ANTENNA FACTBOOK

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To the American Radio Relay League (ARRL) for their patient consultation and meticulous proofreading; to "Kurt N. Sterba," whose barbs in print have laid asunder a number of myth makers; and to my wife, Judy, for her patience and understand while a I prepared this missal instead of paying the attention to her that she richly deserves.

CHAPTER 1

Radio Waves

When we connect a wire between the two terminals of a battery, electric current flows. This current generates a magnetic "field", a zone of energy which extends at the speed of light into space; when we break the circuit, that field collapses back onto the wire. If we reverse the connections back and forth millions or even billions of times per second, each successive pulse's electrical (positive and negative charges) and magnetic (north and south poles) reverse as well. This simulates a basic radio wave, consisting also of a magnetic and electric field vibrating in phase.

The electric ("E" or voltage) field is parallel to the axis of the wire, while the magnetic ("H") field is perpendicular to it. We describe this composite field as "electromagnetic."

Diagrams depicting radio waves as wavy lines or cross-hatched arrows are graphic representations only. There are no "lines of force" as implied when iron filings line up during magnet demonstrations. There is only a field of energy which is, like a beam of light, strongest at its source, weakening uniformly with distance as it spreads its energy over an ever-widening area.

In fact, radio waves and light waves differ only in frequency, with higher-frequency light having greater energy and the ability to be seen by some living organisms. Scientists even refer to an antenna as being "illuminated" by radio energy.

Radio waves can be reflected (bounced) by buildings, trees, vehicles, moisture, metal surfaces and wires, and the electrically-charged upper atmosphere (ionosphere). They can be refracted (bent) by boundaries between air masses, and they can be diffracted (scattered) by a ground clutter of reflective surfaces.

Radio and light waves in the vacuum of space travel approximately 186,000 miles (300 million meters) per second, but when they pass through a dense medium, they slow down; "velocity factor," the reduced speed of a radio signal, is a specification for transmission lines.

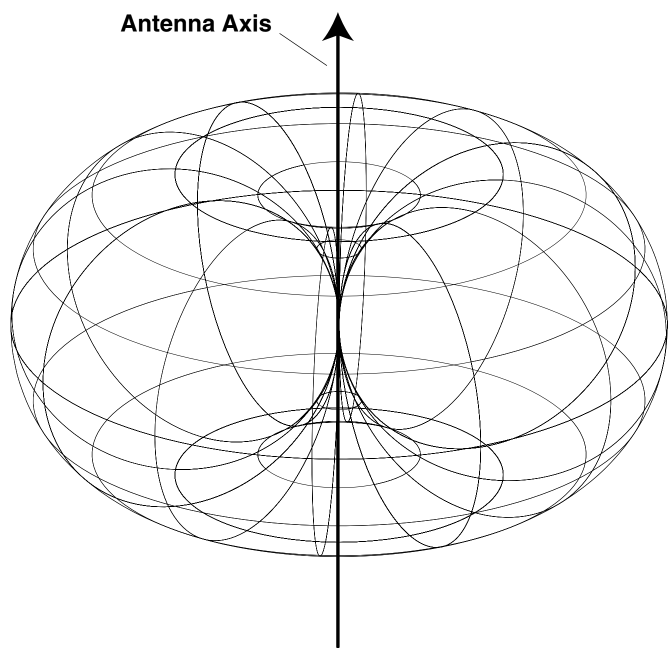

Figure 1.2: A three-dimensional representation of radio waves radiating from a vertical antenna.

When we specify antenna and transmission line lengths, these are electrical wavelengths which are shorter than free-space wavelengths because of this reduction in speed.

Propagation

We refer to the behavior of radio waves as they travel over distance as "propagation." Ground waves stay close to the earth's surface, never leaving the lower atmosphere. They are severely attenuated, rarely reaching more than a few hundred miles even under ideal conditions.

Surface waves are the lowest ground waves, often reaching their destination by following the curvature of the earth. Space waves are the line-of-sight ground waves which travel from antenna to antenna.

Space waves at VHF and UHF, when encountering

The lowest regions of the ionosphere, the D and E layers, are influenced directly by sunlight; their effects begin at sunrise, peak at noon, and disappear after sunset. They absorb radio signals—the longer the wavelength (that is, the lower the frequency), the more the absorption. This explains why daytime reception below about 10 megahertz is so poor.

abrupt weather boundary changes, experience temperature inversions, ducting and other influences which can significantly extend ground wave coverage.

At the upper reaches of our atmosphere, ultraviolet rays from the sun ionize (electrically charge) the air atoms, lending the name "ionosphere" to this highest zone of the earth's atmosphere. Radio waves which reach these ionized layers, averaging 25-200 miles high, are called "sky waves."

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But the E layer also reflects shorter-wavelength (higher frequency) signals back to Earth; the higher the frequency, the more the reflection. This is what provides DX (distance) on the higher shortwave frequencies.

Most DX, however, is produced by the next region up, the F layer, which retains its electrical charge well into the night, reflecting signals back to the earth over great distances.

All of these solar influences increase during sunspot peaks, which occur every 11 years.

The earth itself can reflect radio waves, allowing a phenomenon called "multihop"—combinations of earth reflections and ionospheric refractions producing as many as five skips! Any more skips would be attenuated by ionospheric absorption and terrestrial scattering below usability.

Many radio magazines publish monthly radio propagation forecasts, and a variety of prediction computer programs are available, allowing the user to plan ahead for the most productive use of the spectrum.

At VHF and UHF, ionospheric propagation is rare. Some sporadic E skip, lasting from a few minutes to an hour or more, may occur in the 50-200 MHz range. It is caused by erratic clouds of ionization at an altitude of 75-100 miles.

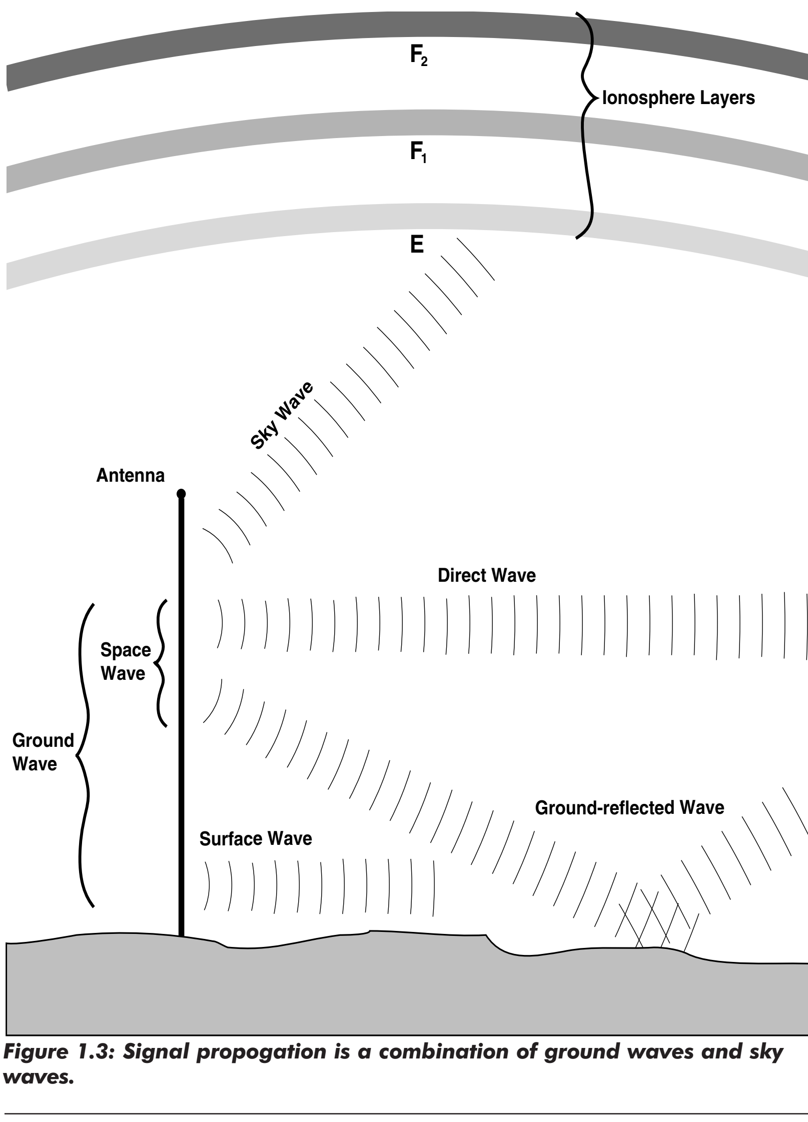

Figure 1.3: Signal propogation is a combination of ground waves and sky waves.

The "shape" of the field of energy emitted by a transmitting antenna, as well as response by a receiving antenna, is known as its pattern. It may be a simple donut shape surrounding the axis of the wire as in a half-wave (or smaller) dipole ("doublet"), or it may be multi-lobed,
as in a multiple-wavelength antenna ("longwire").

Tropospheric scattering in the E and F2 layers is fairly common in the 30-50 MHz spectrum, especially during the daytime and during sunspot peaks. It favors the east in the morning and the west in the afternoon.

Patterns

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The elevation pattern is affected by height above ground, length of the antenna element(s), and the presence of nearby metal, including other antenna elements.

The elevation of the pattern, variously called "radiation angle", "take-off angle", "maximum amplitude elevation", and "launch angle", is an integral part of an antenna's gain characteristics (We will discuss gain in Chapter 3).

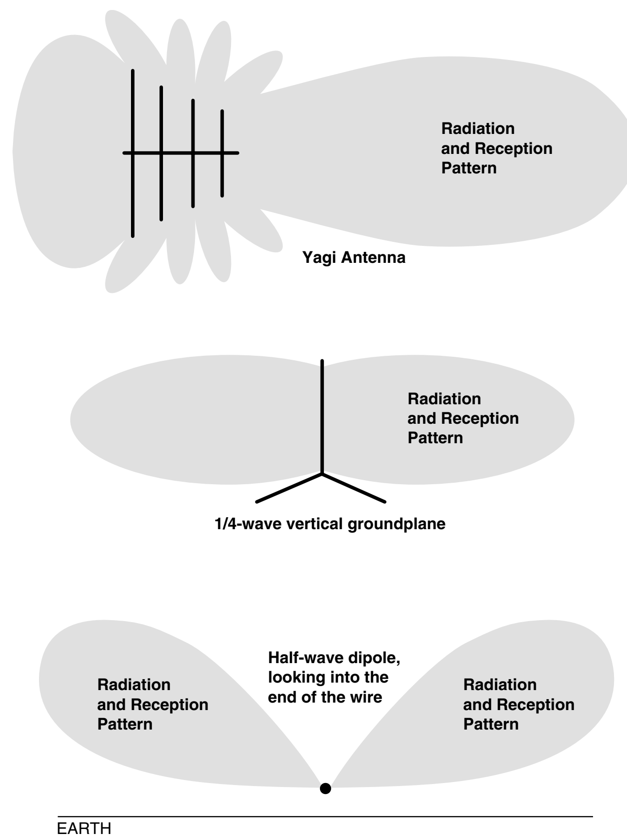


Figure 1.4: Antennas are designed to favor certain directions, both for transmitting and receiving.

CHAPTER 2
Antenna Location

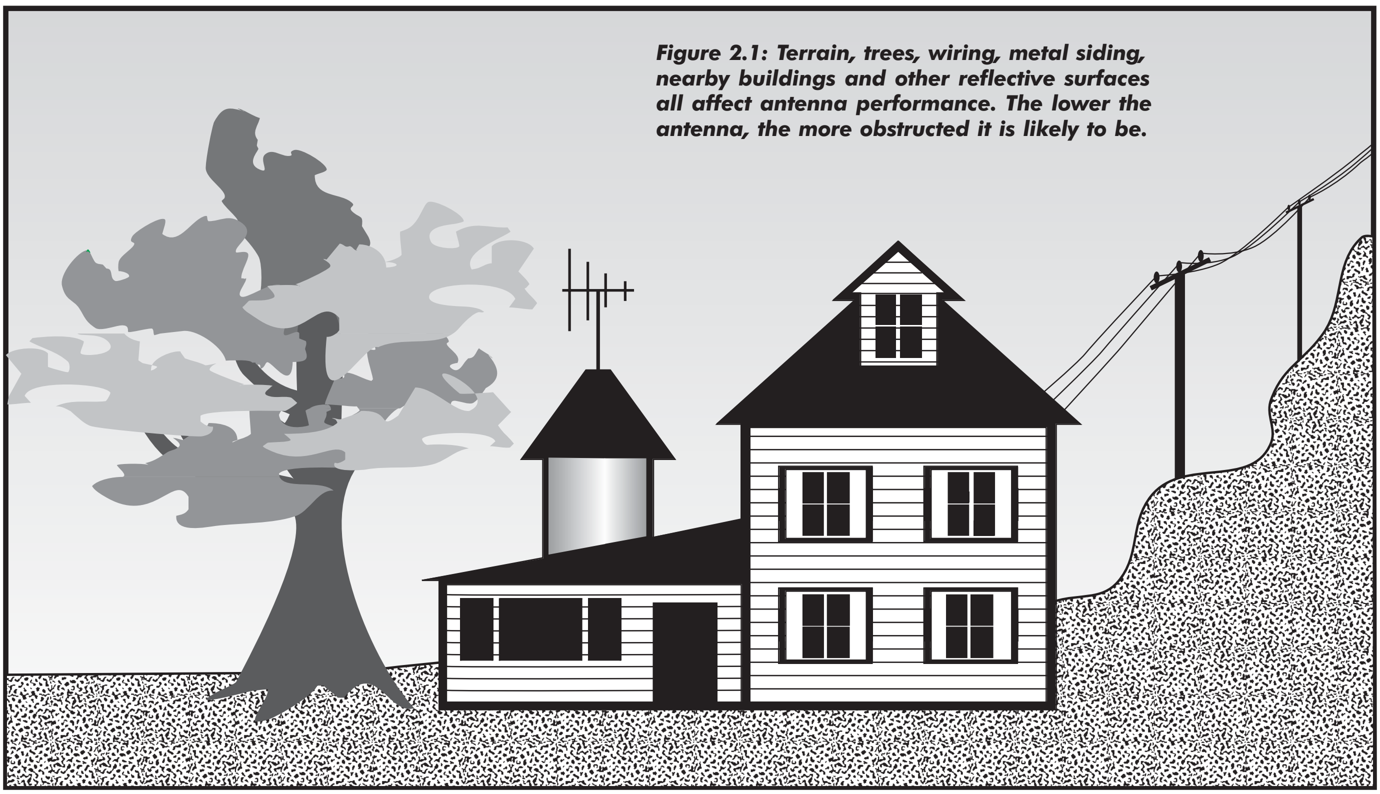


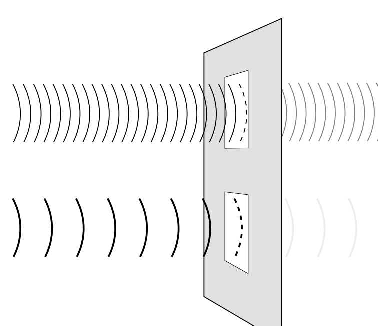
Figure 2.1: Terrain, trees, wiring, metal siding, nearby buildings and other reflective surfaces all affect antenna performance. The lower the antenna, the more obstructed it is likely to be.

A very poor antenna location would be an indoor basement. Signals are unpredictably reflected by metal and wiring in the structure; nearby electric and electronic appliances invite interference to reception; and the earth absorbs transmitted energy as well as reflects signals upward; and it receives signals from overhead, rather than from the horizon. Nearby trees, buildings and hills take their toll, too.

Locating an antenna inside a large building with steel frame and metal reinforcements may attenuate signals up to 25 dB at VHF and UHF, according to one study. Brick walls, slate or tile roofs can account for 6 dB, even more when wet. Shorter wavelengths (900 MHz) get through small windows in shielded walls where longer wavelengths (150 MHz) do not.

The lower the frequency, the more the signal is capable of following the contour of the terrain, and the less likely it is to be absorbed by trees and foliage. One study showed that with dense trees and vertical polarization, attenuation at 30 MHz is about 3 dB, increasing to 10 dB at 100 MHz.

Figure 2.2: The higher the frequency, the shorter the wavelength and the easier it is for a signal to get through an opening in an absorptive or reflective enclosure.



