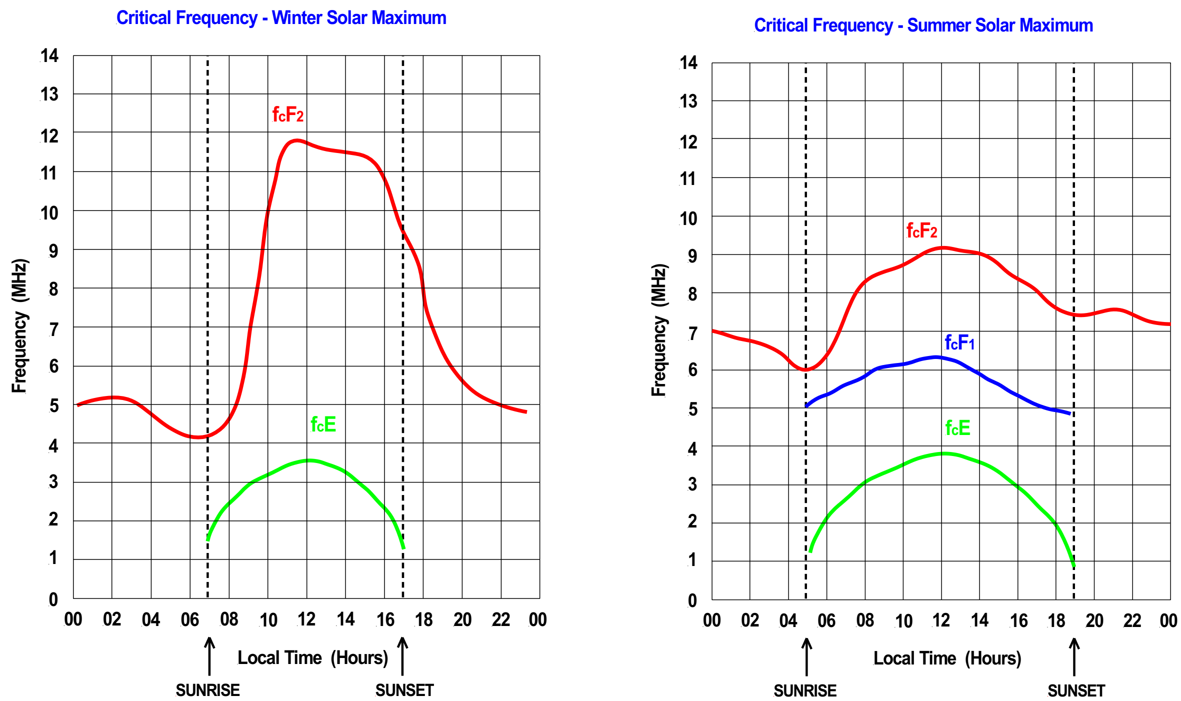


Figure 8 Winter and summer critical frequencies during solar maximum (source: author)

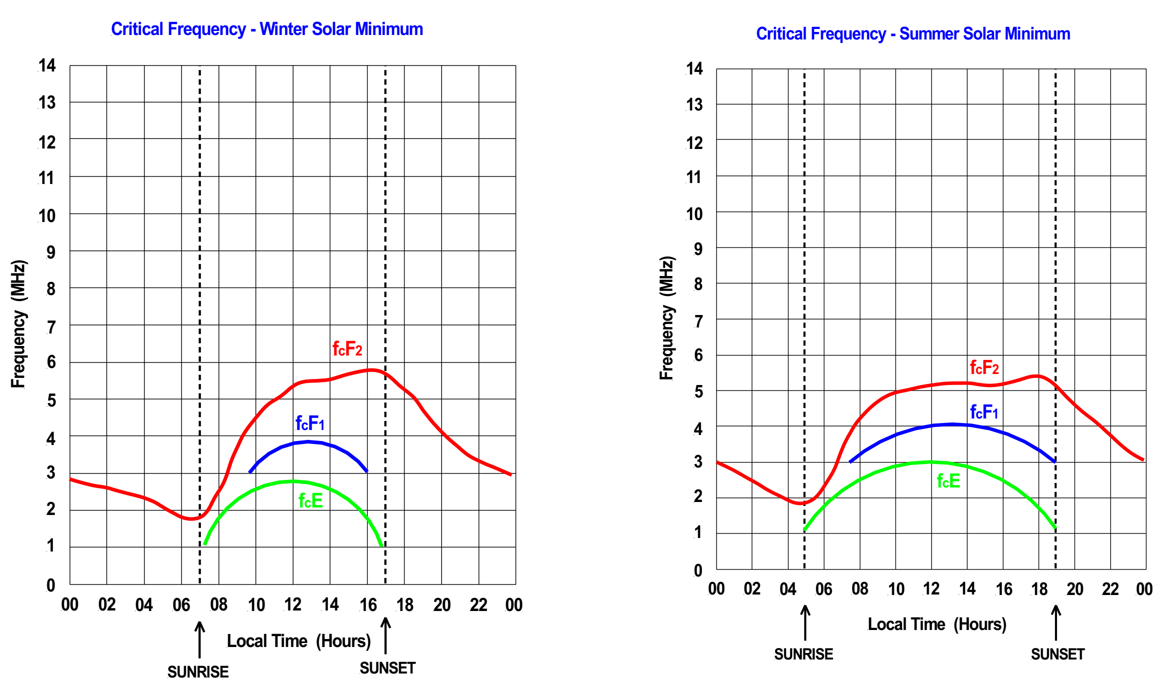


Figure 9 Winter and summer critical frequencies during solar minimum (source: author)

F1 and E critical frequencies vary as expected with critical frequencies slightly higher in the summer than in the winter. During solar maximum the F1 region disappears in the winter.

EUV energy output from the Sun varies with the 11-year solar cycle. Consequently, the level of ionospheric ionization also varies with the solar cycle. This variation is particularly evident in the F2 critical frequency shown in Figure 10. In this figure the solar cycle is represented by the smoothed sunspot number, the magenta ssn trace in Figure 10. As can be seen, the F2 critical frequency (dark blue trace) tracks the solar cycle very closely. The F1 and E critical frequencies also track the solar cycle, but not as dramatically.

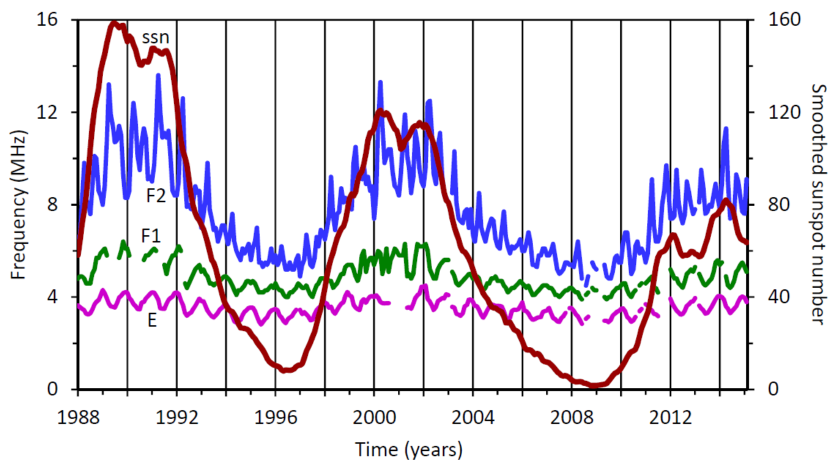


Figure 10 Critical frequency variation with the solar cycle (source: sws.bom.gov.au)

18.2.2 Determining the Current Critical Frequency

The Australian Bureau of Meteorology produces a global F2 critical frequency map that is available on the www.skywave-radio.org website under the Current Conditions tab. The map is created automatically from ionosonde reports received from monitoring stations around the world. The map is updated every 15 minutes.

Figure 11 is the Critical Frequency map for October 20, 2025 at 18:45 UT (11:45 PDT). Over California the critical frequency was 12 MHz.

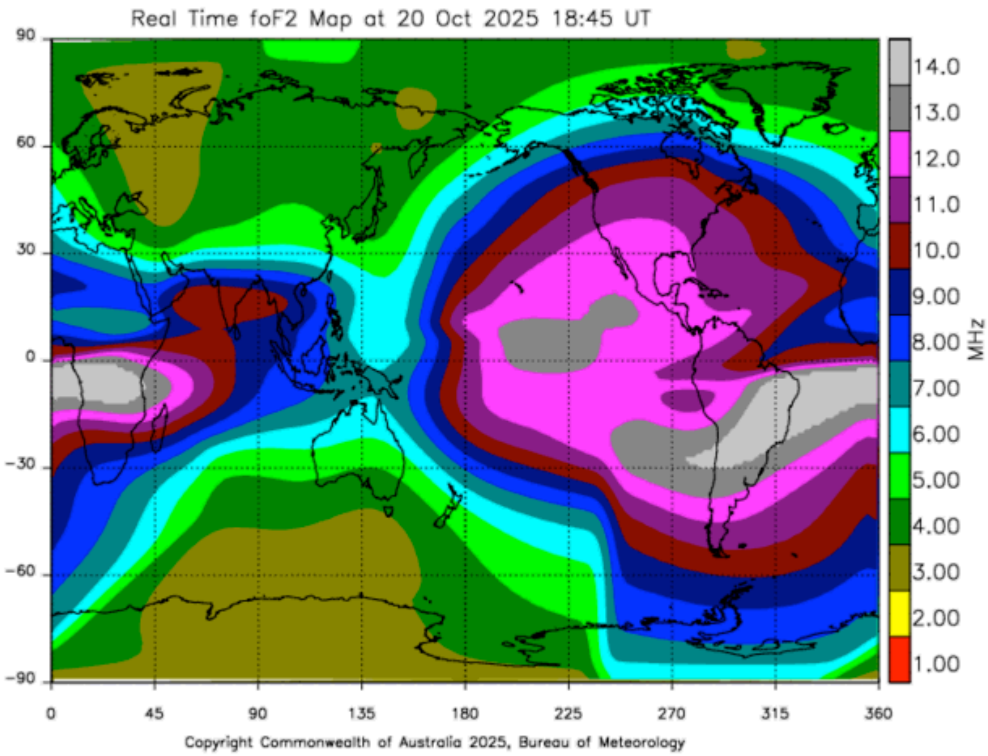


Figure 11 Global critical frequency map for October 20, 2025 at 18:45 UT

Critical frequency f_cF2 and ionospheric height hmF2 charts for specific ionosonde monitoring stations are available by clicking on Vertical Soundings under the Current Conditions tab of the www.skywave-radio.org website and following the instructions provided. Figure 12 is a map of ionosonde stations. The location of a particular ionosonde is determined by clicking on the link provided in the figure and then clicking on the ionosonde (blue dot) of interest. For example, the ionosonde located at Point Arguello, California (designator PA836 PT) is near Vandenburg AFB.

