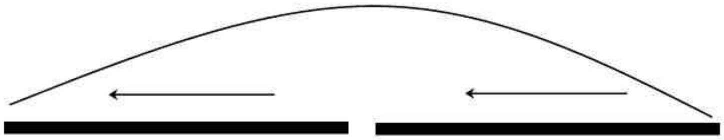
Beams and Directional Antennas

The Horizontal Dipole

Our discussion in this chapter is about the more conventional horizontal dipole and the simplified theory behind dipole based designs. For clarity, we will prefer a reference to the so-called “flat top” dipole. This is for illustrative purposes only, as other types of dipoles are just as effective but have more variable characteristics. We will keep our discussion relatively simple for now.

The dipole is what is known as a linear current device; meaning current in the conductors of a dipole flow in one direction (the straight line of the conductor). All currents in the dipole flow in the same direction at the same time. The illustration below graphically shows what this means.



Current in both condutors of a dipole

The illustration shows how current flows in one half of a RF current cycle (half-wavelength). Obviously, the current will reverse for the other half of the cycle. The high current flow at the feedpoint indicates there is a lower impedance than at the end of the antenna elements. This low impedance condition can occur at any odd multiple ½ wavelength of a dipole (e.g. ½, 1½, and 2½ wavelengths; or ½ wavelength of the fundamental, 1½, 2½ times the fundamental frequency, etc.). When the resonant half-wave dipole is suspended in space, it will exhibit some known and predictable characteristics. The most important of these is impedance.

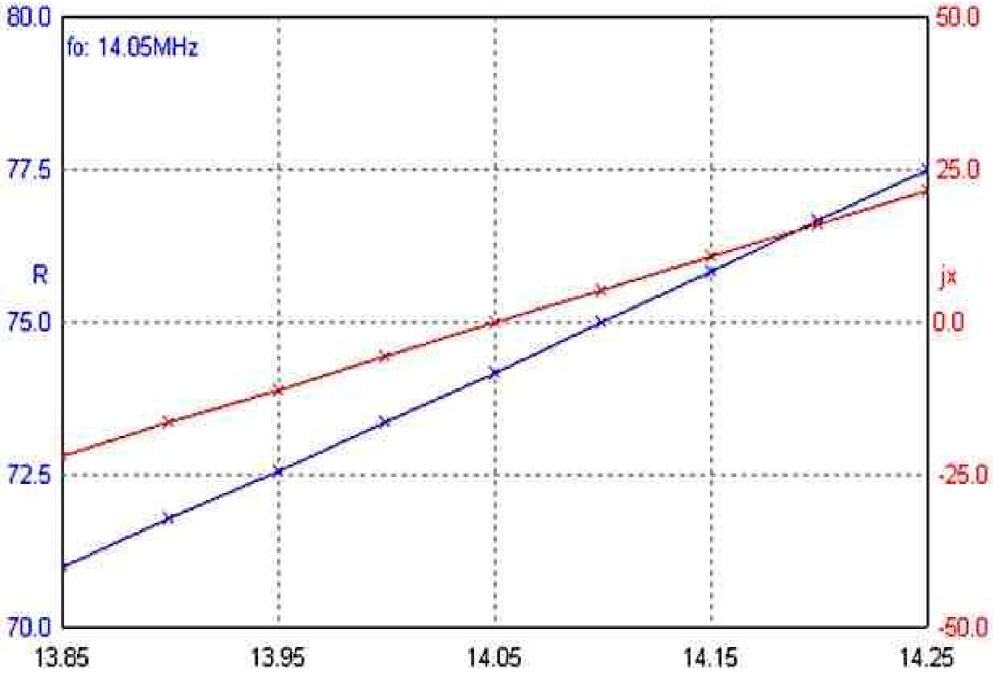
The approximate known impedance of the resonate half-wave dipole in free space (approximate because different calculation methods yield different results and variable factors such as wire diameter and insulation type and thickness have minor effects) is expressed as:

$$73 + j\ 42.5$$

Recent empirical measurements by astronauts have confirmed much of the mathematical research offered so far. Even so, deep space is the only environment to prove the formulas definitively.

Several things should be gleaned from this value:

