1 Introduction

Maximum Usable Angle (MUA) is a very useful tool for determining skip distance. It is also helpful in determining which stations beyond the skip zone are reachable and which are not. Both of these applications are important for Winlink and Winmor emergency communications work. MUA also provides interesting insight into the operational limitations of your antenna and conditions necessary for band openings.

2 Maximum Usable Angle

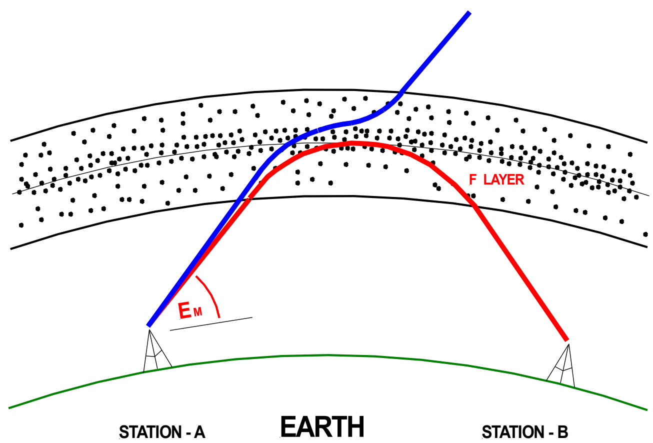

Figure 1 Maximum Usable Angle

Maximum Usable Angle (MUA = E_M) is the highest angle signal that can be transmitted at an operating frequency of f_o and still be refracted back to Earth when the critical frequency is f_c. Transmitting at an angle greater than MUA will cause the signal to penetrate the ionosphere and be lost to outer space, as shown in Figure 1.

The equation for Maximum Usable Angle is:

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

3 An Example – The 80 meter Episode

80 meters is a night time band. In fact, 80 meters is often open all through the night even though higher frequency bands shut down. The author thought that it would be fun to operate 80 meters during the evening. Even operating all night long!

An 80 meter Inverted V antenna was built.

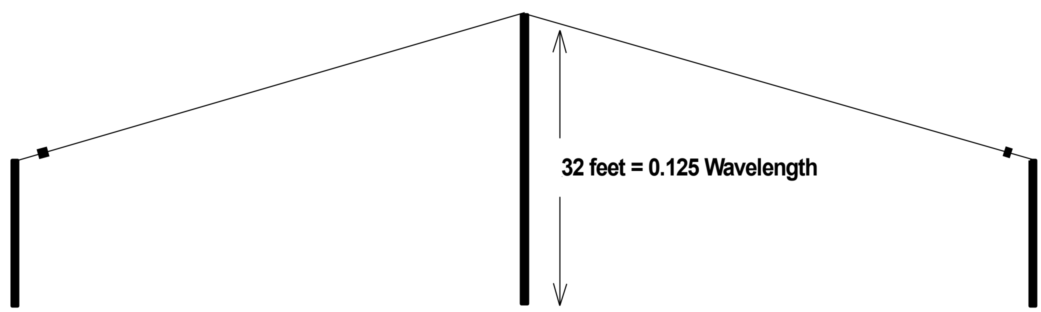

Figure 2 80 meter Inverted V Antenna

The vertical radiation pattern for the antenna is shown below:

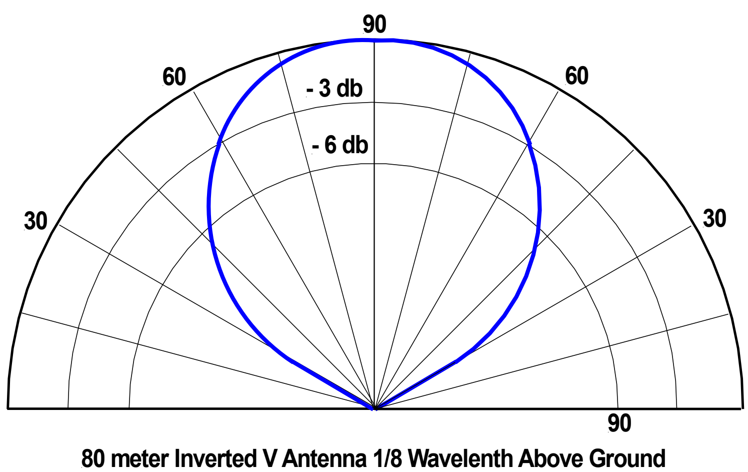

Figure 3 Vertical radiation pattern for 80 meter NVIS antenna

The antenna was, and still is, a good Near Vertical Incident Skywave (NVIS) antenna. The antenna supports close in communications throughout southern California and often into Arizona and Nevada. It is a good antenna.