Because horizontal antennas radiate at right angles to their axes, they should be elevated at least 1/2 wavelength--higher if possible--as measured at their lowest operating frequency, to avoid ground effects which force the pattern upward. An antenna at that elevation can have a 6 dB (one full S-unit) stronger signal than one only 0.1-0.25 wavelengths above the ground.

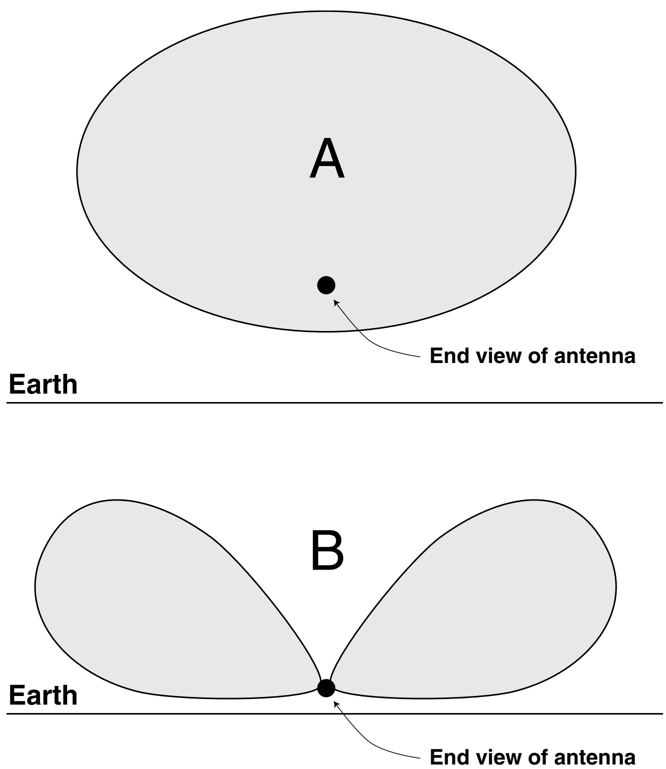


Figure 2.3: A high, horizontal antenna over the ground (A) enjoys a more uniform radiation and reception pattern toward the horizon than a low antenna (B) which is distorted upward by ground relfections.

While ground-mounted verticals are simpler to install than elevated antennas, nearby obstructions profoundly affect their performance.

Because horizontal antennas radiate at right angles to their axes, they should be elevated at least 1/2 wavelength—higher if possible—as measured at their lowest operating frequency, to avoid ground effects which force the pattern upward. An antenna at that elevation can have a 6 dB (one full S-unit) stronger signal than one only 0.1-0.25 wavelengths above the ground. One-half wavelength above the ground at its lowest frequency of operation appears even higher (in wavelengths) at higher frequencies because of their shorter wavelengths.

The Radio HorizonThe Radio Horizon

Radio waves, like light waves, follow the line of sight. Because of the curvature of the earth, higher antennas "see" a farther horizon.

Assuming a flat, unobstructed terrain, the visual horizon is about 8 miles for a 30-foot-elevated antenna, increasing to only 16 miles at 120 feet! Notice the square law effect: it requires roughly four times the height to get twice the distance. Once an antenna is high enough to "see" past nearby obstructions, it takes at least double that height to notice any improvement.

The lower the frequency, the more radio waves are capable of following the curvature of the earth beyond the visual horizon. Typical base-to-mobile communications ranges are about 50 miles in the 30-50 MHz band, 30 miles at 150-174 MHz, 25 miles at 450-512 MHz, and 20 miles at 806-960 MHz. Obviously, these distances will vary depending upon radiated power, receiver sensitivity, antenna gain, elevation and location.

Although the higher the antenna the better, coax cable losses may negate any signal improvement; the higher the frequency, the worse the losses.

For example, at 450 MHz, extending a 30-foot antenna to 60 feet could increase signal strengths by 5 dB, but if you are using common RG-58/U coax, signal strengths may be attenuated by the same amount, resulting in no improvement at all! At 800 MHz, using this small-diameter, lossy cable, signals would get worse with height!

Always use low-loss cable like (in increasing perfor-

$$\text{Distance (mi.)} = \sqrt{1.5 \times \text{Antenna Ht. (ft.)}}$$

Antenna Ht. (ft.)	Visual Horizon (mi.)	Radio Horizon (mi.)
20	5	6
50	9	10
100	12	14

Figure 2.4: A reasonable approximation of the visual horizon; due to groundwave effects, the radio horizon is slightly greater.

Old-style, spark-gap, antenna lightning arrestors were satisfactory for high-voltage-tolerant, tube-type equipment, but not for modern, low-voltage, solid-state equipment. Gas-discharge tubes which fire at well under 100 volts offer better protection, while allowing full amateur transmitter power to pass unaffected.

mance) RG-8/X, RG-8/U, Belden 9913, or 1/2" foam (Andrews) Heliax (all 50 ohm cables); or RG-59/U, RG-6/U or RG-11/U (72 ohm cables).

		LOSS IN dB				
TYPE	**IMPEDANCE**	**1 MHz**	**30 MHz**	**150 MHz**	**450 MHz**	**1000 MHz**
RG-6/U	75	0.5	1.2	2.5	4.2	6.5
R6-8/(foam)	50	0.1	0.9	2.1	3.8	6
RG-8/X(mini)	50	0.5	2	4.5	0.9	13.5
RG-11/U	75	0.3	0.8	1.4	2.6	4.0
RG-58/U	50	0.4	2.5	6	12	17
RG-59/U	75	0.3	2	4.5	8	12
RG-174/U	50	1.9	4	10	21	34
Belden 9913	50	0.1	0.7	1.7	3	4.5

Figure 2.5: Typical coax losses in dB per 100 feet, assuming ideal conditions.

Buried antennas

While a wire antenna on the ground or even buried a few inches under the soil is very inferior to an elevated antenna at shortwave and above, it does respond well to signals below 3 MHz or so. It is virtually immune to lightning, requires no mounting, is essentially invisible, and has excellent noise immunity (which probably accounts for its good reception).

Such an antenna should be insulation-covered to prevent electrical contact with the soil, and should be 100-200 feet in length. It is also a good idea to seal the far end with a dab of silicone rubber to discourage moisture penetration.

Lightning protection

Nothing can withstand a direct lightning hit. The best you can expect from a lightning arrestor or surge protector is to harmlessly short-circuit small voltage spikes resulting from nearby hits.

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During storms or extended periods of non-use, disconnect your antenna line from your radio. You may wish to ground it or, alternatively, hang the connector away from the radio equipment, even hanging it inside a drinking glass for additional insulation.

Improved lightning protection may be realized by suspending the antenna below the top of a well-grounded metal mast (which then becomes a lightning rod), by coiling the coax for about a dozen turns before it enters the building, and by passing the coax through a ten-foot metal pipe which is well grounded.

Although electrical power line protection is beyond the scope of this book, highly-effective metal-oxide varistors (MOVs) are available in strip-line extension cords, and even for circuit-breaker panels to protect the whole house.

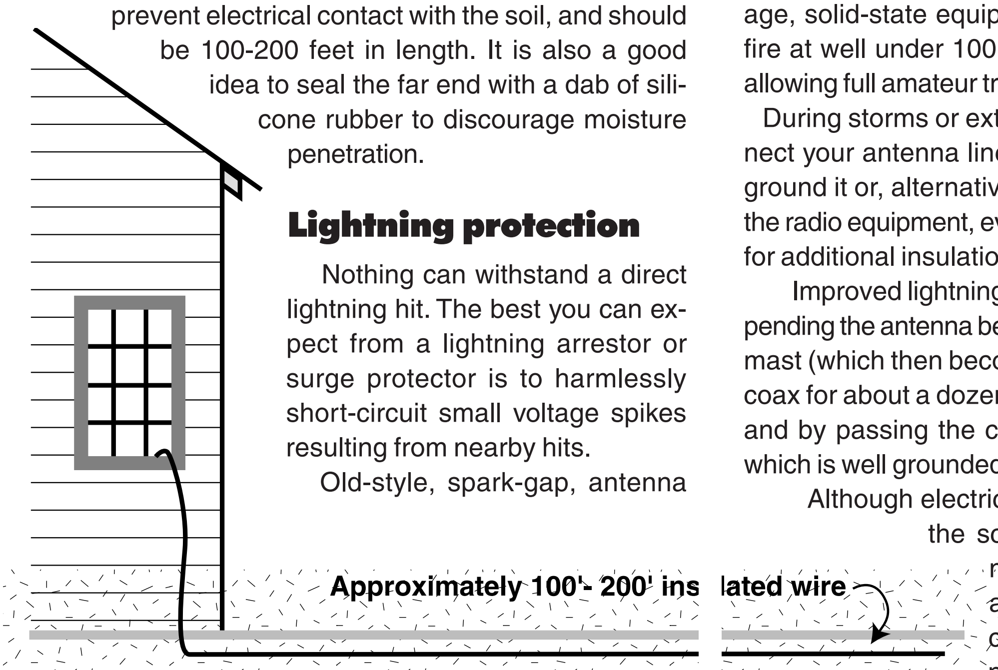

Figure 2.6: An antenna buried just under the surface of the ground may work well below 2-3 MHz.

A good electrical ground consists minimally of two eight-foot metal rods, at least ten feet apart, connected to the radio equipment by a short length of heavy braid. Moist, mineralized soil is best; dry, sandy soil is worst. A radio-frequency (RF) ground, on the other hand, is more extensive.

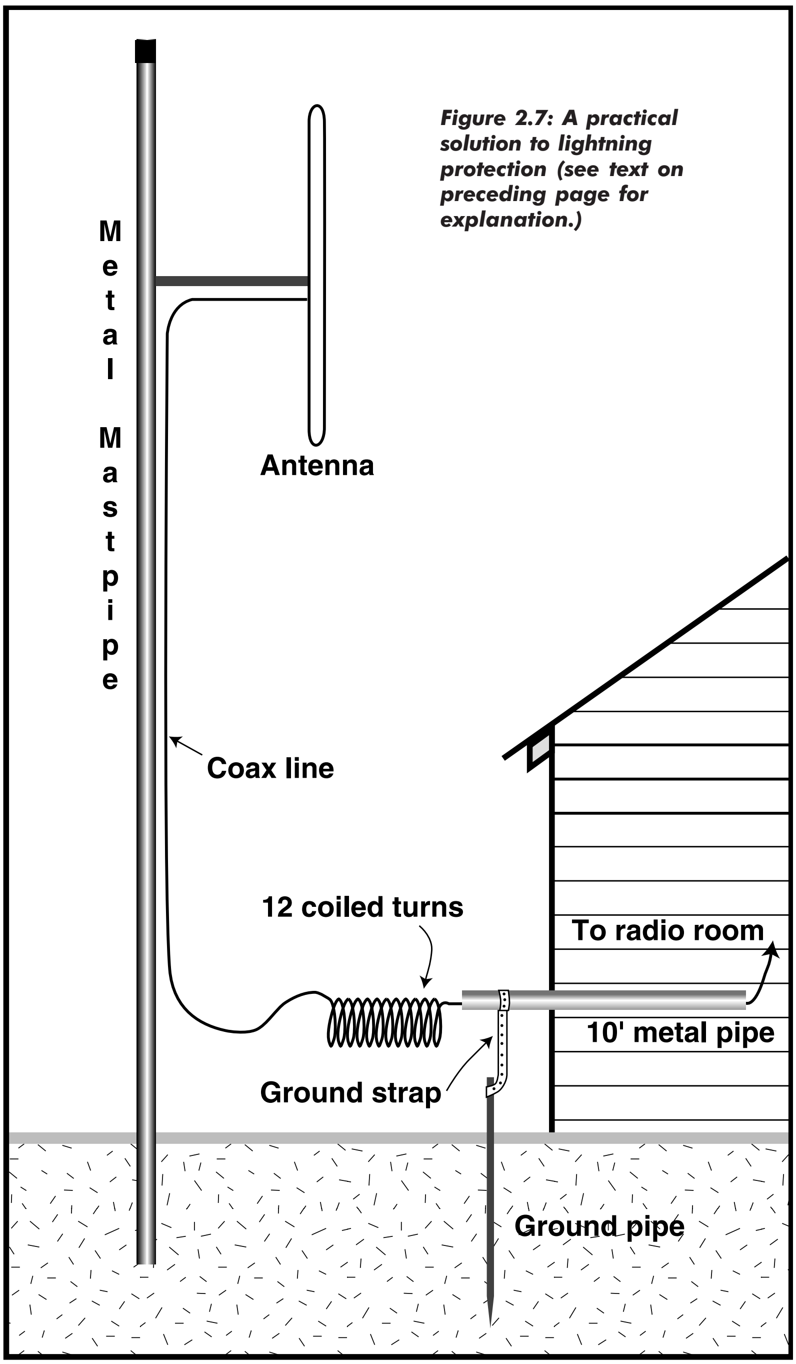

Figure 2.7: A practical solution to lightning protection (see text on preceding page for explanation.)

What is a "ground"?

The earth plays an important role in radio signal propagation, but "grounding" your radio equipment is not one of them. While attaching the chassis of your radio to a buried conductor in moist soil may protect you from electrical shock, will drain off static charge buildup, can help dissipate nearby lightning-induced spikes, and even reduce electrical noise pickup, it will not make received or transmitted signals stronger.

Radio wave travels through space, not through the ground except at very close ranges or at extremely low frequencies. It is intercepted by the antenna metal, not by the soil beneath it which absorbs and dissipates the signal as heat.

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A radio-frequency (RF) ground, on the other hand, is more extensive. A vertical antenna may be thought of as a center-fed dipole turned on its end, and the lower half removed so that we can mount the remaining element on the ground where the coax will be attached. But we must somehow supply that missing half of the antenna.

If we simply bury the needed wire in the ground, the energy that would radiate from that element is absorbed by the mineralized soil, simply heating it. Such an antenna is sometimes referred to as a "worm warmer!"

Instead, we construct a "counterpoise" on or above the soil, a metallic surface emulating a "perfect" (reflective) earth, composed of radial wires connected to, and extending outward from the coax shield at the base of the antennas.

How many spokes of wire, and how long? AM

Because current is at its maximum at the feedpoint, density of metal around the base of the antenna is more important than the length of the radials. If you have 100 feet of wire, ten 10-foot lengths is better than two 50-foot lengths. Receive-only antennas are not so critical.

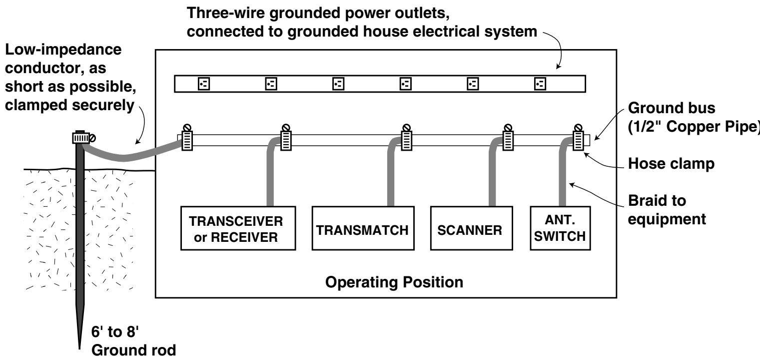

Figure 2.8: A good ground system utilizes short, large-gauge wire to connect radio equipment commonly to at least one deep ground rod.

broadcasters use at least 120; for transmitting purposes, you should use at least 16 1/8-wavelength wires to avoid power losses from soil absorption.

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Even a single quarter-wavelength wire provides counterpoise effect; it may be run randomly or even coiled loosely in some cases. Such a wire is often connected to the chassis of the transmitter if it is "hot" during transmitting as evidenced by painful RF burns when touching the equipment, especially your lip to the mike!

The inverted V antenna is a good example of how to keep the high-current feed point away from absorptive and reflective earth by elevating it to the apex of the antenna. The ends of the drooping elements (high-voltage points) come to within a few feet of the ground where their capacitive interaction with the soil may cause some length detuning of the antenna, but little signal loss.