Figure 13 is the Point Arguello critical frequency chart for October 20, 2025. The red trace is the current f_cF2 critical frequency. The dashed green trace is the estimated critical frequence calculated by the International Reference Ionosphere (IRI) mathematical model. The vertical dashed blue line is the time at which the curves were generated in Universal Time. Left of the blue line is the critical frequency history (what actually happened). To the right of the blue line is a projection of what is expected to happen. At 18:45 UT (11:45 PDT) on October 20 the critical frequency was approximately 12.5 MHz. Figure 14 shows the Ionospheric height for October 20, 2025. At 18:45 UT the height of the F2 layer was roughly 275 km.

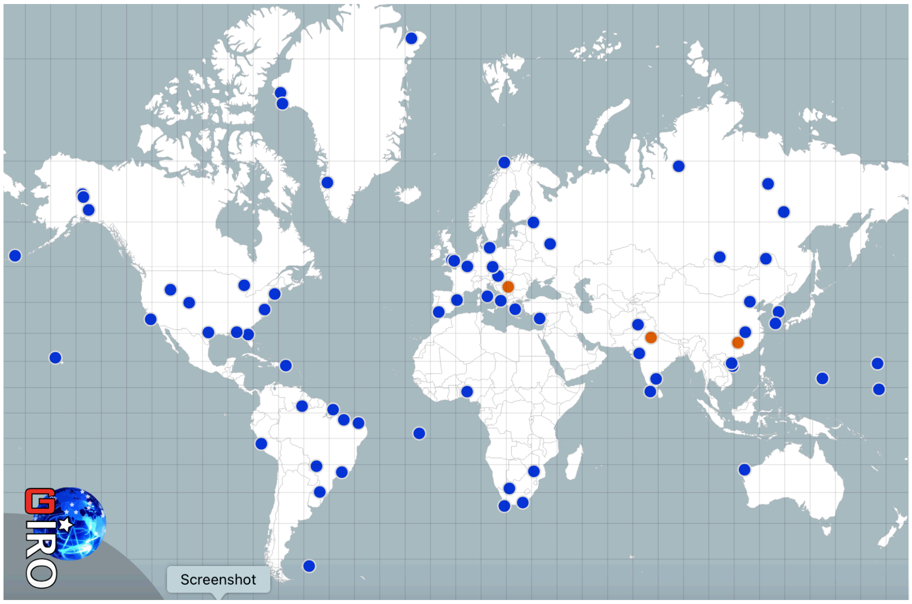


Figure 12 World Map of Ionosondes stations (source: Lowell Digisonde International https://digisonde.com)

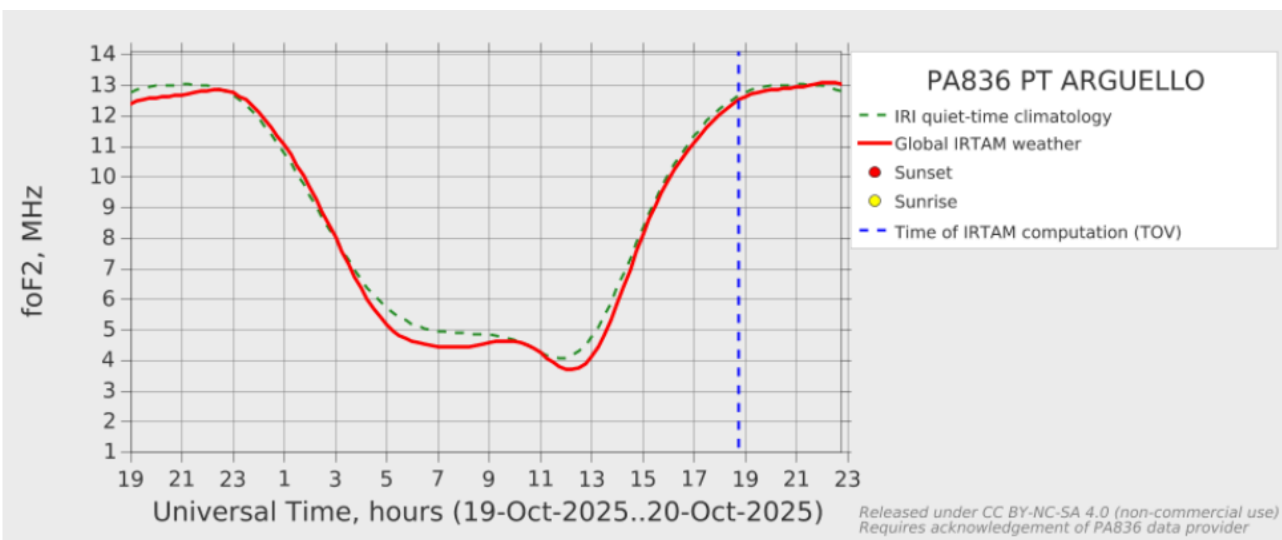


Figure 13 Critical Frequency chart for October 20, 2025, (source: GAMBIT)

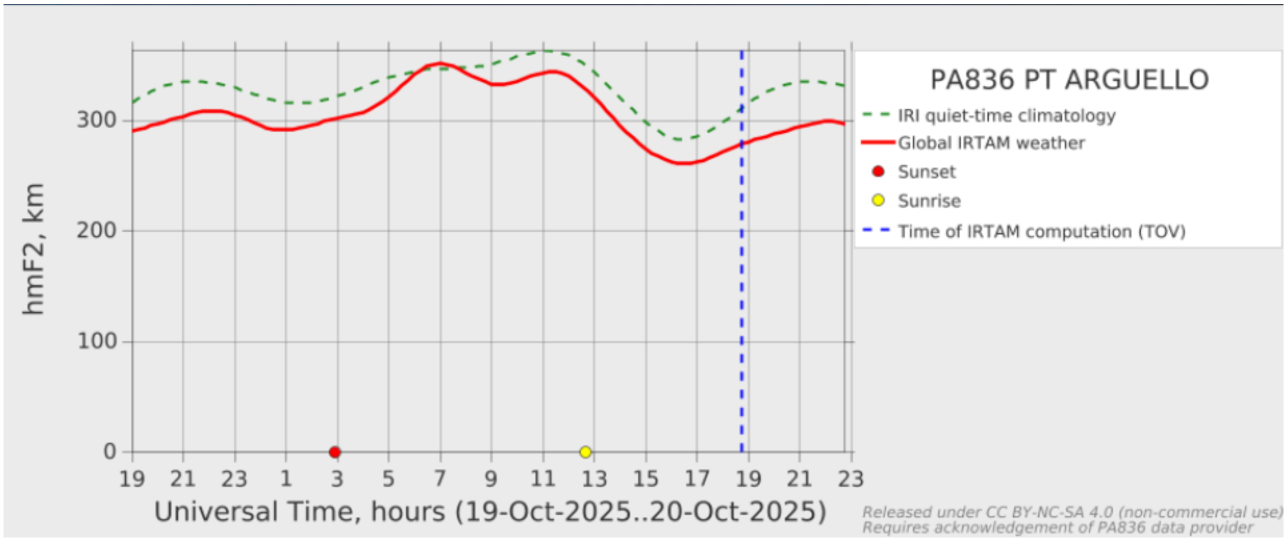


Figure 14 Ionospheric F2 height for October 20, 2025 (source: GAMBIT)

18.2.3 Elevation Angle (E)

In the maximum usable frequency equation, elevation angle E is the angle with respect to the Earth's surface at which a signal is transmitted, as illustrated in Figure 15.

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

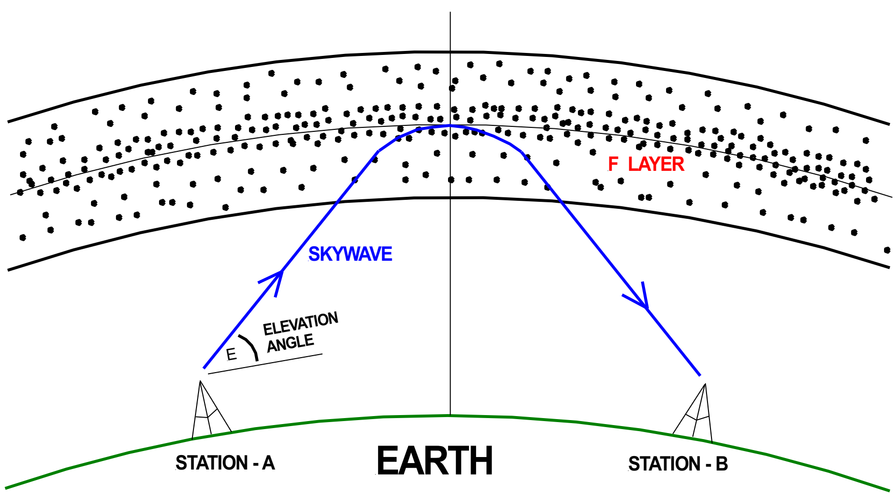


Figure 15 Elevation angle (source: author)

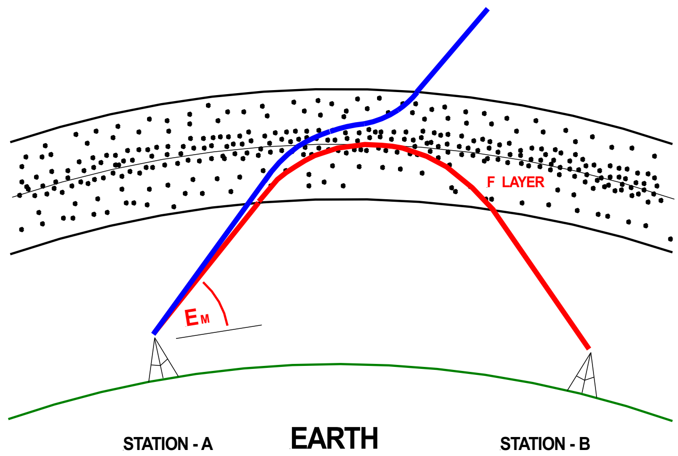


Figure 16 Maximum Usable Angle (MUA) (source: author)

Maximum Usable Angle (MUA) is the highest angle signal (E_M), that can be transmitted and still be refracted back to Earth (red trace in Figure 16). Maximum usable angle is also known as the Critical Angle. Signals transmitted at higher elevation angles (blue trace in Figure 16) penetrate the ionosphere and are lost to outer space. Consequently, a transmitted signal must be below both the maximum usable frequency (MUF) and maximum usable angle (MUA) to return to Earth. The equations for both are provided below for comparison.

