TRANSMITTING ANTENNAS
and
GROUND SYSTEMS
for
1750 METERS

Edited by Michael Mideke

1987

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INTRODUCTION

This collection of articles on 1750 meter transmitting antennas, grounds and related topics includes most of what has appeared on the subject in THE LOWDOWN since 1980. Other material has been drawn from the 1750 METER WESTERN UPDATE. I have added a section on ground systems to fill some minor gaps in the existing material. Additional notes and illustrations are being added on a space-available basis as the cutting and pasting proceeds.

In assembling this collection I've indulged my own inclination to browse and compare, and the result is somewhat redundant. Anyone wishing to put up an effective antenna can refer to any of the three basic articles (Phillips, Pinto or Lee) and learn what he needs to know. Although emphasis varies, the authors all start from the same general premises and arrive at the same general conclusions.

But if you are looking for ideas or seeking the most practical solution to some particular problem, it will be well worthwhile to study all of the authors. Even if none of them address your immediate concern, it may be that their combined ideas will suggest an answer.

For the most part these articles deal with one basic antenna type: the vertical radiator with inductive base loading and capacitive top loading. While there are those who grumble about inefficiency and maintain that this is not much of an answer to the problems of radiating a signal at LF, these antennas have at least two important things going for them - they work and, if constructed to the appropriate dimensions, they are acceptable to the FCC.

It may well be that there are more efficient transmitting antennas for the purpose and it may be that such antennas can be constructed within the dimensional constraints of Part 15. Thus far I've not seen what I consider to be a proven design. Keith Olson (7FS) has been doing interesting work with 1/10 scale helical antennas on 160 meters.

The scaled down approach has a lot of merit. One can find out whether the design works before confronting the difficulties of actually implementing it on longwave. These difficulties are far from insignificant; 15 meters is very small in terms of our wavelengths but it is a big hunk of space in the backyard. Mechanical, electrical and adjustment difficulties abound! I hope the following pages will help to smooth the way.

Michael Mideke- November 1987

TRANSMITTING ANTENNAS FOR 1750 METERS

BY ED PHILLIPS W6IZJ

As mentioned in the introduction (Vol. 7 #1 p 8), successful transmission requires that the transmitting antenna be of maximum possible height, and losses in the antenna and ground system be as low as possible. I shall now describe some general properties of small VLF antennas and their ground systems, and give examples of what you may want to build. The antenna system will first be considered from a constructional point of view, and the electrical properties will be discussed in their relation to the coupling system design and construction. The parameters of the antenna as a circuit element will be given next, followed by the design and construction of the circuits for coupling the antenna to the transmitter, together with methods for their adjustment.

In practice the design of your antenna system may be dictated by the space you have available, as is true in my own case. If your space is limited don't give up, but put up the tallest thing you can, as far away from trees and buildings as you can, and then give it a try. You may be pleasantly surprised!

There are no mysteries to working at 175 KHz, since use of this frequency goes back to the very earliest days of "wireless". In fact, any good old wireless book has a wealth of useful information on antennas and grounds. The advice is excellent but hard to follow. A. P. Morgan's "Wireless Telegraph Construction For Amateurs" (1911) devotes chapter 3 to "aerials and earth connections". A few quotes are of interest:

"In fitting up a wireless station the location and erection of an aerial are of prime importance, and the successful reception and transmission of wireless messages will depend largely upon its condition."

"The higher an aerial is placed above the surface of the earth, the wider will be its electrostatic field, and consequently more powerful electric waves will be developed. But after a height of 180-200 feet is attained, the engineering difficulties and the expenses increase so rapidly that few stations exceed it. Other things being equal, the increased range in transmitting varies as the square of the height of the radiating wires. For example, a 25-foot aerial capable of transmitting one mile theoretically will send waves 16 miles if made 100 feet high.".

"After the limit in a vertical direction has been reached, the only remaining possibilities are to increase the surface and spread out horizontally."

"Ground connections--the importance of a good earth or ground connection can hardly be overestimated. Whenever possible commercial stations are located on moist ground or near a body of water so that a good ground may be secured by imbedding zinc or copper plates in the earth or water."

These quotations are still pertinent today, although note that the quantity which varies as the square of the antenna height is the radiation resistance, not the electric field produced by the antenna, as Morgan implies when he says that increasing the height by four times increases the range by 16 times. However, because of the increase in antenna system efficiency which goes with the increase in height, his remarks about increasing the range of the station are almost correct. A few things I did not quote are also pertinent, especially his remarks on making the antenna installation strong enough to withstand any possible weather, and providing the antenna with a grounding switch for use when lightning is possible. He also emphasizes arranging the antenna so it cannot fall down across power lines, thereby leading to all sorts of unhappy events.

