Facts About Proper VHF Vertical Antenna Design

PUBLISHED BY AEA, THE MANUFACTURER OF ISOPOLE ANTENNAS

Problems of base station antenna design

What is so hard about designing a vertical base station antenna? It's not a trivial question, because four important, interacting design objectives must be dealt with simultaneously.

1. **Decoupling.** The antenna must be so designed that the coaxial cable and mounting structure will not become inadvertent parts of the antenna. A properly designed vertical antenna is said to be "decoupled" from the feed-line and supporting mast. Failure to achieve decoupling can ruin the radiation pattern of the antenna, drastically lower the gain, cause the direction of maximum radiation to be either raised or lowered from the horizon, and allow radio frequency energy to be guided down the outside of the feedline to the transmitter, where it can be coupled into the electric wiring, telephone wiring, and other electronic equipment.
2. **Radiation Pattern and Gain.** The amplitudes and relative phases of the currents excited on the radiating portion of the structure must be controlled to produce the required radiation pattern and gain.
3. **Input Impedance.** The input impedance of the antenna must be well matched to the characteristic impedance of the coaxial feedline over the entire band of frequencies for which the antenna is to be used. In other words, the standing wave ratio (SWR) should be low (under 2 to 1) over the required frequency band.
4. **Mechanical Design.** The antenna must be mechanically designed to withstand severe environmental stresses, including high winds, high and low temperatures, icing, etc. The upper design limits to these stresses beyond which the antenna will be damaged, will strongly influence the cost. Any impedance matching network built into the antenna must be dimensionally stable and weather-protected in order to preserve the tuning. The connector to which the feedline is attached should also be out of the weather.

Proper decoupling: the key to good vertical antenna design

The need for decoupling a vertical antenna from its coaxial feedline can be appreciated by referring to Figure 1. Antennas which are driven by 2-conductor transmission lines always have two terminals, insulated from each other, between which the high frequency AC voltage generated by the transmitter is impressed. Figure 1 shows a typical center driven dipole antenna, with terminals a-b, across which the AC voltage generated by the transmitter is connected. During each cycle of the AC voltage, current flows out on one leg of the dipole and in on the other, leaving positive charge on one extremity and negative on the other. The current then reverses, and the polarity of the charges on the respective extremities is reversed. An electric field is created in the vicinity of the dipole between the separated charges, as shown in Figure 1. The electric field bulges out from the terminals as the charge spreads out toward the extremities. The following charge constitutes the

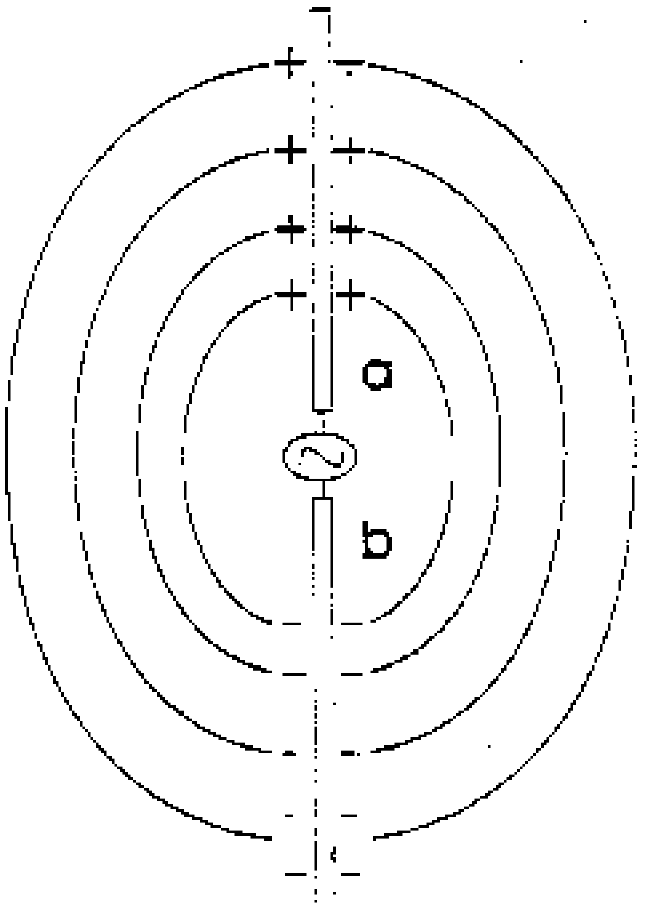


Figure 1 Electric field in vicinity of an isolated center-driven dipole antenna

current on the antenna, and associated with the current is a magnetic field, encircling the wires of the antenna. The AC current is zero at the extremities of the dipole and maximum at about a quarter wavelength in from each end, in what is called a "standing wave" current distribution. The separation of the oscillating charges on the conducting members of the antenna produces the mysterious phenomenon of electromagnetic radiation. If the total length of the vertical center driven dipole of Figure 1 is one-half wavelength, the resulting radiation pattern is well suited for many communication needs. Maximum radiation intensity is directed toward the horizon, and the pattern is omnidirectional in azimuth.

The problem remains of connecting the feedline to the antenna terminals. We might try to bring the coaxial line up from below, connecting the center conductor to the lower extremity of the antenna. What will we do with the outer conductor? Suppose that we just let it terminate at the base of the antenna as shown in Figure 2. The AC voltage from the transmitter is piped up to the antenna within the coaxial cable, and appears between terminal a, the base of the antenna, and terminal b, the lip of the outer conductor.

