Chapter 14

Direction Finding Antennas

The use of radio for direction-finding purposes (RDF) is almost as old as its application for communications. Radio amateurs have learned RDF techniques and found much satisfaction by participating in hidden transmitter hunts. Other hams have discovered RDF through an interest in boating or aviation where radio direction finding is used for navigation and emergency location systems.

In many countries of the world, the hunting of hidden amateur transmitters takes on the atmosphere of a sport, as participants wearing jogging togs or track suits dash toward the area where they believe the transmitter is located. The sport is variously known as fox hunting, bunny hunting, ARDF (Amateur Radio direction finding) or simply transmitter hunting. In North America, most hunting of hidden transmitters is conducted from automobiles, although hunts on foot are gaining popularity.

There are less pleasant RDF applications as well, such as tracking down noise sources or illegal operators from unidentified stations. Jammers of repeaters, traffic nets and other amateur operations can be located with RDF equipment. Or sometimes a stolen amateur rig will be placed into operation by a person who is not familiar with Amateur Radio, and by being lured into making repeated transmissions, the operator unsuspectingly permits himself to be located with RDF equipment. The ability of certain RDF antennas to reject signals from selected directions has also been used to advantage in reducing noise and interference. Although not directly related to Amateur Radio, radio navigation is one application of RDF. The locating of downed aircraft is another, and one in which amateurs often lend their skills. Indeed, there are many useful applications for RDF.

Although sophisticated and complex equipment pushing the state of the art has been developed for use by governments and commercial enterprises, relatively simple equipment can be built at home to offer the radio amateur an opportunity to RDF. This chapter deals with antennas which are suited for that purpose.

RDF by Triangulation

It is impossible, using amateur techniques, to pinpoint the whereabouts of a transmitter from a single receiving location. With a directional antenna you can determine the direction of a signal source, but not how far away it is. To find the distance, you can then travel in the determined direction until you discover the transmitter location. However, that technique does not normally work very well.

A preferred technique is to take at least one additional direction measurement from a second receiving location. Then use a map of the area and plot the bearing or direction measurements as straight lines from points on the map representing the two locations. The approximate location of the transmitter will be indicated by the point where the two bearing lines cross. Even better results can be obtained by taking direction measurements from three locations and using the mapping technique just described. Because absolutely precise bearing measurements are difficult to obtain in practice, the three lines will almost always cross to form a triangle on the map, rather than at a single point. The transmitter will usually be located inside the area represented by the triangle. Additional information on the technique of triangulation may be found in recent editions of *The ARRL Handbook*.

DIRECTION FINDING SYSTEMS

Required for any RDF system are a directive antenna and a device for detecting the radio signal. In amateur applications the signal detector is usually a receiver; for convenience it will have a meter to indicate signal strength. Unmodified, commercially available portable or mobile receivers are generally quite satisfactory for signal detectors. At very close ranges a simple diode detector and dc microammeter may suffice for the detector.

On the other hand, antennas used for RDF techniques are not generally the types used for normal two-way communication. Directivity is a prime requirement, and here the word directivity takes on a somewhat different meaning than is commonly applied to antennas. Normally we associate directivity with gain, and we think of the ideal antenna pattern as one having a long, thin main lobe. Such a pattern may be of value for coarse measurements in RDF work, but precise bearing measurements are not possible. There is always a spread of a few (or perhaps many) degrees on the "nose" of the lobe, where a shift of antenna bearing produces no detectable change in signal strength. In RDF measurements, it is desirable to correlate an exact bearing or compass direction with the position of the antenna. In order to do this as accurately as possible, an antenna exhibiting a null in its pattern is used. A null can be very sharp in directivity, to within a half degree or less.

Loop Antennas

A simple antenna for RDF work is a small loop tuned to resonance with a capacitor. Several factors must be considered in the design of an RDF loop. The loop must be small compared with the wavelength. In a single-turn loop, the conductor should be less than 0.08 wavelength long. For 28 MHz, this represents a length of less than 34 inches (diameter of approximately 10 inches). Maximum response from the loop antenna is in the plane of the loop, with nulls exhibited at right angles to that plane.

To obtain the most accurate bearings, the loop must be balanced electrostatically with respect to ground. Otherwise, the loop will exhibit two modes of operation. One is the mode of a true loop, while the other is that of an essentially nondirectional vertical antenna of small dimensions. This second mode is called the "antenna effect." The voltages introduced by the two modes are seldom in phase and may add or subtract, depending upon the direction from which the wave is coming.

The theoretical true loop pattern is illustrated in **Fig 1A**. When properly balanced, the loop exhibits two nulls that are 180° apart. Thus, a single nullreading with a small loop antenna will not indicate the exact direction toward the transmitter—only the line along which the transmitter lies. Ways to overcome this ambiguity are discussed later.

When the antenna effect is appreciable and the loop is tuned to resonance, the loop may exhibit little directivity, as shown in Fig 1B. However, by detuning the loop so as to shift the phasing, a pattern similar to 1C may be obtained. Although this pattern is not symmetrical, it does exhibit a null. Even so, the null may not be as sharp as that obtained with a loop that is well balanced, and it may not be at exact right angles to the plane of the loop.

