

Introduction

This book is based on a series of articles called “Up the coax” written for the *TARC News* - the official newsletter of The Thibodaux Amateur Radio Club in Thibodaux, LA. The series was originally conceived to fill a learning gap for local hams. A test article was floated and reaction was very positive.

There is no attempt here to educate the reader on basic electronics or the mechanical aspects of antenna building and feedline construction. Learning how to put on a coax connector or to stand-off ladder line, are subjects best left to personal discussions in a one-to-one level meeting with a local Elmer. It is assumed, for this text, that the reader has at least a basic understanding of electronics and electronic theory of AC circuits (requisite for any serious study of antennas) and has viewed with more than passing interest, basic antenna system practice. The reader is provided some basic knowledge of how radio frequencies behave on a radio frequency radiator and feed line, and discussion progresses to the more complex subject of impedance and directional antennas. This is not a reference text. It is a broad sketch of the very detailed and complex subject of antennas and feedlines and the theory that is underlying their design. The reader is allowed to explore at leisure, the details in trusted locally available sources and the reference material listed at the end.

The text is presented in a logically progressive manner. That is to say it is logical to the author, and hopefully to the reader. Knowledge gained in earlier chapters is used to build on more complex theory in successive chapters. Each chapter is a very brief thumbnail treatment of some tediously complex subject matter. Diagrams and graphs are used to visually illustrate the theory discussed in the text. This is not to make light of the complex nature of antennas or feedlines. It is an attempt to provide essential information for the non-technically proficient ham who has a more than passing interest in antenna and feedline theory and operation. Of course there are other text on the subjects covered, too numerous to list in entirety. The sources provided are reliable and credible text that are dedicated and oriented to the serious study of antennas and feedline theory in mind for the radio amateur.

This text should provide the basics for making common choices and decisions in the average (if there is such a thing) ham shack or antenna farm. An effective methodology to study this kind of material would be to use the presented subject as a “springboard” to learning. That is to say, the material presented is designed to stimulate the reader to do the proper research for a full and detailed understanding of the presented subject. There is no attempt to be absolutely and strictly parallel to current and acceptable textbook theory on antennas and feedline. This is not meant to say the information is not accurate. The simplification of any complex subject allows for the elimination of important or meaningful details. It is left to the reader and student to research these details from the material references at the end of the book, from trusted online sources or from reliable and vetted local sources. The references at the end are a very good starting point for in-depth study. The Internet is also a good source of information. However, caution should be exercised when using online information as a reference due to much misinformation and mis-use of fact also being available. Not every Internet source has a thorough understanding of the subjects nor has it necessarily suffered the vetting process of the more reliable texts referenced.

The theory of transmission lines and antennae similar in nature to transmission line is often treated in simple form as a series of spatially diverse lumped constants that are then mathematically treated with Kirchoff's law. However, theoretical assumptions applied to static circuits are not easily transferred to transmission lines or antennas.

Static circuit theory is based on the assumption :

- a. That there are spatially diverse components with electric or magnetic fields. Electric fields are generated generally by capacitance and magnetic fields are generated by inductance.
- b. That currents are equal in magnitudes and phase within each respective component.

These assumptions are not rigid in the respect that one must assume that the time needed to process the currents is shorter than the time of one period (cycle). These assumptions do not directly translate to a dynamic application of a complex structure such as an antenna over real ground. Every element in an antenna or feedline is a carrier of electrical and magnetic properties and thus an influential part of the antenna or feedline in its overall characteristics. In order to simplify and illustrate the complex and highly interactive nature of antennae and feedline components, discussion is reduced to equivalence in the form of common lumped values and static circuits (as can be evidenced by the illustrations in chapter one) where the limitations above are acknowledged. But if we cannot apply such rules to the line as a whole, we can apply these rules to small elements within the whole that can be considered a sum of these processes (an antenna trap for instance). One such application is the method of moments calculations used by popular antenna modeling software programs (EZNEC, NEC4Win, MMANA and MMANA-GAL, etc.). In this method an element of an antenna is treated as a wire that has been arbitrarily segmented. Each segment is used to calculate important features such as current, impedances, phase, and phase angle of current in the middle of each segment. The overall characteristics of the model are an amalgam of each segment calculated individually (the moment) accounting for transitions of diameter of elements (e.g. tapering of tubing), lump constants and proximity to ground. Such programs do a very good job of approximating antenna characteristics without relying on empirical modeling in the real world. They are however not so good at approximating irregular components and matching mechanisms that are not of the straightforward type. The common coaxial linear choke (aka. The bazooka choke), and coaxial stub tuning, are but two examples of simple physical elements that are difficult to model accurately.