The resulting electric field is shown in Figure 2. On each half-cycle, field lines originate on positive charge on the antenna and terminate on negative charge on the outside of the coaxial line. Then, the polarity reverses as the antenna becomes negatively charged, and the upper part of the outer conductor positive. An electromagnetic field is guided down the outside of the outer conductor as shown in Figure 2. The outside of the outer conductor is hot with radio frequency currents all the way down to the transmitter. The actual antenna really consists of a dipole, one side of which is the vertical leg, the other leg being the outside of the outer conductor, the metal chassis of the transmitter and other associated wiring. The radiation pattern of the system is generally unpredictable, and generally bad! The length of the upper leg of the dipole might be ¼ wavelength, ½ wavelength, or something else. In every case, the electromagnetic field will "spill" out from the end of the coaxial cable, exciting current and charge on both the intended "antenna" and the outside of the coaxial line.

This phenomenon can be readily verified by detecting the presence of current on both the antenna wire and the outside of the coaxial line, using the simple pick-up loop described at the end of this booklet. Simply attach a ¼ wave, ½ wave or 5/8 wave whip antenna to the end of a length of coaxial line of arbitrary length (6 or 8 feet would be fine) and connect the other end to a VHF transmitter. Ten watts of power is quite sufficient for a

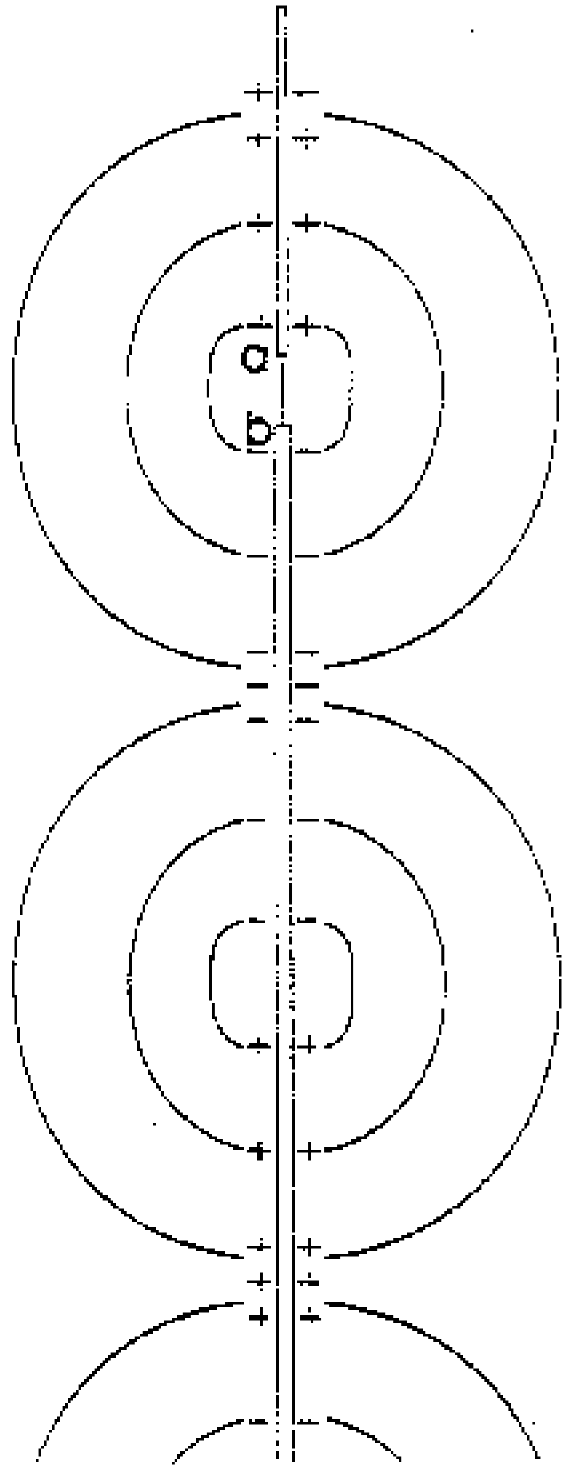


Figure 2 Electric field in vicinity of a whip antenna connected to a coaxial line

test. Support the antenna and coaxial cable above the ground, and hold the pick-up loop close to the antenna. Maximum coupling occurs when the plane of the loop lies in any plane containing the antenna wire (or coaxial line). This current is not leaking through the coaxial line. It emerges from the feed of the coaxial line and flows back over the outside of the outer conductor due to the lack of any form of decoupling.

Some people might say, "Ah, but you don't have any impedance matching between the antenna and the coaxial line!" Impedance matching has nothing to do with the currents spilling out over the coaxial line, as the following example will show.

