TABLE OF CONTENTS

Chapter 1 — CD-ROM Content

Supplemental Articles

- "Radio Mathematics" — supplemental information about math used in radio and a list of online resources and tutorials about common mathematics

Chapter 1

Antenna Fundamentals

Where does the word "antenna" come from? As related by Dr. Ulrich Rohde, N1UL, the term originated with Guglielmo Marconi during early radio tests in 1895 during which he used wire "aerials" attached to a vertical tent pole. The aerial wire then ran down the pole to the transmitter. In Italian, a tent pole is known as "l'antenna central" and so the pole with the wire became simply, "l'antenna." In the beginning of radio, antennas were attached directly to generators and transmitters and were considered part of a common assembly. It wasn't until after 1900 that antennas began to be regarded as separate elements of the system, independent of the transmitter or receiver.

While there are an enormous variety of antennas, they share basic characteristics and all are designed to radiate and receive electromagnetic waves. In this chapter, we begin by defining what an electromagnetic wave is and how it is described. We then define the most important characteristics of an antenna — impedance, directivity and polarization — and show how those characteristics are measured and displayed. Finally, a section reviews how exposure to those waves affects the human body and the measures necessary for all amateurs to use antennas and electromagnetic waves safely.

1.1 INTRODUCTION TO ELECTROMAGNETIC FIELDS AND WAVES

1.1.1 E AND H FIELDS

In 1820 Hans Oerstad discovered that a current flowing in a wire would deflect the needle of a nearby compass. We attribute this effect to a magnetic or H-field, which at any given location is denoted by the letter **H**. The magnetic field's amplitude is expressed in A/m (Amperes/meter) along with a direction. (Direction can also be expressed as some value of phase with respect to a reference.) Because a magnetic field has *both* amplitude and direction, it is a *vector*. Symbols representing a vector are printed in bold-face.

Figure 1.1 shows a typical experimental arrangement that demonstrates the presence of a magnetic field. The shape of the magnetic field is roughly shown by the distribution of the iron filings. This field distribution is very similar to that around a vertical antenna.

A compass needle (a small magnet itself) will try to align itself parallel to **H**. As the compass is moved around the conductor, the orientation of the needle changes accordingly. The orientation of the needle gives the direction of **H**. If you attempt to turn the needle away from alignment you will discover a torque trying to restore the needle to its original

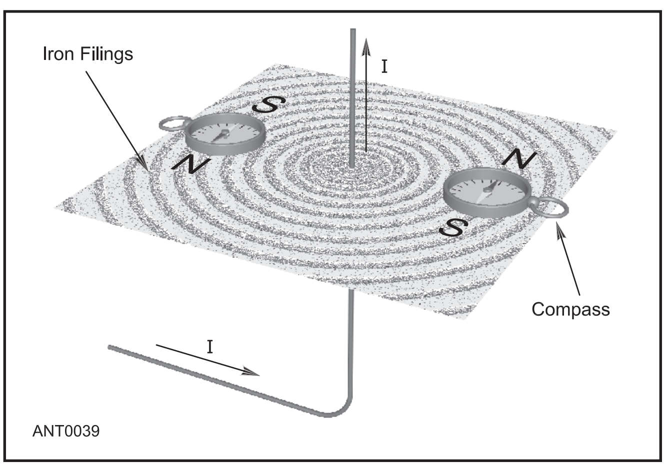


Figure 1.1 — Visualization of a magnetic field. The magnetic lines of force that surround a conductor with an electric current flowing in it are shown by iron filings and small compass needles. The needles point in the direction of the magnetic or H-field. The filings give a general view of the field distribution in the plane perpendicular to the conductor.

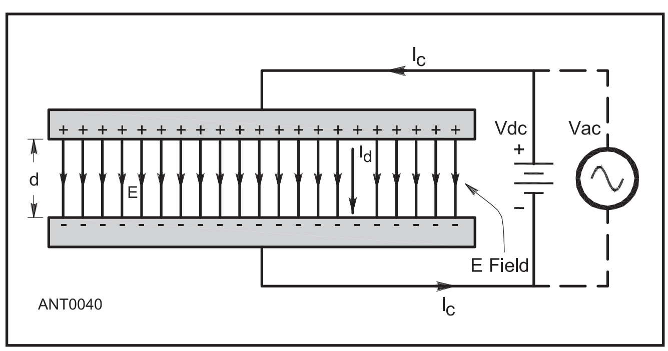


Figure 1.2 — Visualization of an electric field, $E=V_{dc}/d$. When the dc source is replaced with an ac source there will be a displacement current (I_d) flowing between the capacitor plates.

Math Tutorials

You will encounter a fair amount of intermediate-level mathematics in this book. If you would like to brush up on your math skills or learn about an unfamiliar topic, a list of free online math tutorials is included on the CD-ROM included with this book and on the ARRL website under "Math Tutorials" at **www.arrl.org/tech-prep-resource-library**.

position. The torque is proportional to the strength of the magnetic field at that point. This strength is called the *field intensity* or amplitude of H at that point. If a larger current flows in the conductor the amplitude of H will increase in proportion. Currents flowing in an antenna also generate an H-field.

An antenna will also have an electric or E-field, which can be visualized using a parallel-plate capacitor, as shown in **Figure 1.2**. If we connect a battery with a dc potential across the capacitor plates there will be an electric field E established between the plates, as indicated by the lines and directional arrows between the plates. (Like H, the electric field also has an amplitude and direction and so is a vector as well.) The magnitude of vector E is expressed in V/m (volts per meter), so for a potential of V volts and a spacing of d meters, E = V/d V/m. The amplitude of E will increase with voltage and/or a smaller separation distance (d). In an antenna, there will be ac potential differences between different parts of the antenna and from the antenna to ground. These ac potential differences establish the electric field associated with the antenna.

1.1.2 CONDUCTION AND DISPLACEMENT CURRENTS

If we replace the dc voltage source in Figure 1.2 with an ac source, an ac current will flow in the circuit. In the conductors between the ac source and the capacitor plates, current (I_c) flows, because of the movement of charge, usually electrons. But in the space between the capacitor plates (particularly in a vacuum) there are no charge carriers available to carry a conduction current. Nonetheless, current still flows in the complete circuit, and we attribute this to a *displacement current* (I_d) flowing between the capacitor plates to account for the continuity of current in the circuit. Displacement and conduction currents are two different phenomena but they both represent current, just two different kinds. Some observers prefer to call conduction currents "currents" and displacement currents "imaginary currents." That terminology is OK, but to account for the current flow in a closed circuit with capacitance you have to keep track of both kinds of current, whatever you call them. The accepted convention is to use the term "displacement current."

1.1.3 ELECTROMAGNETIC WAVES

An electromagnetic wave, as the name implies, is composed of both an electric field and a magnetic field that vary with time. Electric and magnetic fields that do not change with time, such as those created by a dc current or voltage, are called *electrostatic fields*. The fields of a radio wave are created by an ac current in an antenna, usually having the form of a sine wave. As a result, the fields in a radio wave vary in the same sinusoidal pattern, increasing and decreasing in strength and reversing direction with the same frequency, f, as the ac current. It is the movement of electrons — specifically the acceleration and deceleration as the ac current moves back and forth — that creates the electromagnetic wave.

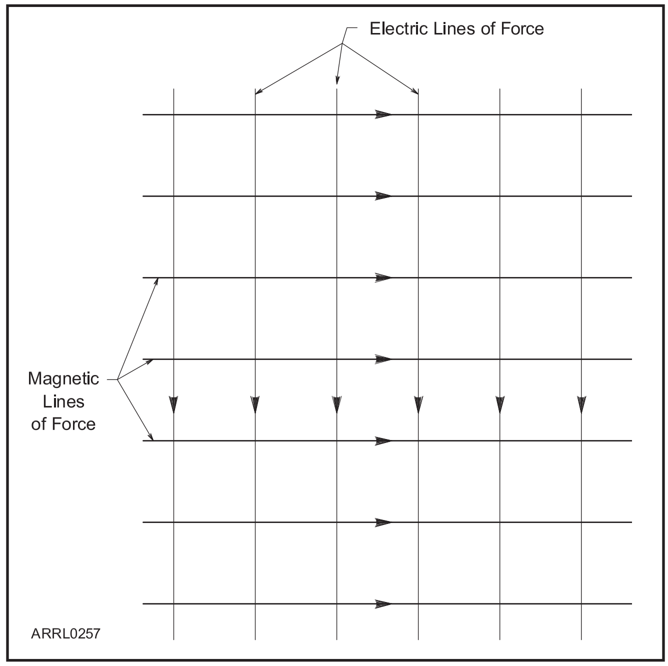


Figure 1.3 — Representation of electric and magnetic lines of force in an electromagnetic wavefront. Arrows indicate the instantaneous directions of the fields for a wavefront in a wave traveling toward you, out of the page. Reversing the direction of one of the fields would also reverse the direction of the wave.

The two fields of the electromagnetic wave are oriented at right angles to each other as shown by **Figure 1.3**. The term "lines of force" in the figure means the direction in which a force would be felt by an electron (from the electric field) or by a magnet (from the magnetic field). The direction of the right angle from the electric field to the magnetic field, clockwise or counterclockwise, determines the direction the wave travels, as illustrated in the figure. This is called a *propagating wave*.

To an observer staying in one place, such as a stationary receiving antenna, the electric and magnetic fields of the wave appear to oscillate as the wave passes. That is, the fields create forces on electrons in the antenna that increase and decrease in a sine wave pattern. Some of the energy in the propagating wave is transferred to the electrons as the forces from the changing fields cause them to move. This creates a sine wave current in the antenna with a frequency determined by the rate at which the field strength changes as the wave passes.

If the observer is moving in the same direction as the wave and at the same speed, however, the strength of the fields will not change. To that observer, the electric and magnetic field strengths are fixed, as in a photograph. This is a *wavefront* of the electromagnetic wave; a flat surface or plane moving through space on which the electric and magnetic fields have a constant value as illustrated in Figure 1.3.

Just as an ac voltage is made up of an infinite sequence of instantaneous voltages, each slightly larger or smaller than the next, an infinite number of wavefronts make up a propagating electromagnetic wave, one behind another like a deck of cards. The direction of the wave is the direction in which the wavefronts move. The fields on each successive wavefront have a slightly different strength so as they pass a fixed location, the detected field strength changes as well. The fixed observer "sees" fields with strengths that vary as a sine wave.

Figure 1.4 is a drawing of what would happen if we could suddenly freeze all of the wave-fronts in the wave and take measurements of the electric and magnetic field strengths in each. In this example, the electric field is oriented vertically and the magnetic field horizontally. (Each of the vertical lines in the electric field can be thought of as representing an individual wavefront.) All of the wavefronts are moving in the direction indicated — the whole set of them moves together at the same speed. As the wave — the set of wavefronts — moves past the receiving antenna, the varying field strengths of the different wavefronts is perceived as a continuously changing wave. What we call a "wave" is really this entire group of wavefronts moving through space.

One more important note about electromagnetic waves: The electric and magnetic fields are *coupled*, that is they are both aspects of the same entity, the electromagnetic wave. They are not perpendicular electric and magnetic fields that simply happen to be in the same place at the same time! The fields cannot be separated, although the energy in the wave can be detected as electric or magnetic force. The fields are created as a single entity — an electromagnetic wave — by the motion of electrons in the transmitting antenna.

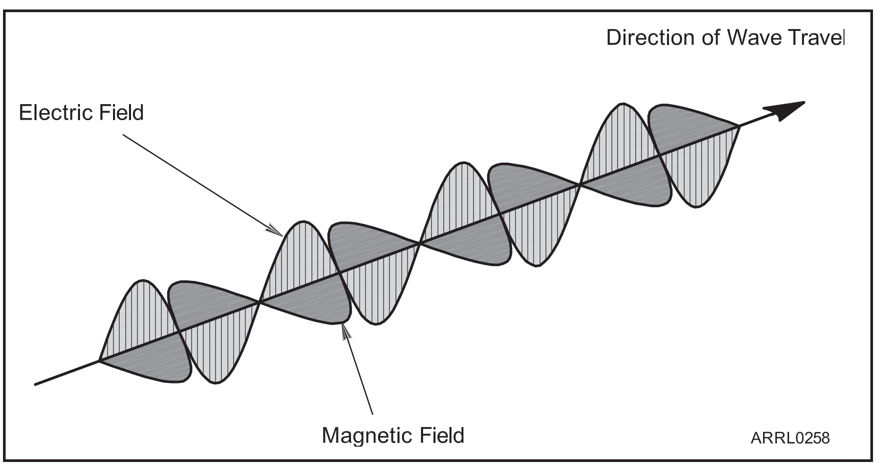


Figure 1.4 — Representation of the magnetic and electric field strengths of an electromagnetic wave. In the diagram, the electric field is oriented vertically and the magnetic field horizontally.

Speed of Propagation and Wavelength

Because the velocity of wave propagation is so great, we tend to ignore it. Only ⅐ of a second is needed for a radio wave to travel around the world — but in working with antennas the time factor is extremely important. The wave concept evolved because an alternating current flowing in a wire (antenna) creates propagating electric and magnetic fields. We can hardly discuss antenna theory or performance at all without involving travel time, consciously or otherwise.

Electromagnetic waves propagate at the speed of light for the medium through which they travel. The speed of light is highest in the vacuum of free space, approximately 300 million or 3×10^8 meters per second. It is often more convenient to remember the speed as 300 m/µs. (A more exact value is 299.7925 m/µs). This is called the wave's *velocity of propagation* and is represented by the familiar "speed of light" symbol, c.

It is also useful to know a radio wave's *wavelength* — the distance traveled during one complete cycle of a wave. Since one complete cycle takes 1/f the velocity of a wave is the speed of light, c, the wavelength, λ, is thus:

$$\lambda = c / f \qquad (1)$$

In free-space

$$\lambda = 299.7925 \times 10^6 / f$$

where λ is the free-space wavelength in meters.

More convenient approximate formulas for use at radio frequencies are:

$$\lambda \text{ in meters} = 300 / f \text{ in MHz, and} \qquad (2a)$$

$$\lambda \text{ in feet} = 983.6 / f \text{ in MHz} \qquad (2b)$$

The ratio between the wave's velocity in a specific medium and that of free space is called the medium's *velocity factor* (VF) and is a value between 0 and 1. If the medium is air, the reduction in velocity of propagation can be ignored in most discussions of propagation at frequencies below 30 MHz. In the VHF range and higher, temperature and moisture content of the medium have increasing effects on the communication range, as will be discussed later in the **Radio Wave Propagation** chapter. In materials such as glass or plastic the wave's velocity can be quite a bit lower than that of free space. For example, in polyethylene (commonly used as a center insulator in coaxial cable), the velocity of propagation is about ⅔ that in free space. In distilled water (a good insulator) the speed is about ⅑ that of free space.