Maximum Usable Frequency

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

where

- MUF = Maximum Usable Frequency,
- f_c = The ionosphere's Critical Frequency, and
- E = Elevation angle of the signal radiating from the transmitting antenna

Maximum Usable Angle

$$MUA = \sin^{-1}\left[\frac{f_c}{f_o}\right]$$

where

- MUA = Maximum Usable Angle,
- f_c = The ionosphere's Critical Frequency, and
- f_o = Operating frequency of the radio transmitter

It is thus important to know the current maximum usable angle (MUA) as well as the MUF.

The chart in Figure 17 provides the MUA for frequency bands 80 through 10 meters based on the ionosphere's critical frequency. The highest possible angle is 90° represented by the black bar at the top of Figure 17.

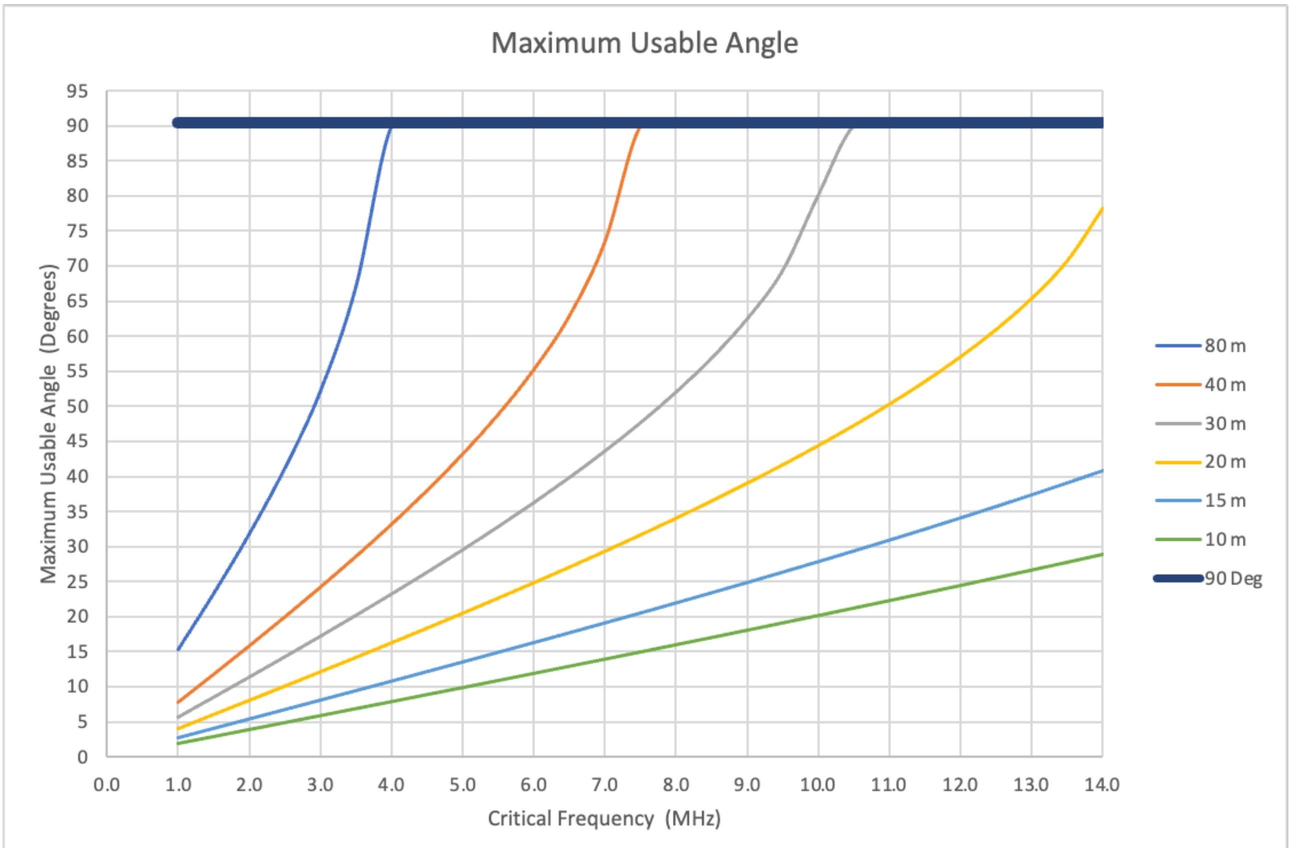


Figure 17 Maximum Usable Angle verses Critical Frequency (source: author)

For example, the chart shows that the MUA = 32° when operating at night on 80 meters with a critical frequency of f_c = 2.0 MHz. Signals transmitted at an elevation angle greater than 32° will be lost to outer space. This could be a serious problem!

The radiation pattern for a typical 80 meter Inverted-V antenna $\frac{1}{8}\lambda$ above ground is shown in Figure 18. In this figure the lowest angle at which this antenna can effectively radiate a signal is approximately 40°. This is the antenna's Lowest Radiation Angle or LRA. The power radiated by the antenna drops off very quickly below its 40° LRA with nearly all of the antenna's energy radiated at higher angles. This generally is not a problem. The antenna is an excellent high angle

Near Vertical Incident Skywave (NVIS) antenna for local and regional communications, particularly for emergency communications work. However, communications using this antenna is impossible at night when the ionosphere's maximum usable angle is less than the angle at which the antenna can transmit signals. At a critical frequency of f_c = 2 MHz the ionosphere's MUA = 32° which is less than the antenna's LRA of 40°. Under these conditions nearly all of the energy radiated by the antenna is lost to outer space. In essence, the antenna stops working late at night! This is a common problem during solar minimum.

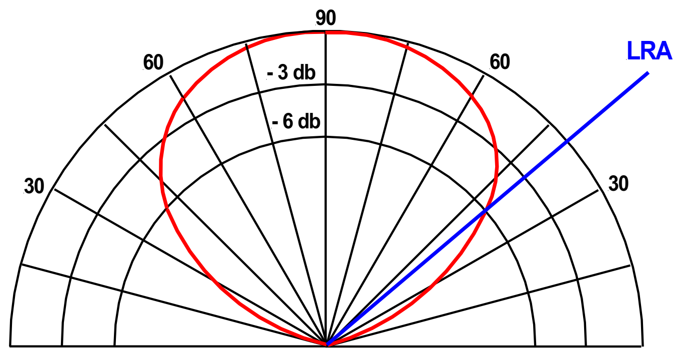


Figure 18 Radiation pattern for an 80 Inverted-V antenna (source: author)

An 80-meter vertical antenna is required for operation throughout the night during years of solar minimum when the critical frequency is very low. Figure 19 shows the radiation pattern for an 80-meter vertical. This is an excellent night time antenna. Nearly all of the antenna's radiation is at an angle below 60°. Notice in Figure 19 that the ionosphere's maximum usable angle (MUA) decreases as the critical frequency (f_c) drops. At a critical frequency f_c = 1 MHz, the MUA is only 15 degrees. As low as that is, it is still well within the vertical antenna's operating range. During solar minimum the critical frequency can easily drop down to 2 MHz at night and at times down to even 1 MHz, as illustrated in Figure 20, mandating the use of a vertical for late night 80-meter emergency communications work.

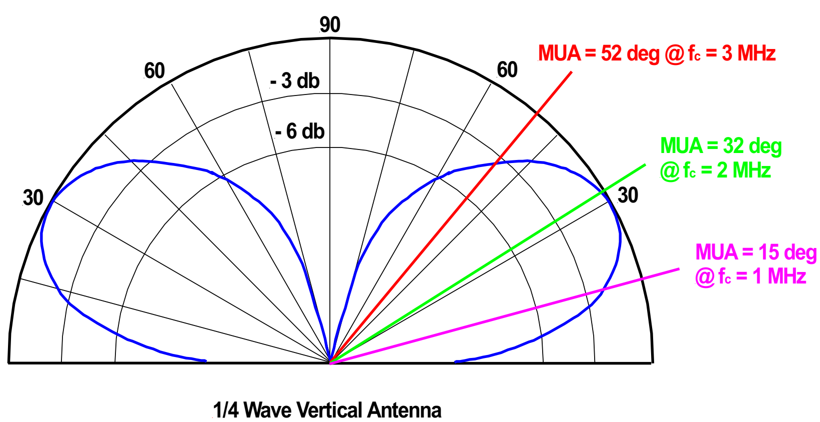


Figure 19 Radiation pattern for an 80 vertical antenna (source: author)

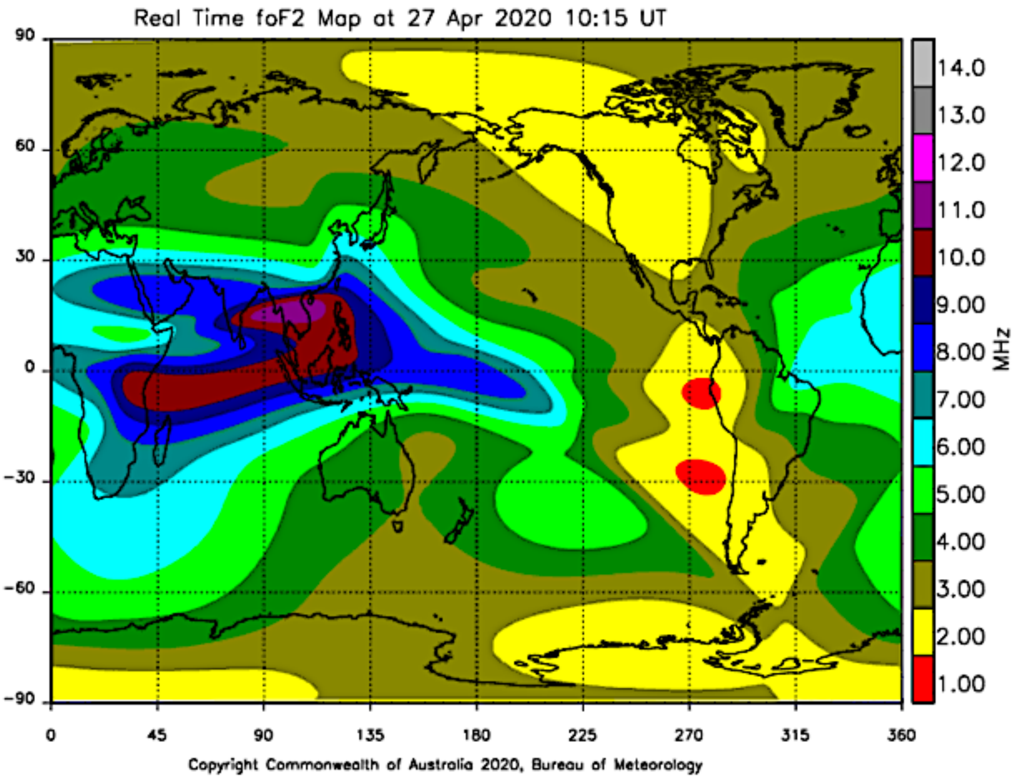


Figure 20 Typical critical frequencies at 2 AM local time during solar minimum

18.2.4 Elevation Angle and Hop Distance

The distance traveled by a signal in one hop through the ionosphere is determined by the elevation angle E at which it is transmitted and the altitude that it is refracted in the ionosphere. A chart of hop distance verses elevation angle is provided in Figure 21.