SWR And What It Is Not

One of the most often discussed topics in Ham Radio (and the most misunderstood) is SWR. If we were to take what is heard on the air as gospel, we would always be in pursuit of the elusive 1:1.00 SWR. Reasoning behind this pursuit is as diverse as ham radio itself. But one thing is obvious when compared with the appropriate literature available from many sources, including the ARRL. Having a low SWR is no more an indication of antenna system performance than a high SWR is a guarantee of power being wasted. If you have only one source of technical information on antennas, make it the ARRL Antenna Book! We will refer to it quite a few times over the next few discussions and the text on the presented subject is thorough and illuminating.

In this series of discussions we will learn some basics, some theory, and dispel a few myths that are generally perpetuated in the Ham Radio community. We want to take a practical, informed approach to antenna system problem solving, rather than “best guess” a solution or follow some of the myths that are perpetuated by less knowledgeable but more vocal hams. You will become armed with the knowledge needed to solve those previously “difficult” antenna system problems on your own.

The first thing to learn about the RF that flows in our coax is that it has unique characteristics. Yes, it is an alternating current much like the 120 VAC coming from the outlet you plug your power supply into. However, the primary difference in RF presenting characteristics that are quite unlike 60 Hz AC, is frequency. These characteristics are present regardless of the type of cable used as transmission line. You may use open wire twin lead as transmission line rather than coaxial cable.

We can describe, in general terms, RF characteristics by behavior:

Skin Effect

This is a term that describes the theory that RF does not travel inside of a conductor as does DC from a battery or 60 cycle AC from the wall outlet. The Radio frequency current is much higher – generally in the range of 100 kilocycles to several hundred gigacycles. Unlike AC current, RF tends to follow the outside of a conductor (hence the term *skin* effect). This particular phenomenon is more pronounced with each increase in frequency. So much so that at microwave frequencies (RF at or above 1.2GHz) it is the dominant characteristic. As we will see later, this is significant in terms of how fast RF is allowed to flow down the transmission line.

Traveling Incident Wave

This term is used to describe RF waves traveling up the transmission line to the antenna. Notice the term describes only the initial power traveling in the direction *toward* the antenna. This will be significant as we define other terms. Traveling wave simply indicates that an alternating cycle of power or voltage is moving with time along the transmission line. For mathematical simplicity, traveling waves are usually discussed for a specific, selected frequency only, as is SWR.

Traveling Reflected (Return) Wave

This term is used to describe the unabsorbed or un-radiated RF waves that flow on the coax from the antenna (or load) to the source.

Velocity Factor

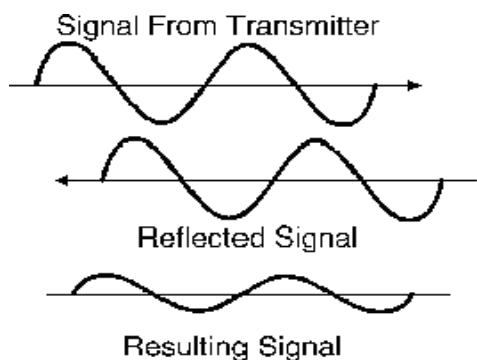
This term describes the delay RF encounters as a traveling wave, caused by the material used as

dielectric in the transmission line. Some materials slow the traveling wave significantly, while other dielectric materials do not. All dielectrics are measured against the standard of air (sea level and 50% humidity) as 1.00 or 100%. Generally speaking, the larger the velocity factor (the ratio of actual propagation time compared to propagation with air dielectric) the closer the resemblance to open wire feedline - which has a velocity factor range of .96 to .99 (virtually no delay of propagation). Do not confuse open wire twin lead transmission line with the close cousin, twin lead, "window" or "ladder" line. Window ladder line has a much higher velocity factor (i.e. lower velocity factor numbers) than open wire line typically ranging in the .85 to .90 values.

When RF must flow on a coaxial cable center conductor and encounters a dielectric material such as polyethylene (PE) the rate of travel along the conductor is slower. How much slower is indicated by the velocity factor expressed in comparison with the velocity of an air dielectric (e.g. .66 or .87 - air dielectric being at or near 1.00). More on this subject later.