Phase of Waves

There will be few pages in this book where phase, wavelength and frequency do not enter the discussion. It is essential to have a clear understanding of their meaning in order to understand the design, installation, adjustment or use of antennas, matching systems or transmission lines in detail. In essence, *phase* means *time*. When something goes through periodic variations as an alternating current does, corresponding instants in succeeding periods are *in phase*.

It is important to distinguish between phase and *polarity*. Polarity is simply a convention that assigns a positive and negative direction or convention. Reversing the leads on a feed line reverses a signal's polarity but does not change its phase.

Phase is a relative measure of time within and between waveforms. The points A, B and C in **Figure 1.5** are all in phase. They are corresponding instants in the current flow, at intervals of 1 λ. The distance between A and B or between B and C is one wavelength. This is a conventional view of a sine wave alternating current, with time progressing to the right. It also represents the *instantaneous* value of intensity of the traveling fields, if distance is substituted for time in the horizontal axis. The field-intensity distribution follows the sine curve, in both amplitude and polarity, corresponding exactly to the time variations in the current that produced the fields. Remember that this is an *instantaneous* picture of the many wavefronts similar to Figure 1.4.

Waves used in radio communication may have frequencies from about 10,000 to several billion Hz. Suppose the frequency is 30 MHz. One cycle, or period, is completed in 1/30,000,000 second. The wave is traveling at 300,000,000 meters per second through the air, so it will move only 10 meters during the time that the current is going through one complete period of alternation. The electromagnetic field 10 meters away from the antenna is caused by the current that was flowing one period earlier in time. The field 20 meters away is caused by the current that was flowing two periods earlier, and so on.

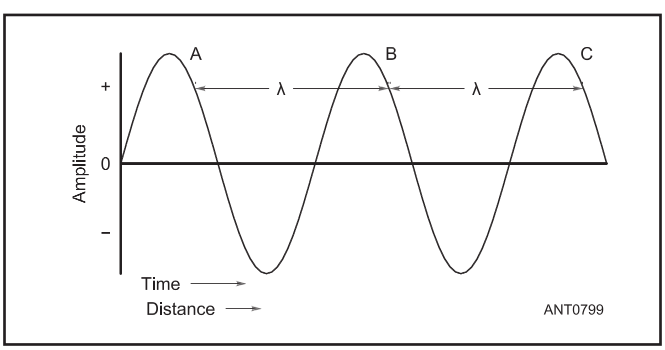


Figure 1.5 — The instantaneous amplitude of both fields (electric and magnetic) varies sinusoidally with time as shown in this graph. Since the fields travel at constant velocity, the graph also represents the instantaneous distribution of field intensity along the wave path. The distance between two points of equal phase such as A-B and B-C is the wave's wavelength.

If each period of the current is simply a repetition of the one before it, the currents at corresponding instants in each period will be identical. The fields caused by those currents will also be identical. As the fields move outward from the antenna they become more thinly spread over larger and larger spherical surfaces centered on the antenna. The field amplitudes decrease with distance from the antenna but they do not lose their identity with respect to the instant of the period at which they were generated. They are, and they remain, in phase. In the example above, on the spherical surfaces separated by intervals of 10 meters measured outward from the antenna, the phase of the waves at any given instant is identical.

These spherical surfaces are the wavefronts described earlier. When the sphere is so large that the surface is essentially flat, the wavefront is called a *plane wave*. On every part of this surface, the wavefront, the wave has the same phase. The wavelength is the distance between two wavefronts having the same phase at any given instant. This distance must be measured perpendicular to the wave fronts along the line that represents the direction of travel.

Wave Polarization

A wave like that in Figure 1.3 is said to be *polarized* in the direction of the electric lines of force. The polarization here is vertical, because the electric lines are perpendicular to the surface of the Earth. If the electric lines of force are horizontal, the wave is said to be horizontally polarized. Horizontally and vertically polarized waves may be classified generally under *linear polarization*. Linear polarization can be anything between horizontal and vertical. In free space, "horizontal" and "vertical" have no meaning, since the reference of the seemingly horizontal surface of the Earth has been lost.

In many cases the polarization of waves is not fixed, but rotates continually, sometimes at random. When this occurs the wave is said to be *elliptically polarized*. A gradual shift in polarization in a medium is known as *Faraday rotation*. For space communication, *circular polarization* is commonly used to overcome the effects of Faraday rotation. A circularly polarized wave rotates its polarization through 360° as it travels a distance of one wavelength in the propagation medium. The direction of rotation as viewed from the transmitting antenna defines the direction of circularity — right-hand (clockwise) or left-hand (counterclockwise). Linear and circular polarization may be considered as special cases of elliptical polarization.

Field Intensity

The energy from a propagated wave decreases with distance from the source. This decrease in strength is caused by the spreading of the wave energy over ever-larger spherical surfaces as the distance from the source increases.

A measurement of the strength of the wave at a distance from the transmitting antenna is its *field intensity*, which is synonymous with *field strength*. The strength of a wave is measured as the voltage between two points lying on an electric line of force in the plane of the wave front. The standard of measure for field intensity is the voltage developed in a wire that is 1 meter long, expressed as volts per meter. (If the wire were 2 meters long, the voltage developed would be divided by two to determine the field strength in volts per meter.)

The voltage in a wave is usually low so the measurement is made in millivolts or microvolts per meter. The voltage goes through time variations like those of the current that caused the wave. It is measured like any other ac voltage — in terms of the RMS value or, sometimes, the peak value. It is fortunate that in amateur work it is not necessary to measure actual field strength as the equipment required is elaborate. We need to know only if an adjustment has been beneficial, so relative measurements are satisfactory. These can be made easily with home-built equipment.

Wave Attenuation

In free space, the field intensity of the wave varies inversely with the distance from the source, once in the radiating far field of the antenna. If the field strength at 1 mile from the source is 100 millivolts per meter, it will be 50 millivolts per meter at 2 miles, and so on. The relationship between field intensity and power density is similar to that for voltage and power in ordinary circuits. They are related by the impedance of free space, which is approximately 377 Ω. A field intensity of 1 volt per meter is therefore equivalent to a power density of

$$P = \frac{E^2}{Z} = \frac{1\ (\text{volt}/\text{m})^2}{377\ \Omega} = 2.65\,\text{mW}/\text{m}^2 \tag{3}$$

Because of the relationship between voltage and power, the power density varies with the square of the field intensity, or inversely with the *square* of the distance. If the power density at 1 mile is 4 mW per square meter, then at a distance of 2 miles it will be 1 mW per square meter.

It is important to remember this so-called *spreading loss* when antenna performance is being considered. Gain can come only from narrowing the radiation pattern of an antenna, which concentrates the radiated energy in the desired direction. There is no "antenna magic" by which the total energy radiated can be increased.

In practice, attenuation of the wave energy may be much greater than the inverse-distance law would indicate. The wave does not travel in a vacuum and the receiving antenna seldom is situated so there is a clear line of sight. The Earth is spherical and the waves do not penetrate its surface appreciably, so communication beyond visual distances must be by some means that will bend the waves around the curvature of the Earth. These means involve additional energy losses that increase the path attenuation with distance, above that for the theoretical spreading loss in a vacuum.

1.2 ANTENNA IMPEDANCE

1.2.1 RADIATION RESISTANCE AND EFFICIENCY

The power supplied to an antenna is dissipated in two ways: radiation of electromagnetic waves and heat losses in the wire and nearby conductors and dielectrics material. The radiated power is what we want, the useful part, but it represents a form of "loss" just as much as the power used in heating the wire or nearby dielectrics is a loss. In either case, the dissipated power is equal to I^2R.

In the case of heat losses, R is a real resistance. In the case of radiation, however, R is a "virtual" resistance, which, if replaced with an actual resistor of the same value, would dissipate the power actually radiated from the antenna. This resistance is called the *radiation resistance* to the radiated electromagnetic wave, also called the *radiation reaction*. Radiation resistance is discussed at great length in Chapter 2 of Kraus's *Antennas* (see Bibliography) for the interested reader. The total power in the antenna is therefore equal to $I^2 (R_r+R)$, where R_r is the radiation resistance and R represents the total of all the loss resistances. Radiation efficiency is defined as:

$$\eta = \frac{R_r}{R_r + R} \tag{4}$$

where loss resistance (*R*) is calculated from (or normalized to) the same point at which R_r is determined. As *R* is reduced, the antenna's radiation efficiency increases.

In antennas that are not electrically small compared to the signal wavelength or that are close to or connected to the ground, the power lost as heat in the conductor does not exceed a few percent of the total power supplied to the antenna. Expressed in decibels, the loss is less than 0.1 dB. The RF loss resistance of copper wire even as small as #14 AWG is very low compared with the radiation resistance of an antenna that is reasonably clear of surrounding objects and is not too close to the ground. You can therefore assume that the ohmic loss in a reasonably well-located antenna is negligible and that the total resistance shown by the antenna (the feed point resistance) is radiation resistance. As a radiator of electromagnetic waves, such an antenna is a highly efficient device.

For antennas that are electrically small, incorporate loading or tuning circuits, or rely on the ground as a path for current, the power losses can be substantial. In these cases, such as small loops, mobile antennas, and vertical monopoles, it is important to reduce loss resistance wherever possible by using high-quality materials, insuring that connections are secure and low-loss, and providing the lowest-loss current path practical.

1.2.2 CURRENT AND VOLTAGE DISTRIBUTION

When power is fed to an antenna, the current and voltage vary along its length. The current is minimum at the ends, regardless of the antenna's length. The current does not actually reach zero at the current minima, because of capacitance

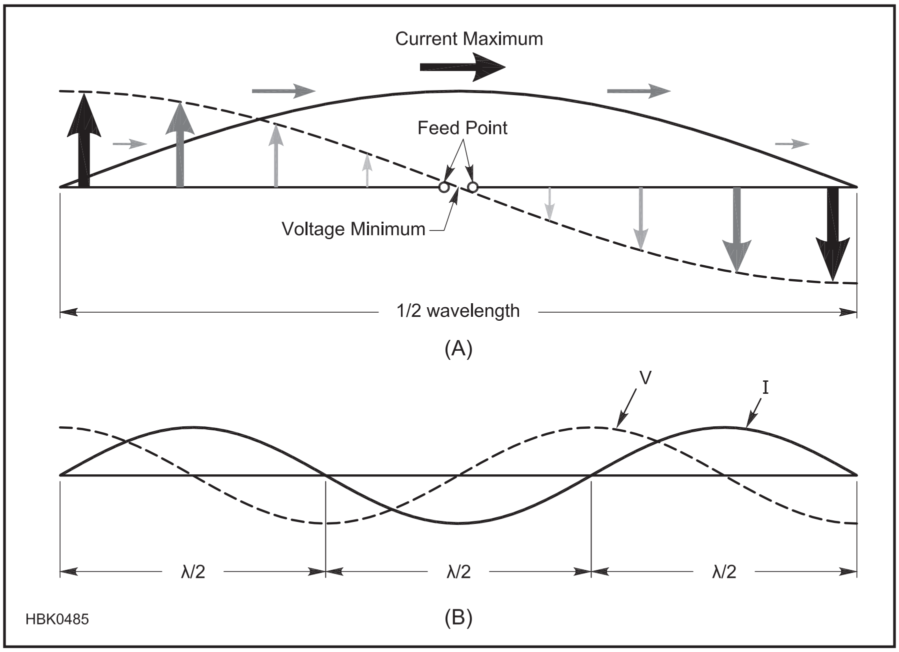


Figure 1.6 — The current and voltage distribution along a half-wave dipole (A) and for an antenna made from a series of half-wave dipoles.

at the antenna ends. Insulators, loops at the antenna ends and support wires all contribute to this capacitance, which is also called the *end effect*. The opposite is true of the RF voltage. That is, there is a voltage maximum at the ends.

In the case of a half-wave antenna there is a current maximum at the center and a voltage minimum at the center as illustrated in **Figure 1.6**. The pattern of alternating current and voltage minimums ¼ wavelength apart repeats every ½ wavelength along a linear antenna as shown in Figure 1.6B. The phase of the current and voltage are inverted in each successive half-wavelength section.

1.2.3 FEED POINT IMPEDANCE

Since amateurs are free to choose our operating frequencies within assigned bands we need to consider how the feed point impedance of a particular antenna varies with frequency within a particular band or even in several different bands if we intend to use one antenna on multiple bands.

There are two forms of impedance associated with any antenna: *self impedance* and *mutual impedance*. As you might expect, self impedance is what is measured at the feed point terminals of an antenna located completely away from the influence of any other conductors.

Self Impedance

The current that flows into an antenna's feed point must be supplied at a finite voltage. The self impedance of the antenna is simply equal to the voltage applied to its feed point divided by the current flowing into the feed point according to Ohm's Law. Where the current and voltage are exactly in phase, the impedance is purely resistive with zero reactance and the antenna is *resonant*. (Amateurs often use the term "resonant" rather loosely, usually meaning "nearly resonant" or "close-to resonant." Resonance has nothing to do with the value of the impedance, only that it is purely resistive.)

Except at the one frequency where it is exactly resonant, the current in an antenna has a different phase compared to the applied voltage. In other words, the antenna exhibits a feed point impedance that is not just a pure resistance. The feed point impedance is composed of either capacitive or inductive reactance in series with a resistance.

Mutual Impedance

Mutual, or coupled, impedance is due to the parasitic effect of nearby conductors located within the antenna's reactive near field. This includes the effect of ground which is a lossy conductor, but a conductor nonetheless. Mutual impedance is defined using Ohm's Law, just like self impedance. However, mutual impedance is the ratio of voltage in one conductor, divided by the current in another (coupled) conductor. Mutually coupled conductors can distort the pattern of a highly directive antenna, as well as change the impedance seen at the feed point. Mutual impedance will be considered in detail in the chapter, **HF Yagi and Quad Antennas**, where it is essential for proper operation of these beam antennas.

Is Resonance Required?

Please recognize that an antenna need not be resonant in order to be an effective radiator. There is in fact nothing magic about having a resonant antenna, provided of course that you can devise some efficient means to feed the antenna. Many amateurs use nonresonant (even random-length) antennas fed with open-wire transmission lines and antenna tuners. They radiate signals just as well as those using coaxial cable and resonant antennas and as a bonus can usually be used on multiple frequency bands. It is important to consider an antenna and its feed line as a system in which all losses should be kept to a minimum.

1.3 ANTENNA DIRECTIVITY AND GAIN

1.3.1 THE ISOTROPIC RADIATOR

Before we can fully describe practical antennas, we must first introduce a completely theoretical antenna, the *isotropic radiator*. Envision, if you will, an infinitely small antenna at a point located in outer space, completely removed from anything else around it. Then consider an infinitely small transmitter feeding this infinitely small, point antenna. You now have an isotropic radiator.

The uniquely useful property of this theoretical point-source antenna is that it radiates equally well in all directions. That is to say, an isotropic antenna favors no direction at the expense of any other. In other words, it has absolutely no *directivity*, which is the property of radiating or receiving more strongly in some directions than in others. The isotropic radiator is useful as a measuring stick for comparison with actual antenna systems.

