CHAPTER 9
HIGH-FREQUENCY ANTENNAS

1. INTRODUCTION

Because of varying operational requirements, a wide variety of antenna systems are used in high-frequency communication systems. The use of single-sideband techniques does not introduce any peculiar requirements on the antenna system. The purpose of this chapter is to review basic antenna theory and to describe the characteristics of typical antennas that may be used in high-frequency communication systems.

The receiving and transmitting antennas together with the intervening medium perform the function of the transmission line in a wire communication system. At large distances the voltage that can be induced in an antenna is greater than that which can be transmitted over wires of a practical size. The attenuation of waves guided by wires increases exponentially with the length of the wire. Thus over long distances, the attenuation in wire is greater than the attenuation due to the three dimensional spreading of radio waves in space.

By the reciprocity theorem, the electrical characteristics of an antenna are the same for transmitting as they are for receiving. However, because of the different applications, certain practical differences between transmitting and receiving antennas exist. The function of a transmitting antenna is to radiate the radio-frequency energy that is generated in the transmitter and guided to the antenna by the transmission line. In this capacity the antenna acts as an impedance matching device to match the impedance of the transmission line to that of free space. In addition, the transmitting antenna should direct the most energy in desired directions and suppress the radiation in other directions where it is not wanted. For reception, however, the optimum condition is not maximum received power but rather maximum signal-to-noise ratio. Although the pattern that gives the first condition may also lead to the second, such is not necessarily the case. For example, a minor lobe in the pattern of a receiving antenna may bring in a large amount of noise if it happens to be pointed toward a noise source, and so result in a low signal-to-noise ratio. On the other hand, as a transmitting antenna, the presence of the lobe may have no ill effect other than the loss of the small amount of power that it radiates. Increasing the directivity of the transmitting antenna will always increase the signal-to-noise ratio at the receiver. Increasing the directivity of a receiving antenna will increase the signal-to-noise ratio unless the noise is coming from the same direction as the signal. Another important factor is that in the high-frequency range the atmospheric noise picked up by a receiving antenna is usually much greater than the receiver set noise. Thus, it is possible to use a very inefficient antenna and/or loose coupling to the receiver without any apparent degradation of the signal-to-noise ratio. Since in a high-frequency communication system the same antenna is commonly used for transmission and reception, the antenna is designed for best over-all performance.

Long distance communication in the high-frequency region relies on the reflection of the radio waves from the ionosphere (see chapter 11). The result of this is that the desired direction of transmission or reception may be from several to many degrees above the horizon, depending upon the distance between the stations and the height of the reflecting layer. To obtain optimum results from any given antenna system, its design should take into account the particular propagation conditions which exist.

2. ANTENNA FUNDAMENTALS

a. RADIATION CHARACTERISTICS OF A LINEAR CONDUCTOR

To radiate electromagnetic and electrostatic energy into space, it is necessary to obtain a circuit which will not confine the useful fields to the immediate vicinity of the lumped inductance and capacitance constituting the circuit where it would be mostly absorbed. A rectilinear conductor of length comparable to a wave length and very small thickness in terms of wave length comprises a circuit with its inductance and capacitance distributed over a large area, and it will radiate a large part of the energy flowing in the conductor. Radiation from this simple antenna takes place by virtue of the expanding magnetic and electrostatic fields accompanying the charges flowing in the conductor. All of the energy traveling in the conductor however is not radiated before it reaches the end of the conductor. Some of it is reflected. These reflections from the discontinuities at the ends produce voltage and current standing waves on the conductor. If the diameter of the radiator is very small in terms of wave length, the rms voltage and current amplitude will vary substantially as a sine function. Examples of voltage and current distribution along several resonant-length wires are shown in figure 9-1.

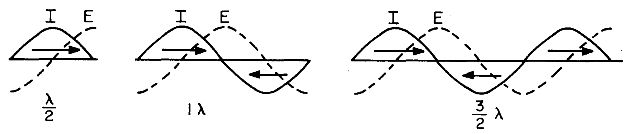


Figure 9-1. Sinusoidal Voltage and Current Distribution on Resonant Wires

The conductor is resonant when it exhibits purely resistive properties, and as in the ordinary tuned circuit, the largest amount of current will be conducted during resonance. Therefore, since the strength of the radiated electromagnetic field depends on the current flowing, it is desirable to make the conductor or antenna resonant. Resonance of the conductor occurs when its length is a half wave length or multiples thereof. A practical rectilinear conductor will resonate when it is slightly less than a half-wave in length due to end effect. End effect is due to a decrease in inductance and an increase in capacitance near the end of the conductor, which effectively lengthens the antenna. End effect increases with frequency and varies with different installations. In the high-frequency region, experience shows that the length of a half-wave radiator is in the order of 5% less than the length of a half-wave in free space. The greater the diameter of the conductor, the greater the difference between its electrical and physical length.

In actual practice, the presence of supporting insulators, feed systems, and surrounding objects such as the earth and other antenna elements have an aggregate effect upon the electrical length which may even exceed the variation in length caused by practical variations in the conductor diameter. This makes the unknown length difficult if not impossible to predict under practical conditions. Therefore, the usual procedure is to cut or adjust the radiator to a length equal to or slightly less than the correct free-space physical length, check the characteristics of the antenna experimentally, and then alter the physical length as necessary.

In order to keep the efficiency of a radiating system high, the ratio of radiated energy to the energy dissipated in the radiator must be high. This means that the antenna must have sufficient physical size in terms of wave length to exhibit appreciable radiation resistance. In the simple linear radiator, radiation resistance may be defined as the ratio of radiated power to the square of the circulating current at a maximum current point on the radiator. The term resistance is actually fictitious but represents a resistance that would dissipate the power that disappears by radiation.

In the case where the antenna is a single half-wave element, the feed point resistance is essentially equal to the radiation resistance if the antenna is fed at the center or current loop. But when the radiating portion of the antenna consists of several elements with complex current distribution and complex mutual impedances, the feed point or input resistance is not the same as the effective radiation resistance. Feed point or input resistance refers to the resistive component of the impedance which the antenna presents to the feed line. Radiation resistance and input resistance, therefore, are not always synonymous.

The resistive and reactive components of the feed point or driving point impedance of a linear radiator are dependent upon both the length and diameter of the conductor. The manner in which these resistive and reactive components vary with change in frequency are dependent on the location of the feed point on the radiator. The feed point of an antenna looks to the transmission line much like a resistance-loaded tuned circuit, series resonant if fed at a current loop and parallel resonant if fed at a voltage loop. This analogy is illustrated for the case of the half-wave radiator in figure 9-2.

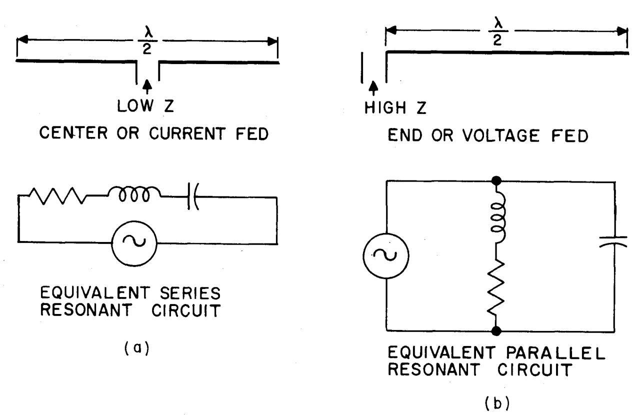


Figure 9-2. Lumped Circuit Analogy for Half-Wave Radiators

Both the feed point resistance and the feed point reactance change more slowly with frequency as the conductor diameter is increased, indicating that the effective Q is lowered as the diameter is increased. However, since the input resistance is nearly all radiation resistance rather than loss resistance, the lower Q does not represent lower efficiency. The lower Q, therefore, is desirable because it permits use of a given radiator over a wider frequency range without resorting to means for eliminating the reactive component. Thus, the use of a large diameter conductor makes the over-all system less frequency sensitive. Radiators with sufficiently low Q to permit their input impedance to remain relatively constant over a wide frequency range are termed broad-band.

Other expedients also will provide a substantial reduction in the frequency sensitivity when broad-band characteristics are a requirement. A method commonly employed takes advantage of the opposite sign of the reactive component in a series tuned circuit with respect to that in a parallel tuned circuit when both are detuned from resonance in the same direction. If the two circuits are properly combined, their reactances cancel resulting in a relatively wide frequency range of zero reactance. A current-fed antenna (series circuit analogy figure 9-2), for example, can be made less frequency sensitive by connecting a parallel resonant circuit using lumped L and C across the feed point, the optimum L/C ratio being most easily determined by experiment. One simple antenna which owes its broad-band characteristics in part to reactance canceling effects similar to those just described is the folded dipole.

b. POLARIZATION

The energy leaving a linear radiator is in the form of electric and magnetic fields that are perpendicular to each other and mutually perpendicular to the direction of propagation. Arbitrarily, the polarization of a radio wave is defined as the orientation of the electric field. This is convenient because the electric component is in the same plane as the linear radiator. Thus, a simple linear radiator oriented horizontally with respect to the earth will emit horizontally polarized waves. It is for this reason that antennas are often referred to as being horizontally or vertically polarized. There are, however, certain types of antennas that emit a complex or elliptical wave, but these are not commonly used in high-frequency communications.

c. RECIPROCITY

Although the classical laws regarding reciprocity must be applied with care to practical antenna problems involving electromagnetic radiators, it may be assumed that the directional characteristics of an antenna system are the same when transmitting as when receiving. In addition, for most practical purposes, an antenna that transmits well in a given direction will also give favorable reception from the same direction despite possible ionosphere variations.

d. IMAGE ANTENNAS

If an absolutely flat, perfectly conducting ground is assumed, the effect of the earth can be duplicated by an image antenna which is a mirror image of the actual radiator. This assumption of a mirror image is useful in determining the impedance and directional characteristics of an antenna located near a reflecting surface. The image representation is illustrated in figure 9-3. Note that while the configuration of the imaginary antenna is a mirror image of the actual radiator, the direction of current flow is not. This is because the phase of a horizontally polarized wave is reversed upon reflection from the perfect ground, while the phase of the vertically polarized wave is not. The result is that corresponding vertical components of current flow are in the same direction, while the corresponding horizontal components are in the opposite direction.

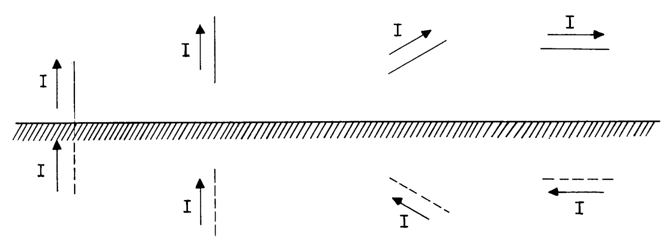


Figure 9-3. Image Antennas

e. MUTUAL IMPEDANCE

The interaction or coupling between two or more antenna elements which are separated by not more than several wave lengths can produce a mutual impedance which is significant when compared to the self-impedance exhibited by either element alone. The magnitude and phase of the mutual impedance depends mainly upon the orientation and spacing of the conductors. The resistive component of the mutual impedance may be either positive or negative; consequently, the presence of a neighboring radiator may either raise or lower the feed point resistance of a given radiator. In addition, the reactive component of the mutual impedance may cause the resonant frequency of the given radiator to be altered, except at certain critical spacings.