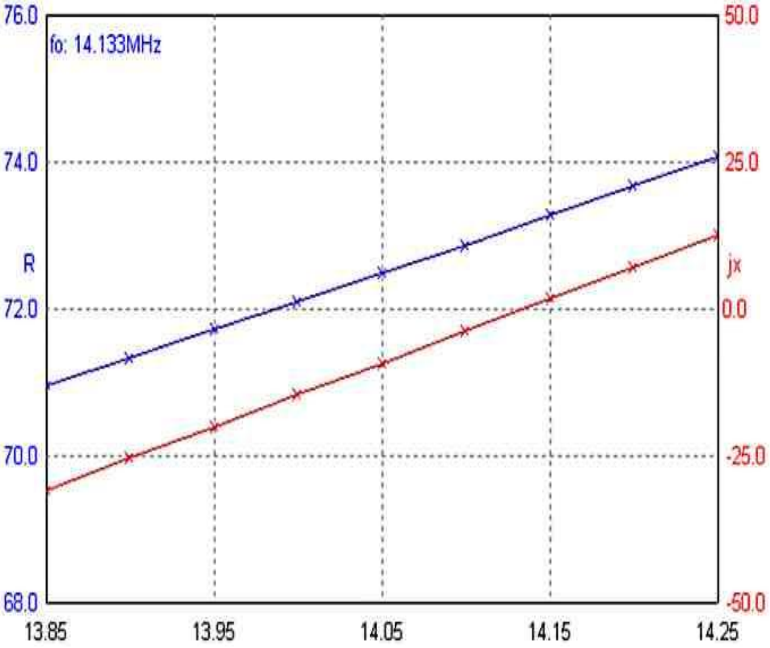
1. It is not 50 ohms like your RG-8 coax. It is 73 ohms. Coax versions are manufactured that have a characteristic impedance of 72 and 75 ohms. These are a better match for this type of antenna at heights exceeding 1 wavelength rather than 50 ohm coax, although it is not a perfect match (i.e. Perfect meaning 1.00:1 SWR).
2. The resonant point is not precise. By that we mean that the reactive value is not zero. There is still some capacitive reactance for the resonant dipole in free space (possibly due to the calculation method or the proximity effect of the two conductors close together).
3. If we were to examine this type of antenna using a sweep of frequencies plotting “R” and “jX” we could see the plot resemble the illustration below. The design frequency is 14.05 mHz.

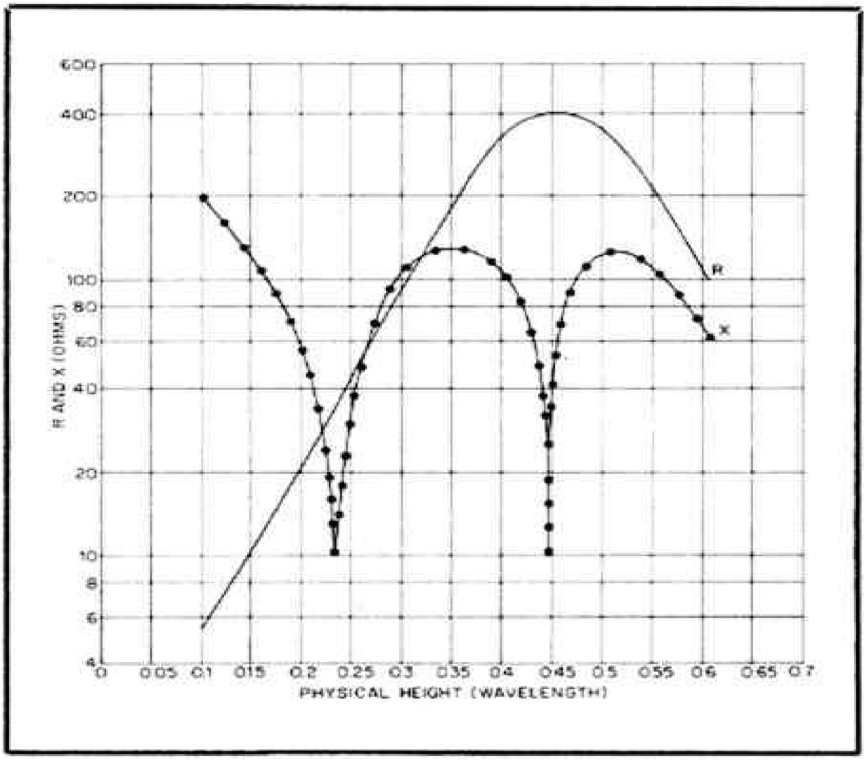


The importance of height above ground

You will recall from our discussion that a dipole in free space does not have to suffer the effects of ground. This predictability is why scientists use the free space model as a statistical and mathematical reference. Let's see what the ground does to our isotropic dipole as we mount it one wavelength above average ground.

It should be obvious, with some observation of the graph, that the overall impedance has lowered substantially. Instead of 73, the impedance is now about 72.5. As well, the resonant frequency has changed, or put another way; the resonant physical length for our dipole at this height is now much shorter (resonate at a higher frequency). This effect of ground proximity is true for any height, bearing in mind any change in height will make substantial changes in impedance. The following graph, used earlier, shows the effect of ground on the impedance at the feedpoint for different heights (in wavelengths) above ground.





