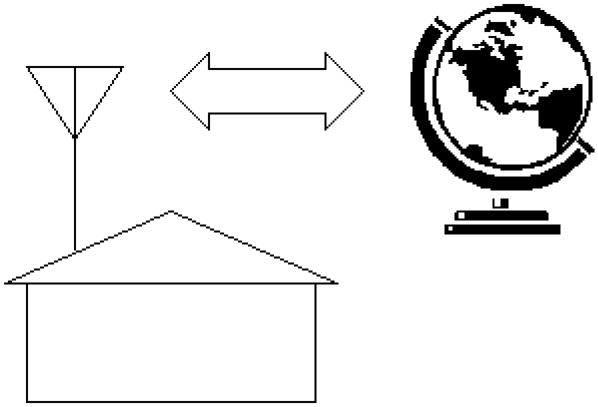

ANTENNA NOTES FOR A DUMMY

Restricted Space Antennas

by Walt Fair, Jr., W5ALT

Before anyone gets upset over the title, let me explain that these notes were written for me. I am an engineer by profession - a petroleum engineer, not an electronics engineer. When it comes to electronics and antennas, I'm still a dummy, but I'm trying to correct that situation!

It hasn't always been easy - electronics experts have written a lot of the literature. Many times I thought I understood something, only to find out I was wrong. Other times I've been totally confused and only after a lot of studying, finally managed to get some concepts into my thick skull.

So, these notes are written for this specific dummy. If they serve to clarify things for others, I'm certainly happy to share them.

Introduction

Unfortunately much of my ham radio "career" has been in places where antenna space has been limited. This has been partly due to formal restrictions, such as operating from a college dormitory where I wasn't even supposed to have an antenna. Sometimes it's been due to other restrictions, like working overseas where my employer specified where I lived and it happened to be an apartment in the middle of a high-rise condominium or from a hotel room while traveling on business. Other times it was due to a desire to stay on good terms with my neighbors. Needless to say, this has been a constraint, but it has not stopped me from operating. As a result of the constraints of limited space, I have invested a lot of effort into understanding more about the performance of small antennas and through experimentation and theory devised ways to continue my ham radio operating even though limited by antenna size.

This document is meant to summarize some of my notes and experiences in design, installation and use of small antennas. By small, that means in terms of wavelengths, not necessarily physical size. For example, a full size dipole for the 2 meter band is less than 40 inches long, so there is rarely a need to use a compromise antenna for that band. On the other hand, even a 40 ft antenna for 160 meters is small in terms of wavelength, since a wavelength is around 500 ft long. So even though my main motivation is for space limited antennas, the notes and concepts described here are also applicable to physically large antennas for the lower bands where the natural antenna size is large compared to normal space limitations.

Please understand that these notes are not meant to show that limited space antennas are better than full sized antennas. That simply is not true. The adage that the more wire you can get up, and the higher you get it, the better it will perform, is usually true. However, as will be seen, antennas are governed by some fairly well defined physical phenomena. As we understand these phenomena, it is possible to construct limited space antennas that perform relatively efficiently. They won’t compete with full sized beams, but they will allow operation, and that is what matters.

Acknowledgments

First, I gladly acknowledge the input of lots of people, from personal and on-line discussions, to magazine articles to textbooks. Especially useful in compiling these notes were **The ARRL Handbook** and **The ARRL Antenna Book**. I've also drawn extensively from things I've read in both **QST** and **QEX**. I've also found the late Joe Carr's books useful, especially **Practical Antenna Handbook**. And, of course, nothing major can be done in today's world of antenna design without some good software. I have made extensive use of **MultiNEC** by Dan Maguire, AC6LA. You can be assured that there is nothing here that I have invented or have any claim of originality.

However, if you find some errors, mistakes or blunders, I must accept full responsibility. Any comments on these notes should be addressed to me at w5alt@comportco.com.

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Electromagnetic Waves

Since antennas radiate energy in the form of electromagnetic waves or radio waves, it is important to understand what they are and how they propagate or travel. We won't get too far into the subject of radio propagation, though. That's a whole separate field of study.

Frequency. Radio waves are characterized by an oscillation. In a wire, one can think of electrons moving back and forth at a certain rate. The electric current flows in one direction for some period of time (half a cycle) and then reverses and flows in the opposite direction for the same amount of time (the other half of the cycle). Thus the motion can be characterized by a frequency measured in cycles per second. Nowadays we use the unit of Hertz (Hz), which is equivalent to cycles per second.

The electrical power grid normally uses a frequency of 60 Hz. However, radio frequencies are much higher so it is more convenient to express frequencies in kHz (1000 Hz), MHz (1,000,000 Hz or 1000 kHz) or even GHz (1,000,000,000 Hz or 1,000,000 kHz or 1,000 MHz). Notice that frequency tells us nothing about the strength of a radio wave. It only tells how fast the electromagnetic field is changing.

Wavelength. In a conductor the moving electrons travel a certain distance during a cycle. It turns out that the velocity of motion does not depend on the frequency, but is a constant that depends on the material. This characteristic velocity is normally written as c and is equal to the speed of light in the medium. In free space, c is about 300,000,000 m/s. Now, if the current flows for F cycles per second, then the time for 1 cycle is 1/F sec. And since the speed is c m/s, we can calculate that the current moved a total distance of c/F meters during the time of 1 cycle. This distance is called the wavelength.

Notice that there is a direct relationship between frequency and wavelength. It doesn't depend upon the strength of the current flow at all. It only depends on the characteristic velocity of the medium in which the current is flowing. In free space, as well as in the earth's atmosphere, the velocity is about 300,000,000 m/s. In copper or aluminum wire the velocity is a little less than 300,000,000 m/s, however. Since the wavelength expresses a natural measurement unit for electromagnetic waves, most measurements in antennas are expressed in terms of wavelengths.

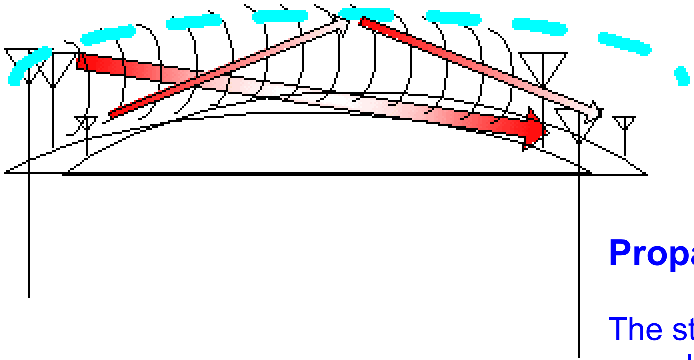
Wavelength is normally represented in equations with the Greek lambda symbol λ. In terms of meters, or feet the relationships are

$$c = 300{,}000{,}000 \text{ m/s} = 984{,}000{,}000 \text{ ft/s} = 186{,}364 \text{ mi/s}$$
$$\lambda(\text{m}) = 300/F(\text{MHz})$$
$$\lambda(\text{ft}) = 984/F(\text{MHz})$$

For reference purposes, here is a table of approximate frequencies and wavelengths for the amateur HF bands. Remember that it is possible to calculate the wavelength for any frequency from the equations.

Band	Frequency (MHz)	Wavelength (m)	Wavelength (ft)
160 meters	1.8	166.7	546.7
80 meters	3.6	83.3	273.3
75 meters	3.8	78.9	258.9
60 meters	5.4	55.6	182.2
40 meters	7.1	42.3	138.6
30 meters	10.1	28.7	97.4
20 meters	14.1	21.3	69.8
17 meters	18.1	16.6	54.4
15 meters	21.1	14.2	46.6
12 meters	24.9	12.0	39.5
10 meters	28.1	10.7	35.0

Here's a good question: What is the wavelength that radiates from the 60 Hz power lines?



Propagation Modes.

The study of radio propagation is a fascinating and complex subject, but we won't go into detail here. The most important thing to remember is that for most purposes there are 3 major modes of radio propagation that may be important for short wave communication.

Line of Sight. In this mode radio waves essentially travel in a straight line. So if you want to communicate by line of sight mode, you must be able to see the other station from your antenna. Obviously, that means the higher the antennas, the longer the distance that can be reached. Although line of sight propagation works at almost any frequency, it is of importance at VHF, UHF and microwave frequencies when other modes don't exist. On the HF frequencies, it really isn't very useful, since we are generally interested in communicating over much great distances.

Ground Wave. In this mode the radio wave follows the ground. Since part of the wave slightly penetrates the earth's surface, it is attenuated and travels slightly slower than the part of the wave above the earth. That causes a "drag" that allows the wave to bend somewhat and follow the curvature of the earth. Of course the constant "drag" causes the wave to lose power, so it eventually fades away. Ground wave propagation is most important at LF and MW frequencies and allows us to hear broadcast medium wave stations over the horizon during the daytime. It may be important for local communication, but not for working DX.

Ionospheric Propagation. In this mode radio waves travel in a more or less straight line until they reach the ionosphere above the earth. Due to the ionization, the waves are refracted and when the ionization is sufficient, they will bounce back toward earth. When conditions are right, there can be multiple reflections with the signal bouncing between the ionosphere and the earth several times. That is how it's possible to propagate signals over the entire world. This mode is mainly responsible for most DX contacts on the HF amateur bands.

As a result of the geometry, it is easy to see that to communicate at large distances, the radio wave needs to leave the antenna at a relatively low angle. That allows it to move the farthest distance before bouncing off the ionosphere. Obviously, if the signal goes straight up, then it will bounce straight down and not go anywhere. As a consequence, we generally want low angle radiation for DX, but somewhat higher angles for closer communications. This will be important when we evaluate antenna designs. Unfortunately it's much easier to install an antenna that propagates straight up due to reflections from the earth.

The answer to the 60 Hz wavelength question is: $\lambda = 300{,}000{,}000/60 = 5{,}000{,}000$ m = 3106 miles!

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Basics Concepts II

In this section we will continue our review of basic concepts important to the understanding of antennas in general, and small antennas in particular.

Skin Effect. When I started messing with antennas I took an ohm-meter and measured the resistance of copper wire. It was pretty low, of course, and hard to measure. Unfortunately the resistance that we are interested in for antenna work is not the resistance that you can measure with a DC ohm-meter. The reason is called skin effect.

Because an alternating current causes an electromagnetic field to form around a conductor and conversely a changing magnetic field causes a current to flow in a conductor, there is a tendency for the current to flow on the outside surface of a conductor. The magnitude of the effect depends mainly on frequency.

The skin effect has two main consequences for us in antenna work. First, since the current flows mainly on the outside of the conductor, there is no advantage to using solid conductors. It is just as efficient to use tubes or pipes that weigh a lot less for large diameter conductors. That certainly makes things easier for us.

The other effect is that the resistance to current flow of the wire will be more than we would normally estimate from DC current measurements. This will impact the antenna efficiency, because the skin effect does indeed cause real losses and heat. To estimate the resistance of copper wire, the following equation can be used, where the resistance is in ohms/ft, frequency is in MHz and diameter in inches.

$$R = 0.000996\ F^{0.5} / d$$

For aluminum, the resistance will be about 1.5 times greater

Gain. Gain is one of those confusing things that says a lot and doesn't tell you much. Basically gain is defined as a power ratio and is usually expressed in decibels, abbreviated "dB". The definition of decibels is $dB = 10 \log(P1/P0)$, where P1 is the power being compared to the reference power, P0.

Now the advantage of reporting gain figures is that it allows a direct comparison of powers. If you have 3 dB of gain, the power is doubled, 10 dB means there is 10 times more power, etc. The problem is you have to define P0, the reference power, or you have no way of knowing what the figure really means.

So, if an antenna has 3 dB of gain over a reference antenna, that means you can get the same signal strength at the receiving end by using the antenna you are evaluating, or by doubling the transmitter power to the reference antenna. At the receiving end there's no way to tell which really occured.

Another important concept concerning gain is that gain always is accompanied by directivity. If an antenna radiates power equally in all directions, then the gain is 0 dB with respect to any direction or with respect to an isotropic radiator. (See next section.) The only way to get more power radiated in one direction is to have less radiated somewhere else. Therefore, if an antenna shows gain in some particular direction, you can rest assured that it worse in other directions.

dBi and dBd. In antenna work there are 2 commonly used gain references: an isotropic antenna (dBi) and a dipole antenna (dBd).

An isotropic antenna is a fictional antenna that radiates equally in all directions in 3D space. It's fictional because no one can actually build one, but the mathematical properties are easily calculated. If an isotropic antenna would yield a certain power density, P0, while an real antenna shows P1, then the antenna gain is 10 log(P1/P0) dBi. The advatage is that it is easily defined and easily calculated and there is no ambiguity to the use of dBi. However, since there is no real isotropic antenna, it's not so easily visualized.

A dipole antenna is a real antenna and they have been built, so a direct comparison to a dipole is possible and the gain in terms of dBd can indeed be measured. Unfortunately, real dipoles are affected by lots of factors, as we shall see later, but gain in terms of dBd is normally referenced to a perfect dipole in free-space. So once again, we're not quite sure what we are comparing. When one takes into account ground reflections, a real dipole often shows gain "relative to a dipole." Talk about confusing!

To avoid confusion once and for all, all gain figures in these notes will be expressed in dBi - relative to an isotropic antenna. If you want to convert the figures to dBd, just subtract 2.14 dB, which is the free-space gain of a dipole in dBi.

Antenna Scaling

Electromagnetic waves have a characteristic length which is related to their frequency, as discussed in a previous section. Since antennas are made to radiate and receive electromagnetic energy, it can be shown that their perfomance depends not on their physical size, but on their dimensions relative to the wavelength.

One fundamental implication of this is that antennas can be scaled from one frequency to another by expressing their dimensions in terms of wavelengths. Thus if we have an antenna design for one frequency, it is easy to convert the design to any other frequency simply by making the antenna the same size in terms of wavelength.

It should be noted that for the procedure to work exactly, all dimensions must be scaled. That includes wire or conductor diameters and height above ground, as well as the lengths of any elements or wires. Normally the lengths are easily scaled, but scaling the height above ground and the wire diameters is difficult in practice. Fortunately the effect of the wire diameter on performance is normally not overly important, as we will see in later sections. The height above ground, however, can have an important effect on the radiation pattern. Generally speaking, scaling an antenna to a lower frequency (ie. longer wavelength) will make the antenna larger and higher above the ground. If we cannot actually raise the antenna, the lower height will probably decrease performance. Conversely, scaling to a higher frequency generally means smaller antennas and we can lower the antenna and still maintain the same performance.

Since we can scale any antenna design to any frequency, it may be much easier to experiment and prototype antennas at very high frequencies, which correspond to short wavelengths and smaller antenna structures. It is much easier to try an antenna designed for the 2 meter band, where a wavelength is less than 7 feet, rather than the 80 meter band, where the wavelength is more like 270 feet.

Scaling Procedure. There often seems to be a lot of confusion over how to actually go about scaling an antenna to a different frequency. Actually the procedure is very straight forward and can be summarized in the following steps:

- Calculate the wavelength *WLold* of the design frequency.
- Calculate the wavelength *WLnew* of the new frequency.
- Calculate the length scale factor by dividing *WLnew* by *WLold*. *SF = WLnew / WLold*
- Note: Since wavelength is inversely proportional to frequency, the scale factor can also be calculated directly from *SF = Fold / Fnew*
- Multiply ***every*** dimension in the original design by the scale factor *SF* to determine the actual antenna dimensions at the new frequency. *Xnew = Xold * SF*

Let's try a simple example to illustrate the procedure. Assume we have a quarter wave ground plane antenna that works great for the 2 meter band (146 MHz), so we want to try the same antenna on 80 meters (3.6 MHz). The 2 meter ground plane antenna has the following dimensions:

Antenna Design for 2 meters

Element	Size	Description
Vertical Element	19.5 inches	Length
Vertical Element	0.5 inches	Diameter
Radials	20.5 inches	Length
Radials	0.25 inches	Diameter
Height	10 feet	Above ground

We proceed by first calculating the wavelength of the original antenna at 146 MHz and determine that WLold = 984 / 146 = 6.7397 feet. Similarly we can calculate the wavelength at the new frequency WLnew = 984 / 3.6 = 273.3333 feet. The scale factor is therefore SF = 273.3333 / 6.7397 = 40.56. Multiplying all of the dimensions by the scale factor gives the following antenna dimensions for our 80 meter version:

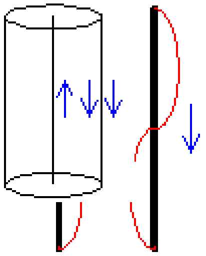
Antenna Scaled for 80 meters

Element	Size	Description
Vertical Element	790.84 inches = 65.9 feet	Length
Vertical Element	20.28 inches = 1.7 feet	Diameter
Radials	831.39 inches = 69.3 feet	Length
Radials	10.42 inches = 0.65 feet	Diameter
Height	405.5 feet	Above ground

As can be seen the 80 meter version of the antenna is enormous! If we could actually build an antenna like that, you can rest assured that it would perform amazingly well!

Antenna Balance

Antenna balance is one of those terms that is tossed around quite a bit and subject to many misconceptions. Actually, the concept of balance stems from transmission line considerations and has very little to do with actual antenna



performance. It does, however, have lots to do with transmission line performance, so it is important to the function of antenna *systems*.

Parallel Line. First, consider a parallel transmission line. In the ideal case, the currents on both conductors are equal and opposite, as shown in the sketch. That means that at any instant the currents on the lines are flowing in opposite directions. A consequence of this is that the electrical and magnetic fields surrounding the two conductors are equal in magnitude, but in opposite directions. At any distance from the line, the fields sum to give the total effect, which is zero, since one is positive and the other is negative.

(Note that for exact cancellation, the conductors have to be at the same exact position, which is impossible. In practice, of course, the conductors must be only "close", so approximate cancellation occurs. With spacings of 1 inch, which is a small fraction of a wavelength at HF, the cancellation is good enough for practical purposes. 1 inch is 0.025 wavelengths at 30 MHz and 0.0025 wavelength at 3 MHz.)

Coaxial Cables. In a coaxial transmission line, the situation is somewhat different. As indicated in the sketch, there are currents on the internal conductor and also on the shield. Due to the "skin effect", the currents will flow on the outside surface of the center conductor. To maintain an electrostatic condition, the current on the shield will flow on the inside surface of the shield. Once again, if the current on the shield and the conductor are equal, the electromagnetic field is confined to the inside of the coax. Therefore, no radiation occurs, since the fields cancel internally and no current is flowing on the outside of the shield.

These represent ideal, balanced conditions. Since away from the transmission line the total electromagnetic field is zero, the transmission line does not radiate and has no effect on antenna performance. In this ideal case, neglecting losses in the wires, *all* of the transmitted power is delivered to the antenna. That, of course, is what we want.

Unbalanced Lines. What happens when the currents on a transmission line are not equal? In the case of a parallel transmission line, the electromagnetic fields around the conductors will not be the same and will not cancel, so radiation from the transmission line occurs. In the case of coaxial cable, the current flowing on the *inside* of the shield will equal the current on the center conductor, thereby maintaining an electrostatic balance inside the cable. However, the difference between the current on the center conductor and the total current on the shield will flow on the *outside* of the shield. The current flowing on the outside of the shield will not be balanced against anything and will cause radiation. In either case, the effect of unbalanced transmission line currents is to cause radiation from the line.

