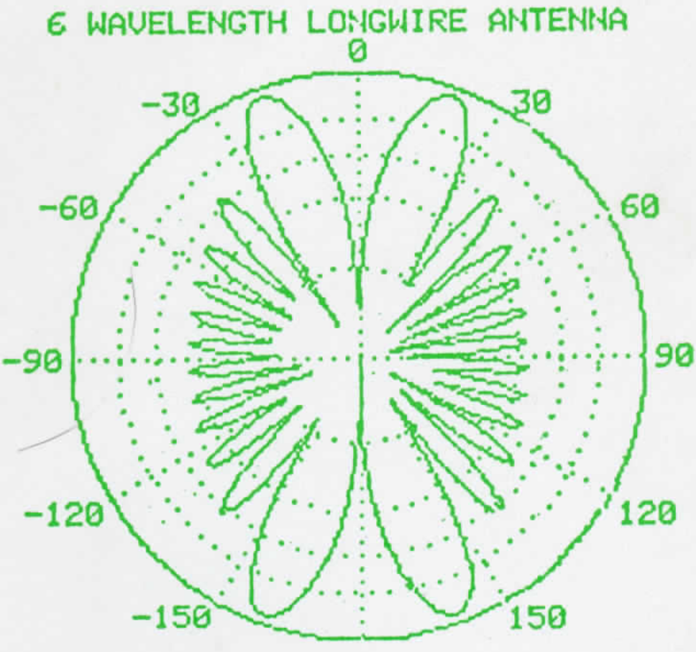
THE WAVE ANTENNA FOR RECEPTION OF MEDIUM AND LONG WAVE

BY

WALTER J. SCHULZ DL/K30QF



WILHELM HERBST VERLAG

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FORWARD

The wave antenna has been with us since the early wireless days. However, very little information has been available to the serious long, medium, and shortwave listener. Particularily how the wave antenna with associated transformers operate and are constructed.

Even among the radio amateur ranks over many years there has been little information available in the literature about this unique antenna system invented by Mr. Harold Beverage.

This small booklet is an attempt to fill the gap on the layman's level. It provides a fundamental overview to the design and construction of the wave antenna system. Along with some history about the antenna's evolution.

The author had the privilege of meeting some of the leading men in radio science on both sides of the Atlantic Ocean; the late Mr. Edmund Laport and also Doctor Walter Dieminger, DL6DS, whose teacher was the famous German Doctor Jonathan Zenneck. Through talking with these men, the author realized that his goal was obtainable to write this small "Help" booklet. Therefore, this booklet became possible through their encouragement.

Further, I would like to thank my wife, Martina for translating this work into the German language for our European friends.

Walter J. Schulz
26 March 1985

THE WAVE ANTENNA FOR RECEIVING MEDIUM AND LONG WAVES

During the pioneering days of the wireless all transmitters operated on extremely long wavelengths, those wavelengths were usually between 1000 to 3000 meters. The transmitting antennas were very small when compared to the operating wavelength, and the antenna radiated in all directions. Unfortunately when this antenna was used for receiving, it was noisy and signals were often covered by static crashes. Besides this particular problem the vertical antenna received in all directions surrounding it.

In an effort to improve signal to noise ratio when receiving practical results were found using a Bent Marconi antenna, the antenna was 1/5 of a wavelength long. When the antenna was placed over the earth's surface this resulted in better reception than the vertical antenna because of its directivity. This antenna was the beginning of the wave antenna invented by Harold H. Beverage, an American.

Harold Beverage had experimented with wires two miles long on cliffs in the state of Maine and found that they had the ability to improve reception of radio signals because of their directivity. Such long antennas had directional qualities that improved radio signals reception, they were later employed by the Radio Corporation of America and American Telegraph and Telephone. It was found through experiments that a balance transmission line (open wire type) could be used as an antenna for reception of long waves.

Why balance transmission line? There is a very simple explanation, as the radio wavefront travels over the surface of the earth the wavefront will tilt toward the direction of travel. Why? The wavefront tilt is caused by the difference between conductivity of the air and the earth's surface. At these very long wavelengths the signal wavefront is absorbed by the earth while the portion of the wavefront traveling through the air is attenuated very little. This situation leads to favorable results when the wavefront travels longitudinally over a receiving wire. The wavefront tilt induces a voltage in the wire and as the wavefront travels forward the voltage amplitude builds. As the voltage amplitude builds, upon reaching the antenna end it is reflected back towards the other antenna end. Usually with a single wire wave antenna the terminating resistance is place there. This causes the reflected wave voltage to be dissipated across the resistance and not reflected back to the receiver, this makes the antenna unidirectional (fig. 1).

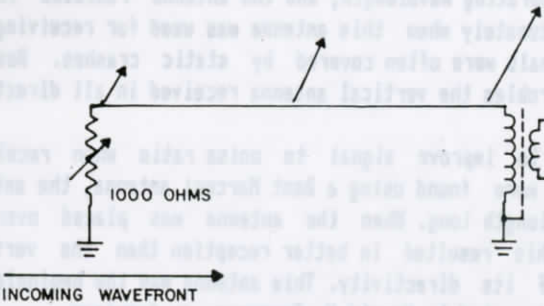
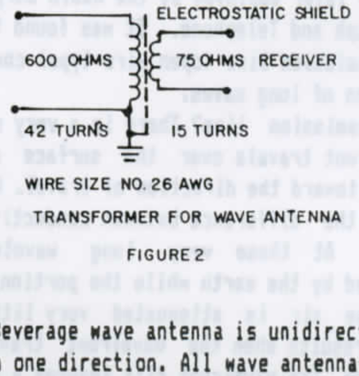


FIGURE 1



WIRE SIZE NO. 26 AWG

TRANSFORMER FOR WAVE ANTENNA

FIGURE 2

A single wire Beverage wave antenna is unidirectional, meaning that it only receives in one direction. All wave antennas work best when cut in multiples of a halfwave. A wave antenna should be no longer than three wavelengths, more than three wavelengths long results in no greater advantage for reception.

It has already been noted by the reader that the antenna system favors only one receiving direction but this can be overcome by using a balanced transmission line. We can take advantage of the properties of a balance transmission line to do two things: discriminate against unwanted signals off to the side of the wave antenna and receive signals in two directions simultaneously.

Using a balance transmission line and grounding one side of the far end but at the same time leaving the other side open, a 180 degree phase reversal takes place. This is useful as the signal travels towards the open end of the line it will be reflected back toward the transformer and dissipated across the damping circuit shown in figure 3. By proper adjustment of the damping circuit signals more than 90 degrees in azimuth can be cancelled out. Signals arriving from the transformer end build and are received.