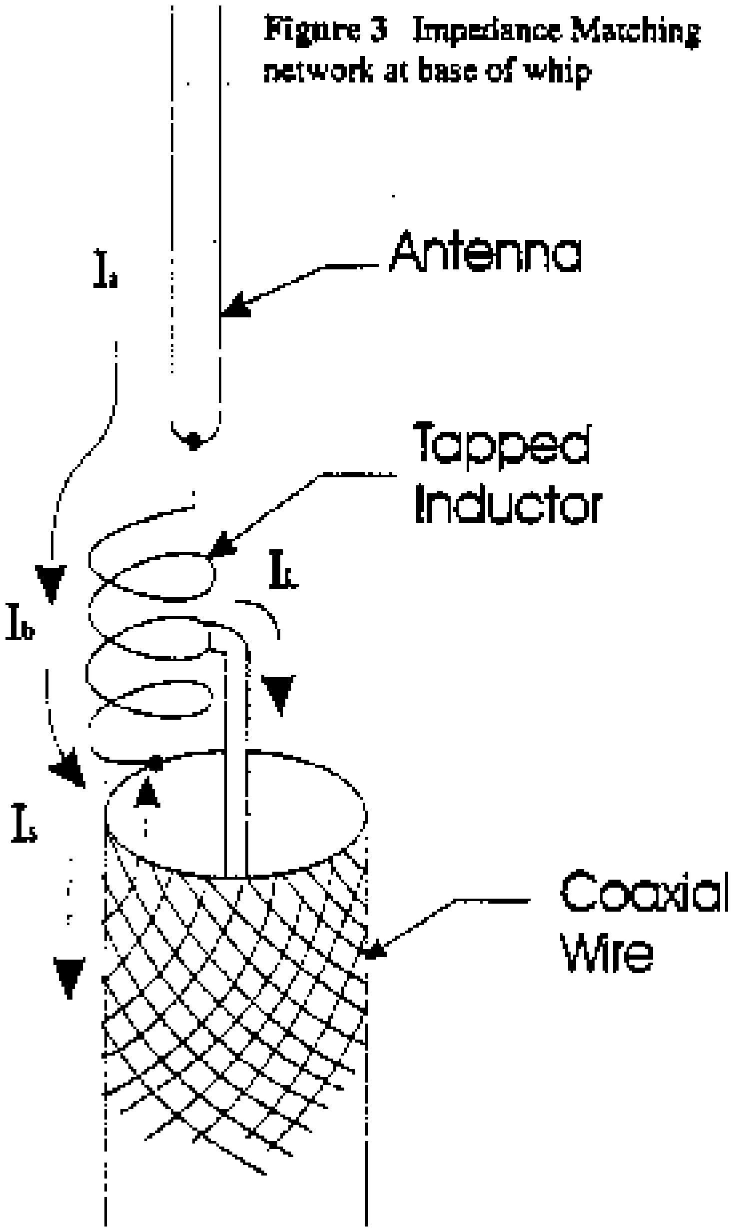


Figure 3 Impedance Matching network at base of whip

Figure 3 shows an impedance matching network of a design used on certain end-driven vertical antennas. The current I_a at the base of the antenna flows into the upper terminal of a tapped inductor. Current I_L flows from the tap into the center conductor of the coaxial line. A current I_L of equal magnitude, but opposite direction, flows on the linear surface of the outer conductor. Current I_b flows in the bottom section of the inductor, below the tap. Finally, a spill-over current, Is, flows on the outer surface of the outer conductor. Kirchoff's current law requires that: $Ia = I_L+I_b$ and $I_s = I_b+ I_L$. We can solve for I_b in the first equation and substitute it in the second to obtain $I_s = I_a$. The spill-over current must be the same as the antenna current, independent of whether the antenna is matched to the coaxial line or not!

Antennas with no decoupling

Unfortunately, from the standpoint of the end user, there are many coaxially driven VHF vertical antennas in use today which totally lack any form of decoupling. These antennas fall into two classes: automotive whips mounted on other than vehicles with metal roofs, and antennas sold for fixed, base station use.

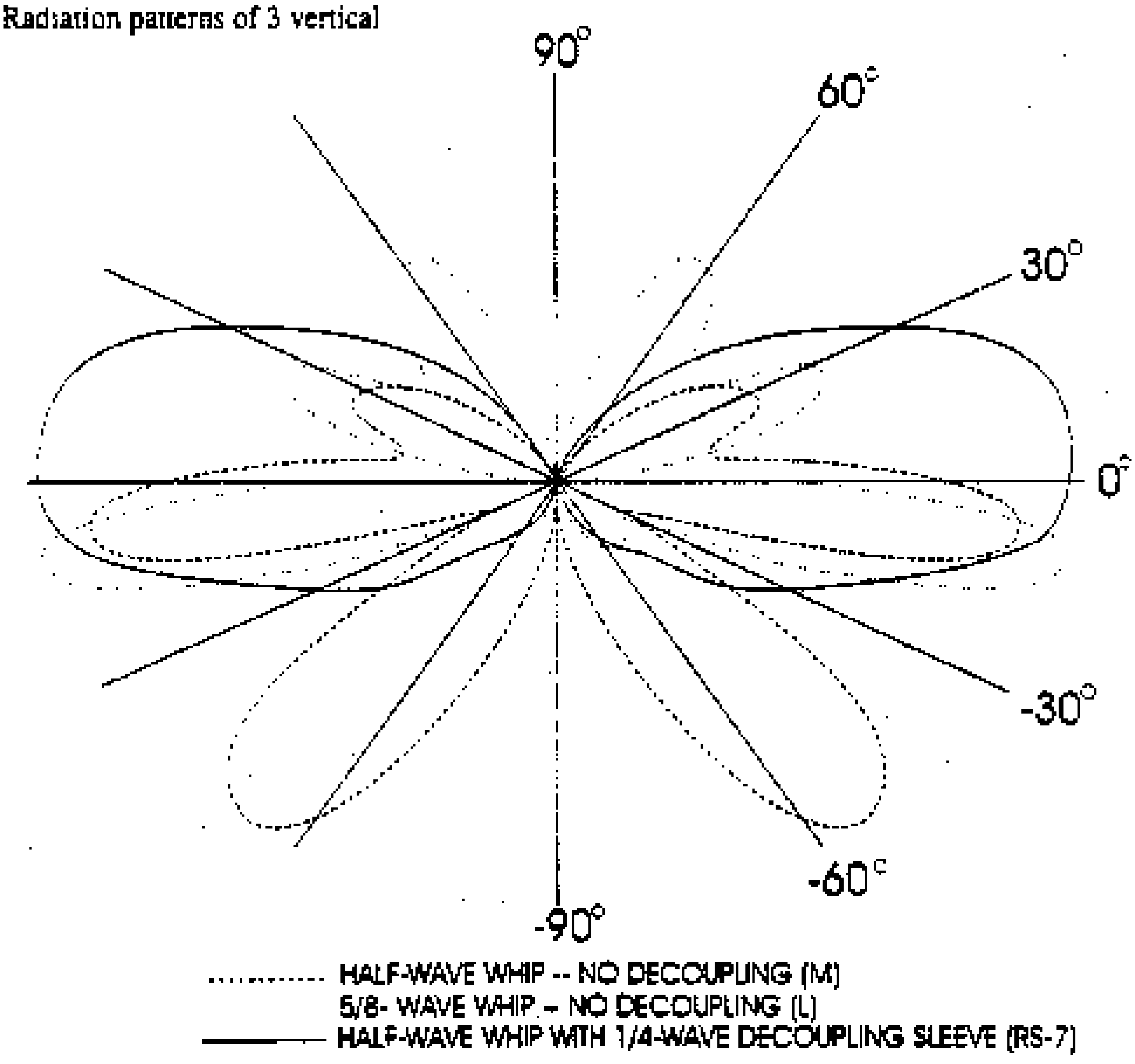
Automotive whips are frequently used by amateur radio operators as temporary base station antennas, connected to the transmitter through a length of coaxial line. While the radiation pattern will be horrible and much of the transmitter power wasted, the amateur operator will usually still be able to communicate with at least some other stations. The situation is more serious when automotive whips are mounted on the mastheads of sailboats for use in the marine VHF band. The spill-over current will flow down the stays and shrouds, as well as the outside of the coaxial line and the mast itself, if the latter is of metallic construction. All of these conductors are long in the wavelengths and will radiate with many narrow lobes in the vertical plane, which rock with the motion of the boat, causing fading, so often experienced in marine communications. The advantage of masthead height to achieve greater VHF range will be lost.