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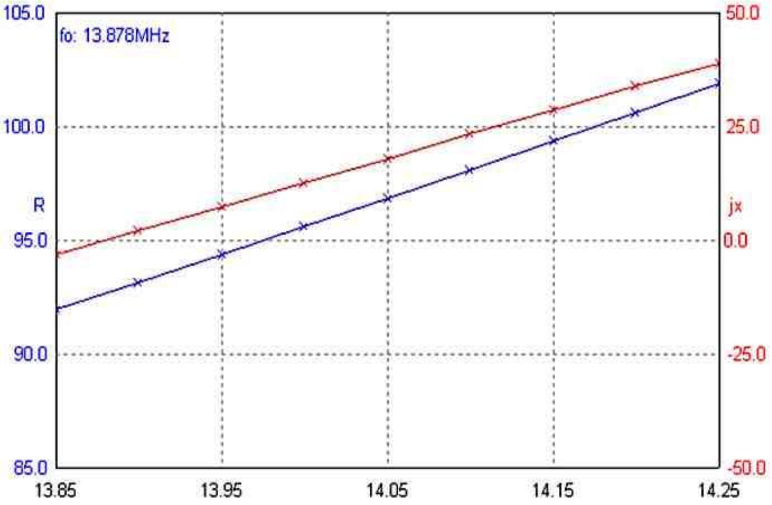
Now lets mount our dipole at a more reasonable height of say 20 ft (6.1142 meters). This height is approximate to 0.28664 wavelengths. A little more than quarter wavelength at our test frequency and a lot less than one wavelength as we started. Take a look at the chart to see if you can predict what the impedance might be.

The impedance at this height is calculated to be 96.884+j1816. WOW! What a difference the ground makes! Now we have a problem. Not only is the impedance much higher than our coax impedance, it is much too long to be resonant for our test frequency (as indicated by the reactive part of the impedance value).

Take a look at the impedance plot for this antenna at 20 ft.:



If nothing else is changed, the SWR on this antenna will be well over 2:1 for 50 ohm coax. To rectify this situation we need to make a slight shift in our analysis. You might recall that in a previous discussion we said that the preferred device to control feedline current (the balun) plays a two-part role, in that it, acts as both an isolation transformer and a balancing transformer. Well, it can transform impedances as well, just as many audio or RF board level components do. For this purpose we construct or purchase a balun that has a 1.5:1 or 2:1 winding ratio. The input side will be 50 ohms and the antenna side will be 75(1.5:1) or 100 ohms (2:1). Problem solved! Almost. We now need a way to calculate the resonant point for 75 or 100 ohms instead of 50 ohms. Because the balun transforms the feedpoint impedances to match our transmission line, we see the antenna impedance (if it is 75 or 100 ohms) transformed to 50 ohms at the coax. Tuning our antenna should now be possible through normal means with our new impedance as the reference to match.

If we analyze the impedance plot for this near-ground dipole we can make an informed guess that we have to shorten the elements in order to bring it to resonance at our test frequency. We must shorten the length by about 2% from the length of the same antenna at our 1 wavelength height. This resonant point yields an impedance of 93.4+j0.051. Because this antenna height will not allow us to use conventional impedance matching, we will not see extremely low SWR readings without using the impedance matching balun mentioned before. This does not mean that the antenna is not effective. It simply means that we must understand the operating limitations of our station and antenna system.

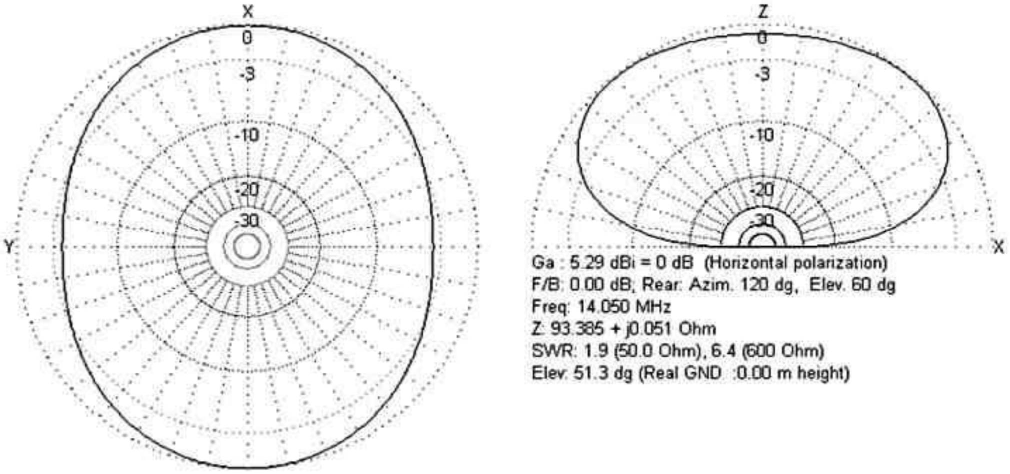
Close-to-the-ground antennas such as we have described are not uncommon and should not be avoided when faced with no other alternative. The unique characteristics and limitations of this type of antenna should be anticipated, however. The radiation resistance is very low (efficiency is low) for near-earth antennas.

But, what if we were not able to erect a completely horizontal dipole? This too is a common situation faced by hams everywhere. The resulting configuration might be one of the alternative dipole types – the inverted “V”, the “slopper”, the folded dipole, the “bent” dipole or “half square”, or the less common horizontal “V”. All of these alternatives present unique characteristics that are widely differing and can be challenging to make efficient in your unique antenna location. Do not hesitate to enlist the help of an experienced Elmer in modeling and analyzing difficult situations for these alternative antenna types or unique installations of conventional dipoles.