You will find later that real, practical antennas all exhibit some degree of directivity. The radiation from a practical antenna never has the same intensity in all directions and may even have zero radiation in some directions. The fact that a practical antenna displays directivity (while an isotropic radiator does not) is usually desirable. The directivity of a real antenna is often carefully tailored to emphasize radiation in particular directions. For example, a receiving antenna that favors certain directions can discriminate against interference or noise coming from other directions, thereby increasing the signal-to-noise ratio for desired signals coming from the favored direction.

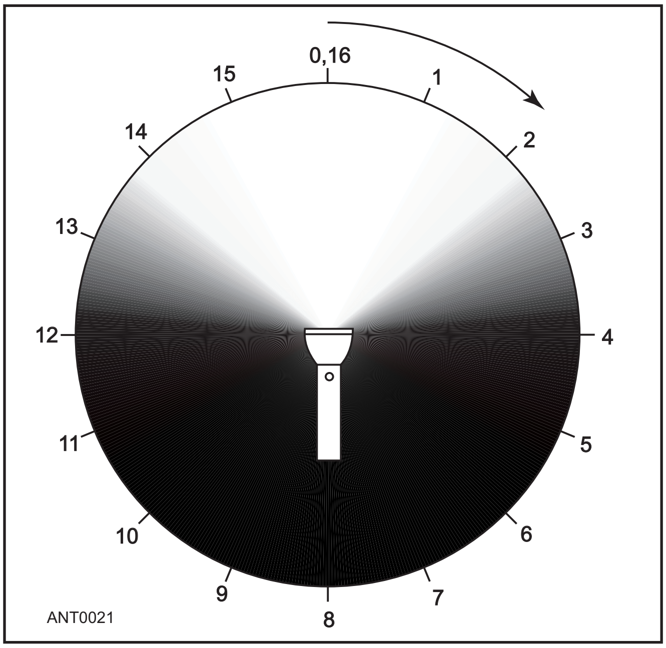


Figure 1.7 — The beam from a flashlight illuminates a totally darkened area a shown here. Readings taken with a photographic light meter at the 16 points around the circle may be used to plot the radiation pattern of the flashlight.

1.3.2 DIRECTIVITY AND THE RADIATION PATTERN

The directivity of an antenna is directly related to the pattern of its radiated field intensity in free space. A graph showing the actual or relative field intensity at a fixed distance as a function of the direction from the antenna system, is called a *radiation pattern*. Since we can't actually see electromagnetic waves making up the radiation pattern of an antenna, we can consider an analogous situation.

Figure 1.7 represents a flashlight shining in a totally darkened room. To quantify what our eyes are seeing we might use a sensitive light meter like those used by photographers, with a scale graduated in units from 0 to 10. We place the meter directly in front of the flashlight and adjust the distance so the meter reads 10, exactly full scale. We also carefully note the distance. Then, always keeping the meter the same distance from the flashlight and keeping it at the same height above the floor, we move the light meter around the flashlight, as indicated by the arrow, and take light readings at a number of different positions.

After all the readings have been taken and recorded, we plot those values on a sheet of polar graph paper, like that shown in **Figure 1.8**. The values read on the meter are plotted at an angular position corresponding to that at which each meter reading was taken. Following this, we connect the plotted points with a smooth curve, also shown in the figure.

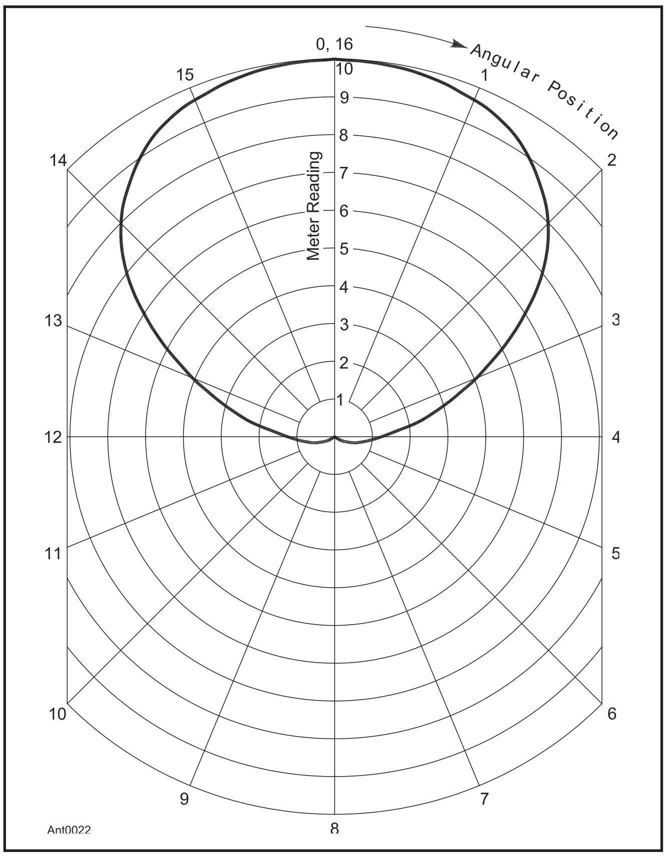


Figure 1.8 — The radiation pattern of the flashlight in Figure 1.7. The measured values are plotted and connected with a smooth curve.

When this is finished, we have completed a radiation pattern for the flashlight.

Antenna radiation patterns can be constructed in a similar manner. Power is fed to the antenna under test and a field-strength meter indicates the amount of signal. We might wish to rotate the antenna under test, rather than moving the measuring equipment to numerous positions about the antenna. Since the pattern while receiving is the same as that while transmitting (see the section on Reciprocity later in this chapter), a source antenna fed by a low-power transmitter illuminates the antenna under test and the signal intercepted by the antenna under test is fed to a receiver and measuring equipment. Additional information on the mechanics of measuring antenna patterns is contained in the chapter **Antennas and Transmission-Line Measurements**.

1.3.3 NEAR AND FAR FIELDS

Some precautions must be taken to assure that the measurements are accurate and repeatable and one of the most important is to prevent mutual coupling between the source and receiving antennas that may alter the pattern you are trying to measure.

This sort of mutual coupling can occur in the region very close to the antenna under test. This region is called the *reactive near-field* region. The term "reactive" refers to the fact that the mutual impedance between the transmitting and receiving antennas can be either capacitive or inductive in nature. The reactive near field is sometimes called the "induction field," meaning that the magnetic field usually is predominant over the electric field in this region. The antenna acts as though it were a rather large, lumped-constant inductor or capacitor, storing energy in the reactive near field rather than propagating it into space.

For simple wire antennas, the reactive near field is considered to be within about a half wavelength from an antenna's radiating center. Later on, in the chapters dealing with arrays of antennas, you will find that mutual coupling between elements can be put to good use to purposely shape the radiated pattern. For making pattern measurements, however, we do not want to be too close to the antenna being measured.

The strength of the reactive near field decreases in a complicated fashion as you increase the distance from the antenna. Beyond the reactive near field, the antenna's radiated field is divided into two other regions: the *radiating near field* and the *radiating far field*. Historically, the terms *Fresnel* and *Fraunhöfer* fields have been used for the radiating near and far fields, but these terms have been largely supplanted by the more descriptive terminology used here. Even inside the reactive near-field region, both radiating and reactive fields coexist although the reactive field predominates very close to the antenna.

Because the boundary between the fields is not a precise distance, experts debate where one field begins and another leaves off but the boundary between the radiating near and far fields is generally accepted as:

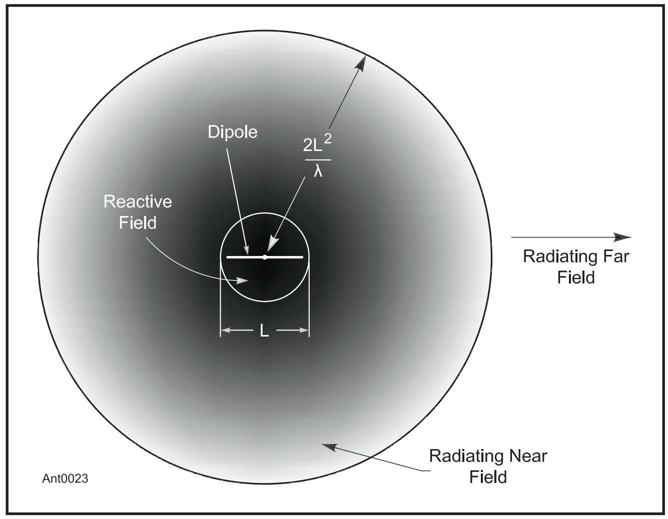


Figure 1.9 — The fields around a radiating antenna. Very close to the antenna, the reactive field dominates. Within this area mutual impedances are observed between the antenna and any other antennas or conductors. Outside the reactive near field, the radiating near field dominates up to the distance shown where L is the length of the largest dimension of the antenna. Beyond the near/far field boundary lies the radiating far field, where power density varies as the inverse square of radial distance.

$$D = \frac{2L^2}{\lambda} \qquad (5)$$

where L is the largest dimension of the physical antenna expressed in the same units of measurement as the wavelength λ. Remember, many specialized antennas do not follow the rule of thumb in Eq 5 exactly. **Figure 1.9** depicts the three fields in front of a simple wire antenna.

Throughout the rest of this book we will discuss mainly the radiating far fields, those forming the propagating electromagnetic waves and which will simply be referred to as the "far field." Far field radiation is distinguished by the fact that the intensity is inversely proportional to the distance, and that the electric and magnetic components, although perpendicular to each other in the wave front, are in phase as defined earlier. The total energy is equally divided between the electric and magnetic fields. Beyond several wavelengths from the antenna these are the only fields we need to consider. This is why for accurate measurement of radiation patterns, we must place our measuring instrumentation at least several wavelengths away from the antenna under test.

1.3.4 TYPES OF RADIATION PATTERNS

In the example of the flashlight, the plane of measurement was at one consistent height above the floor. In **Figure 1.10A** a similar radiation pattern is shown for a half-wavelength dipole (see the **Dipoles and Monopoles** chapter) in free-space, measured in a single plane containing the antenna wire. The antenna is located at the exact center of the plot with its orientation specified by the two-headed

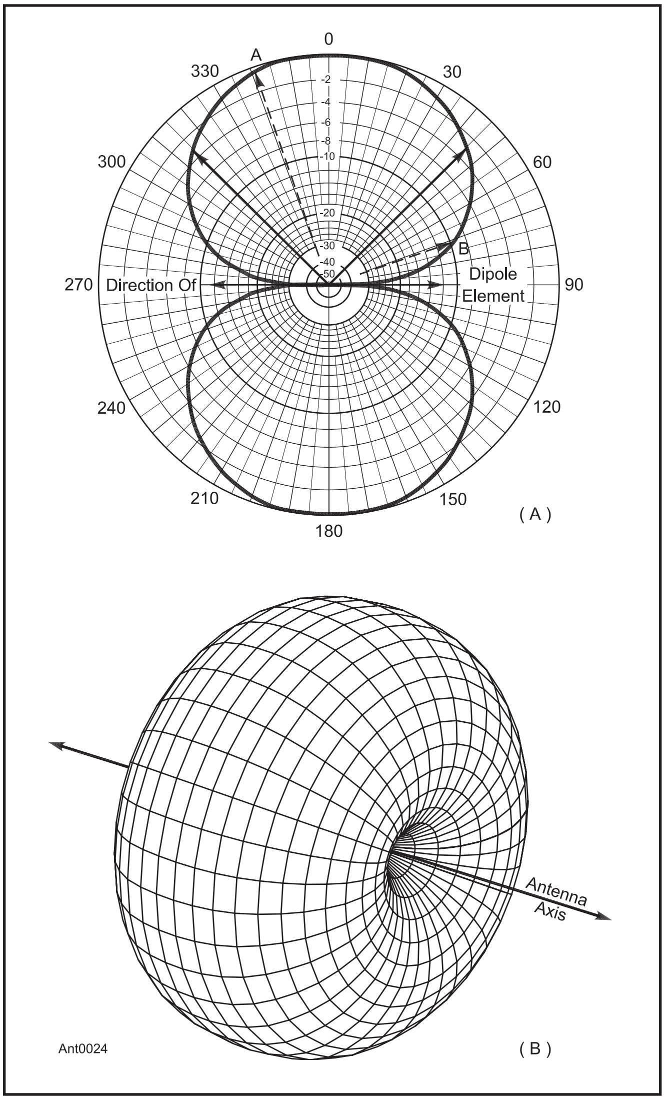


Figure 1.10 — Radiation patterns of a half-wavelength dipole in free-space. At A, the pattern in the plane containing the wire axis. The length of each dashed-line arrow represents the relative field strength in that direction, referenced to the direction of maximum radiation at right angles to the wire's axis. The arrows at approximately 45° and 315° are the half-power or –3 dB points. At B, a wire grid representation of the solid pattern for the same antenna.

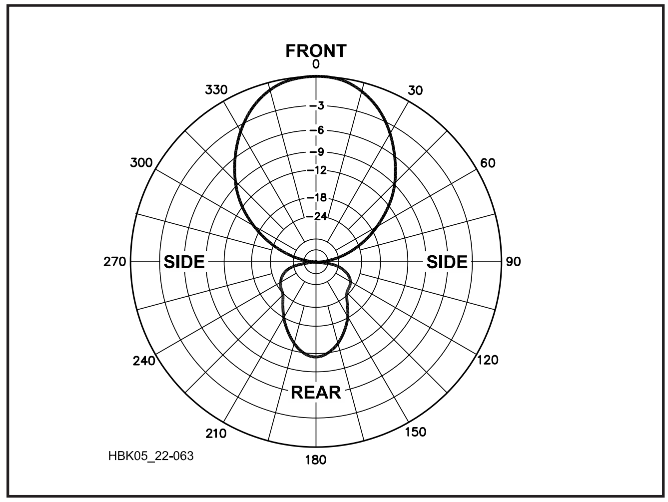


Figure 1.11 — Azimuthal pattern of a typical three-element Yagi beam antenna in free space. The Yagi's boom is aligned along the 0° to 180° axis and the beam's elements are in the plane of the pattern.

arrow. The antenna radiates best broadside to the wire axis and hardly at all off the ends of the wire.

Radiation patterns are graphic representations of an antenna's directivity. Shown in polar coordinates (see the math tutorial reference on the CD-ROM for information about polar coordinates), the angular scale shows direction and the scale from the center of the plot to the outer ring. The smooth line in the shape of a figure-8 shows the relative strength of the antenna's radiated signal at each angle.

The pattern in **Figure 1.11** shows both *nulls* (angles at which a pattern minimum occurs) and *lobes* (radiation at angles between nulls). The *main lobe* is the lobe with the highest amplitude unless noted otherwise and unless several plots are being compared, the peak amplitude of the main lobe is placed at the outer ring as a reference point. The peak of the main lobe can be located at any angle. All other lobes are *side lobes* which can be at any angle, including to the rear of the antenna. In addition to the labels showing the main lobe and nulls in the pattern, the so-called *half-power* points on the main lobe are shown. These are the angles at which the power is one-half of the peak value in the main lobe.