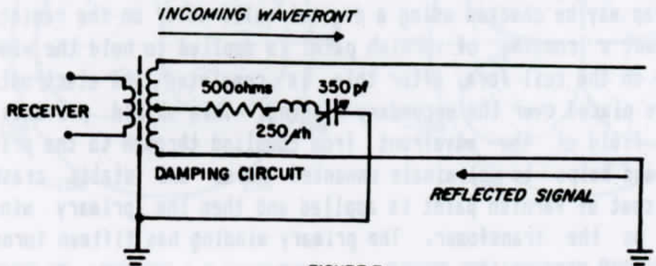
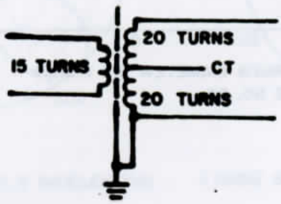


FIGURE 3



TRANSFORMER WITH CENTERTAP

FROM FIGURE 3

FIGURE 4

Figure 5 shows a method of receiving two signals simultaneous using three transformers. The system enables one to plug into either transformer and receive signals from either direction. Construction of the transformers is not difficult. For those who are interested these transformers are designed to match 75 ohm receiver antenna impedance to 600 ohm transmission line (balanced or unbalanced). The transformer secondary winding is wound on 9 centimeter diameter coil form., the material can be any insulating type such as bakelite or fiber. Forty two turns of number 26 AWG (0.40 mm diameter) is wound on it and the winding is centered tapped. Winding balance on either side of the center tap may be checked using a digital multi-meter on the resistance scale. Next a coating of varnish paint is applied to hold the winding in place on the coil form. After this is completed the electrostatic shield is placed over the secondary winding. This shield prevents the electric field of the wavefront from coupling through to the primary winding and helps to eliminate unwanted noise and static crashes. Another coat of varnish paint is applied and then the primary winding is wound on the transfomer. The primary winding has fifteen turns of number 26 AWG wire on it.

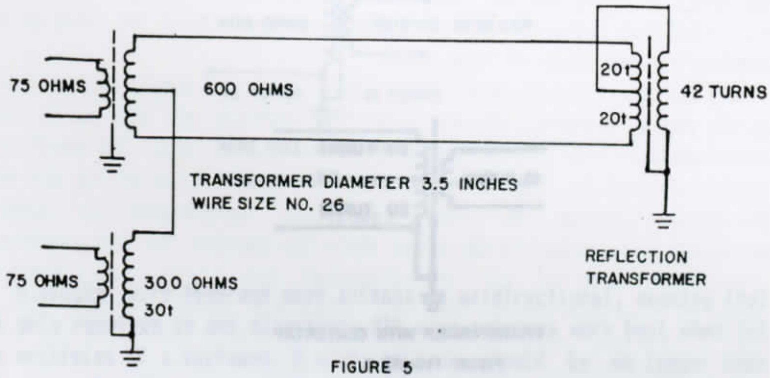


FIGURE 5

Using the configuration shown, reception on long and medium waves can be realized. Friends living in Koln, West Germany have been successful in receiving stations on medium wavelength in New York, Philadelphia cities as well as stations in Brazil, South America.

UNTERMINATED - TRAVELING WAVE

Reception pattern for 0,5 to 3 wavelengths longwire:

FIGURE 6A. LONGWIRE 0.5 WAVELENGTHS

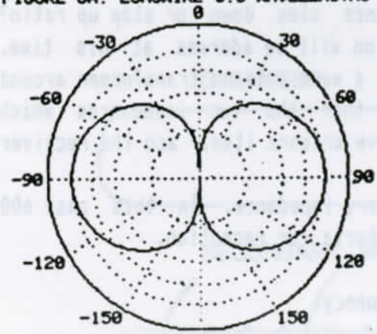


FIGURE 6B. LONGWIRE 1.0 WAVELENGTHS

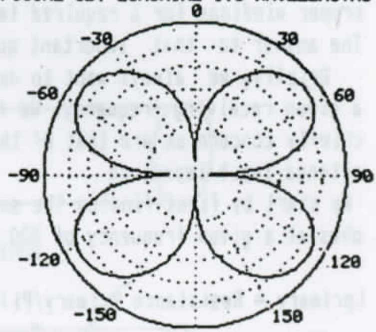


FIGURE 6C. LONGWIRE 1.5 WAVELENGTHS

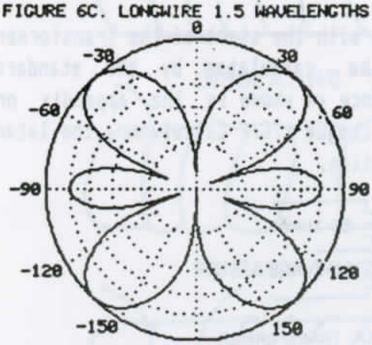


FIGURE 6D. LONGWIRE 2.0 WAVELENGTHS

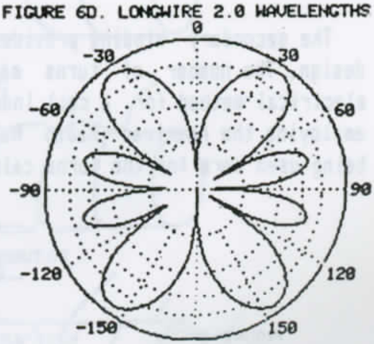


FIGURE 6E. LONGWIRE 2.5 WAVELENGTHS

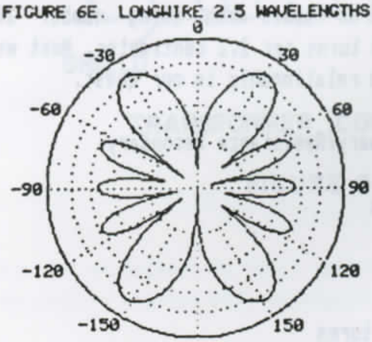


FIGURE 6F. LONGWIRE 3.0 WAVELENGTHS

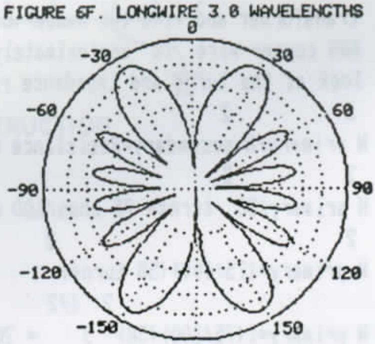


Diagram 1 - 6

CALCULATION OF TRANSFORMER WINDINGS

In the previous discussion we have obtained values for the transformer windings associated with the wave antenna impedance. However, it should be noted that if we don't elect to employ these particular values and coil diameters shown, how shall we derive the proper windings for a required impedance step down or step up ratio? The answer to that important question will be address at his time.

Briefly, we always want to design a wave antenna transformer around a given receiving frequency. We find that the two impedances which chiefly concern us are that of the wave antenna itself and the receiver antenna input impedance

We start by first finding the secondary impedance. In this case 600 ohms at a given frequency of 500 Kilohertz for reception.

$L_{primary}$ = Resistance Primary/Pi(frequency)

$L_{primary} = 600 \text{ ohms}/3.1416(0.5 \times 10^6) = 382$ microhenries

The secondary winding provides us with the start of the transformer design. The number of turns may be calculated by the standard electrical method for a coil inductance as shown in the appendix or employing the American Radio Relay League L/C/F Calculator, the later being used here for the turns calculation.

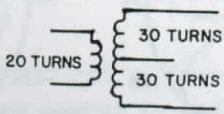


FIGURE 7 WAVE ANTENNA TRANSFORMER

We wish to use 8.89 centimeter diameter coil form for the transformer and find the number of turns needed when using number 26 AWG copper wire is approximately 58 turns per 2.2 centimeter. Next we look at the turns and impedance ratio relationship in our quest.