Beyond SWR – Radiation Patterns

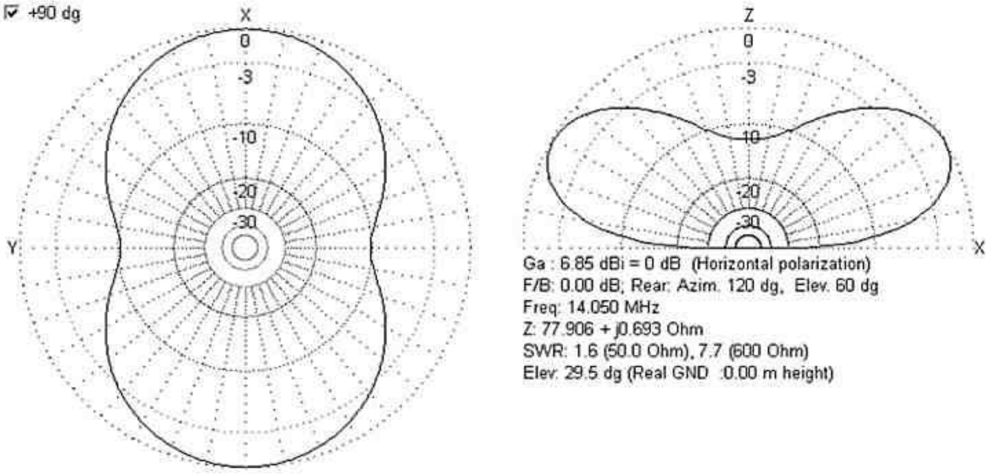
Beyond SWR, we must look at the other aspects to consider when analyzing antenna installations. One of the more important would be the radiation pattern. While actual radiation patterns will vary greatly with each installation, particular antenna types exhibit predictability in radiation patterns where unobstructed by environment. In the case of the horizontal dipole, we can examine the classic example of the half wavelength model at a common height. Our example was previously at 20 feet. We will use this nominal height to illustrate the effects of ground on radiation patterns. This does not in any way indicate the radiation pattern of your particular antenna installation. It is merely a point of reference to discuss the principals involved.

The signal strength plots shown below indicate a common radiation pattern of close-to-earth antennae. The antenna axis is along the Y coordinates of the polar graph and the elevation plot is shown viewed from the end of the wire. Because of the “bubble” like appearance of the elevation pattern, this type of antenna is often referred to as a “cloud warmer” - or more recently, NVIS (for Near Vertical Incident Skywave). Depending on atmospheric conditions, this particular pattern can be invaluable for short distance communication on the lower HF bands even with the lower than normal radiation resistance.



Ga : 5.29 dBi = 0 dB (Horizontal polarization)
F/B: 0.00 dB; Rear: Azim. 120 dg, Elev. 60 dg
Freq: 14.050 MHz
Z: 93.385 + j0.051 Ohm
SWR: 1.9 (50.0 Ohm), 6.4 (600 Ohm)
Elev: 51.3 dg (Real GND :0.00 m height)

Now lets compare this to the same 20 meter antenna placed at 33 feet (10.09 meters).

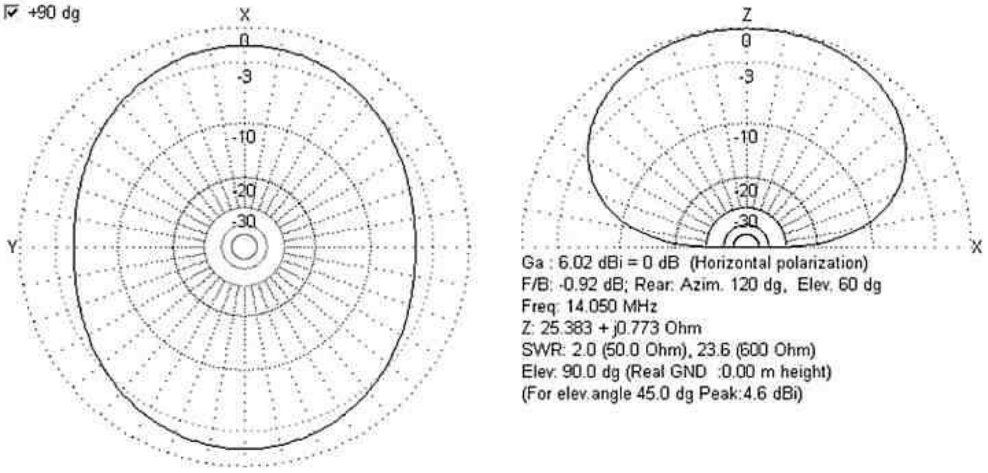


Ga : 6.85 dBi = 0 dB (Horizontal polarization)
F/B: 0.00 dB; Rear: Azim. 120 dg, Elev. 60 dg
Freq: 14.050 MHz
Z: 77.906 + j0.693 Ohm
SWR: 1.6 (50.0 Ohm), 7.7 (600 Ohm)
Elev: 29.5 dg (Real GND :0.00 m height)

No longer are we “warming the clouds”. The radiation pattern has flattened considerably. Now there is a prominent radiation lobe at 29 deg elevation in two directions and gain has increased by almost 3 db. Just as importantly, the impedance is more manageable at 77 ohms. We can get a much better match to 75 ohm coax with this antenna or with 50 ohm coax and a 1.5:1 balun. Of course, just as we observed before, we had to adjust the length of the wire to make it resonate at this height and reduce the SWR versus the length of our antenna at 20 feet.