However, around 10 PM in the evening the antenna seemed to stop working. There were plenty of stations being heard on 80 meters. The Critical Frequency was approximately 3 MHz, so Maximum Usable Frequency (MUF) did not seem to be an issue. So what was happening?

Was it possible that the high radiation angle from the NVIS Inverted V antenna was a problem. To find out, the MUF equation,

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

where E is the elevation angle, was solved for angle instead of frequency giving the equation for MUA:

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

Plugging in the values for my particular situation yielded:

$$MUA = E_M = \sin^{-1}\left[\frac{f_c}{f_o}\right] = \sin^{-1}\left[\frac{3.0\ MHz}{3.8\ MHz}\right] = 52°$$

for a critical frequency $f_c = 3\ MHz$

and an operating frequency $f_o = 3.8\ MHz.$

The MUA of 52 degrees turned out to be too low for my 80 meter Inverted V antenna.

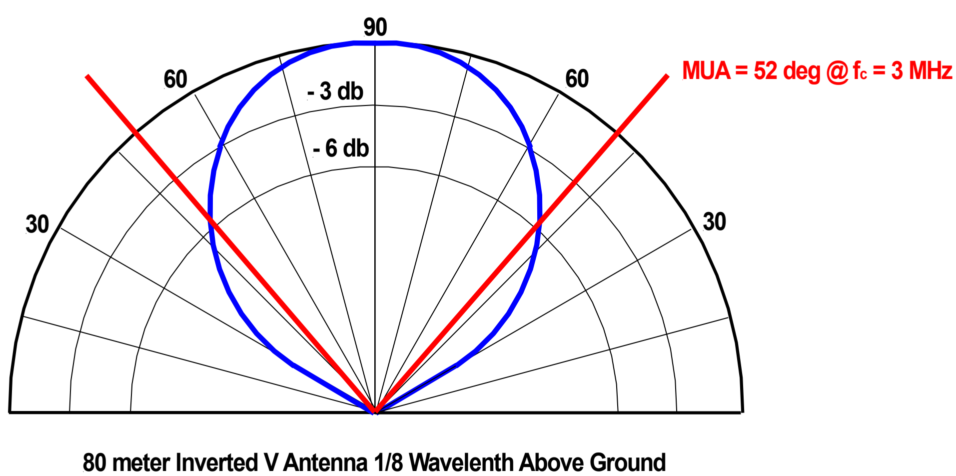

Figure 4 MUA vs Antenna radiation pattern

Nearly all of the energy from the antenna was radiated at angles greater than the MUA and being lost to outer space.

It became clear that to operate 80 meters late at night either

- The height of the Inverted V antenna had to be greatly increased to get a lower angle radiation pattern, an option which was not practical for me, or
- A vertical antenna would be required.

A vertical antenna can work down to a critical frequency of nearly 1 MHz, as shown in Figure 5.

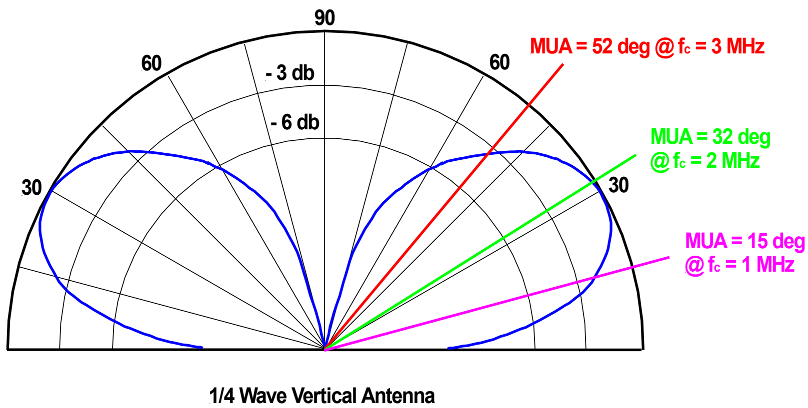

Figure 5 MUA vs Antenna radiation pattern for a vertical antenna

How low can the critical frequency get? Figure 6 shows that during solar minimum the critical frequency can easily get down to 2 MHz at night and at times down to even 1 MHz.

From this experience it became apparent that two 80 meter antennas would be required for emergency communications work. While an 80 meter vertical antenna works well late at night, its low angle of radiation does not provide coverage for stations 50 to 300 miles away. A NVIS Inverted V antenna works well to cover these close in stations early in the evening when the MUA is great enough to support operation of the antenna. VHF and UHF equipment became generally available in the late 1960s. Before that time Inverted V antennas were used on 80 meters, both day and night, to provide the same type of local communications that 2 meters is used for today.