The antennas which Morgan describes are all tall structures with some form of "flat top" or capacitive top loading. Figures 1 and 2 are copied from E. E. Bucher's "The Wireless Experimenters Manual" (1920), and illustrate two methods of constructing an antenna with top loading. In each case the loading consists of a group of horizontal wires spread out as much as possible to increase the capacitance to ground. The purpose of this top loading is to increase the current at the top of the antenna, thereby increasing its radiation resistance. The radiation resistance of an antenna is a fictitious resistance which, when multiplied by the square of the current flowing in the base of the antenna, gives the radiated power; increasing the radiation resistance increases the power radiated for a given antenna current. For a very short antenna the radiation resistance is proportional to the squares of the effective height and of the frequency. For an unloaded antenna 50 feet high the theoretical radiation resistance at 175 KHz is only 0.0312 ohms! This is only a very tiny fraction of the minimum total resistance with which the antenna system can be built, and shows the importance of keeping the losses as low as possible. As an example of what this means, if the antenna current is 0.2 amperes, a typical value for a one watt transmitter and fairly low loss antenna system (sum of ground and loading coil resistance equal to 25 ohms), the radiated power will be only about 1/800 watt, and the efficiency will be only 1/8 percent!

For a straight vertical radiator whose length is a small fraction of a wavelength (the wavelength of a 175 KHz signal is 5620.4 feet) the antenna current decreases linearly to zero at the top. If capacitance is added at the top, the current there is increased. If the current at the top is equal to the current at the base the radiation resistance will be four times that of an unloaded antenna. For the example given above this would mean an increase in radiation resistance to 1/8 ohm, of radiated power to 1/200 watt (5 whole milliwatts!), and the efficiency would be 1/2 percent. The effective range of the station would be doubled. Now that I have discussed the merits of top loading I must point out that in all probability you will not be able to use very much of it. I have no idea how the FCC would feel about antenna installations like those in the examples above, particularly if the height of the vertical section is the magic 15 meters, but it is doubtful that they would be very happy. If we fudge the 15 meters to 50 feet, which was in the old regulations before the FCC "went metric", a literal interpretation would say that a single vertical conductor 50 feet long is all that is legal, and if the matter ever came to an argument I am sure that is what the ruling would be. (The best way to win such an argument is to avoid it: keep your signals clean and your out of band radiation to a minimum and you will not bring attention to yourself.)

Two points regarding top loading may be in order. First, if we accept the total length of the antenna to be 50 feet, then there is no advantage to reducing the height of the antenna and running part of it horizontally to produce top loading. If you can get 50 feet use it. If not, then make the vertical section as tall as you can and add top loading to bring the total length to 50 feet. An "L" shaped antenna will be slightly better than a "T" shaped one in this case. Second, in principle the top loading can be made more effective if the antenna loading coil (or part of it) is placed at the top of the antenna. Examples of such tuned top loading circuits for use on 160 meters are given in "The ARRL Antenna Book", which is recommended reading, particularly in the older editions which may be available in libraries or from long time hams. I believe that the problems in adjusting such loading coils, together with the fact that their losses will probably be excessive, makes such techniques of little or no value for 1750 meters, and I recommend their use only to the advanced experimenter. In the discussion to follow only base tuning will be considered.

Let us now consider some specific antennas. Figure 3 shows an antenna similar to the previous examples; it is "best but clearly illegal". A 50 foot vertical wire is top loaded by a flat top of horizontal wires, supported by wooden poles. The whole setup is placed over a salt water ground plane, which serves two important purposes. First, a connection to the salt water provides an effective, low resistance ground system. Second, the effect of the salt water is to make the resistance of the ground plane under the antenna very low. This minimizes the losses due to the currents which flow in the ground under the antenna due to capacitive coupling; they are a very important component of the total antenna (as contrasted to the loading coil) loss. More of this later. The only purpose of this example is to show what could be done if the FCC restrictions are ever lifted.

Before discussing "how to build an antenna" let's consider "where to build it?" The environment in which the antenna system is installed is the hardest part of the system to control, but it is of great importance in determining the antenna's overall performance. Because of capacitive coupling from the radiator, RF currents will flow in every object near the antenna, and the presence of electrically lossy material will increase the losses in the antenna circuit. (For all practical purposes only things within a radius equal to the height of the antenna are important loss contributors.) Any buildings or vegetation will have significant electrical loss, and detract from the antenna performance, so the first rule to try to follow is to keep the antenna at least 50 feet from any trees or buildings. This means, of course, that you have to run power and control leads out to the base of the antenna, and they may be inconveniently long.

Even if there are no objects above ground in the vicinity of the antenna, the ground itself can and will provide very significant losses. All of the current which flows in the antenna must return in (or on the surface of) the ground, and most soil is very lossy. For this reason it was common practice in the early days of wireless to locate transmitting stations at salt marshes, and build the antennas over them. In addition, hundreds of conducting cables were laid in or on the ground under the antenna to further reduce the loss, with some installations having literally hundreds of miles of them. These practices are still necessary and are still followed, in spite of the immense cost associated with them. In the case of simple vertical towers the ground system usually consists of "radials", or wires radiating from the base of the antenna in all directions to a distance at least equal to the height of the tower. The radials are usually buried beneath the earth with a special plow, in order to get them out of the way.

In principle there is a clear distinction between radial systems and ground systems. The primary purpose of the radials is to eliminate losses due to currents which are induced in the ground by the electric field of the antenna, and even fairly short radials accomplish this. However, there are still currents flowing in the ground beyond the radials, and a conventional ground is often needed in addition to the radials. If the soil conductivity is poor the radials, together with a few ground rods and a connection to the water pipes, will probably be about the best ground that can be hoped for.