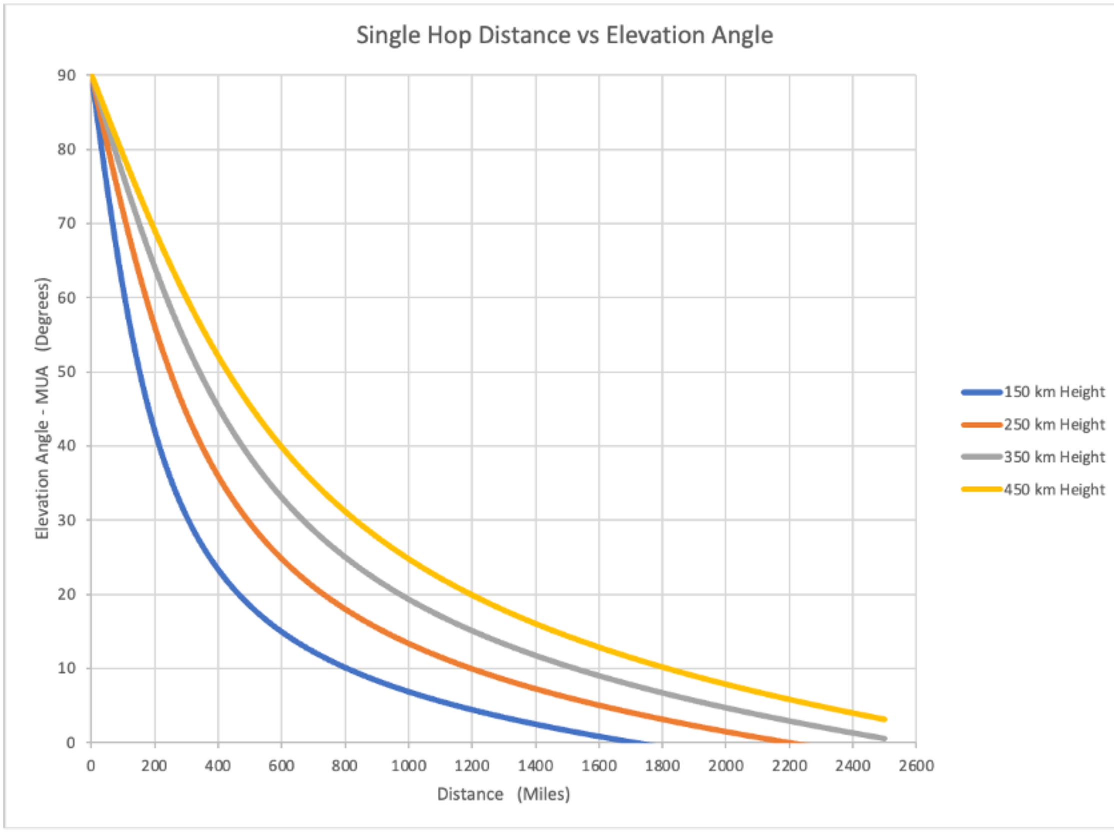


Figure 21 Distance vs elevation angle (source: author)

For example, a signal transmitted at an elevation angle of 30º and refracted in the ionosphere at an altitude of 250 km (the red trace in Figure 21) will return to Earth approximately 500 miles from the transmitting site.

The equation required to produce the distance verses elevation angle chart is derived below using Figure 22.

In Figure 22, T is the location of the transmitting station and R the receiving station's location. The green arc labeled "D = Distance" is the ground distance between the transmitting and receiving sites.

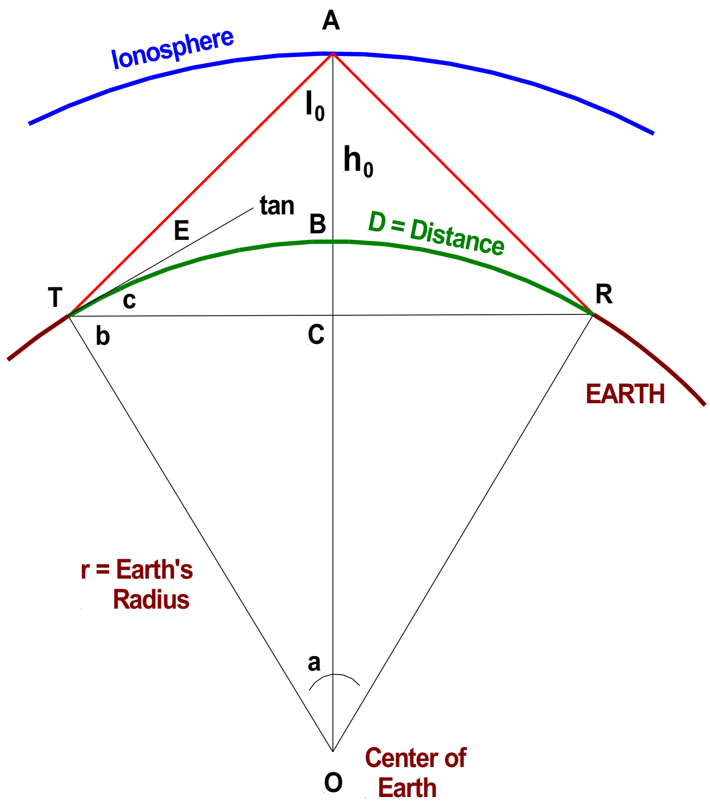


Figure 22 Deriving the distance verses elevation angle equation (source: derived from Davies)

The line segment BA is the virtual altitude h_0 of the ionospheric point at which the transmitted radio signal (red trace) is reflected back to Earth arriving at the receiving station R. The angle I_0 is the angle of incidence (with respect to vertical) of the radio signal with the ionosphere. The angle E is the elevation angle of the transmitted signal relative to ground at the transmitting site. Ground at the transmitting site is represented by the line tangent to Earth at the transmitting point T. In Figure 22 this line is labeled "tan".

The radius of the Earth is denoted by r (approximately 4,000 miles) and is measured from the center of the Earth (O) to the Earth's surface. The Distance D from the transmitting to the receiving site is the arc along the Earth surface from T to R. The length of this arc is

$$D = ra$$

were a is the angle in radians at the center of the Earth measured between the two radii OT and OR. Rearranging terms

$$a = \frac{D}{r}$$

The following trigonometric relations can be derived from the above figure

$$\sin\frac{a}{2} = \frac{TC}{r}$$

$$TC = r\sin\frac{a}{2}$$

$$\cos\frac{a}{2} = \frac{OC}{r}$$

$$OC = r\cos\frac{a}{2}$$

$$OB = r$$

$$BC = OB - OC = r - r\cos\frac{a}{2} = r\left[1 - \cos\frac{a}{2}\right]$$

$$h = h_0 + BC = h_0 + r\left[1 - \cos\frac{a}{2}\right]$$

$$\tan I_0 = \frac{TC}{h} = \frac{r\sin\frac{a}{2}}{h_0 + r\left[1 - \cos\frac{a}{2}\right]}$$

$$I_0 = \tan^{-1}\left[\frac{r\sin\frac{a}{2}}{h_0 + r\left[1 - \cos\frac{a}{2}\right]}\right]$$

$$E = 90° - I_0 - c$$

$b + c = 90° =$ the angle between the radius of a circle and the tangent to the circle (the Earth)

$$c = 90° - b$$

$$b = 90° - \frac{a}{2}$$

$$c = 90° - \left(90° - \frac{a}{2}\right)$$

$$E = (90° - I_0) - \left[90° - \left(90° - \frac{a}{2}\right)\right]$$

Since

$$a = \frac{D}{r}$$

$$E = (90° - I_0) - \left[90° - \left(90° - \frac{D}{2r}\right)\right]$$

$$I_0 = \tan^{-1}\left[\frac{r\sin\frac{a}{2}}{h_0 + r\left[1 - \cos\frac{a}{2}\right]}\right]$$

$$E = \left[90° - \tan^{-1}\left[\frac{r\sin\frac{D}{2r}}{h_0 + r\left[1 - \cos\frac{D}{2r}\right]}\right]\right] - \left[90° - \left(90° - \frac{D}{2r}\right)\right]$$

To evaluate this equation the 90º terms must be converted to radians. An angle $g°$ is converted to g radians by the following equation

$$g = \frac{\pi}{180} g° \quad and \quad g° = \frac{180}{\pi} g$$

If

$$g° = 90°$$

then

$$g = \frac{\pi}{180} g° = \frac{\pi}{180} 90 = 1.57\ radians$$

Substituting 1.57 radians for 90º, the equation for elevation angle E becomes

$$E = \left[1.57 - \tan^{-1}\left[\frac{r\sin\frac{D}{2r}}{h_0 + r\left[1 - \cos\frac{D}{2r}\right]}\right]\right] - \left[1.57 - \left(1.57 - \frac{D}{2r}\right)\right] \; radians$$

Since we want elevation angle expressed in degrees, we must convert E radians to E°, so

$$E° = \frac{180}{\pi}E = 57.296\,E$$

and

$$E° = 57.296\,E = 57.296\left[1.57 - \tan^{-1}\left[\frac{r\sin\frac{D}{2r}}{h_0 + r\left[1 - \cos\frac{D}{2r}\right]}\right]\right] - \left[1.57 - \left(1.57 - \frac{D}{2r}\right)\right]$$

There are only three independent variables in this equation

r = the radius of the Earth,

h_0 = the altitude at which the radio wave is reflected from the ionosphere, and

D = the distance from the transmitting to the receiving station.