The above examples represent misuse of the product. Whip antennas, which give excellent performance when mounted on the horizontal metallic surfaces of automobiles, are simply not intended to be thrust into the air at the end of a length of cable.

A more serious situation exists in the case of non-decoupled antennas which are sold for base station and other non-automotive uses. End driven vertical half-wave dipoles with absolutely no decoupling are on the market specifically for marine masthead use and a number of base station antennas with absolutely no decoupling are offered to the amateur radio market. Advertising claims made by manufacturers of some of these antennas simply cannot be substantiated.

Figure 4 shows measured radiation patterns on three antennas, two with absolutely no decoupling and a third with excellent decoupling.

Figure 4 Radiation patterns of 3 vertical antennas



All three antennas were measured with an attached 8 ½' length of coaxial line in a straight line from the base of the antenna.

Antenna 1 is a half-wave whip with a tuner at the base, advertised for small boat masts. Note the butterfly pattern with major lobes of radiation at high and low angles and a loss of signal toward the horizon.

Antenna 2 is a 5/8 wavelength whip and its pattern is even more horrible than the first, with stronger lobes at high and low angles.

Antenna 3 is a base driven, half-wave whip with a quarter wavelength decoupling sleeve. Note that the main lobe of the pattern is directed toward the horizon. This pattern is virtually unaffected by the length of cable leading up to the antenna. The slight asymmetry in the shape of the lobe is a result of the small current spilling over onto the outside of the decoupling sleeve, which is actually in phase with the current on the antenna and produces a small, omni-directional gain over an ideal half wave whip.

How to properly decouple the antenna

The first step in achieving good decoupling of a vertical whip is to bring the coaxial line up through a quarter wave sleeve, as shown in Figure 5. This antenna, called a "sleeve dipole" has been widely used for many years. The sleeve is connected to the outer conductor of the coaxial line at the feedpoint, and extends down around the coax for a quarter wavelength. The center conductor extends above the feedpoint for a quarter wavelength. The antenna behaves like a vertical, center-driven half-wave dipole. The bottom of the sleeve is a point of high charge concentration, yielding considerable electric field coupling to the outer conductor of the coax line, as shown in Figure 5. A certain amount of "spill-over" current will flow down the outside of the outer conductor. While this effect is minimized by employing a large ratio between the diameters of the sleeve and of the coax line, much more complete decoupling is achieved by installing a second quarter wavelength decoupling sleeve below the first, as shown in Figure 6. The radiation patterns of these antennas are substantially independent of the length of the coaxial line, or of any metallic mast on top of which the antenna may be mounted. As a matter of fact, radiation from the small current existing on the lower decoupling sleeve combines fortuitously with the radiation from the vertical dipole to produce a broad lobe in the vertical plane, centered on the horizon.