The effect of a perfectly flat, perfectly conducting ground upon the impedance characteristics and current distribution of a radiator is the same as that produced by the mutual impedance exhibited by an image antenna which is substituted for the perfect earth. The effect of the actual earth and surroundings is not easily determined in most cases, except by experiment.

f. ANTENNA DIRECTIVITY

When an antenna radiates more strongly in some directions than in others, it is said to possess directivity. Even the simplest, free-space, linear radiator exhibits some directional characteristics. The more the radiation is concentrated in a certain direction, the greater will be the field strength produced in that direction for a given amount of total power radiated. Thus, the use of a directional antenna produces the same result in the desired direction as an increase in transmitter power.

The increase in radiated power in a certain direction, as a result of inherent directivity, with respect to some reference antenna is termed the gain or more specifically directivity gain of the antenna. The reference antenna is commonly the hypothetical isotropic radiator which is assumed to radiate equally well in all directions. More practically, the reference antenna is the simple half-wave dipole which has a free-space directivity gain of 1.64 in power over the isotropic radiator. This means that in the direction of maximum radiation the dipole will produce the same field strength as an isotropic radiator which is radiating 1.64 times as much power. The directivity of an elementary dipole provides a free-space gain of 1.5 over the isotropic radiator. As a convenience, the power gain of an antenna system is frequently expressed in decibels. (db = 10 $\log_{10}\frac{P_1}{P_2}$ where $\frac{P_1}{P_2}$ = power gain) In the case of the free-space, half-wave dipole, $P_1/P_2 = 1.64$, which is equivalent to 2.15 db. Power gain can be expressed with reference to any antenna if the reference is specified.

A graphical representation of the directional characteristics of a given antenna is termed its radiation pattern and illustrates the relative magnitude of radiation intensity as a function of direction. The free-space directivity or radiation patterns of the isotropic radiator, the elementary dipole and the half-wave dipole are shown in figure 9-4. The patterns show the relative magnitude of field strength for points at constant range in any plane which includes the radiator. Since field strength is based on voltage, its magnitude is proportional to the square root of radiated power. Directivity patterns are sometimes drawn to a power scale and less frequently to a db scale, but field strength plots are the most common and generally the most useful.

Figure 9-4 illustrates that more directivity is obtained from the half-wave radiator than from the elementary dipole which is much shorter than a half wave. The half-wave dipole, in fact, may be considered to be made up of a large number of elementary dipoles strung together as a chain, and the resultant radiation pattern is the summation of the fields from each elementary dipole. Stated somewhat differently, the interference, due to the radiation from different portions of the radiator arriving at a given point in space, determines its directivity. This wave interference is the basic mechanism that controls antenna directivity, whether the antenna is a simple half-wave dipole, a wire many half wave lengths long, or a complex combination of radiating elements.

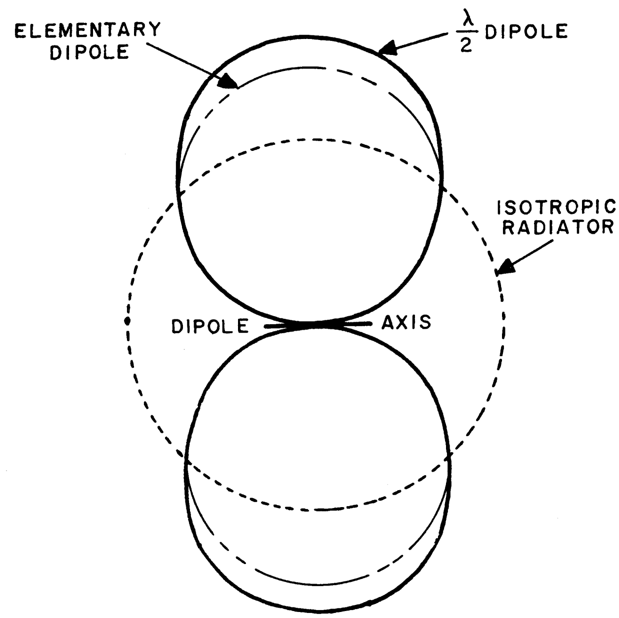


Figure 9-4. Polar Diagram of Radiation Patterns of an Isotropic Radiator, Elementary Dipole, and Half-Wave Dipole, in Free Space

In actual practice, high-frequency antennas are located in the presence of ground where their performance is considerably modified. This is particularly true with respect to the directional properties and more specifically the vertical directivity of the antennas. Waves that are radiated from the antenna at angles below the horizontal are reflected by the earth and combine with, or interfere with the direct waves that are radiated at angles above the horizontal. The resultant vertical radiation pattern is determined by this interference which depends upon the orientation of the antenna with respect to earth, the height of the antenna, the character of the ground, and the directional properties of the actual antenna. The resultant vertical directivity can be determined with good accuracy by using the "image" antenna concept previously described and more specifically illustrated in figure 9-5.

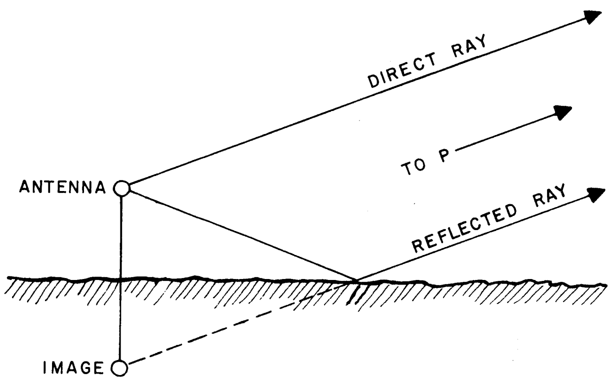
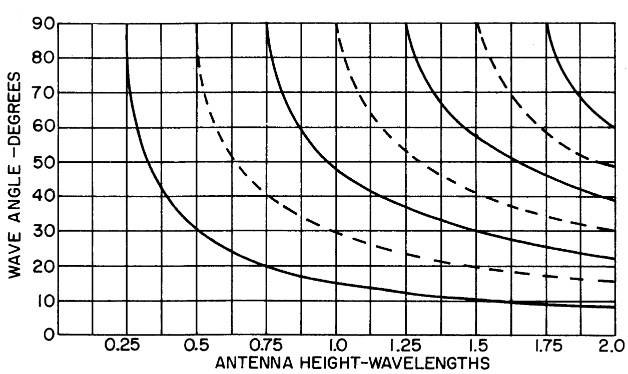


Figure 9-5. Image Antenna and Ground Effect

At some vertical angles above the horizontal, the direct and reflected waves reach the same point in space in phase, and the resultant field strength is the sum of the two. At other vertical angles the two waves arrive at a point in space out of phase, and the resultant field strength is the difference of the two. Thus, the effect of the ground increases the intensity of radiation at some angles and decreases it at others. At the particular vertical angle where the resultant field intensity is doubled (under ideal ground reflection conditions) a gain of 6 db can be realized over that when the antenna is operating in free space.

The vertical angles (wave angle) at which maxima and minima occur due to ground reflection for antenna heights up to two wave lengths are shown in figure 9-6.



SOLID LINES ARE MAXIMA, DASHED LINES MINIMA, FOR ALL HORIZONTAL ANTENNAS AND FOR VERTICAL ANTENNAS OF LENGTH EQUAL TO AN EVEN MULTIPLE OF A HALF WAVELENGTH FOR VERTICAL ANTENNAS AN ODD MULTIPLE OF A HALF WAVE IN LENGTH THE DASHED LINES ARE MAXIMA AND THE SOLID LINES ARE MINIMA.

Figure 9-6. Angles of Ground Reflection Factor Maxima and Minima for Antenna Heights up to Two Wave Lengths

The curves are for perfect ground but give a close approximation for actual earth, provided the ground is flat.

For most practical antennas, a single cross-sectional view of the solid or three-dimensional pattern will not sufficiently describe the directional characteristics. However, it is not necessary to show the relative magnitude of radiation at all points in space to give a useful picture of the directional properties of the antenna.

The pertinent data in the case of ground wave propagation is a plot of the field strength versus compass direction at constant range. This gives the horizontal pattern at ground level. Where the sky wave is the chief mode of propagation, information on the relative field strength at various vertical angles is pertinent, and a single vertical cross section of the solid pattern taken along the direction of maximum ground level radiation often will give the necessary data. Patterns of this type are referred to as vertical patterns, depicting vertical directivity in a certain azimuth direction. Occasionally, the patterns in these two principal planes do not furnish adequate information, and additional horizontal patterns at various vertical angles may be required.

The following is a list of the terminology used to describe directive arrays with a brief definition of each term.

A driven element is one that receives power from the transmitter usually through a transmission line.

A parasitic element is one that obtains power solely through coupling to another element in the array because of its proximity to such an element.

A driven array is one in which all the elements are driven.

A parasitic array is one in which one or more of the elements are parasitic elements. At least one element in a parasitic array must be a driven element, since it is necessary to introduce power into the array.

A broadside array is one in which the principal direction of radiation is perpendicular to the axis of the array and to the plane containing the elements.

An end-fire array is one in which the principal direction of radiation coincides with the direction of the array axis.

The major lobes of the directive pattern are those in which the radiation is maximum. Lobes of lesser radiation intensity are called minor lobes.

The beam width of a directive antenna is the width, in degrees, of the major lobe between the two directions

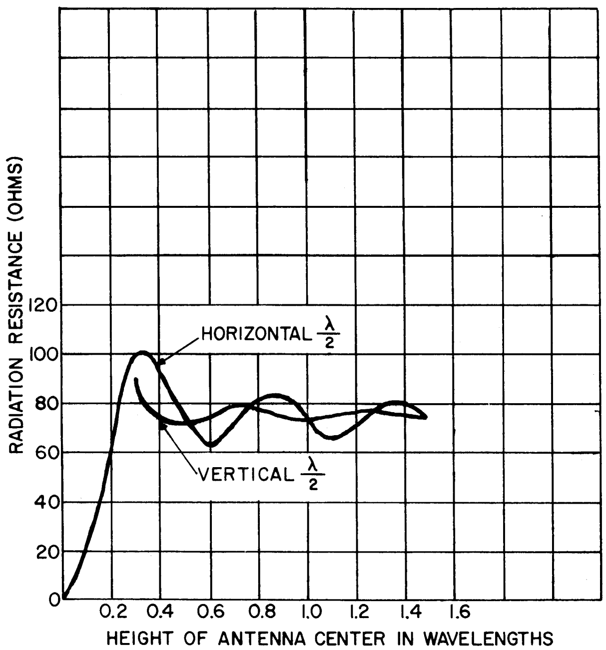


Figure 9-7. Variation of the Radiation Resistance of a Theoretical Half-Wave Dipole with Height above a Perfectly Conducting Earth

at which the relative radiated power is equal to one-half its value at the peak of the lobe. At these half-power points, the field intensity is equal to .707 times its maximum value, or 3 db down from maximum.