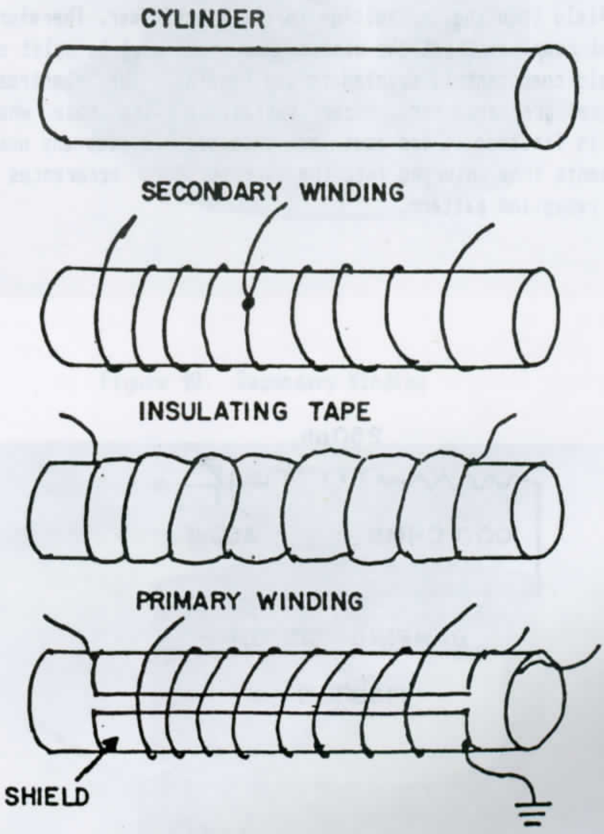
N^2 primary/N^2 secondary=Resistance Primary/Resistance Secondary

N^2 primary/58^2 turns= 75 ohms/600 ohms

N^2 primary=(75/600)(58 turns)^2

N primary=$[(75/600)(58)^2]^{1/2}$ = 20.5 turns

From this simple manipulation the number of turns for the transformer primary and secondary are readily found. Remember the impedance at the center tap when employed with another transformer for simultaneous reception is 300 ohms (half of 600 ohms). Therefore the secondary winding of this transformer must be 300 ohms impedance to work properly.

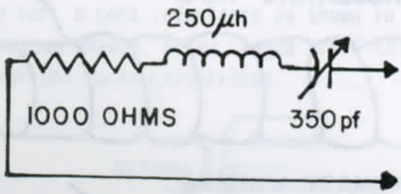


TRANSFORMER CONSTRUCTION

FIGURE 8

The author used with success a fiber cylinder for the transformer coil form. The secondary winding was wound as the first layer on the form and a coat of varnish was applied. The coat of varnish is used to hold the windings in place. The glass or cambric tape is wound over the winding to provide an insulating layer between the secondary winding and the winding to provide an insulating layer between the secondary winding and the electrostatic shield.

The electrostatic shield's function is to stop radio wavefront electrical field inducing a voltage in the transformer. Therefore the shield is not complete about the winding but it must be split so the magnetic field component is coupled to the winding. The electrostatic shield must be grounded for proper operation. Also note when the transformer is finished it too must be shielded to stop any unwanted field components from entering into the circuit. Such occurences will distort the reception pattern.



DAMPING CIRCUIT

FIGURE 9

After the shield is in place another layer of insulating tape is placed over the shield. Once this is completed the primary winding is wound and varnish applied to it.