The inverted “V” antenna

We made reference to alternative versions of the “flat top” dipole earlier. We only have space to demonstrate one of the many we mentioned – the inverted “V”. The illustration shown below is for an inverted “V” dipole at our test frequency with the feedpoint raised to 33 ft. and the ends drooping to within 8 feet of the ground. Admittedly, this is not ideal (the ideal spread angle for the inverted “V” is much more than 45 deg.) but it is much more common.



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Ga : 6.02 dBi = 0 dB  (Horizontal polarization)
F/B: -0.92 dB; Rear: Azim. 120 dg,  Elev. 60 dg
Freq: 14.050 MHz
Z: 25.383 + j0.773 Ohm
SWR: 2.0 (50.0 Ohm), 23.6 (600 Ohm)
Elev: 90.0 dg (Real GND  :0.00 m height)
(For elev.angle 45.0 dg Peak:4.6 dBi)
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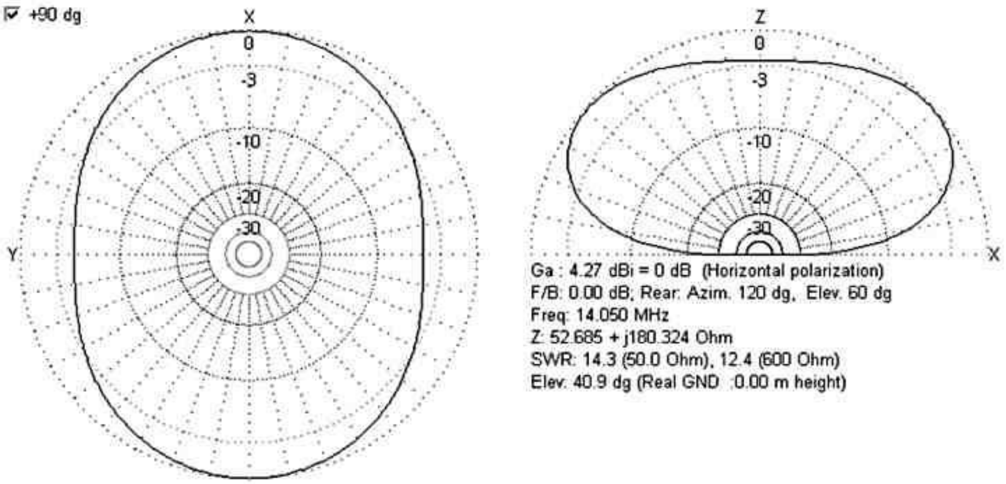
It can be seen from the model that the radiation pattern is common for a close-to-ground antenna but the impedance is brought to very low values by the close proximity of the element ends to ground (this directly translates to high SWR). This impedance value may be outside the range of most tuners and common mode radiation (i.e. coax radiation) may be unacceptable when using an in-shack tuner. When practicable, raising the ends to the ideal height would produce a much more desirable situation as evidenced by the plot below.