Front-to-back ratio means ratio of the power radiated in the forward direction to the power radiated in the opposite direction.

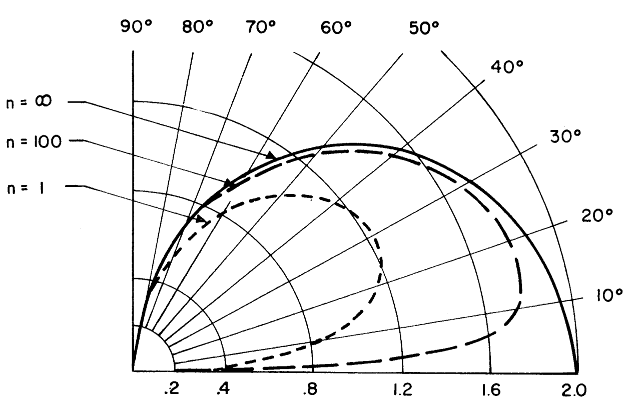


Figure 9-8. Vertical Radiation Pattern of a Vertical Dipole at the Surface of an Earth of Finite Conductivity

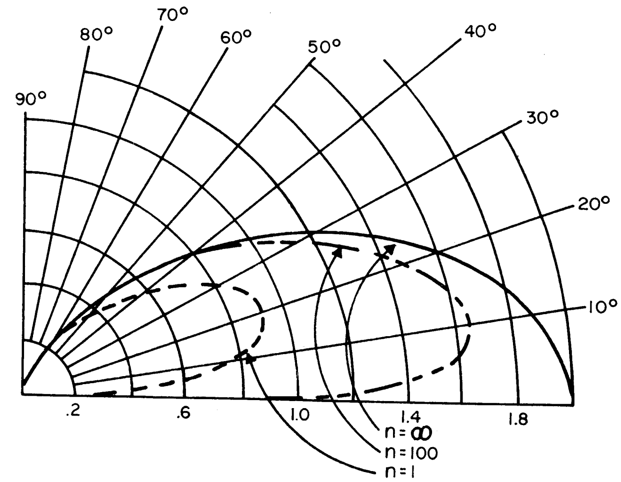


Figure 9-9. Vertical Radiation of a Vertical Dipole a Quarter Wave Length Above an Earth of Finite Conductivity

3. TYPICAL HIGH-FREQUENCY ANTENNAS

The types of antennas used in high-frequency communication systems are many and varied. In the following section, a few of the more common types are described to illustrate some of the basic principles of operation, construction, and performance of suitable radiating systems.

a. THE PRACTICAL HALF-WAVE DIPOLE

Although fundamental antenna theory is usually based on a theoretical dipole, one having infinitely thin cross section and sinusoidal current distribution, the practical half-wave dipole has a finite diameter and a current distribution that is not exactly sinusoidal. These factors affect both its directional and its impedance characteristics. However, the difference between the theoretical and actual radiation pattern of the center-fed, half-wave dipole is negligible, and for all practical purposes, the theoretical pattern can be assumed. The effect on impedance characteristics is more pronounced. The radiation resistance of the theoretical free-space, half-wave dipole is 73 ohms, while the radiation resistance of the practical half-wave dipole in free space is in the order of 65 to 70 ohms. This is due to the resonant length of the actual dipole being slightly less than a half wave.

In addition to the above effects, an actual dipole is always located above the ground, so that theoretical free-space conditions do not apply. Figure 9-7 illustrates the variations in radiation resistance of a theoretical half-wave dipole with height above a perfectly conducting ground. For a practical half-wave dipole over actual ground, the variations will be lower, but the chart shows the approximate magnitude of the

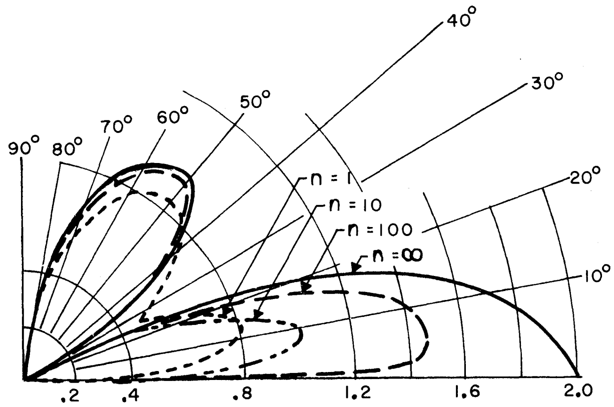


Figure 9-10. Vertical Radiation Pattern of a Vertical Dipole a Half Wave Length Above an Earth of Finite Conductivity

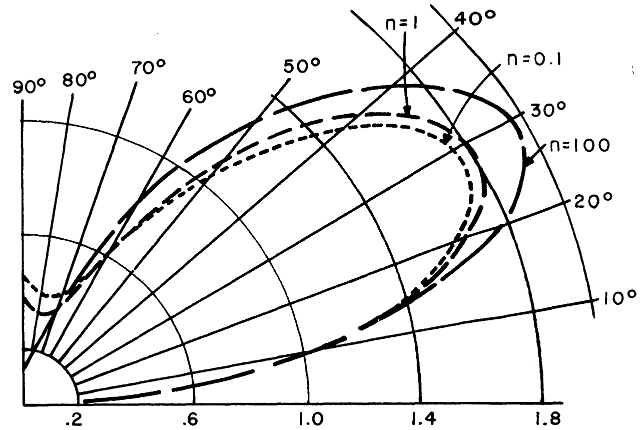


Figure 9-12. Vertical Radiation Pattern (in the plane perpendicular to the axis of the dipole) of a Horizontal Dipole a Half Wave Length Above an Earth of Finite Conductivity

change to be expected. Figures 9-8 through 9-12 illustrate the space wave vertical patterns of short vertical and horizontal dipoles above earths of various conductivities.

$n = \frac{x}{\epsilon_r}$ ϵ_r = Relative Dielectric Constant of Earth.

$x = \frac{18 \times 10^3 \sigma}{f_{nc}}$ σ = Conductivity

$\epsilon_r = 15$ For these examples.

$n = \infty$ Represents perfect ground case.

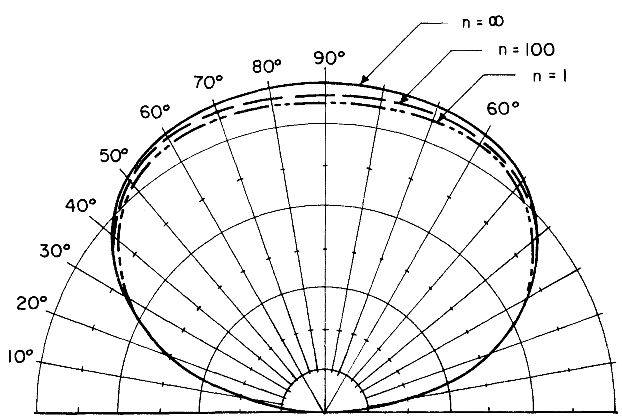


Figure 9-11. Vertical Radiation (in the plane perpendicular to the axis of the dipole) of a Horizontal Dipole a Quarter Wave Length Above an Earth of Finite Conductivity

For greater heights above the earth, the vertical pattern becomes multilobed. The approximate location of the maxima and minima of these patterns can be obtained by considering the perfect ground case shown in figure 9-6.

The most practical method of feeding a dipole antenna depends upon various considerations involved in the particular installation. Figure 9-13 shows

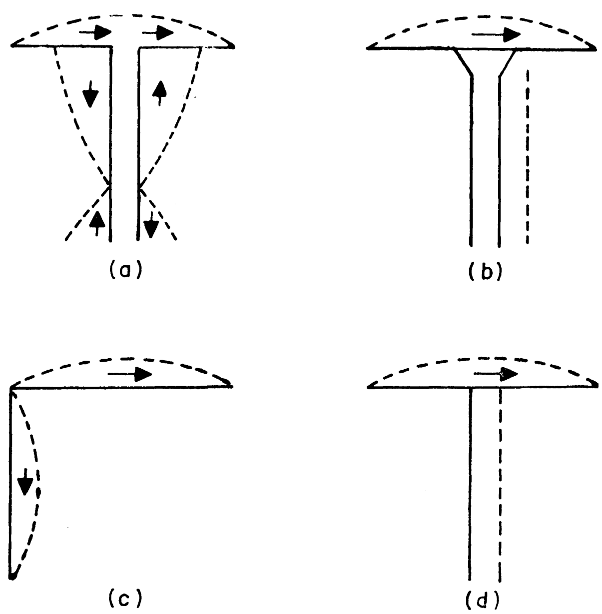


Figure 9-13. Common Methods of Exciting High-Frequency Antennas

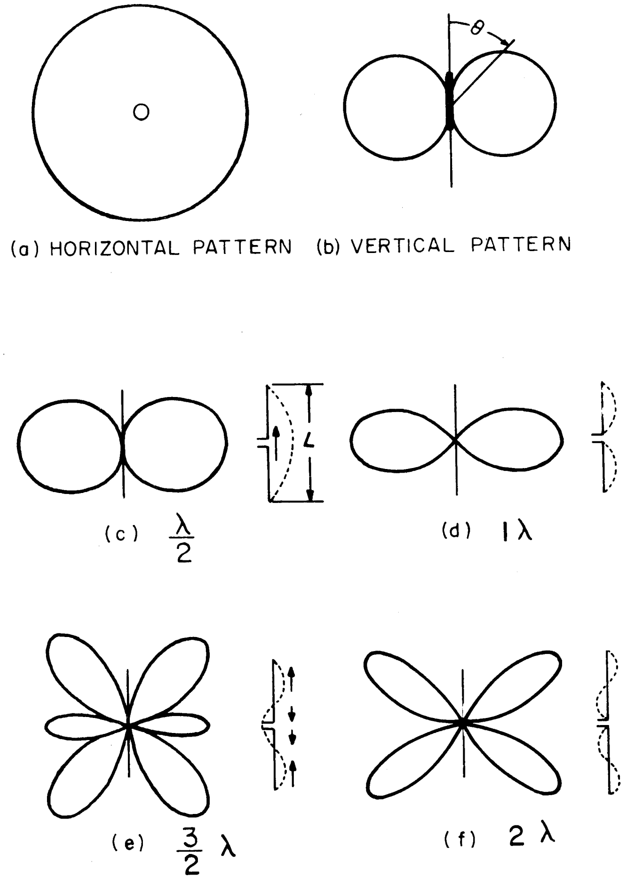


Figure 9-14. Radiation Patterns of Center-Fed Vertical Dipoles

several common methods of excitating high-frequency antennas. Figure 9-13(a) shows the balanced-line type of center feed. Because of the mismatch between the high characteristic impedance of open-wire lines and the low input resistance of a resonant dipole, this manner of excitation results in standing waves on the feed line as indicated in the figure. However, with solid dielectric, low-impedance lines, this mismatch can be almost completely eliminated. The "delta-match" or "shunt-feed" arrangement of figure 9-13(b) can result in a good impedance match and low standing waves on the feed line if the various dimensions are properly chosen. The simplest of all methods of excitation is the single-wire line "end-fed" arrangement of figure 9-13(c). In this case, the vertical "transmission line" also radiates energy; a result that may or may not be desired. By connecting the vertical wire at a lower impedance point along the horizontal antenna, as in figure 9-13(d), a better impedance match and lower standing-wave ratio on the feed line can be obtained. This results in less radiation from the vertical wire, which now carries a traveling-wave current distribution. Optimum dimensions for the types of feed shown in figure 9-13(b) and (d) are dependent on the height of the antenna above ground and upon the conductivity of the ground. These dimensions may best be determined by experiment in each case.