There are various things that can cause a transmission line to be unbalanced. If an antenna is fed off-center, there may be a natural tendency for more current to flow into one side of the feed point than the other, resulting in an unbalanced condition. Also, since the transmission line connects to the antenna, at least part of it is close to the antenna. The radiation from the antenna will, therefore, induce currents on the transmission line. For parallel line, the effect may not be too great, since equal currents are induced on both conductors. Parallel ine is often refered to as balanced line. When using parallel line, it is good practice to minimize the induced currents by running the parallel line perpedicular to the antenna for some distance away from the antenna itself.

On the other hand, coaxial line has the center conductor shielded, so induced currents will tend to be mainly on the shield. That leads to an unbalanced condition with radiation from the feedline ocurring as a consequence. In addition, most of the time the coax shield is connected to ground, either at the antenna or the transmitter. Since the voltage at ground should be constant, the full voltage differential occurs on the center conductor, which leads to an unbalanced condition. For this reason, coaxial cable is often refered to as unbalanced line. Other measures must be taken to minimize the transmission line imbalance.

What happens when the transmission line is unbalanced? In that case, the currents are not equal and opposite, so at any distance from the line, the electromagnetic fields do not cancel. That means that some radiation will occur and, of course, whatever part of the power is radiated from the line does not reach the antenna. That's not good, since it means that our antenna is actually receiving less power than the transmitter is supplying.

What happens to the power radiated from the transmission line? Well, it is radiated, just like the power radiated from the antenna. In other words, the transmission line has become part of the antenna, so if we want to understand the performance of the antenna, including its radiation pattern, we have to include the effect of the transmission line.

Is that a bad thing? Well, it depends. If we want to control the pattern and efficiency of the antenna, it means we better make sure the feedline doesn't radiate or the antenna's pattern will be distorted and not what we expected. If we don't care about the antenna pattern, then the energy is radiated, so it will contribute to the total radiated power. In fact, in some compromise antennas, the radiation from the transmission line may be important and in some cases may be as great as the radiation from the main part of the antenna.

Antenna Balance. Now that we understand the issue of transmission line balance, we can understand the effect of antenna balance. In order to feed power to the antenna, we need to connect the 2 wires of the transmission line to the antenna. But the current distribution along an antenna is mainly determined by its geometry. There will be zero current (essentially) at the ends and the currents will take a sinusoidal distribution along the wires. If the antenna is symmetric and fed at the center, it is easy to show that the current on both sides of the feed point is the same magnitude, but in opposite directions. That is exactly what we need for our balanced feed line, so the antenna is called "balanced".

However, it is not neccesary to feed an antenna in the center, nor is it neccesary to make it symmetrical. In either of those cases, the antenna currents most likely will not be equal and opposite. When we connect our transmission line to the antenna, the currents in the transmission line will most likely not be balanced, so feedline radiation will occur. In that case we say that the antenna is "unbalanced".

Transmitter Output. A further complication arises due to the way that most transmitters are constructed. The power output consists of 2 terminals which should be connected to the transmission line, of course. The problem is that in nearly every practical transmitter, one of the terminals (coax shield) is connected to ground. Now, by definition, if we have a good ground connection, the voltage there is always zero relative to ground potential. That means that the full voltage fluctuation occurs on the other terminal (coax center). Thus, the transmitter output cannot be balanced and is inherently an unbalanced output.

Baluns. So what can we do to minimize feedline radiation and get all the available power to the antenna? The solution is called a **balun**, which stands for "balanced to unbalanced" transformer. The subject of baluns is beyond the scope of this discussion, but the purpose is to force the currents to be balanced on one side of the transformer and yet allow them to be unbalanced on the other side.

Thus, if we connect coaxial cable to a balanced antenna, like a center-fed dipole, we can use a balun at the feed point to ensure that the antenna currents stay balanced, but allow the use of coaxial cable without ill effects. Similarly, if we feed a balanced antenna with a balanced parallel line, we can put a balun at the transmitter end of the line to ensure balanced currents on the feedline, but still connect to the unbalanced transmitter output.

It should be noted that many baluns include some impedance transformation for antenna or feedline matching. Impedance matching is a different issue and will not be discussed in this section. However, if you see a balun specified as a 1:1 balun, there is no impedance matching built-in. On the other hand, a 4:1 balun indicates that besides the balun operation, the impedance is transformed by a ratio of 4:1. This would be useful for converting a 300 ohm TV twin lead transmission line to 75 ohms, which is perfect for use with 75 ohm coax and is acceptable for use with a 50 ohm transmitter output.

Impedance Matching

Impedance matching is another subject which often causes confusion. In this section we'll take a look at why we should worry about impedance matching in antenna systems and what effect may be due to a matched or unmatched condition. It will be seen that impedance matching is important in two separate instances for very different reasons: the transmitter to transmission line match and the transmission line to antenna match.

Transmitter Power. We've all heard that our transmitters have an output impedance of 50 ohms. (No, you can't measure that with an ohm meter - I tried.) Or perhaps in the transmitter specifications it says that the transmitter will deliver 100 watts, for example, into a 50 ohm load, which is the same thing. What does that mean? What is the significance of 50 ohms?

First, remember that power is voltage times current: P = E I. Also from Ohm's Law voltage is current times resistance: E = I R. Therefore, we can calculate the needed voltage and current from power and resistance using I = SQRT(P / R) and V = SQRT(P R).

Let's say we have a transmitter output of 100 watts. If the transmitter is connected to a 50 ohm dummy load, then we can calculate that the current is 1.414 amps and the voltage is 70.721 volts, forgetting about whether that is peak, average, RMS or whatever. (You can check that 1.414 x 70.721 = 100) This means that the manufacturer (or circuit designer, if it's homebrew) is willing to guarantee that the transmitter will generate 1.414 amps at 70.721 volts, which is what is needed to output 100 watts into a 50 ohm load. And that's *all* it means.

What happens if we want to put 100 watts into a different load, say 25 ohms or 100 ohms? In the same way, from Ohm's Law we can calculate that the current and voltage for 100 watts into a 25 ohm load are 2 amps and 50 volts, while for a 100 ohm load the current is 1 amp at a voltage of 100 volts. Notice that in the first case the current is higher (2 amps instead of 1.414 amps), while in the second case the voltage is higher (100 volts, instead of 70.721 volts). Now perhaps the transmitter will handle that, but the manufacturer isn't willing to guarantee it.

Likewise, we can calculate the current and voltage required to generate 100 watts into any type of load. We will see that in all cases, either the current will be higher than 1.414 amps or the voltage required will be higher 70.721 volts. Sooner or later we will arrive at a current or voltage that exceeds the design specifications of the transmitter circuits. In that case, most modern transmitters contain additional circuitry to limit the current or voltage, hence reducing the output power. Of course the alternative is to exceed the ratings of the internal circuitry and burn up the transmitter.

So, in order to get the most power out of the transmitter, it is neccesary to ensure that the transmitter is connected to a 50 ohm load. If the load impedance is different, then the transmitter will require either more current or more voltage, and the manufacturer isn't willing to guarantee that it will deliver. That's why we want to match the load impedance at the transmitter output to 50 ohms. It has nothing to do with the function or efficiency of the antenna. We can do that in several ways, including the use of an antenna tuner at the transmitter output. We are simply making sure that the transmitter is operating within its specifications. Nothing more.

When should we be worried about matching the transmitter to the transmission line? If the transmitter is generating full power into the line, then there is no more power available. Spending time and effort improving the match will not increase the power output of the transmitter, since it's already at maximum. If the transmitter is generating less than maximum power, however, improving the match will allow it to generate more. In that case the effort may be worthwhile.

Transmission Lines. The subject of transmission lines is an entire field of study in and of itself, so we won't cover very much here. However, at least a basic understanding of transmission line theory is essential to understanding antenna systems. After all, the transmission line is what delivers power from the transmitter to the antenna, or from the antenna to a receiver. We certainly want to make sure that all the power gets where we want it to go. The ARRL Handbook, the ARRL Antenna Book, or most any textbook on antennas has a more detailed description and discussion of transmission lines.

It is well known that every common type of transmission line has a characteristic impedance. When you hear of 50 ohm coax or 75 ohm cable or 300 ohm twin lead, the 50, 75 and 300 ohm numbers refer to the characteristic impedance of the particular transmission line. It can also be shown that when a transmission line is terminated in a load that matches its characteristic impedance, the power is totally absorbed in the load, which is what we want from our antenna systems. However, if the line is terminated in an impedance that is not the same as its characteristic impedance, then the power is not totally absorbed and some of it is reflected back down the line toward the tranmitter. When it reaches the transmitter, it again is reflected back towards the load. After all, we hope that the transmitter is generating power, not absorbing it!

This process of reflecting power back and forth between the transmitter and load eventually leads to a steady state condition where a distribution of current exists on the transmission line. The power all eventually gets absorbed by the load, but in the meantime there is a higher current on the transmission line than need be. Since a higher current means more losses within the transmission line, due to wire resistance and other effects, when the load is not matched to the transmission line, there will be more losses in the line. Remember that power losses are represented by $I^2 R$, so doubling the current will cause $2^2 = 4$ times more losses.

In addition, the current reflected back and forth creates standing waves on the transmission line. That means that the voltage and the current vary along the line when the load is not equal to the characteristic impedance of the line. We can use an SWR (Standing Wave Ratio) meter to measure the magnitude of these waves. The SWR meter gives the ratio of the highest and lowest voltage along the line, which is the same as the ratio of the highest to lowest currents on the line. A perfect match is a standing wave ratio of 1:1, meaning that the highest and lowest voltages and currents are equal; in other words, there is no variation along the line.

When should we be worried about matching our antenna, which is the load, to the transmission line? As shown in most books about antennas and transmission lines, the power losses on the line depend on the line length, the type of transmission line, the frequency and the SWR on the line. So, in order to determine whether the losses due to mismatch are important, it is neccesary to determine the feedline losses.

Parallel lines normally have a relatively low loss and are not severely affected by high SWR or mismatch. Generally speaking, rarely will there be a major benefit from improving the match to parallel lines, unless the frequency is very high or the line is very long. At normal HF frequencies and lines less than 100 feet long, the improvement will not usually be noticable.

Coaxial cables, however, generally have a higher loss and are more dramatically affected by high SWR and mismatch. Especially for longer lines and higher frequencies, improving the match between the antenna and the feed line may well yield a significant improvement in antenna performance by reducing transmission line losses. For both parallel and coaxial transmission lines, refer to the charts in most textbooks to determine the magnitude of the losses.

Another of the concepts related to transmission lines was discussed in the previous section on antenna balance. It must be noted that the consequence of a mismatch is entirely different from the concept of balance. *They have absolutely nothing to do with each other.* It is possible to have a matched system with a SWR of 1:1 and still have an unbalanced feed line. Likewise, it is quite easy to have a balanced feedline and have a terrible SWR and high transmission line losses.

Finally, we noted that matching the transmitter to the transmission line and matching the transmission line to the antenna serve 2 very different purposes. Note that matching the transmission line to the antenna may well ensure that all power is absorbed by the antenna and therefore radiated, but it will not ensure that the transmitter is operating at maximum efficiency. Likewise, matching the transmitter to the transmission line will not affect the transmission line losses, since those are determined only by the match between the transmission line and antenna.

What is SWR?

SWR or *Standing Wave Ratio* is one of the most misunderstood terms in amateur radio. Even though every antenna and transmission line book that I have seen is quick to point that out, it *still* is the source of many misconceptions. To most hams with an SWR meter, SWR is whatever the meter reads and if the meter says there's no problem, then all is well. That simply isn't true. In this section, we'll try once again to explain what exactly SWR is and isn't. There are enough problems in antenna design and construction without adding another source of confusion! Especially when dealing with compromise antennas, we need to make sure we undertand exactly what SWR means, since we generally will have short, low impedance antennas and SWR can be a major source of inefficiencies.

Back to Transmission Lines. In the previous section the subject of matching an antenna to a transmission line was discussed and it was pointed out that matching the antenna to the transmission line is very different than matching the transmitter to the line. It was also mentioned that every transmission line has a characteristic impedance, which is normally 50, 75, 300 or 450 ohms, depending totally on the construction of the line.

In the best circumstances, we would use a 50 ohm transmission line to connect a 50 ohm impedance antenna to a transmitter rated at 50 ohms output impedance. In that case everything is matched and as long as we make sure there are no currents flowing on the coax shield, everything should work great. Since all parts of the system are matched, transmission line losses are minimized, the transmitter can operate at its designed efficiency and almost all of the power output by the transmitter will get to the antenna and be radiated.

But what happens when we connect a 50 ohm transmission line to an antenna with a feed point impedance that is not 50 ohms? Let's say, for example, that the antenna has an input impedance of 10 ohms resistive, which is not too uncommon in short antennas. Notice that the transmission line is 50 ohms and is matched to the 50 ohm transmitter output. However, the impedance mismatch between the 50 ohm transmission line and the 10 ohm antenna causes an SWR of 50/10 = 5:1 and a substantial amount of power is reflected from the antenna back down the transmission line. More than likely the protective circuits in the transmitter will cause it to reduce power.

Standing Waves. Consider what is happening in the transmission line. The transmitter is feeding power (current and voltage) at a certain frequency or wavelength into the line. At the antenna or load end, some of the power is absorbed by the load or radiated. The rest of the power is reflected back along the line towards the transmitter. All along the transmission line the forward and the reflected current and voltages combine to give the total current and voltage anywhere along the line. As long as the load impedance, line length and frequency do not change, a stable pattern of voltage and current peaks and valleys will appear on the line. That is called a "standing wave," since it doesn't change. The ratio of the maximum voltage to the minimum voltage is a measure of the mismatch and is called the "Voltage Standing Wave Ratio" or VSWR.

In the same way, the ratio of the maximum to minimum current is called the "Current Standing Wave Ratio" or ISWR, where the I stands for current. It can be shown that the ISWR is the same as the VSWR, but VSWR is normally easier to measure. Normally we just say SWR, implying VSWR. But don't forget that what is being described is the voltage distribution along the transmission line caused by the mismatch between the transmission line and the load or antenna.

In our example, the SWR on the transmission line is 5:1. This is equal to the ratio of the antenna impedance (10 ohms) to the transmission line characteristic impedance (50 ohms). Thus, without knowing anything else, we know that the maximum voltage along the line is 5 times the minimum voltage. And we also know that the maximum current on the transmission line is 5 times the minimum current on the line. Since resistive losses depend on the current squared (I^2), we also know that whatever losses there are on the line are larger than if the current were smaller.

Impedance. What about the impedance? We know that at the antenna the impedance is 10 ohms. We also know that impedance is the ratio of voltage to current and both voltage and current are changing along the line, since we have standing waves. In fact they both change by a factor of 5, in the example. Let's assume that the current is minimum and the voltage maximum at the antenna. Then 1/4 wavelength away from the antenna the current is maximum and the voltage is minimum. It can be shown that at that point the voltage is 5 times greater than at the antenna and the current will be 5 times less, so the impedance will be 25 times greater. Instead of 10 ohms, it will be 250 ohms. Notice that 250/50 = 50/10 = 5, which is the SWR.

Now, since in our example, there is a point on the transmission line (at the antenna) where the impedance is 10 ohms and there is also another point on the line (1/4 wavelength away) where the impedance is 250 ohms, it stands to reason that there is some point on the line in between where the impedance is exactly 50 ohms. In fact, that is correct. If we found that point and connected the transmitter exactly at the 50 ohm impedance point, the transmitter would be satisfied and transmit at full efficiency. But, **the current and voltage distribution along the line is still the same!** There are still standing waves, there is still higher current than necessary, and there are still excess losses in the transmission line because of the standing waves.

So, let's see what happens with our SWR meter. If we connect the transmitter directly to the antenna and measure the SWR there, the meter will read an SWR of 5:1, just as expected. If we connect the transmitter exactly at the 50 ohm impedance point, the meter will read an SWR of 1:1. If we connect the transmitter at the 1/4 wavelength point, where the impedance is 250 ohms, the meter will again read 5:1, since 250/50 = 5.

How can that be? The SWR isn't changing, because the standing waves still exist due to the impedance mismatch between the 50 ohm transmission line and the 10 ohm antenna. Yet the meter reads anywhere from 5:1 down to 1:1 and back to 5:1, depending on where the transmitter and meter are connected. What the heck is going on!?

SWR Meters. To understand this phenomenon we need to know exactly what a typical SWR meter is measuring. Notice that it is **not** measuring the maximum and minimum voltages (or currents) along the transmission line. Obviously it can't do that because it is only at one place on the transmission line. That means that it is **not** measuring the transmission line SWR, even though it is called an "SWR Meter." So just what is it measuring?

The ARRL Antenna Book and other textbooks that describe SWR meters generally talk about bridge circuits and directional couplers. In these circuits the transmitted signal is fed across a bridge consisting of resistors that equal the transmission line characteristic impedance of 50 ohms. (Note that some professional meters may use other impedances, but they are generally expensive and not used for amateur purposes.) The meter is essentially measuring the ratio of the impedance *at the point it is inserted* to 50 ohms. Thus, in the example, it will read anywhere from 50/10 = 5 to 50/50 = 1 back to 250/50 = 5, depending on where in the line it is inserted.

*In other words, the common SWR meter measures the ratio of impedance to 50 ohms. It does **not** measure the transmission line "standing wave ratio."*

It is apparent that we need to keep the SWR as close to 1:1 as possible to reduce feed line losses. However, our meter cannot read the actual SWR on the transmission line and just because it indicates 1:1 does not mean that the transmission line and antenna are matched with no standing waves on the transmission line. What are we to do?

At this point, it would behoove anyone interested in optimizing their antenna to grab a book on transmission lines and study the distribution of impedance along a line. The example used here showed a purely resistive load. While things are more complicated when the antenna shows a resistive and reactive load, the concepts are the same. There is one place along the transmission line where we can always guarantee that we can read the actual SWR with respect to a 50 ohm line. That is exactly at the antenna. In other words, if you want to know what the SWR is for line losses, then read the SWR using 50 ohm coax at the antenna, not at the transmitter.

The RF Ground

One often hears about the need for a ground or ground system. There are recommendations to run 1/4 wave counterpoise(s) and do other things to ensure a good RF ground is available for optimum performance. In this section, let's take a look at what a ground is and isn't and whether one is needed or not. In general, there are 3 separate uses for a ground system in the typical ham shack: safety ground, lightning ground and RF ground. We will evaluate in detail only the RF ground here, after briefly taking a look at the other types of grounds.

The Safety Ground. First, we'll take a look at the safety ground system. In most houses and buildings one of the wires in the normal electrical wiring is connected to ground for safety purposes. Certainly we do not want to risk anyone being electrocuted by touching the chassis of any of our radios or other appliances. The best way to ensure that doesn't happen is to connect the grounded electrical wire to the chassis. Then if someone touches the chassis, they are at ground potential and no harm is done. This ground system should be part of the electrical wiring of the building. If it isn't, that problem should be fixed before going any further! All electrical codes require a functioning ground system as a normal part of home and building electrical wiring.

But then we run an *additional* ground wire for our radio equipment. Normally this additional ground wire is connected, either directly or indirectly to the chassis of the radios, tuner, amplifiers, etc. So we now have the situation where the chassis of our equipment is connected to ground through 1) the house electrical system and 2) our additional ground wire. One could certainly ask the question: Why 2 separate connections for the same thing?

Under normal circumstances having 2 ground connections will be unnoticable. Problems can occur, however, if the house ground comes loose. In that case, the entire house would be grounded through the radio ground connection. While that might be better than having no safety ground at all, that probably is not the purpose most hams had in mind. Of course, the proper action is to fix the house ground! In that case, the additional ground is not needed for safety purposes.