Don't confuse a ground-mounted, counterpoised vertical with an elevated ground-plane antenna. On the ground we are trying to prevent radiation from being absorbed by

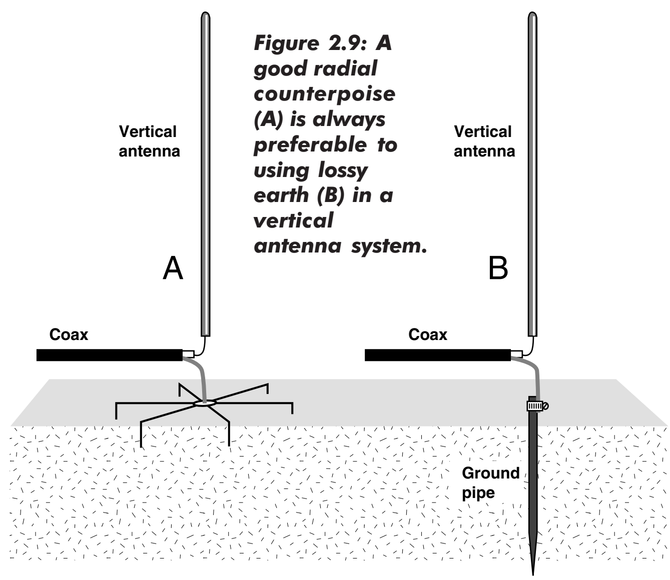

Figure 2.9: A good radial counterpoise (A) is always preferable to using lossy earth (B) in a vertical antenna system.

the soil; an elevated ground-plane antenna, however, behaves more like a dipole in free space, with the radials supplying half of the antenna and forming the pattern.

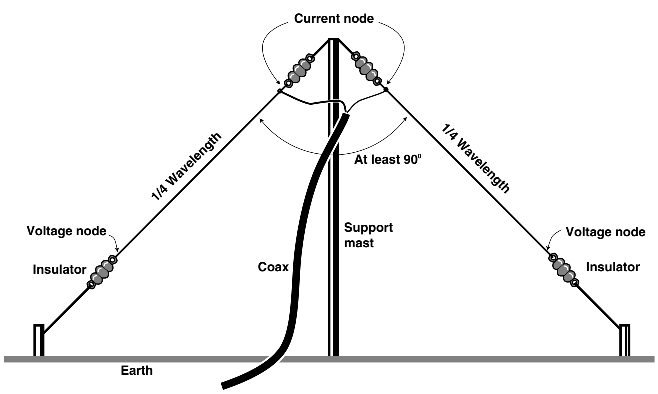

Figure 2:10: The inverted V is a popular dipole configuration.

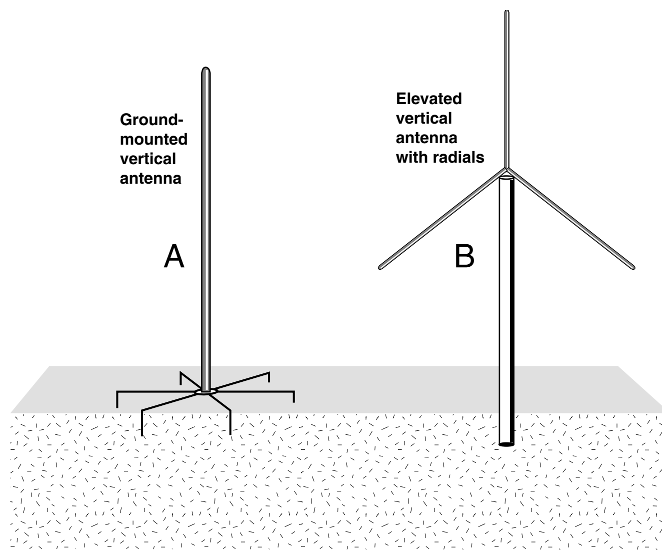

Figure 2.11: The radial counterpoise on a ground-mounted vertical (A) prevents soil absorption of the radio waves; the radials on an elevated vertical (B) are part of the antenna itself and help shape the pattern.

CHAPTER 3

Construction and Size

Two neighboring shortwave listeners decide to erect antennas to monitor 41-meter (7.1-7.3 MHz) international broadcasting. One neighbor, using rocks as counterweights, throws about 50 feet of small-gauge hookup wire over a couple of tree limbs; it sags in a number of places, has no insulators other than its plastic covering, and averages some 30 feet in the air. At the center cut of the wire he has soldered a 50-foot length of TV coax which he runs down to his receiver.

His neighbor, a purist, erects two 30 foot telephone poles 60 feet apart, stretching 66 feet of heavy gauge, silver plated, uninsulated wire between porcelain insulators. At the center he carefully attaches a commercial coax connector, from which he runs a 50-foot length of large-diameter, low-loss, RG-8/U coax.

Does he hear signals better? Nope. Assuming identical environment and antenna orientation, reception will be identical. The difference in signal strengths between 50 and 66 feet is imperceptible; the plastic-coated wire insulates it from the moist tree limbs, but even if it touched, the resistance of the trees would not contribute significant signal loss; signal absorption by foliage at 7 MHz is minimal; the resistance of the thinner wire is less than one ohm; and the difference between 50 feet of RG-58/U and RG-8/U at 7 MHz is a mere fraction of a dB.

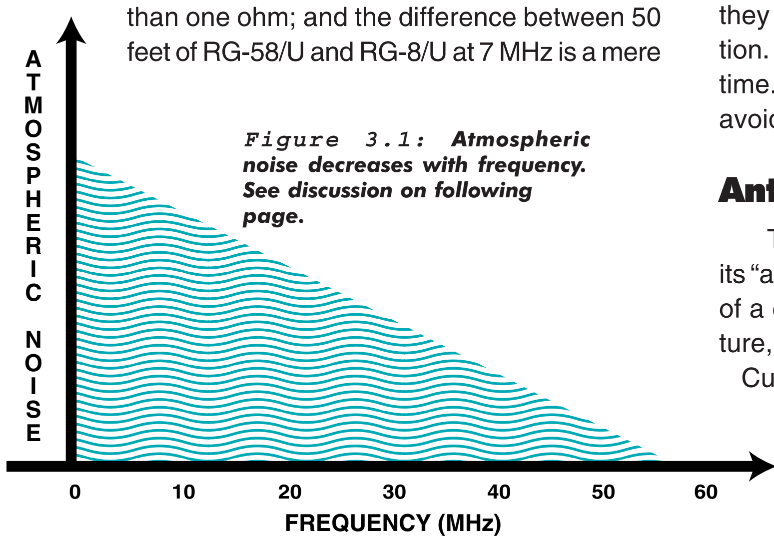

Figure 3.1: ***Atmospheric noise decreases with frequency. See discussion on following page.***

For receiving purposes, an antenna may be thick or thin; its texture may be solid, stranded or tubing; its composition may be any metal—gold, steel, copper, lead or aluminum; it may be covered with insulation or left bare. All signals will sound the virtually the same.

Finally, even if signal strengths were reduced considerably, they would still be just as audible, because at shortwave, once there is enough signal to be heard above the atmospheric noise ("static"), a larger antenna will only capture more signal *and noise.* The S-meter may read higher, and the speaker volume may come up, but you would hear the same signal-plus-noise increase with the smaller antenna by simply turning up the volume control. (See "Antenna Size" below)

So why bother with good construction practices?

Heavy gauge, stranded wire will withstand ice, wind loading, and flexing better than thin solid wire, and it will radiate transmitted power more efficiently. Commercially-made center insulators with built-in connectors are more rigid and water resistant than soldered connections, and they can be easily disconnected for servicing or inspection. Sturdy, insulated suspension is more durable over time. And keeping antennas away from tree foliage may avoid some signal loss at higher frequencies.

Antenna Size

The energy-intercepting area of an antenna is called its "aperture" (another similarity to light as in the aperture of a camera lens) or "capture area;" the larger its aperture, the more signal it captures.

Curiously, a large antenna is not necessarily better at transmitting—or receiving—than a smaller antenna. If a small element can be designed to be just as efficient as a large antenna, and radiates it in the

As we tune upwards from 50 MHz, atmospheric noise diminishes; therefore, larger and better-matched antenna systems do improve reception because they help overcome receiver noise, which can be higher than atmospheric noise there. Ultimately, once the aperture is great enough to overcome receiver noise . . . larger aperture will only pick up more noise.

same pattern, there is no benefit in using a larger antenna unless it offers “gain.”

Similarly, all antennas of the same size—wire dipoles, folded dipoles, fans, trap antennas, cages, or any other—radiate the same amount of power. Their relative advantages come from pattern directivity.

The U.S. Coast Guard found several decades ago that a five-foot antenna was adequate for HF reception 100% of the time. Remember, the purpose of an antenna is to detect enough signal to overcome the receiver’s own internally-generated noise; once that is accomplished, more signal means more atmospheric noise with its attendant interference from strong-signal overload.

As mentioned earlier, below approximately 50 MHz, atmospheric noise (“static”) becomes increasingly worse the lower we tune. Once we detect enough signal to overcome the receiver’s own self-generated circuit noise, more aperture will only increase the atmospheric noise right along with the signal—unless the antenna pattern is focused away from (“nulls”) the source of the noise, or favors the direction of the signal or, preferably, both.

As we tune upwards from 50 MHz, however, atmospheric noise diminishes; therefore, larger and better-matched antenna systems do improve reception because they help overcome receiver noise, which can be higher than atmospheric noise at VHF/UHF.

Ultimately, once the aperture is great enough to overcome receiver noise at these higher frequencies, just as at the lower frequencies, larger aperture will only pick up more noise, so directivity should be the goal for better reception.

Antenna Gain

Signal improvement may come from greater aperture, or from intentionally distorting (shaping) the field to produce a narrower pattern. While larger aperture simply increases background noise as well as signal, directivity favors one (or more) direction(s) at the expense of others. This reduces overall pickup (better signal-to-noise-ratio), concentrating on a target direction for receiving and/or transmitting.

Such pattern re-direction often refers to “front-to-back ratio” and “side lobe rejection”, illustrating how improvement in one direction comes at the (desirable) loss in others.

The pattern can be shaped by adding parasitic (unconnected to the feed line) elements called reflectors and

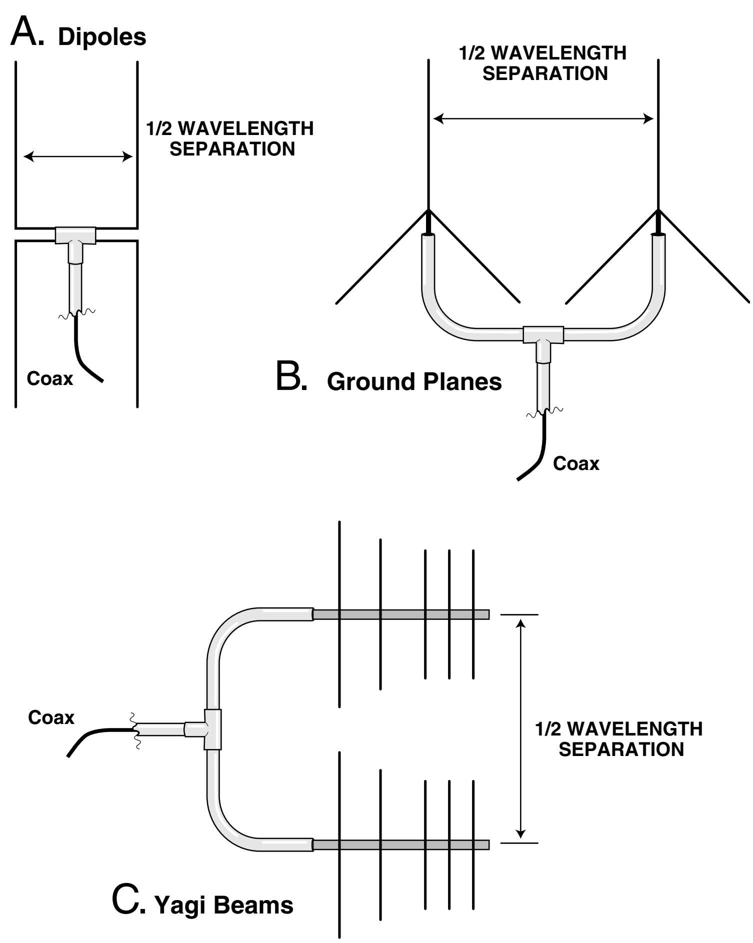

Figure 3.2: ***Stacking any two identical antennas, regardless of their individual gains, will increase total gain by 3dB.***

Antenna performance is usually compared to a half-wave dipole reference. Some antenna manufacturers compare their gains to an "isotropic" radiator, a theoretical (non-existent) antenna which radiates uniformly in all direction. This gives manufacturers a 2.1 dB higher gain claim than if they compared it to a real antenna: a halfwave dipole.

directors (see Yagi below). Feed point mismatch does not affect an antenna's gain or pattern.

Adding a second identical antenna separated by 1/2 wavelength and connected in phase ("stacking") will increase transmitted and received signal strengths by 3 dB. Thus, two 1-dB-gain antennas will provide 4 dB total gain, and two 20-dB-gain interconnected antennas will provide 23 dB total gain.

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Unless the claimed gain figure is followed by dBd or dBi, referencing a dipole or isotropic radiator in free space, it is meaningless and suspect.

Assuming we run the transmission line away at right angles from the antenna for at least a quarter wavelength, the location of the feed point causes very little distortion of the pattern, but the impedance selection varies dramatically.

Is a good transmitting antenna always a good receiving antenna? Yes, if its aperture is large enough to capture enough signal to overcome receiver noise. The law of reciprocity states that if an antenna system efficiently radiates a signal into space, it will just as efficiently deliver an intercepted signal to a receiver.

Is a good receiving antenna a good transmitting antenna? Not necessarily. If randomly erected, it may be

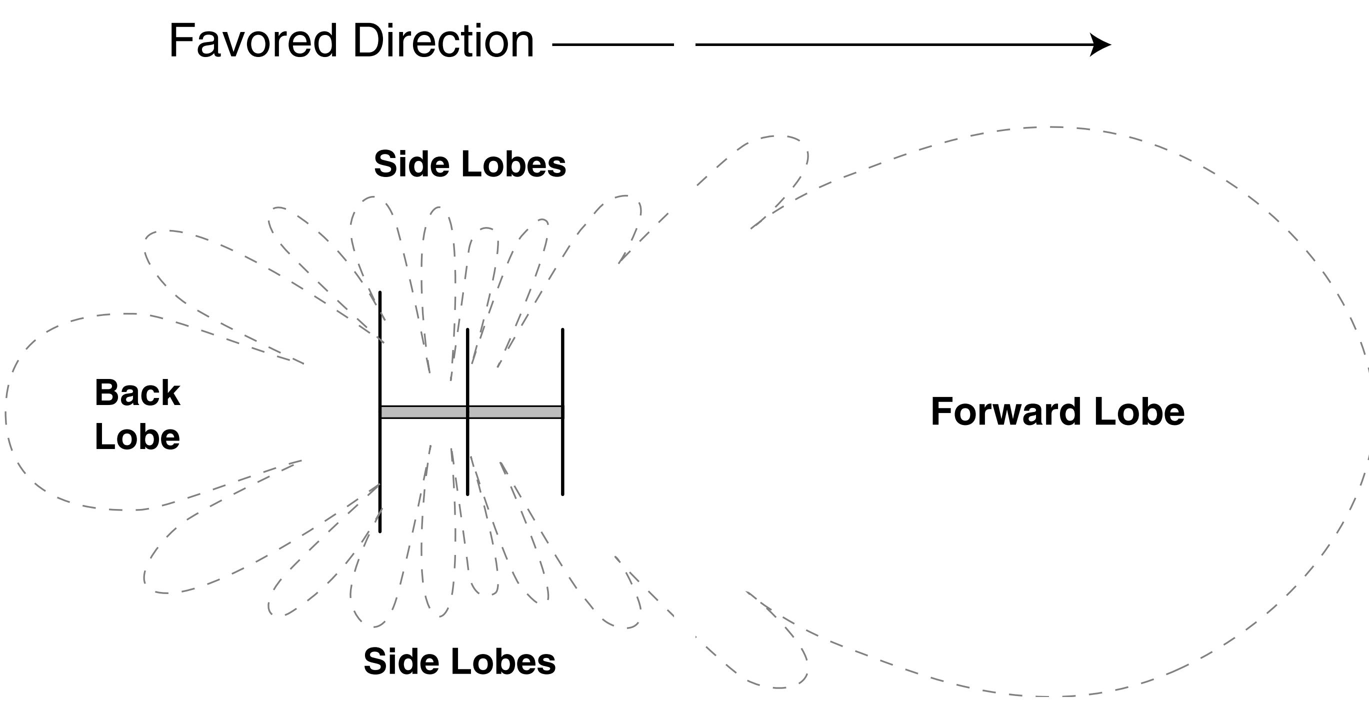

Figure 3.3: The yagi is a popular beam antenna with good forw d gain.