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Ga : 4.27 dBi = 0 dB  (Horizontal polarization)
F/B: 0.00 dB; Rear: Azim. 120 dg,  Elev. 60 dg
Freq: 14.050 MHz
Z: 52.685 + j180.324 Ohm
SWR: 14.3 (50.0 Ohm), 12.4 (600 Ohm)
Elev: 40.9 dg (Real GND  :0.00 m height)
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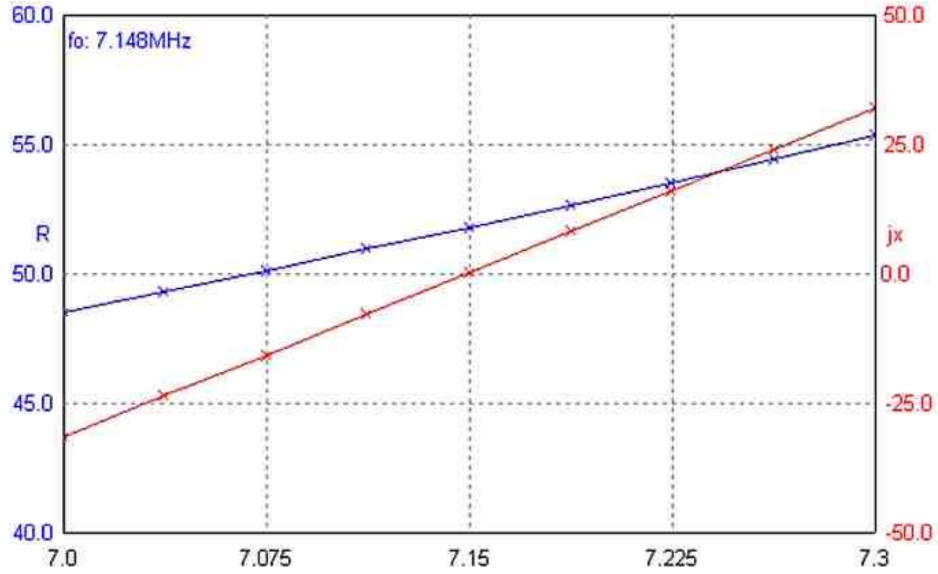
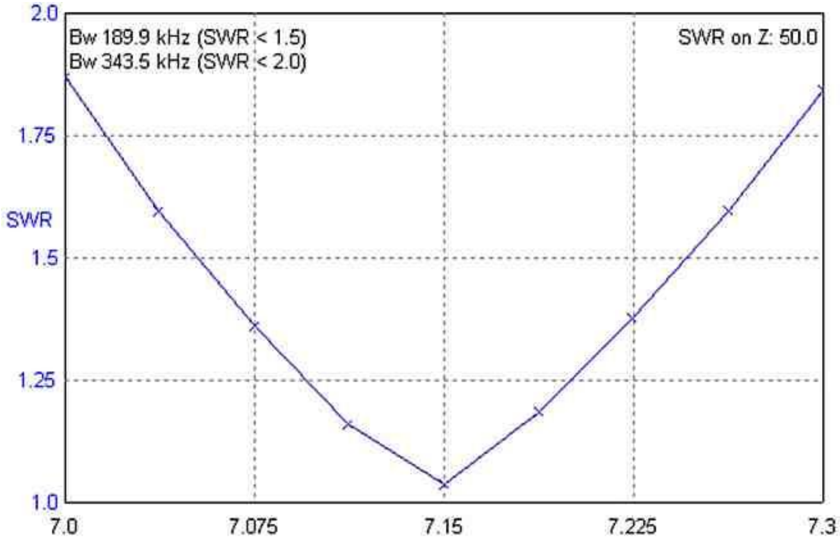
The length, height and end points have been adjusted for a more optimum feedpoint impedance. The characteristics of this situation make it much more manageable by station equipment with much less undesirable effects (common mode radiation). You should also notice the reduction of the “cloud warming” radiation. The very high angle of take-off (approx. 45 deg.) makes this a very good short to medium range antenna at this frequency.

The practical inverted “V”

Is it possible to have a near-to-earth antenna that matches our coax better and provides adequate performance? Anything is possible – some things just take a little longer. Seriously, it is possible with the inverted “V” to get a good match, even on 40 meters and below, at a common height. The following chart shows what would possibly result if you placed a properly tuned 40 meter inverted “V” at 40 feet with the ends at only 8 feet above ground. We have tuned the length to be resonant on the center of the 40 meter band. Also included is the SWR plot for a 300 kHz sweep of that band.



Inverted "V" for 40 meters at 40 feet



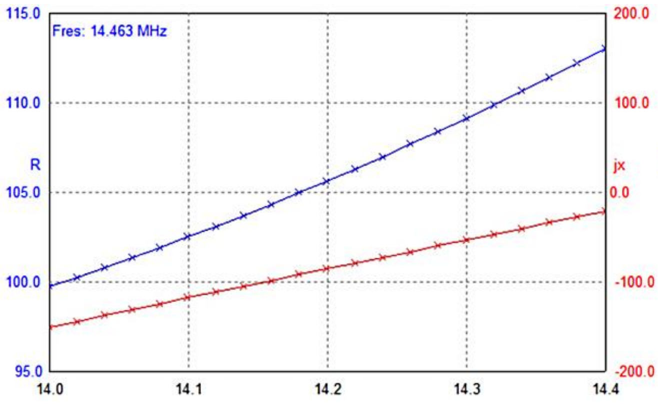
SWR Plot for 40 meter inverted "V" at 40 feet

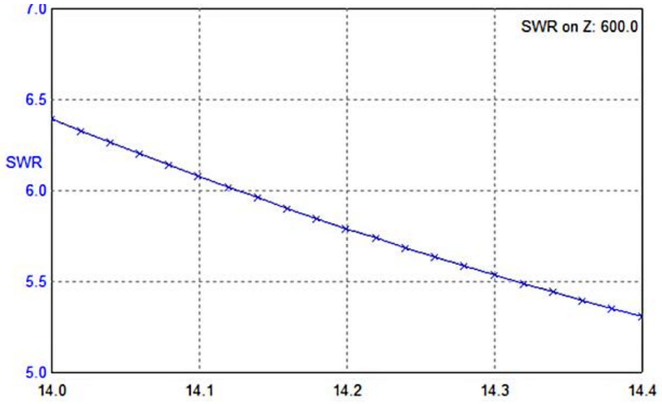
Potential users of this type of antenna should remember that it exhibits the displayed characteristics at 40 meter frequencies and the stated height only. A completely different set of characteristics will be observed on other bands, at other frequencies, etc. and may not be as desired or expected.