Although the directional properties of the elementary and half-wave dipoles have been illustrated in part previously, they are shown in figure 9-14 for convenience of comparison. The patterns shown are for free-space conditions and must be modified by the ground factor to represent actual conditions.

In the plane of polarization, the relative field intensity (radiation pattern) of the elementary or short dipole, as shown in figure 9-14(b), may be expressed by:

$$E(\Theta) = \sin \Theta$$

For the half-wave dipole of figure 9-14(c), the relative field intensity is:

$$E(\Theta) = \frac{\cos\left(\frac{\pi}{2} \cos \Theta\right)}{\sin \Theta}$$

For a dipole of any length (figures 9-14(d), (e), (f)), the relative field intensity is:

$$E(\Theta) = \frac{\cos \frac{2\pi H}{\lambda} - \cos\left(\frac{2\pi H}{\lambda} \cos \Theta\right)}{\sin \Theta}$$

where $H = \frac{L}{2}$ and λ = wave length.

The directional properties of actual dipoles are also affected by location of the feed points. Experimental patterns for several different conditions are illustrated in figure 9-15.

b. ELECTRICALLY SHORT ANTENNAS

At the lower frequencies where wave lengths are long, it often becomes impractical to employ antennas of resonant length. Some practical antennas at these frequencies are, therefore, electrically short and are usually of the vertical ground-based type. To attain an efficiency comparable to that of a half-wave antenna, the height of the vertical radiator should be $\frac{\lambda}{4}$, but when this is not possible, the effective height should be that corresponding to $\frac{\lambda}{4}$. An antenna that is much less than $\frac{\lambda}{4}$ in height exhibits poor impedance characteristics and becomes an inefficient radiator. As an example, the input impedance at the base of a vertical radiator of height $\frac{\lambda}{8}$ is in the order of -j500 ohms reactive and only about 8 ohms resistive. With this low radiation resistance, the ratio of power radiated to the power available from the transmitter is very small.

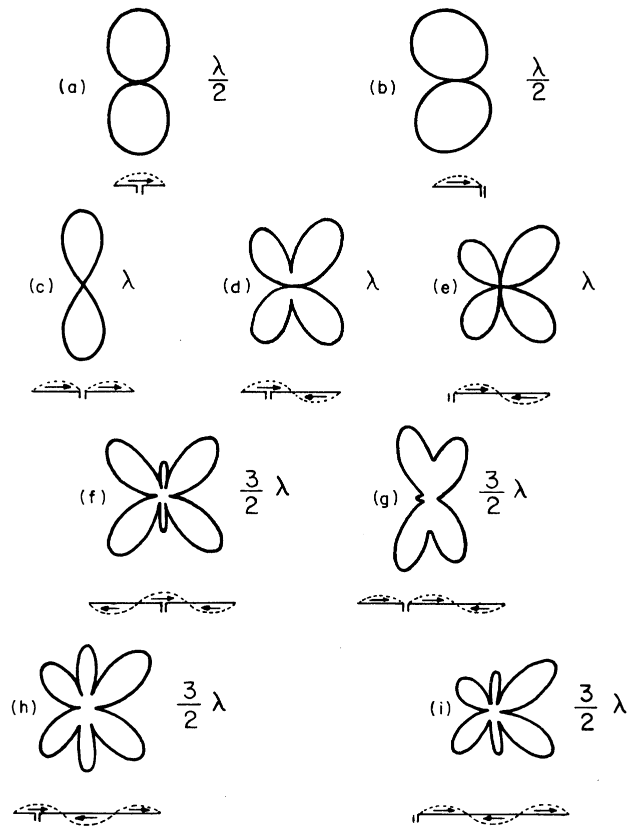


Figure 9-15. Experimental Patterns of Wire Antennas with Different Feed Points

There are several methods of improving or compensating for the poor input impedance of short antennas, but some yield more efficient operation than others. One of the more efficient methods is to increase the effective length of the antenna by top loading which consists of adding some form of capacity hat or a horizontal portion to the structure. The familiar L and T type radiators are of this class. This also has the effect of decreasing the large capacitive reactance of the short antenna (see figure 9-16).

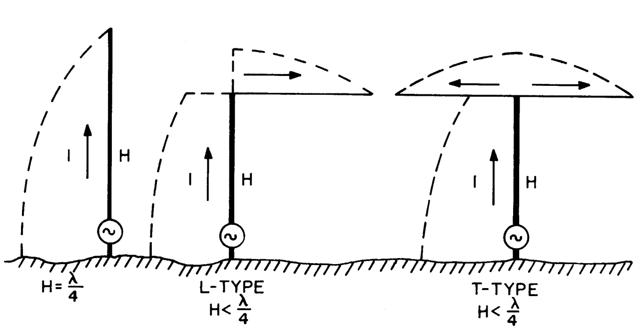


Figure 9-16. Top-Loaded Antennas

The radiation patterns of the L and T type antennas are essentially that of a short vertical monopole. Polarization is chiefly vertical because the largest amount of current is in the vertical portion of the radiator. There is, however, a small amount of horizontally polarized energy radiated due to the currents in the horizontal members. This radiation is small not only because these horizontal currents are small, but also because the horizontal portion of the antenna is close to ground and, therefore, close to its image. For a perfectly conducting ground, the image antenna carries an equal and opposite current which tends to cancel a large part of the horizontally polarized radiated field.

The decision as to which type of top loaded antenna to employ and the amount of top loading to use is usually dictated by the facilities available rather than by optimum design.

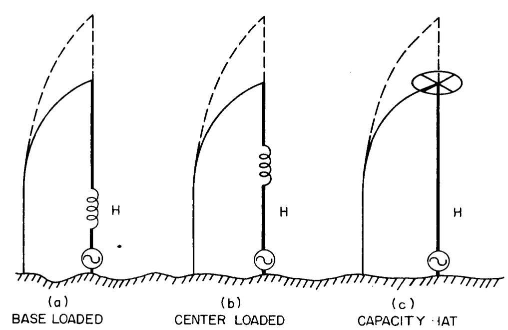


Figure 9-17. Current Distrubution for Short Vertical Antennas, $H < \frac{\lambda}{4}$

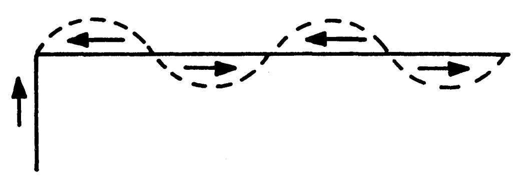
The electrical length of a radiator can be modified also by the insertion of a lumped reactance at one or more points along the radiator. In the case of the short vertical antenna, a series lumped inductance is commonly inserted to increase its effective length. This is referred to as base or center loading depending upon the placement of the loading coil. Because of the I^2R loss in the coil which is determined by the Q of the coil and the point in the radiator where the coil is inserted, this method of resonating the antenna is less efficient than that of top loading where distributed type circuit constants are employed. Losses with a given coil are greater when it is located at the base of the radiator than when it is located at the center, but to resonate the same antenna, a larger coil is required at the center than at the base. The capacity hat loading, that is, placing a disk or ring on the top of the short radiator, is more desirable, but because of the size of the hat required to resonate the antenna, it often becomes impractical. As a compromise, both the capacity hat and series inductance are often employed.

Antennas that are too long for resonance are not as often encountered as short antennas. However, if it is necessary to decrease the effective length of a long antenna, a series capacitance can be used just as the series inductance is used to increase the effective length of a short antenna. Although these methods are most often used with grounded vertical antennas, they apply equally well to suspended vertical or horizontal radiators.

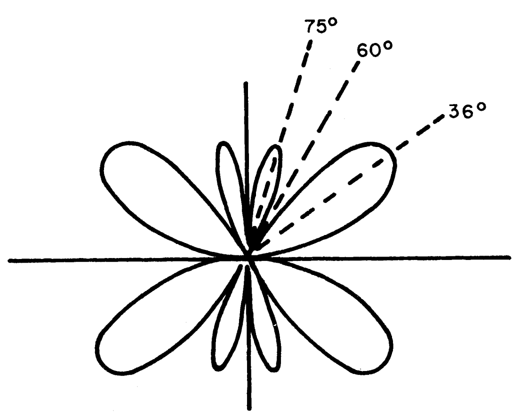
c. LONG WIRE ANTENNA

A single long wire radiator is the simplest form of directional antenna if its directivity is compared to that of a half-wave dipole. The performance of a single long wire, however, does not begin to compare with the performance of arrays which utilize a combination of long wires. The single long wire ordinarily is employed only for reasons of available space or convenience.

Figure 9-18 shows the radiation pattern and current distribution of an end-fed, 2λ, single wire in free space. This pattern is symmetrical with respect to the wire, with the major lobes in both forward and backward directions forming a three-dimensional cone. If the end-fed long wire is terminated in its characteristic impedance by means of a resistance



(a)



(b)

Figure 9-18. (a) Theoretical Current Distribution and (b) Radiation Pattern of a Two-Wave Length End-Fed Antenna

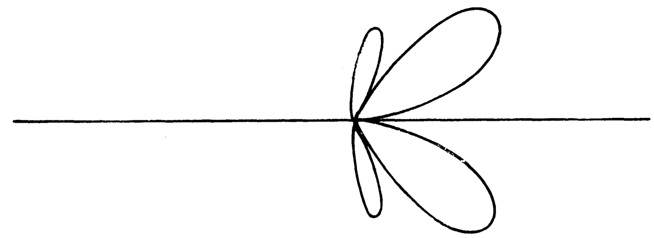


Figure 9-19. Radiation Pattern for Terminated 2λ Long Wire Antenna

connected from the far end to ground, the current distribution along it is essentially that of a traveling wave, and the resultant free-space pattern will be that of the forward lobe only as shown in figure 9-19.