The graph for elevation angle $E°$ verses distance D is obtained by holding $r \; and \; h_0$ constant while varying D over a range from 1 to 2,500 miles. Doing this produces the graph shown in Figure 21.

18.2.5 Maximum Usable Frequency Verses Critical Frequency

The maximum usable frequency is always equal to or greater than the ionosphere's critical frequency. At an elevation angle of 90°, straight up, MUF = f_c. MUF increases, becomes greater than f_c, as the elevation angle E decreases. For example, at an elevation angle of 90°

$$MUF = \frac{f_c}{\sin E} = \frac{f_c}{\sin 90°} = \frac{f_c}{1} = f_c$$

At an elevation angle of 45°

$$MUF = \frac{f_c}{\sin E} = \frac{f_c}{\sin 45°} = \frac{f_c}{0.707} = 1.41\,f_c$$

18.2.6 Maximum Usable Frequency - Example

The maximum usable frequency for a radio circuit depends on the distance between the transmitting and receiving stations. Assume that a radio net between stations in San Diego, San Bernardino, and Sacramento is in progress. In Figure 23 the maximum usable frequency (MUF_2 blue trace) from San Diego to Sacramento is higher than MUF_1 (red trace) from San Diego to San Bernardino. This can easily be seen in the MUF equation.

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

The large elevation angle E_1 required to reach San Bernardino results in MUF_1 being smaller than that for Sacramento (MUF_2).

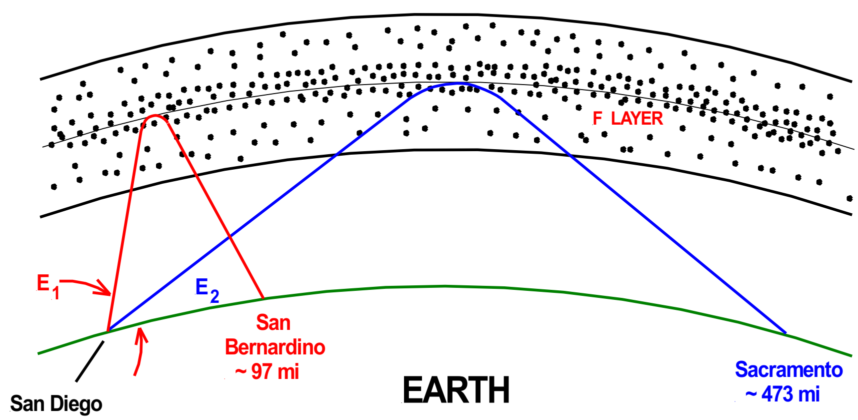


Figure 23 Calculating MUFs from San Diego to San Bernardino and Sacramento (source: author)

The elevation angles E_1 and E_2 required to transmit from San Diego to San Bernardino and Sacramento are determined using the distance verses elevation angle chart in Figure 24. The distance from San Diego to San Bernardino is approximately 97 miles while that to Sacramento is around 473 miles.

The height of the ionosphere's F2 layer must be known to use the chart. The current height is obtained by clicking on Vertical Soundings under the Current Conditions tab of the www.skywave-radio.org website. For California the regional F2 height on June 3, 2020 at 17:00 UT (10 AM local time) was 250 km.

At a distance of 97 miles the elevation angle E_1 required for transmitting from San Diego to San Bernardino, with a F2 layer height of 250 km, is approximately 75° (using the red height trace in Figure 24). Similarly, the elevation angle E_2 for communicating a distance of 473 miles to Sacramento is 30°. Figure 25 summarizes these results.

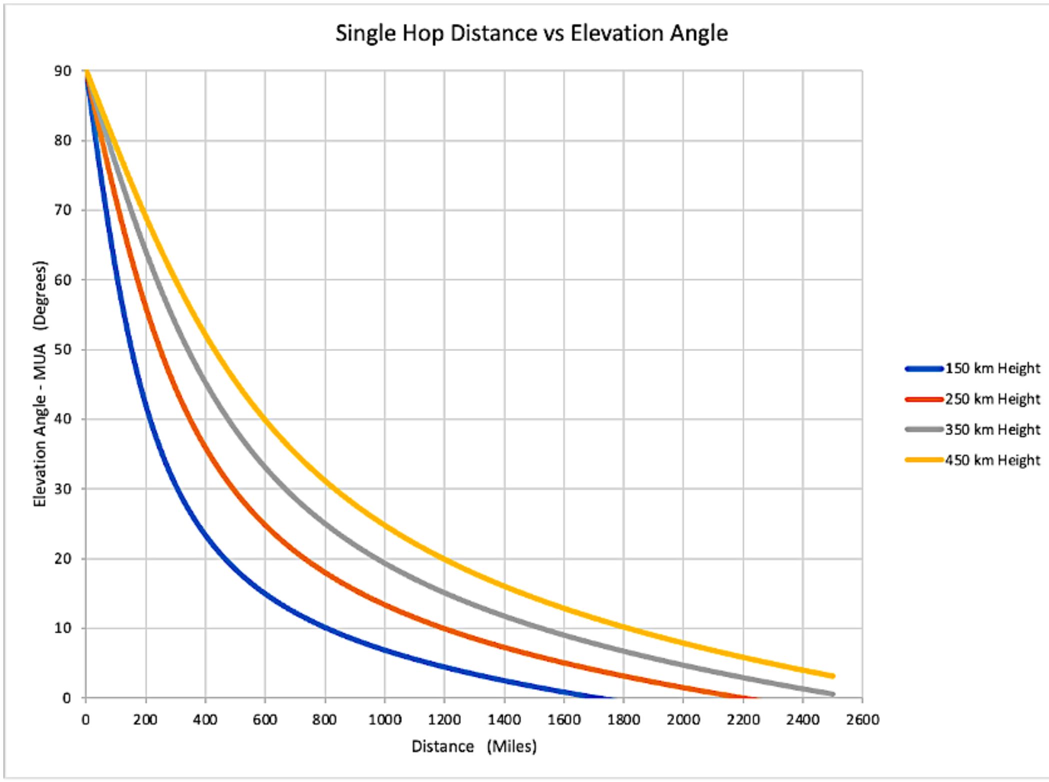
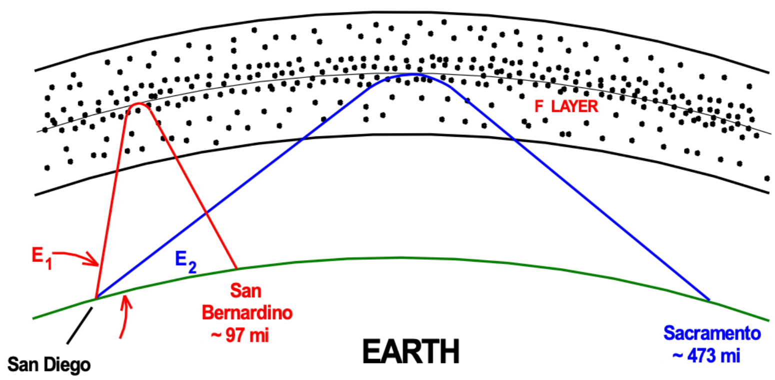


Figure 24 Distance vs elevation angle (source: author)



- E1 = 75 deg
- E2 = 30 deg
- f_c = ?

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

Figure 25 Elevation angles for San Bernardino and Sacramento (source: author)

The next step in calculating the maximum usable frequencies for San Bernardino and Sacramento is to determine the ionosphere's critical frequency at the time of the net. Figure 26 shows the Critical Frequency for June 3, 2020 at 17:00 UT. Over California the Critical Frequency was between 4 to 5 MHz.

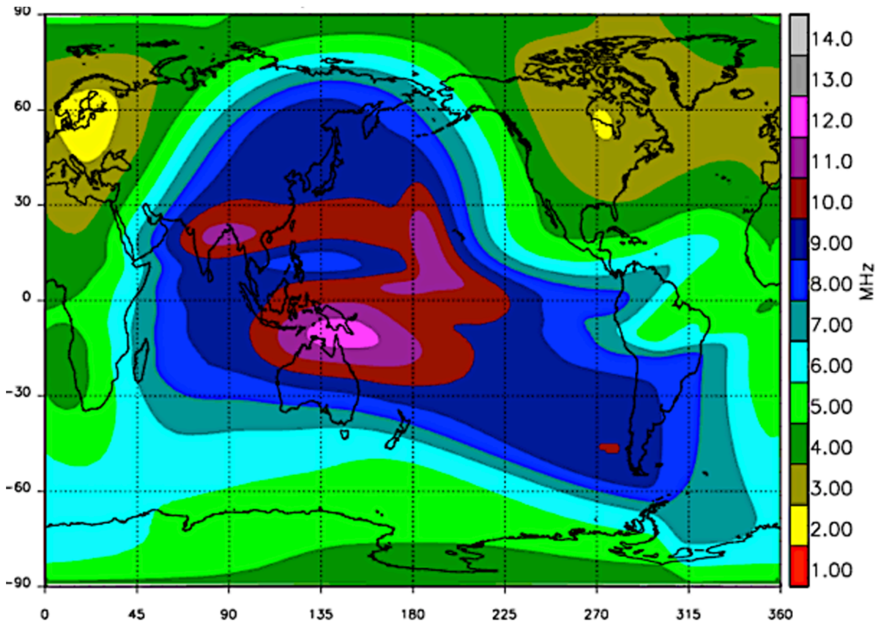


Figure 26 Critical Frequency for June 3, 2020 at 17:00 UT

Using a critical frequency of 5 MHz, the maximum usable frequencies for San Bernardino and Sacramento are

$$San\ Bernardino\colon\ MUF_1 = \frac{f_c}{\sin E_1} = \frac{5\ MHz}{\sin 75°} = 5.18\ MHz$$

$$Sacramento\colon\ \ MUF_2 = \frac{f_c}{\sin E_2} = \frac{5\ MHz}{\sin 30°} = 10\ MHz$$

At the net's operating frequency of 7.2 MHz (40 meters) San Diego could not reach (or hear) San Bernardino because the maximum usable frequency for that path (5.18 MHz) was less than the net's frequency of 7.2 MHz. That is, signals from San Diego "skipped over" San Bernardino. Sacramento could easily be reached since the maximum usable frequency for the Sacramento path (10 MHz) was greater than the net's operating frequency (7.2 MHz).