By now it should be obvious that objects close to the radiating elements cause considerable changes in the impedances and radiation patterns of the various versions of dipoles.

The non-resonate dipole

Up to this point we have discussed dipoles that are resonate. But, dipoles can be effective radiators when of non-resonate lengths as well, provided you find an efficient way to feed it. The classic non-resonate dipole antenna is the open wire fed dipole. This antenna can be of any length, but traditionally a length of 100-136 feet is not uncommon. The next illustration is of a classic non-resonate dipole antenna feedpoint impedances in the 20 meter band.





This 100 foot dipole is up 12 meters (approx. 39 feet) and fed with open wire line that is 600 ohms characteristic impedance. One of the first things to notice is that the antenna resonate point is out of the ham bands. Since the reactive values never cross the zero line, we can conclude that it is not resonate at any amateur frequency. We can also see that the SWR is quite high at all frequencies in band.

Despite the noted characteristics, this is a very effective antenna and great all around performer. How can this be? you ask. It is possible because we have fed the antenna with a very efficient feed line that can accommodate high SWR with negligible loss at our operating frequencies. We also use an appropriate balanced line, low insertion loss, open wire tuner to match our transmitter to the feedline. All inefficiencies that can be reduced, have been made insignificant. This same approach can be used for antennas of several non-resonate types. Needless to say the graphs would be quite different for different types, bands and mounting heights, but this system is easily adjustable to be a good radiator with little change.

Antennas in this class include the so-called “Zepp” and “double-Zepp” antennas, the off-center fed “classic” Windom, and any other variation that is a non-resonate dipole.

Lets consider what happens when the dipole is allowed to come in close proximity to other conductors that are near its resonant frequency (e.g. the classic Yagi beam).

Beams and directional arrays

We noted that radiating elements very close to ground tend to lower the feedpoint impedance. The same is true of a radiator in close proximity to conductors that are near the same wavelength. This phenomenon was first observed before WWII by two Japanese scientists H. Yagi and S. Uda. Hence the name Yagi Uda style directional antenna. In a Yagi configuration, sympathetic radiators positioned close in proximity and parallel to the radiating elements will lower the feedpoint impedance significantly. To fully understand the theory of Yagi beam construction (and other similar dipole based antennas) we should start by understanding how RF currents are generated on beam elements.

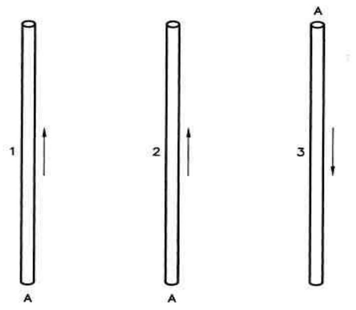


Fig 7—This drawing illustrates the phase of currents in antenna elements, represented by the arrows. The currents in elements 1 and 2 are in phase, while that in element 3 is 180° out of phase with 1 and 2.

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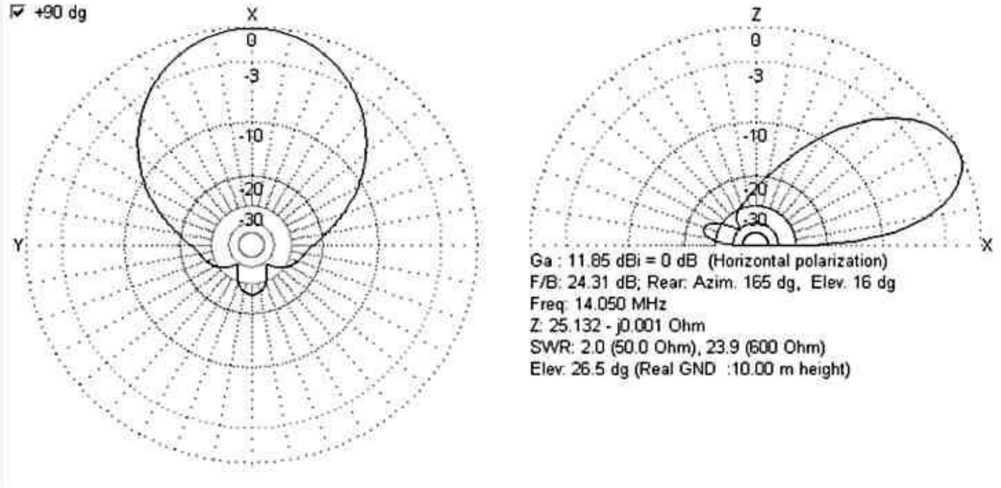
At the first of this chapter we noted that currents in the dipole elements flow in only one direction at a time and in the same direction. The illustration depicts RF currents on a three element Yagi, where element 2 is the center-fed dipole radiator.