Standing Waves and Standing Wave Ratios (SWR, VSWR, etc)

Standing waves are the result of the encounter between *forward traveling waves* and *return traveling waves*. This being said, it is also true that there is no standing wave if there is no forward power (traveling incident wave). The assumption is always made that the frequency of the incident and return waves (traveling return wave) remain the same as does the length of the antenna and transmission line. This encounter is best illustrated by the figure below.



Notice that where the traveling wave peaks approach the same polarity and phase, so does the magnitude of the standing wave (even though the waves are traveling in opposite directions). The polarity of the standing wave magnitude is determined by the magnitude of the additive waves (i.e. two positive magnitudes produce a positive standing wave magnitude and two negative magnitudes produce negative standing wave magnitudes where their amplitude and phase occur simultaneously of the same magnitude direction and phase).

When the comparisons are of the voltage magnitudes, we speak of VSWR or *voltage standing wave ratio*. There are other comparisons that are similar, but are rarely used in ham radio. These will not be discussed here. The term SWR in this text is used interchangeably with VSWR.

Causes of SWR

So now that we have defined some of the more common terms we use when talking about transmission line and antennas, let's look at some of the causes of SWR.

The most common cause of VSWR on the feedline is a mismatch of characteristic impedances. This choice of words is important in understanding SWR. A transmission line is not a simple resistive value as we would think of it in passive components in the rig we use. Nor is it a simple inductive or capacitive reactance. In fact the coax or twin lead transmission line you use has a dynamically complex characteristic. The two conductors that make up a transmission line (the two parallel wires of open feed line, or the shield and center conductor of a coaxial line) are arranged in such a way that the electrical

field of one conductor is offset exactly, or nullified by the opposite electric field of the other conductor. The two conductors in such close proximity exhibit a complex set of characteristics that we call impedance. The illustration below is from the ARRL Antenna Book chapter on transmission lines.

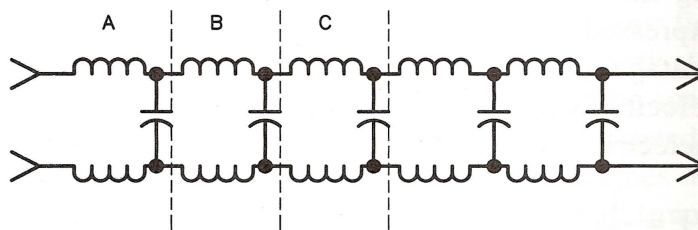


Fig 5—Equivalent of an ideal (lossless) transmission line in terms of ordinary circuit elements (lumped constants). The values of inductance and capacitance depend on the line construction.

Courtesy ARRL Antenna Book© 20th Edition

Characteristic Impedance

The complex characteristic impedance of transmission lines and antennae is expressed in writing it like this:

$$\mathbf{R +jX}$$

It is expressed this way to show the complex nature of transmission lines (or antennas). The “R” term represents the “resistive” or often called the “real” part of the characteristic value, while the “+ or - jX” indicates the reactive or “imaginary” part of the characteristic value. It is possible to have a zero value for the reactive term, in which case the only important value is “R”. Both antennas and transmission lines exhibit this complex character. The theory underlying antenna and transmission line characteristics is explained very well in the ARRL Handbook and in the ARRL Antenna Book. It is well worth the reading to fully understand this subject. The discussion presented here is merely food for thought as a lead-in to the broader subject.

A mismatch may occur in either part of the characteristic impedances of the source or load (i.e. coax or antenna). This mismatch gives rise to inefficiencies in the transfer of power from the delivery vehicle (your coax) to the destination (your antenna). When the coax is not able to transfer all the delivered power to the load, the undelivered portion is returned to the source. This returned and undelivered power is the reflected traveling wave defined earlier.

Impedance mismatches occur for various reasons. The most common are: transmission line impedance and antenna feedpoint impedance mismatch, open feedline circuit or shorted feedline circuit.

Reasons for impedance mismatch

You may encounter any or all of these conditions as your ham radio experience grows longer.

Should we be concerned when a VSWR can be measured on our coax? That depends. Remember we discovered that your feedline and antenna are complex in character. So too are the conditions under which we may become concerned about SWR. To simplify the answer somewhat, let's look at a common situation.