Actually, the pattern for any antenna is three-dimensional and therefore cannot be represented by a single-plane drawing. The total radiation pattern of an antenna in free space would be found by measuring the field strength at every point on the surface of an imaginary sphere having the antenna at its center. The information so obtained would then be used to construct a solid figure, where the distance from a fixed point (representing the antenna) to the surface of the figure is proportional to the field strength from the antenna in any given direction. Figure 1.10B shows a three-dimensional solid representation of the radiation pattern of a half-wave dipole. Figure 1.10A can be thought of as a cross-section of the solid pattern through the axis of the antenna. Two such diagrams, one in the plane containing the straight wire of a dipole and one in the plane perpendicular to the wire, can convey a great deal of information. After a little practice and with the exercise of some imagination, the complete solid pattern can be visualized with fair accuracy from inspection of the two planar diagrams, provided of course that the solid pattern of the antenna is smooth such as for simple antennas like the dipole of Figure 1.10.

Azimuth and Elevation Patterns

When a radiation pattern is shown for an antenna mounted over ground rather than in free space, we automatically gain two frames of reference: *an azimuth angle* and an *elevation angle*. The azimuth angle is usually referenced to 0° in

Introduction to the Decibel

The power gain and pattern measurements such as front-to-back ratio of an antenna system are usually expressed in decibels (dB). The decibel is a practical unit for measuring power ratios because it is more closely related to the actual effect produced at a distant receiver than the power ratio itself. One decibel represents a just-detectable change in signal strength, regardless of the actual value of the signal voltage. A 20-decibel (20 dB) increase in signal, for example, represents 20 observable steps in increased signal. The power ratio (100 to 1) corresponding to 20 dB gives an entirely exaggerated idea of the improvement in communication to be expected. The number of decibels corresponding to any power ratio is equal to 10 times the common logarithm of the power ratio, or

$$dB = 10 \log_{10} \frac{P_1}{P_2}$$

If the voltage ratio is given, the number of decibels is equal to 20 times the common logarithm of the ratio. That is,

$$dB = 20 \log_{10} \frac{V_1}{V_2}$$

When a voltage ratio is used, both voltages must be measured across the same value of impedance. Unless this is done the decibel figure is meaningless, because it is fundamentally a measure of a power ratio.

The main reason a decibel is used is that successive power gains expressed in decibels may simply be added together. Thus a gain of 3 dB followed by a gain of 6 dB gives a total gain of 9 dB. In ordinary power ratios, the ratios must be multiplied together to find the total gain.

A reduction in power is handled simply by subtracting the requisite number of decibels. Thus, reducing the power to ½ is the same as subtracting 3 decibels. For example, a power gain of 4 in one part of a system and a reduction to ½ in another part gives a total power gain of 4 × ½ = 2. In decibels, this is 6 – 3 = 3 dB. A power reduction or loss is simply indicated by including a negative sign in front of the appropriate number of decibels.

When P_2 or V_2 are some fixed reference value, a letter is added to "dB" to indicate "decibels with respect to" the reference value. This allows absolute values of power and voltage to be expressed in dB, as well. You will often encounter dBm (P_2 = 1 mW) and dBµV (V_2 = 1 µV) in Amateur Radio.

For more information about the decibel, read "A Tutorial on the Decibel" available at **www.arrl.org/files/file/Instructor%20resources/A%20Tutorial%20on%20the%20Dec-N0AX.pdf**.

the direction of maximum radiation from the antenna or it could be referenced to True North for an antenna oriented in a particular compass direction.

The elevation angle is referenced to the horizon at the Earth's surface, where the elevation angle is 0°. Of course, the Earth is round but because its radius is so large, it can in this context be considered to be flat in the area directly under the antenna. An elevation angle of 90° is directly above the antenna (the *zenith*) and the angles then reduce back to 0° toward the horizon directly behind the antenna. (Professional antenna engineers often describe an antenna's orientation with respect to the point directly overhead — using the zenith angle, rather than the elevation angle. The elevation angle is computed by subtracting the zenith angle from 90°.)

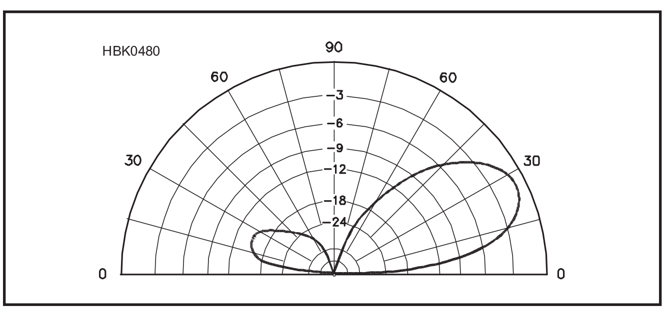


Figure 1.12 — Elevation pattern of a three-element Yagi beam antenna placed 1/2 wavelength above ground. The Yagi's boom lies on the 0°-0° axis and the elements are perpendicular to the page on the same axis.

Figure 1.11 is an *azimuthal* or *azimuth pattern* that shows the antenna's gain in all horizontal directions (azimuths) around the antenna. As with a map, 0° is at the top and bearing angle increases clockwise. (This is different from polar plots generated for mathematical functions in which 0° is at the right and the angle increases counter-clockwise.)

Figure 1.12 is an *elevation pattern* that shows the same antenna's directivity but this time at all vertical angles. In this case, the horizon at 0° is located to both sides of the antenna and the zenith (directly overhead) at 90°. The plot shown in Figure 1.12 assumes the presence of ground (drawn from 0° to 0°). The ground reflects or blocks radiation at negative elevation angles, making below-surface radiation plots unnecessary. In free-space, the plot would include the missing semicircle with –90° at the bottom. Without the ground reference, the term "elevation" has little meaning, however.

For amateur work, relative values of field strength (rather than absolute values) are quite adequate in pattern plotting. In other words, it is not necessary to know how many microvolts per meter a particular antenna will produce at a distance of 1 mile when excited with a specified power level. (This is the kind of specification that AM broadcast stations must meet to certify their antenna systems to the FCC.)

Regardless of whether the data is collected by measurements, simulated by computer software, or calculated from theoretical equations, it is common to normalize the plotted values so the field strength in the direction of maximum radiation coincides with the outer edge of the chart. That way, on a given system of polar coordinate scales the shape of the pattern is not altered by proper normalization, only its size.

(See the sidebar "Coordinate Scales for Radiation Patterns" later in this chapter for information about how radiation pattern scales are determined.)

E and H-Plane Patterns

You'll also encounter *E-plane* and *H-plane radiation patterns*. These show the antenna's radiation pattern in the plane parallel to the E-field or H-field of the antenna. For antennas with horizontal elements, the E-field is in the horizontal plane so the E-plane radiation pattern is the same as an azimuthal pattern in the plane of the antenna. The H-field is perpendicular to the E-field, so the H-plane pattern is in a plane perpendicular to the E-plane pattern. If the E-plane pattern is an azimuthal pattern, then the H-plane pattern will be an elevation pattern.

It's important to remember that the E-plane and H-plane do not have a fixed relationship to the Earth's surface. For example, the E-plane pattern from a horizontal dipole is an azimuthal pattern but if the same dipole is oriented vertically, the E-plane pattern becomes an elevation pattern. For this reason, most E- and H-plane radiation patterns are created with the antenna in free space.

1.3.5 DIRECTIVITY AND GAIN

Let us now examine directivity more closely. As mentioned previously, all practical antennas, even the simplest types such as dipoles, exhibit directivity. Here's another picture that may help explain the concept of directivity. **Figure 1.13A** shows a balloon blown into its usual spherical shape. This represents a "reference" isotropic source. Squeezing the balloon in the middle in Figure 1.13B produces a dipole-like figure-8 pattern with peak levels at top and bottom larger than the reference sphere. Compare this with Figure 1.13C. Next, squeezing the bottom end of the balloon produces a pattern that gives even more "gain" compared to the reference.

Free-space directivity can be expressed quantitatively by comparing the three-dimensional pattern of the antenna under consideration with the perfectly spherical three-dimensional pattern of an isotropic antenna. For an isotropic antenna, the field strength (and thus power per unit area, or *power density*) is the same everywhere on the surface of an imaginary sphere having a radius of many wavelengths and centered on the antenna. For a directive antenna radiating the same total power as an isotropic antenna and surrounded by the same sphere, the directivity results in greater power density at some points on the sphere and less at others. The ratio of the maximum power density to the average power density taken over the entire sphere (which is the same as from the isotropic antenna under the specified conditions) is the numerical measure of the directivity of the antenna.

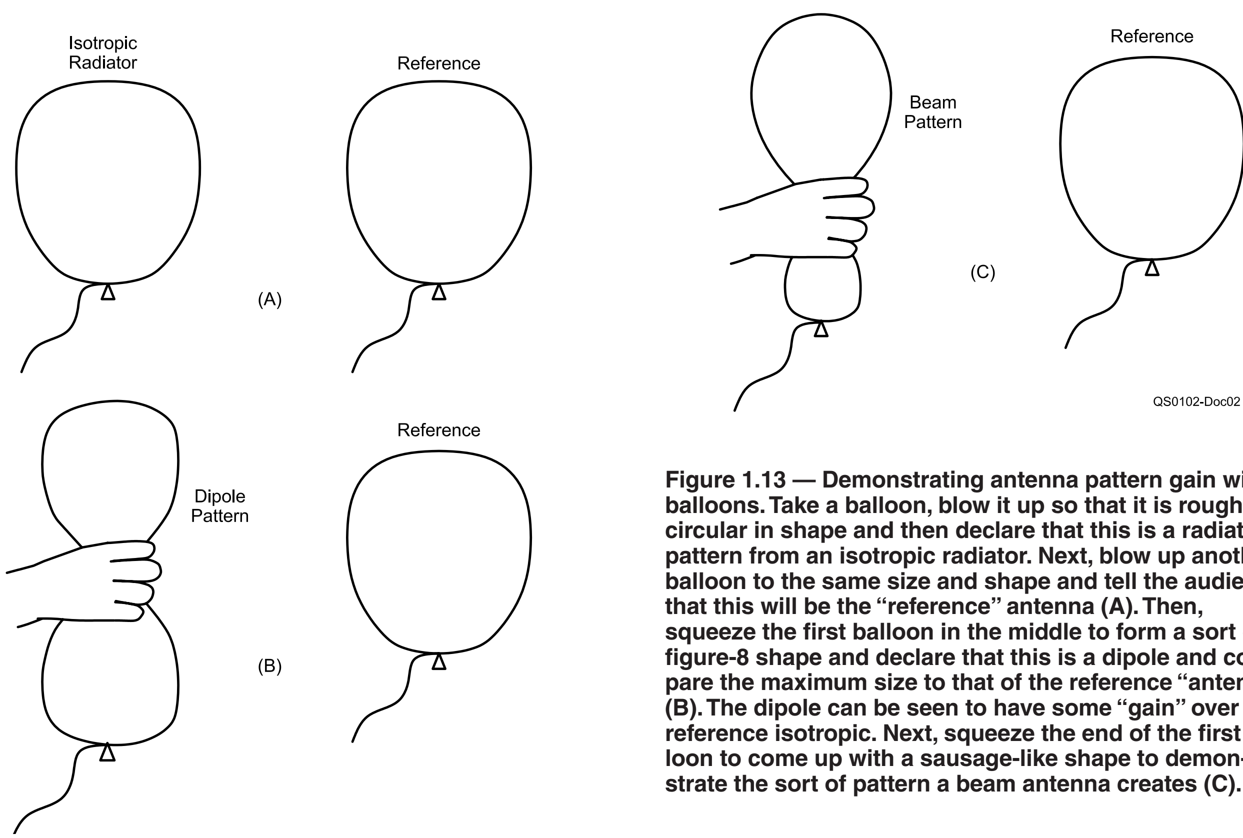


Figure 1.13 — Demonstrating antenna pattern gain with balloons. Take a balloon, blow it up so that it is roughly circular in shape and then declare that this is a radiation pattern from an isotropic radiator. Next, blow up another balloon to the same size and shape and tell the audience that this will be the "reference" antenna (A). Then, squeeze the first balloon in the middle to form a sort of figure-8 shape and declare that this is a dipole and compare the maximum size to that of the reference "antenna" (B). The dipole can be seen to have some "gain" over the reference isotropic. Next, squeeze the end of the first balloon to come up with a sausage-like shape to demonstrate the sort of pattern a beam antenna creates (C).

Coordinate Scales for Radiation Patterns

A number of different systems of coordinate scales or grids are in use for plotting antenna patterns. Antenna patterns published for amateur audiences are sometimes placed on rectangular grids, but more often they are shown using polar coordinate systems. Polar coordinate systems may be divided generally into three classes: linear, logarithmic and modified logarithmic.

A very important point to remember is that the shape of a pattern (its general appearance) is highly dependent on the grid system used for the plotting. This is exemplified in **Figure 1.A**, where the radiation pattern for a beam antenna is presented using three coordinate systems discussed in the paragraphs that follow.

Linear Coordinate Systems

The polar coordinate system in Figure 1.A (part A) uses linear coordinates. The concentric circles are equally spaced, and are graduated from 0 to 10. Such a grid may be used to prepare a linear plot of the power contained in the signal. For ease of comparison, the equally spaced concentric circles have been replaced with appropriately placed circles representing the decibel response, referenced to 0 dB at the outer edge of the plot. In these plots the minor lobes are suppressed. Lobes with peaks more than 15 dB or so below the main lobe disappear completely because of their small size. This is a good way to show the pattern of an array having high directivity and small minor lobes. Linear coordinate patterns are not common, however.

Logarithmic Coordinate System

Another coordinate system used by antenna manufacturers is the logarithmic grid, where the concentric grid lines are spaced according to the logarithm of the voltage in the signal. If the logarithmically spaced concentric circles are replaced with appropriately placed circles representing the decibel response, the decibel circles are graduated linearly. In that sense, the logarithmic grid might be termed a linear-log grid, one having linear divisions calibrated in decibels.