18.2.7 Maximum Usable Frequency Chart

As we have seen, maximum usable frequency depends directly on critical frequency f_c and on the elevation angle E at which a signal is transmitted according to

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

Figure 27 shows the MUF verses critical frequency for various elevation angles. For example, at a critical frequency of 8 MHz, the MUF is approximately 31 MHz when transmitting at an elevation angle of 15^o (red trace). At an elevation angle of 25^o (yellow trace) the MUF is about 20 MHz.

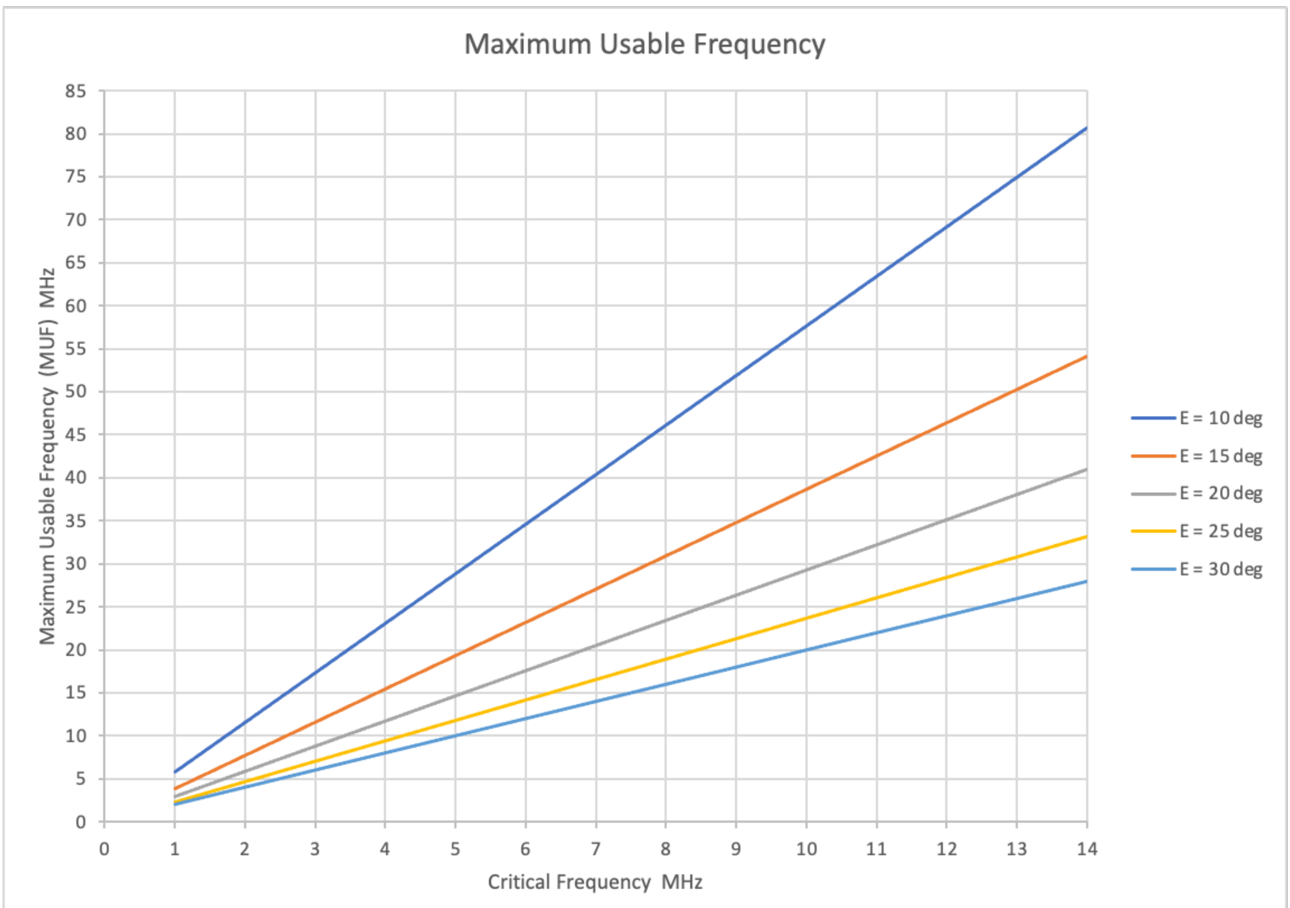


Figure 27 Maximum usable frequency chart (source: author)

A signal transmitted at a very low angle, say E = 10^o, will have a much higher MUF than a signal transmitted at an elevation angle of 20^o. The MUFs at a critical frequency of 8 MHz are 46 MHz and 24 MHz respectively from Figure 27.

Published MUF values are typically for signals transmitted at extremely low angles of less than 5°. Most amateur radio operators cannot achieve published MUF values because the lowest angles that their antennas can transmit at are generally10° or more. For a published MUF of 40 MHz, the highest frequency band that you can communicate on may be 15 meters (21 MHz) because of antenna limitations.

As discussed earlier, the lowest angle signal that can be transmitted, i.e. the lowest radiated angle (LRA), is determined by your antenna's vertical radiation pattern as illustrated in Figure 28. LRA is the low angle at which an antenna's radiated power drops 6 db from its maximum. The antenna's radiated power drops very quickly at angles below its LRA. In addition, an antenna's highest radiated angle (HRA) is the angle at which its high angle radiated power also drops by 6 db from its maximum. By knowing your antenna's LRA, you can determine your MUF for the current critical frequency by using the chart in Figure 27.

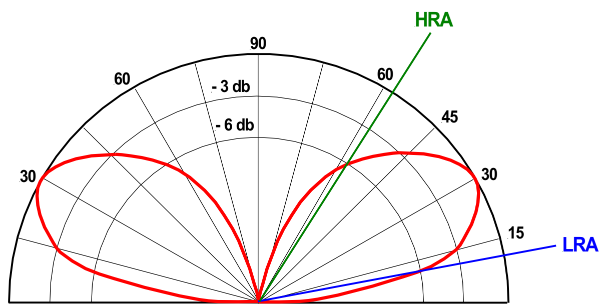


Figure 28 Typical antenna vertical radiation pattern (source: author)

For long distance DX communications, you want to transmit at the maximum usable frequency determined by your antenna's LRA and the current critical frequency using Figure 27. Your LRA also determines the longest hop distance that you can achieve. Long hops reduce the number of passes through the ionosphere required to reach a destination, minimizing signal losses. For example, at an F2 height of 250 km (red trace in Figure 29) a signal transmitted at an elevation of 10° will have a hop distance of approximately 1,200 miles.

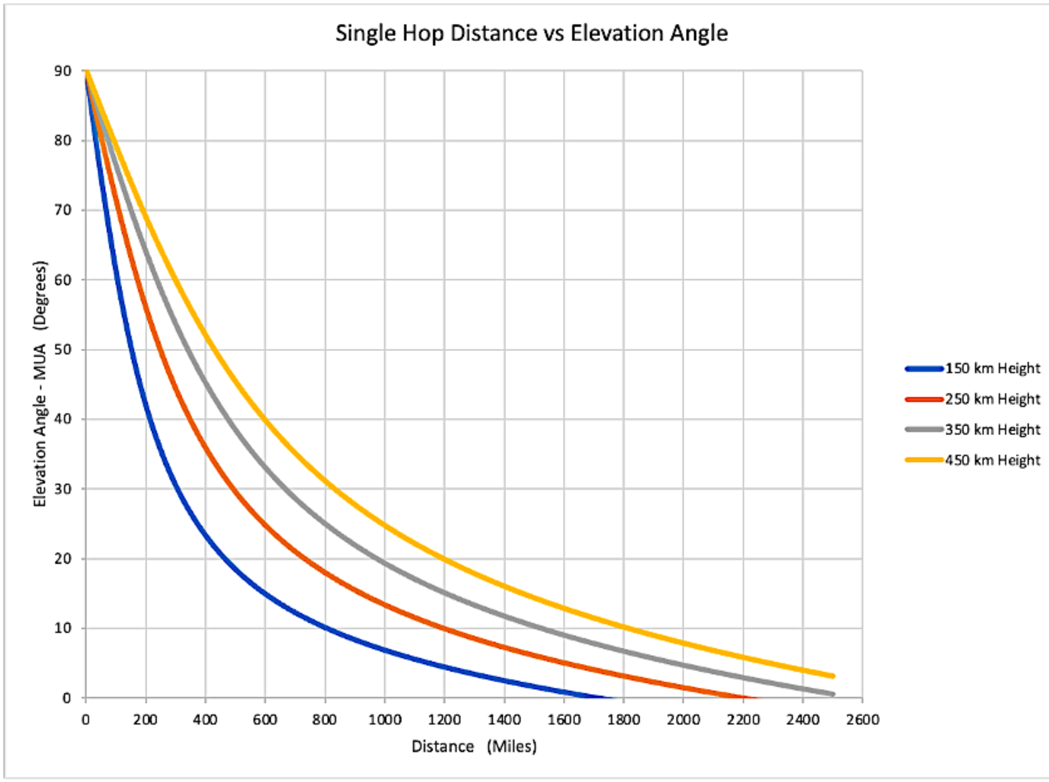


Figure 29 Distance verses elevation angle (source: author)

18.2.8 MUF Provided by Ionograms

Current maximum usable frequency can also be determined from ionogram charts.

The red trace in Figure 30 illustration the propagation path of a signal transmitted at an oblique angle by a radio station at site T. At an altitude of h km, refraction in Earth's ionosphere bends the signal back toward Earth where it is received by the radio station at site R. While the red trace accurately portrays the path of the radio signal through the ionosphere, its curved shape can complicate propagation analysis without adding any additional useful information. In these situations, it is easier to assume that radio signals are reflected back to Earth by the ionosphere instead of refracted.

The blue trace in Figure 30 shows the path that the signal would follow from radio station T to the receiving station at R if the signal were reflected in the ionosphere. Notice that the reflection point A at an altitude h'_o is greater than the signal's actual refraction altitude h.

The magenta trace on the right side of Figure 30 illustrates a signal transmitted vertically straight up into the ionosphere. Such a signal is typically transmitted by an ionosonde for the purpose of generating an ionogram (the red trace in Figure 31) depicting current ionospheric conditions. The altitude at which the vertical signal is reflected back to Earth is designated as h'_v. For example, the red trace in Figure 31 shows that the refection altitude h'_v for an ionogram frequency (f_v) of 6 MHz is around 320 km.