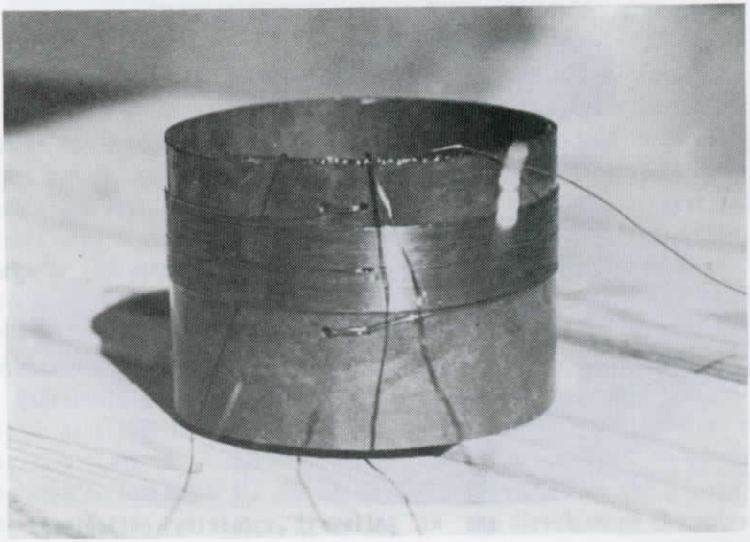


Figure 10 Secondary Winding

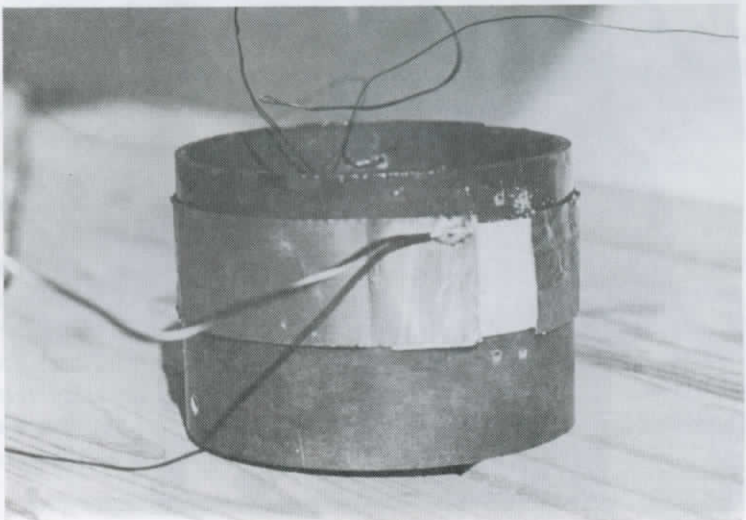


Figure 11 Insulating Tape and Shield

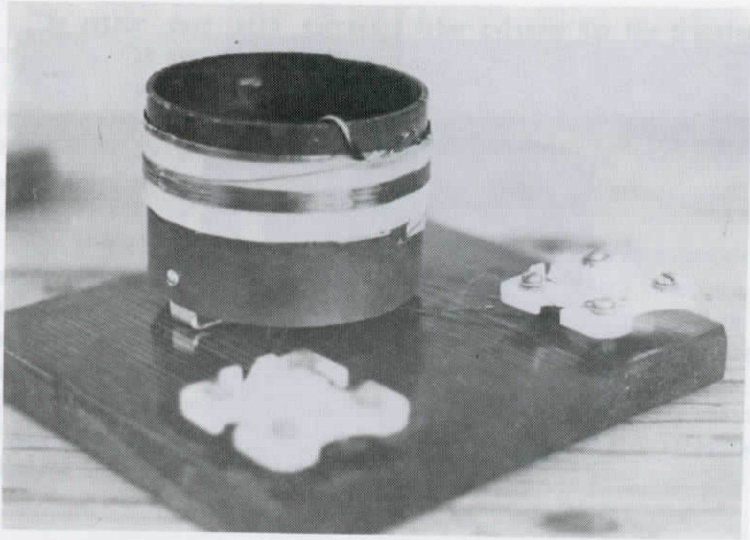


Figure 12   Primary Winding

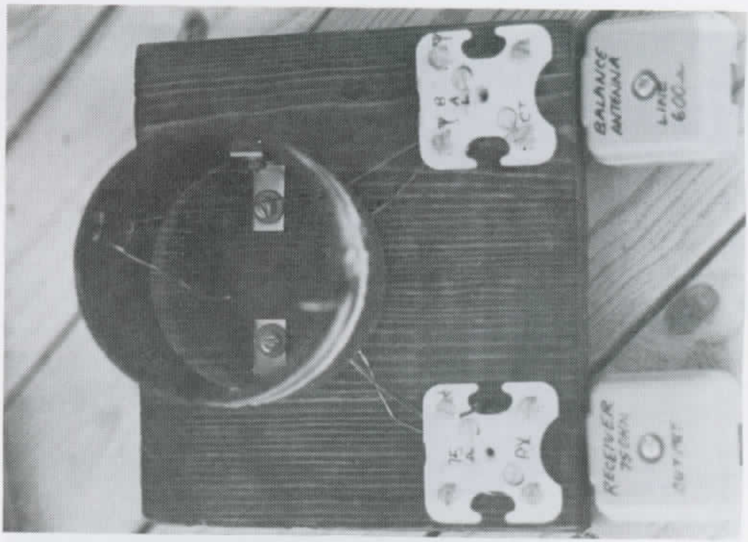


Figure 13   Complete Transformer Construction

CALCULATING WAVE ANTENNA SURGE IMPEDANCE

The wave antenna usually consists of two parallel conductors, similar to a balanced transmission line. Although a single conductor can be employed when signal discrimination is not needed, both antenna types can be considered a transmission line. From experience we know such lines will have a series inductance and a shunt capacitance distributed along itself. These electrical characteristics yield a surge or characteristic impedance for a given line. The surge impedance is a very important value. Terminating the far end of the antenna, away from the receiver antenna end, employing a single conductor makes the antenna reception pattern unity directional.

Wavefronts arriving from the receiver end of the antenna, build in signal amplitude until reaching the terminating impedance. There the signal voltage is completely dissipated across the terminating resistance. Therefore all the energy is transferred from the antenna to the terminating resistance, traveling in one direction on the antenna length, this action makes the antenna receive in one direction.

However, it should be noted when the terminating resistance is not the same as the antenna surge impedance a mismatch occurs and voltage reflections will occur traveling back towards the radio receiver end of the antenna. Then the antenna is no longer unidirectional.

Sometimes we make use of this particular effect with standing waves to cancel out unwanted signals being received on the antenna. Still it is important that the maximum energy be transferred to the reflection transformer on balance lines. This can only be done by making the transformer secondary winding equal to the antenna characteristic impedance.

One of the most simplest methods is shown in figure 14. A resistance decade box is used in conjunction with listening to the receiver audio output. A signal off the antenna back is received and the resistances are changed until minimum signal level is heard in the earphones. When this condition is achieved the antenna becomes primarily unidirectional. This method is most commonly used with single wire wave antennas but how do we find the characteristic impedance of balance wire wave antenna?

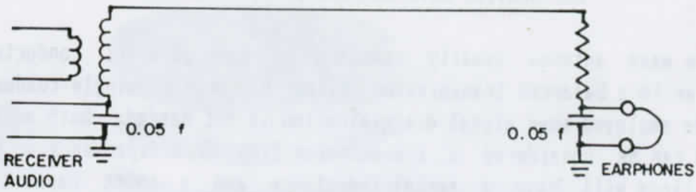


FIGURE 14

SURGE IMPEDANCE ON BALANCED WIRES

The wave antenna may be compared to a single or balanced transmission line. This implies that the equations for a single and balance conductors, that determine line characteristic impedance, can be employed to find the proper termination resistance on the wave antenna. Unfortunately these equations are approximate because they only consider the antenna structure as having a mirror image underneath the earth's surface. The equations do not consider the dielectric and conductivity properties of the earth underneath the antenna. As a consequence, we find that the antenna characteristic impedance usually is different and that the velocity of propagation along the antenna is somewhat slower than the speed of light (Reception patterns shown here are for 80% velocity).

Among one of the most simple ways to determine the characteristic impedance of a balance line is to measure its impedance at the receiver antenna end while the far end is short circuited or open circuited (fig. 15)

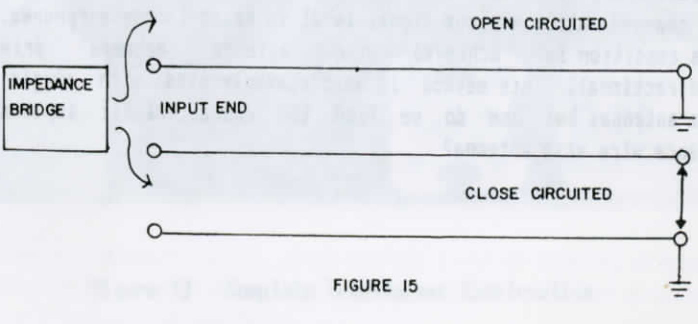


FIGURE 15

This is accomplished using a radio frequency impedance bridge or a very simple noise bridge employed by radio amateurs. Then it follows that the equation below becomes very useful.

$$Zo=[(Zo\ open\ circuit)(Zo\ short\ circuit)]^{1/2}$$

Let Zo = characteristic impedance
Zo=open circuit
Zsc=short circuit

Next the propagation constant along the wave antenna can be found employing the following two equations below once Zoc, Zsc and Zo are known.

n=propagation constant

$$n=1/2l\ COSH^{-1}\ (Zoc + Zsc)/\ (Zoc - Zsc) \quad or$$

$$n=1/2l\ Log_e\ 1 + (Zsc/Zoc)\ /\ 1 - (Zsc/Zoc)$$

let l=length

LINE ATTENUATION OF THE WAVE ANTENNA

Again we must consider the wave antenna as a transmission line and determine the attenuation per unit length of the antenna system. This is accomplish by employing the following test setup in conjunction with the wave antenna (fig. 16). The radio frequency ammeter (A) measures the current I1 at the receiver end of the line. While ammeter (B) measures current I2 at the wave antenna far end. The current I2 should always read a lesser amplitude value than the ammeter (A) reading current I1 because of the radio frequency resistance presented by the antenna length. Once the two current values are known attenuation per unit length is obtained from the following equation:

$$= Log_e\ (I1/I2)/antenna\ length$$

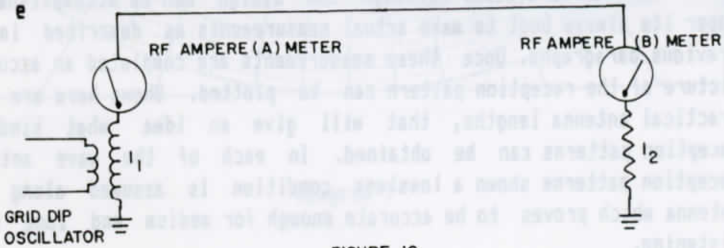


FIGURE 16

WAVE ANTENNA RECEPTION PATTERN

The reason that the equations for velocity of propagation and attenuation constant are shown is to make it possible to calculate the radio reception pattern for a wave antenna. We may assume that an wave antenna with a lossless condition exists, and then employ the following equation:

$$Io = \frac{COS\,\phi\; e^{j\frac{2Pi\,COS\,\phi}{\lambda}(L)}}{\left[\alpha + j\frac{2Pi}{n}(l - n\,COS\,\phi)\right]}\left\{ l - e^{-\left[\alpha + j\frac{2Pi}{n}(l - n\,COS\,\phi)\right]L} \right\}$$

Let = wavelength
l= antenna length in meters
= attenuation factor
0= azimuth angle
n= number of intgers

Abbreviated form of the equation above:

f(0) = COS 0 /(1 - n COS 0) SIN 1(1 -n COS 0) / 2

The reception pattern is governed generally by the earth constants below the antenna system. Although the design can be accomplished on paper its always best to make actual measurements as described in the previous paragraphs. Once these measurements are completed an accurate picture of the reception pattern can be plotted. Shown here are some practical antenna lengths, that will give an idea what kind of reception patterns can be obtained. In each of the wave antenna reception patterns shown a lossless condition is assumed along the antenna which proves to be accurate enough for medium and long wave listening.