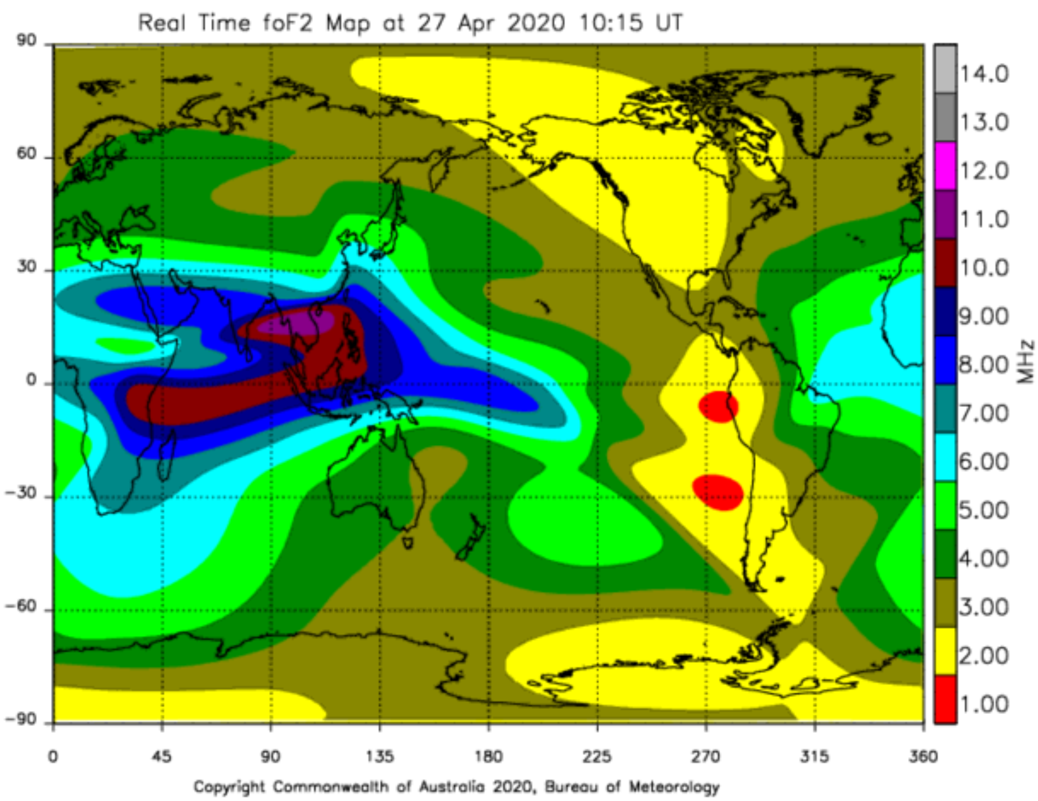

Figure 6 Critical Frequency Map

4 Skip Distance

In Figure 7, increasing the elevation angle E shortens the distance transmitted in a single hop. The shortest possible distance (from Point A to B) occurs when E = MUA, the red path in Figure 7. Signals transmitted at an angle greater than the MUA are lost to outer space. Thus Station B is the closest station that Station A can contact. Stations in the Skip Zone (closer to Station A) can not be reached or heard by Station A, they are “skipped over”.

Skip distance charts, like the one shown in Figure 8, can be created for each frequency band. The chart allows the skip distance to be read directly. In addition, the chart gives an indication of what stations outside the skip zone (see Figure 7) can be reached and which can not. This is critical for emergency communications.