E. A. Laport gives an excellent description of ground systems in his "Radio Antenna Engineering", McGraw Hill, 1952. Section 1.12 discusses VLF ground systems, while section 2.5 describes broadcast antenna ground system design. The latter section is of most interest, since in it he gives data on the performance of a simple vertical radiator with various lengths and numbers of radials. The results may be very crudely summarized by saying that radials of length equal to the antenna height are almost as good as those of infinite length, and that a length of half the antenna height (outside diameter of radial system equal to antenna height) is about 2/3 as effective as very great length. Furthermore, 2 radials are about half as good as a very large number, and 16 radials are within a few percent of being as good as 112. Applying this information to our hypothetical tower installation, we can say that it will be near to ideal in performance if the tower is at least 50 feet away from trees and buildings, and if the ground under it is provided with 4 or more radials whose length is at least 25 feet and preferably 50 feet. Improvements will result from more and longer radials but the increase in performance is probably not worth the extra trouble. The size of the wire used for the radials is not particularly important, so long as it is strong enough to withstand whatever mistreatment it may experience in installation, and even galvanized iron clothesline wire will do in a pinch.

Unfortunately, it will be very hard to find room for this "ideal" antenna installation, and you will probably have to fall back on the advice I gave above. Make the antenna as high as you can, as far away from trees and buildings as you can, put down as many radials as you can find room for, and feel that you have done your best. Your antenna system will certainly work, and the results will probably satisfy you. In this discussion I have omitted one thing which may be of interest to those who really have a lot of space and ambition. The laying of the radials in or under the ground is done mainly to keep them out of the way, and results in an increase in loss because the current must "flow" through the ground to reach them. A better practice, but one which is much more awkward, would be to place the radials above the ground by several feet. I doubt if the difference in performance would be noticeable, but it would be a noble experiment. Such installations are called "counterpoises", and were fairly common in the early days of wireless. They might still be of considerable interest to someone who wished to install his antenna on top of a house, where the length of the ground lead would be considerable. The counterpoise would be installed on top of the roof, with as many radiating wires as possible, run out as far as possible. It would probably be OK to run them over the edge of the roof and down to ground level. I have an idea that such an installation might work very well, since it would place the antenna well out of the way of most trees, and would also be convenient for the use of guy wires.

As an example of an installation which violates most of the rules given above, I will use my own antenna system to show "what not to do". The tower is installed in the only spot my wife would permit, between the "radio room" and the driveway. One wall of our house is only two feet away, and extends up to the 30 foot mark. Two large oak trees grow within less than ten feet of the tower, and numerous camellia bushes are planted near the base. The soil in our neighborhood is shallow, with loose gravel and boulders underneath, and the water table is at least 100 feet down. I have a fairly good ground connection in the form of a number 4 wire running to a recently installed copper water connection to the street. The pipe has a total length of about 200 feet, but there are no radials and I have no space to put them. The total resistance of my antenna system at present is about 65 ohms, although when I first installed the VLF gear and had the oak trees pruned way back I measured something like 25 ohms, and could get about 0.22 amperes antenna current with one watt input to the final. I believe that in this installation the loss due to the trees is dominant, although as a second factor all of the surrounding ground is very dry due to being under houses and driveways. Cliff Walker has a much simpler antenna in the middle of his back yard, with a water pipe ground, and puts out about twice as strong a signal as I do. I think the absence of the big trees is one major difference, and the presence of a watered lawn beneath the radiator may be another.

Now for some specific examples of possible antenna construction. In general, the construction of the radiating section is independent of whether top loading is used, so most of the examples apply with or without it. The simplest and easiest antenna to install is a free standing tower of the type used to support TV antenna arrays or VHF/UHF transmitting and receiving antennas. These towers have the advantage of occupying minimum "floor space" and can be purchased from many manufacturers or distributors. This is a good way to go if you can afford it, but the price is high. As an example picked at random from a recent issue of WORLDRADIO NEWS, Hill Radio, 2503 GE Road, Bloomington, IL 61701, offers a Rohn 48 foot "BX" free standing tower for $213.40. You may be able to do a little better or a little worse by shopping around locally, but this is the general price range. Since the only wind loading on the tower will be that of its own structure, you should be able to get by with the very lightest weight of towers and save some money that way. For this expense you get an antenna which can be installed anywhere you can find a few square feet of ground space, and one that will not involve a tangle of guy wires. If your yard is as crowded as mine this may be the only way you can go.

The tower is a radiator (antenna), not an antenna system. In addition to the surrounding physical environment which was discussed above in "where to install it", the complete antenna system includes the radiator, the base insulator(s), and the base itself. The latter two components are worth discussing. Insulation of the antenna is very important, since losses in the insulator can be a major contributor to overall antenna loss, particularly in wet weather. A shunt loss resistance of a megohm in parallel with your antenna can seriously reduce its efficiency. In the case of a free standing tower the base insulators must carry the full mechanical wind load of the antenna, and their choice must be a compromise between electrical performance and strength. My own antenna is a Hygain HT-18 "High Tower" which originally came with some kind of black "mud" base insulators. When I first got on VLF I discovered that I could not load my antenna at all when the base was wet, or even when the weather was moist. I couldn't measure the shunt loss because it was so high, but I would guess it as less than 100K ohms. I was lucky enough to find some Mycalex insulators at a local surplus store, and the antenna now is supported by nine of them, each one inch square and two inches high. Since Mycalex is very weak in tension, I added a bolt, which is insulated by an epoxy-glass bushing, to each corner of the base to keep the insulators under compression when the wind blows. Even this insulation degrades in wet weather, and I regularly clean the insulators and spray them with silicone oil lubricant, which helps make the water "bead up" instead of forming a film across the whole insulator.