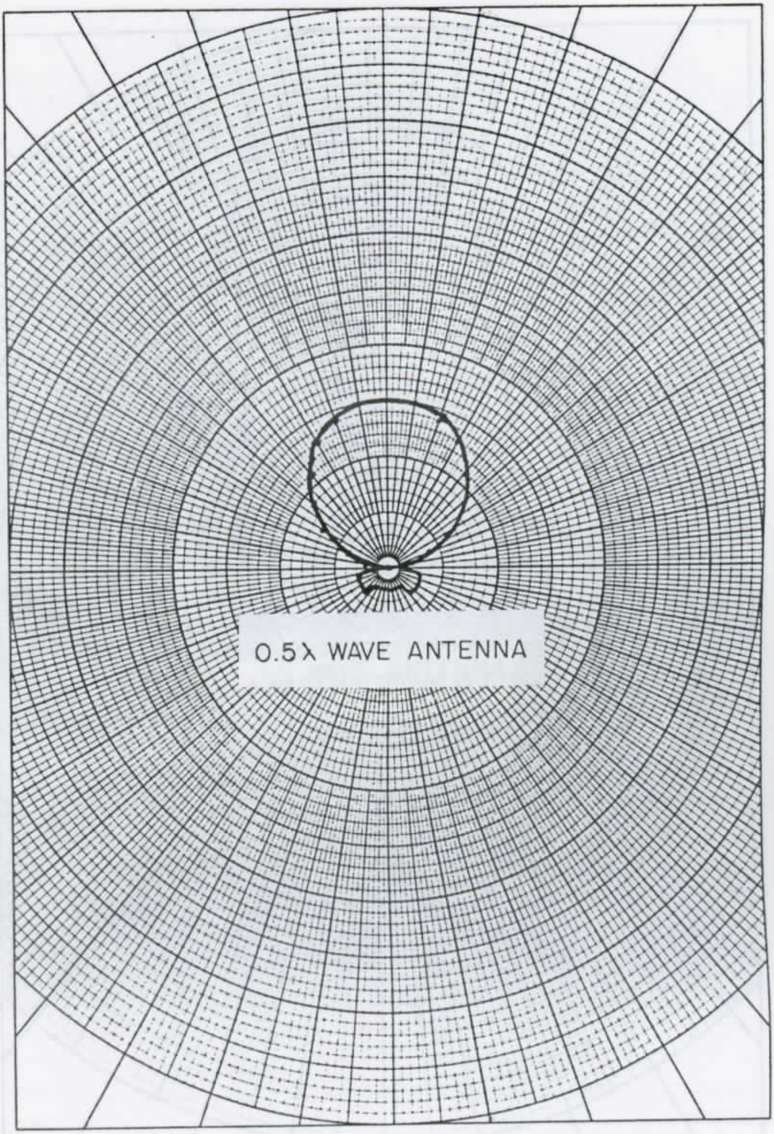


Diagram 7

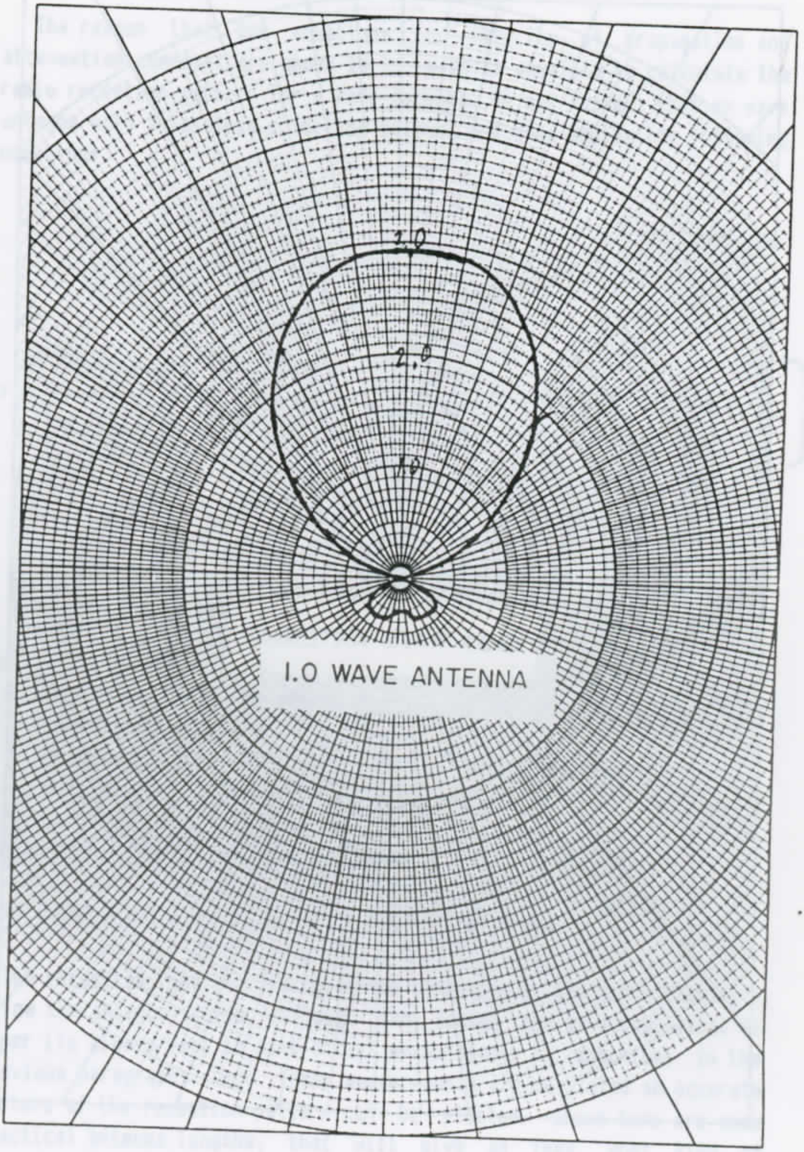


Diagram 8

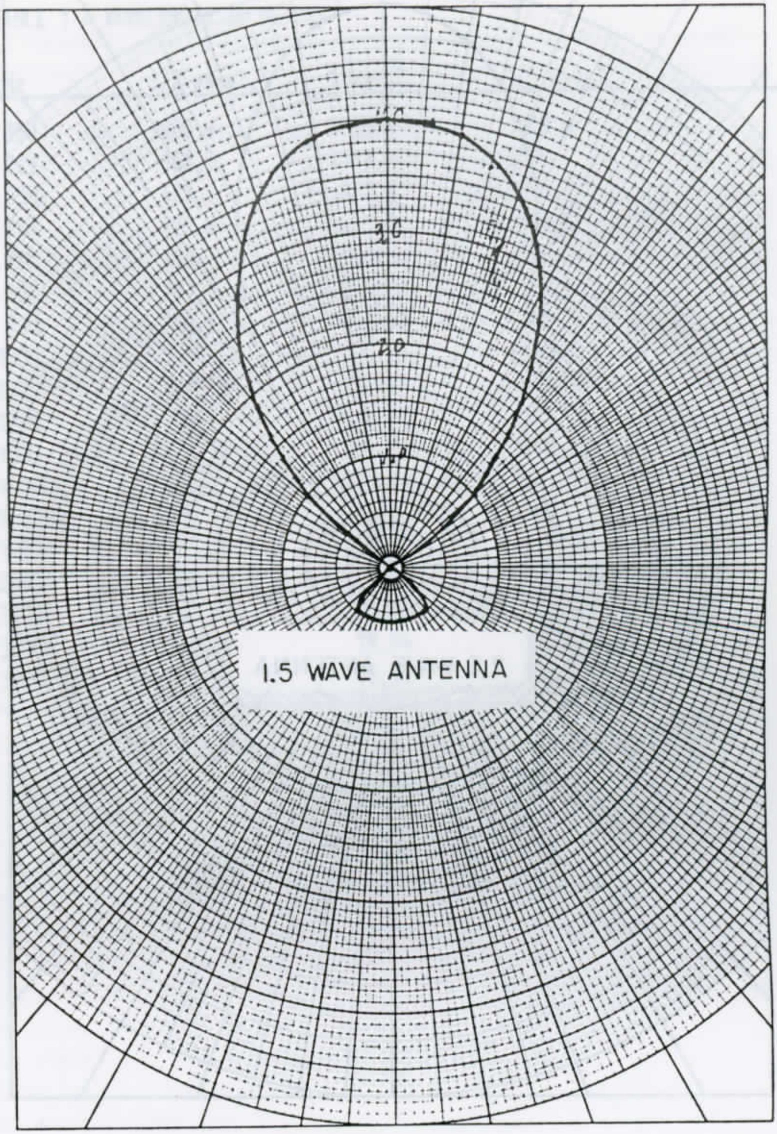


Diagram 9

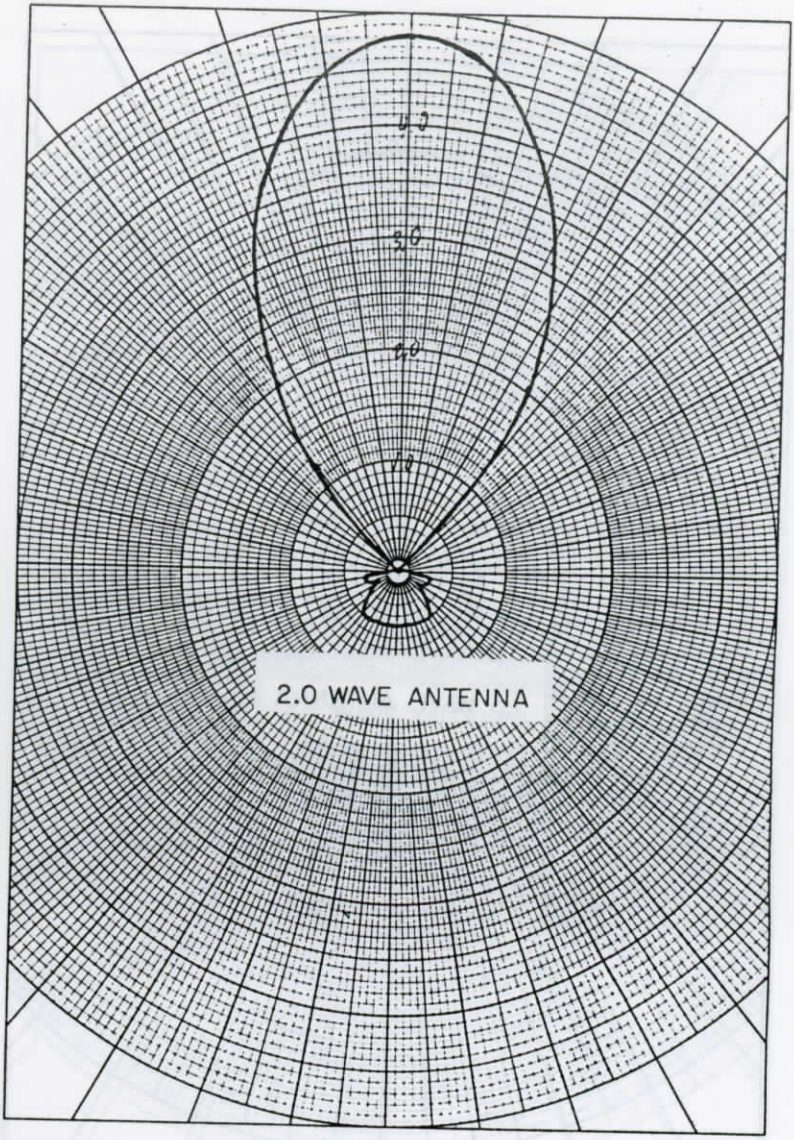


Diagram 10

TABLE 1 - WAVELENGTH IN METERS

kHz	1/2 wavel.	1 wavel.	1,5 wavel.
150	1000 ■	2000 ■	3000 ■
225	666,7	1333,3	2000
350	428,6	857,1	1285,7
550	272,8	545,5	818,3
750	200	400	600
800	187,5	375	562,5
900	166,67	333,33	500
1000	150	300	450
1100	136,36	272,73	409,09
1200	125	250	375
1300	115,38	230,77	346,15
1400	107,2	214,3	321,5
1500	100	200	300
1800	83,33	166,66	249,99
2000	75	150	225
3500	42,85	85,71	128,56
3800	39,47	78,94	118,41
3900	38,46	76,92	115,38

GENERAL NOTES ON THE WAVE ANTENNA

The wave antenna has been employed by communications companies and government agencies worldwide over many years. For this reason there is much practical information and experience on the antenna system in the literature available to professionals. When highly directional receiving antenna is needed with a good front to back ratio the wave antenna is very useful. Particularily on the very low, low and medium wavelength bands. Optimum performance is obtained with antenna lengths of one halfwave intervals up to a maximum length of three wavelengths.

The wave antenna is usually placed one tenth (1/10) the operating wavelength above the earth's surface. But ten feet average height above the earth's surface is adequate and at the same time will provide a constant velocity of propagation along the antenna for different seasonal changes that affect the earth's surface. A wave antenna that is errected below ten feet will be affected by seasonal changes, and the reception pattern will vary accordingly to these changes. Errecting the wave antenna results in another problem, when the downleads are too long. The downleads start to pickup signals interfering with wave antenna action. This problem can be minimumized by using shielded downleads shown in figure 17.