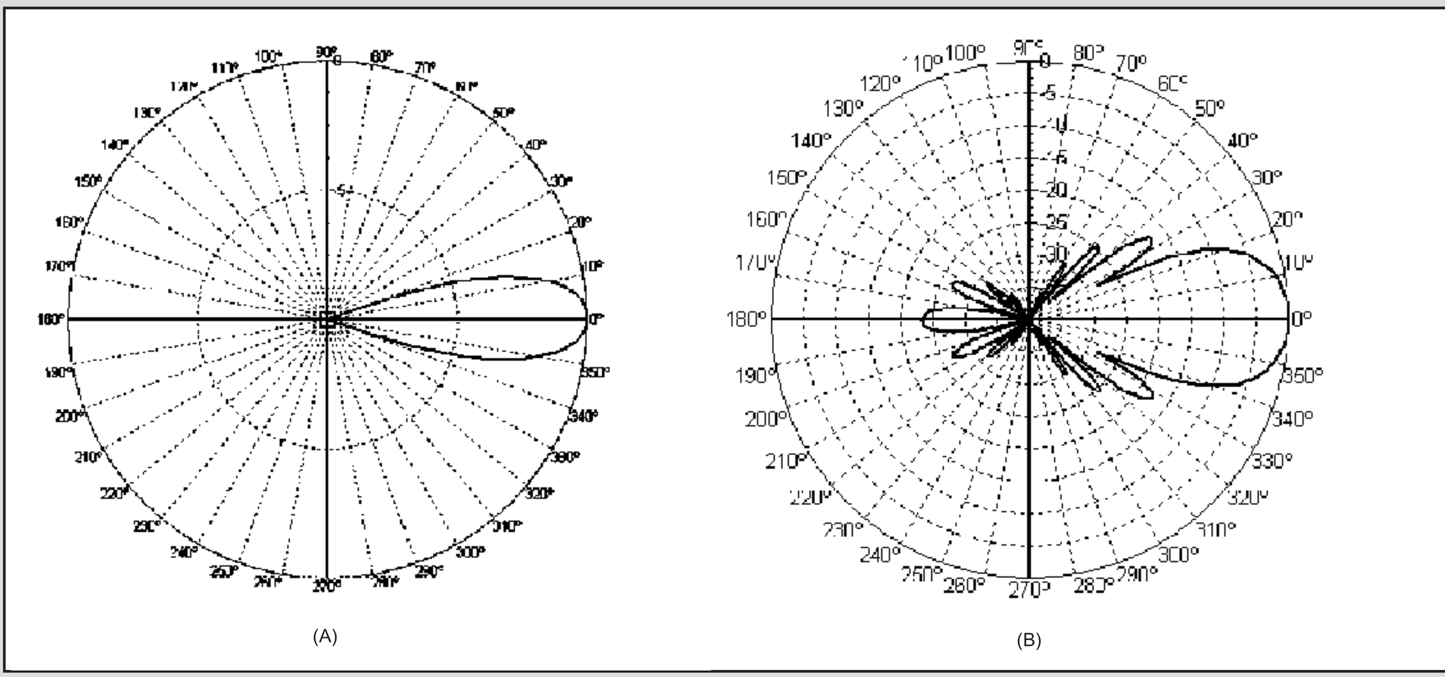


Figure 1.A — Radiation pattern plots for a high-gain Yagi antenna on different grid coordinate systems. At A, the pattern on a linear-power dB grid. Notice how details of side lobe structure are lost with this grid. At B, the same pattern on a grid with constant 5 dB circles. The side lobe level is exaggerated when this scale is employed. At C, the same pattern on the modified log grid used by ARRL. The side and rearward lobes are clearly visible on this grid. The concentric circles in all three grids

This grid enhances the appearance of the minor lobes. If the intent is to show the radiation pattern of an array supposedly having an omnidirectional response, this grid enhances that appearance. An antenna having a difference of 8 or 10 dB in pattern response around the compass appears to be closer to omnidirectional on this grid than on any of the others. See Figure 1.A (part B).

ARRL Log Coordinate System

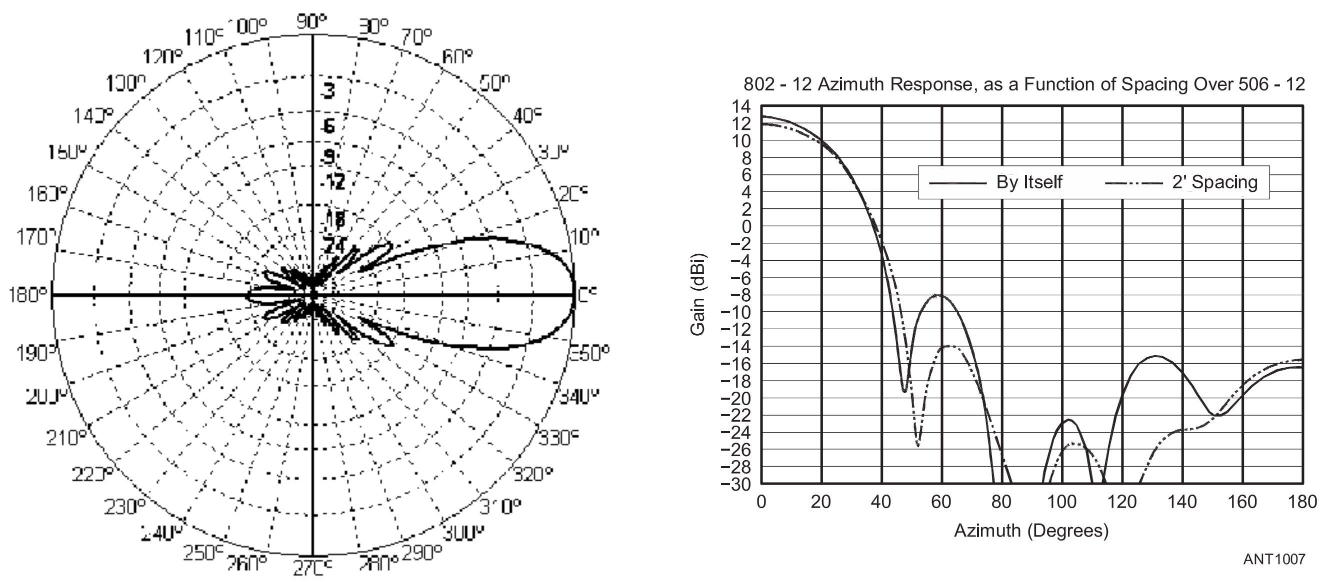
The modified logarithmic grid used by the ARRL has a system of concentric grid lines spaced according to the logarithm of 0.89 times the value of the signal voltage. In this grid, minor lobes that are 30 and 40 dB down from the main lobe are distinguishable. Such lobes are of concern in VHF and UHF work. The spacing between plotted points at 0 dB and –3 dB is significantly greater than the spacing between –20 and –23 dB, which in turn is significantly greater than the spacing between –50 and –53 dB.

For example, the scale distance covered by 0 to –3 dB is about 1⁄10 of the radius of the chart. The scale distance for the next 3-dB increment (to –6 dB) is slightly less, 89% of the first, to be exact. The scale distance for the next 3-dB increment (to –9 dB) is again 89% of the second. The scale is thus constructed so that the innermost two circles represent –36 and –48 dB and the chart center represents –100 dB.

The periodicity of spacing thus corresponds generally to the relative significance of such changes in antenna performance. Antenna pattern plots in this publication are made on the modified-log grid similar to that shown in Figure 1.A (part C).

Rectangular Grid

Antenna radiation patterns can also be plotted on rectangular coordinates with gain on the vertical axis in dB and angle on the horizontal axis as shown in Figure 1.A (part D). Multiple patterns in polar coordinates can be difficult to read, particularly close to the center of the plot. Using a rectangular grid makes it easier to evaluate low-level minor lobes and is especially useful when several antennas are being compared.



(C)

(D)

are graduated in decibels referenced to 0 dB at the outer edge of the chart. The patterns look quite different, yet they all represent the same antenna response! D shows the rectangular azimuthal patterns of two VHF Yagi antennas. This example shows how a rectangular plot allows easier comparison of antenna patterns away from the main lobe.

Directivity is computed as:

$$D = \frac{P}{P_{av}} \tag{6}$$

where
D = directivity
P = power density at its maximum point on the surface of the sphere
P_{av} = average power density

P_{av} is equivalent to the power density from a loss-free isotropic radiator with the same radiated power. D can be expressed in dB with respect to a reference antenna as 10 log [D/D_{ref}]. If the reference antenna is an isotropic antenna, then D_{dBi} = 10 log [D]. If the reference antenna is a dipole, then D_{dBd} = 10 log [D / 1.64]. The term *receive directivity factor* (*RDF*) is also used and is the difference between an antenna's peak gain and gain averaged over all directions. (See reference for Ordy in Bibliography)

The *gain* of an antenna is closely related to its directivity. Because directivity is based solely on the shape of the directive pattern, it does not take into account any power losses that may occur in an actual antenna system. To determine gain, these losses must be subtracted from the power supplied to the antenna. The loss is normally a constant percentage of the power input, so the antenna gain is:

$$G = k\frac{P}{P_{av}} = kD \tag{7}$$

where
G = gain (expressed as a power ratio, usually in dB)
D = directivity
k = efficiency (power radiated divided by power input) of the antenna
P and P_{av} are as above

For many of the antenna systems used by amateurs, the efficiency is quite high (the loss amounts to only a few percent of the total). In such cases the gain is essentially equal to the directivity. The more the directive diagram is compressed — or, in common terminology, the sharper the lobe — the greater the power gain of the antenna. This is a natural consequence of the fact that as power is taken away from a larger and larger portion of the sphere surrounding the radiator, it is added to the volume represented by the narrow lobes. Power is therefore concentrated in some directions at the expense of others. In a general way, the smaller the volume of the solid radiation pattern, compared with the volume of a sphere having the same radius as the length of the largest lobe in the actual pattern, the greater the power gain.

As stated above, the gain of an antenna is related to its directivity, and directivity is related to the shape of the directive pattern. A commonly used index of directivity, and therefore the gain of an antenna, is a measure of the width of the major lobe (or lobes) of the plotted pattern. The width is expressed in degrees at the half-power or –3 dB points and is often called the *beamwidth*.

This information provides only a general idea of relative gain, rather than an exact measure. This is because an absolute measure involves knowing the power density at every point on the surface of a sphere, while a single diagram shows the pattern shape in only one plane of that sphere. It is customary to examine at least the E-plane and the H plane patterns before making any comparisons between antennas.

A simple approximation for gain over an isotropic radiator can be used, but only if the side lobes in the antenna's pattern are small compared to the main lobe and if the resistive losses in the antenna are small. When the radiation pattern is complex, numerical integration is employed to give the actual gain.

$$G \approx \frac{41253}{H_{3dB} \times E_{3dB}} \tag{8}$$

where H_{3dB} and E_{3dB} are the half-power points, in degrees, for the H and E-plane patterns.

1.3.6 RADIATION PATTERN MEASUREMENTS

Given the basic radiation pattern and scales, it becomes easy to define several useful measurements or metrics by which antennas are compared by using their azimuthal patterns.

Because an isotropic antenna has equal gain in all directions it is often used as a reference for gain measurements. Gain with respect to an isotropic antenna is stated as dBi. Another common gain reference is that of a dipole's maximum gain, broadside to the antenna. Gain with respect to this value is noted in dBd. The dipole's maximum gain is 2.15 dB greater than that of the isotropic antenna. To convert from gain given as dBi to dBd, subtract 2.15 dB. Note that to specify gain in dBd, the dipole must be at the same effective height as the antenna being specified. Alternately, the free-space values for gain could be used. Be sure to state clearly which set of values are used.

Next to gain, the most commonly-used metric for directional antennas is the *front-to-back ratio* (*F/B*) or just "front-to-back". This is the difference in dB between the antenna's gain in the specified "forward" direction and in the opposite direction. The front-to-back ratio of the antenna in Figure 1.11 is about 11 dB. *Front-to-side ratio* is also used and is the difference between the antenna's "forward" gain and gain at right angles to the forward direction. This assumes the radiation pattern is symmetric and is of most use to antennas such as Yagis and quads that have elements arranged in parallel planes. The front-to-side ratio of the antenna in Fig 1.11 is more than 30 dB. Because the antenna's rear-ward pattern can have large amplitude variations, the *front-to-rear ratio* is sometimes used. Front-to-rear uses the average of rear-ward gain over a specified angle, usually the 180° semicircle opposite the direction of the antenna's maximum gain, instead of a single gain figure at precisely 180° from the forward direction.

In Fig 1.11, the antenna's beamwidth is about 54°, since the pattern crosses the –3 dB gain scale approximately 27° to either side of the peak direction. Antenna patterns with comparatively small beamwidths are referred to as "sharp" or "narrow."

An antenna with an azimuthal pattern that shows equal gain in all directions is called *omnidirectional*. This is not the same as an isotropic antenna that has equal gain in all directions, both vertical both horizontal.

Because an isotropic antenna has equal gain in all directions it is often used as a reference for gain measurements. Gain with respect to an isotropic antenna is stated as dBi. Another common gain reference is that of a dipole's maximum gain, broadside to the antenna. Gain with respect to this value is denoted dBd. The dipole's maximum gain is 2.15 dB greater than that of the isotropic antenna. To convert from gain given as dBi to dBd, subtract 2.15 dB. Note that to specify gain in dBd, the dipole must be at the same effective height as the antenna being specified. Alternately, the free-space values for gain could be used. Be sure to state clearly which set of values are used.

1.4 ANTENNA POLARIZATION

We've now examined the first two of the three major properties used to characterize antennas: the impedance and the radiation pattern. The third general property is polarization. An antenna's polarization is defined to be that of its electric or E-field, in the direction where the field strength is maximum.

For example, if a half-wavelength dipole is mounted horizontally over the Earth, the electric field is strongest perpendicular to its axis (that is, at right angle to the wire) and parallel to the Earth. Thus, since the maximum electric field is horizontal, the polarization in this case is also considered to be horizontal with respect to the Earth. If the dipole is mounted vertically, its polarization will be vertical. See **Figure 1.14**. Note that if an antenna is mounted in free space, there is no frame of reference and hence its polarization is indeterminate.

Antennas composed of a number of elements arranged so that their axes lie in the same or parallel directions have the same polarization as that of any one of the elements. For example, a system composed of a group of horizontal dipoles is horizontally polarized. If both horizontal and vertical elements are used in the same plane and radiate in phase, however, the polarization is the resultant of the contributions made by each set of elements to the total electromagnetic field at a given point some distance from the antenna. In such a case the resultant polarization is still linear, but is tilted between horizontal and vertical.

In directions other than those where the radiation is maximum, the resultant wave even for a simple dipole is a combination of horizontally and vertically polarized components. The radiation off the ends of a horizontal dipole is actually vertically polarized, albeit at a greatly reduced amplitude compared to the broadside horizontally polarized radiation — the sense of polarization changes with compass direction.

Thus it is often helpful to consider the radiation pattern from an antenna in terms of polar coordinates, rather than trying to think in purely linear horizontal or vertical coordinates. The reference axis in the polar system shown in **Figure 1.15** is vertical to the earth under the antenna. The zenith angle is usually referred to as θ (Greek letter theta) and the azimuth angle is referred to as ϕ (Greek letter phi). Instead of zenith angles, most amateurs are more familiar with elevation angles, where a zenith angle of 0° is the same as an elevation angle of 90°, straight overhead. Native *NEC* or *MININEC* computer programs use zenith angles rather than elevation angles, although most commercial versions automatically reduce these to elevation angles.