The choice of base insulators will depend on what you can find, with ceramic and glass being the best choices from the electrical standpoint, but the poorest mechanically. Glass impregnated epoxy is very strong and expensive, while hardwood boiled in paraffin will also serve well, but is subject to deterioration due to moisture, so that it may need replacing from time to time. Regardless of the material from which the insulators are made, you should keep them clean and spray them with silicone lubricant regularly.

Whatever you do remember that insulating materials tend to be brittle and weak in tension, and that the wind loads at the base of your antenna will be hundreds of pounds. If you can arrange to keep the insulators in compression you will be much safer. The choice of materials is best left to your own ingenuity, but remember that you don't want your antenna to tumble down, wrecking itself and everything in the vicinity! While we are on this subject I must emphasize the importance of following the manufacturer's instructions as to the size and depth of the concrete base which is needed to keep the antenna from overturning in the wind. My tower has a base 3 feet square and 3 feet deep, which is supposed to hold it in a 75 mile per hour wind. That's a yard of Ready Mix, but worth it for the peace of mind it brings.

Most of you probably won't want to go to the expense of a free standing tower, and the inconvenience of providing it with adequate base insulators and guys. The best compromise antenna is probably made from a 40 or 50 foot telescoping antenna mast of the type commonly used to support FM and TV antennas. Radio Shack lists a 36 foot mast for $42.95, and the local radio stores seem to have slightly taller ones for about a dollar a foot. This antenna will need plenty of guy wires, but is relatively easy to erect and has the advantage that almost no construction is required other than to provide it with a good base insulator. Since this insulator will be in compression it may be made of glass, ceramic, or any other good insulating material. A large glass beverage bottle will serve quite well, though you have to be careful to mount it so it cannot be broken by the sideways motion of the mast during installation or while being blown by the wind. To be sure of electrical continuity, the sections should be electrically connected by soldering wires between them (may be difficult, most mast material "doesn't like to solder"), or using self tapping screws and washers to secure wire jumpers between sections. The guys may be metallic, and if so should be broken every 10 feet or less with "egg" type strain insulators. Polypropylene and polyethylene rope is quite cheap, and will serve very well when dry. It has the advantage of not requiring insulators.

If you get a mast of less than 50 feet you have many choices of how to use it. First of all, you can use it as is, with some loss in efficiency. If you don't mind taking it down later for improvements this may be your best choice, since you can get on the air sooner. Second, you can extend it to 50 feet with the 5 and 10 foot mast sections which can be had where you get the mast. This should be pretty easy to do. Third, you can top load it, either at its existing height or with a combination of extension mast and top loading. This is where the interpretation of the FCC rules is fuzzy, since they leave no way to figure what the "length" of a top loading device is. For example, suppose you load a 40 foot tower with a solid disk 10 feet in diameter. Is the "total length" 40 feet plus 10 feet? Is it 40 feet plus 5 feet, the maximum distance from the base to the furthermost extremity of the antenna? I have no idea, and don't advise an inquiry. I would feel free with my conscience if I used the last definition, which would allow a total height of 45 feet with a 10 foot top loading disk, and a total height of 40 feet with a 20 foot one. The latter would be a stinker to build, and would flap in the breeze unless it were guyed well. In practice a solid disk, unless it is made of screen or chicken wire supported with some sort of frame, is impractical and the use of a round "hoop" of wire or tubing supported with cross pieces fastened to the top of the mast, is most convenient. The ARRL Antenna Handbook has several illustrations on the construction of top loading sections. In spite of my remarks that the antenna should be 50 feet high if possible, I feel anyone will be satisfied with the performance of a 40 foot mast with an 8 to 12 foot loading hoop at the top of it.