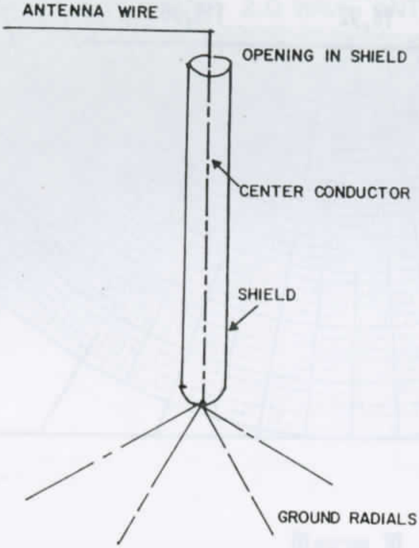


FIGURE 17

Another question to be answered is how to support the wave antenna. The usual practice is to construct the wave antenna on supporting cross arms if balanced or multi-wire constructed. In the single wire case on single wooden poles spaced fifty feet apart (see figures 18 and 19). The supporting wooden poles or posts should be twelve feet in length and cresosoted. Two feet depth in the earth's soil is required to support the post. Or one fifth (1/5) the total post length is buried into the ground.

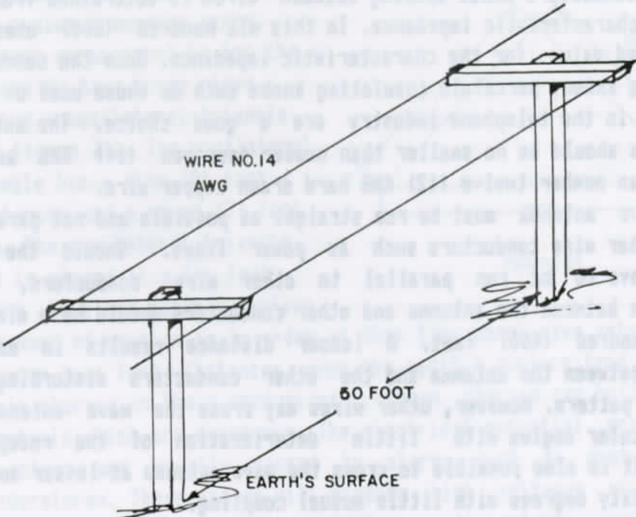


FIGURE 18

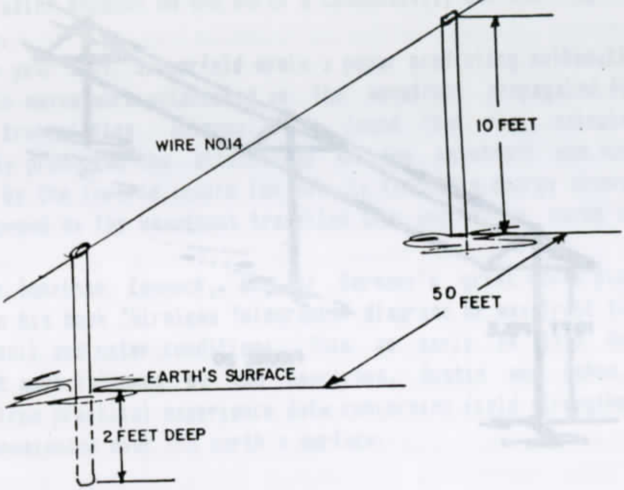


FIGURE 19

The balance transmission line, consisting of the wave antenna, metallic conductors whose spacing between wires is determined from the required characteristic impedance. In this six hundred (600) ohms is the desired value for the characteristic impedance. Once the conductor spacing is known, porcelain insulating knobs such as those used on farm fences or in the telephone industry are a good choice. The antenna conductors should be no smaller than number fourteen (14) AWG and no larger than number twelve (12) AWG hard drawn copper wire.

The wave antenna must be run straight as possible and not parallel to any other wire conductors such as power lines. Should the wave antenna have to be run parallel to other wire conductors, the separation between the antenna and other conductors should be a minimum of four hundred (400) feet. A lesser distance results in mutual coupling between the antenna and the other conductors disturbing the reception pattern. However, other wires may cross the wave antenna at peripendicular angles with little deterioration of the reception pattern. It is also possible to cross the wave antenna at lesser angles down to sixty degrees with little mutual coupling.

Another trick that should be mentioned is to add two or more wires to the single wire wave antenna (see figure 20). Using parallel wires instead of a single conductor reduces the characteristic impedance of the wave antenna and resistance of the ground return. This permits employing a lower value of terminating resistance at the antenna far end.

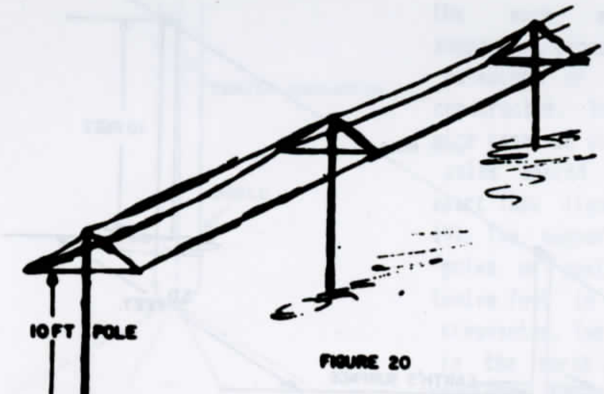


FIGURE 20

The antenna input impedance will then remain fairly constant over a wide frequency range. The best arrangement is for the antenna to have three wires forming a equilateral triangle (see figure 21). The equilateral triangle has a five (5) foot hypotenuse and a seven (7) foot base. The equilateral triangle base is placed at a ten foot height above the earth's surface.

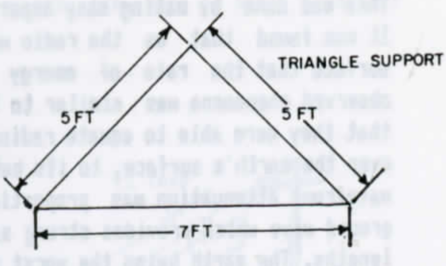


FIGURE 21

A word of caution is in order at this time about wave antennas. Wave antennas span long distances over the earth's surface tend to collect static charges on their conductors. These charges can build to large potentials which are dangerous. The electrical potential presented on the antenna are usually caused by storms such as dust, snow, and thunderstorms. These storms will produce high voltages which make it necessary to install lighting arrestors on the antenna conductors to ground.

The wave antenna depends on wavefront tilt. As a vertically polarized radio wave travels from the transmitter antenna at very low, low, and medium wavelengths the groundwave travels along the earth's surface. Actually the wavefront is traveling in two different conducting mediums, the air and in the earth's upper surface. The depth of penetration depends on the earth's conductivity and the frequency of operation.

In the year 1909, Sommerfeld wrote a paper predicting mathematically that radio waves were attenuated as the wavefront propagated forward from the transmitting antenna. He found that his calculations accurately predicted the attenuation of the wavefront was not only governed by the inverse square law but by the radio energy absorption. This happened as the wavefront travelled over and in the earth's upper surface.

Doctor Jonathan Zenneck, one of Germany's great radio pioneers, showed in his book "Wireless Telegraphy" diagrams of wavefront tilt for various soil and water conditions. This as early as 1915. But more important work followed by two Americans, Austin and Cohen. They derived from practical experience data concerning field strengths radio wave transmission over the earth's surface.