The input impedance of such a terminated long wire will remain essentially constant due to the absence of standing waves on the antenna. Standing waves are the result of reflections from the end of the wire, but since the terminating resistance absorbs the energy at the end of the line, there is none to be reflected.

An antenna many wave lengths long will exhibit the properties of a terminated antenna because all of the energy traveling away from the transmitter will be radiated before it gets to the end of the antenna; consequently, there will be none left to reflect back toward the transmitter. Such an antenna is called a traveling wave antenna as opposed to an antenna which has a wave reflected from its end causing a standing wave. The number and position of the lobes of such an antenna depend on its length.

Two long wires arranged in the form of a "V" will, where the apex angle is optimum, provide good directivity. The two wires are fed at the apex of the V by means of a balanced line, so that equal currents of opposite phase flow in corresponding parts of the two wires. The apex angle is so chosen that the main lobes of the two long wires reinforce along the bisector of the V and tend to cancel in other directions. If a pair of two-wave length wires were used, the proper apex angle would be about 72°. In figure 9-20, lobes 1' and 1'' add to form lobe 1 of the resultant pattern as do lobes 3' and 3'' to form lobe 3. The rest of the major and minor lobes of the individual wires tend to cancel each other, and the result is a radiation pattern that is more directive than that of a single long wire.

It is possible to obtain a unidirectional characteristic by terminating the far end of each leg with the proper resistance to ground, but it is difficult to obtain good terminations of the type required; therefore, such an arrangement is seldom employed. The rhombic

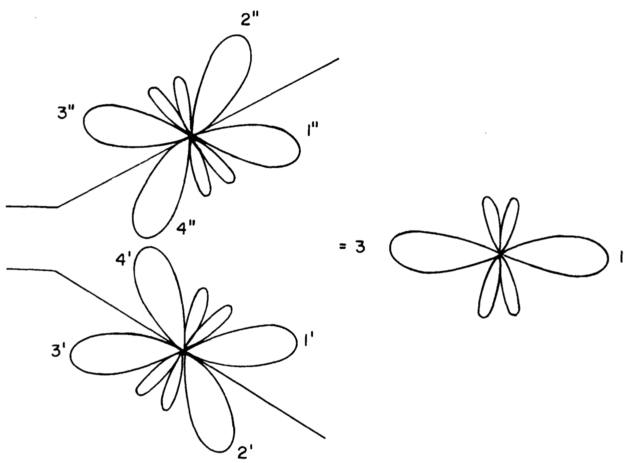


Figure 9-20. V Antenna

antenna is a much more satisfactory unidirectional antenna of the terminated type and is one of the most widely used high-frequency directional antennas in military and commercial service for point to point communication. The rhombic antenna consists of four, long wire radiating elements arranged in the shape of a rhombus, from which the antenna gets its name. The basic rhombic antenna is shown schematically in figure 9-21. The important dimensions are the leg lengths L, the tilt angle ϕ, the elevation above ground, and the terminating resistance R. The

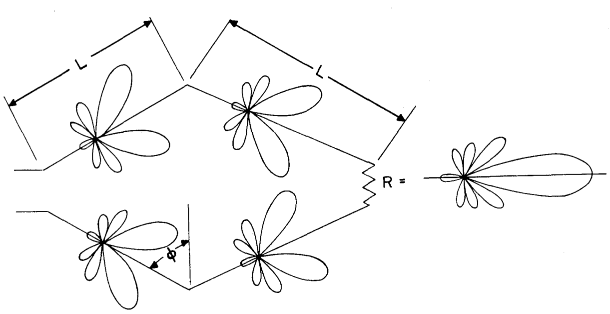


Figure 9-21. Rhombic Antenna

rhombic antenna is sometimes described, on the basis of its geometrical appearance, as two V antennas connected back to back and terminated to give a unidirectional pattern. The four long wires are arranged to produce reinforcement of the main lobes in the forward direction. This antenna is simple to construct, has high gain, is unidirectional, and most important, provides good performance over a broad frequency range. It has the disadvantage of requiring a large amount of real estate and provides less discrimination than a broadside curtain and reflector combination having comparable gain. Typical gains of practical size rhombic antennas employed in the high-frequency region range from about 8 to 15 db above that of a half-wave dipole at the same height above ground.

d. PHASED DIPOLE ARRAYS WITH PARASITIC ELEMENTS

When an element $\frac{\lambda}{2}$ in length is placed parallel and closer than about one-half wave length to a driven element, the mutual impedance is sufficient to cause a relatively large amount of current to flow in the undriven or "parasitic" element. Under these conditions the parasitic element will have appreciable effect upon the radiation pattern. By slightly detuning the parasitic element from resonance, variations in phase of the currents can be obtained with only a small effect upon the relative magnitude of current flowing in the parasitic element. The amount of current flowing in the parasitic element is chiefly a function of spacing. From a practical standpoint, however, the reduction in input resistance of the driven element with closer spacing limits the extent to which the relative current in the parasitic element may be increased.

An array consisting of one driven dipole element and one or more parasitic dipole elements is commonly known as a parasitic array or Yagi antenna (figure 9-22). It is most frequently designed to produce unidirectional pattern characteristics. A parasitic element is termed a reflector when it is behind the driven element in a unidirectional parasitic array, and a director when it is ahead of the driven element. More than one reflector is seldom employed in a simple parasitic array, but several directors are common.

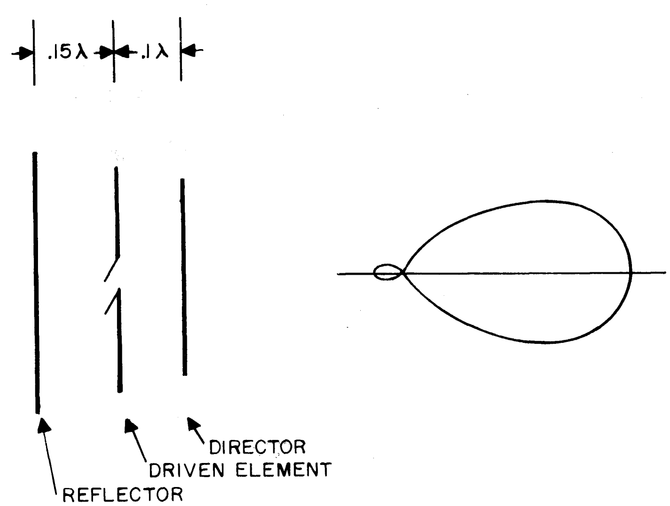


Figure 9-22. Three Element Parasitic Array

Parasitic elements are ordinarily tuned to give the desired amount and kind of reactance by control of their physical length. The parasitic element length which gives maximum gain usually does not provide maximum front to back discrimination for a particular spacing, however, adjusting the parasitic element length for maximum discrimination usually results in only a small reduction in forward gain.

One of the more popular parasitic arrays for high-frequency operation is the horizontal three element Yagi shown in figure 9-22. The director is about 5% shorter, and the reflector is about 5% longer than the resonant driven element. Although the actual directivity gain and front-to-back ratio depends on many parameters, an average gain of approximately 8 db above that of a $\frac{\lambda}{2}$ dipole, and a front-to-back ratio of about 18 db can be expected. The azimuth half-power beam width is about 50°. Its compact construction makes mechanical rotation a simple matter, and when so employed, the array usually is constructed of self-supporting tubular elements and often is referred to as a three-element rotary beam.

In no case can a conventional parasitic array qualify as a "broad-band" antenna, because even though extremely large diameter elements may be used, a moderate change in frequency seriously upsets the reactance and phase relationships of the various elements which in turn affect the directional characteristics.

e. THE FOLDED DIPOLE

If a half-wave radiator is constructed of two, identical, close-spaced, parallel conductors which are shorted at the ends and the combination is fed as shown in figure 9-23(a), equal and in phase currents may be considered to flow in each conductor. With this arrangement the current at the feed point for a given power is only half that which would flow in a single element alone, which means that the input impedance is four times as high. The center impedance of the dipole as a whole is the same as the impedance of a single conductor dipole (approximately 70 ohms). A given amount of power will therefore cause a definite value of current, I. In the ordinary half-wave dipole, this current flows at the junction of the line and the antenna. In the folded dipole the same current also flows, but is equally divided between two conductors in parallel. The current in each conductor is therefore $\frac{I}{2}$. Consequently, the line sees a higher impedance because it is delivering the same power at only half the current. Actually, the feed point impedance is slightly less than four times that presented by one of the conductors without the other present. This is because the effective length to diameter ratio (and therefore the radiation resistance)

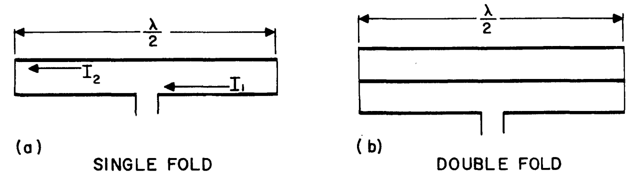


Figure 9-23. Half-Wave Folded Dipole

is lowered appreciably when the second conductor is added. The mean value of the feed point impedance in actual practice is about 250 ohms for effective heights greater than one-eighth wave length assuming horizontal polarization. The half-wave dipole formed in this way will have the same directional properties and total radiation resistance as an ordinary dipole. Figure 9-24 shows the impedance step-up ratio for the two conductor folded dipole.

The feed point impedance can be further increased by the three element arrangement shown in figure 9-23(b). For the case where the three conductors are identical and equally spaced, the effective impedance transformation is roughly nine times as compared to a single conductor alone. This raises the average input impedance in practical installations in which the effective height of the horizontal radiator exceeds one-eighth wave length to about 580 ohms.

The two element dipole method of increasing the impedance transformation is not recommended for ratios greater than 10, because the broad-band feature becomes degraded for extreme ratios. For ratios greater than 10, it is recommended that the desired transformation be obtained by increasing the number of conductors as in figure 9-23(b).