If you are willing to spend more construction time in

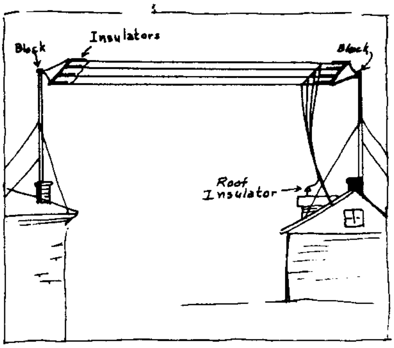

FIGURE 1 AN INVERTED "L" AERIAL

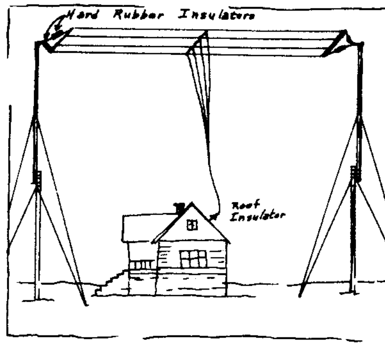

FIGURE 2 A "T" AERIAL

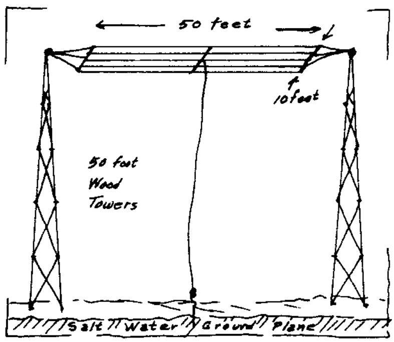

FIGURE 3 BEST BUT ILLEGAL

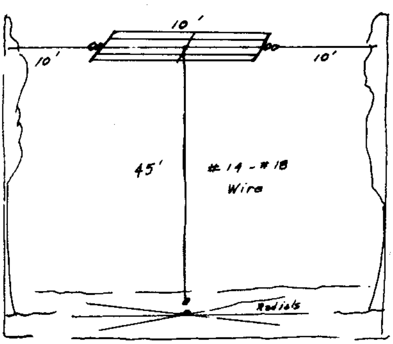

FIGURE 4 FINE IF YOU HAVE THE TREES

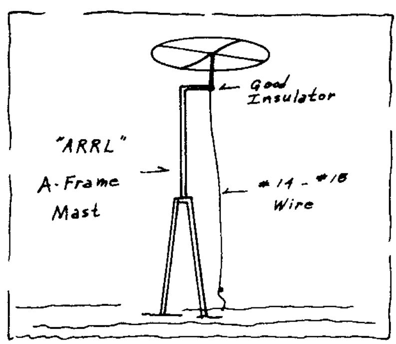

FIGURE 5 "ARRL" A-FRAME MAST AND "HOOP"

order to save some money, you can make your own mast using the 1-1/4" 5 and 10 foot TV mast extensions mentioned above. They cost less than half as much as the telescoping masts, but will require more guys to make them secure, and should be reinforced with a wooden rod at each joint. The suggestions on base insulator, electrical continuity, and guys which were given for the telescoping mast should be followed here too. This mast will be pretty "rickety" so plan out the erection in advance. Make sure you have enough guys, and get enough help so you can handle the emergency situations which are almost certain to develop. Good luck!

If you are fortunate enough to have some big trees in your yard with reasonable spacing between them, you can save even more money by using the construction of Figure 4. Pick two spots about 45 or 50 feet above the ground, and provide them with pulleys and halyards. A top loading structure consisting of several wires held apart with 10 foot spreaders is isolated with insulators, following the same procedure as described above for the guys for the mast. Don't forget that it will be mighty hard to clean the insulators once they are installed, and use good ones to start with. The vertical radiator is a wire descending from the center of the loading section to the ground, where it is anchored with an insulator. This will be a very effective antenna if the trees are at least 50 feet or so apart, and will still work if they are much closer together. A variant of this theme would be to use a single tree with a slanting top loading section, and the halyards brought down to some convenient lower level such as the corner of a house or garage. Remember that trees and antennas like to move around when the wind blows, and leave enough slack to allow for the motion, or else use a spring or pulley and weight to keep the lines reasonably tight.

If all else fails you can always make your own "tree" following the design for an "A-Frame Mast" which was found in all of the ARRL "The Radio Amateur's Handbook" and ARRL Antenna Handbook editions before 1980. (For some mysterious reason the A-frame design is omitted from the new handbooks, even though it has been "the old standby" for generations of hams!) You will need about 60 feet of 2" by 2"s, which even in these days of sky high lumber prices may still be an attractive way to go, and you will need guys and space to install them. If you want a single mast design I suggest that shown in Figure 5. The top of the mast is equipped with a bracket and insulator(s) to hold the top loading hoop, and the radiator is a wire descending to the ground at the base. The same precaution with respect to the top insulator applies as in the previous example, and the guys should be broken with insulators as described for the metallic mast.

With any of these alternate antenna systems the use of a good ground and radials is just as important as it is with the free-standing tower described first, and their design and installation should be considered in planning your antenna.

I have not tried to discuss all possible methods of antenna construction, but just to give some pointers you can use in planning your own version. If you are lucky enough to have space for a 50 foot tower with lots of radials, mounted over good moist ground, you are going to have a really king sized signal. If you can't meet all of these requirements, follow the suggestion in the beginning: put up the tallest structure you can, as far away from trees as you can, with the best ground you can scrape together, and with radials if possible. You can't fail to put out a usable signal!

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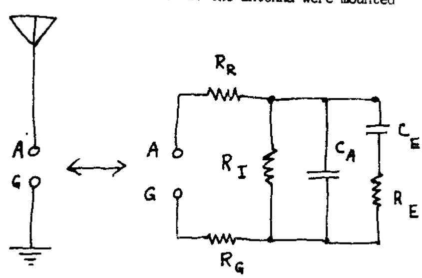
COUPLING THE VLF ANTENNA TO THE TRANSMITTER

By Ed Phillips W6IZJ

The previous section (Vol 7 #7 page 10) discussed transmitting antenna system design, construction and preferred installation sites. Efficient means of tuning the antenna and for coupling it to the VLF transmitter will be considered here, since they have a very strong influence on the success of the transmitting station. The subject will be introduced by examining the electrical parameters of the antenna, to give a feel for the sizing of the tuning components and of the impedance to be coupled.