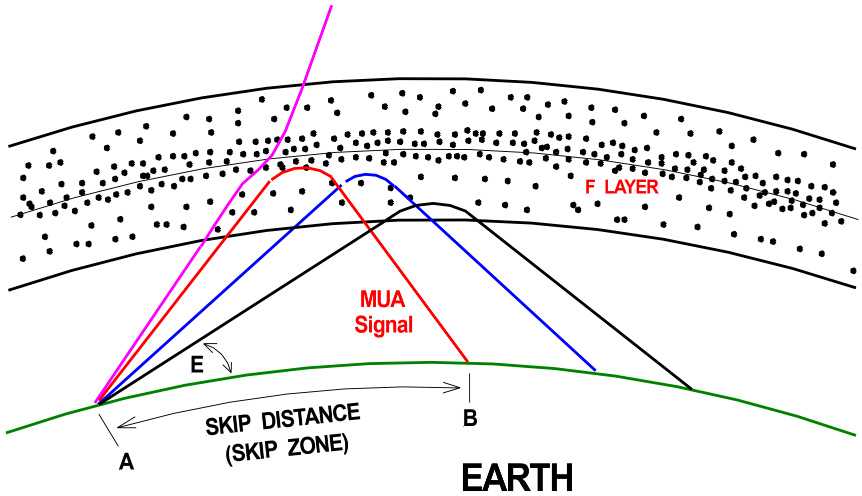

Figure 7 Skip Distance

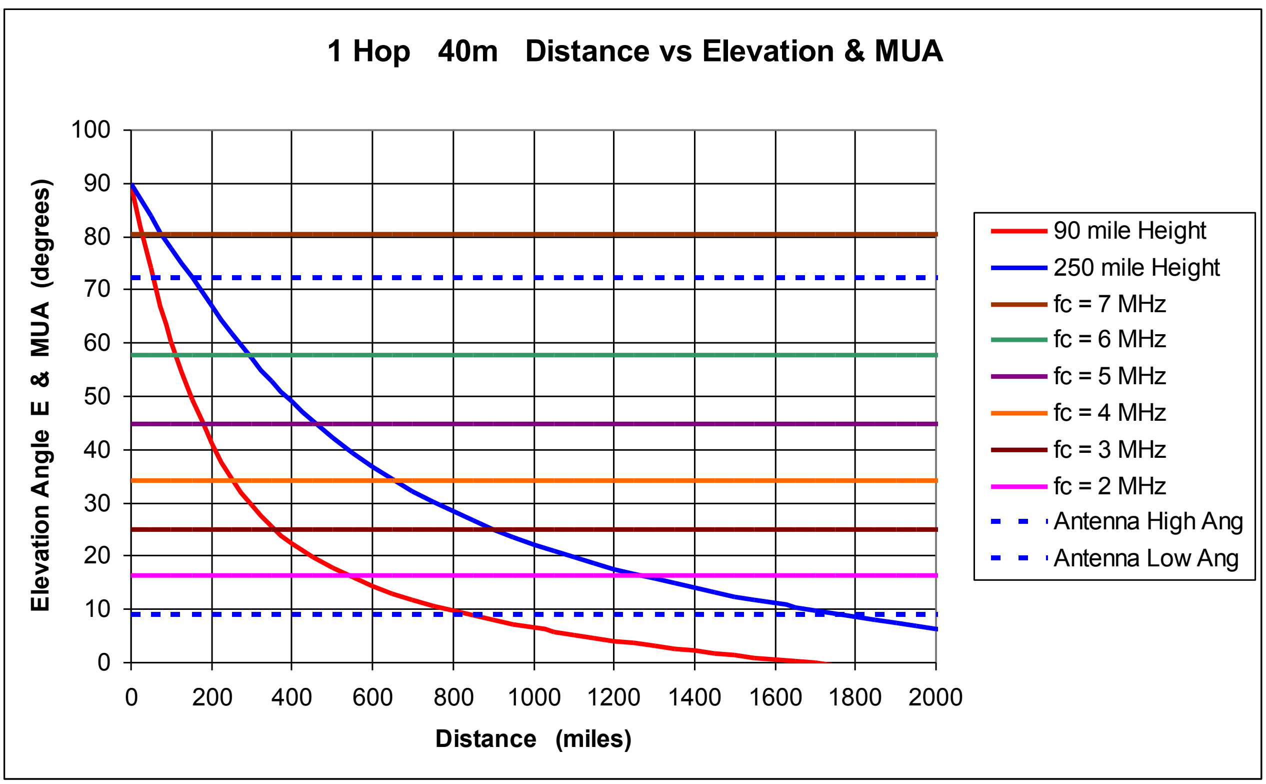

Figure 8 Skip distance chart for 40 meters

The blue curved line in Figure 8 gives the distance vs elevation angle for a hypothetical signal refracting back to Earth from an altitude of 250 miles, near the top of the F region. The red curved line is the distance vs elevation angle for a signal refracting at an altitude of 90 miles, near the bottom of the region. For a real signal propagating through the F region, refraction will actually occur at some point between these two extremes. The horizontal lines in Figure 8 show the Maximum Usable Angle for various critical frequencies f_c . The horizontal dashed blue lines are the maximum and minimum angles at which signals are radiated from an antenna having a vertical radiation pattern similar to that shown in Figure 5. That is, the antenna can not effectively transmit a signal at an angle greater than about 70 or lower than 10 degrees.

The maximum elevation angle (MUA) a signal can be transmitted at to reach a station a certain distance away is limited by:

- The maximum refraction point in the F Layer (the blue curve) or
- The current critical frequency f_c ,

whichever yields the smallest angle. The minimum elevation angle is determined by the lowest refraction point (the red curve). Again, the elevation angle of a signal actually propagating through the F Layer will be somewhere between these two extremes.