This was done by making many experimental field strength measurements. It was found that as the radio wavefront passed over the earth's surface that the rate of energy absorption was logarithmic. This observed phenomena was similar to transmission line behavior. This met that they were able to equate radio wavefront behavior, as it traveled over the earth's surface, to its behavior on a transmission line. The wavefront attenuation was proportional to frequency when using the ground wave which provides strong signals at very low, low, and medium lengths. The earth being the worst conductor while air being a better one. Therefore as the waveront travels forward from the antenna it is absorbed by the earth more than the air and the wavefront leans forward in the direction of propagation. A wavefront traveling over seawater is almost perfectly straight (peripenicular to the earth's surface) while over rocky and sandy soil the wavefront tilt is considerable. Therefore, to obtain optimum results using a wave antenna, it should be installed over poor or medium soils of low conductivity. Further this antenna works very well up to about three megahertz.

ALTERNATE METHOD TO THE WAVE ANTENNA

Many of us have restricted conditions that do not permit us to errect a wave antenna. A balanced transmission line (two conductors) wire type is the best choice for a wave antenna on long, and medium waves. Also good radio reception can be had on shortwaves too. In a effort to obtain a good antenna system with a minimum reception of interfering noise one can use the telephone drop wires leading from the telephone plant to the house where the radio receiver is stationed. What follows then is a technique whereby this method can be applied. Here in America some DXers take advantage of the telephone plant for radio reception on long, medium, and shortwaves.

We are primarily interested only in single balance pair telephone line coming into the home. This pair consists of a tip and ring conductors in telephone language. Usually in rural plant there is a long drop (conductors run from the pole or main cable span) from the outside of the house. The advantage of this run may be taken by sementing the line electrically. This means we only want a segment between one half wavelength or multiples thereof, for a particular wavelength. To accomplish this we use radio frequency blocking trap, this leaves the telephone line intact for talking (talk battery of 48 volts direct current is passed along with alternating current ringing voltages) but radio frequency currents are stopped (see figure 22). It

It should be noted that permission from the local telephone company must be obtained before any modifications are made to their telephone plant property.

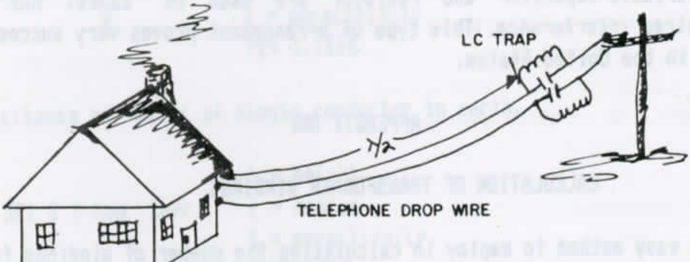


FIGURE 22

From figure 22 we see how this is accomplished but the line segment must also be coupled to the radio receiver. It should be noted even if we do not segment the telephone line, the balanced line itself will make a excellent antenna for radio reception. To obtain our goal the wave antenna transformer shown in figure 23 is used with additional hardware. A capacitor is inserted in series with each leg of

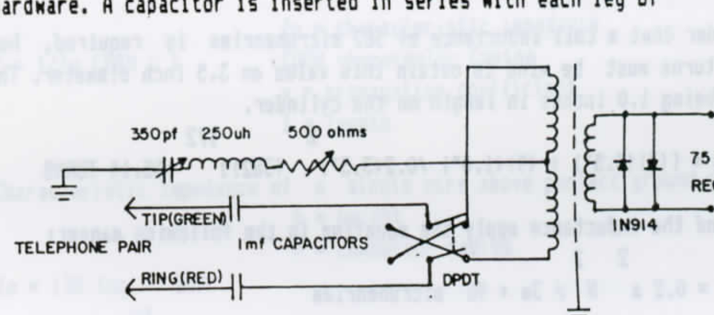


FIGURE 23

the transformer secondary and the balanced line. This capacitor blocks the forty-eight (48) volt talk battery from the transformer, but allows the one hundred twenty (120) volt alternating current ringing voltage to pass to ground. Next the transformer has two diodes shunted across the primary winding, this is to prevent any foreign voltages or surge voltages reaching the radio receiver antenna input.

Notice a double pole double throw reversing switch is in series with the balanced line. Usually the telephone line is twisted about itself to eliminate cross talk within a telephone cable. Should it be desired to null out an interfering radio station signal, the tip and ring conductors may have to be reversed at the transformer secondary. Then the variable capacitor and resistor are used to cancel out the undesired interference. This type of arrangement proves very successful here in the United States.

APPENDIX ONE

CALCULATION OF TRANSFORMER WINDINGS

An easy method to employ in calculating the number of windings for a given inductance value is by using the American Radio Relay League L/C/F Calculator. However, we may simply calculate the number of required turns employing the following formula:

Let a = coil diameter
  b = coil length
  L = inductance in microhenries

$$N = [(3a + 9b / 0.2(a)^{2} (L)]^{1/2}$$

Consider that a coil inductance of 382 microhenries is required, how many turns must be wind to obtain this value on 3.5 inch diameter. The coil being 1.0 inches in length on the cylinder.

$$N = [(3)(3.5") + (9)(1.0") /0.2(3.5")^{2} (382)]^{1/2} = 55.14 \text{ TURNS}$$

To find the inductance apply the equation in the following manner:

$$L = 0.2\,a^{2}\,N^{2} / 3a + 9b \text{ microhenries}$$

Consider the above numbers in the previous example, finding the inductance.

$$L = 0.2(3.5")^{2} (55.14)^{2} /3(3.5") + 9(1.0") \text{ microhenries}$$

$$L = 7519.442/19.5 = 382 \text{ microhenries}$$

SOURCE: American Radio Relay League Handbook 1945

APPENDIX TWO

Capacitance per meter of two parallel bare wires.

$$C = Pi\ E / \log_e d/r$$

d = distance
r = radius
E = permittivity
Pi= 3.1416

Capacitance per meter of single conductor to earth.

$$C = 2Pi\ E / \log_e 2h/r$$

h = height
r = radius
E = permittivity
Pi=3.1416

Turns Ratio

$$N1^2 / N2^2 = R1 / R2$$

Capacitance of a transmission line.

$$C = 1/Zo\ COSH\ v\ l$$

Zo = characteristic impedance
COSH =hyperbolic Cosine
v = propagation coefficient
l = length

Characteristic Impedance of a single wire above perfect ground plane.

h = height
r = conductor radius

$$Zo = 138 \log_{10} 2h/r$$

Characteristic Impedance of two parallel bare wires above perfect ground plane.

$$Zo = 276 \log_{10} 2S/r$$

S = Space between two wires
r = wire radius

Lumped Transmission Line circuit constants.

$l = 0.279 \log_{10} h/r$ microhenries per foot.

$C = 3.66 / \log_{10} (h/r)$ microfarads per foot

$R = (f)^{1/2} / r$ mirco ohms per foot

Surge Impedance

$Zo = L/C^{1/2}$

APPENDIX THREE

Finding balanced transmission line spacing between conductors for a given characteristic impedance.

Example

Let d = wire diameter
S = spacing between conductors
Zo= 600 ohms
Wire number (No.) American Wire Guage 14 = 1.163 mm.

$Zo = 276 \log_{10} 2S/d$

S = (d)(Antilog Zo / 276) / 2

S = (1.163 mm)(Antilog 600 / 276) / 2 = 86.7886 mm or 8.67 cm.

APPENDIX FOUR

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Editor in Chief Rich Rosen

APPENDIX FIVE

INCHES = CENTIMETERS / 2.54

or

CENTIMETERS = 2.54 X INCHES

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