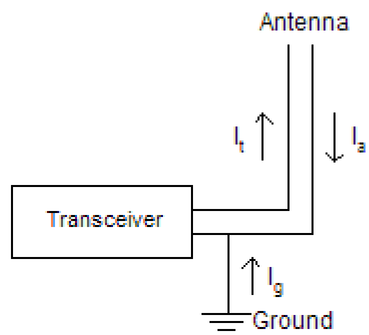
In any case, the issues surrounding a safety ground are covered by the building electrical codes. For further information on safety grounding, consult the electrical codes and guidelines for house and building electrical wiring.

Lightning Ground. Another use for a ground connection is to divert lightning which may strike an antenna to the ground, thereby by-passing problems in the shack. However, if the antenna is connected to our rig and our rig is connected to the ground, then all of the current from lightning striking the antenna must pass through the antenna, feedline, radio and ground connection. Most likely it will burn up lots of things on its way there!

The subject of a lightning ground is an entirely different matter, since its purpose should be to bypass the current from a lightning strike away from our house and equipment. This subject is important, but beyond the scope of this dicussion. Additional information is available in various books on antennas and from companies that specialize in lightning arrestors and diverters.

RF Ground. So, now we have ensured that our equipment is grounded for safety and lightning purposes. What is the reason and utility of providing an RF ground? Let's take a look at 2 fairly common ham situations.

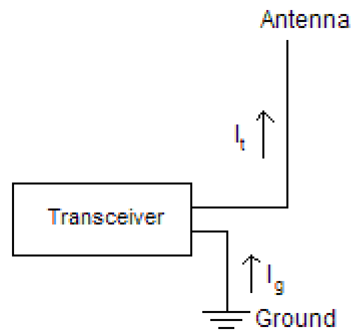
Balanced Transmission Line. In the first situation, we will consider that the transmitter is using a feedline to a remote antenna. If we look at the RF circuit of such a station setup, it would look similar to the following figure:



Using this figure as a guideline, it is apparent that the current from the transmitter, I_t, will be equal to the current from the antenna, I_a, plus the current going to the ground, I_g. If our transmission line is balanced, however, we know that the current on both feedline conductors is equal. So if $I_t = I_a$, then obviously $I_g = 0$. And if $I_g = 0$, then we can disconnect the ground wire and not observe any difference.

For this situation, the purpose of the RF ground is to make up for deficiencies in the balance of the antenna. Any excess (i.e. common mode current) will be bypassed to ground instead of going back to the rig and radiating from power cords, etc. But, it should also be apparent that whatever current goes to ground represents energy that is produced by the transmitter and is not radiated. That represents an inefficiency in the system. Although the ground may appear to solve some RF feedback problems, it does so at the expense of antenna system efficiency. It would be better to get rid of the common mode current by improving the feedline balance. In this case the presence of the ground should have no effect on a properly installed antenna system.

End Fed Random Wire. The second situation is where our antenna consists of an end fed wire. The RF circuit for this setup is shown in the following figure. As can be seen there is no direct return path for the antenna current, I_t, so therefore the return path is through the ground connection and thus I_g must be equal to I_t.



So, what happens if we disconnect the ground? According to the figure there would be no return path for current, we would have an open circuit and the system would not work. In practice, though, there would always be some sort of return path, through our house wiring, even through someone's fingers touching the case. Of course we probably don't want our house wiring or our bodies to be part of our antenna system! In this case, the RF ground is absolutely necessary to avoid problems. So what do you do when a good RF ground connection is not available?

The answer can be seen by comparing the preceeding two figures. We can see that the need for the RF ground is due to the lack of a return path and due to not having a balanced antenna/feedline system. So if we can't get a good RF ground, we can convert the antenna to a more balanced system by adding the missing antenna element. Some people choose to call it a counterpoise or artificial ground, but as can be seen, it is really just making up for the lack of a current return on an unbalanced antenna.

Conclusions? So what can we conclude from this evaluation? Basically it appears that if we have a balanced antenna feed line with no common mode currents, there is no benefit to having a good RF ground. It is only when the antenna transmission line is unbalanced that an additional return path for the current is needed and an RF ground can supply that. However, it is generally agreed that the ground is the most inefficient part of any antenna system, so whatever curents flow to ground represent inefficiencies in the antenna system.

My recommendation is that when possible a good RF ground is a nice backup, just in case something goes wrong. However, checking the current flowing on transmission lines and in the ground connection should be done periodically. If the currents are large enough to be noticeable, then something should be done to reduce them.

In the cases where one cannot install a good RF ground, such as in the upper floors of a multi-story building, don't dispair. It simply means that we're *forced* to take care of the common mode currents and make sure our system is balanced. In general, using a counterpoise or artificial ground wire can appear to help, but the best solution is to take care of the real problem, which are due to common mode currents caused by an unbalanced system.

Antenna Tuners

If you have to operate out of restricted spaces, you will likely be advised to use an antenna tuner sooner or later. These devices are one of the "must have" items around many ham shacks, however, there is quite a bit of misunderstanding as to what they will do and not do, as well as how to use them effectively. In this section we'll take a look at the subject of antenna tuners.

What Is It? Recall from the discussion of impedance matching and SWR, that it is important to have the transmitter matched to the transmission line to get optimum power from the transmitter. As mentioned, most transmitters work optimally into a 50 ohm load, however, there are times when despite our best efforts, our antenna system does not present a 50 ohm load to the transmitter. So what can we do, besides operate at very low power or get off the air? What we need is a device that will transform the impedance at the transmission line to 50 ohms so our transmitter is happy. Such a device is known as an "antenna tuner."

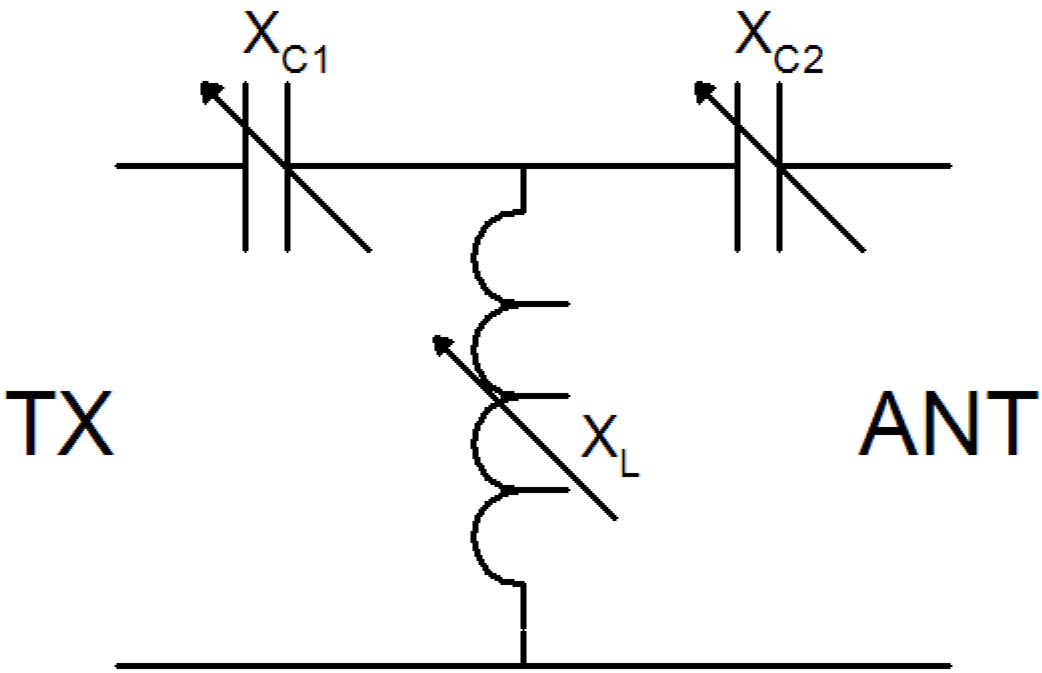
Note that in my opinion the name "antenna tuner" is a source of much confusion. This device does not "tune" an antenna. You can only tune an antenna by adjusting the antenna itself. It is more properly called an "impedance transformer." All it does is transform the impedance at the transmitter end of the transmission line to a value close to 50 ohms so the transmitter can operate efficiently. If you had a high SWR on the feed line before using a tuner, you still have the same high SWR on the line afterwards. As can be seen from the review of SWR previously presented, the SWR depends on the transmission line and the antenna and not on anything else. So if you have losses in your transmission line, a tuner won't fix those. It will only allow the transmitter to accept the mismatched line and output power. Nothing more.

If this seems confusing, please review the sections on impedance matching and SWR. It is important that this concept be understood!

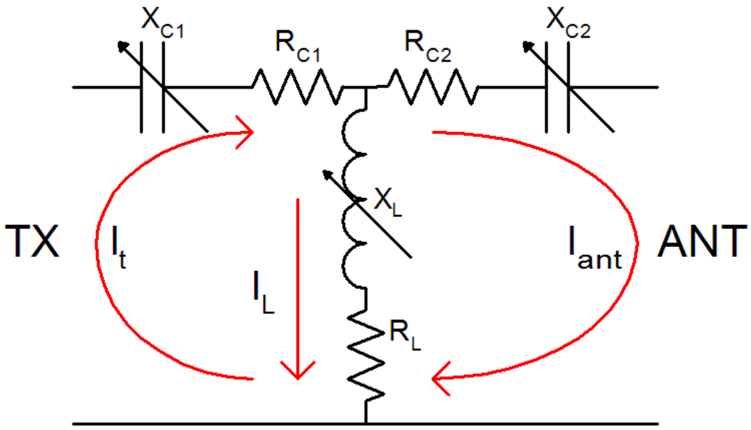
How Do They Work? We know from basic electronics that we can place resistors in series and parallel to get any particular resistance we want. Of course, resistors dissipate energy in the form of heat, so we wouldn't purposely use resistors in an antenna system. However, from basic electronics we also know that we can use inductors and capacitors to change the impedance of a circuit. Moreover, ideal inductors and capacitors have the very nice property that they do not dissipate energy, but only store energy in electric or magnetic fields. If this doesn't make sense, a review of basic electronics is recommended.

So, by using the energy storage properties of inductors and capacitors, it is possible to transform the impedance of the antenna system to 50 ohms without losing energy in the process. This is how an antenna tuner works.

Most ham tuners use 2 variable capacitors and an inductor arranged in a T configuration, as shown in the following diagram. Due to the configuration, this is commonly called a T-network. Other arrangments are possible, including Pi-networks (which look like the Greek π symbol, and simpler L-networks that use only a single inductor and capacitor arranged in an L configuration. For the remainder of this discussion, we'll consider only the commonly used T-network.



As can be seen in the above diagram, there are no resistive components, so there are no resistive losses. Voltage and current varies in the circuit, but nothing is lost and all power is transferred from the transmitter to the antenna. Unfortunately, in the real world, every component has some resistance and inductors and capacitors are not perfect. The real equivalent diagram, showing the circulating currents in the T-network is shown in the following figure. Note that the resistors, R_{C1}, R_{C2}, and R_L are not physical resistors, but represent internal resistance in the wires, capacitors and coil.



Normally we can neglect the resistance in the capacitors and wiring, since it is very small. That means we can take R_{C1} anf R_{C2} out of the diagram, since they do not contribute to any significant loss. However, inductors may not be so ideal and the resistance represented by R_L is most likely *not* insignificant. So whatever current flows through the coil also flows throw the associated resistance, R_L. This will lead to a power loss equal to the current squared times the resistance or $P_{Loss} = I_L^2 R_L$. And since whatever power is lost in the resistance R_L cannot get to the antenna, it represents a real loss in antenna system efficiency.

So, since we need to transform the impedance so that our transmitter works properly, it is important to understand how to use a tuner.

Tuner Adjustment. Without getting into the details of the T-network, one "feature" of these impedance matching circuits is that there are often multiple values of inductance and capacitance that give the same impedance transformation. For details, check the ARRL Handbook, the ARRL Antenna Book or various articles in both QST and QEX. You can rest assured that antenna system efficiency has been evaluated by hams over the years.

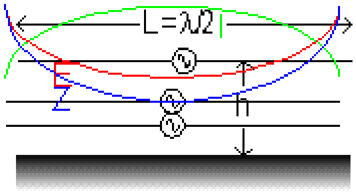
Now, since we have a choice of what values of capacitance and inductance to use, we can devise a strategy that is as efficient as possible. Obviously, from the above discussion, we want to keep the current in the coil as small as possible, so that the losses associated with that current are small. If we can always maintain the minimum necessary current in the inductor, we are guaranteed that our tuner is operating as efficient as possible. And since the losses are proportional to the current squared, if we can maintain half the current I_L, we will have only one quarter of the losses.

Consider that the tuner has been adjusted and presents a 50 ohm load to the transmitter. Therefore, no matter what, as long as the transmitter is delivering full power, the current through C1 is the transmitter current. In the case of a 100 watt transmitter, this will be 1.414 amps. (Remember 1.414 amps at 70.7 volts is equivalent to 100 watts across a 50 ohm load.) Thus it can be seen that, if we are able to obtain a match, the capacitor nearest to the transmitter has *no effect* on the loss. However, by varying the inductance and the capacitor closest to the antenna, the relative amount of current going through the inductor can be controlled. In fact, it can be seen that to get the smallest current through the coil, we would like to have the largest value of X_L possible along with the smallest value of X_{C2}.

This, then, indicates the proper method for adjusting a tuner to minimize losses. The procedure can be summarized in the following steps:

1. Set L to the largest inductance (largest possible X_L)
2. Set C1 and C2 to the largest capacitance (smallest possible X_{C1}, X_{C2})
3. Adjust C1 for best match. If SWR doesn't drop, leave it at maximum capacitance
4. Adjust C2 for best match. If SWR drops, alternately adjust C1 and C2
5. If no acceptable match, reduce L slightly and go to step 2.

By following this procedure it is normally possible to find the minimum loss configuration which matches the transmitter and the transmission line. Note that most tuner manufacturers recommend setting both capacitors to mid-scale and adjusting the inductance, then adjusting the capacitors. While this often works, it does not guarantee minimum losses in the tuner. And, especially if we are in a limited space situation with compromise antennas, we certainly don't want to squander any power or operate at lower efficiency when we don't have to!



Dipoles

Horizontal Dipoles

Now that we've gotten some preliminaries out of the way, we can start to look at some actual antennas. It seems that most antenna texts start out with dipole antennas, so that must be a pretty good starting point.

What is it? A dipole antenna is simply a straight section of wire fed with an RF signal. Normally it is fed in the center and is resonant, as indicated in the diagram. In these notes we will consider a dipole to be near resonant. If it's not resonant or nearly so, we'll call it a "doublet". In the literature, there doesn't seem to be a consistent nomenclature, though.

Length. A resonant dipole is very close to 1/2 wavelength long. It's not quite 1/2 wavelength because the speed of light, "c", is a little slower in copper or aluminum than in free space. There is also a reduction in the velocity due to stray capacitance from insulation or corrosion on the wires. The resonant length is also affected somewhat by the conductor diameter, with larger diameters giving somewhat shorter antennas. For practical purposes, the length of a resonant dipole can be estimated as 95% of the length of a half wave in free space. The formula is then

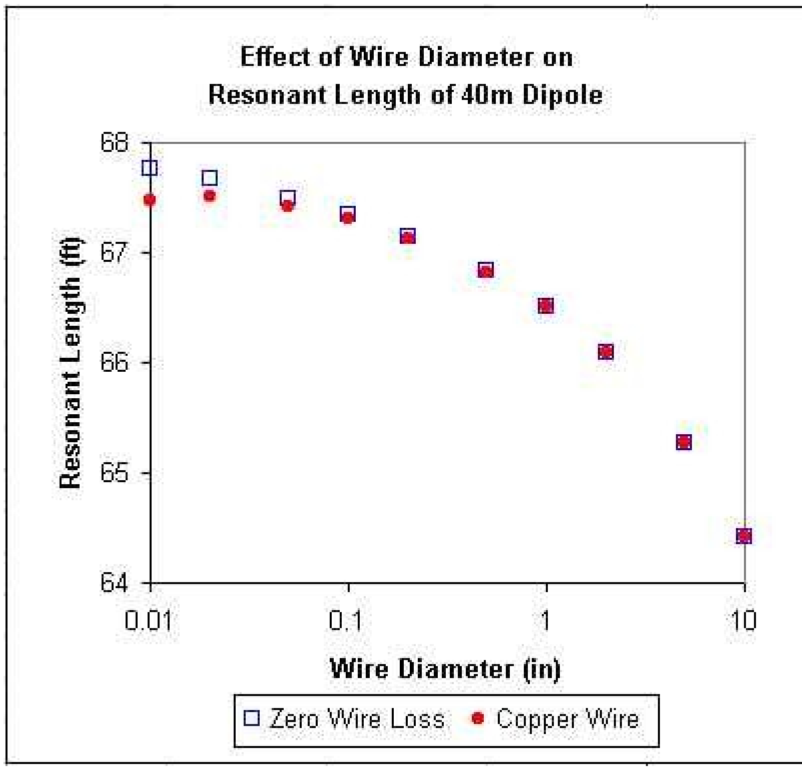
$$L = 0.95\ (0.5)\ c/F$$
$$L\ (m) = 142.5/F(MHz)$$
$$L\ (ft) = 468/F(MHz)$$

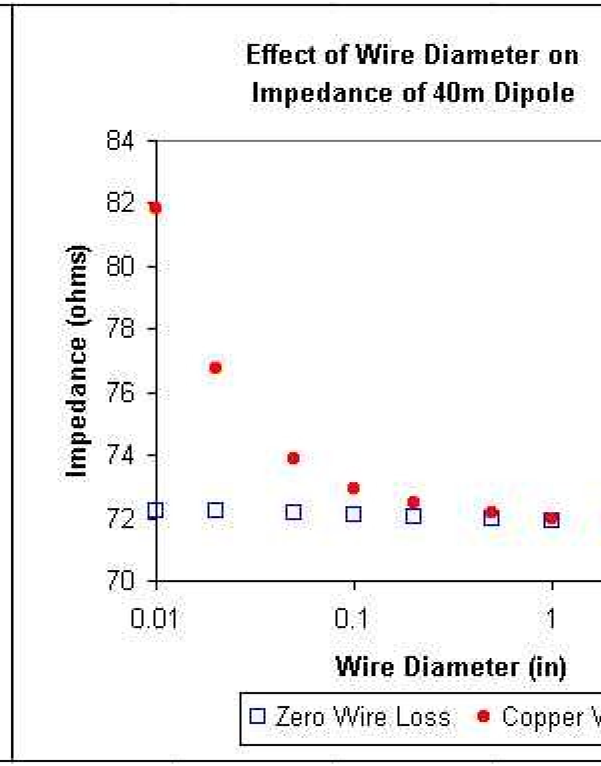
Here's a question: What is the length of a center fed resonant dipole for the 6 meter band (50.1 MHz)?

Current and Voltage. The antenna has nearly zero current at the ends. It's not quite zero due to capacitive end effects, but if it's not very close to zero, you'll see arcing! It also has a current maximum at the center. The voltage distribution on the dipole is nearly opposite that of the current distribution. The minimum voltage is at the center, while the ends have a very high voltage.

Impedance. Remember that impedance is defined as the ratio of voltage to current. From Ohm's Law, Z = E/I. That means that the impedance of the dipole is minimum at the center and maximum at the ends. The high impedance at the ends means that it may be very hard to feed the antenna at the ends. Since the impedance is nearly infinite, it acts like an open circuit and little power is transferred. In order to feed a dipole at the ends, special matching provisions will be needed.