In Figure 8, the minimum skip distance is the distance at which the lowest refraction point, the red curve, intersects the current critical frequency f_c MUA line. The actual skip distance may be longer than this, but it can not be any shorter. For example, the 40 meter minimum skip distance at a critical frequency of 3 MHz is about 350 miles (the point at which the red curve and the brown 3 MHz critical frequency line intersect). This is the closest station that can be reached.

Why is this the minimum skip distance? Tracing upward along the red curve to angles greater than the critical frequency MUA line would produce shorter skip distances. However, signals transmitted at greater than the MUA are lost to outer space. So we can not go above the MUA for the current critical frequency. In this example we can not go above 25 degrees. Tracing horizontally along the MUA line to the left of the red curve would also produce shorter skip distances, but the red curve represents the lowest refraction point in the F region. So we can not go to the left of the red line for signals propagating through the F region of the ionosphere. The only directions of movement possible are horizontally along the MUA line to the right of the red curve or down the red curve to angles below the MUA line. Movement in either of these two directions produces a longer skip distance, which under actual conditions may be the case. For example, the skip distance would be longer if the signal transmitted at the maximum usable angle penetrated further into the F region (to the right of the red curve) before refracting back to Earth. But, the skip distance can not be any shorter than the distance at which the red curve and the current critical frequency MUA line intersect.

5 Reachable Stations

At a critical frequency of $f_c = 5\ MHz$, a station 600 miles away can be reached in a single hop by transmitting at an angle somewhere between 15 to 38 degrees. This is a wide range of angles, well within the capabilities of the transmitting antenna, that spans the entire width of the F region from the bottom of the region to the top as represented by the red and blue curves respectively in Figure 9. It is almost certain that at a some height within the F region, between an angle of 15 to 38 degrees, the signal will be refracted back to Earth and reach the station 600 miles away. During the day, a further condition is that the signal not be absorbed in the D Layer. At a critical frequency of $f_c = 3\ MHz$ the upper angle is limited to 25 degrees by the critical frequency so the range of angles is 15 to 25 degrees. In order to reach the station 600 miles away the signal must be refracted in the lower half of the ionosphere, between the red curve and the brown critical frequency line as shown in Figure 9. Refracting back to Earth from a point higher in the ionosphere (between the brown MUA line and the blue curve) is not possible since a signal transmitted at an angle greater than the MUA will be lost to outer space. Under the conditions given here for $f_c = 3\ MHz$, reaching the station 600 miles away may be more questionable.