The folded dipole exhibits a flatter impedance versus frequency characteristic than a simple dipole. That is, the reactance varies rather slowly as the frequency is varied on either side of resonance, and the result is broader band operation. This flatter impedance versus frequency characteristic is due to the fact that the conductors in parallel form a single conductor of greater diameter and, in addition, the system as seen by the line is not only an antenna but also consists of two (or more) short-circuited quarter-wave transmission lines. As shown by transmission line theory, the reactance of a quarter-wave shorted section varies inversely as the reactance of the antenna with frequency. Thus, the two reactances cancel for an appreciable percentage of change in frequency.

f. REFLECTOR TYPE ANTENNAS (BILLBOARD)

The radiation from a single dipole element can be concentrated into a restricted solid angle by the use

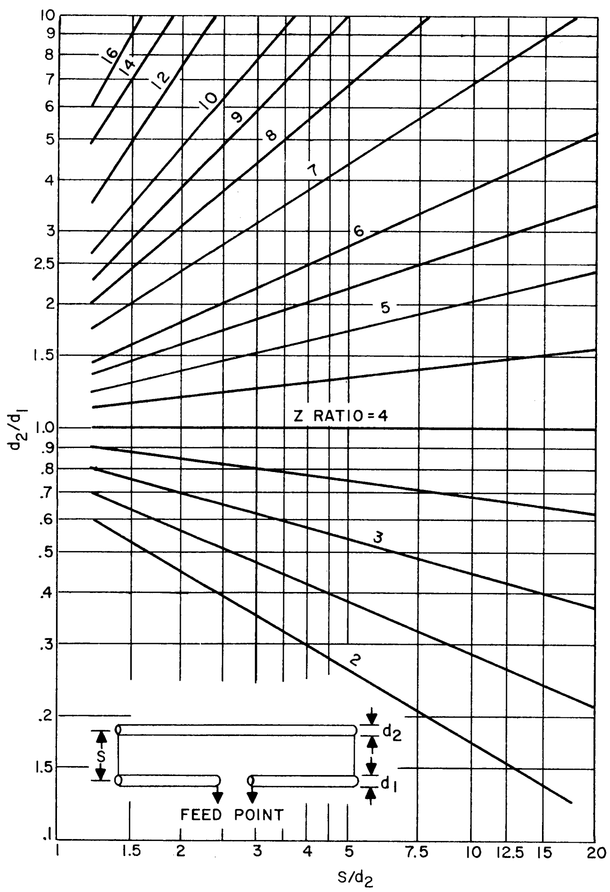


Figure 9-24. Impedance Step-Up Ratio

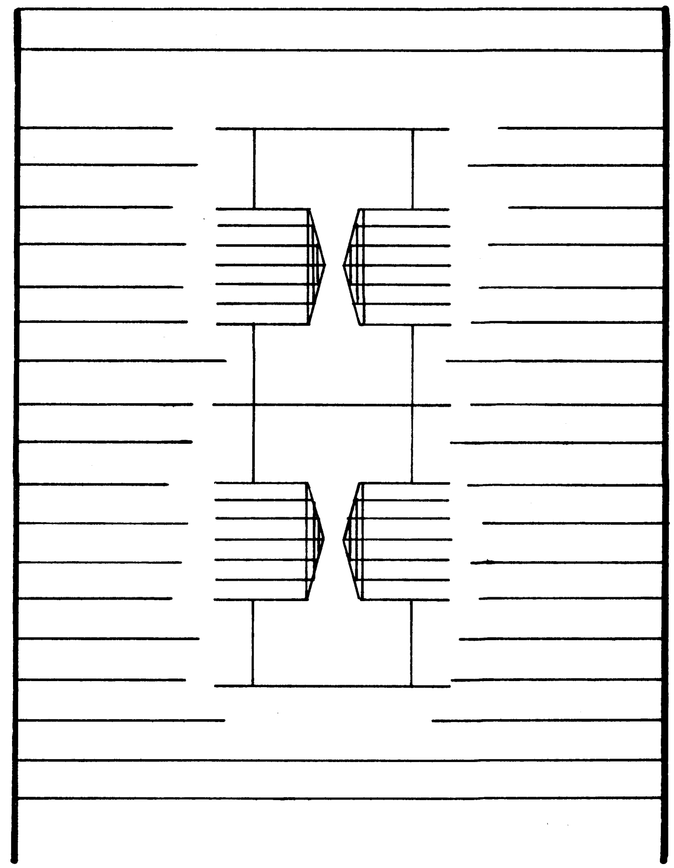


Figure 9-26. High-Frequency, Broad-Band, Billboard Antenna

of a reflecting screen, producing the same beaming effect as an array of dipoles. Although the reflecting screen can take any of numerous shapes, the most desirable being determined by the particular directivity pattern desired, mechanical design considerations usually limit the shape to a flat surface for operation in the high-frequency region, and is commonly referred to as a billboard antenna. The reflecting screen normally is made up of a curtain of equally spaced wires parallel to the dipole as shown in figure 9-25. With a single half-wave dipole spaced

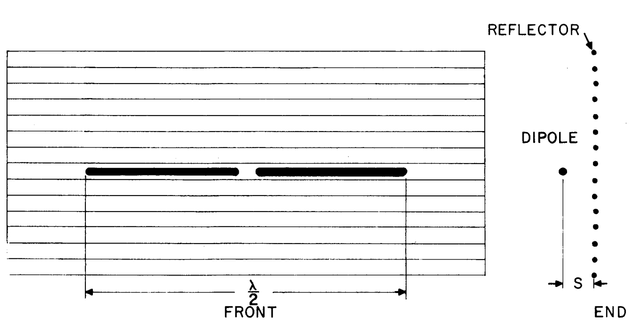


Figure 9-25. Billboard Antenna

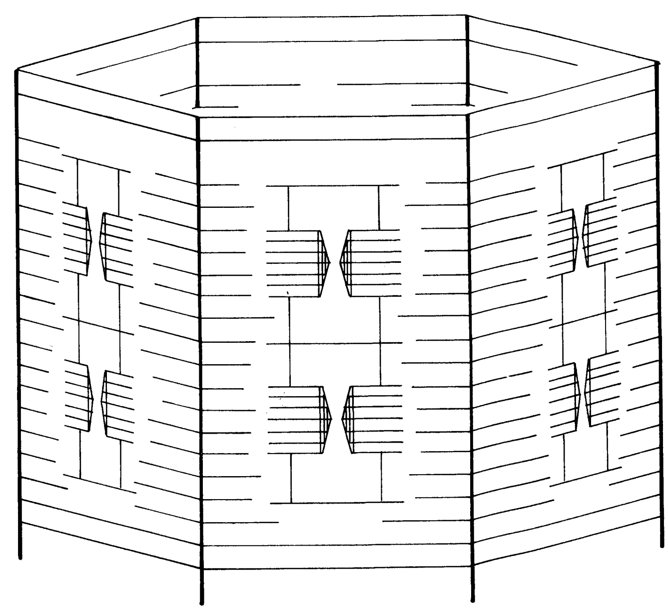


Figure 9-27. Steerable Beam Antenna

a quarter-wave from the screen, a gain of about 5.5 db over a free-space half-wave dipole can be realized. The half-power beam width in the plane of polarization is about 60° with essentially no secondary lobes. More directivity and consequently higher gain can be achieved by employing an array of dipoles in front of the screen.

Although this type of antenna usually is not considered to be broad band, a somewhat more complex structure as shown in figure 9-26 will cover a frequency range of 2:1 or greater with both patterns and input impedance remaining satisfactory. Azimuth half-power beam width varies from about 55° to 70° while the vswr remains under 2:1 over its 2:1 frequency range. The radiator consists of two vertically stacked broad-band (low Q) folded-type dipoles constructed of self-supporting tubular elements. Directivity gain depends on the mean height of the radiator above ground, but for practical heights, an average gain of about 13 db above that of a free-space half-wave dipole can be realized.

If a number of individual billboard-type antennas are arranged as shown in figure 9-27, and the proper switching is employed, an antenna system with a rotating or steerable beam is achieved. With the particular geometry shown, the azimuth beam is essentially that of a single billboard antenna. In more complex systems, however, several adjacent panels can be simultaneously and properly energized to form a more directive pattern. Directivity gains that are comparable to those of the high-frequency rhombic antenna would then be possible.

4. LOGARITHMICALLY PERIODIC ANTENNAS

a. PRINCIPLES OF OPERATION

Figure 9-28 illustrates one of an infinite variety of types of log periodic antennas. The two half structures are formed by transverse wires with their extremities alternately connected by radial wires and their centers connected with wires running the length of the structures. The two structures are fed against each other at their vertices by a balanced two wire line or a coaxial line running along the center line of one structure. The angles α and ψ define the exremities of the transverse wires and the orientation of the two half structures. The lengths of the transverse wires or the distances of the wires from the feed point are arranged so that they form a geometric sequence of terms. The geometric ratio, τ , which is defined in figure 9-28 by $R_n + 1/R_n$ determines the periodicity of the structure. If the structure was of infinite extent it can be seen that the electrical characteristics would be the same for any two frequencies related by some integral power of τ. When these characteristics are plotted on a logarithmic frequency scale, these frequencies are equally spaced with a separation or period of logarithm $1/\tau$. Thus the characteristics, such as the radiation pattern and input impedance, must repeat periodically with the logarithm of the frequency; hence the name log periodic antennas. Now, if the defining parameters can be adjusted such that the variation of electrical characteristics over one period is small, then this will hold true for all periods, the result being an extremely broadband antenna. A period of frequency is defined by the frequency range