If vertical and horizontal elements in the same plane are

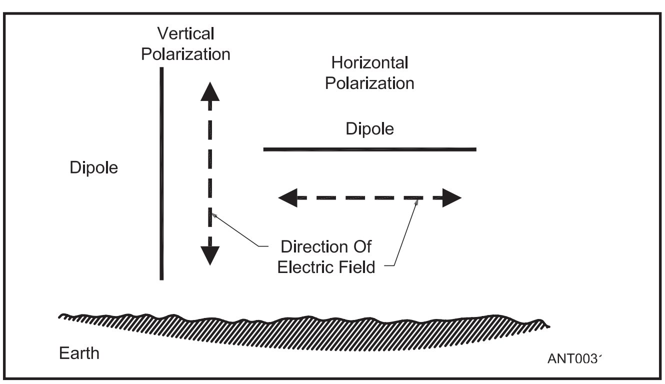


Figure 1.14 — Vertical and horizontal polarization of a dipole above ground. The direction of polarization is the orientation of the electric field in the direction of maximum field strength.

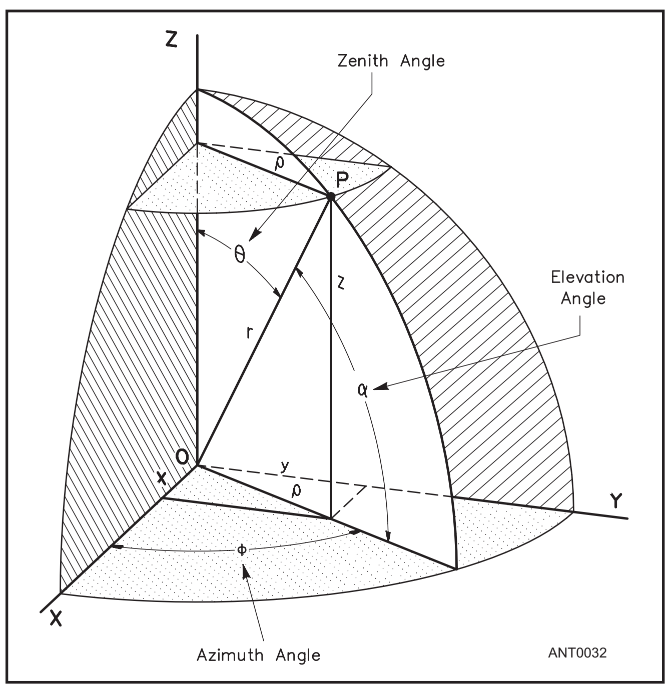


Figure 1.15 — Diagram showing polar representation of a point P lying on an imaginary sphere surrounding a point-source antenna. The various angles associated with the coordinate system are shown referenced to the x, y, and z-axes.

fed out of phase (where the beginning of the RF period applied to the feed point of the vertical element is not in time phase with that applied to the horizontal), the resultant polarization is elliptical. Circular polarization is a special case of elliptical polarization. The wave front of a circularly polarized signal appears (to a stationary observer) to rotate every 90° between vertical and horizontal, making a complete 360° rotation once every period. *Instantaneous polarization* is the polarization of the wave at the stationary observer at a specific instant in time. *Circular polarization* is frequently used for space communications, and is discussed further in the chapter **Antennas for Space Communications**.

Sky-wave transmission usually changes the polarization of traveling waves. (This is discussed in the chapter **Radio Wave Propagation**.) The polarization of receiving and transmitting antennas in the 3 to 30 MHz range, where almost all communication is by means of sky wave, need not be the same at both ends of a communication circuit (except for distances of a few miles). In this range the choice of polarization for the antenna is usually determined by factors such as the height of available antenna supports, polarization of man-made RF noise from nearby sources, probable energy losses in nearby objects, the likelihood of interfering with neighborhood electronics and general convenience.

1.5 OTHER ANTENNA CHARACTERISTICS

Besides the three main characteristics of impedance, directivity and polarization, there are some other useful properties of antennas.

1.5.1 RECIPROCITY IN RECEIVING AND TRANSMITTING

Many of the properties of a resonant antenna used for reception are the same as its properties in transmission. It has the same directive pattern in both cases, and delivers maximum signal to the receiver when the signal comes from a direction in which the antenna has its best response. The impedance of the antenna is the same, at the same point of measurement, in receiving as in transmitting. This is the principle of *reciprocity*.

In the receiving case, the antenna is the source of power delivered to the receiver, rather than the load for a source of power (as in transmitting). Maximum possible output from the receiving antenna is obtained when the load to which the antenna is connected is the same as the feed point impedance of the antenna. We then say that the antenna is matched to its load.

The power gain in receiving is the same as the gain in transmitting, when certain conditions are met. One such condition is that both antennas must work into load impedances matched to their own impedances, so that maximum power is transferred in both cases. In addition, the comparison antenna should be oriented so it gives maximum response to the signal used in the test. That is, it should have the same polarization as the incoming signal and should be placed so its direction of maximum gain is toward the signal source.

In long-distance transmission and reception via the ionosphere, the relationship between receiving and transmitting, however, may not be exactly reciprocal. This is because the waves do not always follow exactly the same paths at all times and so may show considerable variation in the time between alternations between transmitting and receiving. Also, when more than one ionospheric layer is involved in the wave travel (see the chapter **Radio Wave Propagation**), it is sometimes possible for reception to be good in one direction and poor in the other over the same path.

Wave polarization usually shifts in the ionosphere. The tendency is for the arriving wave to be elliptically polarized, regardless of the polarization of the transmitting antenna. Vertically polarized antennas can be expected to show no more difference between transmission and reception than horizontally polarized antennas. On the average, however, an antenna that transmits well in a certain direction also gives favorable reception from the same direction, despite ionospheric variations.

1.5.2 ANTENNA BANDWIDTH

The *bandwidth* of an antenna refers generally to the range of frequencies over which the antenna can be used to obtain a specified level of performance. The bandwidth can be specified in units of frequency (MHz or kHz) or as a percentage of the antenna's design frequency.

Popular amateur usage of the term antenna bandwidth most often refers to the 2:1 SWR (standing wave ratio) bandwidth, such as, "The 2:1 *SWR bandwidth* is 3.5 to 3.8 MHz" or "The antenna has a 10% SWR bandwidth" or "On 20 meters, the antenna has an SWR bandwidth of 200 kHz." (Standing wave ratio is discussed in the **Transmission Lines** chapter.) Other specific bandwidth terms are also used, such as the *gain bandwidth* (the bandwidth over which gain is greater than a specified level) and the *front-to-back ratio bandwidth* (the bandwidth over which front-to-back ratio is greater than a specified level).

As operating frequency is lowered, an equivalent bandwidth in percentage becomes narrower in terms of frequency range in kHz or MHz. For example, a 5% bandwidth at 21 MHz is 1.05 MHz (more than wide enough to cover the whole band) but at 3.75 MHz only 187.5 kHz! Because of the wide percentage bandwidth of the lower frequency bands (160 meters is 10.5% wide, 80 meters is 13.4% wide) it is difficult to design an antenna with a bandwidth that covers the whole band.

It is important to recognize that SWR bandwidth does not always relate directly to gain bandwidth. Depending on the amount of feed line loss, an 80 meter dipole with a relatively narrow 2:1 SWR bandwidth can still radiate a good signal at each end of the band, provided that an antenna tuner is used to allow the transmitter to load properly. Broadbanding techniques, such as fanning the far ends of a dipole to simulate a conical type of dipole, can help broaden the SWR bandwidth.

Q of Antennas

As with circuits, antennas can also be considered to have Q which affects their SWR bandwidth. In an antenna, Q is a measure of how much energy is stored compared to how much is radiated during each cycle. Higher values of Q can result from low radiation resistance, as is the case for electrically small antennas, and result in reduced antenna bandwidth. High-Q antennas often have high voltage and currents due to the high stored energy, just as high-Q LC circuits have high voltages and circulating currents. This is discussed in detail in the paper by Yaghjian and Best, "Impedance, Bandwidth and Q of Antennas," listed in the Bibliography section of this chapter.

1.5.3 FREQUENCY SCALING

Any antenna design can be scaled in size for use on another frequency or on another amateur band. The dimensions of the antenna may be scaled with Eq 9 below.

$$D = \frac{f1}{f2} \times d \tag{9}$$

where

D = scaled dimension

d = original design dimension

f1 = original design frequency

f2 = scaled frequency (frequency of intended operation)

From this equation, a published antenna design for, say, 14 MHz can be scaled in size and constructed for operation on 18 MHz, or any other desired band. Similarly, an antenna design could be developed experimentally at VHF or UHF and then scaled for operation in one of the HF bands. For example, from Eq 9, an element of 39.0 inches length at 144 MHz would be scaled to 14 MHz as follows: D = 144/14 × 39 = 401.1 inches, or 33.43 feet.

To scale an antenna properly, all physical dimensions must be scaled, including element lengths, element spacings, boom diameters and element diameters. Lengths and spacings may be scaled in a straightforward manner as in the above example, but element diameters are often not as conveniently scaled. For example, assume a 14 MHz antenna is modeled at 144 MHz and perfected with ⅜-inch cylindrical elements. For proper scaling to 14 MHz, the elements should be cylindrical, of 144/14 × ⅜ or 3.86 inches diameter. From a realistic standpoint, a 4-inch diameter might be acceptable, but cylindrical elements of 4-inch diameter in lengths of 33 feet or so would be quite unwieldy (and quite expensive, not to mention heavy). Choosing another, more suitable diameter is the only practical answer.

Diameter Scaling

Simply changing the diameter of dipole type elements during the scaling process is not satisfactory without making a corresponding element-length correction. This is because changing the diameter results in a change in the length/diameter (l/d) ratio from the original design, and this alters the corresponding resonant frequency of the element. The element length must be corrected to compensate for the effect of the different diameter actually used.

To be more precise, however, the purpose of diameter scaling is not to maintain the same resonant frequency for the element, but to maintain the same ratio of self-resistance to self-reactance at the operating frequency — that is, the Q of the scaled element should be the same as that of the original element. This is not always possible to achieve exactly for elements that use several telescoping sections of tubing.

Tapered Elements

Rotatable beam antennas are usually constructed with elements made of metal tubing. The general practice at HF is to taper the elements with lengths of telescoping tubing. The center section has a large diameter, but the ends are relatively small. This reduces not only the weight, but also the cost of materials for the elements. Tapering of HF Yagi elements is discussed in detail in the chapter on **HF Yagi and Quad Antennas**.

Length Correction for Tapered Elements

The effect of tapering an element is to alter its electrical length. That is to say, two elements of the same length, one cylindrical and one tapered but with the same average diameter as the cylindrical element, will not be resonant at the same frequency. The tapered element must be made longer than the cylindrical element for the same resonant frequency.

A procedure for calculating the length for tapered elements has been worked out by Dave Leeson, W6NL, from work done by Schelkunoff at Bell Labs and is presented in Leeson's book, *Physical Design of Yagi Antennas*. On the *ARRL Antenna Book* website is a subroutine called *EFFLEN.FOR*. It is written in Fortran and is used in the *SCALE* program to compute the effective length of a tapered element. The algorithm uses the Leeson-Schelkunoff algorithm and is commented step-by-step to show what is happening. Calculations are made for only one half of an element, assuming the element is symmetrical about the point of boom attachment.

Also, read the documentation SCALE.PDF for the *SCALE* program, which will automatically do the complex mathematics to scale a Yagi design from one frequency to another, or from one taper schedule to another. (Both *SCALE* and EFFLEN.FOR are available for download from **www.arrl.org/antenna-book-reference**.)

1.5.4 EFFECTIVE RADIATED POWER (ERP)

In many instances it is important to evaluate the effectiveness of the total antenna system from the transmitter to the radiated signal. This is done by computing the system's *effective radiated power* (*ERP*). ERP is calculated by beginning with the *transmitter power output* (*TPO*), subtracting attenuation in the transmission line and all losses from connectors or other devices between the transmitter and antenna, and then adding the antenna gain. All of the gain and loss values are stated in decibels so that the calculations are straightforward additions and subtractions. If antenna gain is specified in dBi (decibels with respect to an isotropic antenna), the result is EIRP — Effective Isotropic Radiated Power. ERP and EIRP calculations are most often used in Amateur Radio in association with frequency coordination as described in the **Repeater Antenna Systems** chapter.

Here is an example calculation of a typical repeater antenna system

TPO = 100 watts = 50 dBm
Transmission line attenuation = 2.4 dB
Losses in RF connectors and antenna coupling network = 1.7 dB
Antenna gain = 7.5 dBi
EIRP = 50 dBm – 2.4 dB – 1.7 dB + 7.5 dB = 53.4 dBm = 219 watts

1.6 RF RADIATION AND ELECTROMAGNETIC FIELD SAFETY

Amateur Radio is basically a safe activity. In recent years, however, there has been considerable discussion and concern about the possible hazards of electromagnetic radiation (EMR), including both RF energy and power-frequency (50-60 Hz) electromagnetic (EM) fields. FCC regulations set limits on the maximum permissible exposure (MPE) allowed from the operation of radio transmitters. These regulations do not take the place of RF-safety practices, however. This section deals with the topic of RF safety.

This section was prepared by members of the ARRL RF Safety Committee and coordinated by Dr Robert E. Gold, WBØKIZ. It summarizes what is now known and offers safety precautions based on the research to date.

All life on Earth has adapted to survive in an environment of weak, natural, low-frequency electromagnetic fields (in addition to the Earth's static geomagnetic field). Natural low-frequency EM fields come from two main sources: the sun and thunderstorm activity. But in the last 100 years, man-made fields at much higher intensities and with a very different spectral distribution have altered this natural EM background in ways that are not yet fully understood. Researchers continue to look at the effects of RF exposure over a wide range of frequencies and levels.

Both RF and 60-Hz fields are classified as *nonionizing radiation,* because the frequency is too low for there to be enough photon energy to ionize atoms. (*Ionizing radiation*, such as X-rays, gamma rays and even some ultraviolet radiation has enough energy to knock electrons loose from their atoms. When this happens, positive and negative ions are formed.) Still, at sufficiently high power densities, EMR poses certain health hazards. It has been known since the early days of radio that RF energy can cause injuries by heating body tissue. (Anyone who has ever touched an improperly grounded radio chassis or energized antenna and received an *RF burn* will agree that this type of injury can be quite painful.) In extreme cases, RF-induced heating in the eye can result in cataract formation, and can even cause blindness. Excessive RF heating of the reproductive organs can cause sterility. Other health problems also can result from RF heating. These heat-related health hazards are called *thermal effects.* A microwave oven is a positive application of this thermal effect.

There also have been observations of changes in physiological function in the presence of RF energy levels that are too low to cause heating. These functions return to normal when the field is removed. Although research is ongoing, no harmful health consequences have been linked to these changes.

In addition to the ongoing research, much else has been done to address this issue. For example, FCC regulations set limits on exposure from radio transmitters. The Institute of Electrical and Electronics Engineers, the American National Standards Institute and the National Council for Radiation Protection and Measurement, among others, have recommended voluntary guidelines to limit human exposure to RF energy. The ARRL has established the RF Safety Committee, consisting of concerned medical doctors and scientists, serving voluntarily to monitor scientific research in the fields and to recommend safe practices for radio amateurs.