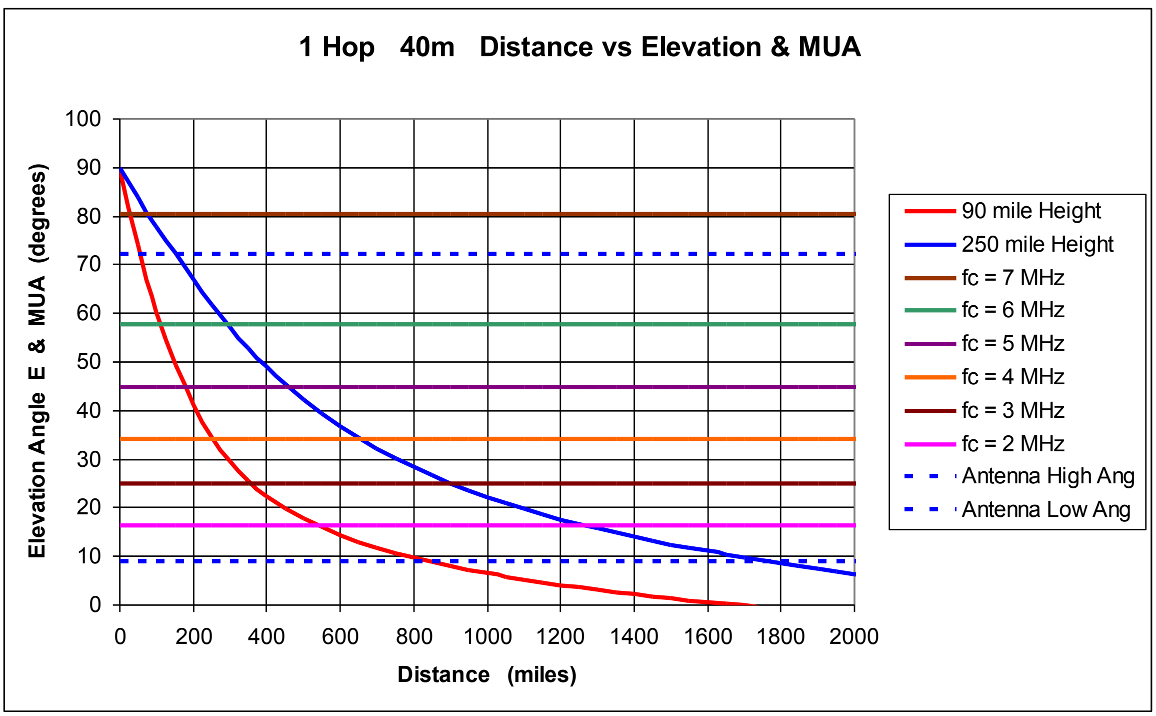

Figure 9 Determining Reachable Stations

A station 1,600 miles away can not be reached in a single hop because the required elevation angle is below what the transmitting antenna can support, as illustrated in Figure 9. At a critical frequency of $f_c = 3\ MHz$ the range of angles required to reach 800 miles is 10 to 25 degrees. Again, this ranges of angles spans nearly the entire width of the F region. So the chance of achieving 800 miles in one hop is pretty good. Consequently, reaching the station 1,600 miles away in 2 hops is probably also good. There are however a couple of concerns. The range of angles needed to reach 800 miles pushes the lower limits of the transmitting antenna. During the day, when the D Layer is present, transmitting at a low elevation angle means the signal spends a fair amount of time passing through the D Layer. This increases the chance that it will be completely absorbed, as shown in Figure 10, and never reach 800 miles. During the day we want to transmit at the highest angle possible to minimize the amount of time spent in the D Layer. At night, when there is not a D Layer, 800 miles can probably be reached in one hop and 1,600 miles in the second hop.

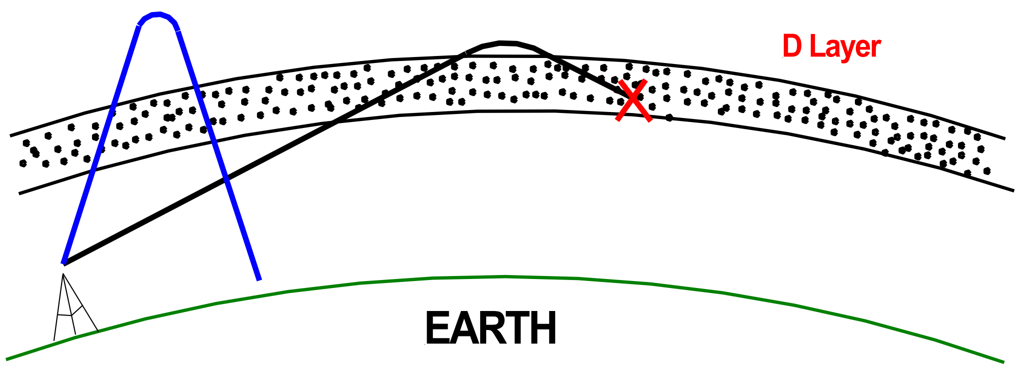

Figure 10 Signal transmitted at a low angle more likely to be absorb by the D Layer

6 Skip Distance Determined by Your Antenna

Skip distance may be determined by your antenna IF:

- The maximum radiated angle of your antenna, MRA shown in Figure 11,
- Is less than the MUA determined by the critical frequency f_c

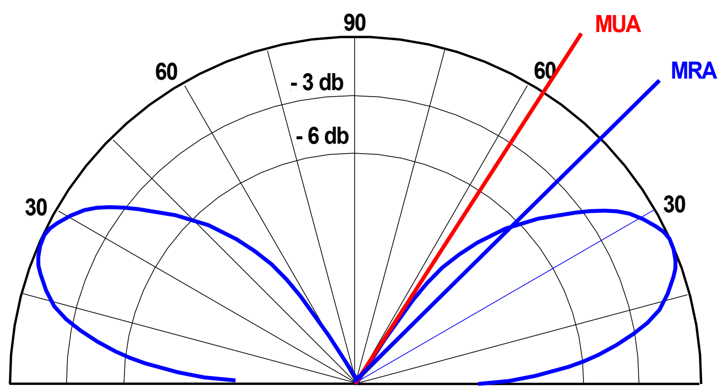

Figure 11 Maximum Radiated Angle (MRA)

Referring to Figure 9, the skip distance for a MUA = 60 degrees is 100 miles. However, the skip distance for a 40 meter vertical antenna with an MRA of 45 degrees will be around 200 miles, not the 100 miles indicated by the 60 degree MUA. Stations closer than 200 miles will be skipped over by the vertical antenna.

7 Minimum Critical Frequency and Band Conditions

Minimum Critical Frequency f_{cm} is the lowest critical frequency that will allow operation on a given frequency band. f_{cm} is a very useful number since you can use it to quickly determine what band conditions are likely to be by simply looking at a current critical frequency map like the one in Figure 12.