Notice the direction of the arrows indicating direction of current flow for one half of the current cycle. Current in the radiator element 2 creates a magnetic field that induces current electromagnetically in element 3 (the director) and element 1 (the reflector). N*ote: the radiator, often called the driven element, is center fed and may also incorporate matching components*. The distance between each of the elements determines whether the resulting radiation pattern is subtractive or additive in a particular direction. Common spacing places the reflector at about .15 wavelength behind and the director about .14 wavelength in front of the radiator element. This relationship is important if radiation pattern directionality is to be established that is common for Yagi style antennae. Of course, other spacing arrangements are possible but yield differing results. Elements can be spaced to maximize gain or maximize front to back directivity. Compromises are often made to one or the other to arrive at a suitable design.

Placing sympathetic, passive elements close to the dipole radiator in this way produces a more directional radiation pattern versus the dipole alone. The next illustration depicts the radiation pattern of a three element yagi at our 20 meter test frequency at a common height of 33 feet.



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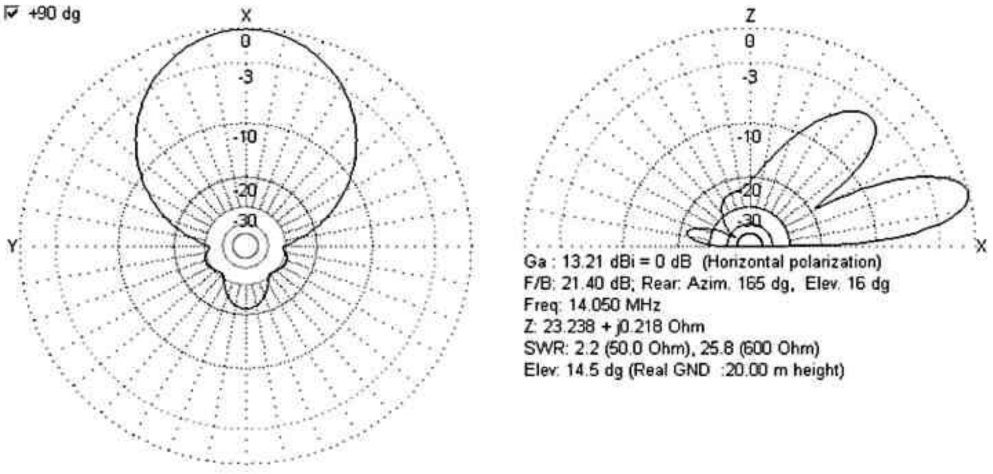
Ga : 11.85 dBi = 0 dB  (Horizontal polarization)
F/B: 24.31 dB; Rear: Azim. 165 dg,  Elev. 16 dg
Freq: 14.050 MHz
Z: 25.132 - j0.001 Ohm
SWR: 2.0 (50.0 Ohm), 23.9 (600 Ohm)
Elev: 26.5 dg (Real GND  :10.00 m height)
```

Radiation pattern of 3 element Yagi at 33 ft

Now we can see why the Yagi is one of the most popular directional antennae sold in the US. The directional gain has increased dramatically, and the takeoff angle has lowered to 26.5 degrees over the dipole alone. This antenna style is even more effective if given more height. The takeoff angle (the vertical angle at which there is maximum radiation) lowers and impedance increases.

This style of directional antenna while effective, presents a feedpoint matching challenge. You should notice the feedpoint impedance is only 25 ohms without matching due to the close proximity of other sympathetic elements and the ground. Application of creative matching techniques (like the tuned hairpin stub or balanced “T”) can bring this impedance very close to our desire for 50 ohms at the coax without a balun and allow for adjustments where height and environment require. Let's look at the three element Yagi mounted at the proper height and properly matched.



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Ga : 13.21 dBi = 0 dB  (Horizontal polarization)
F/B: 21.40 dB; Rear: Azim. 165 dg,  Elev. 16 dg
Freq: 14.050 MHz
Z: 23.238 + j0.218 Ohm
SWR: 2.2 (50.0 Ohm), 25.8 (600 Ohm)
Elev: 14.5 dg (Real GND  :20.00 m height)
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In this scenario, we can see a different radiation pattern than before. Now there are two forward lobes of radiation. One at 14.5 degrees and another at about 47 degrees. This is quite convenient for both long and short hop propagation conditions. Maximum gain has increased by almost 3 db.

Construction is relatively simple, having only three elements which are insulated from a supporting boom. Homebrew plans for such an antenna are available from a number of sources and online. Commercial versions of this antenna have been available for decades at reasonable costs.

Just a reminder

Just a reminder for those who may not recall our admonition at the beginning. This text is designed to be a thumbnail treatise of a very complex subject area. It is designed to be a consolidated view of the covered subjects and not an in-depth discussion. We have avoided the finer points of math and technology theory in order to bring forward information relevant and important to making day to day decisions in the ham shack.

Further study is recommended in the text listed in the references. The ARRL antenna course is very helpful and enlightening - well worth the time and expense. The antenna course material is available as a student manual in print as well. It is available separately from ARRL Publications. Even if you do not take the course for credit, the printed material is invaluable as a reference. The ARRL Antenna Book comes with a CD that has the EZNEC computer program for antenna analysis.