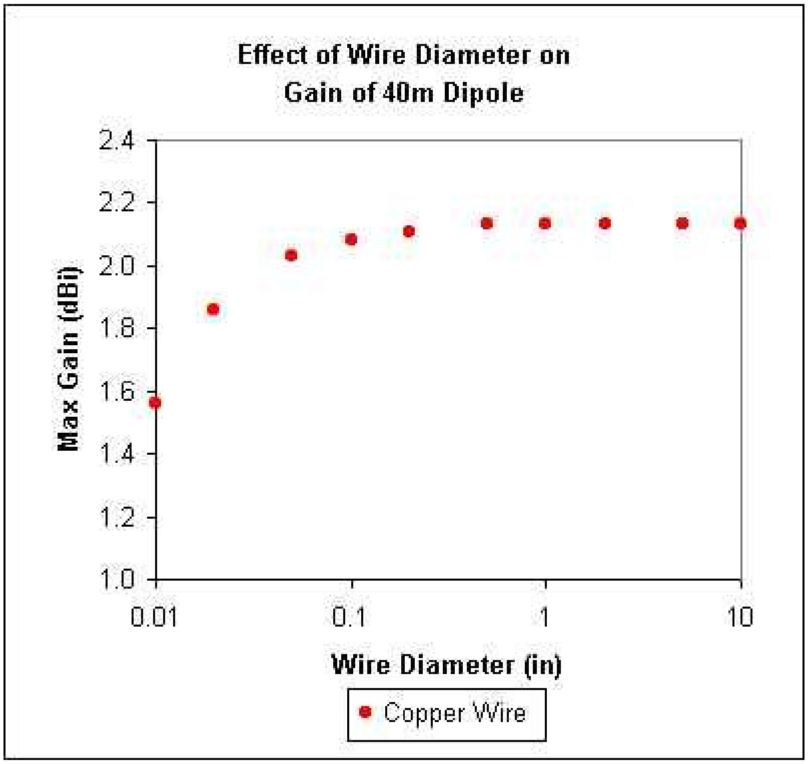
In free space, the impedance of a center-fed half wave resonant dipole is about 72 ohms. That is a near perfect match for 75 ohm coax and quite acceptable for 50 ohm coax, too. Unfortunately, the impedance in the real world depends on the height above ground and the ground quality.





Conductor Diameter. The figures above, computed using MultiNEC, show the effect of conductor diameter on the resonant length and impedance of a 40m dipole at 7.1 MHz. Note that the formula says that the resonant length would be 468/7.1 = 65.9 ft. In most cases the NEC predicted length in free space is somewhat longer, but the effect of insulation, ground and other factors is not accounted for. It is recommended that when you construct a dipole, cut the wires a little longer than required, then trim the antenna to resonance. It's easier to cut than to splice additional wire.

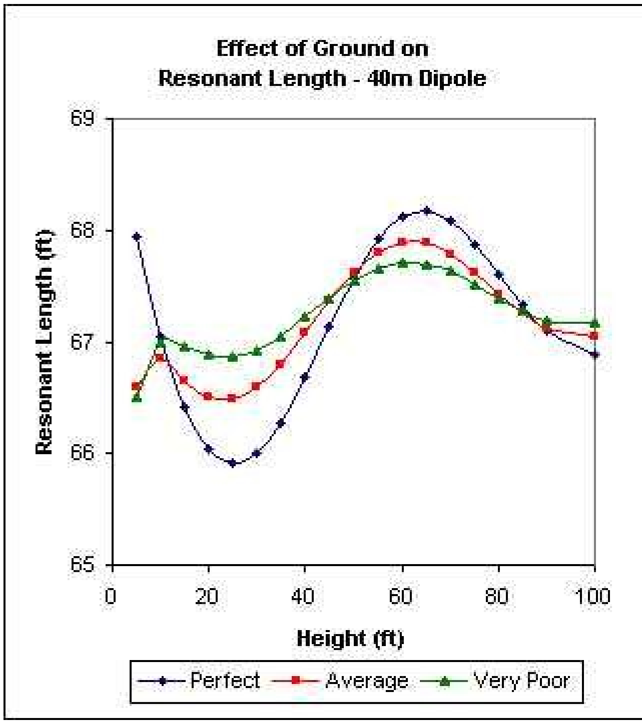
Note that for diameters larger than about 1 in, there is no perceptable affect of wire diameter and the antenna performs as if it were made with no losses. The biggest difference between the zero loss and copper wire cases occurs when the wire diameter is 0.25 in or less. Although the resonant length is a little smaller with copper wire, the major effect is an increase in impedance. This increase is mainly due to the wire resistance which increases in proportion to 1/D because of the skin effect. The following figure shows the effect on the antenna gain.

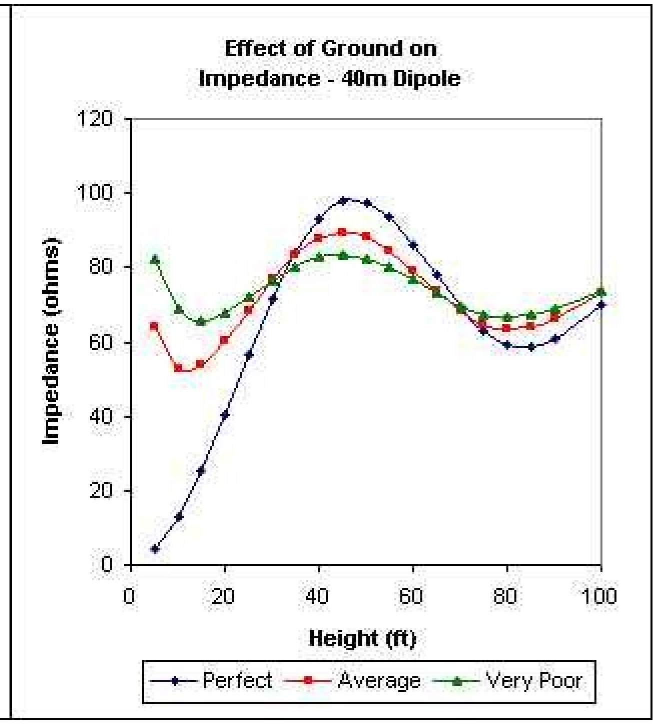


What can we learn from this simple exercise? First, as far as a 40m dipole is concerned, there's no reason to use a conductor larger than about 1 in, but that's still too large for most installations, space limited or not. If we take 72 ohms as the radiation resistance, then the difference in impedance represents losses in the wire. To stay above 95% efficiency, we want the impedance to be less than about 72/0.95 = 76 ohms. From the graphs, that happens whenever the wire diameter is larger than about 0.03 inches, which corresponds to roughly AWG #20 wire. As long as the wire is larger than that, the effect is not going to be noticeable.

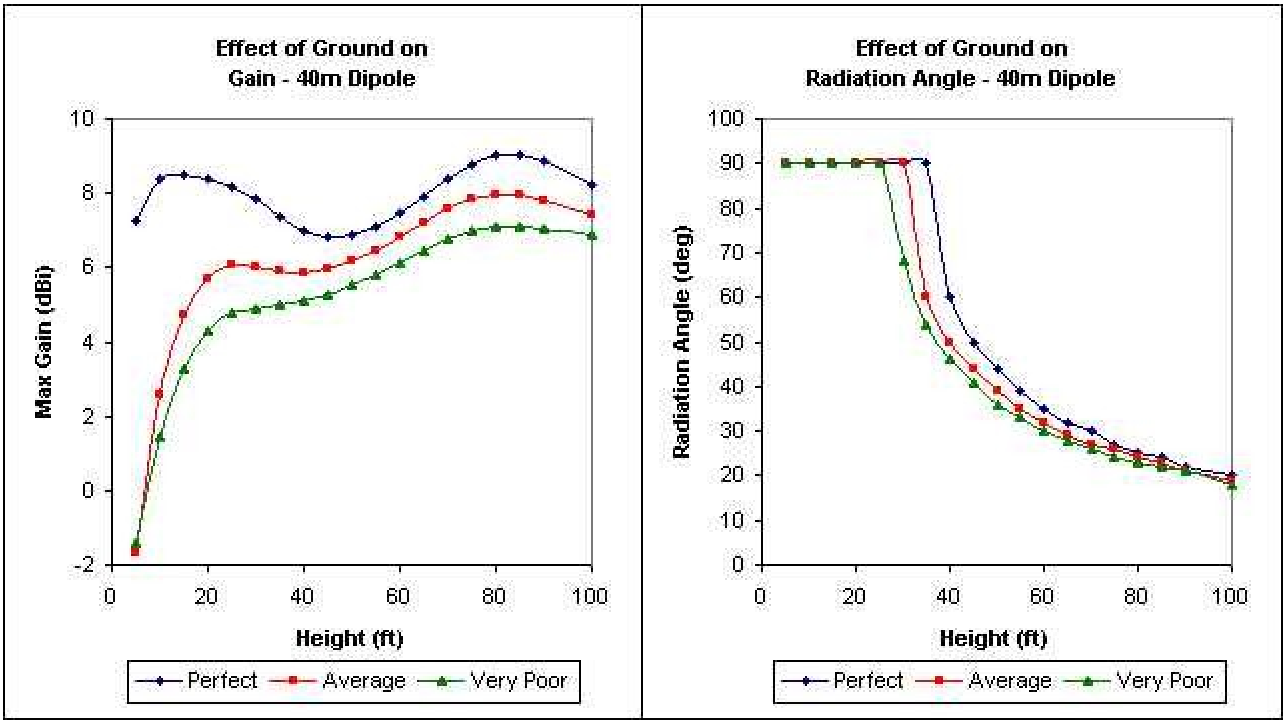
We can cross check the results from the impedance calculation with the antenna gain results. Note that 95% efficiency is equivalent to 10 log(0.95) = 0.22 dB drop in gain. Since the free space gain of a lossless dipole is about 2.14 dBi, we are at 95% efficiency when the gain drops to about 1.92 dBi. That happens with a wire diameter less than about 0.03 in, confirming the earlier evaluation. These results can be scaled for other frequencies. For 80m, the limit will be approximately double the wire diameter or on the order of #14 AWG wire.

Effect of Ground. The effect of a ground does several major things to a dipole antenna. First, it causes the signal to be reflected which modifies the radiation pattern. (We haven't talked about that yet, but we will.) Second, the reflected signal influences the antenna and changes the impedance. Third, the ground will absorb some of the signal, decreasing the efficiency. The following figures show the effect of ground on a 7.1 MHz dipole made from #14 copper wire with various ground conditions.





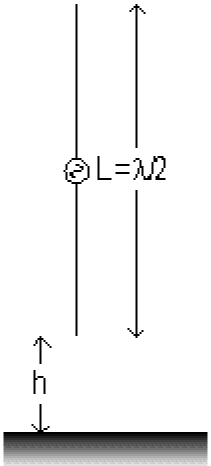
First, notice that the resonant length and impedance both vary quite a bit depending on the ground conditions, which we normally have no control over. The resonant length can vary from 66 to 68 ft, with the larger variations over a perfectly conducting ground. The impedance also will vary from very low to around 100 ohms, with the perfect ground showing the larger variations. Therefore, in building a dipole, we shouldn't be too concerned about exactly estimating the resonant length or the impedance. We'll always have to adjust the length for resonance and the impedance will generally be in an acceptable range, unless we are over a perfect ground.



But what about gain and perfomance? As the above figures show, there are also variations in the gain and the take off angle. First, notice that at heights below about 30 ft, the take off angle is 90 degress - straight up. That means that most of the radiation is going vertically upward, so the antenna will be less than optimum for DX contacts. If we want to obtain a low angle of radiation, say 20 to 30 degrees, then we better invest in some tall towers! Surprisingly, the poorer ground shows the lower takeoff angles at lower heights, so that may be good.

Notice in the gain graph that the curves for less than ideal ground conditions are lower than that for a perfect ground. The model for a perfect ground has no ground losses - all energy is reflected. The difference between the curves shows the loss due to real world ground conditions. As can be seen, there is at least a 1 dB loss from perfect to average ground and another 1 dB loss from average to poor ground. Remember that each dB represents about 20% loss of the radiated power. But worse for limited space conditions is the situation at low heights. At heights less than about 30 ft, losses can be on the order of 4 to 6 dB. That amounts to losing about 60 - 75% of the radiated power warming the ground, while most of the rest of the power warms the clouds overhead!

The answer to the 6 meter dipole length is:
L = 492/F(MHz) = 468/50.1 = 9.34 ft or 9 ft 4 in, approximately
Due to conductor size, etc., the actual length will vary

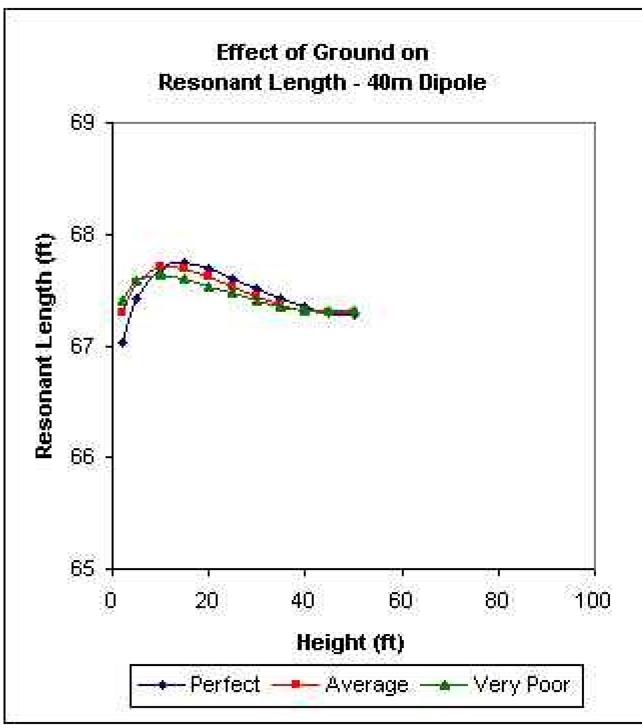


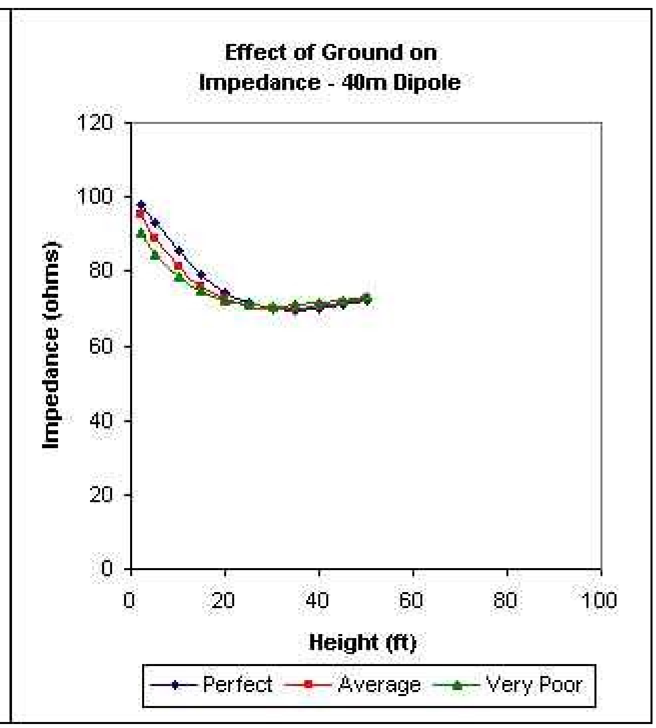
Vertical Dipoles

Now that we understand how a horizontal dipole performs, we can look at the same antenna mounted vertically. Recently there has been quite a bit of interest in vertical dipoles and in this section we'll see why.

What is it? A vertical dipole antenna is simply a dipole antenna that is mounted vertically instead of horizontally. Because of the orientation, it will have some characteristics different than a horizontally mounted dipole. The length will still be approximately 1/2 wavelength, so the same formula can be used to estimate the size.

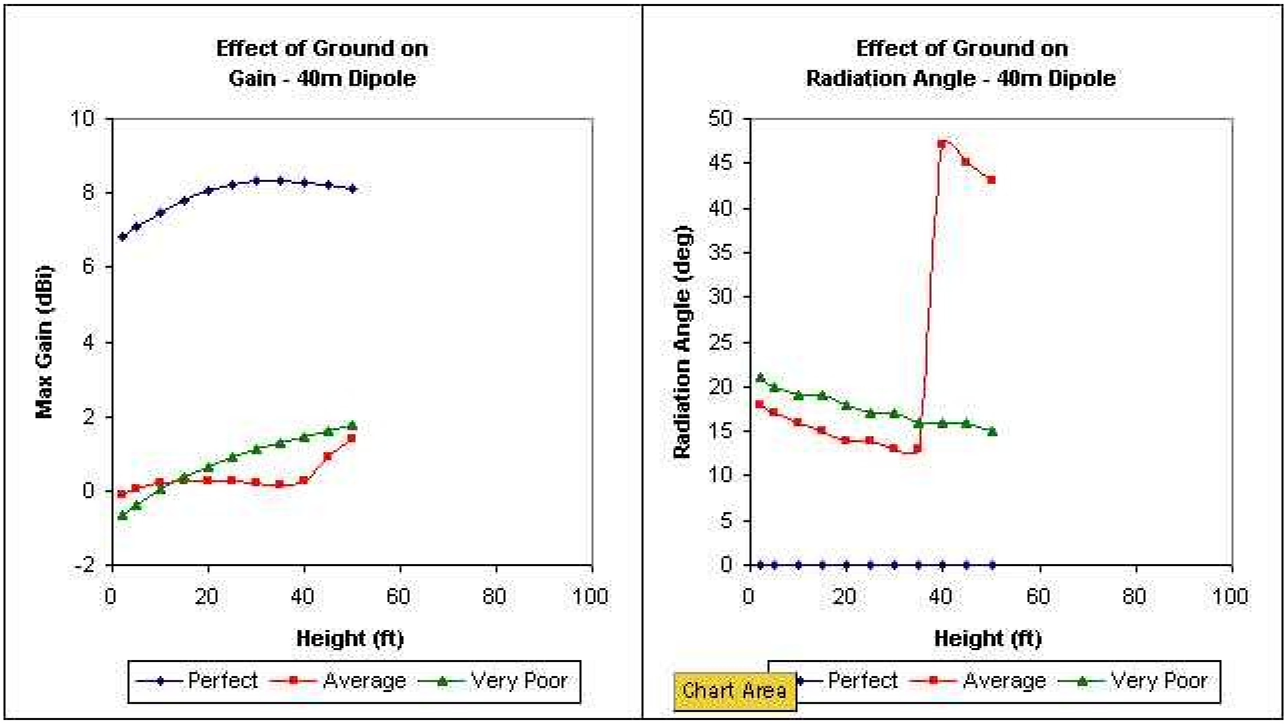
Notice that without a ground reference, there is nothing to determine whether an antenna is mounted horizontally, vertically, or at some other orientation. Therefore, the free-space performance of a vertical dipole is the same as for a horizontal dipole. Without the earth for a reference, we have no way of telling them apart. That means that the comments on wire size from the previous section apply here and need not be repeated. The following evaluations were done using a vertical dipole made from #14 AWG copper wire. The height indicates the height from ground level to the bottom of the antenna. The feedpoint is halfway up the antenna.