The equation for minimum critical frequency is derived by solving the maximum usable angle equation

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

for f_c . Doing so gives the minimum critical frequency equation shown below.

$$f_{cm} = f_o \sin E_a$$

where

f_{cm} = lowest critical frequency capable of supporting transmissions from your antenna

f_o = your desired operating frequency

E_a = the elevation angle of a signal radiating from you antenna.

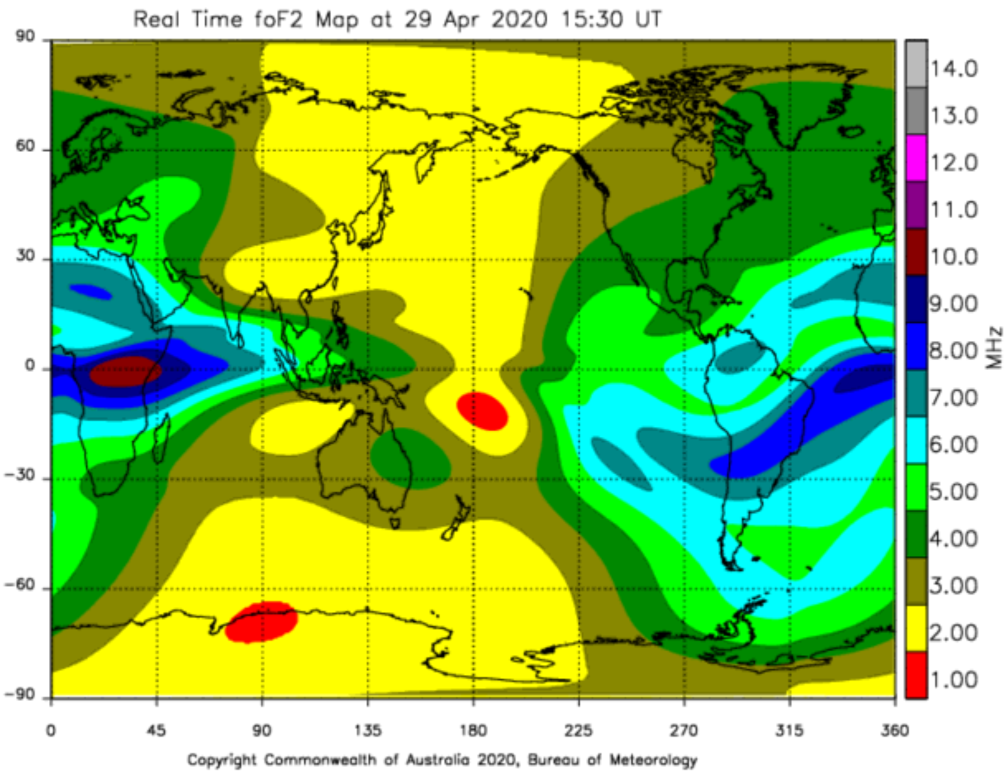

Figure 12 Determining current f_{cm} using global critical frequency map

Minimum critical frequency depends on the characteristics of your antenna. For example, the minimum critical frequency required for operations on 20 meters, using the ½ wave dipole in Figure 13, is shown below.

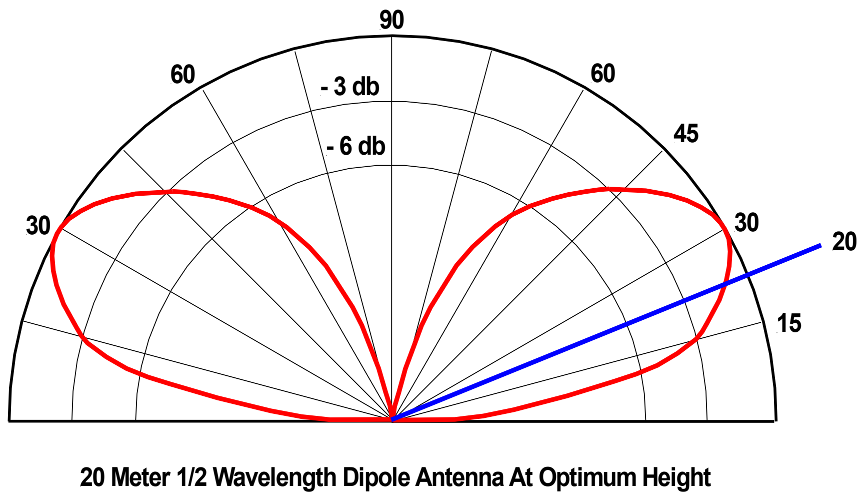

Figure 13 Calculating minimum required frequency for 20 meters

$$f_{cm} = f_o \sin E_a$$

$$f_o = 14.2\ MHz$$

f_{cm} = 7.1 MHz @ E_a = 30 degrees

f_{cm} = 4.9 MHz @ E_a = 20 degrees

f_{cm} = 3.7 MHz @ E_a = 15 degrees (at -3 db point on the antenna pattern)