1.6.1 THERMAL EFFECTS OF RF ENERGY

Body tissues that are subjected to *very high* levels of RF energy may suffer serious heat damage. These effects depend on the frequency of the energy, the power density of the RF field that strikes the body and factors such as the polarization of the wave.

At frequencies near the body's natural resonant frequency, RF energy is absorbed more efficiently, and an increase in heating occurs. In adults, this frequency usually is about 35 MHz if the person is grounded, and about 70 MHz if insulated from the ground. Individual body parts may be resonant at different frequencies. The adult head, for example, is resonant around 400 MHz, while a baby's smaller head resonates near 700 MHz. Body size thus determines the frequency at which most RF energy is absorbed. As the frequency is moved farther from resonance, less RF heating generally occurs. *Specific absorption rate (SAR)* is a term that describes the rate at which RF energy is absorbed in tissue.

Maximum permissible exposure (MPE) limits are based on whole-body SAR values, with additional safety factors included as part of the standards and regulations. This helps explain why these safe exposure limits vary with frequency. The MPE limits define the maximum electric and magnetic field strengths or the plane-wave equivalent power densities associated with these fields, that a person may be exposed to without harmful effect — and with an acceptable safety factor. The regulations assume that a person exposed to a specified (safe) MPE level also will experience a safe SAR.

Nevertheless, thermal effects of RF energy should not be a major concern for most radio amateurs, because of the power levels we normally use and the intermittent nature of most amateur transmissions. Amateurs spend more time listening than transmitting, and many amateur transmissions such as CW and SSB use low-duty-cycle modes. (With FM or RTTY, though, the RF is present continuously at its maximum level during each transmission.) In any event, it is rare for radio amateurs to be subjected to RF fields strong enough to produce thermal effects, unless they are close to an energized antenna or un-shielded power amplifier. Specific suggestions for avoiding excessive exposure are offered later in this chapter.

1.6.2 ATHERMAL EFFECTS OF EMR

Research about possible health effects resulting from exposure to the lower level energy fields, the athermal effects, has been of two basic types: epidemiological research and laboratory research.

Scientists conduct laboratory research into biological mechanisms by which EMR may affect animals including humans. Epidemiologists look at the health patterns of large groups of people using statistical methods. These epidemiological studies have been inconclusive. By their basic design, these studies do not demonstrate cause and effect, nor do they postulate mechanisms of disease. Instead, epidemiologists look for associations between an environmental factor and an observed pattern of illness. For example, in the earliest research on malaria, epidemiologists observed the association between populations with high prevalence of the disease and the proximity of mosquito infested swamplands. It was left to the biological and medical scientists to isolate the organism causing malaria in the blood of those with the disease, and identify the same organisms in the mosquito population.

In the case of athermal effects, some studies have identified a weak association between exposure to EMF at home or at work and various malignant conditions including leukemia and brain cancer. A larger number of equally well designed and performed studies, however, have found no association. A risk ratio of between 1.5 and 2.0 has been observed in positive studies (the number of observed cases of malignancy being 1.5 to 2.0 times the "expected" number in the population). Epidemiologists generally regard a risk ratio of 4.0 or greater to be indicative of a strong association between the cause and effect under study. For example, men who smoke one pack of cigarettes per day increase their risk for lung cancer tenfold compared to nonsmokers, and two packs per day increases the risk to more than 25 times the nonsmokers' risk.

Epidemiological research by itself is rarely conclusive, however. Epidemiology only identifies health patterns in groups — it does not ordinarily determine their cause. And there are often confounding factors: Most of us are exposed to many different environmental hazards that may affect our health in various ways. Moreover, not all studies of persons likely to be exposed to high levels of EMR have yielded the same results.

There also has been considerable laboratory research about the biological effects of EMR in recent years. For example, some separate studies have indicated that even fairly low levels of EMR might alter the human body's circadian rhythms, affect the manner in which T lymphocytes function in the immune system and alter the nature of the electrical and chemical signals communicated through the cell membrane and between cells, among other things. Although these studies are intriguing, they do not demonstrate any effect of these low-level fields on the overall organism.

Much of this research has focused on low-frequency magnetic fields, or on RF fields that are keyed, pulsed or modulated at a low audio frequency (often below 100 Hz). Several studies suggested that humans and animals can adapt to the presence of a steady RF carrier more readily than to an intermittent, keyed or modulated energy source.

The results of studies in this area, plus speculations concerning the effect of various types of modulation, were and have remained somewhat controversial. None of the research to date has demonstrated that low-level EMR causes adverse health effects.

Given the fact that there is a great deal of ongoing research to examine the health consequences of exposure to EMF, the American Physical Society (a national group of highly respected scientists) issued a statement in May 1995 based on its review of available data pertaining to the possible connections of cancer to 60-Hz EMF exposure. This report is exhaustive and should be reviewed by anyone with a serious interest in the field. Among its general conclusions were the following:

1. The scientific literature and the reports of reviews by other panels show no consistent, significant link between cancer and power line fields.

2. No plausible biophysical mechanisms for the systematic initiation or promotion of cancer by these extremely weak 60-Hz fields has been identified.

3. While it is impossible to prove that no deleterious health effects occur from exposure to any environmental factor, it is necessary to demonstrate a consistent, significant and causal relationship before one can conclude that such effects do occur.

In a report dated October 31, 1996, a committee of the National Research Council of the National Academy of Sciences has concluded that no clear, convincing evidence exists to show that residential exposures to electric and magnetic fields (EMFs) are a threat to human health.

A National Cancer Institute epidemiological study of residential exposure to magnetic fields and acute lymphoblastic leukemia in children was published in the

FCC RF-Exposure Regulations

FCC regulations control the amount of RF exposure that can result from your station's operation (§§97.13, 97.503, 1.1307 (b)(c)(d), 1.1310 and 2.1093). The regulations set limits on the maximum permissible exposure (MPE) allowed from operation of transmitters in all radio services. They also require that certain types of stations be evaluated to determine if they are in compliance with the MPEs specified in the rules. The FCC has also required that five questions on RF environmental safety practices be added to Novice, Technician and General license examinations.

These rules went into effect on January 1, 1998 for new stations or stations that file a Form 605 application with the FCC. Other existing stations had until September 1, 2000 to be in compliance with the rules.

THE RULES

Maximum Permissible Exposure (MPE)

All radio stations regulated by the FCC must comply with the requirements for MPEs, even QRP stations running only a few watts or less. The MPEs vary with frequency, as shown in **Table A**. MPE limits are specified in maximum electric and magnetic fields for frequencies below 30 MHz, in power density for frequencies above 300 MHz and all three ways for frequencies from 30 to 300 MHz. For compliance purposes, all of these limits must be considered separately. If any single limit is exceeded, the station is not in compliance.

The regulations control human exposure to RF fields, not the strength of RF fields. There is no limit to how strong a field can be as long as no one is being exposed to it, although FCC regulations require that amateurs use the minimum necessary power at all times (§97.311 [a]).

Environments

The FCC has defined two exposure environments — controlled and uncontrolled. A controlled environment is one in which the people who are being exposed are aware of that exposure and can take steps to minimize that exposure, if appropriate. In an uncontrolled environment, the people being exposed are not normally aware of the exposure. The uncontrolled environment limits are more stringent than the controlled environment limits.

Although the controlled environment is usually intended as an occupational environment, the FCC has determined that it generally applies to amateur operators and members of their immediate households. In most cases, controlled-environment limits can be applied to

Table A — (From §1.1310) Limits for Maximum Permissible Exposure (MPE)

(A) Limits for Occupational/Controlled Exposure

Frequency Range (MHz)	*Electric Field Strength (V/m)*	*Magnetic Field Strength (A/m)*	*Power Density (mW/cm²)*	*Averaging Time (minutes)*
0.3-3.0	614	1.63	(100)*	6
3.0-30	1842/f	4.89/f	$(900/f^2)$*	6
30-300	61.4	0.163	1.0	6
300-1500	—	—	f/300	6
1500-100,000	—	—	5	6

f = frequency in MHz
* = Plane-wave equivalent power density (see Note 1).

(B) Limits for General Population/Uncontrolled Exposure

Frequency Range (MHz)	*Electric Field Strength (V/m)*	*Magnetic Field Strength (A/m)*	*Power Density (mW/cm²)*	*Averaging Time (minutes)*
0.3-1.34	614	1.63	(100)*	30
1.34-30	824/f	2.19/f	$(180/f^2)$*	30
30-300	27.5	0.073	0.2	30
300-1500	—	—	f/1500	30
1500-100,000	—	—	1.0	30

f = frequency in MHz
* = Plane-wave equivalent power density (see Note 1).
Note 1: This means the equivalent far-field strength that would have the E or H-field component calculated or measured. It does not apply well in the near field of an antenna. The equivalent far-field power density can be found in the near or far field regions from the relationships: $P_d = |E_{total}|^2 / 3770$ mW/cm² or from $P_d = |H_{total}|^2 \times 37.7$ mW/cm².

your home and property to which you can control physical access. The uncontrolled environment is intended for areas that are accessible by the general public, such as your neighbors' properties.

The MPE levels are based on average exposure. An averaging time of 6 minutes is used for controlled exposure; an averaging period of 30 minutes is used for uncontrolled exposure.

Station Evaluations

The FCC requires that certain amateur stations be evaluated for compliance with the MPEs. Although an amateur can have someone else do the evaluation, it is not difficult for hams to evaluate their own stations. The ARRL book *RF Exposure and You* contains extensive information about the regulations and a large chapter of tables that show compliance distances for specific antennas and power levels. Generally, hams will use these tables to evaluate their stations. Some of these tables have been included in the FCC's information — OET Bulletin 65 and its Supplement B. If hams choose, however, they can do more extensive calculations, use a computer to model their antenna and exposure, or make actual measurements.

Table B — Power Thresholds for Routine Evaluation of Amateur Radio Stations

Wavelength Band	*Evaluation Required if Power* (watts) Exceeds:*
MF	
160 m	500
HF	
80 m	500
75 m	500
40 m	500
30 m	425
20 m	225
17 m	125
15 m	100
12 m	75
10 m	50
VHF	
All bands	50
UHF	
70 cm	70
33 cm	150
23 cm	200
13 cm	250
SHF	
All bands	250
EHF	
All bands	250

Repeater stations (all bands)

Non-building-mounted antennas: Height above ground level to lowest point of antenna < 10 m and power > 500 W ERP

Building-mounted antennas: Power > 500 W ERP

*Transmitter power = Peak-envelope power input to antenna. For repeater stations *only,* power exclusion based on ERP (effective radiated power).

Categorical Exemptions

Some types of amateur stations do not need to be evaluated, but these stations must still comply with the MPE limits. The station licensee remains responsible for ensuring that the station meets these requirements.

The FCC has exempted these stations from the evaluation requirement because their output power, operating mode and frequency are such that they are presumed to be in compliance with the rules.

Stations using power equal to or less than the levels in **Table B** do not have to be evaluated. For the 100-W HF ham station, for example, an evaluation would be required only on 12 and 10 meters.

Hand-held radios and vehicle-mounted mobile radios that operate using a push-to-talk (PTT) button are also categorically exempt from performing the routine evaluation. Repeater stations that use less than 500 W ERP or those with antennas not mounted on buildings, if the antenna is at least 10 meters off the ground, also do not need to be evaluated.

Correcting Problems

Most hams are already in compliance with the MPE requirements. Some amateurs, especially those using indoor antennas or high-power, high-duty-cycle modes such as a RTTY bulletin station and specialized stations for moonbounce operations and the like may need to make adjustments to their station or operation to be in compliance.

The FCC permits amateurs considerable flexibility in complying with these regulations. As an example, hams can adjust their operating frequency, mode or power to comply with the MPE limits. They can also adjust their operating habits or control the direction their antenna is pointing.

More Information

This discussion offers only an overview of this topic; additional information can be found in *RF Exposure and You* and on the ARRL website at **www.arrl.org/rf-exposure-regulations-news**. The ARRL website also has links to the FCC website, as well as OET Bulletin 65 and Supplement B and links to software that hams can use to evaluate their stations.

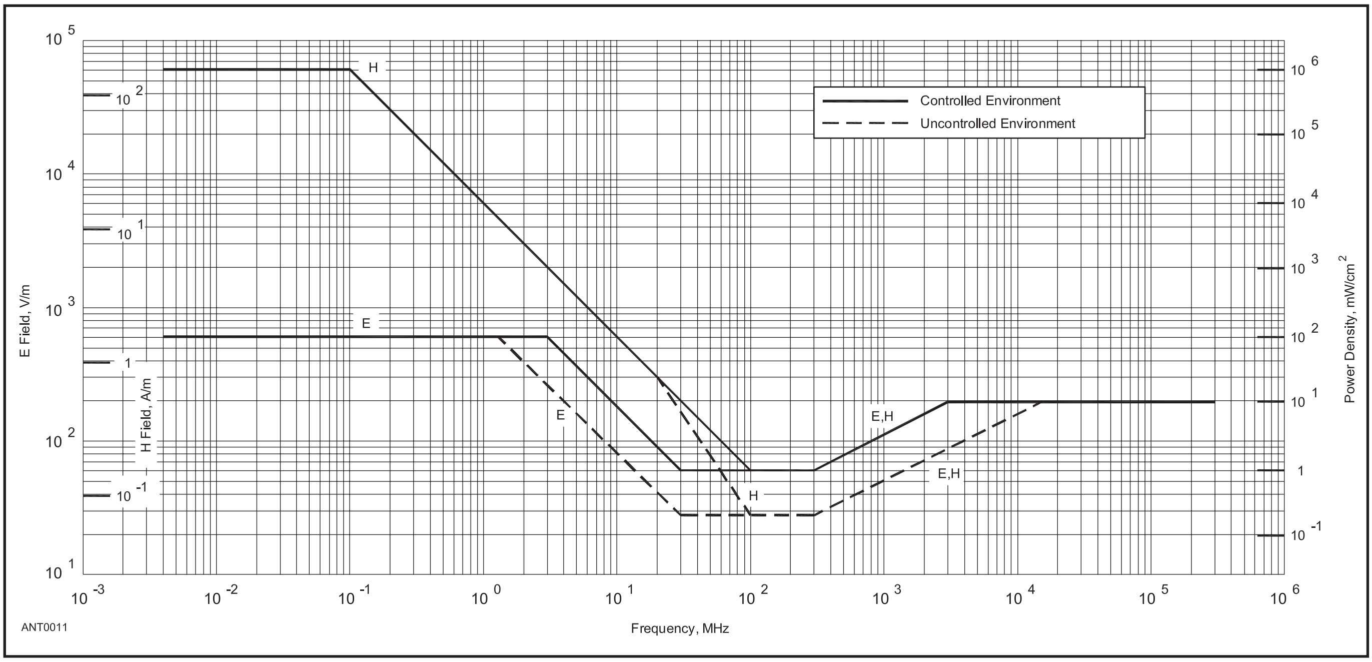


Figure 1.16 — 1991 RF protection guidelines for body exposure of humans. It is known officially as the "IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz."