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power-lossy, its pattern will be unpredictable, and reactance may shut down a transmitter with built-in protection against mismatches.

Why heavy-gauge wire or metal tubing for transmitting? Radio frequency energy flows on or near the surface of a conductor; the larger the surface, the less resistance which would otherwise waste power as heat.

Arrays

Depending upon its thickness, taper and length, a mass of metal, brought within one-quarter-wavelength of a "radiator" (the driven element, connected to the feed line), will interact with the field, "focusing" the energy to produce directivity (gain).

Probably the best known of these combinations is the Yagi-Uda array, named for the two Japanese scientists who developed the antenna in 1928. While Uda actually did all the developmental work, Yagi published the results, so the antenna, as fate would have it, usually bears his name alone. Curiously, the Japanese did not use the Yagi in World War II.

The modern Yagi consists of a half-wavelength driven element, a single rear reflector about 5% longer, and one or more forward directors about 5% shorter. The elements are usually spaced 0.15-0.2 wavelengths apart. Depending upon the number of directors, a Yagi may have six to twenty decibels (6 - 20 dBd) gain over a half-wave dipole in free space.

There are many computer programs available for designing Yagis as well as other popular antennas.

CHAPTER 4
Matching the System

The term "impedance matching" always comes up when referring to an antenna and transmission line. To impede means to oppose, so what is being opposed in an antenna system?

When a battery is connected to a light bulb, the resistance of the filament is the impedance, dissipating the opposed energy as heat and light. Ohm's law reveals that there is a simple relationship between resistance, voltage and current.

When a transmitter is connected to an antenna in free space, RF energy is radiated into space; the voltage and current are controlled both by the antenna's radiation resistance and any capacitive or inductive reactances which may be present.

Why does an open circuit like a dipole accept and radiate power? An antenna is a specialized form of transmission line; it is coupled to space, which has an impedance of 377 ohms. The center feed point impedance of a half-wave dipole, however, is much lower than that.

Resonance

The impedance of an antenna is a combination of radiation resistance, conductor resistance, and reactance. Radiation resistance is desirable; it's what accepts power and radiates it into space. Conductor resistance, however, wastes power as heat.

Reactance opposes incoming energy; it is caused when an antenna is too long or too short at a particular frequency, so that when the wave (signal voltage) traveling along the antenna is reflected from the ends, it returns to the feed point "out of phase" with the incoming wave.

A half-wave antenna is naturally "resonant"; an arriving signal travels that half-wave length in half its cycle, then reflects back in the other direction, finishing that cycle when it returns to its starting point, the electromagnetic equivalent of a vibrating guitar string.

Measurements will reveal maximum current (and minimum voltage) at the center, and maximum voltage (minimum current) at the ends of the wire.

A multiple-half-wave (full-wave, wavelength-and-a-half, etc.) antenna will have a standing wave on every half-wavelength section.

An infinitely-thin, half-wave dipole in free space (at least several wavelengths away from other objects) would have a center feed point impedance (radiation resistance) of 73 ohms. Constructed of normal wire the impedance is closer to 65 ohms; if thicker tubing, 55-60 ohms. This impedance rises as we move the feed point off center.

Proximity to the earth's surface also alters the feed point resistance of a horizontal dipole, typically dropping from 100 to nearly 0 ohms as the antenna is lowered from 0.33 wavelengths to the earth's surface, and fluctuating between 60 and 100 ohms at heights between 0.33 and 1 wavelength.

Vertical dipoles fare better since their patterns do not radiate directly downward where they would interact with

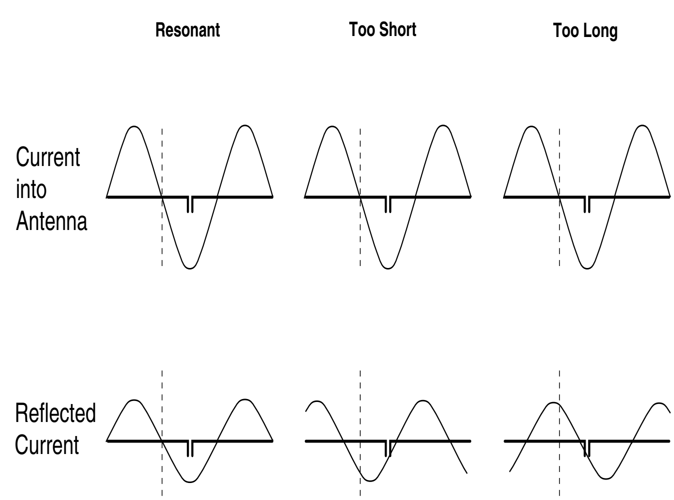

Figure 4.1: Radiation resistance of two popular antennas over perfectly-conductive grounds.

What really happens with an impedance mismatch? Some of the signal voltage reflects from the feedline/antenna junction back to its source where it is re-reflected and eventually radiated into space. The mismatch does not cause radiation from the feedline. When receiving, all signal voltage gathered by a matched antenna is fed to the receiver, but with a mismatch, the reflected signal is radiated back into space. In practice, this is of minor consequence.

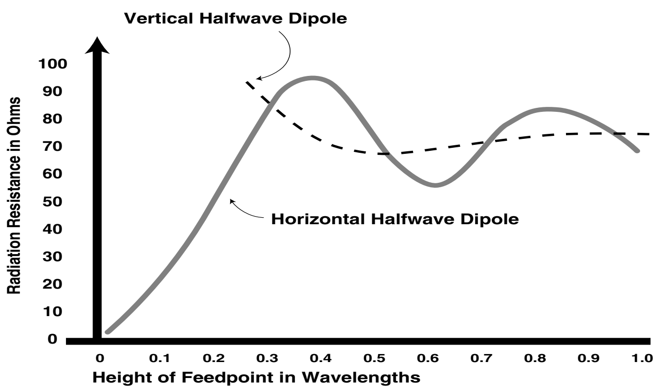

Figure 4.2: Whether a simple dipole (A) or a folded dipole (B), the wave travels the same direction on all elements.

the earth. Once elevated at least 0.25 wave length, their impedance remains a relatively constant 70 ohms. A drooping-radial, ground-plane vertical has a lower impedance, nominally 50 ohms, while a ground-plane vertical with horizontal radials has a feed point impedance of about 35 ohms.

If 50-ohm coax is attached to an antenna's 50-ohm feed point, we have a perfect (1:1 ratio) impedance match, but if that 50 ohm coax is attached either to a 25 or 100 ohm feed point, we have a 2:1 impedance mismatch (50/25 or 100/50).

Is that bad? No. Is 3:1? No. The simple fact is that if there is no resistive loss in the feed line or antenna (of course, there always is), 100% of the generated power will be radiated by the antenna regardless of the mismatch.

What really happens with an impedance mismatch? Some of the signal voltage reflects from the feed line/antenna junction back to its source where it is re-reflected and eventually radiated into space. The mismatch does not cause radiation from the feed line.

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The Transmission Line

In the early days of radio when open-wire transmission lines were common, the voltage fields produced by standing waves would light up bulbs and deflect meters brought near the lines; nowadays, with the near-universal use of coaxial cable which encloses the electrostatic fields, such measurements are not as easy.

Connecting an unbalanced line (coax) to a balanced antenna can cause RF currents to flow on the outside of the line, but these are not standing waves.

So what gives a transmission line its characteristic impedance (surge impedance)? A feed line can be considered as a radio-frequency, low-pass filter consisting of an infinite number of series inductances shunted by an infinite number of parallel capacitances.

The impedance of this distributed network is theoretical, based upon the dielectric constant of the insulation, the spacing of the conductors, no losses, and infinite length.

While the most common feed line impedances are 50, 75 and 300 ohms, there are more than two dozen commercially-available impedances from 32 to 600 ohms.

Why have we chosen impedance standards like 50 and 75 ohms for coax? For transmitters, the best power handling is at 77 ohms, while the best voltage tolerance

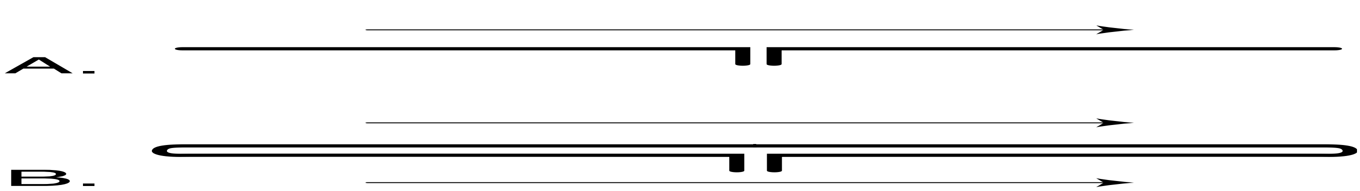


Figure 4.3: A feedline may be visualized as a low-pass filter consisting of an infinite number of series inductances and parallel

The impedance measured at the bottom of an electrical-half-wavelength transmission line (or any multiple half-wavelengths), regardless of the characteristic impedance of the feedline, is the feedpoint impedance of the antenna. For example, if, at some frequency, an antenna has a feedpoint impedance of, say, 143 ohms, then we will read 143 ohms at the bottom of a 50-, 75- or 300-ohm, electrical half-wavelength line connected to it.

is under 30 ohms; 50 ohms is a good compromise and it matches several standard antenna designs. For receiving purposes, 75 ohms is optimum for low coax losses, so it was adopted by the cable TV industry. Conveniently, it also matches several antenna designs.

The impedance a transmitter or receiver "sees" when it is mismatched to a length of transmission line connected to an antenna is a composite of the length of the line along with its losses, the SWR (see "Traveling Waves" below), and the load (feed point impedance of the antenna to which it is connected). If they are all properly matched, however, the impedance is determined only by the characteristic of the line.

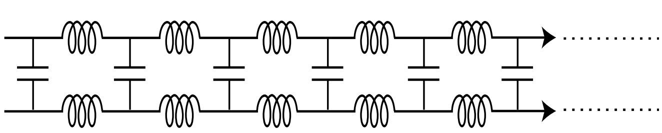
Magical line lengths

Trick No.1: The impedance measured at the bottom of an electrical-half-wavelength transmission line (or any multiple half-wavelengths), regardless of the characteristic impedance of the feed line, is the feed point impedance of the antenna.

For example, if, at some frequency, an antenna has a feed point impedance of, say, 143 ohms, then we will read 143 ohms at the bottom of a 50-, 75- or 300-ohm, electrical half-wavelength line connected to it.

Keep in mind that this is an electrical half-wavelength; we must multiply the free-space half-wavelength by the velocity factor of the coax. For example, a half-wavelength at 14 MHz is 33 feet; using coax with a velocity factor of 66% would mean that you would actually cut the line to a length of 22 feet.

Trick No.2: We can use a quarter-wavelength piece of



Fiugure 4.4: *If a transmission line of an impedance is one-half wavelength long at some frequency, the impedance measured at the bottom of the line will be that of the feedpoint of the antenna.*

transmission line as an impedance-matching transformer using the formula:

For example, by substituting actual values in the solution below, if we wish to attach a 100-ohm antenna to a length of 50 ohm cable, we can insert a quarter-wavelength matching stub of 70 (practically, 72-75) ohm cable.

Don't forget to multiply the free-space quarter-wavelength by the velocity factor and shorten the length of the cable accordingly. For example, a quarter-wavelength at 14 MHz is 234/14, or 16.7 feet; using coax with a velocity factor of 66%, the actual physical length would be cut to 11 feet.

If the line needs to be physically longer, use odd multiples of the quarter-wavelength and the transformation will remain the same.

But remember, most antennas exhibit a very-narrow frequency bandwidth for a given impedance, so all this magic occurs only around one frequency; on single-element antennas like dipoles and verticals, it also works on odd-harmonic multiples, although the match degrades as we increase the number of multiples.

Standing waves or traveling waves?

When the system is non-resonant, the waves reflect from any point where the impedance changes, passing each other in phase. In a typical antenna system, the reflections are produced solely by differences between the impedances of the antenna and the transmission line.

Early instrumentation could not detect which waves were being measured, the forward or reflected. Since their superimposed voltages measured higher on a voltmeter, and were periodically distributed along the transmission line, they were assumed to be *standing* waves.

When the system is non-resonant, the waves reflect from any point where the impedance changes, passing each other in phase. In a typical antenna system, the reflections are produced solely by differences between the impedances of the antenna and the transmission line.

The comparison of those summed voltage peaks to the minimum voltages interspersed between them is called "voltage standing wave ratio" or "VSWR". Engineers prefer to measure the "voltage reflection coefficient," the comparison of the reflected voltage to the incident voltage at any one point on the line.

Since power (watts) is a product of voltage times current, as the current rises, the voltage falls (and vice versa); thus, the current peaks are half way between the voltage peaks. The ratio of the current peak to minimum is the same as that of the voltage, so "VSWR" is usually shortened to "SWR" to accommodate both units.

For example, if a 200-ohm resistive antenna feed point is attached to a 50-ohm line, we would have a 4:1 SWR. The presence of inductive or capacitive reactance adds further to an antenna's impedance.

When transmitting, the high voltages produced by high SWR may arc across the feed line insulation or tuning components, and high current may waste energy by heating the feed line conductors. Since these are stationary points on the line for any particular frequency, the transmitter (or matching device) may experience either high voltage or high current, depending upon the length of the line.

In a receiving system, antenna/transmission line mismatch will also produce losses in the transmission line; additionally, any impedance mismatch between the receiver and the antenna system will reflect power back to the antenna where it will be re-radiated back into space.

Feedline loss

Single-wire feed, popular in the early 1900s but now virtually abandoned, matched best at high-impedance feed points (hundreds or even thousands of ohms); it was commonly used to off-center-feed antennas in the early days of radio, often with an SWR exceeding 10:1, but efficient radiators.

The lowest-loss transmission line commercially available is open-wire, parallel feed line ("ladder line"). It accommodates high power and high SWR with virtually no

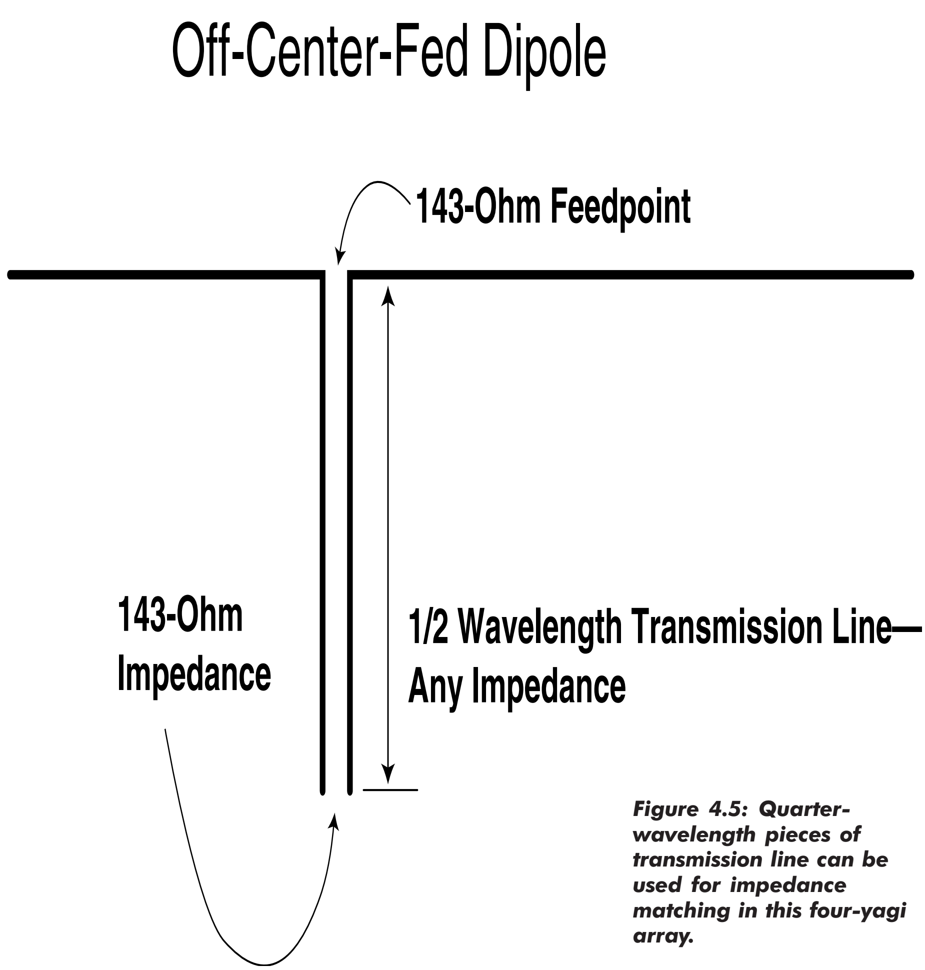


Figure 4.5: Quarter-wavelength pieces of transmission line can be used for impedance matching in this four-yagi array.