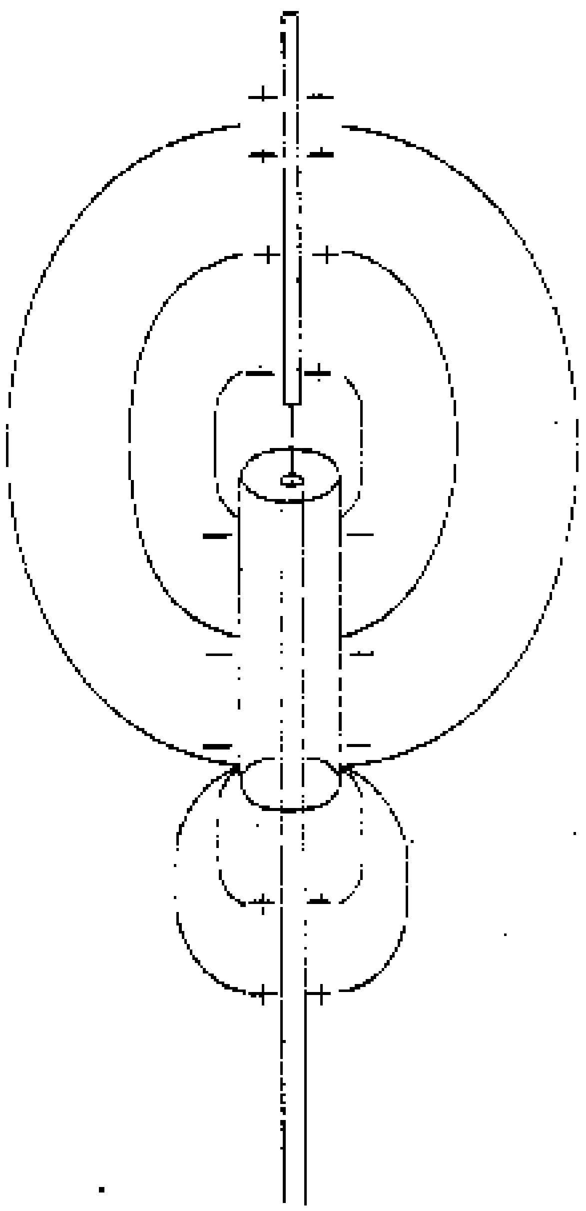


Figure 5 Fields around a sleeve dipole

Another effective form of decoupling is shown in Figure 7. In this design, the radiating element consists of a half-wave whip base-driven through a quarter-wave decoupling sleeve. Since the current along the whip is distributed in the form of a standing wave with maximum amplitude in the center, the base of the whip is a point of low current and high voltage. As explained in the previous section, the magnitude of the current spilling over the outside of the decoupling sleeve must be equal to that of the current flowing into the base of the whip.

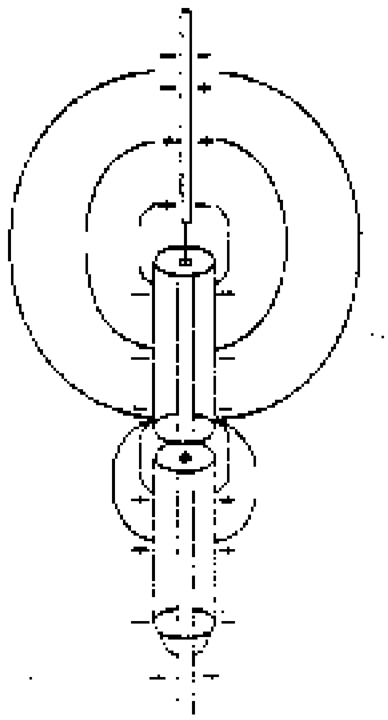


Figure 6 Sleeve dipole with additional decoupling sleeve

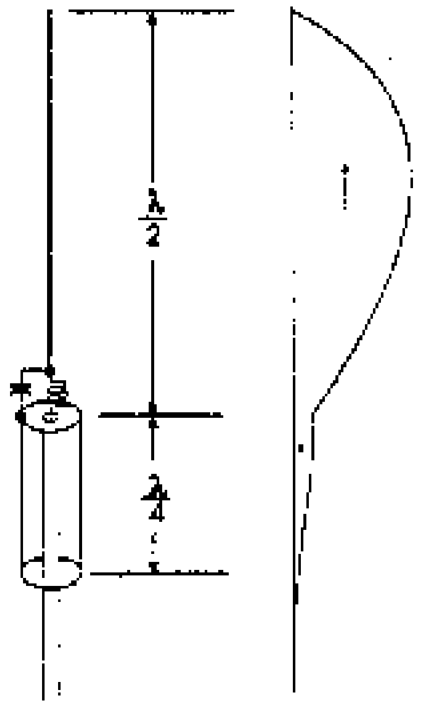


Figure 7 End-driven half-wave dipole with quarter wave decoupling sleeve

Since this current is small, the spill-over current is also small. The spill-over current is also distributed as a standing wave, with maximum amplitude at the top, where the sleeve connects to the outer conductor of the coaxial line, and minimum amplitude at the bottom or open end of the sleeve. The current distribution on the entire antenna is sketched in Figure 7. The current coupled onto the outside of the coaxial line below the sleeve is extremely small, as can be experimentally verified with the RF detector described at the end of this booklet. Since the input impedance of this antenna is high, a tuner is necessary to transform the impedance to 50 ohms. An L-C network for matching purposes can be built-in at the feedpoint.

Achieving omnidirectional gain

The most practical way to obtain omnidirectional gain in a vertical antenna system is to stack a number of separate antennas to form a vertically oriented colinear array. It is relatively easy to obtain 3 dB of omnidirectional gain with respect to a vertical half-wave dipole. Higher gains require much more complex structures, multiple feedpoints, power dividers, phasing sections, impedance matching networks, etc. While 3 dB of omnidirectional gain can be obtained in antennas costing little more than simple decoupled half-wave whips, higher gain antennas are generally much more expensive.

One of the most popular ways to obtain 3 dB of omnidirectional gain over a vertical half-wave dipole is to employ a center driven dipole whose total length is 1 ¼ wavelengths, that is, 5/8 wavelength on each leg. The properties of such a dipole have been known for many years. When oriented vertically and well decoupled from the coaxial feed cable, this antenna produces almost exactly 3 dB of omnidirectional gain with respect to a half-wave dipole, yet requires but one feed point. The 1¼ wavelength (or "twin 5/8") design produces the maximum possible gain for a single dipole. If the antenna is either shorter or longer, the gain drops off.