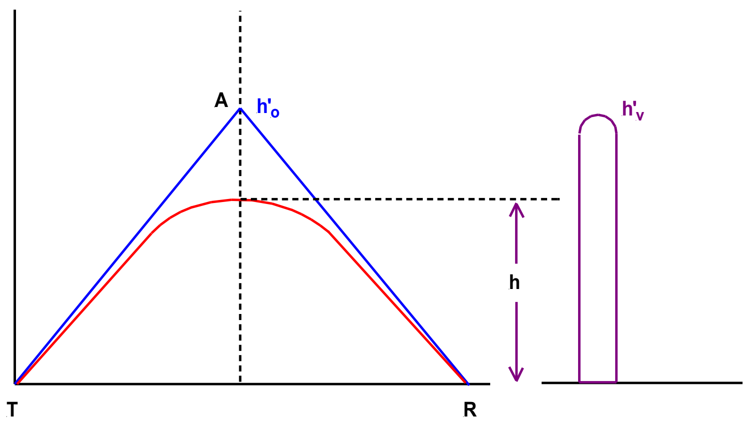


Figure 30 Ionospheric Propagation Virtual Height (source: author)

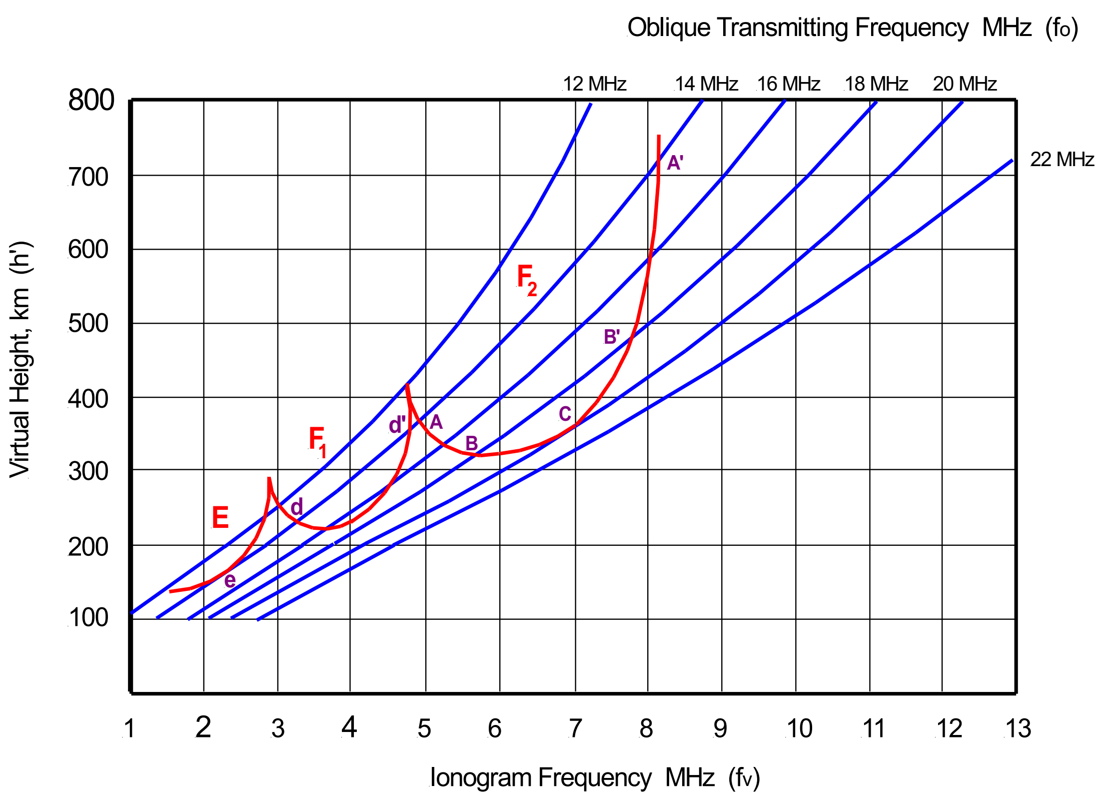


Figure 31 Ionogram superimposed on transmission curves (source: derived from Davies)

In 1935 D. F. Martyn showed that the reflection heigh h'_o of an oblique wave is the same as the reflection height h'_v of a wave transmitted vertically. Martyn's theorem permits an ionogram (red trace in Figure 31) to be superimposed on transmission curves (blue traces in Figure 31) to graphically determine the MUF between two stations D km apart. The blue transmission curves in Figure 31 are obtained from the equation

$$h' = \frac{D}{2\sqrt{(f_o/f_v)^2 - 1}}$$

by holding the distance D between two stations constants, selecting a value for the oblique transmission frequency f_o, and varying the vertical incident frequency f_v over a range of values to produce a single transmission curve. The value of f_o is incremented and the process repeated forming the next transmission curve. The procedure is continued over the range of f_o values of interest forming a family of transmission curves.

The shape of the red ionogram trace in Figure 31 indicates that F2, F1, and E regions of the ionosphere are present. The intersection of a blue transmission curve having a frequency f_o with the red ionogram trace gives the virtual height of reflection for that transmitted signal. For example, a signal transmitted at a frequency of 14 MHz intersects the ionogram trace at 5 places, points A and A' in the F2 region, d and d' in the F1 region, and point e in the E region. These 5 points are the only points in the ionosphere at which the 14 MHz signal in this example can reflect and reach the receiving site R located a distance of D km from the transmitting station T. Each of these reflection points identifies a particular propagation path from T to R. Thus 5 different propagation paths are possible. A different set of transmission curves, reflection points, and propagation paths are required to reach some other receiving station R' located a distance E km from the transmitter.

There are two reflection points in the F2 region of the ionosphere (A and A'). The propagation path corresponding to the lower reflection point, point A, is called the low-angle path or ray while the signal reflecting at point A' is the high-angle propagation path. The high-angle path is frequently referred to as a Pedersen ray. There are also two reflection points in the F1 region (d and d') producing a low-angle propagation path and a high-angle path for that region as well. In this example, only a single reflection point occurs in the E region of the ionosphere.

A signal transmitted from the ground will be reflected by the first reflection point that it encounters. In Figure 31 the first 14 MHz reflection point encountered is in the E region of the ionosphere. While reflection is technically possible in both the F1 and F2 regions, no reflections occur at these higher altitudes since the signal is reflected by the E layer. The F1 and F2 regions are said to be screened by the E region since the E region prevents signals from reaching the higher F1 and F2 layers.

In this example, an 18 MHz signal intersects the ionogram curve only in the F2 region of the ionosphere. Consequently the 18 MHz signal cannot reflect from either the E or F1 regions of the ionosphere. Moving to a transmitting frequency of 18 MHz or higher prevents the E and F1 regions from screening the F2 region.

Notice that the virtual heights for the two 18 MHz reflection points (B and B') are closer together than the 14 MHz reflection points A and A'. B and B' are separated by only 130 km in virtual height while A and A' are 310 km apart. Increasing the transmitting frequency further to 20 MHz causes the low-path and high-path reflection points to merge at a single point C. In fact, the 20 MHz transmission curve is tangent to the ionogram at point C. Increasing the transmitting frequency just a little more, say to 21 MHz, will cause the resulting transmission curve to miss the ionogram altogether. In this example, 20 MHz is the maximum usable frequency for signals transmitted a distance of D km from Station T to Station R. A signal with a frequency higher than 20 MHz will penetrate the ionosphere and be lost to outer space.

Any signal with a frequency lower than the F2 maximum usable frequency will intersect the F2 segment of the ionogram in two places, as illustrated in Figure 31. The same is true for the F1 and E maximum usable frequencies. In Figure 31, a 14 MHz signal intersects the ionogram trace at only one point, point e, in the E region of the ionosphere. Thus, in this example, 14 MHz is the MUF for signals reflecting in the E region.

The above observations are particularly important. All signals propagating through the ionosphere at a frequency below the MUF will follow two paths from the transmitter T to the receiving station R. The two paths are the high-angle path and the low-angle path. The two paths become closer together as the transmitting frequency is increased. The two paths merge, becoming a single path, at the signal's maximum usable frequency. Merging of the two paths enhances the strength of the received signal.

Both the low-angle and the high-angle signals arrive at the receiving station. Unfortunately, the path followed by the high-angle signal is longer than the low-angle path meaning that the two signals are out of phase when they arrive at the receiving station. The out of phase signals interfere with each other causing the resulting received signal to fade in and out.

The high-angle signal is more sensitive to small changes in ionospheric conditions than the low-angle signal. Consequently, the high-angle signal tends to become de-focused and weaker than the low-angle signal. The signal received at the receiving station is generally the low-angle signal with the contribution, and interference, from the high-angle signal usually being less important. However, in some cases, ionospheric conditions are such that it is the high-angle signal that is actually received.

As a final note before leaving this section. The ionogram shown in Figure 31 is for the ordinary or o-mode of propagation. Including the extra ordinary x-mode of propagation adds a second ionogram trace slightly displaced from the o-mode ionogram. In the equation

$$h' = \frac{D}{2\sqrt{(f_o/f_v)^2 - 1}}$$

there are now two ionosonde frequencies, f_{vo} for the vertical o-mode signal and f_{vx} for the vertical x-mode signal. This adds a second set of reflection points. Consequently, there are 4 propagation paths when transmitting at a frequency below the MUF. These paths are the low-angle and high-angle o-mode paths and the low-angle and high-angle x-mode paths. The o-mode and x-mode paths frequently end up at different destinations.

18.3 Frequency of Optimum Transmission

Working at the Maximum Usable Frequency is literally “living on the edge”. Small changes in critical frequency and other ionospheric parameters cause the MUF to be in a continuous state of change. At one moment a MUF signal refracts back to Earth illustrated by the red trace in Figure 32. At the next moment it is lost to outer space (the black trace). Consequently, signals transmitted at the MUF frequently fade in and out. Communications is generally more stable by transmitting at a frequency slightly lower than the MUF. It is generally accepted that the Frequency of Optimum Transmission (FOT) is 80 to 85% of the MUF.