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the transmitter (or matching device) may experience either high voltage or high current, depending upon the length of the line.

loss.

Disadvantages of open-wire feeders include:
(1) A separation requirement between it and any nearby moisture or metal to avoid some SWR increase from coupling its unenclosed field (equivalent to two to four times the separation of its two wires);
(2) Unbalancing the line by allowing one wire to come closer to nearby metal or moisture;
(3) Inability to bend at sharp angles without additional reflective losses;
(4) Impedance mismatch when attaching to standard low impedance antennas and transmitters (except when used in multiples of a half-electrical-wavelength long at specific frequencies);
(5) Balanced matching requirements when used with unbalanced equipment (like every transmitter made!);
(6) Vulnerability to electrical noise pickup if slightly unbalanced;
(7) Changes in characteristic impedance from rain, ice and snow;
(8) and absence of parallel-line connectors on radio equip-

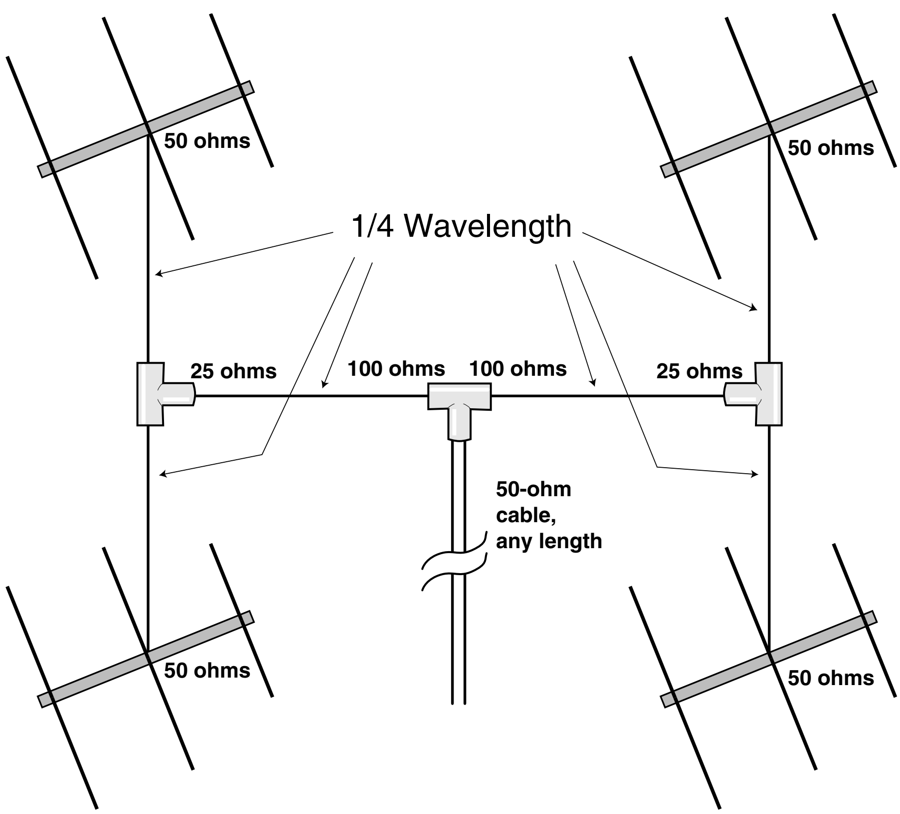


Figure 4.6: Power reflected back from impedance mismatch creates fixed, periodic voltage and current peaks (standing waves) along the transmission line.

$$\text{Total Impedance} = \sqrt{100 \text{ ohms} \times 25 \text{ ohms}} = 50 \text{ ohms}$$

Generally speaking, the thinner the coax, the poorer the cable. Skinny RG-174/U should be used only for the shortest runs (a few feet). Never use shielded audio cable in place of coax for radio frequency work; it has dreadful shielding, inviting interference, and is very lossy. Its reputation for causing radio-frequency interference (RFI) when used to interconnect digital accessories is notorious!

ment.

Solid-dielectric, parallel feed line like TV twin lead may also be used for receiving and low-power transmitting provided all the caveats of open-wire feeders are observed. Because its closer conductor spacing confines its field more, it may be brought within two or three inches of nearby metal or moisture. But the plastic insulation on inexpensive TV twin-lead disintegrates with time, collecting moisture and residue in its cracks, making it lossy.

Coaxial cable, on the other hand, may approach the efficiency of open wire, may be run underground or through metal pipe, is electrical-noise resistant, and mates easily with conventional connectors.

The reasons that most coax is lossier than open-wire feeders are:

(1) Its conductors are smaller, offering more resistance to waste the current as heat.

(2) The dielectric (insulation) surrounding the conductor dissipates some power; the higher the frequency, the higher the dissipation.

These two factors explain why large-diameter, foam-dielectric, short-length, coax cables are preferred, especially for transmitting. There is also a safety reason: coax doesn't radiate its energy. Of course, mammoth coax is wasted if smaller will do; after all, in house wiring, we don't use enormous #4 bus wire when #12 safely passes all the current that is required.

So what is the best coax? Generally speaking, the bigger the better, with aluminum-sheathed hard line taking the prize. But will you know the difference between that and, say, Belden 9913, foam dielectric RG-8/U, RG-213/U or RG-214/U? Not unless you are running at least 100 feet at 1000 MHz or higher, or are transmitting more than 1000 watts.

For receiving purposes, or for transmitting up to 200

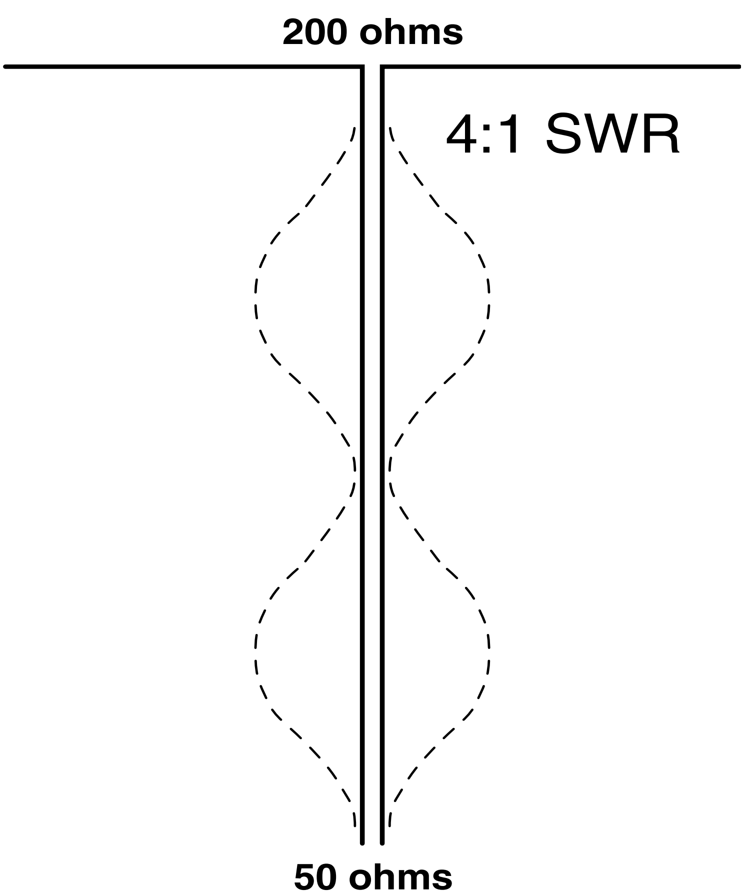


Figure 4.7: The loss characteristics published for coax cable assume a perfect (1:1) impedance match. To calculate the total loss due to mismatch:

(1) Find the manufacturer's loss figure in decibels for the frequency in question on the left vertical axis ("Line Attenuation dB");

(2) Find the SWR on the bottom horizontal axis ("SWR at load");

(3) Where the curved (dB) and vertical (SWR) lines meet, read the closest left-hand attenuation in dB. You may have to approximate positions for values between the printed curves.

For example, if, at some frequency in question, your perfectly-matched coax has an attenuation of 2 dB, the attenuation of the line with a 6:1 SWR would be 4 dB. Similarly, a 1.5 dB rated cable (a value between 1.0 and 2.0 dB curves) with a 5:1 SWR would have a loss of about 3 dB.

So how does transmission line loss in decibels translate to percentage of power loss? If system impedances are matched properly, a 1 dB loss uses up 20% of the power; 3 dB represents 50%; and 6 dB attenuation means that 75% of the power is being used to heat the coax, whether transmitting or receiving.

watts, it's even easier. Since we aren't developing high voltages, we can use smaller-diameter cable, just so long as it's not lossy. Generally speaking, coax with high velocity factor ratings are the least lossy.

Below 30 MHz use RG-58/U, RG-59/U, RG-6/U, or RG-8/X for runs of up to 100 feet. For VHF/UHF to 1000 MHz, use any but the RG-58/U; the RG-6/U and RG-8/X are good choices.

Don't let 70 ohm (instead of 50 ohm) impedance throw you; you won't hear the difference for receiving, and the impedance mismatch for a 50 ohm transmitter is only 1.4:1—inconsequential, resulting in a loss of less than 0.2 dB—imperceptible.

Generally speaking, the thinner the coax, the poorer the cable. Skinny RG-174/U should be used only for the shortest runs (a few feet). Never use shielded audio cable in place of coax for radio frequency work; it has dreadful shielding, inviting interference, and it is very lossy. Its reputation for causing radio-frequency interference (RFI) when used to interconnect digital accessories is notorious!

But even coax deteriorates with time; foam-dielectric coax, initially superior in performance, loses grace first, falling victim to moisture intrusion. Many experts (especially cable manufacturers!) recommend replacing coax every five years.

But how do we know if the coax is still good? One way is to short-circuit the far end of the cable and attach the near end to an SWR meter which, in turn, is connected to a low-power transmitter. The short will reflect 100% of the power reaching it, sending it back to be registered as reflected power. The higher the SWR, the better, because it means that energy is not being absorbed along the way. Replace coax that shows a short-circuit SWR lower than 3:1.

A high SWR between the feed line and antenna may appear as a low SWR at the transmitter. Corroded or loose connectors, lossy cable and other resistive agents can all contribute to a deceptively low SWR reading.

Since no cable is 100% efficient, the SWR measured at the transmitter will always be lower than the actual mismatch at the antenna; the poorer (lossier) the cable, the lower—and more misleading—the reading. Only by connecting an SWR meter directly to the antenna feed point can we get a true SWR reading. Use good cable and that SWR difference is but a few percent.

So how does transmission line loss in decibels translate to percentage of power loss? If system impedances are matched properly, a 1 dB loss uses up 20% of the power; 3 dB represents 50%; and 6 dB attenuation means that 75% of the power is being used to heat the coax, whether transmitting or receiving.

In an unmatched system, line losses are even worse. High-SWR voltages dissipate more power in the transmission line's dielectric (insulation breakdown), current peaks dissipate more power in the conductor (resistive losses), and both effects are aggravated by rising frequency. The result is power being wasted as heat.

For example a 6:1 SWR in 100 feet of RG-8/U at 14 MHz produces only a 1 dB loss, butat 450 MHz it becomes 6 dB, and at 900 MHz, 8 dB. With poorer-quality cable, losses are much worse. It pays to use good cable!

Keep in mind that these are coax losses; if you use open-wire feeders, the loss at 10:1 or even 20:1 SWR is insignificant. Such high SWR was present on early, micro-power earth satellites, but we heard them fine 23,000 miles below, demonstrating once again that SWR alone has nothing to do with radiation efficiency.

Contrary to popular myth, high antenna SWR does not radiate any more harmonics or television interference (TVI) than a 1:1 SWR, assuming that the transmitter is properly tuned.

Keeping SWR to a minimum by proper transmission-line impedance matching is a preventive against damage, especially to modern transceivers with marginal power specifications. Automatic power-reduction circuits often kick in with an SWR as low as 2:1, making matching a requirement to achieve full output power.

Every length of metal has some frequencies at which it is naturally resonant; that is, the inductive or capacitive reactance is zero, leaving only the radiation resistance. If an antenna is too long for it to be naturally resonant at some desired frequency, we say it is inductive; a series capacitance can "tune out" that inductive reactance which opposes the incoming RF power. Conversely, an electrically-short (capacitive) antenna can be adjusted by a series inductance.

Tuning the system

Antenna tuners, antenna tuning units (ATUs), transmatches, couplers and matchboxes are different names for the same thing, combinations of adjustable capacitors and coils to compensate for inductive and capacitive reactances in the antenna system. Transmatches (the preferred term) also provide adjustable impedance transformation between the receiver or transmitter and line, and some provide balanced-to-unbalanced matching as well.

Every length of metal has some frequencies at which it is naturally resonant; that is, the inductive or capacitive reactance is zero, leaving only the radiation resistance.

If an antenna is too long for it to be naturally resonant at some desired frequency, we say it is inductive; a series capacitance can "tune out" that inductive reactance which opposes the incoming RF power.

Conversely, an electrically-short (capacitive) antenna can be adjusted by a series inductance. Contrary to popular notion, a loading coil does not add the "missing length" to a short antenna; its inductive reactance cancels the antenna's capacitive reactance.

We can also neutralize these reactances with a transmatch connected at the transmitter output. Quoting antenna guru Walt Maxwell, W2DU, when the transmatch is properly tuned, "...the entire system is made resonant...all reactances in the system are cancelled...the net reactance is ZERO! In addition, by obtaining a conjugate match at the antenna tuner, a conjugate match is inherently obtained at any other junction in the system where a mismatch existed prior to obtaining the match with the tuner."

Figure 4.8: The transmatch corrects for inductive and capacitive reactance in an antenna system and can provide impedance transformations as well.

The transmatch is adjusted to provide capacitive and inductive values of equal magnitude, but opposite phase, to the incoming reflected power, thus re-reflecting them back toward the antenna in phase with the transmitted power.

We don't alter any of the reactances in the antenna system, we merely neutralize their effects by offering additional reactances tuned opposite in phase. And we match all impedances in the process. All that is left is the antenna's radiation resistance, so all power is radiated.

This "tuned feeders" approach can be used with single wire, open parallel line, twin lead, or coax equally well.

A transmatch, typically attached between the transmitter (or receiver) and feed line, can only impedance-match those two points; it has no effect whatsoever on matching the feed line to the antenna. We would need to connect the transmatch between the feed line and antenna feed point to affect that match.