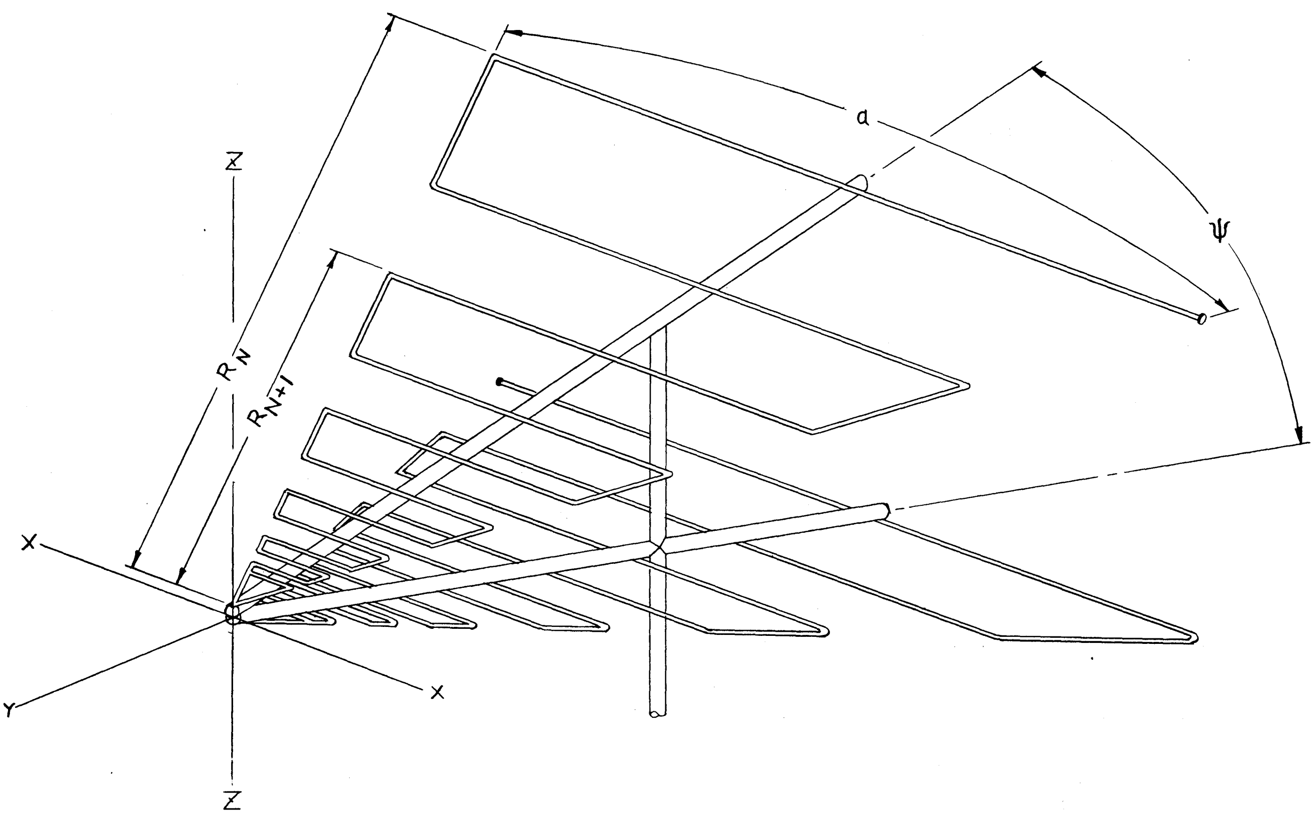


Figure 9-28. Log Periodic Antenna Showing Design Parameters

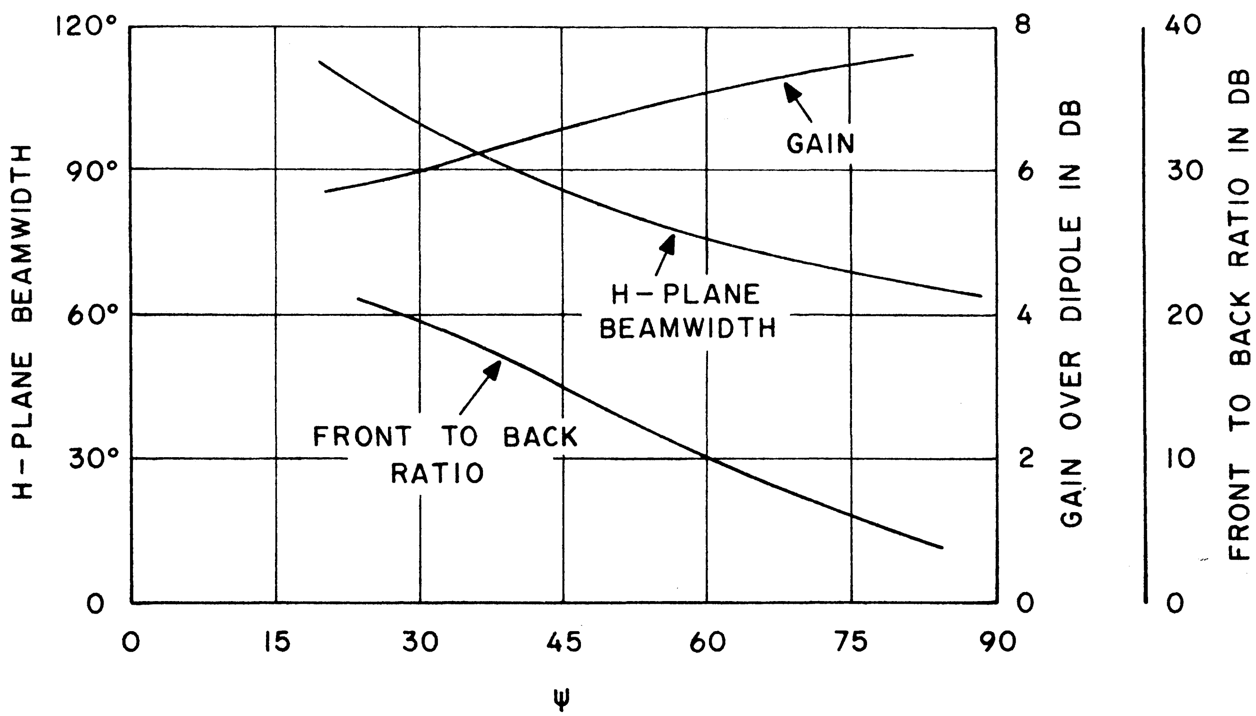


Figure 9-29. Effect of Angle ψ on Pattern Characteristics for Antenna with $\alpha = 60°$ and $\tau = .6$

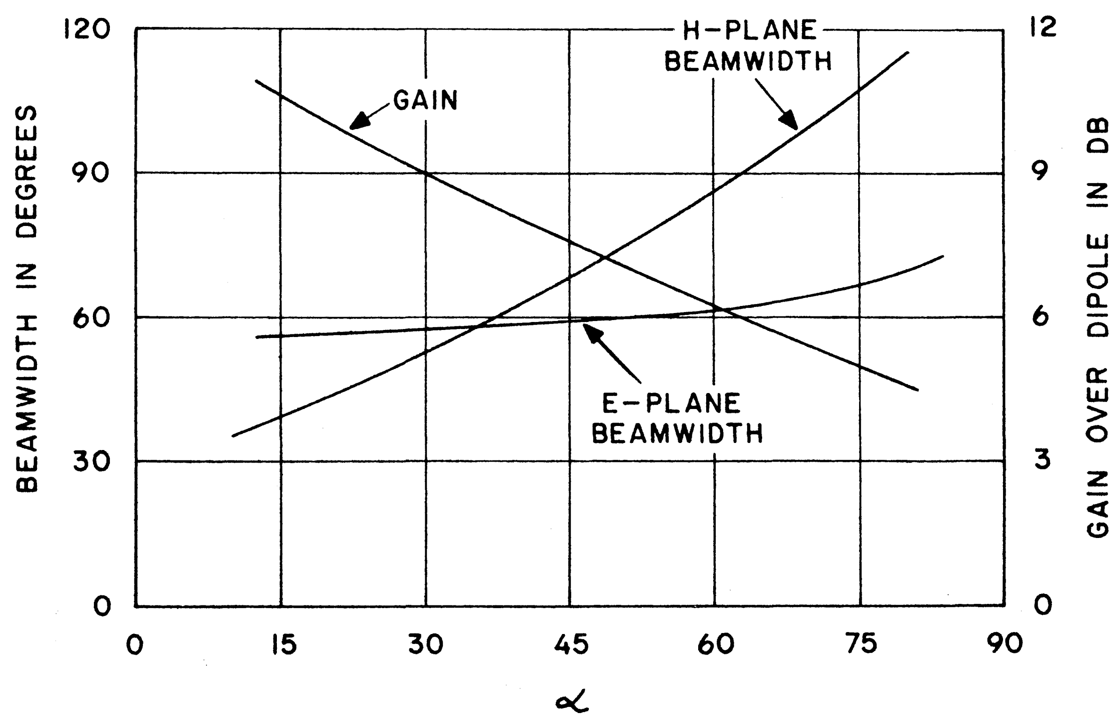


Figure 9-30. Effect of Angle α on Pattern Characteristics for Antenna with $\psi = 30°$

of τf to f. Fortunately, it has been found that even with finite structures, there are several types of log periodic structures for which the variation is negligible. Unfortunately, since log periodic antennas are too complex to analyze by present day theoretical methods, they must be investigated by logical experimental methods. However, their repetitive nature greatly simplifies the initial experimental investigation because the characteristics need only be measured over one period of frequency. The operation over other periods may be readily predicted.

The antenna of figure 9-28 produces a unidirectional beam in the direction of the positive Y axis (that is, in the direction that the structure points) with horizontal polarization. The low frequency limit of the antenna occurs when the longest transverse element is approximately 1/2 wavelength long. As the frequency is increased, a smaller and smaller portion of the antenna is used to produce the beam. As one progresses from the feed point, it is found that the magnitude of the currents drops off quite rapidly after the point where a 1/2 wavelength long transverse element exists. The high frequency limit is obtained when the shortest transverse element is approximately 3/8 of a wavelength long. The pattern characteristics are very similar to that obtained when the two half structures are replaced by two three-element Yagi antennas. These types of structures have a characteristic impedance ranging from 70 to 200 ohms depending upon the values of the design parameters. Although the input impedance is not quite frequency independent, the vswr of the input impedance referred to the characteristic impedance is less than 1.5:1 or 2:1 over the bandwidth of the antenna.

Figures 9-29 and 9-30 demonstrate the dependence of some of the electrical characteristics upon the design parameters of the structure of figure 9-28. In figure 9-29, the H-plane (YZ plane) beamwidth, front to back ratio, and gain are plotted versus the angle ψ with the parameters $\alpha = 60°$ and $\tau = .6$ held constant. For ψ equal to 180°, a bidirectional beam is produced. The E-plane (XY plane) beamwidth is nearly independent of the angle ψ and its value is 63°. Notice that if both high gain and front to back ratio are desired, a compromise value of ψ must be chosen. Figure 9-30 illustrates the variation of beamwidths and gain with the parameter ψ held constant. For these curves, the value of τ varies from .85 to .6 as α changes from 15° to 75°. Notice that the E-plane beamwidth is nearly independent of the parameter α. For high gain, it can be seen that small values of α are required. On the other hand, since the length of the longest transverse element is fixed for a given low frequency limit, the total length of the structure must be increased as α is made smaller. Thus, a compromise between gain and size of the structure must be made.

b. UNIDIRECTIONAL HF ROTATABLE ANTENNAS

There are many applications in high frequency communications for which log periodic antennas are very adaptable. Ground to air and ground to ground communications is an area which demands antennas

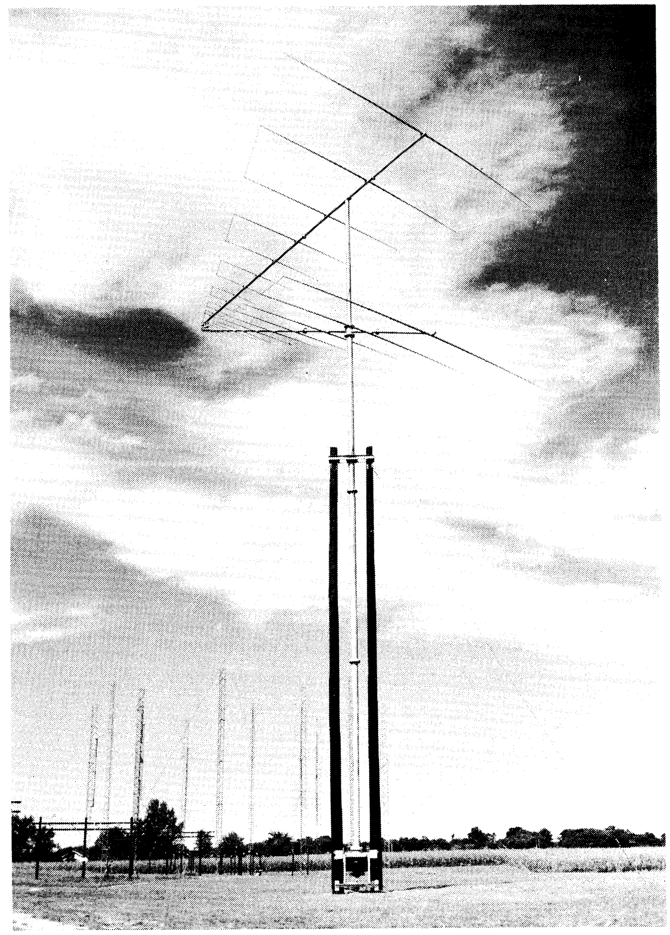


Figure 9-31. Collins Unidirectional Antenna 237A-2

with extreme bandwidths. Collins 237A-2 unidirectional antenna shown in figure 9-31 is well suited for this area of communications. The antenna, which is rotatable, covers the frequency range of 11.1 - 60 mc with a vswr less than 2:1. It provides a horizontally polarized unidirectional beam with a free space gain of 8 db over an istropic antenna with side-lobes greater than 16 db down. It has a power handling capacity of 50 kw peak power. In addition to the 237A-2 antenna which covers the 11.1 to 60 mc range, antennas with frequency ranges of 6.5 - 60 mc and 19-60 mc have also been developed.