Figure 8 shows how this dipole can be employed in a vertical orientation. Notice that the coaxial line is brought up to the center of the dipole, where the center conductor excites the upper 5/8 wavelength element. The lower 5/8 element consists of the outside of the outer conductor, down for a distance of 3/8 wavelength from the feedpoint, and then the outside of a ¼ wavelength decoupling sleeve. The "spill-over" current, which must be equal to the current at the base of the upper element, constitutes the current entering the lower element of the dipole. The lower 5/8 element terminates at the open end of a resonant quarter-wavelength sleeve. Tests have shown the presence of a small amount of spill-over current below this sleeve. Accordingly, a second resonant sleeve is necessary to produce a high degree of decoupling. The current distribution along the antenna is sketched in Figure 8. Note the standing wave distribution, and the fact that the upper and lower current "loops" are in phase with each other. This is the desired action which produces the gain. Note also that there is a phase reversal of the currents near the feed point. The effect produces small "side lobes" at high and low angles - a characteristic of most gain-type antenna arrays.

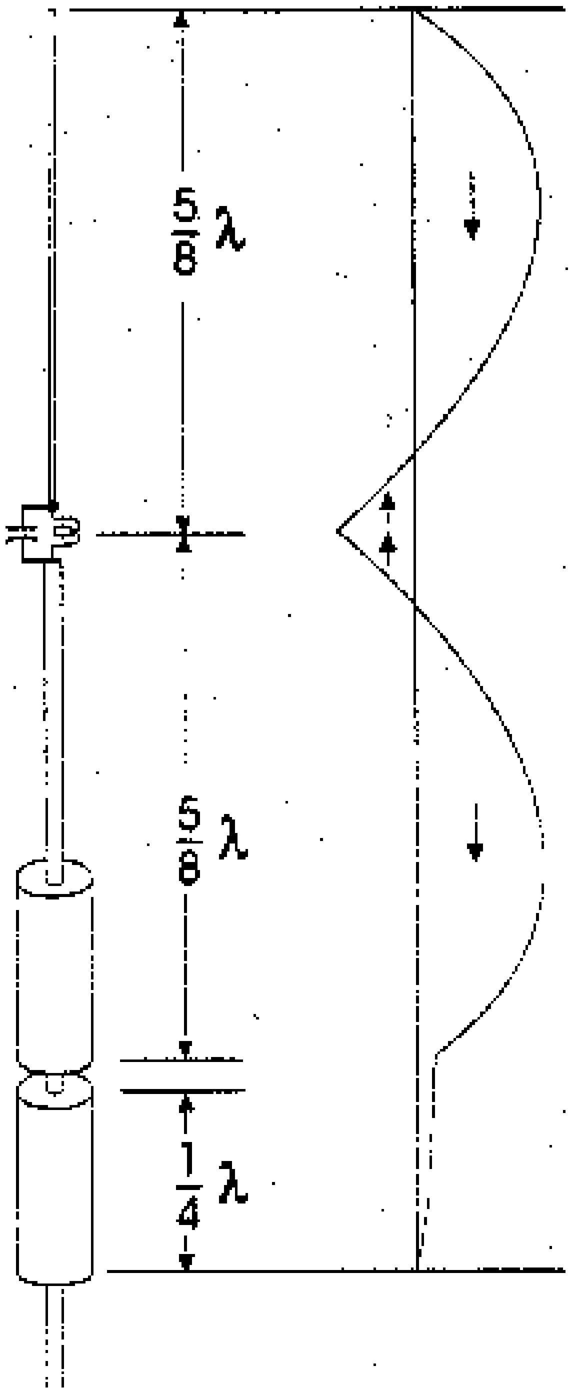


Figure 8 Center-driven twin-5/8 dipole with twin decoupling sleeves

The decoupling sleeves are filled with Styrofoam cores with a central hole to accommodate the coaxial line. An L-C network is used at the feed-point to match the antenna impedance to 50 ohms. The entire antenna is fitted snugly inside a stiff, tapered fiberglass tube, and weather sealed.

Gain

The stated gain of an antenna must use a reference to have any meaning. Commercial antenna manufacturers use a free space half-wave dipole as the gain reference and the gain will be shown with the subscript "d" (for dipole). So the number 3 dBd indicates 3 dB more power in the direction of maximum radiation than a dipole.

Another common reference is gain over the mythical isotropic radiator. This is a non-existing, but mathematically convenient antenna that radiates with the same power intensity in all directions. The gain of a half-wave dipole is 2.15 dBi and our 3 dBd antenna is 5.15 dBi.

In order to make the gain numbers larger, some manufacturers use gain numbers that could theoretically be achieved if the antenna were placed over a perfect, infinitely large ground plane so that all the power delivered to the antenna would be above the ground plane. This theoretically would double the power above the ground plane and add another 3 dB. Our dipole could have an "advertised gain" of 5.15 dB and our 3 dBd antenna could be advertised to have a gain of 8.15 dB. Note that there is no reference in these numbers. The prospective antenna purchaser should insist on the gain reference.

Vertical base station antennas should have their direction of maximum radiation on the horizon. Some commercial antennas intended for amateur use cannot control their pattern and may be several dB down on the horizon. Gain is, unfortunately, measured in the direction of maximum radiation; not on the horizon. Two antennas with 3 dBd of gain may be miles apart in performance due to their differing angles of maximum radiation.

An antenna whose maximum radiation is at zero degrees elevation (like the IsoPole) is an important consideration.