You are installing a 2 meter mobile rig in your car. The antenna is installed and you ran RG58/U cable to the rig and you follow the manufacturer's instructions to the letter. But when the VSWR is measured you find a VSWR ratio of 2.0:1.

We are assuming the manufacturer's instructions include proper grounding instructions, which you follow. Is this 2.0:1 VSWR a problem?

Myth #1

First let's dispel myth #1 - That you will burn out the final transistors in your rig due to a 1.5:1 or even a 2:1 SWR from RF entering the finals of your radio. Most modern VHF rigs will handle a very wide SWR range without damage. This relatively minor SWR will NOT harm most modern rigs on the market today, notwithstanding some increase in heating due to the SWR. Higher VSWR situations may make RF power transmission very inefficient for the final stages of the transmitter. These inefficiencies cause the final transistors to work harder to produce power – and yes if the SWR is high enough, as in a short circuit condition, and the rig is in transmit mode long enough, there could be thermal break down in the finals. But notice - this is due to the loss of efficiency, NOT reflected RF.

How about performance? Does this 2.0:1 VSWR affect performance?

Good performance is a result of removing as many inefficiencies as possible from the antenna system. Previously, we discussed how impedance mismatches give rise to inefficiencies in the transfer of power to the antenna. That power must go somewhere. The truth is that more power may be lost in loading components (loading and matching coils are usually the culprit in mobile antennas or traps in stationary antennae) than your coax.

It does not get transferred to the rig finals: goodbye Myth #1.

I²R Losses

Power that is unused by the antenna will continue to travel on the transmission line back and forth from source to antenna until it is absorbed or dissipated by the actual (read it "real") resistance of the transmission line wire in what is known as I²R losses, the load (your antenna elements and loading components), or power dissipating system components (including the ground system). This loss of efficiency amounts to an attenuation that can dissipate as much as 2-3% or more out of 50 watts leaving your transmitter (given the RG58 coax in our scenario) over a long length of coax.

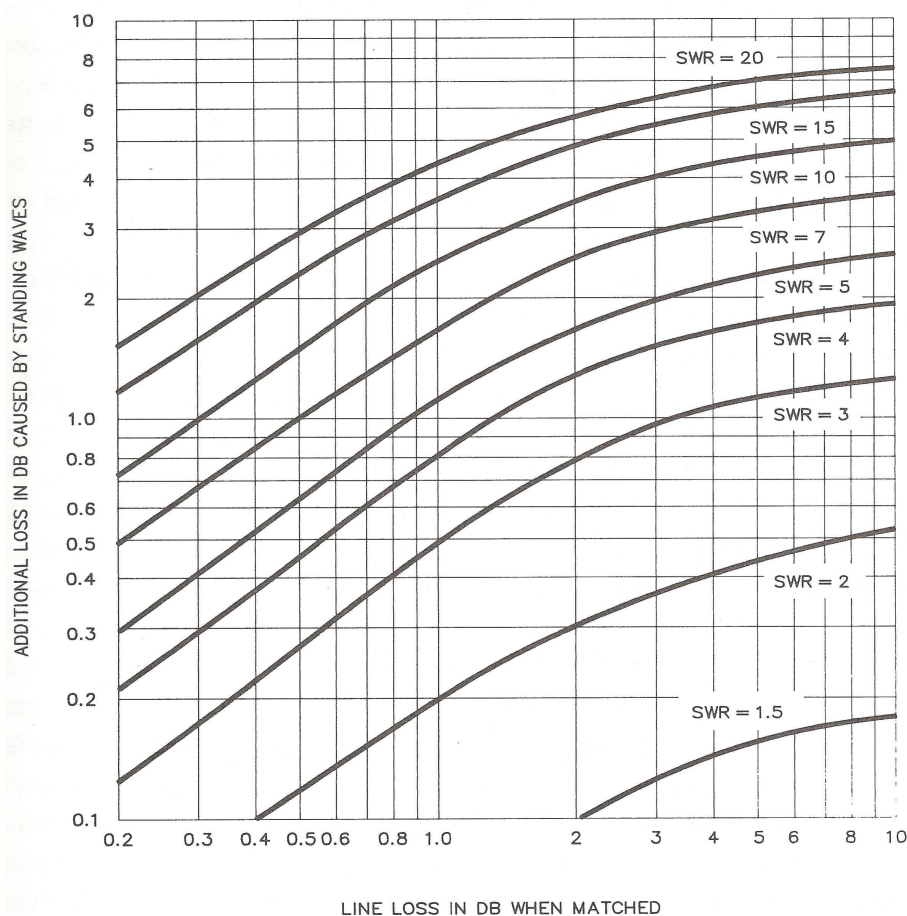
More importantly, the losses will attenuate incoming signals as well, due to the aforementioned inefficiencies. This phenomenon is known as reciprocity. In other words: to receive well you must transmit efficiently. The graph below illustrates the amount of loss due to attenuation by the coaxial feedline. It also makes clear that investment in high quality feed line could pay you back with very good weak signal performance.