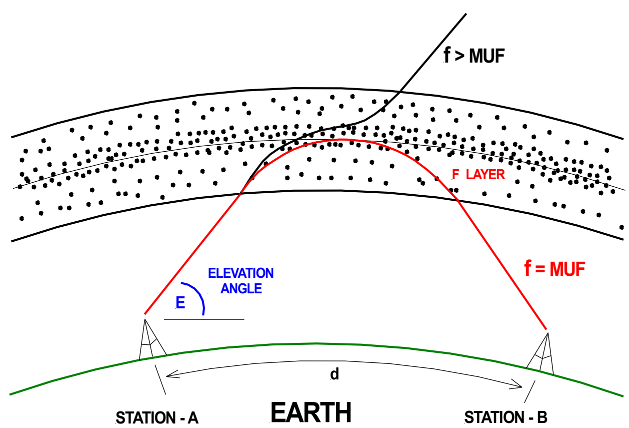


Figure 32 Signal with f > MUF is lost to outer space (source: author)

The MUF in the earlier example of communications between San Diego and Sacramento is 10 MHz. The FOT for this path is approximately 8.2 MHz. This is comfortably above the 7.2 MHz operating frequency, explaining the excellent stable communications between San Diego and Sacramento predicted in the example. The MUF for communications between San Diego and San Bernardino is 5.18 MHz, below the communication net operating frequency. The FOT for this path is approximately 4.25 MHz. For the particular time and date used in the example, achieving successful communications between San Diego and San Bernardino requires moving down to 80-meters.

FOT can be directly read from Hourly Area Prediction (HAP) charts provided by the Australian Bureau of Meteorology. HAP charts predict the optimum frequency for communicating between a specified city (the Base City) and a selected distant location. Los Angeles, California is the base city for the HAP chart shown in Figure 33.

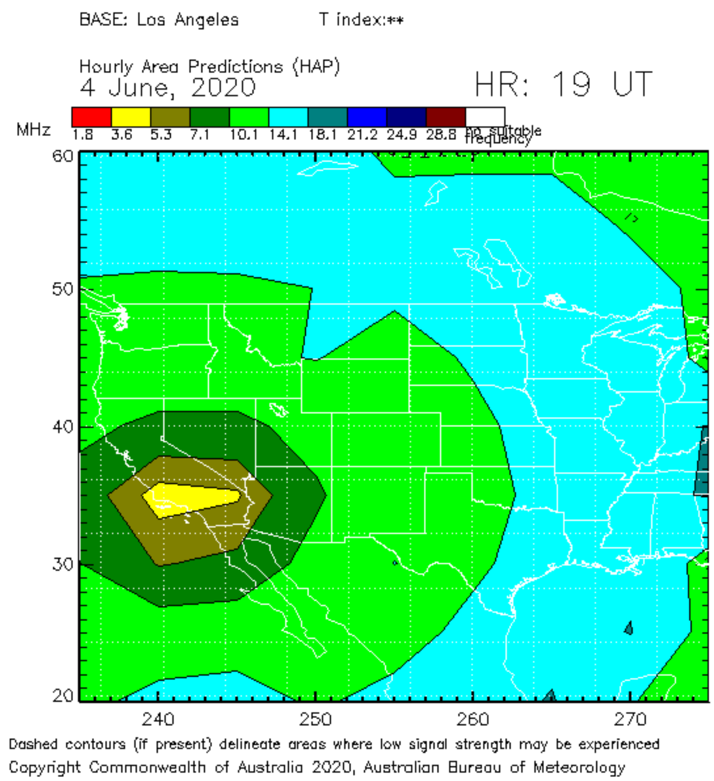


Figure 33 HAP Chart (source: Australian Bureau of Meteorology)

The vertical axis of the chart is degrees Latitude. The horizontal axis is degrees East Longitude, that is measured eastward around the Earth from the Prime Meridian. The color band at the location of the base city (yellow in this example) is by definition the critical frequency f_c at the time the chart was produced.

The HAP chart color bands represent the recommended HF frequency (FOT) for communicating between the base city and a selected distant location for a given date and hour. There are several different versions of the HAP chart available. The colored regions shown in the Figure 33 HAP chart represent different amateur radio frequency bands. For example, 30 meters (10.1 MHz) is the FOT for communicating between Los Angeles, California and Portland, Oregon at 1900 UT (noon local time) on June 4, 2020. The critical frequency at that time (during solar minimum) was around 4.5 MHz.

A HAP Chart is an estimate of the current FOT. Remember that FOT < MUF, specifically

$$FOT \equiv 0.825\, MUF$$

Consequently, for a given FOT shown in a HAP chart, the corresponding

$$MUF \approx 1.2\, FOT$$

In Figure 33 the MUF for Los Angeles to Portland is approximately

$$MUF \approx 1.2\ FOT = 1.2(10.1\ MHz) = 12.12\ MHz$$

Since FOT is an estimate, it is possible that communications between Los Angeles and Portland could be conducted on 20 meters (14.2 MHz). However, it is unlikely that Portland could be reached on 17 meters (18.1 MHz).

A HAP Chart is a starting point in selecting a frequency band.

The FOT shown in the Figure 33 HAP chart for Los Angeles to Portland is 30 meters. Note that this is the highest frequency band for dependable communications from Los Angeles to Portland. Any frequency band lower than the FOT could also be used, for example, 40 meters. However, the 40-meter path could encounter multi-path interference and deep D Layer absorption not present on 30 meters. In general, the best communications between two stations is obtained using the FOT frequency.

The HAP chart in Figure 34 could have been used to predict communication conditions between San Diego, Sacramento, and San Bernardino during the June 3, 2020 communications net. San Diego is not in the HAP chart data base. So, the map for the next closest large city (Los Angeles) has to be used and visually shifted downward to be centered on San Diego. When this is done, the FOT to Sacramento is 40 meters (dark green region of the chart). Thus, San Diego could easily hear Sacramento. The FOT to San Bernardino is 80 meters (the yellow region of the chart). Consequently, on this particular day and time San Diego could not hear San Bernardino on the 40 meters. Instead, San Bernardino traffic had to be relayed to San Diego through Sacramento.

HAP charts, and instructions for using them, are found under the "Tools" tab of the www.skywave-radio.org website.

FOT charts, similar to the one in Figure 35, are also available under the "Tools" tab of the website. The chart in Figure 35 could have as well been used to predict communication conditions between San Diego, Sacramento, and San Bernardino. In the example the elevation angle between San Diego and San Bernardino $E_1 = 75^o$, the angle for San Diego to Sacramento $E_2 = 30^o$, while the critical frequency was 5 MHz. For the San Diego to San Bernardino path with $E_1 = 75^o$ and 5 MHz critical frequency, the chart shows that the FOT is approximately 4.5 MHz. The FOT for San Diego to Sacramento with $E_2 = 30^o$ is approximately 8.5 MHz.

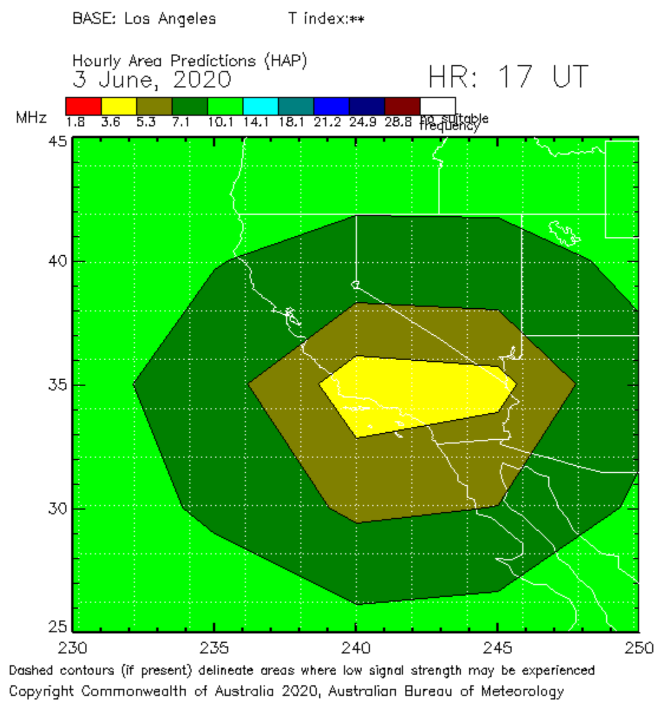


Figure 34 HAP chart for the communication net on 6/3/2020

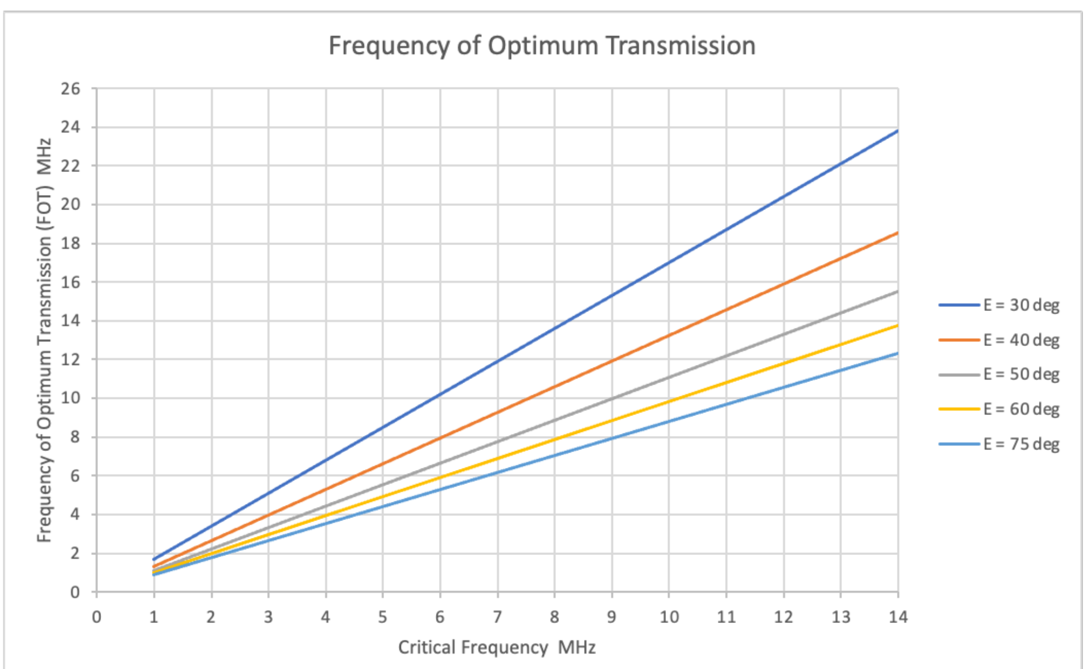


Figure 35 Frequency of optimum transmission (source: author)

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