Just because it's a transmatch doesn't mean it's a *good* transmatch—flimsy construction and small-gauge wire may mean

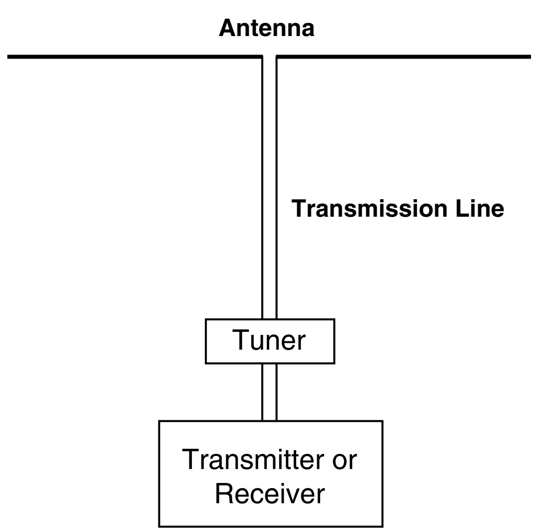


Figure 4.10: *An "antenna tuner" doesn't tune the antenna; it corrects for reactances in the entire system as seen at its location in the line.*

Efficiency is a commonly misunderstood concept in antenna system design; it is simply the percentage of transmitter-generated signal which is radiated by the antenna, or received signal voltage which is delivered to the receiver. If there were no resistive or insulation losses, any antenna and feedline would be 100% efficient whether or not they are properly matched.

additional losses, especially at higher power levels. High-power transmatches are invariably more efficient than the low-power variety.

Efficiency

Efficiency is a commonly misunderstood concept in antenna system design; it is simply the percentage of transmitter-generated signal which is radiated by the antenna, or received signal voltage which is delivered to the receiver. If there were no resistive or insulation losses, any antenna and feed line would be 100% efficient whether or not they are properly matched.

Balanced or unbalanced?

Most elevated, horizontal antennas are fed at or near the center; they are said to be balanced, both from a standpoint of symmetry as well as reference to ground. Most vertical antennas are unbalanced, often making use of radial systems as an artificial ground reference.

There is nothing inherently superior about one over the other; it is merely a question of whether they are best fed by twin lead (balanced) or coax (unbalanced). Balun (balanced-to-unbalanced) transformers (see chapter 6, Accessories) as well as transmatches can be used for matching balanced to unbalanced feeds, and for matching impedances.

What is the penalty for misbalancing the feed point? It may cause some RF current to flow on the surface of the feed line, or some stray radiation from the feed point, producing some distortion in the pattern's symmetry, affecting gain somewhat.

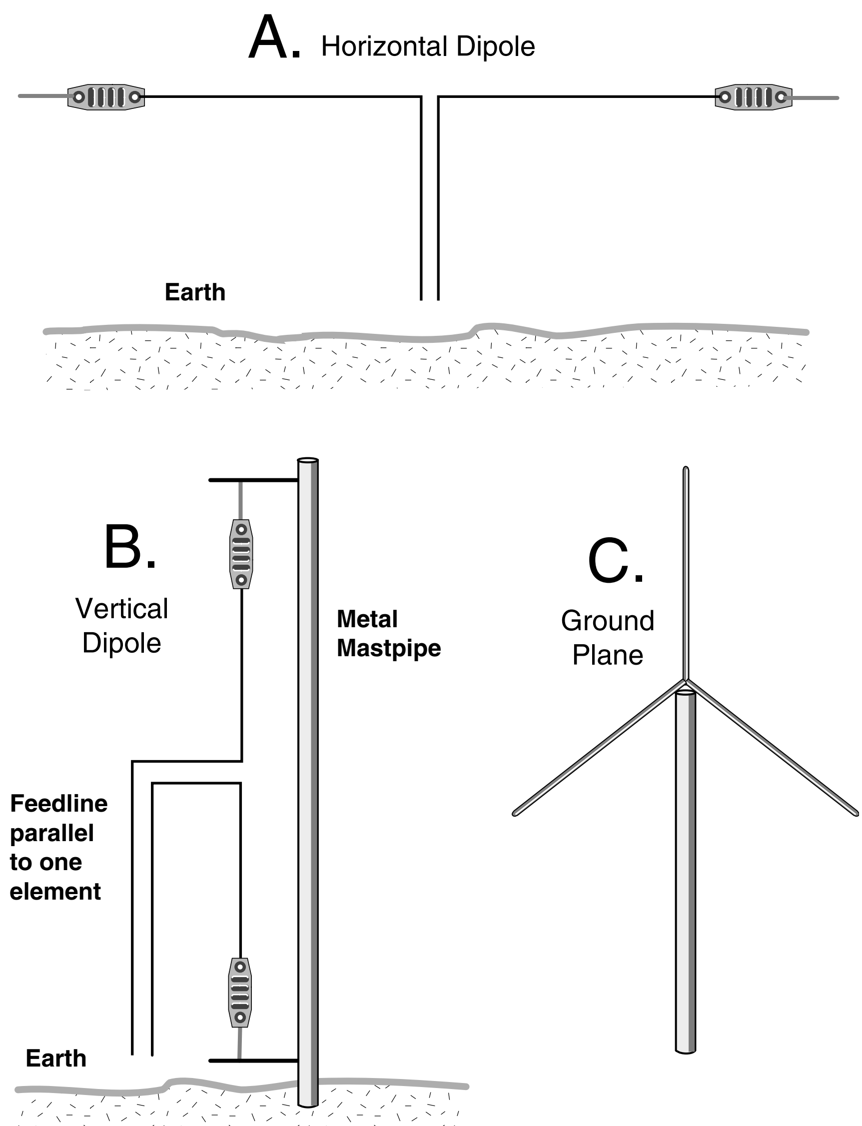


Figure 4.10: An antenna is "balanced" withe respect to its symmetry and its relationship to the earth, as shown in "A" when that symmetry is distorted by environmental influences as in "B," or by design of the antenna itself as in "C," the pattern is disturbed.

CHAPTER 5

Types of Antennas

The term "polarization" refers to the relative position of the electric component of the radio wave with respect to the earth's surface.

A vertical antenna, often referred to as a "Marconi" (or "whip" if short), has its element(s), and therefore its electric field, perpendicular to the earth; a horizontal antenna, variously called a "Hertz", "flat top" or "Zepp" (after the trailing antennas on the Zeppelins), has its element(s) and electric field parallel to the earth.

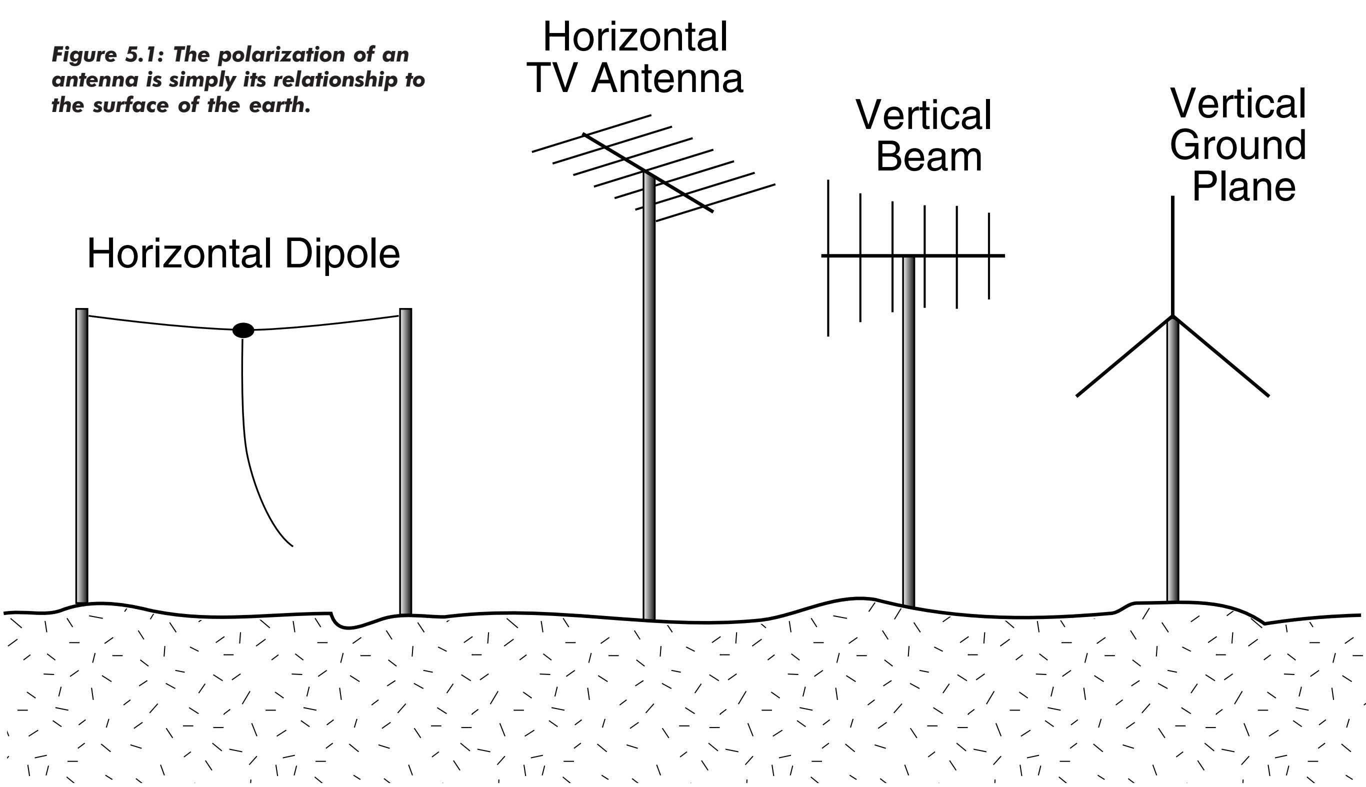
Neither polarization is inherently superior. The choice is made on a basis of practical considerations such as the likelihood of a horizontal antenna causing television interference (TVI), the possibility of interaction with nearby metallic masses in the same plane, a desired pattern, reduction of noise pickup from power lines and accessories, the area available, or ease of mounting.

Vertical antennas have only one mounting point and, properly placed, radiate uniformly toward the horizon in all compass directions; their low angle of radiation favors distant communications.

Horizontal wire antennas must be elevated at least a half-wavelength above the earth for a low angle of radiation and reception; they utilize at least two suspension points, and radiate primarily at right angles to the wire axis. It is more practical to make a long horizontal antenna than a tall vertical antenna because of the support requirements.

At high frequency (shortwave), there is little difference in performance between properly installed horizontal and vertical antennas. Distant signals arrive with mixed polarization, and sometimes even the compass direction (azimuth or bearing) is unpredictable.

Figure 5.1: The polarization of an antenna is simply its relationship to the surface of the earth.



Vertical antennas have only one mounting point and, properly placed, radiate uniformly toward the horizon in all compass directions; their low angle of radiation favors distant communications. Horizontal wire antennas must be elevated at least a half-wavelength above the earth for a low angle of radiation and reception.

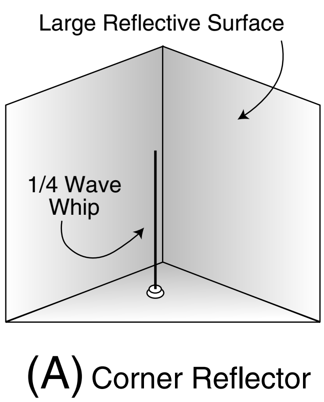
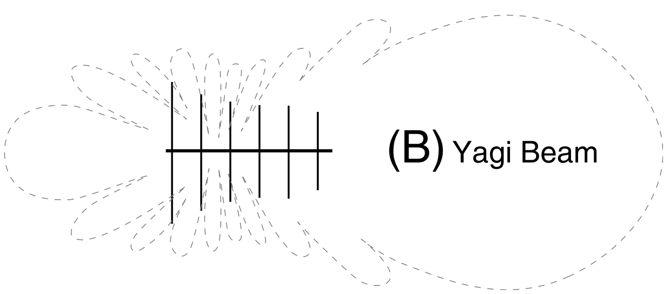


Figure 5.2: The gain of an antenna may come from increasing its aperture (A) or narrowing its pattern (B).



For VHF/UHF, vertical polarization is the rule since mobile communications dominate this part of the spectrum, and it is easiest to mount a whip antenna on the vehicle.

Except in the city where buildings reflect signals, short range VHF/UHF communications retain their original polarization.

Dipoles

The most common basic antenna is the half-wave dipole, a length of wire at low frequencies, or tubing at VHF/UHF, which is cut at the center and connected to a transmission line.

Such an antenna matches coax well for about +/-5% of its design center frequency, but the impedance steadily rises beyond that, requiring an antenna "tuner" (transmatch) for transmitting.

On odd harmonics (3rd, 5th, etc.) of the fundamental design frequency, the impedance lowers again, making the antenna multiband even without a tuner.

A half-wave dipole is a half-wavelength long only at one frequency; that same length is a full-wavelength at twice the frequency, and a quarter-wavelength at half the frequency.

The theoretical length in feet of a half-wave dipole in free space is found by dividing 492 by the frequency in megahertz. But support insulators and wires at the ends (“end effect”) makes the antenna about 5% capacitively shorter. Divide, instead, 468 by the frequency in megahertz; thus, a 7 MHz, half-wave dipole would be 67 feet long.

Since it is more convenient at VHF and UHF to calculate in inches, divide 5616 (468 times 12 inches) by the frequency in megahertz. Thus, a 146 MHz dipole would be 38 inches long.

At its design frequency and below, the radiation and receiving pattern is perpendicular to the element, but as the harmonic multiple increases, the pattern changes, and the lobes now favor the ends of the antenna with resultant gain. This should be taken into consideration for wide frequency applications.

Such an antenna can be erected to favor ground-wave communications at the lower frequencies, and sky-wave DX at higher.

While it may be tempting to erect the longest dipole we can consistent with our real estate, a quarter-wave

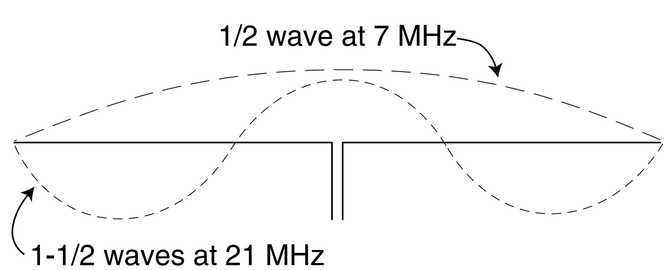


Figure 5.3: A 67-foot dipole is half-wavelength at 7 MHz, but 1-1/2 wavelengths at 21 MHz. As the frequency increases, wavelength decreases.

So why doesn’t a long, horizontal shortwave antenna make a great scanner antenna? For one thing, as you use a given length antenna at higher and higher frequencies, it has large numbers of lobes and nulls, making it very directional. Not only that, but most VHF/UHF signals are vertically polarized.

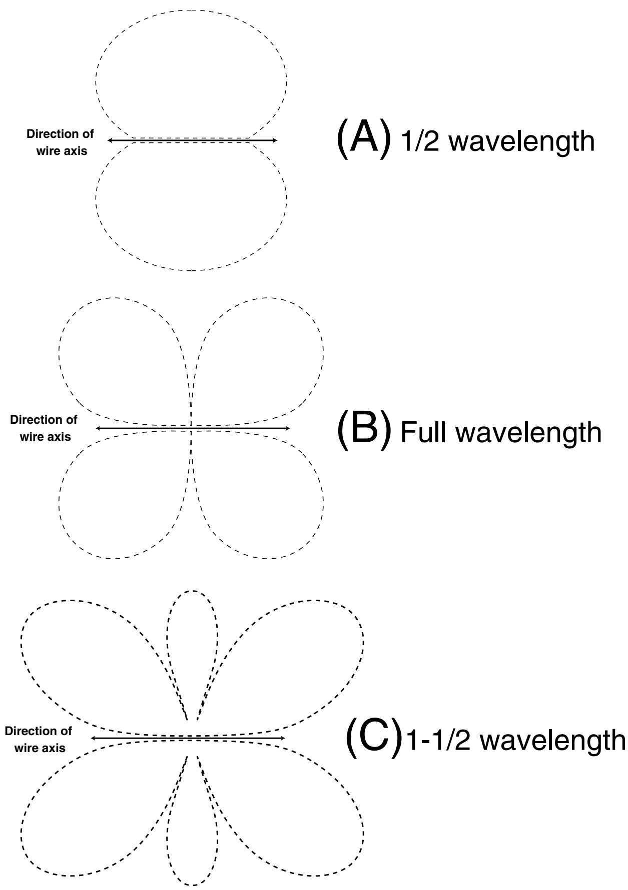


Figure 5.4: A halfwave dipole (A) as seen from above has a classical figure-eight pattern at right angles to the curve. The same antenna at twice the frequency, now a full wavelength,
has a cloverleaf pattern. As the frequency increases as

dipole captures only 3 dB (half an S-unit) less than a halfwave dipole. We won’t hear much difference. For transmitting, if properly matched, the radiated power is virtually identical.