More to the point of our discussion, the graph illustrates plainly that high SWR readings (i.e. above 7.0:1) are not as detrimental due to transmission line loss as some would have us to believe.

Feedline Losses

Since we are considering only the antenna system (leaving the rig or tuner out of it for now) we must consider the loss of efficiency to be due to the difference in characteristic impedance of the transmission line and the impedance of the antenna at the feed point and our ability to compensate for it or I²R losses in the grounding system and loading or matching components. This difference could be due to an improper selection of coax type (RG59 instead of RG58 or vice versa, or RG-58 instead of RG8X as in our 2 meter scenario). Inefficiencies could also be due to an improperly tuned antenna. Tuning an antenna usually involves changing the characteristic impedance at the feedpoint by changing the length or adjusting a matching network that is part of the antenna. We will look at proper selection of feedline type and antenna feed point matching later.

Now let's change the scenario to 440 MHz instead of 2 meters. The major factor in this scenario, (even if the antenna is perfectly matched) is attenuation by the RG58/U coax. It is a whopping 10 db per 100 feet for 400 MHz! That is an increase of more than 20 over the 2 meter scenario. Compare that to only 1.5 db/100 ft. at 3.5 mHz.



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This is a scenario where a SWR of 2.0:1 is significantly high due to the amount of power that would be dissipated in the coax due to SWR induced I²R losses. Accordingly, weak signals being received could be attenuated to the point of unreadable, simply being lost in the coax.

So is it worth hours of cutting and measuring for that .5 SWR decrease in terms of signal received? Only you can make that decision. But given the information learned so far, you should think long and hard before spending tons of time and possible money for nominal improvements in lower SWR

readings below 220 MHz. At amateur frequencies, the losses in wire or aluminum components of the radiating elements and coax are a very small percentage of overall system losses.

More significant than feedline losses, can be the losses in the grounding system of the antenna. These losses dissipate power without the benefit of radiation of a usable signal (hence the term loss). These losses are generally classed as I^2R losses. This type of power loss can be viewed as resistance because it is a loss of power to dissipation in heat much as a resistor would provide to DC circuits. Among the many factors that cause ground losses in stationary vertical antennas, is soil composition and content. Not all soil is the same from place to place. The composition and content affects the conductivity of RF in the ground in the presence of a radiation field from the antenna. For mobile verticals, the poor ground has even more significance. We will see the significance of this in a later chapter.

The sum total of all losses in the system is known as *radiation resistance*. The antenna will dissipate some (hopefully most) of the signal as radiation. Some will be dissipated as heat loss in the antenna elements and coax. The rest will be lost to ground loss resistance. It should be noted for later reference that the proximity to ground greatly affects radiation resistance without increasing signal radiation strength. We can conclude that radiating close to ground is not as efficient as far away from ground. A low radiation resistance means much power is wasted sending RF current to dissipating components rather than radiating components. Conversely, a higher radiation resistance generally indicates more RF is reaching radiating components than dissipated.

The goal is to supply the radiating elements as much power as possible at the best match possible to avoid significant VSWR. As a general rule – close to ground antennas are not as efficient (i.e. Low radiation resistance values) as antennas mounted very high (more than $\frac{1}{4}$ wavelength with much higher radiation resistance values). The so-called NVIS and vertical antenna fit the former type while a horizontal dipole mounted more than $\frac{1}{4}$ wavelength above ground is of the latter type. More on the effects of ground later.

To summarize, SWR does not present nearly as much loss as the improperly chosen coax type for our operating frequencies. And SWR losses may be partially overcome by wise antenna selection for gain and directivity plus signal to noise characteristics rather than the whimsy of the latest or most popular of antennas. More significant losses than SWR may occur where improper grounding or poor ground systems exist that would absorb and dissipate power wastefully. The key to any antenna system performing well is to eliminate as many inefficiencies as possible.