Figure 1 is a simplified view of the electrical properties of a typical 50 foot antenna at an operating frequency of 175 KHz. If the antenna were mounted



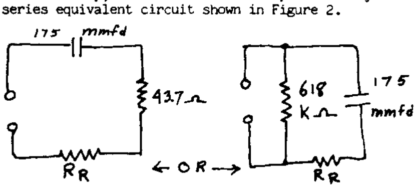
TYPICAL VALUES FOR 50 FOOT ANTENNA

R_G - 10 ohms to 50 ohms
C_A - 150 mmfd
R_I - 1 megohm to 2 megohms
C_E - 25 uufd } Depends on surrounding trees,
R_E - 500 ohms } buildings, etc.
R_R - 0.031 ohms - useful radiation resistance

FIGURE 1 VLF ANTENNA CIRCUIT ELEMENTS

over a perfectly conducting ground plane, and on perfect insulators, its input impedance would consist of the radiation resistance R(R) in series with the capacitance C(A). As discussed before, the radiation resistance is a fictitious resistance which, when multiplied by the square of the RF current flowing into the antenna terminals, gives the value of the radiated power. In this example it is only about 0.031 ohms! The capacitance of the 150 mmfd (pf) would represent a typical telescoping TV mast, mounted well away from any conducting structures. The effect of the non-ideal installation may be seen from the other circuit elements in Figure 1. First, the ground system will have a resistance (R(G)) which appears directly in series with the radiation resistance and the antenna capacitance, with typical values from 10 ohms to 50 ohms, depending on the type and moisture content of the soil, and the size of the ground rods or radial system used. This resistance represents a loss, and a very serious one. Note that even if the resistance can be held to 10 ohms it is still almost 300 times the radiation resistance, and that the maximum efficiency of such an antenna could be only 0.3 percent. In addition to the ground circuit loss, there will be additional losses due to any capacitance between the antenna and surrounding lossy materials such as trees and buildings. These are represented by a capacitance C(E) in series with a loss resistance R(E), and the values shown are only a very rough guess based on my own observations. Their effect is to increase the capacitance of the antenna and to introduce additional loss. A final loss which must be included is the shunt loss resistance of the base insulators, and my experience indicates that a value of one or two megohms is typical for good insulators, while a value of perhaps 100 K ohms is representative of bad ones.

When all of these losses and spurious capacitances are summed up, the antenna can be represented by the series equivalent circuit shown in Figure 2.



Values for R_G = 20 ohms, R_I = 2 megohms, R_E = 500 ohms

FIGURE 2

EQUIVALENT CIRCUIT OF ANTENNA AT 175 KHz

A ground resistance of 20 ohms, an insulator resistance of 2 megohms, and the values of C(E) and R(E) from Figure 1 were used to calculate the values shown; these values represent a pretty good installation. The equivalent capacitance is 175 mmfd, and the total series resistance is 43.7 ohms. Another way of representing the antenna is by the shunt equivalent circuit which is also shown. Examination of these circuits will show that the effects of ground resistance, insulator resistance, and loss due to trees or buildings are roughly equal. In order to increase the station efficiency all must be minimized, and even when everything possible has been done this efficiency won't be very high! For this example it is the ratio of the 0.031 ohm radiation resistance to the 43.7 ohm series loss resistance, or only 0.07 percent. Don't get discouraged at this point; for my own station the total loss resistance is about 65 ohms, and the efficiency is only about 0.05 percent, but I still get out pretty well!

So far we have discussed a hypothetical antenna system. What will the parameters of yours be? Unfortunately there is no practical way of predicting the losses, and you will just have to do your best to minimize them by following the practices outlined in the transmitting antenna section. It is, however, possible to estimate the capacitance of the antenna, and to predict the radiation resistance pretty accurately. The estimation of antenna capacitance is necessary in order to plan the design of the antenna coupling circuit, and the calculation of radiation resistance is an exercise in futility, so formulas for calculating them are given below.

Calculation of the exact capacitance of a short vertical antenna, even for the ideal conditions where it is located over a perfectly conducting ground, and where it is completely isolated from all other conductors which might have mutual capacitance to it, is difficult and no simple formula exists. A rough approximation for this capacitance, and one that is often quoted, is the following (I have changed it to common units):

$$C = 7.359H/(\mathrm{Log}(24H/D) - 0.43)$$

Where:

C is the capacitance in mmfd (pf)
Log is the logarithm to the base 10
H is the height in feet, and
D is the average diameter in inches.

I have calculated the value of capacitance for several possible types of antenna conductors, and for the entire range of heights which might be of interest. The following Table gives these estimated capacitances for the various combinations of antenna height and antenna diameter I considered. Note that these values are very approximate, and strongly dependent on the surroundings, including effects of nearby trees, buildings, power lines, and other conductors. In general, actual values will be slightly larger due to these effects.