Length and Impedance. Notice that in the above figure the vertical dipole varies much less in both resonant length and impedance than the horizontal dipole. In addition, the variation does not depend very much on the quality of the ground. That is very different than its horizontal counterpart. Note that at low heights, which is usually the rule since this antenna is some 66 feet tall by itself, the impedance is somewhat higher than the horizontal dipole, varying between 70 and 100 ohms.

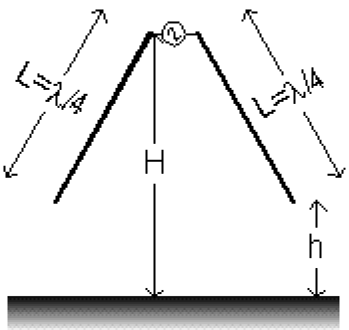
It seems that by mounting the dipole vertically, we have reduced its sensitivity to ground effects and that could be important. However, not all is perfect.



First the good news. As the above figure on the right shows, the take off angle is generally low. In fact, with a perfect ground it's zero degrees, so this antenna might be excellent for working DX. Over an average ground, putting it up too high even raises the take off angle, so we don't want it more than about 1/4 wavelength up unless the ground is very poor.

Then comes the bad news. Many advertise that the antenna is not affected by the ground and the figures we have looked at show that to be true for the most part. But the above left hand figure shows the effect on gain - that's a different story. As can be seen, the difference in gain between the antenna over a perfect ground and over a real ground is large. At low heights the antenna radiates about like an isotropic radiator at low radiation angles, with about a 7 dB loss from the perfect case. Investigating why clearly shows that the difference is losses to the ground.

So, after looking at these performance indicators, it seems aparent that mounting the dipole vertically reduces the sensitivity to the ground conditions, but the ground still has a profound affect on the performance. However, comparing it to a horizontal dipole, the radiation at low angles should still be better. The figures indicate that this type of antenna should be easy to adjust for resonance, no matter where it is mounted.

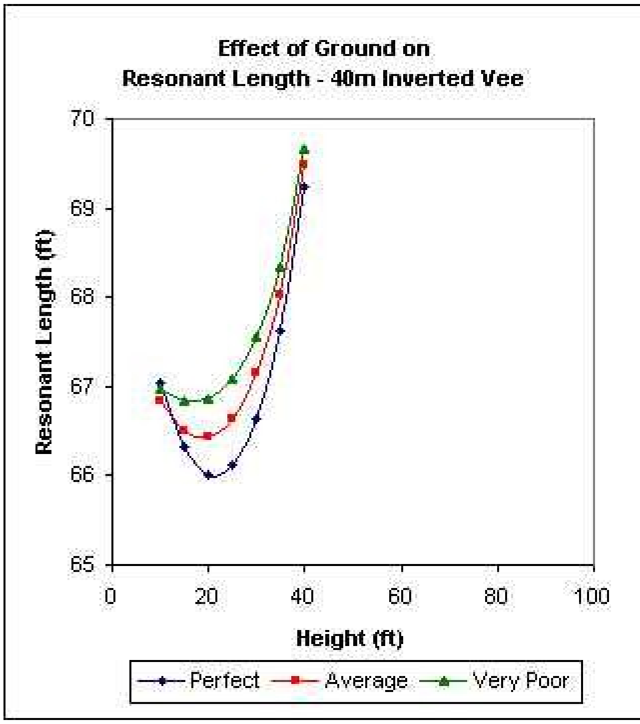


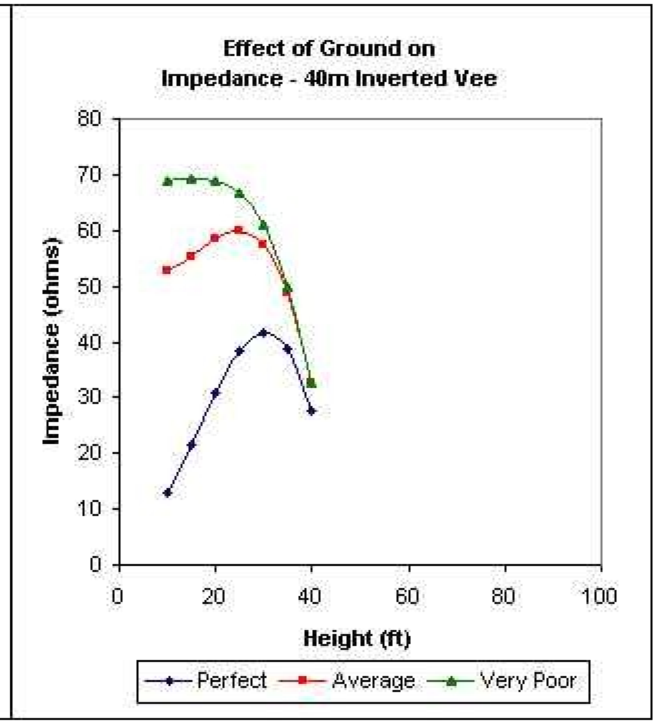
Inverted Vee Dipole

Having looked at both horizontal and vertical dipoles, one way to reduce the area needed for a dipole is to droop the sides. This popular design is called the inverted Vee and is a proven performer.

What is it? An inverted Vee dipole is a dipole with both legs slanting down towards the ground in the shape of an upside down V. The obvious advantages of this design is that it takes up less horizontal space than a horizontal dipole and only requires 1 support to hold up the center of the antenna, instead of 2 supports for the ends of a normal dipole.

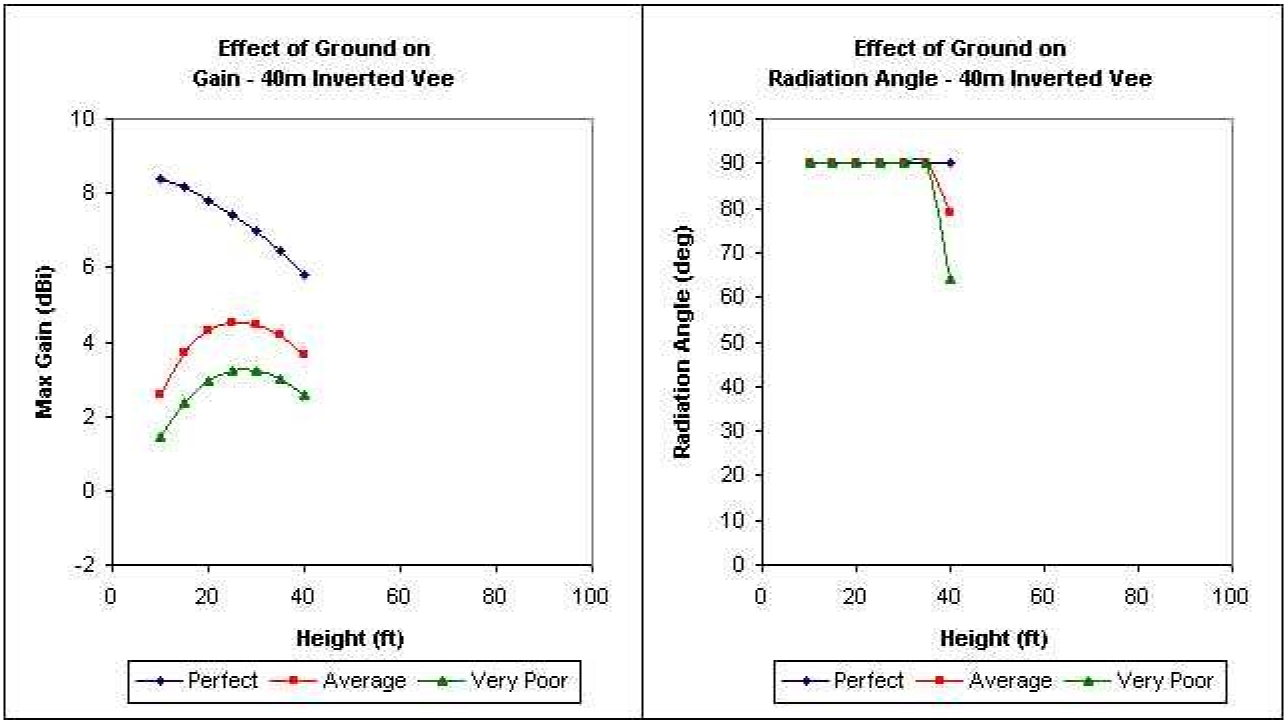
The obvious parameter to look at for this antenna is the height of the center or peak of the antenna. Since we are interested in limited space antennas, for modeling purposes, we will keep the ends 10 ft off the ground (so people don't stumble into to them) and use #14 AWG wire as for the previous dipole models. Notice that the center can't be any higher than λ/4 or the wires will be vertical and we no longer have a dipole. In the model, if the height of the center is 10 ft, then we have a 10 ft high horizontal dipole with all the characteristics shown in an earlier section.





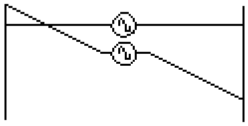
Length and Impedance. Notice that in the above figure the inverted Vee resonant length and impedance varies quite a bit depending on the ground conditions. The total length can vary up to about 3 feet and the length of each leg is half the total length. The impedance also varies from 10 to 70 ohms, but except for the case of a perfect ground, the low end of the range is around 30 ohms.

One attribute often touted for an inverted Vee is that the drooping of the wire ends causes a decrease in the impedance. It is often claimed that at around a 45 to 60 degree angle a 50 ohm impedance is obtained. While it is generally true that the impedance decreases, except over a perfect ground, the actual impedance can be higher or lower, but normally not too far from 50 ohms. It appears that center heights between about 25 and 35 feet may be a good compromise to obtain a reasonable match, but in any case, the impedance is never too bad.



The effect of ground on the inverted Vee can be seen in the above left hand figure. As seen, the less perfect grounds give a gain that is in the 3 to 4 dBi range, comparable with a horizontal dipole of similar height. But as the right hand figure shows, except for the case where the antenna is nearly vertical, the maximum radiation is always straight up at 90 degress.

So what can we conclude about the inverted Vee dipole? In general it seems to behave much as a horizontal dipole at a simlar height. It's impedance and resonant length variations should make it reasonbly simple to tune for resonance and match to 50 ohm coax. The fact that it needs only 1 support is a plus in terms of installation. Often that consideration makes it the only feasible type of dipole that can be installed and it's nice to know that it is not too much of a compromise.

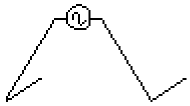


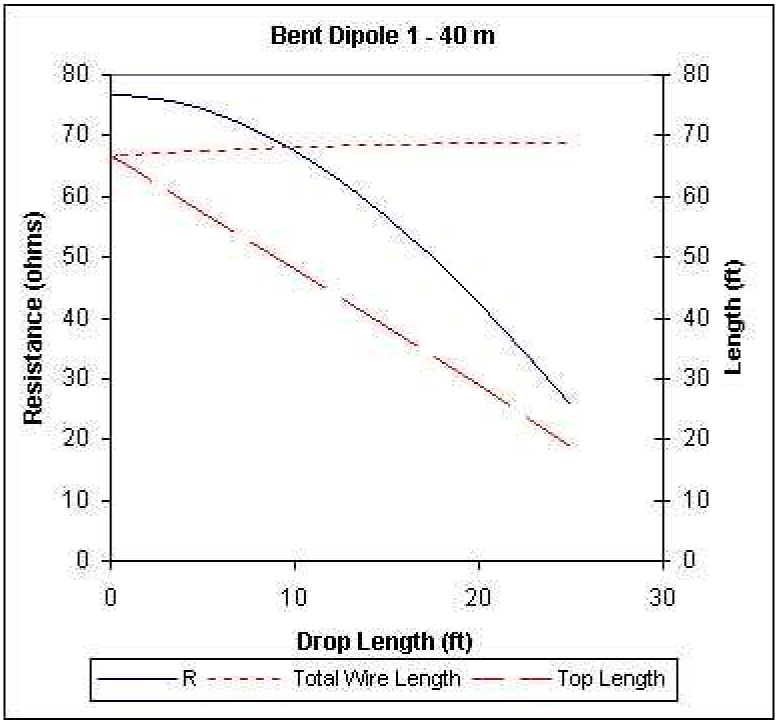
Bent Dipoles

One way to fit a dipole antenna in a restricted space is to bend the legs. They can be bent horizontally, drooped downward, or any other imaginable configuration to fit in the space available. If the resonant length doesn't change much and the impedance remains close to that for a straight dipole, we would expect a dipole with bent legs to work OK. Remember, whatever energy is fed to the antenna will radiate if it isn't lost in resistance.

What is it? A bent dipole is simply a dipole antenna that has its legs bent in order to fit in the available space, instead of running in a straight line. The number of ways that a dipole can be bent is limitless, so we can't look at all the possibilities. Here we'll look at 3 fairly common cases using our 40 meter dipole.

Drop Legs. The first case is where we simply allow the legs of the dipole to drop straight down. Of course the dipole must be high enough that the legs don't touch the ground. We'll keep the top section of the dipole 30 ft above ground and drop the legs and see what effect that has on the resonant length and impedance characteristics of the antenna.

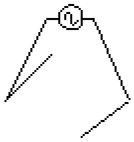


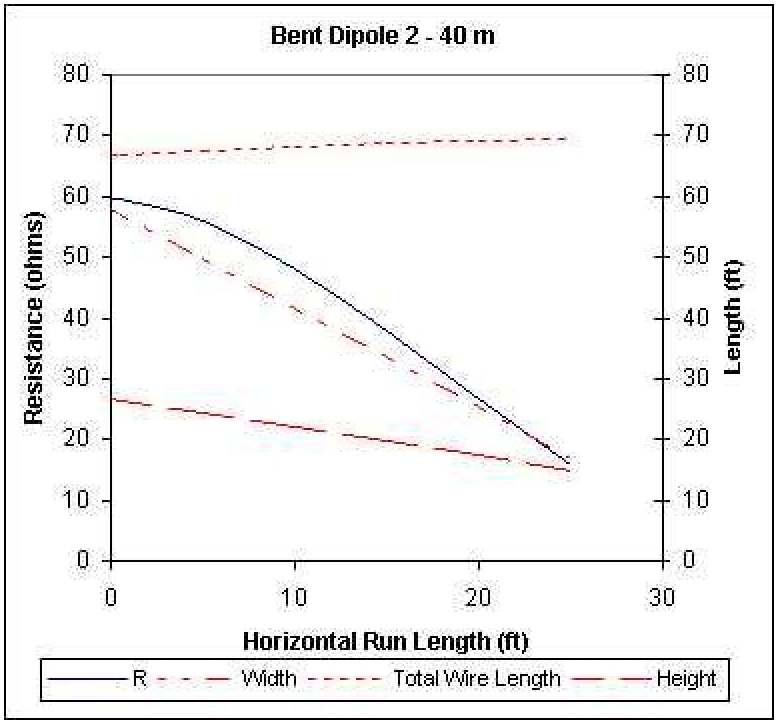


The above figure shows the effect of dropping the legs of the dipole straight down. Notice that the total wire length increases a little as more of the wire is dropped straight down, but for all of the cases is between 66 and 70 feet. The long dashed line shows the horizontal length needed for the antenna. At 25 feet of drop length, the antenna will fit into about 20 feet of horizontal space, a significant space reduction. As can be seen the input impedance drops also, but even the smallest horizontal and longest drop lengths it stays above 25 ohms, so matching to 50 ohm feedline would not be a problem.

If we want to build an antenna like this, the procedure would be to cut the antenna wires somewhat longer than a horizontal dipole and then trim them to resonance. A 10% increase in wire length would be a good conservative estimate of the wire needed. Continued shortening of the horizontal section shows a decreased input impedance and in the limit the antenna would look like an open 1/4 wave section of twin lead transmission line.

Partially Horizontal Inverted Vee 1. The second bent dipole we'll look at is an inverted Vee with the ends of the legs running horizontal. This would be used to accomodate an inverted Vee when there isn't enough space or height to build the normal antenna. The legs slant down as in a normal inverted Vee until they are 10 ft off the ground, then run horizontal. In this case the legs run off in the same direction, representing what would be done if the antenna is erected at the edge of a property, with the peak next to the house and the legs running away from the house.

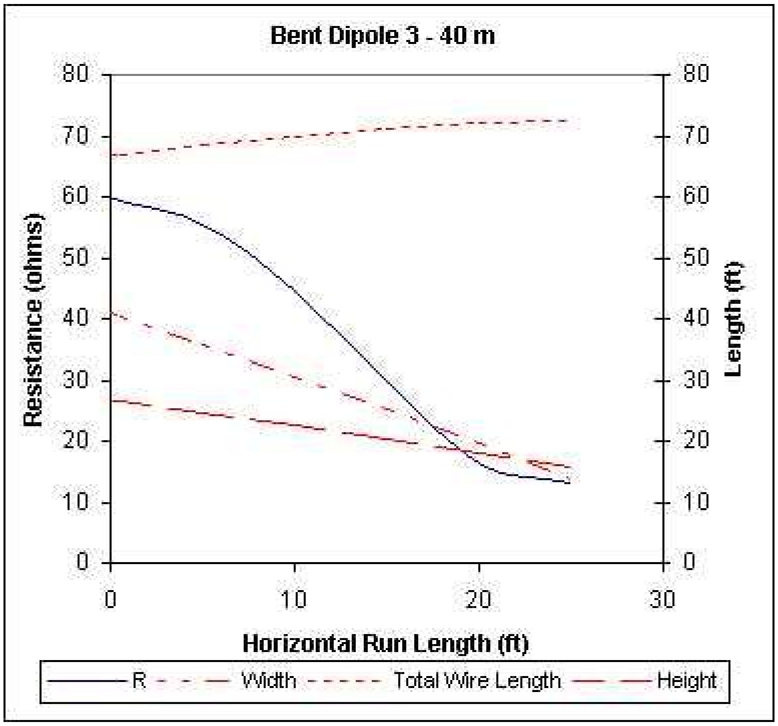




As shown in the above figure, as the horizontal legs are lengthened, the height and width required to install the antenna decrease and the total wire length increases slightly. The increase in wire length is nearly the same as for the drop leg dipole we looked at before. For all cases, the total amount of wire is between 66 and 70 feet, so the same guidelines for constructing it would apply as for the previous bent dipole - cut the wires about 10% longer and then trim with the antenna in place.

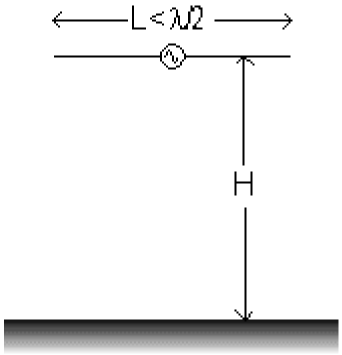
Note that the impedance for this antenna is a little lower, just as for the inverted Vees we looked at in an earlier section. Until the horizontal legs get over about 20 ft long, the impedance is still above 25 ohms, so matching should be fairly easy. Note that with 20 ft horizontal legs, the antenna can be installed in a space about 20 ft by 17 ft and is only 15 feet high.

Partially Horizontal Inverted Vee 2. The third bent dipole is also an inverted Vee with the ends of the legs running horizontal, but in opposite directions. This would be used to accomodate an inverted Vee when there isn't enough space or height to build the normal antenna. The legs slant down as in a normal inverted Vee until they are 10 ft off the ground, then run horizontal. In this case the legs run off in opposite directions, representing what would be done if the antenna is erected in the middle of a backyard and run diagonally.