The “Longwire”

Many shortwave enthusiasts mistakenly refer to a random wire antenna as a “longwire,” but it doesn’t qualify unless it is at least a full wavelength long at its operational frequency. Thus, a 150 foot antenna is just a halfwave dipole at 3 MHz, but it is a longwire above 6 MHz.

So why doesn’t a long, horizontal shortwave antenna make a great scanner antenna? For one thing, as you use a given length antenna at higher and higher frequencies, it has large numbers of lobes and nulls, making it very directional. Not only that, but most VHF/UHF signals are vertically polarized.

Even if it were suspended vertically, the longwire antenna pattern would favor VHF/UHF signals off its ends—above and below, not off its sides. And finally, impedance mismatch would cause considerable signal loss in the transmission line at VHF and even more at UHF.

Ground planes

The ground plane may be thought of as a vertical dipole in which the bottom element is replaced by an array of horizontal (or nearly so) elements simulating a perfectly conductive earth.

Like the dipole, the ground plane’s feed point impedance and radiation angle rise with frequency, reducing effectiveness on harmonic operation, except for working or monitoring aircraft and space satellites!

Mobile antennas

In an automotive environment, the vehicle body is the ground plane; it determines the radiation (and reception) pattern of the signal. Directivity generally favors the mass of metal—a roof-mounted whip has a basically-omnidirectional pattern, while a rear-bumper mount favors the forward direction of the vehicle.

At frequencies above 10 MHz or so, the surface area of the vehicle and the length requirements for a vertical antenna are practical for efficient operation; a quarterwave whip is resonant, exhibiting a feed point impedance of about 36 ohms, a good match for conventional 50-ohm cable.

But as frequencies lower, the electrically-short an-

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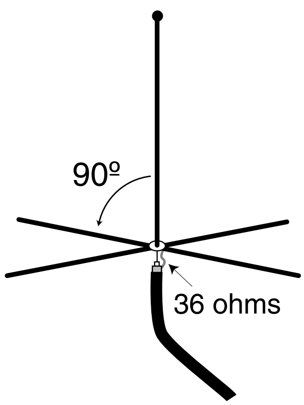
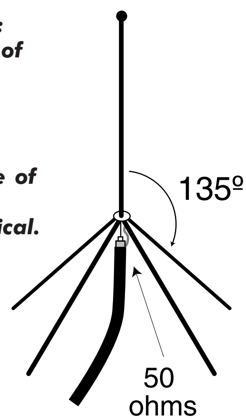


Figure 5.5: The angle of the radial elements affect the feedpoint impedance of a ground plane vertical.



tenna possesses less and less radiation resistance (only a fraction of an ohm at 2 MHz), and more and more capacitive reactance which must be cancelled by a series inductance (loading coil).

Base-loading the whip requires less inductance than center- or top-loading because the upper whip section's capacitance with the car body reduces its own capacitive reactance; but the radiation resistance remains low (in some cases a few ohms), so that coil and transmission line resistances contribute a proportionately-higher loss.

Raising the position of the loading coil changes the current distribution along the antenna, increasing the radiation resistance, but the longer loading coil requirement introduces more resistive loss.

A position approximately 2/3 the way up the whip may be an optimum compromise. But as the frequency of operation lowers, choosing a high-power-rated coil with low resistive loss becomes increasingly important, even for receiving and low-power transmitting.

When all resistive losses are kept low and the reactances are tuned out, the typical input impedance of an HF mobile antenna remains in the 10-20 ohm range. A broadband impedance-matching transformer is recommended for transmitting.

In a poorly-designed mobile antenna installation, resistive loss may be so high that it approaches that of the radio and coax, so a matching network is not required—but the performance is awful!

Grounded antennas

It is actually possible to connect one end of an antenna to a solid earth ground with excellent results. This is the principle behind the Beverage. Why doesn't the ground trickle off all the signal voltage? Because of standing waves. We are dealing with high frequency alternating current, not DC. The element is long enough to utilize reflected signal voltage to cancel any short-circuiting to ground.

Just as with a dipole or vertical in which one element set is connected to the grounded shield of the coax transmission line, this antenna detects the voltage difference

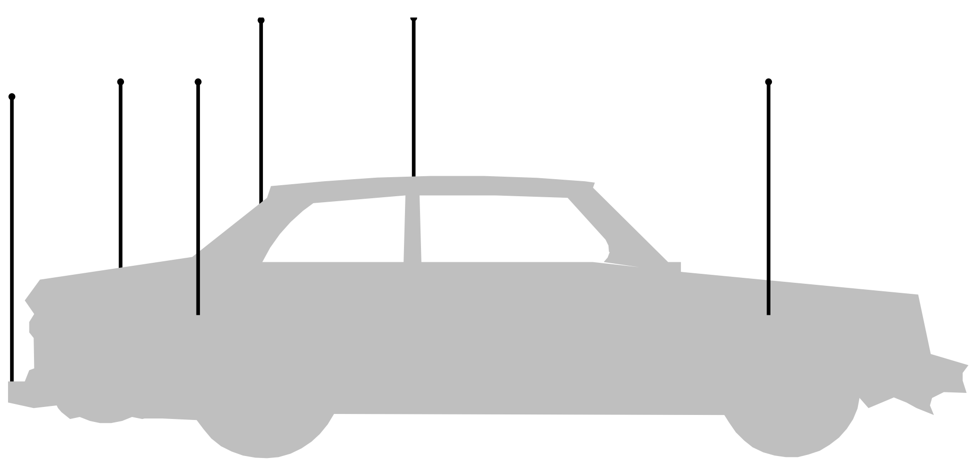


Figure 5.6: The mobile radio enthusiast has a number of antenna location choices with rooftop the best. Other spots include rear bumper, trunk lid, rear and front cowls, and rear window.

It is actually possible to connect one end of an antenna to a solid earth ground with excellent results. This is the principle behind the Beverage. Why doesn't the ground trickle off all the signal voltage? Because of standing waves. We are dealing with high frequency alternating current, not DC. The element is long enough to utilize reflected signal voltage to cancel any short-circuiting to ground.

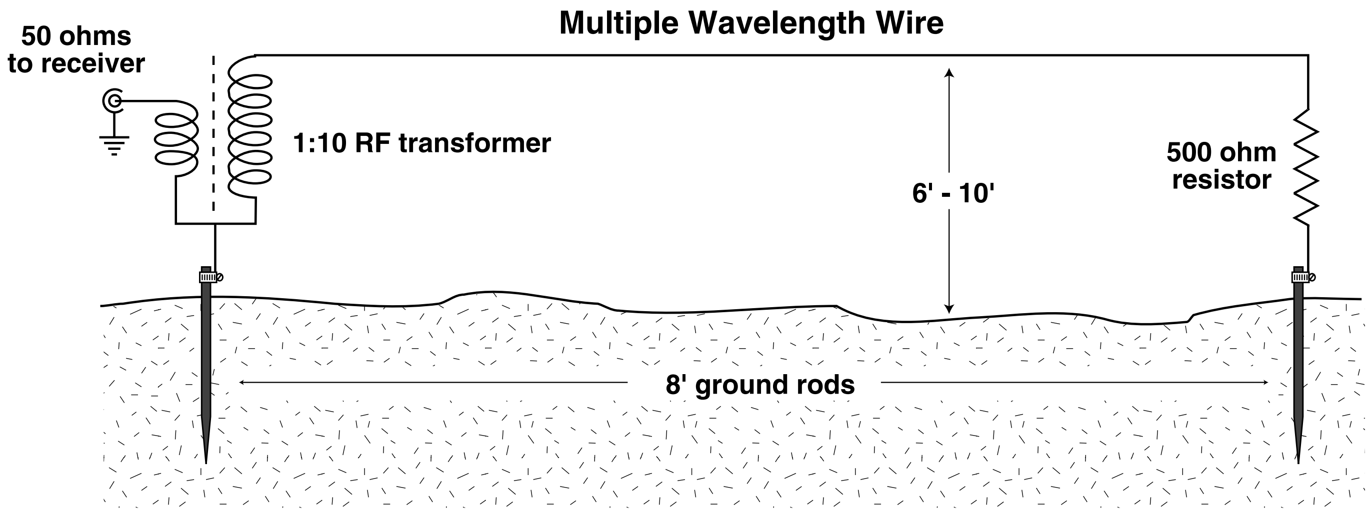


Figure 5.7: The Beverage is an example of a high performance, low frequency, grounded receiving antenna.

between the elements, and that is what is sensed by the receiver as a signal. This is why a car body, in spite of the fact that it is "grounded" to the frame, and thus to the radio, can be used as an antenna. Arriving radio waves create standing waves, voltage points that can be tapped for their energy and fed to a receiver or, reciprocally, will accept energy from a transmitter and radiate it into space.

Traps

For multiband operation, a trap (a coil and capacitor in parallel) may be placed between sections of an antenna to provide automatic selection of appropriate lengths for given frequencies. The trap is high Q (sharply tuned) to the resonant frequency of the length closest to the feed point, providing several hundred ohms impedance isolation from the adjoining section(s).

At other (non-resonant) frequencies, the coil simply adds slight electrical length between the adjoining elements, all of which now add to the total antenna length. In this manner, a combination of elements and traps allow resonant operation on several bands without the need of a transmatch. The sections are arranged in frequency order with the highest frequency closest to the feed point.

If a transmatch is available, a trapped antenna is undesirable since it suffers from the traps' resistive losses, gaps in frequency coverage, more components to fail, and higher cost than a simple dipole.

Active or Passive Antennas?

With one singular exception, all antennas are passive; that is, they have no amplifying electronic circuitry. They simply reflect, refract, radiate or conduct the electromagnetic energy which reaches them. The exception is the active (voltage probe or E-field) antenna.

An active antenna consists of a short (a few inches to a few feet) receiving element coupled to a wideband, small-signal amplifier. It is not used for transmitting.

While active antennas may have small size and wide bandwidth, and can deliver large signals to the receiver, they have their disadvantages. They are expensive, require power, may burn out or degrade in performance from nearby lightning or strong signals, generate noise and intermodulation interference ("intermod"), and are usually placed close to interference-generating electronic appli-

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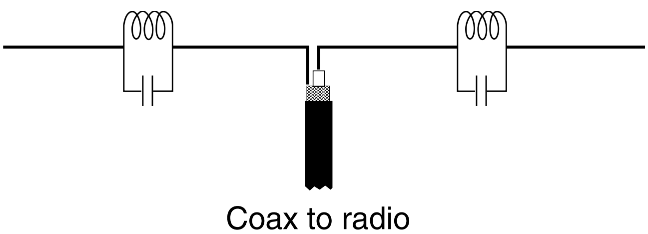

Figure 5.8: Traps are used to isolate antenna element lengths for multiband operation.

ances.

Don't use an active antenna if an adequate passive antenna is available.

Invisible Antennas

Appearances or deed restrictions sometimes require a hidden antenna. Receiving antennas are much less demanding and easier to hide, but even transmitting antennas can be inconspicuous. Of course, VHF and UHF antennas, because of their compact sizes, are easier to hide than HF antennas, but even HF antennas can be unimposing.

An attic crawl space is the first recommendation; it provides shelter, separation from reflective surfaces or electrical wiring, and elevation. Always use low-loss, well-shielded coax transmission line to prevent appliance noise pickup during receive, and stray radiation during transmit. A balun transformer and ferrite-bead choke may be useful as well (see "Accessories").

Wire antennas may be run along baseboards, ceiling molding, behind curtains, and even under eaves, rugs or carpeting. If outdoors is accessible, a thin, high wire is virtually invisible, especially if it is covered with grey (neutral color) insulation; run it from the roof to a tree.

A ground rod would be virtually invisible by its nature.

A wire antenna in a tree is also inconspicuous. It can be run vertically up the trunk, suspended in the branches, or even constructed as a wire array for gain and directivity; remember, an antenna element doesn't have to be straight. The coax feed line can be trenched just beneath the soil.

Resourceful hams, SWLs and scanning enthusiasts have often resorted to make-do antennas: bed springs, filing cabinets, rain gutters and downspouts, aluminum window frames, curtain rods, *disconnected* telephone or power lines, metal flagpoles, aluminum ladders, fences, wheelbarrows, grocery carts, and even vehicle-mounted antennas coax-fed into the radio room!

CHAPTER 6
Accessories

Connectors and Adaptors

At audio frequencies, any kind of connector will work just so long as it can handle the voltage and current. But at RF, connector design is critical. Audio connectors like RCA phono connectors and earphone plugs become increasingly deficient with frequency, and have no specific impedance characteristics. They are usable up to about 30 MHz for receiving purposes.

Motorola connectors, developed for AM car radios, were grandfathered into VHF use when FM coverage was added to those radios.

Early VHF converters needed Motorola connectors in order to interface with the car radios; then mobile scanners adopted them since the car antenna could be called into limited service for local scanner reception. Marginal in performance at VHF/UHF, Motorola plugs have been abandoned by scanner manufacturers in favor of infinitely-superior BNC connectors.

The BNC was named for its configuration and inventors—a (B)ayonet design by (N)eill and (C)oncelman, excellent for applications to at least 1000 MHz.

Neill also contributed his initial to the N connector, developed during World War II for military UHF communications. It is an excellent, waterproof, choice through at least 2000 MHz, but harder to assemble since it is designed for large RG-8/U and R-213/U cables. Concelman's initial adorns the less popular C connector of World War II.

The PL-259 (UHF) connector, developed during the 1930s, is still a popular favorite for ham and CB transceivers as well as shortwave receivers. It works well up to at least 50-100 MHz.

Low-cost, TV-type F connectors work extremely well through 1000 MHz and higher, but they require solid-center-wire cable, and adaptors are always needed to interconnect them with communications equipment.

Some imported nickel-plated connectors are poorly made; their loose fittings and out-of-tolerance thread pitches can add noise, intermittent performance, signal loss, and electrolytic corrosion to the system. On the other

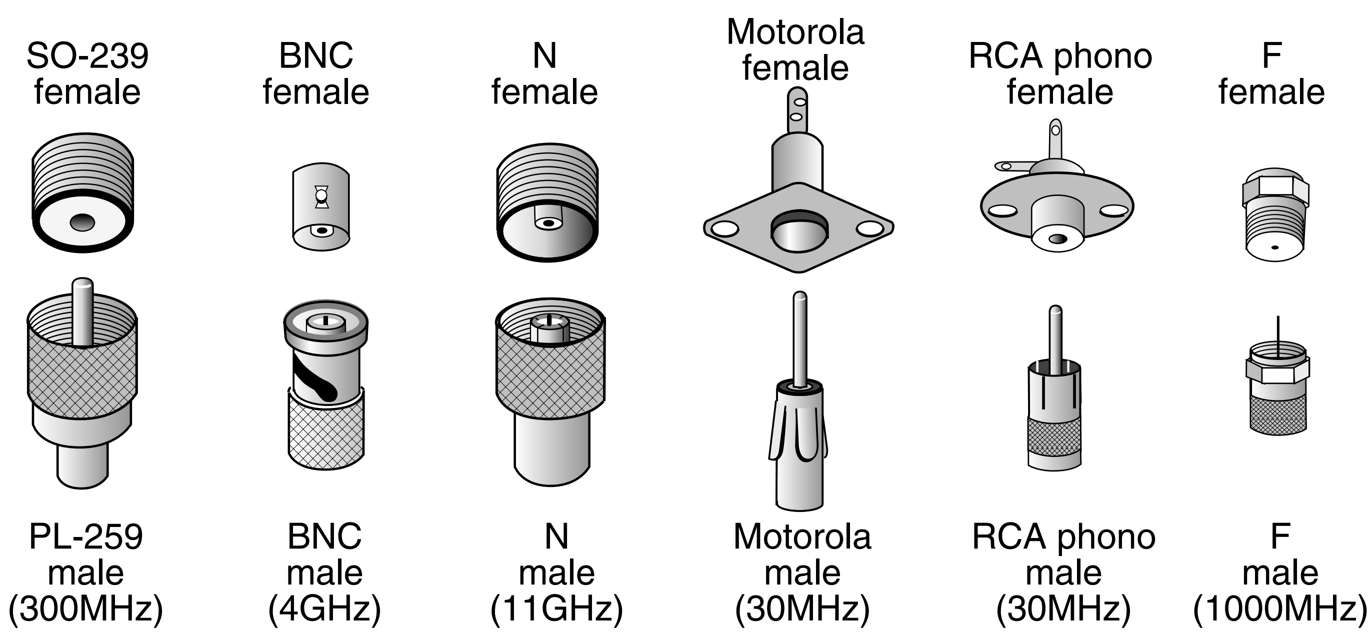

Figure 6.1: The most common antenna connectors and their maximum recommended frequencies.