ANTENNA DIAMETER (INCHES)	CAPACITANCE IN MMFD FOR ANTENNA HEIGHT IN FEET OF: 10	20	30	40	50
0.064 (#14 wire)	23.4	42.7	61.0	78.6	95.7
0.102 (#10 wire)	25.0	45.4	64.6	83.1	101.0
1.00	37.7	65.4	91.0	115.3	138.9
1.25	39.7	68.3	94.7	119.9	144.2
1.625	42.3	72.1	99.6	125.7	150.9
3.00	50.0	83.0	113.2	141.8	169.4
5.00	58.8	94.8	127.7	158.8	188.7

The diameter of 1.25 inches is typical of common 10 foot TV mast extensions, while the diameter of 1.625 inches is typical of the average diameter of a telescoping type TV antenna mast of 40 or 50 foot height. The diameter of 5 inches is typical of the smaller self-supporting towers.

The capacitance of a top loading device is even harder to estimate. Figures in the ARRL Antenna Handbook show that for a solid disk, the capacitance is given by the following approximation:

$$C(TOP) = 10\ D \ \text{mmfd}$$

Where D is the diameter of the disk, measured in feet.

A more convenient way to make the top loading device is as a hoop with crossbars to support it, and the capacitance will probably be pretty close to that for the solid disk, particularly if several additional "spokes", even of pretty small wire, are added.

The radiation resistance may be calculated by this formula:

$$R(E) = 0.03124\ (F/175)^2\ (H/50)^2 \text{ ohms}$$

Where F is the operating frequency in KHz and H is the height in feet. This value is correct for an antenna without capacitive loading at the top. For an antenna with top loading the radiation resistance is increased by the factor

$$(1 + I(TOP)/I(BASE))$$

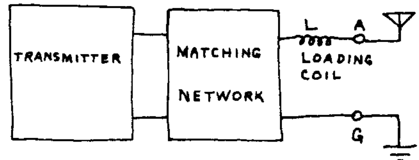
Where I(TOP) is the current flowing at the top of the antenna and I(BASE) is the current flowing in the base. A very crude estimate of this current ratio may be calculated from

$$I(TOP)/I(BASE) = C(TOP)/C(BASE)$$

Where C(TOP) is the top loading capacitance, and C(BASE) is the sum of the antenna capacitance and the top loading capacitance. This last formula will give optimistic results, since the formula for C(TOP) includes the effect of capacitance to the antenna beneath it, but it does show that even modest amounts of top loading will do some good. For example, if an 8 foot diameter top loading hoop predicted capacitance of 80 mmfd is used, the radiation resistance of the example antenna will be increased from 0.03 ohms to about 0.056 ohms, and the radiated power will go up by 80 percent. This is not an enormous change, but it will increase the station range by 40 percent and is certainly worth the effort involved.

To summarize all of this, a typical antenna will look like a capacitance of about 150 mmfd to 200 mmfd in series with a resistance of perhaps 10 ohms minimum to over a hundred ohms maximum. Almost all of this resistance is due to losses; the useful (radiation) resistance is only about 30 milliohms, or an insignificant fraction of the total. The job of the tuning and coupling circuits is to transfer as much as possible of the transmitter output power to the antenna, in order to maximize the current which will actually flow in the radiation resistance and thereby end up being transmitted to the world. If the transmitter is assumed to be 100 percent efficient, which isn't too optimistic, and if the output power is assumed to be coupled to the antenna with 100 percent efficiency, which unfortunately is pretty optimistic, then all of the power will be dissipated in the antenna losses. For the sample antenna with series loss of 43.7 ohms, one watt of transmitter power would result in an antenna current of 0.151 amperes, and the radiated power would be about 0.71 milliwatts, for an overall efficiency of only 0.071 percent! The reactance of the 175 mmfd is about 5200 ohms, so that for this current the voltage drop across it will be about 787 volts. If the antenna were to be connected directly to the transmitter output, this would need to be the rms voltage across its tank circuit, and the DC supply voltage to the final power amplifier would have to be over 1100 volts. Such a transmitter can actually be built with TV sweep tubes, but most experimenters would prefer to go all solid-state, so some form of matching circuit is needed between the antenna and the transmitter.

Figure 3 shows one way of coupling a short antenna to the transmitter. It is typical of the circuits used with a 160 meter vertical antenna, or with a mobile antenna for any of the HF Ham bands. The capacitance of the antenna is resonated with a series loading inductor, and a matching network is used to couple the resulting impedance (of the loading coil and antenna in series) to the transmitter. For our sample antenna parameters if the loading coil were lossless the net impedance would be the series resistance of 43.7 ohms.



Example: For 175 mmfd antenna capacitance
L = 4726 mh at 175 KHz operating frequency.

FIGURE 3

ONE WAY TO COUPLE ANTENNA AND TRANSMITTER

If the transmitter operated from a 15 volt DC supply voltage the rms voltage across its tank circuit would be about 10 volts, and the required load resistance would be 100 ohms for an output power of 1 watt. The matching network would thus need to have an impedance ratio of about 2.3 to 1. While this is a perfectly practical coupling technique, it has two undesirable properties. First, the components in the matching network may be quite lossy, though for cases where the required transmitter load resistance is greater than the antenna circuit resistance the antenna could simply be tapped down on the tank coil, eliminating the matching network. Second, the selectivity, or ability to reject harmonic radiation, is quite poor. This will increase the possibility of harmonic interference with broadcast band receivers, and undesired attention from the FCC.