As shown in the figure, the width required to install the antenna is less than the case above, although the needed heights are similar. Since the horizontal wires are closer together, there is more interaction and the impedance drops faster. For horizontal run lengths of 15 feet or less, the impedance still stays above 25 ohms, so matching should be OK. For longer leg lengths, though, the impedance is lower and matching will be more difficult. In addition, more wire is needed to bring the antenna to resonance, but not much more. Note that for 20 foot horizontal legs, the antenna can be installed in a space that is about 20 ft by 20 ft and 18 feet high.

Summary. Based on these analyses, it appears that the dipole is pretty forgiving. You can bend the wires and decrease the space required to install the antenna quite a bit without affecting the performance too much. In general, bending the legs of the dipole will decrease the impedance slowly, so matching shouldn't be a big problem except in the extremes. In general the wire will need to be somewhat longer, but not overly so. In cases of extreme contortions, the impedance will be less, the wire needed for resonance will be longer, and it may be necessary to use a tuner or some sort of matching network.



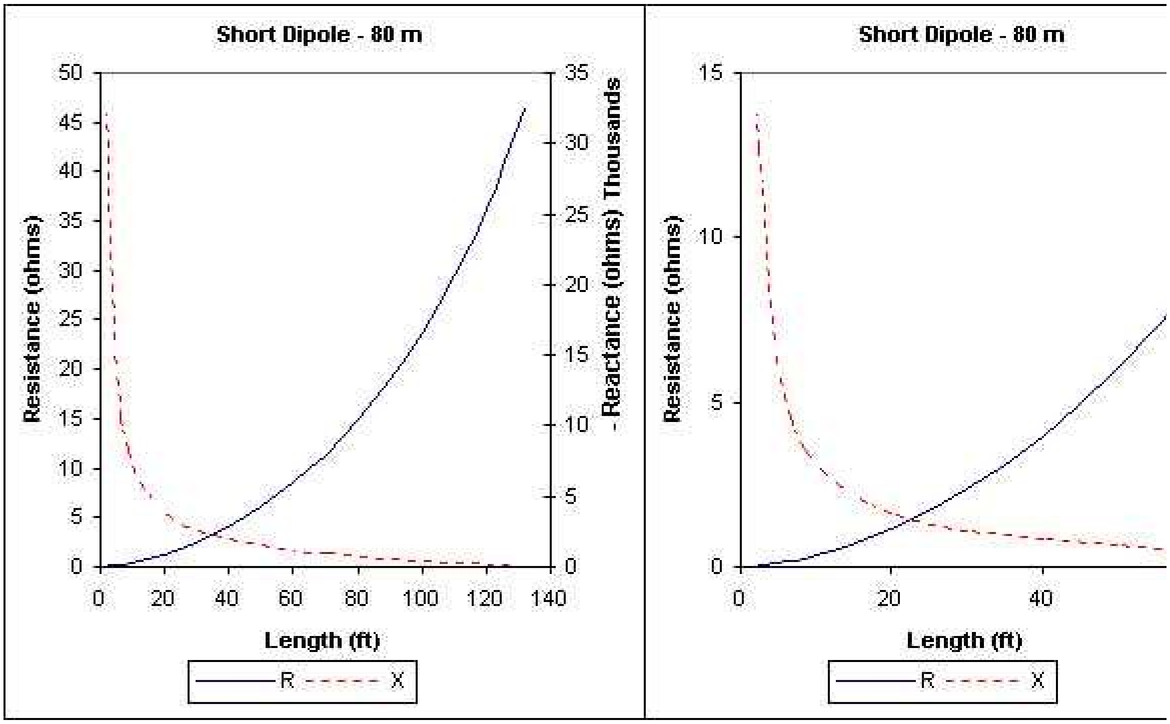
Shortened Dipoles

Since we're interested in antennas for restricted space, a short dipole is an obvious option. For purposes of this and following compromise antenna discussions, the examples will be focused toward 80 meter operation at 3.6 MHz, since that is a major challenge for restricted space environments.

What is it? A shortened dipole is simply a dipole antenna that has been shortened. Since it is shorter than its resonant length, it will not be resonant and will exhibit both resistance and reactance at the feed point. Shortened antennas tend to have a capacitive reactance and therefore need an inductance to cancel the capacitance and bring the antenna back to resonance. Normally the resistive impedance also drops as the antenna is shortened, so additional impedance transformation will be needed to effectively match the antenna.

A shortened dipole will act similar to a full sized resonant dipole in many ways. The effect of ground will still be important, current will be maximum in the center and very close to zero at the ends with maximum voltage at the ends and minimum in the center. If the antenna is center fed, it will still be balanced, with equal voltage and current distributions on both legs.

From the principle of conservation of energy, we know that if we can feed energy into an antenna, it will radiate. We also know that with a suitable matching network, we can feed power into nearly anything, including a shortened dipole. So what's the trade-off? Let's look at a shortened dipole mounted 20 feet above an average ground. The antenna will be made using #14 wire and fed in the center.



Length and Impedance. Notice that in the above figures the impedance is shown with 2 components: resistive and reactive. The left hand figure shows that at a length of about 133 ft the antenna is a full sized dipole and resonant, with about 46 ohms resistive impedance and no reactance. As the antenna is shortened, the resistive impedance drops fairly rapidly and the capacitive reactance rises. Notice that the reactive impedance scale is in **thousands of ohms**, while the resistance scale is in **ohms**. The right hand figure is a close-up view of the shorter lengths. Remember that a 40 meter dipole was about 66 ft long, so we are looking at what happens when the dipole is shortened to half of its normal size or less. Conversely, it can be viewed as what happens when we try to use a dipole for a higher band at 80 meters.

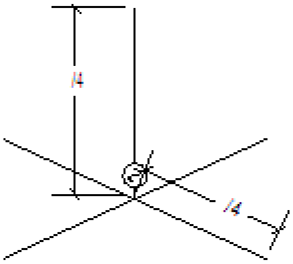
Note that at around 40 ft, the resistive impedance is 4 ohms and below about 20 feet, drops to less than 1 ohm. Meanwhile the reactive impedance at 40 ft is about 2000 ohms and at lengths less than 20 ft rises above 4000 ohms rapidly. That's not a problem in itself, since we can always use a coil to cancel the reactance and then match the resistive part with a matching network.

The problem is that our coil and matching network will be made of real components and will have resistance in it. Usually the coil contains the most wire and will normally have the most resistance and the Q of the coil is the ratio of its reactive to resistive impedance. So a fairly good coil might have a Q of about 600. That means for 2000 ohms reactance, the coil will offer around 2000/600 = 3.3 ohms resistance. That means that the coil resistance is getting very close to the radiation resistance and the efficiency is approaching 50%.

But it gets worse. At less than 20 ft antenna lengths, the reactive impedance rises much faster. For 4000 ohms reactance the resistance in the coil would be 4000/600 = 6.7 ohms, while the radiation resistance is 1 ohm or less. Thus most of the power will be used up in the coil resistance and not radiated.

That's is the problem with short antennas in general and with dipoles in particular, in this case. The lower radiation resistance and the high impedance causes significant losses in any sort of matching network. Failure to consider those losses will lead to an antenna that loads, but doesn't radiate.

For this reason, shortened dipoles can work quite well as long as the shortening isn't too severe. If they get really short, extreme care will be needed in the matching network to make sure that the resistive losses are low. Remember, if you can feed power into an antenna, what isn't lost to resistive heat will radiate, so the resistive losses relative to the radiation resistance must be minimized.



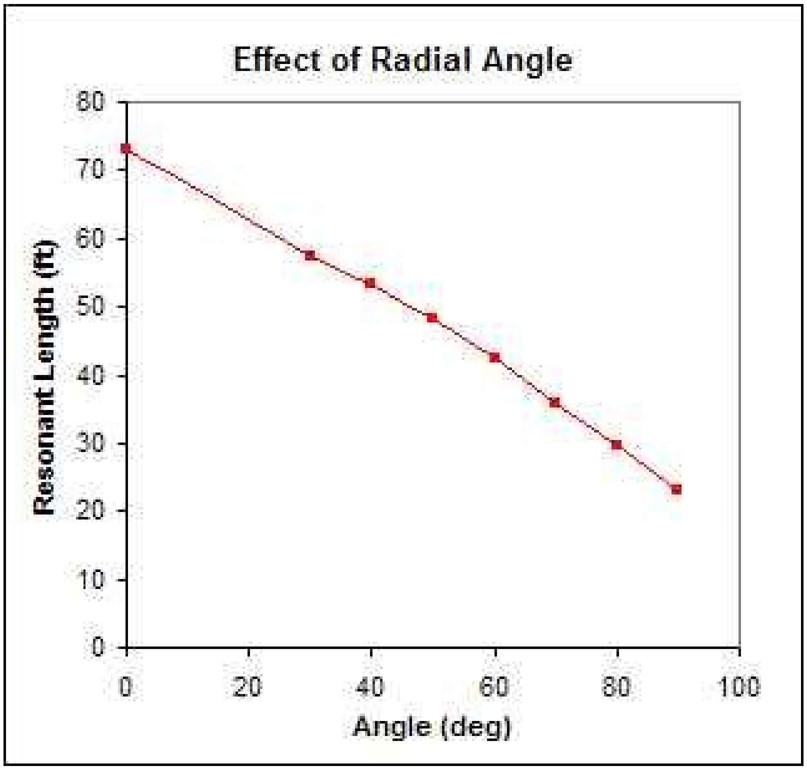
Ground Plane Verticals

Quarter Wave Groundplane Vertical

Having looked at dipole antennas, it is apparent that the antenna currents are symmetric about the center of the antenna. In other words, if you divide the antenna at the center feed point, the 2 halves of the antenna look like mirror images of each other. With that in mind, it would be interesting to see if 1/2 of the antenna could be replaced by something else. This would result in shortening the antenna by 1/2. As it turns out, it is indeed possible to do that. The resulting antenna is normally mounted on or near the ground in a vertical position. In this section we will describe the resulting 1/4 wave ground plane vertical.

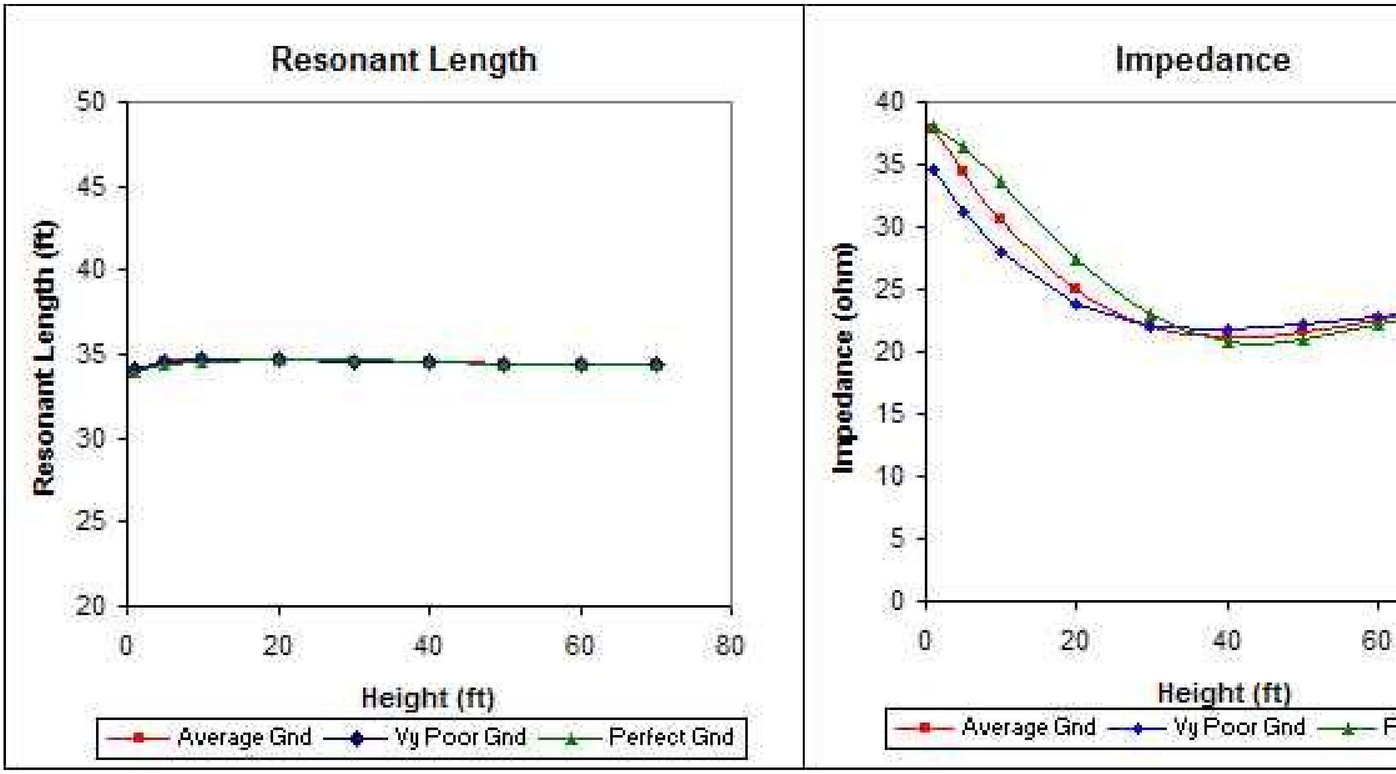
What is it? Let's start with a center fed vertical dipole, which was analyzed in a previous section. One way to visualize how to shorten the antenna is to progressively modify it. First we split the wire below the feed point into 4 wires. Next, keeping the 4 strands evenly spaced, we raise the ends of the wires until they are horizontal.

As shown in the following graph, when the "radials" are at 0 degrees, the impedance is about 70 ohms, since we are really dealing with a vertical dipole. As the radials are raised to an angle of 90 degrees, the impedance drops to around 20 ohms. Notice that when the radials are at an angle of about 45 degrees, the impedance is very close to 50 ohms, which is similar to the inverted Vee.

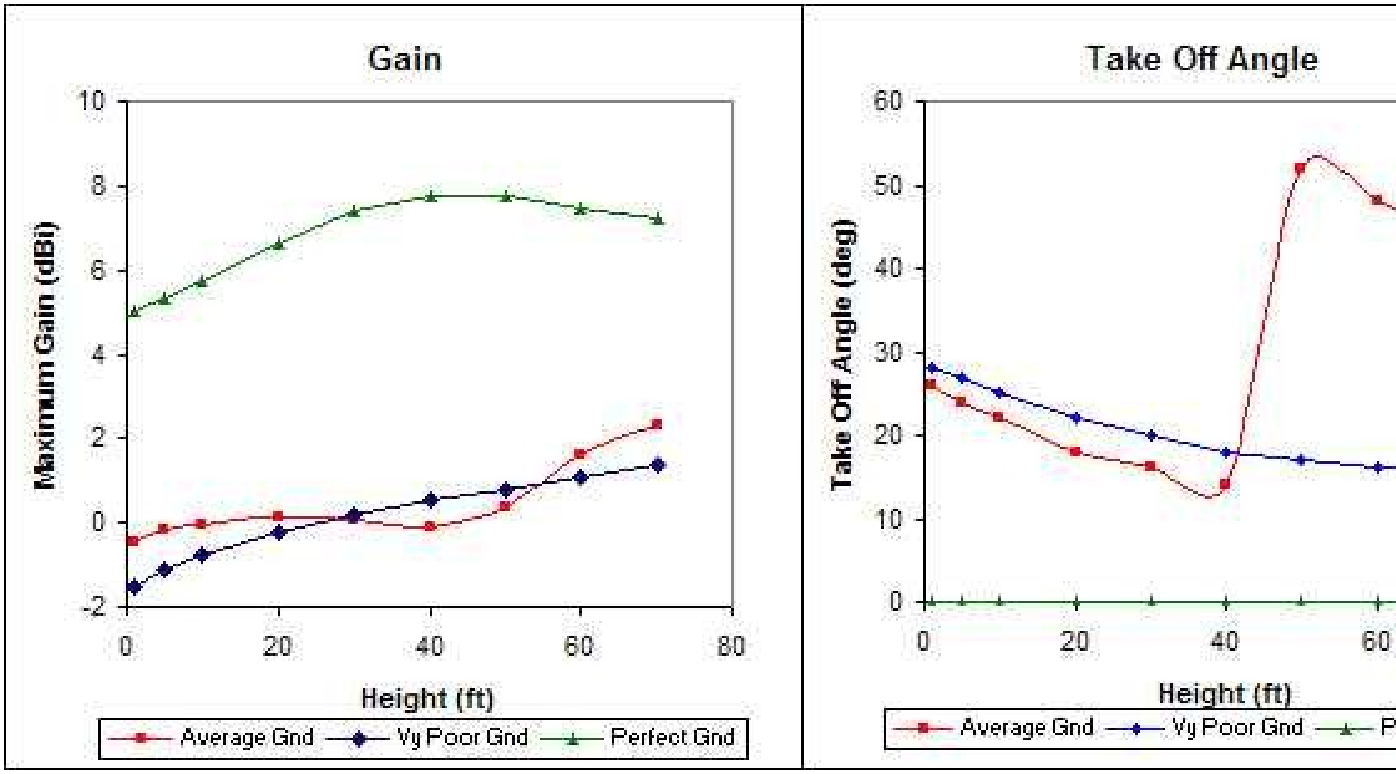


Height. It has already been demonstrated that a vertical dipole is somewhat immune to the effects of a ground on its impedance. It might be expected that the ground plane vertical would also be immune to the efects of ground.

The effects of a real ground on the resonant length and impedance is shown in the following figures. Even thugh it doesn't look like it, there really are 3 curves on the resonant length graph! As can be seen, neither the resonant length nor the impedance vary dramatically with ground conditions, but the impedance will depend upon the height above ground and range from around 20 to 40 ohms.

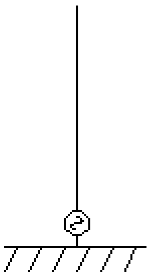


It was also shown, however, that the vertical dipole gain depends on the ground conditions. By analogy it would be expected that the ground plane vertical would also be affected by the same factors. As the following graphs show, that conjecture would be true. A comparison with the similar graphs presented for the vertical dipole shows that the shape and tendencies are indeed the same. The gain for the ground plane is very nearly constant and equal to an isotropic antenna at low heights and real ground conditions. Meanwhie the take-off angle appears to be in the range of 15 to 20 degrees for most cases at low heights. Note that the better ground conditions give a lower angle.



Conclusions. So what can we conclude about the ground plane vertical? In general it seems to behave much as a vertical dipole at a similar height. It's impedance and resonant length variations should make it reasonably simple to tune for resonance and the impedance should present a reasonable match to 50 ohms, even though it is a little low. In addition, since it can be mounted very close to the ground and provide a reasobably low take-off angle, it should indeed be a reasonable antenna for practical use.

Of course, hams have known that for a long, long time. But it is nice to know that the theory agrees with practice.



Ground vs. Radials

The need for radials with a ground mounted vertical has invoked lots of discussion among amateurs over the years. The literature contains many references to how many radials are needed, how long they should be and what affect they will have on the performance of a vertical antenna. And yet lots of confusion still exists. In this section we will take a look at ground mounted and above ground mounted vertical antennas, especially with respect to the radials and try to make some sense out of the subject.