A preamplifier connected to a poorly-located antenna will not perform as well as a well-placed, larger "passive" (unamplified) antenna, but it may be the only alternative when the better antenna is not practical. If a shortwave receiving antenna is at least 20 feet long and in the clear, a preamplifier is probably unnecessary.

hand, a lab test at Grove Enterprises showed only a fraction of a dB loss at 1 GHz from five different, imported, nickel-plated adaptors cascaded in series.

But to be safe, it's always better to choose a branded, silver (or gold) plated connector or adaptor if available; better yet, use a cable with the correct connectors instead of adaptors.

Preamplifiers

A Preamplifier ("pre-amp" or "signal booster") is simply a small-signal amplifier placed between the antenna and receiver. When integrated with a small receiving antenna, it is called an active antenna (see Chapter 5).

A preamplifier connected to a poorly-located antenna will not perform as well as a well-placed, larger "passive" (unamplified) antenna, but it may be the only alternative when the better antenna is not practical. If a shortwave receiving antenna is at least 20 feet long and in the clear, a preamplifier is probably unnecessary.

A preamp must have a lower noise figure (self-generated "hiss") than the receiver, or the only thing it accomplishes is increasing both signal and noise, just as if you had merely turned up the receiver's volume control.

Figure 6.2: A preamplifier should only be used in exceptionally weak signal areas.

It must have wide dynamic range—the ability to amplify weak and strong signals equally without becoming overloaded and thus generating spurious signal products (intermodulation) which interfere with normal reception.

At VHF and especially UHF and above, where transmission line losses may become significant, a preamplifier mounted at the antenna will boost signals above the loss characteristic of the line. Still, the preamp is vulnerable to all the problems described above.

Even when working perfectly, a preamp can cause the receiver to overload and generate intermod of its own, desensitizing it to weak signals, aggravating images, or even damaging its delicate RF amplifier circuitry. Use it as a last resort.

Splitters and combiners

A splitter is essentially a broadband RF transformer which allows one signal source to be equally divided into two or more paths; this allows, for example, several receivers to operate from one antenna.

Since a typical two-way splitter is an RF voltage divider, each output will be reduced by 3 dB, half the original power level.

Connected in reverse, a splitter becomes a combiner, allowing two signal sources to add; this allows, for example, two separate-frequency antennas to be used simultaneously with one receiver.

But if the two antennas have a similar frequency response, they can produce destructive interference (signal canceling) from certain directions, while providing 3 dB overall gain in other directions.

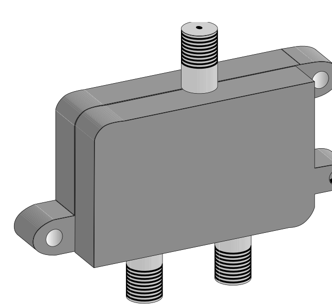

Figure 6.3: Splitters are used to feed one antenna to two (or more) receivers; they can also be used in reverse to combine two (or more) antennas to operate one receiver.

Most balun transformers incorporate a step-up ratio (typically 4:1), allowing low-impedance coax to correctly match high-impedance antenna feedpoints, or a simple 1:1 ratio to allow low-impedance coax to be connected to a low-impedance, balanced feedpoint.

Basically, they comprise a directional array—a "beam" antenna.

TV splitters marked "V/U" or "VHF/UHF" or "54-890 MHz" actually work reasonably well from the low HF range (typically 3 MHz) up through 1000 MHz.

While there are transmitter splitters and combiners, those made for receivers are far more common and less expensive. They will also allow low power—a few watts—to pass without much problem, but higher power levels will heat the fine winding and saturate the small ferrite core, wasting power and even destroying the device.

Balun transformers

The term "balun" (an acronym for "balanced to unbalanced") is a wideband RF transformer which allows an unbalanced transmission line (coax) to be used with a balanced antenna (dipole or beam). Many transmatches include balun circuitry.

Most balun transformers incorporate a step-up ratio (typically 4:1), allowing low-impedance coax to correctly match high-impedance antenna feed points, or a simple 1:1 ratio to allow low-impedance coax to be connected to a low-impedance, balanced feed point.

Instead of a 1:1 balun transformer, a ferrite bead RF choke at the antenna-coax feed point will reduce RF on the feed line by absorbing unbalanced power.

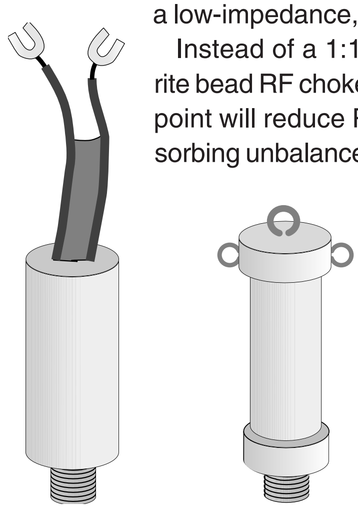

Figure 6.4: Balun transformers are used for matching coax to antennas.

Like splitters, VHF/UHF TV balun transformers can be used with VHF/UHF scanners, shortwave receivers down to about 3 MHz, and even for low-power (a few watts) transmitters.

If a balun transformer is connected between the feed line and antenna, a transmatch will still resonate the entire system—balun, antenna, feed line, tuner, and interactive environment (tower, nearby wires, trees, rain gutters, etc.).

But the tuner does not change the antenna's natural feed point impedance; if there was a mismatch between it and the balun or feed line before the tune-up, it will remain even after the tuner is adjusted to resonance and shows a 1:1 match.

A balun works properly only with resistive (non-reactive) loads; system reactances can cause impedance transformation ratios different from what was intended. Therefore, it is not a good idea to use a balun over a wide frequency range on a narrowband antenna. Baluns also add losses due to wire resistance and possible core saturation during transmit.

Attenuators

It may seem rather self-defeating to make received signals weaker, but under some conditions it is advisable. For example, if you live near several broadcast transmitters, or a high-powered paging transmitter, or if most signals in your area are quite strong, they may be too hot for your receiver or scanner to handle.

Receivers may "come apart" under these conditions, generating spurious signals (intermod) or even desensitizing, making weak-signal reception virtually impossible.

If your outdoor antenna causes either of these symptoms, an attenuator may be the prescription; some receivers and scanners have them built in.

Figure 6.5: Attenuators reduce signal overload. They may be either variable (shown above) or fixed.

No filter is perfect in its characteristics; desired signals near the edges of the design range (cutoff frequencies) will also be attenuated somewhat. Even at the center of its attenuation range, some strong signals may still get through. A credible manufacturer will publish the response curves of his filters to reveal their limitations.

But if an attenuator is likely to make desirable weak signals unreadable, try a filter.

Filters

A filter is a tuned circuit which allows only certain frequencies to pass; their generic names imply what they do.

A low-pass filter passes low frequencies and attenuate higher; a high-pass filter passes high frequencies and attenuates lower; a band-pass filter passes a specific range of frequencies; a band-reject ("suck-out") filter attenuates a swath of spectrum; a trap or notch filter attenuates a very narrow range of frequencies, and a peaking filter passes a very narrow range of frequencies..

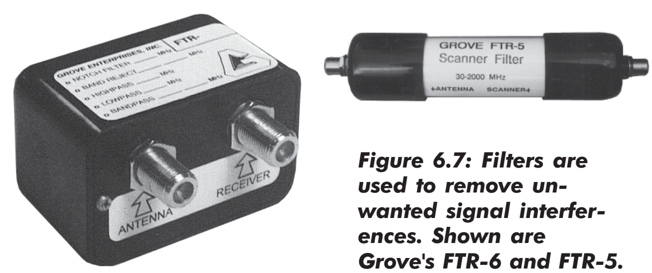

Figure 6.7: Filters are used to remove unwanted signal interferences. Shown are Grove's FTR-6 and FTR-5.

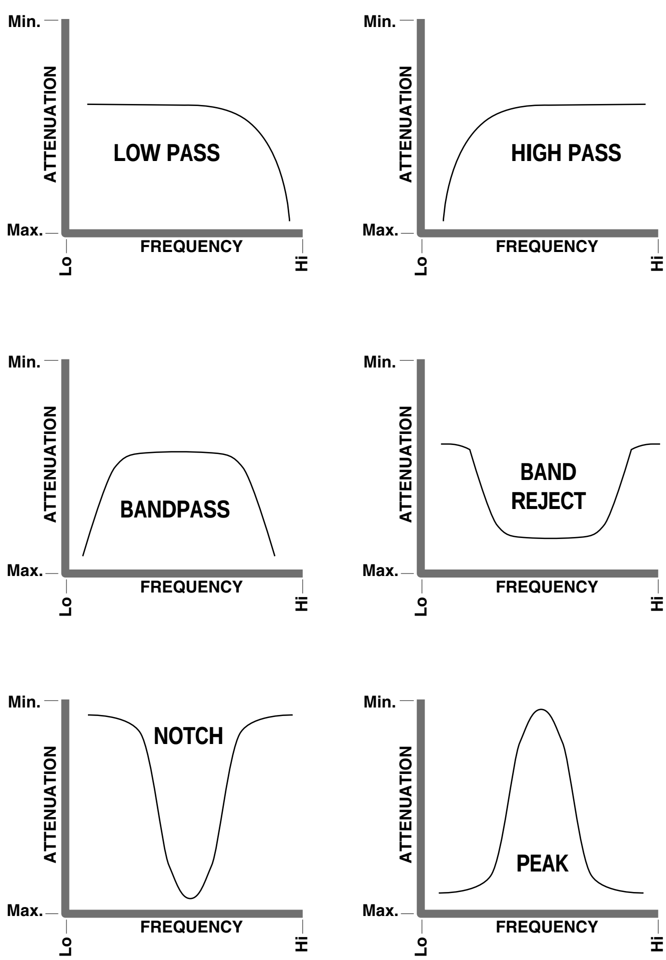

Figure 6.6: Types of filters.

Filters can be used with transmitters to reduce harmonic and other spurious signal radiation, or with receivers and scanners to selectively reduce strong, interfering signal frequencies.

No filter is perfect in its characteristics; desired signals near the edges of the design range (cutoff frequencies) will also be attenuated somewhat. Even at the center of its attenuation range, some strong signals may still get through. A credible manufacturer will publish the response curves of his filters to reveal their limitations.

Antenna switches

It is often desirable to select among two or more antennas for optimum reception or transmission. For receiving purposes, or even for low power (a few watts) transmitting, TV coax antenna switches work admirably from DC through 1000 MHz.

CB-type antenna switches work fine up to about 30 MHz both for receiving and transmitting. For higher power, especially at higher frequencies, select a commercial coax switch

Figure 6.8: Antenna switches should be chosen carefully, both to handle high power when used for transmitting, and for low loss when used at VHF/UHF.

CHAPTER 7

Biohazards

rated for the frequency range and power required.

It has long been known that electromagnetic radiation can produce effects in biological organisms; of particular concern to hobbyists is the influence of radio waves on the human body.

If we consider the adult as an antenna, it has a natural resonance between 35 MHz (grounded) and 70 MHz (insulated from ground). Body parts, too, are resonant—the head at around 400 MHz (700 MHz for infants). Since the body is a lossy conductor, it dissipates much of the induced energy as heat.

But in most cases it is not thermal affects that are of the greatest concern. On-going controversy revolves around whether cancer may be induced by low-level AC fields from power lines and associated equipment and appliances, and even radio fields modulated by frequencies around 60 Hz.

Virtually all studies suggest that power levels under 100 watts or so into an outdoor antenna are safe. Concern mounts with indoor, attic, mobile, and low directional antennas. Until all the facts are known, follow these guidelines:

(1) Keep away from antennas and open-wire feed lines that are transmitting.

(2) Elevate well overhead any transmitting antennas, especially directional beams which concentrate their energy.

(3) Operate nearby transmitting antennas (mobile, attic, in-room) at low power (nominally no more than 25 watts).

(4) Operate RF power amplifiers with their covers in place.

(5) Hold hand-held transceivers away from your head by using extension mikes.

(6) Stay at least two feet away from power transformers.

APPENDIX

Facts, Not Fiction

1. Except for very thin wires, most antennas are efficient radiators. Virtually all losses in an antenna system occur in the feed line.

2. A high standing wave ratio (SWR of 3:1, 6:1, etc.) merely indicates the presence of power reflections on the feed line due to impedance mismatch. If there are no losses in the feed line, all reflected transmitter power will be returned to and radiated by the antenna; for receiving systems, all captured signal power will be returned to the receiver. If there is an impedance mismatch between the receiver and transmission line, however, reflected signal power will return to the antenna where it will be re-radiated back into space

3. Reflected power does not flow back into the transmitter and cause damage or overheating. If damage occurs, it is due to mistuning the amplifier.

4. A low SWR reading only means that the transmitter, feed line and antenna system are impedance-matched; it does not necessarily mean that everything is working properly. Corroded or intermittent connectors, ineffective grounds, lossy cable and other resistive agents can all give a deceptively low SWR. Unless an antenna is broadband by design, a low impedance maintained over a wide frequency range without retuning is particularly suspect.

5. Neither an antenna nor the feed line needs to be self-resonant (no inductive or capacitive reactances) to perform properly. Virtually any antenna and its feed line, no matter how reactive, can be brought to resonance by a transmatch.

6. Using low-loss transmission line, and at frequencies below 30 MHz or so, signals experiencing an SWR of at least 3:1 and perhaps as high as 5:1 will be indistinguishable from signals produced by a perfect 1:1 impedance match.

7. Adjusting a transmatch at the radio position does not alter the reactance or impedance of either the antenna or the feed line; it brings the entire mismatched and reactive system into resonance by "conjugate matching," introducing reactance-canceling capacitances and inductances of its own, so that the attached receiver or transmitter senses only a resistive load.

8. A large antenna does not radiate more power than a small antenna, nor is more power radiated from a particular configuration (dipole, vertical, beam, quad, cage, bowtie, rhombic, loop, etc.). But a large antenna does radiate a more concentrated, directional field than a small antenna, and it captures more signal energy during reception.

9. No transmission line needs to be a specific length if a transmatch is available. Adjusting the length of a feed line does not alter the SWR, just the impedance measured at the tuner/feed line connection.

10. High SWR in a coax feed line does not cause RF currents to flow on the outside of the line, nor will the coax radiate. High SWR on an open wire feed line will not cause the feed line to radiate just so long as the currents are balanced, wire spacing is small compared to wavelength, and there are no sharp bends.

11. Assuming low-loss feed line, an SWR meter will read the same at the antenna feed point, anywhere on the feed line, and at the transmitter.

12. Raising or lowering an antenna to adjust its feed point impedance has no significant effect on power radiated, only the shape of its elevation pattern. However, raising the pattern between 3 and 20 degrees from the horizon can improve DX communications.

13. A frequency meter or dip oscillator connected at the bottom of a feed line cannot measure the resonant frequency of the antenna; it measures only the combined resonance of the antenna plus the feed line.

14 A balun transformer on a transmitting antenna will match impedances correctly only if it is used within its power limitations; excessive current may saturate its core, wastefully heating the balun while giving a deceptive SWR reading.

15 A loading coil on a short antenna doesn't add missing length, it adds inductive reactance to cancel the capacitive reactance of the short antenna.

16. A transmatch doesn't "fool" the transmitter or receiver into "thinking" it is connected to the correct impedance any more than an AC wall adaptor "fools" a radio into "thinking" it is getting 12 volts DC when it is plugged into 120 volts AC. In both cases power and impedance transformations really occur.

RECOMMENDED READING

The ARRL ANTENNA BOOK, published by the American Radio Relay League, 225 Main St., Newington, CT 06111.

ANTENNAS by J.D. Krauss, second edition, 1988; McGraw-Hill Book Co.