A critical frequency greater than 7 MHz will allow the antenna to be used at a radiation angle of 30 degrees, its best angle of radiation. The performance of the antenna decreases at lower critical frequencies. At f_{cm} = 3.7 MHz the maximum usable angle of radiation from the antenna is 15 degrees. Energy radiated at angles above 15 degrees (most of the antenna's radiation) will be lost to outer space. The performance of the antenna at radiation angles below 15 degrees is questionable.

The antenna pattern shown in Figure 13 is typical of 20 meter antennas used by amateur radio operators. Consequently, we can expect fewer and fewer people to be operating on 20 meters as the critical frequency drops below 7 MHz. At some point, near a critical frequency of 3 MHz, the band becomes dead, that is, no one is operating on the band.

The minimum critical frequency calculated here assumes there is no absorption in the D Layer. When absorption is considered, the minimum critical frequency that is actually usable will be higher than what is shown here. That is, a signal transmitted at 15 degrees is more likely to be absorbed than a signal transmitted at 20 degrees. This consideration is particularly significant on 40 and 80 meters and during mid day on 20 meters.

Operations on 20 meters is probably not very good for the conditions shown in Figure 12 since the critical frequency is only 3 to 4 MHz throughout the United States and into Europe. Conditions are even worse to the west.

As a second example, let us look at the minimum critical frequency for 80 meters using an antenna with the vertical radiation pattern shown in Figure 14.

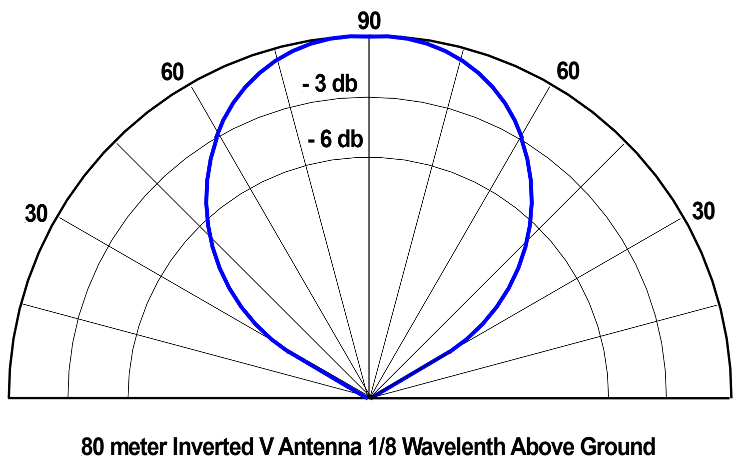

Figure 14 Determining minimum critical frequency for an 80 meter antenna

Most of the energy radiated by this antenna is at an elevation angle greater than 60 degrees. For this angle the minimum critical frequency is:

$$f_{cm} = f_o \sin E_a$$

where

$f_o = 3.8\ MHz$

f_{cm} = 3.3 MHz @ E_a = 60 degrees

This antenna will not be very useful at critical frequencies below 3.3 MHz

The minimum critical frequency by band is given in Table 1 for antennas having elevation patterns similar to that shown in Figure 13.

Band	f_{cm} @ **15°**	f_{cm} @ **20°**	f_{cm} @ **30°**	**Type of Antenna**
15 meters	5.5 MHz	7.3 MHz	10.6 MHz	Dipole or Vertical
20 meters	3.7 MHz	4.9 MHz	7.1 MHz	Dipole or Vertical
30 meters	2.6 MHz	3.5 MHz	5.0 MHz	Dipole ($1/2\ \lambda\ heigh$) or Vertical
40 meters	1.9 MHz	2.4 MHz	3.6 MHz	Dipole ($1/2\ \lambda\ heigh$) or Vertical
80 meters	1.0 MHz	1.3 MHz	1.9 MHz	Vertical

Table 1 Minimum Critical Frequencies by Band

Notice, at an angle of 30 degrees f_{cm} is one half of the operating frequency f_o and conditions are fairly good. At an angle of 14.5 degrees f_{cm} is one quarter of the operating frequency and conditions are not so great for the antenna pattern shown in Figure 13. So, in very general terms, a band will probably be open if f_{cm} is one quarter to one half of the operating frequency, one half being better.