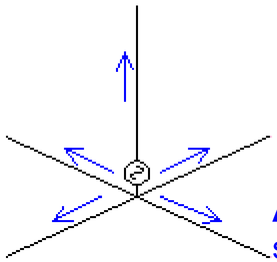
Ground Mounted Vertical. First, let's look at a ground mounted vertical antenna. As shown in the sketch, it consists of a vertical radiator that is mounted directly on the ground and fed at the base. As should be apparent, in the case of a perfect ground, the potential (voltage) with respect to ground is precisely zero on the side of the feed point attached to ground. That means that the entire voltage of the source is applied to the vertical radiator. This is different than a dipole, where the voltage swing is applied to both sides of a dipole.

In a dipole, the voltage with respect to ground is equal and opposite on both sides of the feed point. In a ground mounted vertical with a *perfect* ground, the voltage on the ground side of the feed point is always zero with respect to ground. This is inherently an unbalanced antenna and there's not much that can be done to change that. It will also have a take off angle of zero degrees and an impedance of 36 ohms at resonance.

Note that a perfect ground has zero resistance and reactance. Therefore there can be no voltage differences, no matter how much current is flowing in the ground, and therefore no losses. So far so good.

But what happens in the "real world"? In reality, there is no such thing as a perfect ground with zero resistance and reactance. Real ground conditions do indeed induce losses and there are voltage gradients caused by ground currents around an antenna. So what can be done?

One approach is to make the ground as close to perfect as we can. That means putting a metal plate or mesh or a large number of radials at the surface of the ground to decrease the ground resistance and impedance. Obviously, the more metal we can put down, the better it will approach a perfect ground and the more efficient the antenna will perform. That's why we often hear the guidelines that "the more radials, the better." An alternative is to mount the antenna over salt water, which has a very low resistivity and makes an excellent ground. We are simply trying to turn our real ground into something as close to a perfect ground as possible.



Above Ground Verticals. In a vertical antenna mounted above ground, the situation is a little different. As shown in the figure, the antenna is usually fed at the base of the vertical element, however, the radials are not directly connected to the ground and there is nothing to keep them at ground potential. In this situation, the radials *will* have current flowing on them and at the feed point the current on the vertical element will be balanced by the current flowing on all of the radials. This is still not a balanced antenna, though, since the currents are not symmetrical around the feed point. In fact they flow vertically on the vertical element and horizontally (or at some other angle) on the radials.

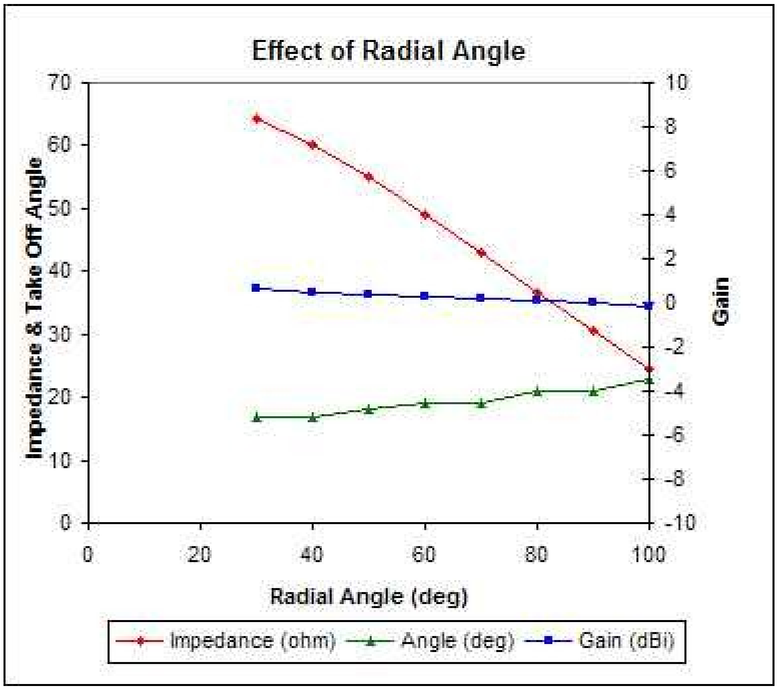
Now, since there is current flowing on the radials, there will also be radiation from the radials, but we want to minimize the radiation in order to maintain the desireable properties of the vertical antenna, including low angle of radiation. One way to do that is to arrange the radials symmetrically about the base of the vertical. In the case of symmetric radials, the current in each radial is flowing in an opposite direction (away from the center) to the current on the radial directly opposite to it and the total radiation in the horizontal plane will cancel. Therefore, in that respect, the radials will have little effect on the low angle radiation.

But not all is perfect. There will also be radiation vertically from the radials and some of that will interact with the ground. Of the part that interacts with the ground, some radiation will be reflected and some ground currents will be induced, leading to ground losses. But that's not what we wanted!

So what can be done? One obvious possibility is to mount the antenna as high as possible, thereby minimizing the interaction with the ground and avoiding ground losses as much as possible. Hence the guideline "The higher the better". The other possibility is to add as many radials as possible in order to minimize the current on each radial. The current on each radial will be equal to the total current on the vertical element divided by the number of radials, so "the more the better".

Another way to look at the effect of radials in a vertical mounted above ground is that the radials are shielding the antenna from ground. In effect we are trying to create an "artificial ground" that is better than the real ground that mother nature gave us to work with. From that viewpoint we would like to have as many radials as possible, as long as possible. Again, consistent with the guidelines commonly quoted by amateurs. However, in my opinion, that viewpoint is too simplistic, since it ignores the fact that we can never completely shield the antenna from the ground in practice. No matter what, there will always be a potential difference between the radials and the ground, so there will be some interaction. It seems much better to forget about the analogy of shielding and just treat the antenna and radials as a complete antenna system that will interact with the ground to some extent. The important point is that, whether we want to think about them separately or not, the radials are part of the antenna.

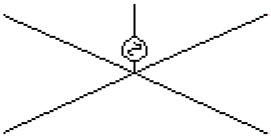
Radial Angle. It has been stated many times that angling the radials downward at a 45° angle will improve an antenna. Let's see what happens when the radials are not horizontal, as in the ideal case above.



The above graph shows the impedance, the take off angle and the gain of a ground plane vertical as a function of the radial angle. In all cases, the lowest part of the radials was 10 ft above an average ground, which would represent mounting the antenna so the radials don't cause problems for people walking nearby. As can be seen, the gain doesn't vary much at all and neither does the take off angle. Certainly we probably could not detect the small differences in gain and take off angle shown. However, the impedance does vary from some 70 ohms for a vertical dipole to about 25 ohms when the radials are horizontal.

The implication of this graph is that the angle of the radials will have a minimal effect on the antenna perfomance, but it will change the feed point impedance. The minimal effect on the radiation can be understood by noting that the radials are symmetrical and their radiation in the horizontal plane cancels, as previously noted. However, somewhere around 45° the feed point impedance is very close to 50 ohms at resonance. So from an impedance matching standpoint, there is a reason to make the radials slope downward at an angle of about 45°. Changing the angle on the radials may make the antenna perform a little better, but it will also be somewhat easier to match.

Bent Radials. Since we're interested in limited space antennas, one common problem is what to do when you don't have room for the radials. After all, the radials for a 40m groundplane vertical require about 33 ft of space around the antenna.



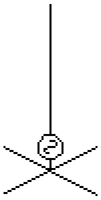
Fortunately, the exact position of the radials isn't all that important. Just as we noted that we can bend a dipole all around and it will still work, so we can bend the radials around, too. In fact, as long as we keep the radials symmetric, there will be little effect on the antenna performance, since radiation from the radials will still cancel. Although the computed performance isn't shown here, it is even possible to arrange the radials in a spiral pattern around the base of the vertical and still maintain performance and impedance characteristics.

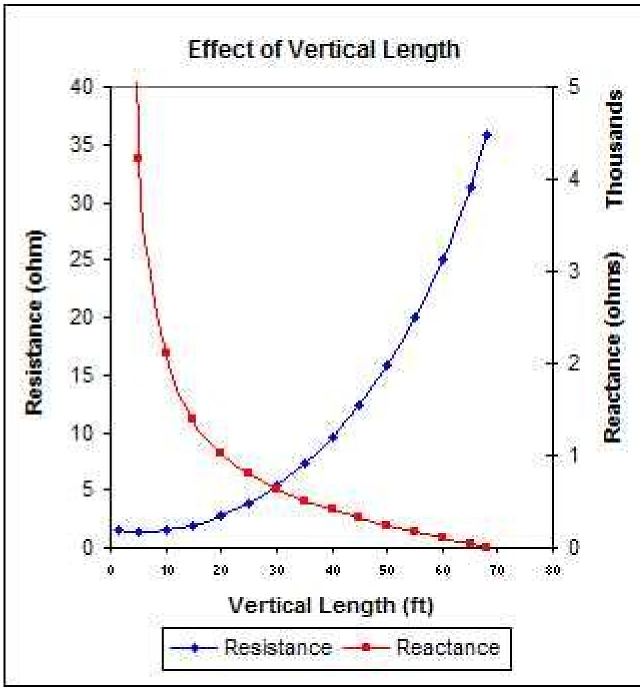
So, just as for the dipole, the ground plane vertical can be modified within reason and still be made to work under less than ideal circumstances.

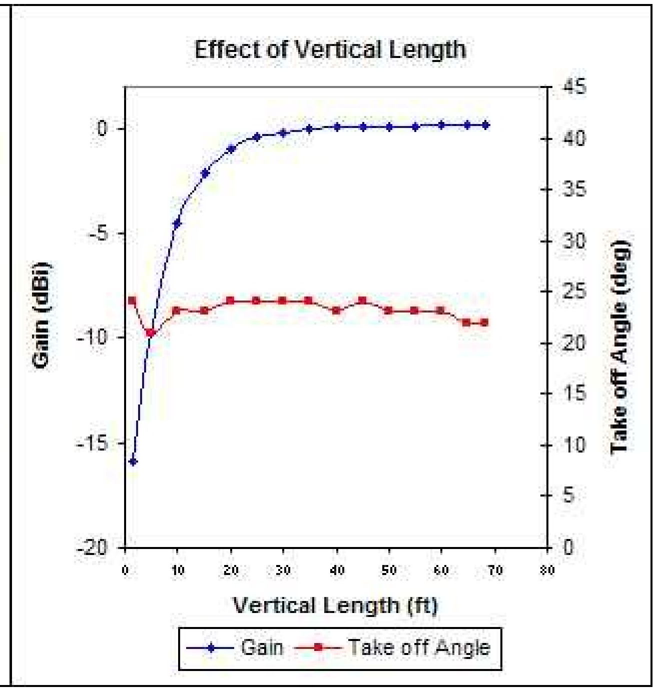
Short Verticals

In the previous section we saw that the ground plane vertical can be an effective antenna and can be used in a space limited situation, since the vertical takes up little area. However, it may still be too big for practical reasons due to the need for radials. In addition there may be height limitations that cause problems. Especially if we are forced to use indoor antennas, getting a full 1/4 wavelength in a living room may be impractical. In this section we'll look at how to further shorten the vertical part of the antenna and what effect that has on performance. Later we'll look at how to keep the radials down to a manageable size in restricted situations. And finally we'll look at what happens when both the vertical element and the radials have to be shortened.

Shortening the Vertical. First, let's look at a ground plane vertical for 80m (3.6 MHz), which as in the case of a shortened dipole, is a big challenge for limited space antennas. In this case we'll assume that the radials are the right length (about 68 ft long) and the base of the antenna is 10 ft above an average ground.



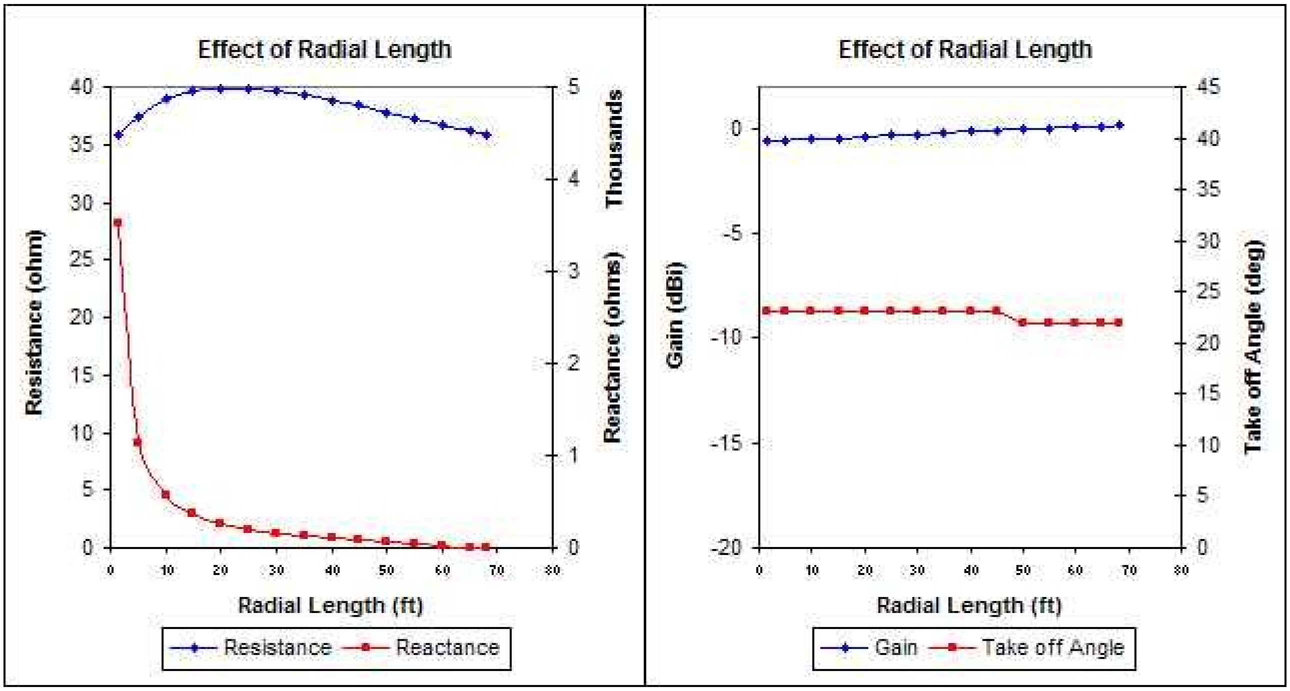




As can be seen in the left hand figure, as the vertical is shortened, the resistive impedance drops from about 36 ohms to about 1.5 ohms. Meanwhile the capacitive reactance increases from zero at resonance (68 ft) to more than 5000 ohms at very short lengths. Just as we noticed for the short dipoles, this has severe implications when we consider that any matching coil will have resistance due to the coil Q which will be greater than the resistive impedance at short lengths. But, it gets worse!

As the right hand graph shows, the take off angle doesn't change much, but stays around 20 - 25 degrees. However, the gain changes dramatically, going from near 0 dBi (equal to an isotropic antenna) to 10 and even 15 dB of **loss** at small vertical lengths. In effect, as the vertical element is shortened, the radials become relatively more important and their interaction with the ground dominates the antenna performance. Hence most of the signal is lost in warming the ground (10 dB loss represents a 90% loss in radiated power). So the net effect is that with small vertical elements, we will lose a lot of power in the matching network, then most of the rest will simply warm the ground. That certainly isn't very encouraging!

Shortening the Radials. Now let's look at what happens when we have plenty of vertical space, but no room for radials. Once again, we'll look at an 80m vertical at 3.6 MHz, but now assume that the vertical element is the right size, about 68 ft. Once again, the base of the antenna will be 10 ft above an average ground.

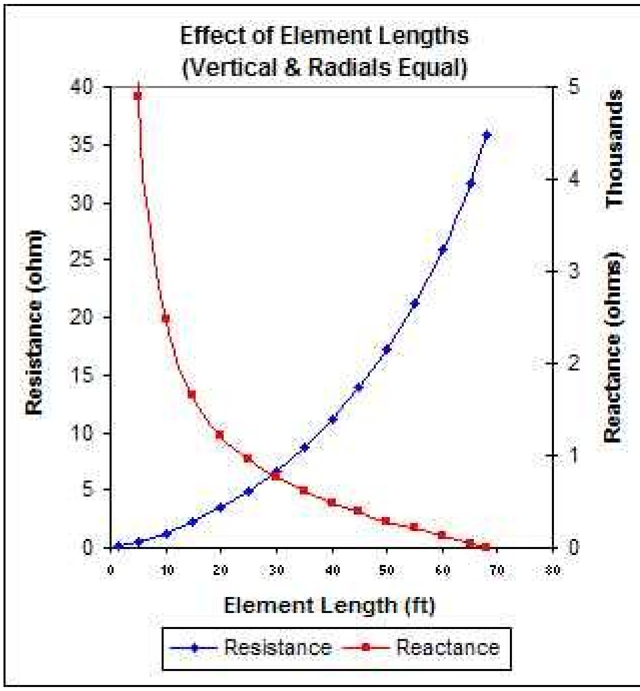


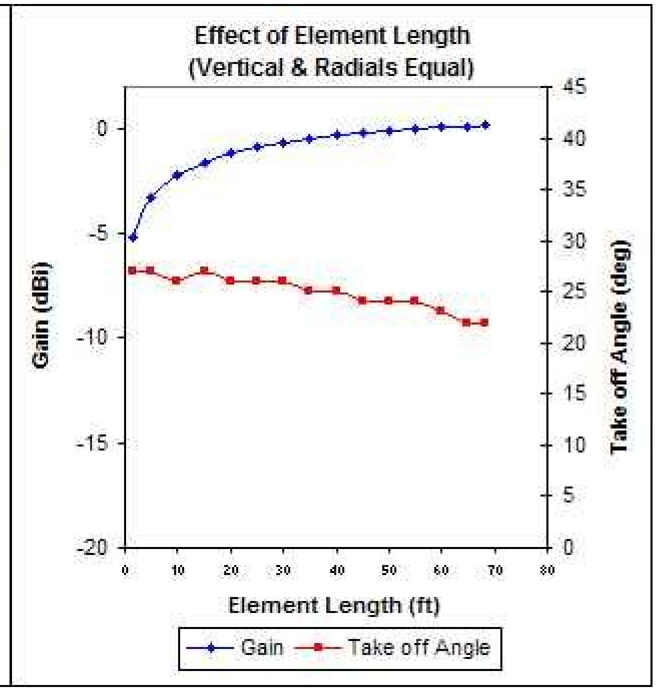
As the left hand graph above shows, the resistive impedance stays in the range of 35 to 40 ohms for nearly all radial lengths. Meanwhile, as the radials are shortened, the capacitive impedance rises but doesn't get extremely large until the radials become very short, less than 10 ft. Both of those observations are encouraging, since we can always add a simple coil to cancel the reactance and be left with a resistive impedance that will work well into 50 ohm coaxial cable.

The right hand graph is also interesting. As can be seen, the take off angle stays at 22 - 23 degrees, no matter what the length of the radials are. In addition, the gain stays steady, too, at just below 0 dBi. Why is this so much different than the previous case where the vertical was shortened?

If we compare the geometry of the two situations, in the first case it is apparent that the radials dominate the antenna structure when the vertical element is short. This causes most of the radiation to penetrate the ground, with the associated losses. We could say the antenna is mostly cooking earth worms. When the radials are shortened, however, there is *less* radiation penetrating the ground, so less losses occur. The impedance is still adversely affected, but at least we are not heating the ground as much. This clearly shows that if we have to shorten either the vertical or the radials, it is much better to shorten the radials!

Shortening Everything. Unfortunately sometimes we don't have room for either a full size vertical element or full sized radials. In this section we'll see what happens when we have to shorten everything. Again, we'll consider an 80m antenna at 3.6 MHz with its base 10 ft above an average ground. In the shrunken model, both the vertical and radial elements will be shortened, but their sizes will be kept equal.