IsoPole™

The same twin-5/8 wavelength design shown in Figure 8 is used in the AEA IsoPole antenna, shown in Figure 9. Models of this antenna are produced for the 144-148 MHz, 220-225 MHz and 420-450 MHz amateur bands (the two meter IsoPole can be tuned anywhere between 138 and 174 MHz for commercial applications).

The design objectives for the IsoPoles were challenging:

1. to produce a gain-type omnidirectional vertical antenna with excellent decoupling,
2. capable of accepting full legal power,
3. impedance matched at the factory for complete coverage of the respective commercial & amateur bands,
4. with input coaxial connectors and matching section protected from the weather,
5. all at an attractively low price.

To reach these objectives, innovation was necessary. For example, the conical shape of the decoupling sleeves was chosen to achieve structural rigidity, good decoupling via a wide mouth diameter, and a simple means for clamping the sleeve to the mast. These mechanical advantages, combined with certain electrical properties of noncylindrical sleeves have led AEA to obtain patent protection for this design.

The IsoPole is designed to be mounted atop a metallic pipe or mast. The base of the upper element of the antenna contains an insulating section of Delrin® and metal sleeve to slip over the top of the mast. The coaxial connector is located within this sleeve, allowing the coaxial cable (usually RG 8/U) to be brought up inside the

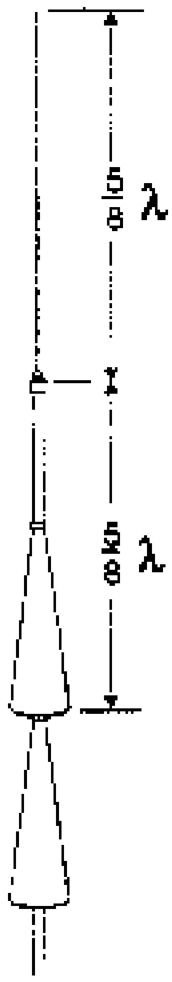


Figure 9 The AEA IsoPole antenna

mast. The RF connection to the antenna is therefore completely out of the weather. The insulating section houses the L-C tuner, which is pre-adjusted at the factory to provide low SWR over the entire band. The L-C tuner compensates for the slight impedance mismatch introduced by the common (VHF) female SO-239 connector used. For best results, the user should employ a BNC or type N fitting at the transceiver end of the RG 8/U cable.

While hardly necessary, the user of the antenna, if he so desires, can tune the IsoPole to a specific frequency using an SWR bridge. This is done by lengthening or shortening the upper element (which is constructed of two telescoping sections) for minimum SWR and making a corresponding adjustment of the distance between the feed point and the mouth of the upper decoupling sleeve.

Other twin-5/8 antennas

Some manufacturers offer twin-5/8 antennas which are driven at the lower extremity, as shown in Figure 10. A phasing section is used at a point 5/8ths wavelength down from the tip in order to obtain the desired current distribution. The coaxial connector for the feed line, the matching network, the base insulator, and the hardware for mounting the antenna atop a mast are all located at the lower extremity. Antennas of this design have absolutely no decoupling. The same current entering the base of the antenna must spill-over the mast (if metallic) and the outside of the coaxial line. Currents on the mast and coaxial line radiate and create fields which combine with those radiated from the antenna. The resulting radiation pattern is virtually unpredictable, and varies with every installation. Figure 11 shows a superimposition of two radiation patterns, one for an AEA IsoPole, and the other for a non-decoupled twin-5/8 antenna as supplied by its manufacturer. These patterns were measured on an antenna pattern range at a nearby university, using high standards of antenna engineering practice. The patterns were measured in such a way that the effect of the presence of the earth on the two antennas was identical. In each case, a length of 8-1/2 feet of coaxial cable was mounted so as to extend beyond the bottom extremity of the antenna in a straight line. Radiation patterns were recorded in dB on a linear chart recorder, and transferred carefully to polar plots showing relative radiated power vs. vertical angle, to simplify interpretation of the results.

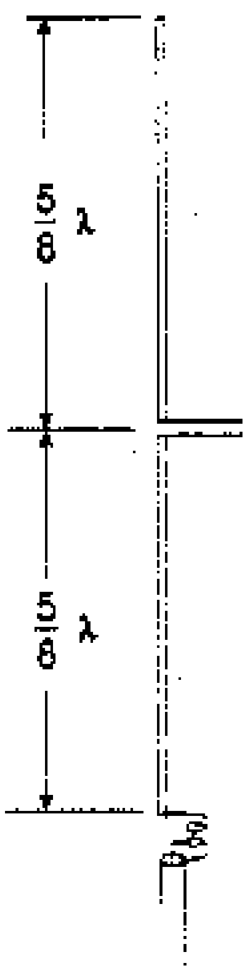


Figure 10 End-driven twin-5/8 antenna with no decoupling

Note that the main lobe of the IsoPole is centered on the horizon, while the main lobe of the non-decoupled antenna is tilted upward, with a corresponding loss of power in the direction of the horizon. This effect was produced by radiation from the currents spilling out on the 8-1/2 feet of coaxial cable. Longer cable runs could be expected to produce much more serious degradation of the