New England Journal of Medicine in July 1997. The exhaustive, seven-year study concludes that if there is any link at all, it is far too weak to be concerned about.

Readers may want to follow this topic as further studies are reported. Amateurs should be aware that exposure to RF and ELF (60 Hz) electromagnetic fields at all power levels and frequencies has not been fully studied under all circumstances. "Prudent avoidance" of any avoidable EMR is always a good idea. Prudent avoidance doesn't mean that amateurs should be fearful of using their equipment. Most amateur operations are well within the MPE limits. If any risk does exist, it will almost surely fall well down on the list of causes that may be harmful to your health (on the other end of the list from your automobile). It does mean, however, that hams should be aware of the potential for exposure from their stations, and take whatever reasonable steps they can take to minimize their own exposure and the exposure of those around them.

Safe Exposure Levels

How much EM energy is safe? Scientists and regulators have devoted a great deal of effort to deciding upon safe RF-exposure limits. This is a very complex problem, involving difficult public health and economic considerations. The recommended safe levels have been revised downward several times over the years — and not all scientific bodies agree on this question even today. An Institute of Electrical and Electronics Engineers (IEEE) standard for recommended EM exposure limits was published in 1991 (see Bibliography). It replaced a 1982 American National Standards Institute (ANSI) standard. In the new standard, most of the permitted exposure levels were revised downward (made more stringent), to better reflect the current research. The new IEEE standard was adopted by ANSI in 1992.

The IEEE standard recommends frequency-dependent and time-dependent maximum permissible exposure levels. Unlike earlier versions of the standard, the 1991 standard recommends different RF exposure limits in controlled environments (that is, where energy levels can be accurately determined and everyone on the premises is aware of the presence of EM fields) and in uncontrolled environments (where energy levels are not known or where people may not be aware of the presence of EM fields). FCC regulations also include controlled/occupational and uncontrolled/general population exposure environments.

The graph in **Figure 1.16** depicts the 1991 IEEE standard. It is necessarily a complex graph, because the standards differ not only for controlled and uncontrolled environments but also for electric (E) fields and magnetic (H) fields. Basically, the lowest E-field exposure limits occur at frequencies between 30 and 300 MHz. The lowest H-field exposure levels occur at 100-300 MHz. The ANSI standard sets the maximum E-field limits between 30 and 300 MHz at a power density of 1 mW/cm^2 (61.4 V/m) in controlled environments — but at one-fifth that level (0.2 mW/cm^2 or 27.5 V/m) in uncontrolled environments. The H-field limit drops to 1 mW/cm^2 (0.163 A/m) at 100-300 MHz in controlled environments and 0.2 mW/cm^2 (0.0728 A/m) in uncontrolled environments. Higher power densities are permitted at frequencies below 30 MHz (below 100 MHz for H fields) and above 300 MHz, based on the concept that the body will not be resonant at those frequencies and will therefore absorb less energy.

In general, the 1991 IEEE standard requires averaging the power level over time periods ranging from 6 to 30 minutes for power-density calculations, depending on the frequency and other variables. The ANSI exposure limits for uncontrolled environments are lower than those for controlled environments, but to compensate for that the standard allows exposure levels in those environments to be averaged over much longer time periods (generally 30 minutes). This long averaging time means that an intermittently operating RF source (such as an Amateur Radio transmitter) will show a much lower power density than a continuous-duty station — for a given power level and antenna configuration.

Time averaging is based on the concept that the human body can withstand a greater rate of body heating (and thus, a higher level of RF energy) for a short time than for a longer period. Time averaging may not be appropriate, however, when considering nonthermal effects of RF energy.

The IEEE standard excludes any transmitter with an output below 7 W because such low-power transmitters would not be able to produce significant whole-body heating. (Recent studies show that hand-held transceivers often produce power densities in excess of the IEEE standard within the head.)

There is disagreement within the scientific community about these RF exposure guidelines. The IEEE standard is still intended primarily to deal with thermal effects, not exposure to energy at lower levels. A small but significant number of researchers now believe athermal effects also should be taken into consideration. Several European countries and localities in the United States have adopted stricter standards than the recently updated IEEE standard.

Another national body in the United States, the National Council for Radiation Protection and Measurement (NCRP), also has adopted recommended exposure guidelines. NCRP urges a limit of 0.2 mW/cm^2 for non-occupational exposure in the 30-300 MHz range. The NCRP guideline differs from IEEE in two notable ways: It takes into account the effects of modulation on an RF carrier and it does not exempt transmitters with outputs below 7 W.

The FCC MPE regulations are based on parts of the 1992 IEEE/ANSI standard and recommendations of the National Council for Radiation Protection and Measurement (NCRP). The MPE limits under the regulations are slightly different from the IEEE/ANSI limits. Note that the MPE levels apply to the FCC rules put into effect for radio amateurs on January 1, 1998. These MPE requirements do not reflect and include all the assumptions and exclusions of the IEEE/ANSI standard.

Cardiac Pacemakers and RF Safety

It is a widely held belief that cardiac pacemakers may be adversely affected in their function by exposure to electromagnetic fields. Amateurs with pacemakers may ask whether their operating might endanger themselves or visitors to their shacks who have a pacemaker. Because of this, and similar concerns regarding other sources of electromagnetic fields, pacemaker manufacturers apply design methods that for the most part shield the pacemaker circuitry from even relatively high EM field strengths.

It is recommended that any amateur who has a pacemaker, or is being considered for one, discuss this matter with his or her physician. The physician will probably put the amateur into contact with the technical representative of the pacemaker manufacturer. These representatives are generally excellent resources, and may have data from laboratory or "in the field" studies with specific model pacemakers.

One study examined the function of a modern (dual chamber) pacemaker in and around an Amateur Radio station. The pacemaker generator has circuits that receive and process electrical signals produced by the heart, and also generate electrical signals that stimulate (pace) the heart. In one series of experiments, the pacemaker was connected to a heart simulator. The system was placed on top of the cabinet of a 1-kW HF linear amplifier during SSB and CW operation. In another test, the system was placed in close proximity to several 1 to 5-W 2 meter hand-held transceivers. The test pacemaker was connected to the heart simulator in a third test, and then placed on the ground 9 meters below and 5 meters in front of a three-element Yagi HF antenna. No interference with pacemaker function was observed in these experiments.

Although the possibility of interference cannot be entirely ruled out by these few observations, these tests represent more severe exposure to EM fields than would ordinarily be encountered by an amateur — with an average amount of common sense. Of course, prudence dictates that amateurs with pacemakers, who use hand-held VHF transceivers, keep the antenna as far as possible from the site of the implanted pacemaker generator. They also should use the lowest transmitter output required for adequate communication. For high power HF transmission, the antenna should be as far as possible from the operating position, and all equipment should be properly grounded.

Low-Frequency Fields

Although the FCC doesn't regulate 60-Hz fields, some recent concern about EMR has focused on low-frequency energy rather than RF. Amateur Radio equipment can be a significant source of low-frequency magnetic fields, although

Table 1.1
Typical 60-Hz Magnetic Fields Near Amateur Radio Equipment and AC-Powered Household Appliances
Values are in milligauss.

Item	*Field*	*Distance*
Electric blanket	30-90	Surface
Microwave oven	10-100	Surface
	1-10	12"
Personal computer	5-10	Atop CRT monitor
	0-1	15" from screen
Electric drill	500-2000	At handle
Hair dryer	200-2000	At handle
HF transceiver	10-100	Atop cabinet
	1-5	15" from front
1-kW RF amplifier	80-1000	Atop cabinet
	1-25	15" from front

(Source: measurements made by members of the ARRL RF Safety Committee) there are many other sources of this kind of energy in the typical home. Magnetic fields can be measured relatively accurately with inexpensive 60-Hz meters that are made by several manufacturers.

Table 1.1 shows typical magnetic field intensities of Amateur Radio equipment and various household items. Because these fields dissipate rapidly with distance, "prudent avoidance" would mean staying perhaps 12 to 18 inches away from most Amateur Radio equipment (and 24 inches from power supplies with 1-kW RF amplifiers).

Determining RF Power Density

Unfortunately, determining the power density of the RF fields generated by an amateur station is not as simple as measuring low-frequency magnetic fields. Although sophisticated instruments can be used to measure RF power densities quite accurately, they are costly and require frequent recalibration. Most amateurs don't have access to such equipment, and the inexpensive field-strength meters that we do have are not suitable for measuring RF power density.

Table 1.2 shows a sampling of measurements made at Amateur Radio stations by the Federal Communications Commission and the Environmental Protection Agency in 1990. As this table indicates, a good antenna well removed from inhabited areas poses no hazard under any of the IEEE/ANSI guidelines. However, the FCC/EPA survey also indicates that amateurs must be careful about using indoor or

Table 1.2
Typical RF Field Strengths Near Amateur Radio Antennas

A sampling of values as measured by the Federal Communications Commission and Environmental Protection Agency, 1990

Antenna Type	*Freq (MHz)*	*Power (W)*	*E Field (V/m)*	*Location*
Dipole in attic	14.15	100	7-100	In home
Discone in attic	146.5	250	10-27	In home
Half sloper	21.5	1000	50	1 m from base
Dipole at 7-13 ft	7.14	120	8-150	1-2 m from Earth
Vertical	3.8	800	180	0.5 m from base
5-element Yagi	21.2	1000	10-20	In shack
			14	12 m from base at 60 ft
3-element Yagi	28.5	425	8-12	12 m from base at 25 ft
Inverted V	7.23	1400	5-27	Below antenna at 22-46 ft
Vertical on roof	14.11	140	6-9	In house
			35-100	At antenna tuner
Whip on auto roof	146.5	100	22-75	2 m antenna
			15-30	In vehicle
			90	Rear seat
5-element Yagi	50.1	500	37-50	10 m antenna at 20 ft

Table 1.3
RF Awareness Guidelines

These guidelines were developed by the ARRL RF Safety Committee, based on the FCC/EPA measurements of Table 1.2 and other data.

- Although antennas on towers (well away from people) pose no exposure problem, make certain that the RF radiation is confined to the antennas' radiating elements themselves. Provide a single, good station ground (earth), and eliminate radiation from transmission lines. Use good coaxial cable or other feed line properly. Avoid serious imbalance in your antenna system and feed line. For high-powered installations, avoid end-fed antennas that come directly into the transmitter area near the operator.
- No person should ever be near any transmitting antenna while it is in use. This is especially true for mobile or ground-mounted vertical antennas. Avoid transmitting with more than 25 W in a VHF mobile installation unless it is possible to first measure the RF fields inside the vehicle. At the 1-kW level, both HF and VHF directional antennas should be at least 35 ft above inhabited areas. Avoid using indoor and attic-mounted antennas if at all possible. If open-wire feeders are used, ensure that it is not possible for people (or animals) to come into accidental contact with the feed line.
- Don't operate high-power amplifiers with the covers removed, especially at VHF/UHF.
- In the UHF/SHF region, never look into the open end of an activated length of waveguide or microwave feed-horn antenna or point it toward anyone. (If you do, you may be exposing your eyes to more than the maximum permissible exposure level of RF radiation.) Never point a high-gain, narrow-bandwidth antenna (a paraboloid, for instance) toward people. Use caution in aiming an EME (moonbounce) array toward the horizon; EME arrays may deliver an effective radiated power of 250,000 W or more.
- With hand-held transceivers, keep the antenna away from your head and use the lowest power possible to maintain communications. Use a separate microphone and hold the rig as far away from you as possible. This will reduce your exposure to the RF energy.
- Don't work on antennas that have RF power applied.
- Don't stand or sit close to a power supply or linear amplifier when the ac power is turned on. Stay at least 24 inches away from power transformers, electrical fans and other sources of high-level 60-Hz magnetic fields.

attic-mounted antennas, mobile antennas, low directional arrays or any other antenna that is close to inhabited areas, especially when moderate to high power is used.

Ideally, before using any antenna that is in close proximity to an inhabited area, you should measure the RF power density. If that is not feasible, the next best option is make the installation as safe as possible by observing the safety suggestions listed in **Table 1.3**.

It also is possible, of course, to calculate the probable power density near an antenna using simple equations. Such calculations have many pitfalls. For one, most of the situations where the power density would be high enough to be of concern are in the near field. In the near field, ground interactions and other variables produce power densities that cannot be determined by simple arithmetic. In the far field, conditions become easier to predict with simple calculations.

The boundary between the near field and the far field depends on the wavelength of the transmitted signal and the physical size and configuration of the antenna. The boundary between the near field and the far field of an antenna can be as much as several wavelengths from the antenna.

Computer antenna-modeling programs are another approach you can use. *MININEC* or other codes derived from *NEC* (Numerical Electromagnetics Code) are suitable for estimating RF magnetic and electric fields around amateur antenna systems.

These models have limitations. Ground interactions must be considered in estimating near-field power densities, and the "correct ground" must be modeled. Computer modeling is generally not sophisticated enough to predict "hot spots" in the near field — places where the field intensity may be far higher than would be expected, due to reflections from nearby objects. In addition, "nearby objects" often change or vary with weather or the season, so the model so laboriously crafted may not be representative of the actual situation, by the time it is running on the computer.

Intensely elevated but localized fields often can be detected by professional measuring instruments. These "hot spots" are often found near wiring in the shack, and metal objects such as antenna masts or equipment cabinets. But even with the best instrumentation, these measurements also may be misleading in the near field.

One need not make precise measurements or model the exact antenna system, however, to develop some idea of the relative fields around an antenna. Computer modeling using close approximations of the geometry and power input of the antenna will generally suffice. Those who are familiar with *MININEC* can estimate their power densities by computer modeling, and those who have access to professional power-density meters can make useful measurements.

While our primary concern is ordinarily the intensity of the signal radiated by an antenna, we also should remember that there are other potential energy sources to be considered. You also can be exposed to RF radiation directly from a power amplifier if it is operated without proper shielding. Transmission lines also may radiate a significant amount of energy under some conditions. Poor microwave waveguide joints or improperly assembled connectors are another source of incidental radiation.

Further RF Exposure Suggestions

Potential exposure situations should be taken seriously. Based on the FCC/EPA measurements and other data, the "RF awareness" guidelines of Table 1.3 were developed by the ARRL RF Safety Committee. A longer version of these guidelines, along with a complete list of references, appeared in a *QST* article by Ivan Shulman, MD, WC2S ("Is Amateur Radio Hazardous to Our Health?" *QST* , Oct 1989, pp 31-34). For more information or background, see the list of RF Safety References in the next section.

In addition, the ARRL has published a book, *RF Exposure and You*, that is helping hams comply with the FCC's RF-exposure regulations. The ARRL also maintains an RF-exposure news page on its website. See **www.arrl.org/rf-exposure**. This site contains reprints of selected *QST* articles on RF exposure and links to the FCC and other useful sites.

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