One thing which is a function of the antenna parameters alone is worth mentioning at this point. The antenna loading coil will not be lossless. If it has the rather good "Q" (ratio of reactance to series loss resistance) of 250 the effect of its loss will be to add an additional series loss resistance of about 20.8 ohms to the 43.7 ohms of the basic antenna for a total of 64.5 ohms. This means that the maximum antenna current for 1 watt transmitter power input can be only 0.125 amperes, the radiated power will be 0.48 milliwatts, and the efficiency will be only 0.048 percent! This is about the case with my own antenna, which has a measured loss resistance of about 65 ohms. The design and construction of loading coils will be described later. The only way to reduce the loading coil loss is to make its "Q" as high as possible through using a large diameter and winding it with the largest wire you can afford. By increasing the antenna capacitance through use of top loading its reactance, and hence the reactance of the loading coil, will be reduced so that for a given Q the actual series loss resistance will be reduced. This is a substantial added benefit of top loading.

Figure 4 shows an easier way to couple the antenna to the transmitter, and one I strongly recommend. You will find numerous examples of it in Ken Cornell's VLF Scrapbook. The loading coil is connected between the antenna and ground, and is inductively coupled to the transmitter by mutual inductance between it and the tank circuit, as shown pictorially. The advantage of this coupling technique, compared to the previous one is that transmitter loading (the load resistance coupled into the transmitter tank circuit) may be varied by changing the distance between the tank circuit and the loading coil, which should now be called the coupling coil. Large spacing results in "loose" coupling

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or light transmitter loading, while closer spacing increases the coupling and the transmitter power input. The transmitter may be run at any supply voltage where it is efficient and the power output (and hence the input) may be set to the desired value by simply adjusting the coupling. This transmitter may be a

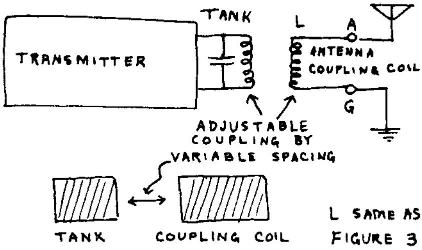
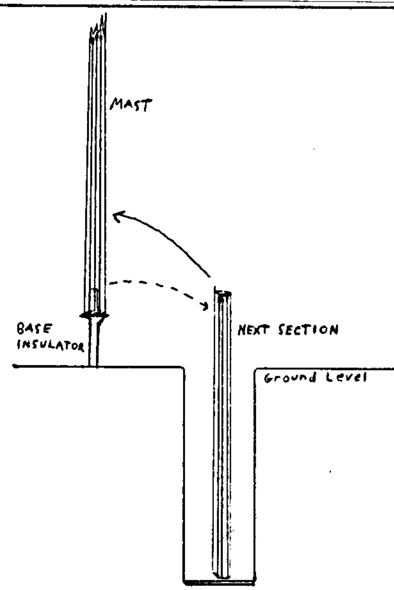


FIGURE 4 AN EASIER WAY TO COUPLE ANTENNA

transistorized one working with six volts collector supply or it may use tubes and run at 300 volts plate supply, and the loading coil will be the same. "Only the coupling need be changed." While the major attraction for this coupling method is its simplicity, it also provides better harmonic signal reduction than the first one, and at no added cost.

This discussion is directed toward the design and construction of coupling circuits, and their adjustment will be described later. However, a few additional comments on coupling circuits are in order here. Most solid state transmitters will have a rather low loaded tank circuit "Q" (the load resistance for proper power output will not be very much greater than the reactance of the tank circuit tuning capacitor) and some readjustment of antenna tuning will be required as the coupling is varied. To be specific, if the antenna is tuned to resonance with very light coupling, as the coupling is increased it will be necessary to increase the loading coil inductance in order to keep the tuning at the point of maximum power output. Consequently, the complete antenna coupling circuit must include some provision for adjusting this tuning, and will not be quite as simple as I have shown. As an alternative to varying the inductance of the coupling coil I have found it convenient to adjust the antenna tuning by connecting a variable capacitor across either the whole coil or part of it. While such a tuning method increases the loss somewhat, it is much easier than building a coupling coil with variable inductance, at least in my opinion. I have recently had the opportunity to test some tank circuits built by Ken Cornell and by Jack Althouse of Palomar Engineers. Both used a variable tuning core for inductance adjustment and had very low loss, but the adjustment of tuning required very delicate variation of the position of the slug, and I think the beginner will have an easier time if he follows my suggestion.



ANOTHER USE FOR POSTHOLES

Solo or short-handed erection of sectional masts can be greatly simplified by digging a posthole alongside the antenna base. The hole should be deep enough to contain all but a foot or two of the mast sections you are using. It should have something solid at the bottom to prevent clogging the mast sections with dirt. A lining of 4" plastic sewer pipe will make the hole permanent, preventing cave-ins. Begin by erecting 15 feet or so of mast in the normal fashion. Mount the loosely guyed mast on the base insulator, put the next section in the hole. Then lift the mast from base insulator to the top of the new section. Loosen the guys a bit more and lift the extended mast back to the base insulator. Repeat the process until full height is achieved. The higher you go the harder (and slower!) it gets. 40 feet is about the limit for solo work with 5" sections.