The nature of these antennas is such that the characteristic impedance can vary from 100 - 200 ohms depending on the design parameters. In order to match this impedance to the 50 ohm input a broadband impedance tapered line is incorporated in the antenna. The tapered line is contained inside the lower boom and then brought down the vertical supporting mast. The vertical mast which supports the antenna, as well as the lower boom which supports the elements, are also used as the outer conductor of the coaxial feed line. At the bottom of the vertical supporting mast a transition is made in the coax to permit the use of a 3-1/8 inch rotary coaxial joint. This provides 360° azimuthal coverage.

c. POINT TO POINT UNIDIRECTIONAL ANTENNA

The HF Communications antenna problem is defined by the mode of propagation in this frequency range. From approximately 2 to 30 mc long distance communication is by means of refraction of waves directed into the earth's upper atmosphere by the ionized gases that are present there. Depending on the state of the ionosphere and the angle of incidence of the impinging wave there exists a maximum frequency at which the wave will be refracted back to earth. At frequencies greater than this maximum usable frequency (MUF) the waves penetrate the ionosphere and are useless for terrestial communication. Since the condition of the ionosphere is a function of time of day, latitude and sun spot cycle among other things the MUF over a long path may lie almost anywhere in the H.F. spectrum sometime in a period of months or years. Consequently, if a single antenna is to be used it must be usable over the entire high frequency spectrum. An additional consideration is the desirability of directing as much of the radiated energy as possible at the so called control point of a given path. The control point is that region or regions of the ionosphere in which the transmitted field is refracted back to earth in the direction of the receiving station. For a single hop path this region lies half way between the two stations. That part of the radiated energy that is not directed at the control point is lost as far as useful point to point communications is concerned.

Figure 9-32 shows a typical log periodic antenna which, when placed over ground, has the properties that its patterns, as well as impedance, are essentially independent of frequency. This means that the gain in a chosen direction above the horizon will be constant over any frequency range desired and can vary from 8 - 14 db over an isotropic radiator depending upon the design parameters.

It has been found that the phase center of these antennas is located a fixed number of wavelengths from their feed point. That is, the distance from the feed point to the phase center measured in wavelengths is constant. As a consequence of this phenomenon,

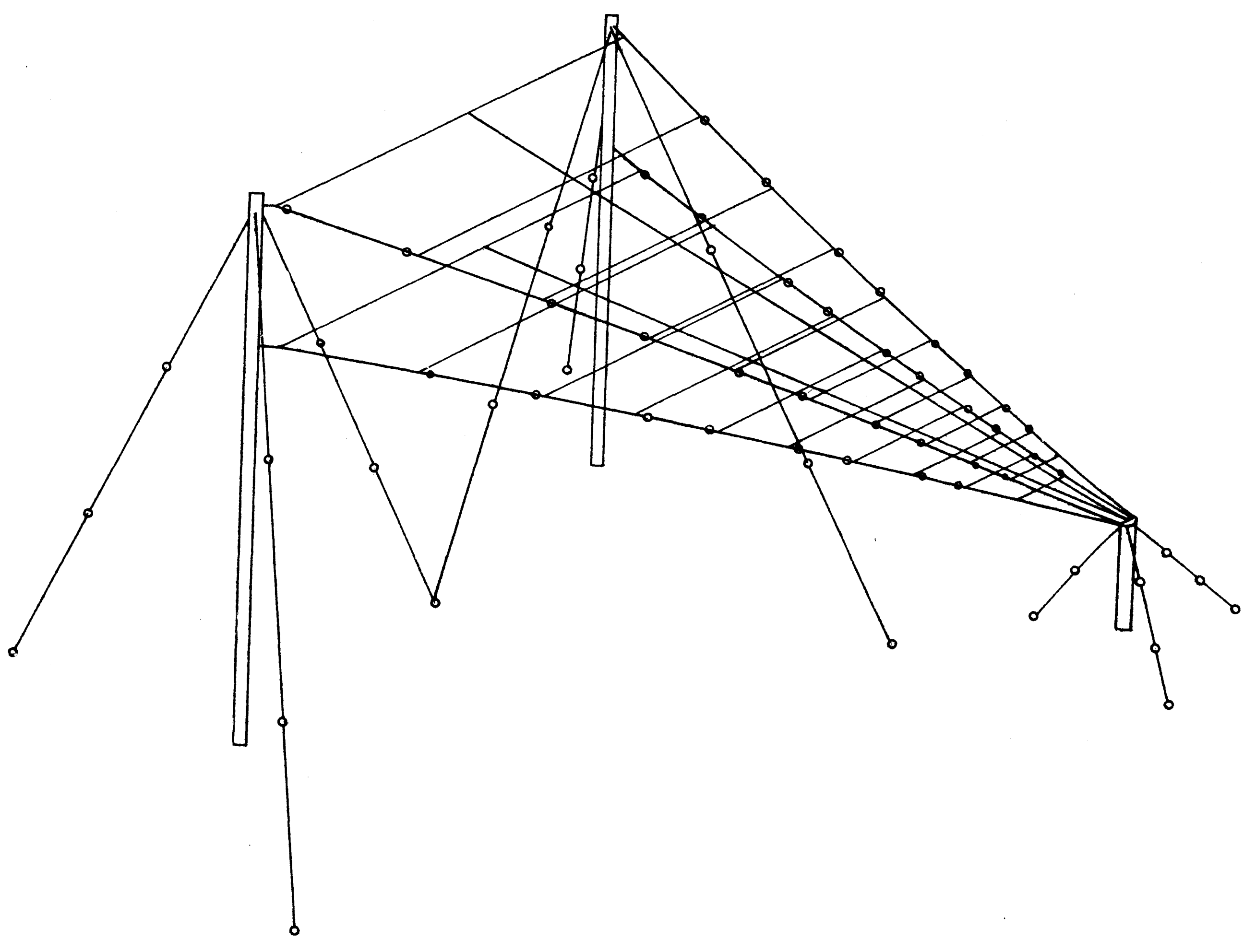


Figure 9-32. Logarithmically Periodic Antenna for Use in Point to Point Communications

when these antennas are placed at an angle with respect to ground and with their feed point at ground level, the distance from the ground to the antenna phase center measured in wavelengths is independent of frequency. The vertical plane pattern of antenna and ground system is therefore independent of frequency (to the same degree that the ground conductor and dielectric constant are independent of frequency) with the beam maximum occurring at an elevation angle determined by the angle at which the antenna is inclined to the ground. Also, an antenna of this nature produces a moderate gain (8 - 14 db over a dipole), and the maximum gain is realized over the entire frequency range. Other antennas of higher gain do not always have their main beam pointed at the desired angle and as a result, far less than maximum gain is quite often realized.

d. HORIZONTALLY POLARIZED OMNIDIRECTIONAL ANTENNAS

Still another type of log periodic antenna is the 237B series omnidirectional horizontally polarized antenna shown in figure 9-33. The antenna consists of two planar structures placed at right angles to each other and proportioned so as to produce an omnidirectional horizontally polarized radiation pattern. This structure is also of a repetitive nature so that its performance is essentially independent of frequency. With parameters of $\alpha = 97.5°$ and $\tau = .6$, a deviation of $\pm 1\frac{1}{2}$ db from omnidirectional is experienced with a maximum deviation of $\pm 2\frac{1}{2}$ db. The resultant cross polarization is 9 db down with minimum and maximum values of 7 db and 14 db respectively. The vswr of this antenna is less than 2:1 over the entire frequency range of the antenna. As in the case of the 237A antennas, the frequency ranges of the 237B antennas are 6.5 - 60 mc, 11.1 - 60 mc, and 19 - 60 mc.

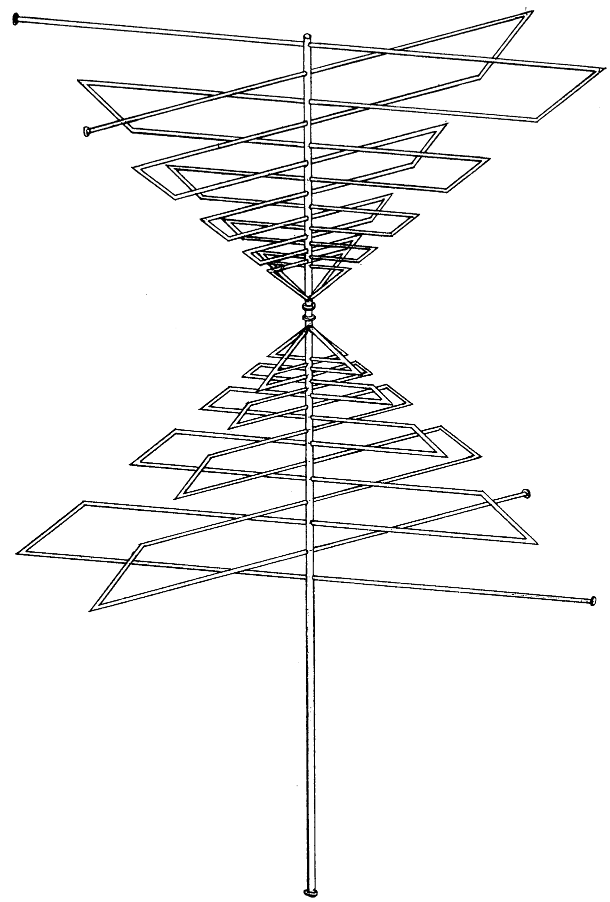


Figure 9-33. Horizontally Polarized Omnidirectional Antenna

These antennas represent a major advancement in the design of omnidirectional antennas. In the past, vertically polarized omnidirectional antennas have been designed which would operate over 3:1 or 4:1 frequency ranges with good impedance characteristics, but with radiation patterns that deteriorate at the high end of the frequency band. In addition, vertically polarized antennas are susceptible to extreme ground losses over poor earth. The 237B antennas are less susceptible to ground losses since they are horizontally polarized and their free space patterns are essentially independent of frequency.