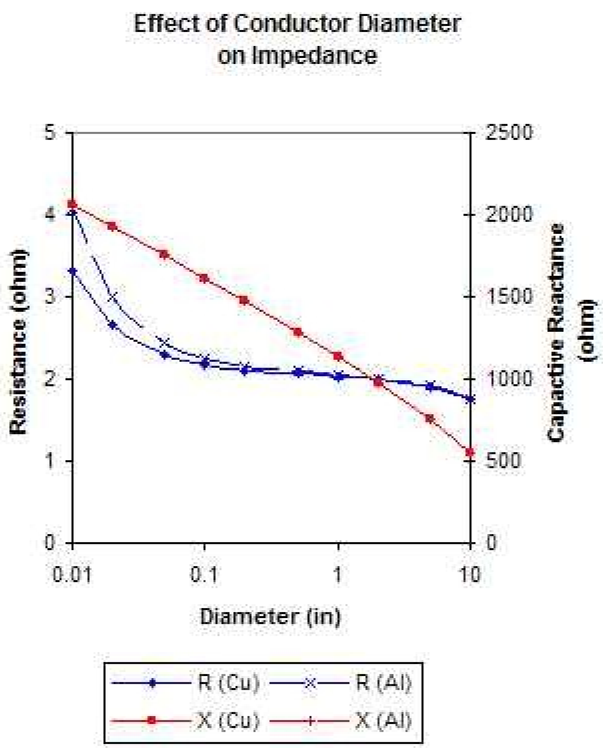


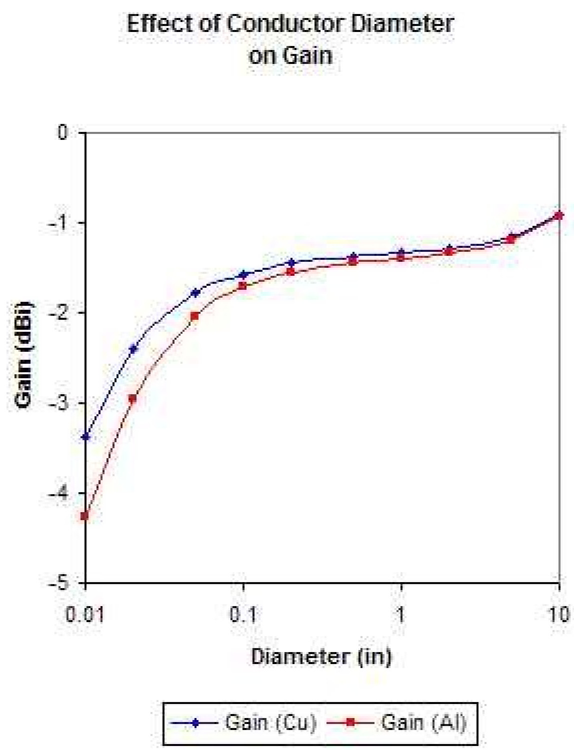
As shown in the above graphs, the performance is similar to the case where only the vertical element is shortened, but not quite as severe until the lengths are very small. The gain does not drop quite as rapidly and the take off angle changes slowly. The resistive impedance, however, drops quickly and the capacitive reactance rises as the antenna is shrunken.

Essentially, as the antenna shrinks, it changes impedance since the size is too small to be anywhere near resonance. However, since the relative effect of the radials is not decreasing, a substantial part of the energy is lost in a combination of resistive wire losses and ground losses. In trying to feed this antenna when it is small, much of the transmitter power would likely be lost in the resisitance of any coil used in matching, just as described above. Although not as bad as keeping the radials long, this isn't a very efficient antenna when it gets very short.

Since we saw a significantly better performance when the radials were shortened, it might seem possible to try to keep the radials shorter than the vertical element. The idea in doing this would be to minimize the interaction between the radials and ground, while still shortening the vertical element. Unfortunately, although not presented here, the results are not very different from the case where the radials are the same size as the vertical element. It appears that there is little remedy for the problem. If you can keep the vertical element as close to full size as possible, you will be much better off.

Effect of Diameter. We showed in the section on dipoles that a larger conductor diameter was better and that below AWG #20 wire, the resistive losses in the wire seemed to become important. So far, all of the antennas in this section were modeled using #14 wire. What happens if we use larger conductors? To evaluate this, we use a 15 ft vertical element with a varying diameter while keeping the radials 15 ft long, but made with #14 wire. The base will still be at 10 ft above an average ground.





As the left hand plot shows, when the wire diameter is below about 0.1 in, losses (indicated by the increased resistance) start to get more important and are worse for aluminum than for copper conductors. However, if the diameter stays above about 0.1 in, the effect is minimal. Obviously, since every little bit helps, using as large a diameter as possible is best, but especially above 1 or 2 inches, the effect isn't important. In addition, for diameters larger than about 0.5 - 1 inch, the difference between aluminum and copper conductors is negligable. Also interesting is that there is no difference between copper and aluminum is terms of the reactive (capacitive) impedance and only the resistance is affected by the type of metal.

The right hand graph shows the gain as a function of the conductor size. (The take off angle varies very slightly, always around 26 - 28 degrees, so is not shown). As can be seen, copper conductors always give more gain, but for diameters larger than about 0.5 in, the difference between copper and aluminum is small. Generally the larger the diameter, the more gain that will be obtained, but as the diameter gets larger, the benefit is less. It appears that from gain, impedance and structural considerations, 1 - 2 inches is perfectly acceptable and further increases in diameter probably aren't worth the extra weight and cost of metal. After all the total diference between 0.1 and 10 inch diameters is less than 1 dB, which probably wouldn't be noticed.

As a result of looking at various means for shortening a vertical antenna, it seems apparent that we want to keep the vertical element full sized if at all possible. However, when that is not possible, shrinking the antenna can be expected to cause low resistive impedance, high capacitive reactance and problems with low gain due to resistive losses and ground losses. We also have seen that increasing the diameter of the conductor helps minimize losses, but that going to more than 1 or 2 inches diameter isn't usually worth the cost and effort.

Small Antennas - General Notes

All of the information presented in previous notes is interesting and important for a general understanding of how antennas work and what controls their performance. But, as radio amateurs, we are interested in actually making the antennas work. As usual, the theory is important, but the practical aspects of antenna design and construction are important, too. This section collects some guidelines for use in putting together a working antenna system in cramped quarters.

Site Survey. Perhaps when one thinks about a site survey for an antenna, the first thing that comes to mind are surveyors and lots of area to describe. While that may be true for professional installations, that isn't neccesary for most of us. What we really need is a description of the area we have available for installing antennas, along with some notes on the good and bad points. We need to keep in mind any constraints and also take advantage of any positive factors.

Remember that it's easy for most people (me included) to be negative and see the problems. You may have to force yourself to be the "eternal optimist" to find some advantages, but you can be sure that most every situation does have some advantages. Don't overlook the good points, no matter how insignificant they may seem.

Keep an Open Mind. As was pointed out in the previous notes, anything will work as an antenna to some degree subject to 3 major constraints:

- You can load it
- It doesn't have lots of internal resistance
- You don't lose too much energy to the ground

Ask for advice, too. Several times my wife, who knows nothing about radio, has suggested something that I've been able to turn into a workable antenna. Anything from curtain rods to toilet brushes may be of use in figuring out how to get something to radiate.

If It Isn't Broke, Don't Fix It. That advice is a hallmark of many engineering activities, but in this case, it is really bad advice. My opinion is that *every* antenna installation can be improved and if we don't try to continually optimize, we'll never get a better working system. Of course, if you are already on the DXCC Honor Roll using limited space antennas or have already talked to everyone you want to have a QSO with, maybe you've reached the peak of optimization.

The problem with evaluating your own antenna is just this: What are you comparing it to? Normally we have nothing to compare with directly, so if we make lots of contacts, we assume the antenna is great. However, we almost never know how many contacts we *didn't* make. It isn't until you improve the antenna and make the additional contacts that one can look back and say that the improvement was worth it.

First Make It Work, Then Make It Work Better. That's an old adage that I learned doing computer programming and it holds true for antenna work, too. You'll find that it is often easier to modify an antenna system than it is to build one in the first place. At least with a working antenna, one can figure out where it is lacking and what it does well. Once we understand that, we're well on our way to modifications with a fair chance of actually improving things.

For example, rather than spending lots of time worrying about ground losses or feed line radiation, put up a dipole and see how it works. Once it's up and working, then see if it acts like there's too much ground loss or if it acts like the feed line is radiating. Once we know how bad those problems are, then we can figure out how to fix them.

Learn How to Model. With modern PC's and readily available software, one of the major tools available to hams is antenna modeling software. With the right software (and an understanding of how to use it!) it's possible to model most antennas that hams use. This provides a powerful tool for evaluating our antenna systems and understanding how to improve them. My personal approach is to build some sort of antenna and observe and measure its performance. Then model it and adjust the model until it agrees fairly well with my observations. Once that is done, then I can change the dimensions, feed point, wire size, or anything else in the model to see if it makes things any better. And when I find a way to make it better, I've got a better than even chance that my changes will actually work.

But at the same time, remember that an antenna model is just a model. An antenna model won't work DXCC - you have to build, install, adjust and use the actual antenna! So don't get too caught up in the modeling. Just don't forget that modeling is a tool, but the goal is to get the signals on the air.

Case Study 1
Travel Antenna for Hotels

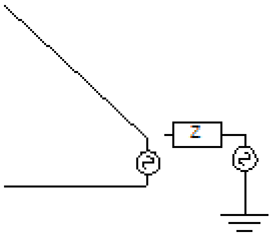
Since I often do quite a bit of traveling and stay in hotels, I needed a good small antenna to carry with me. I didn't want to drag an extra suitcase to hold my radio gear, so everything needed to fit in my laptop computer case, along with the computer. I also didn't want to arouse airport security, so it had to be simple and not too bulky. What I came up with is simple, small, has never aroused curiosity and it works with my FT-817 QRP rig. I've used it in Venezuela, Bolivia, Mexico and across the US and had many enjoyable QSOs.

Site Survey. The site survey for this situation is understandably general, since I never know where I will be when I use the antenna. Even so, there are a few constraints I can define, as well as pros and cons of the situation from an antenna standpoint.

Item	Comments
Frequency Range	7 - 30 MHz
Area Available	Standard hotel room
Height Available	About 3 m floor to ceiling
Height Above Ground	Hopefully above the 2nd or 3rd floor
Ground Quality	Probably very poor soil, but sometimes close to sea water
Access to Roof	No way
Access to Outside	Through windows or balcony

Advantages	• Antennas close to station
	  o short feed line (low losses)
	  o convenient to adjust (no trip outside)
	• Resonable height
	  o lower ground losses
	  o no tower, masts needed
	  o can lay wires on the floor

Disadvantages	• Can't use "long" elements



	• Affect of nearby objects (walls, wiring, etc.) • No good RF ground
Other Constraints	• Small and light weight • Easily put up and taken down • No bulky electronics to attract attention

As can be seen, there are some advantages to this situation, even though it may not be readily apparent at first thought. I can usually request a hotel room on the top floor or as high up as possible. Of course the disadvantages are the size constraints, the unknown ground quality and the effect of nearby objects that changes with every trip.

Preliminary Design. My first try was to use a Radio Shack reel antenna (normally sold for SWL use) along with a small MFJ tuner. The reel antenna contains about 19 feet of stranded #20 wire in a small case that allows it to be reeled in when not in use. The antenna wire was connected as a random wire and worked well on 20m and higher frequencies. I made quite a few QRP contacts using that system.

There were, however, 3 problems that still needed to be overcome:

- - the tuner was not able to match on 30 and 40 meters
- - the tuner was a little large to fit easily in my computer case
- - the tuner and cables did cause airport security to ask questions, although I was never stopped from carrying them.

The preliminary antenna was working and the problems with it had been identified and mostly understood. It was time to figure out how to modify the antenna to get rid of the problems, and hopefully make it work even better.

Modified Design. As can be seen, all of the problems stemmed from using the tuner. If I could eliminate the tuner, then the system would work according to my needs. So, I got out my antenna modeling software and decided to figure out why the antenna wouldn't work on 30 and 40m and also see if there was a way to get rid of the tuner.

Modeling the antenna at 40m showed that an end-fed wire presented an extremely high impedance , explaining why the tuner wouldn't work. I decided to see if I could add a counterpoise to help get it to tune. While in the process of playing with the model, I discovered that if I used 2 wires it was fairly easy to get an exact match to 50 ohms. The modeling indicated that with 1 wire about 1/3 wavelength long and the other about 1/6 wavelength long, if the angle between the wires was around 45º, a perfect match could be attained. That meant there would be no need for a tuner at all.

The next step was to try it. I measured out 1/3 wavelength for 15 meters and connected the wire to the coax center conductor of the FT-817 and clipped the other end to some curtains. Next I measued out 1/6 wavelength and alligator clipped that to the coax outer shield connector and laid the wire on the floor. Sure enough, a slight length adjustment on the shorter wire and the SWR was 1:1, just as predicted. I then repeated the experiment on 20 meters and 30 meters with success. Unfortuantely the wires were too short to get 1/3 wavelength on 40 meters, but with both reels fully extended, the SWR was acceptable on 40m, too.

As a result, I now do not carry the tuner with me at all and have never been asked anything by airport security. The entire antenna system consists of 2 Radio Shack reel antennas that are small enough to fit in my shirt pocket when not in use. There is no feed line or tuner, so losses are small. Modeling indicates the antenna has some gain broadside to the wires. Of course, this is still a compromise antenna, but I have been able to make many contacts from hotel rooms without much problem. The design now fulfills my requirements, but I reserve the right to modify it later if I see a better way to do things.

Case Study 2
Halfway Up a Highrise Condominium

In this case study, I'll explain how I put together a working antenna system inside a condominium in Maracaibo, Venezuela. I had no choice on the location, since my employer paid for lodging. I lived there several years, so the antennas were always an evolving system. During the first 2 years I worked All 50 US States, as well as 155 countries and got enough cards for DXCC. My contacts were on all bands 40m and above and on all modes, including SSB, CW, PSK31, RTTY, MFSK and Hell. In addition, I worked over 125 grid squares on 6m, including several stations in Scandinavia and the former Soviet Union. Most contacts were made with 100 watts, but quite a few were QRP.

Site Survey. Here's a synopsis of the site survey that I made for this antenna installation in cramped quarters. The location is on the 10th floor of a 15 story high rise condominium. There is no balcony and many people told me it looked pretty bleak for putting up any ham antennas. Well, I think they looked at the limitations and forgot that there are some significant advantages, too. As the saying goes, when you get a lemon, make lemonade. But first we need to find out how much of a lemon it is!

Item	Comments
Frequency Range	7 - 50 MHz (Too much QRN on 80 and 160m)
Area Available	About 9 m x 4 m in the living room
Height Available	About 3 m floor to ceiling
Height Above Ground	About 30 m above ground level
Ground Quality	Probably very poor soil
Access to Roof	Unlikely
Access to Outside	Through windows only

Advantages	• Antennas close to station
	  o short feed line (low losses)
	  o convenient to adjust (no trip outside)
	• High above ground
	  o lower ground losses
	  o no tower, masts needed
	  o can lay wires on the floor

Disadvantages	• Can't use "long" elements • Affect of nearby objects (walls, wiring, etc.) • No good RF ground

As can be seen, there are some advantages to this location, even though it may not be readily apparent at first thought. In order to find the advantages, we may need to be sort of "the eternal optimist." This list may expand as we learn more and think more about the situation, but it is a decent starting point. Our problem now is to design an antenna system that takes advantage of the positive points and minimizes the effect of the disadvantages.

Preliminary Design. Once we understand what advantages and disadvantages we are working with, we can now design a preliminary antenna system that takes account of these constraints. In this example, we know we will need to use a counterpoise or radials with any kind of vertical or will need some sort of dipole so that the RF ground is not an issue. We also know that height above ground will not be something to worry too much about and if we need to adjust the antenna for different bands, it will not be a big chore.

Antenna	Comments
Center Fed Dipole/Doublet	• Doesn't need an RF ground • Can use entire horizontal space • Can hang outside the windows
GP Vertical	• Doesn't need an RF ground • Will be very short • Hard to install radials

When we look at the possibilities, it is apparent that the dipole seems to be the better candidate and should be easy to make and install. The first attempt was to string 65 feet of #14 stranded copper wire outside the windows. It was fed with about 5 feet of coax using an MFJ tuner. The wire was supported by 4 plastic cup hooks glued to the brick on the outside wall of the building within an arm's length of the windows. Since there wasn't enough room to run the 65 ft in straight line, the wire drooped as needed between the hooks. I then had a way to get on the air.

On the air tests showed that the antenna performed quite well on 30 meters and higher frequencies, but was not very good on 40m. Modeling showed that the SWR on the short piece of coax was enormous on most bands and that was compounded by not having very high quality coax. In fact, on some bands the SWR would jump erratically, probably due to beakdown of the dielectric and high voltages in the tuner.

After evaluating the antenna, I decided that using a lower loss transmission line should help. I took down the coax and installed a short piece of 300 ohm TV twin lead from the antenna to the balanced line output of the tuner. The improvement was apparent on all bands and some nice DX was worked on 40m. With the low loss twin lead, the signals seemed to improve by about an S-unit. When you're dealing with a compromise antenna, every little bit helps!

Case Study 3
Indoor Multiband Vertical

In this case study, I decided that it would be nice to see how a short vertical antenna worked inside the condominium in the previous example. The site conditions are the same, so will not be repeated here.

Preliminary Design. The preliminary design was driven more by physical constraints than by antenna theory. I bought 3 meters of aluminum curtain rod tubing from a hardware store along with 10 meters of 3 conductor solid copper house wiring. After taking the plastic jacket off of the 3 wire bunde, I ended up with 3 10 meter lengths of wire. Two of these were laid along the baseboards as radials as far as they would go without crossing doors, etc. The 3rd wire was used to wind a loading coil on a 5 inch plastic waste basket. The aluminum was mounted on top of a toilet brush holder that served as a support for the antenna. With the antenna in a corner of the room, it was out of the way. About 25 ft of coax was used to feed the antenna from my MFJ tuner. The center coax conductor was attached to an alligator clip to select a coil tap, while the shield was connected to the radials.

Initial tests showed that the antenna worked quite well on 6, 10, 12, 15 and 17 meters. On those bands it was as least as good as my doublet and on 10, 12 and 15 meters it appeared to be slightly better. I could tune it on 30 and even 40 meters, but the signals were substantially worse that the doublet. I used the antenna like that for about a year and worked lots of DX.

While thinkng about the antenna and how to improve on it, I realized that the 25 ft of poor quality coax wasn't helping anything, especially since the SWR was pretty bad on the lower frequencies. After doing some modeling, it seemed that the perfomance depended more on the transmission line SWR than on the actual antenna radiation characteristics. In addition, the coax was laying very close to one of the radials, so that didn't seem to help the situation either.

In order to try and improve things, I got rid of the loading coil and installed a remote antenna tuner at the base of the vertical. In addition, I added a coil of coax to form a choke balun to try to reduce the feed line current. The improvement was immediately obvious, with signals improving by about 5 - 6 dB on receive. My signal reports also improved correspondingly. The antenna now performs at about as good as the doublet on 20 and 30m and at times gives much lower noise on receive on 40 meters, too.

http://www.comportco.com/~w5alt/antennas/notes/ant-notes.php?pg=1

Above is the Authors Website that contains all information above and much more.