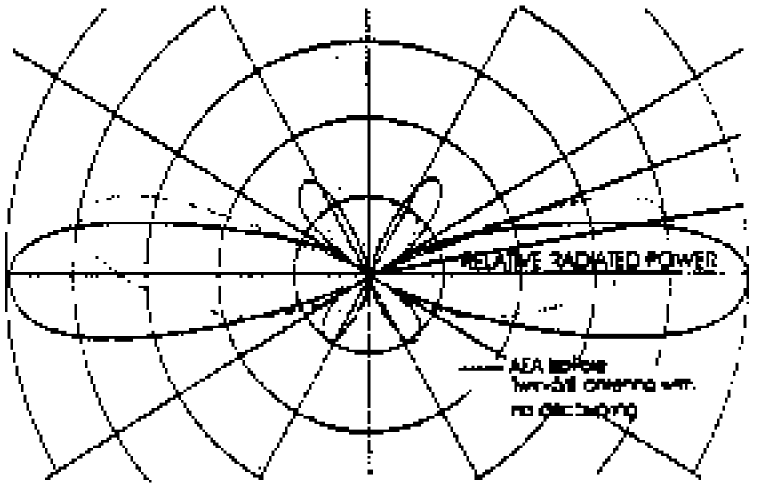


Figure 11 Radiation patterns of AEA IsoPole compared to that of non-decoupled twin-5/8 antenna

radiation pattern, in the form of many sharp lobes caused by the "long-wire" radiation from the feed line phasing in and out with respect to the radiation from the antenna. While there would be a finite chance that radiation from the feed line might combine fortuitously with that from the antenna to create a net gain, this result is improbable. The loss of performance of the non-decoupled antenna will vary with each installation, and can easily be in the range of 3 to 6 dB below its well decoupled counterpart.

How to make an RF detector

A simple series circuit consisting of a loop of wire, a pilot light and a tuning capacitor, makes an inexpensive and highly effective detector of antenna currents and the spill-over effect.

Figure 12 shows a typical detector, using a square loop of wire 2 inches on a side. A No. 49, 2 volt, 60 mA. Pilot light should be used in order to obtain enough sensitivity for good results with as little as 10 watts of transmitter power. The variable capacitor can be a compression-mica, air dielectric, ceramic, or tubular plastic variety. A dielectric handle of wood or plastic should be glued to the loop in order to prevent the user's hand from detuning the detector or the antenna.

To tune the detector, bring the loop up close to the antenna while the transmitter is on, with the plane of the loop. Adjust the capacitor with an insulated tuning tool to obtain maximum brightness of the lamp. You may have to back the loop away from the wire to avoid burning out the lamp during tuning. With the suggested capacitor, the loop should be able to tune to any frequency between 140 and 230 MHz.

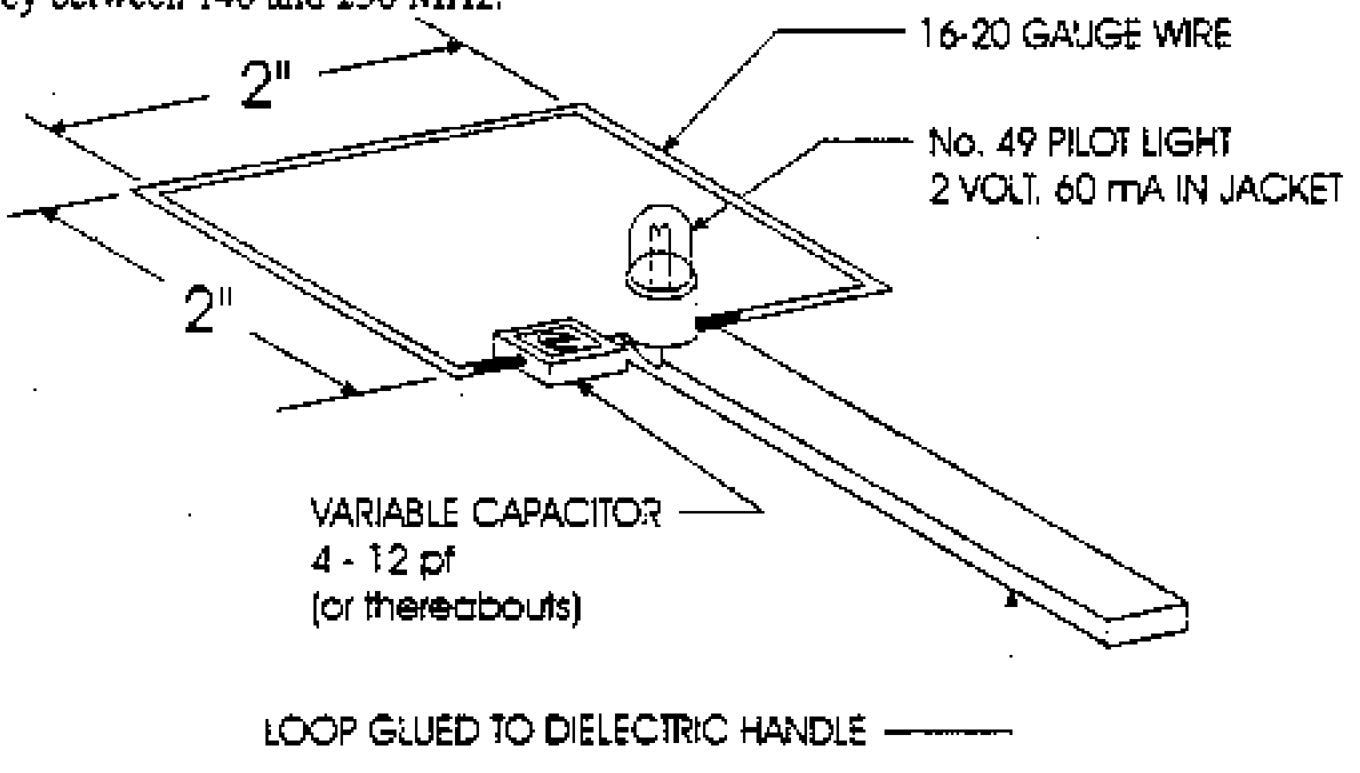


Figure 12 Simple RF detector