By suitable detuning, the unidirectional cardioid pattern of Fig 1D may be approached. This adjustment is sometimes used in RDF work to obtain a unidirectional bearing, although there is no complete null in the

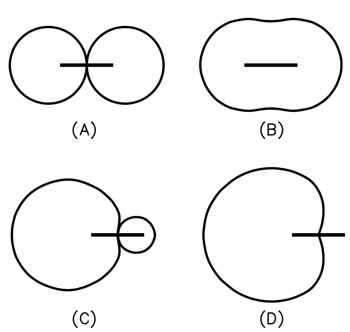

Fig 1—Small-loop field patterns with varying amounts of antenna effect—the undesired response of the loop acting merely as a mass of metal connected to the receiver antenna terminals. The heavy lines show the plane of the loop.

pattern. A cardioid pattern can also be obtained with a small loop antenna by adding a sensing element. Sensing elements are discussed in a later section of this chapter.

An electrostatic balance can be obtained by shielding the loop, as shown in **Fig 2**. The shield is represented by the broken lines in the drawing, and eliminates the antenna effect. The response of a well constructed shielded loop is quite close to the ideal pattern of Fig 1A.

For the low-frequency amateur bands, single-turn loops of convenient physical size for portability are generally found to be unsatisfactory for RDF work. Therefore, multiturn loops are generally used instead. Such a loop is shown in **Fig 3**. This loop may also be shielded, and if the total conductor length remains below 0.08 wavelength, the directional pattern is that of Fig 1A. A sensing element may also be used with a multiturn loop.

Loop Circuits and Criteria

No single word describes a direction-finding loop of high performance better than "symmetry." To obtain an undistorted response pattern from this type of antenna, it must be built in the most symmetrical manner possible. The next key word is "balance." The better the electrical balance, the deeper the loop null and the sharper the maxima.

The physical size of the loop for 7 MHz and below is not of major consequence. A 4-foot loop will exhibit the same electrical characteristics as one which is only an inch or two in diameter. The smaller the loop, however, the lower its efficiency. This is because its aperture samples a smaller section of the wave front. Thus, if loops that are very small in terms of a wavelength are used, preamplifiers are needed to compensate for the reduced efficiency.

An important point to keep in mind about a small loop antenna oriented in a vertical plane is that it is vertically polarized. It should be fed at the bottom for the best null response. Feeding it at one side, rather than at the bottom, will not alter the polarization and will only degrade performance. To obtain horizontal polarization from a small loop, it must be oriented in a horizontal plane, parallel to the earth. In this position the loop response is essentially omnidirectional.

The earliest loop antennas were of the "frame antenna" variety. These were unshielded antennas which were built on a wooden frame in a rectangular format. The loop conductor could be a single turn of wire (on the larger units) or several turns if the frame was small. Later, shielded versions of the frame antenna became popular, providing electrostatic shielding—an aid to noise reduction from such sources as precipitation static.

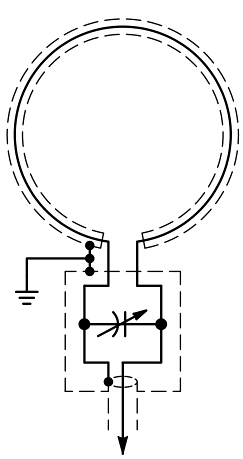

Fig 2—Shielded loop for direction finding. The ends of the shielding turn are not connected, to prevent shielding the loop from magnetic fields. The shield is effective against electric fields.

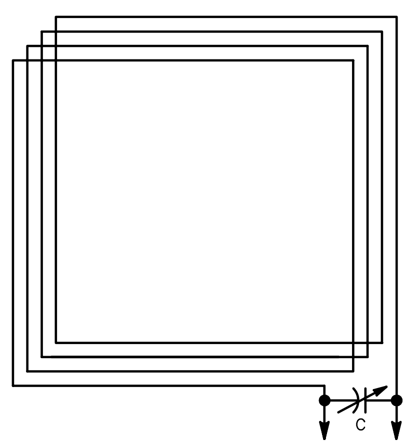

Fig 3—Small loop consisting of several turns of wire. The total conductor length is very much less than a wavelength. Maximum response is in the plane of the loop.

Ferrite Rod Antennas

With advances in technology, magnetic-core loop antennas later came into use. Their advantage was reduced size, and this appealed to the designers of aircraft and portable radios. Most of these antennas contain ferrite bars or cylinders, which provide high inductance and Q with a small number of coil turns.

Magnetic-core antennas consist essentially of many turns of wire around a ferrite rod. They are also known as loop-stick antennas. Probably the best-known example of this type of antenna is that used in small portable AM broadcast receivers. Because of their reduced-size advantage, ferrite-rod antennas are used almost exclusively for portable work at frequencies below 150 MHz.

As implied in the earlier discussion of shielded loops in this chapter, the true loop antenna responds to the magnetic field of the radio wave, and not to the electrical field. The voltage delivered by the loop is proportional to the amount of magnetic flux passing through the coil, and to the number of turns in the coil. The action is much the same as in the secondary winding of a transformer. For a given size of loop, the output voltage can be increased by increasing the flux density, and this is done with a ferrite core of high permeability. A $^1/_2$-inch diameter, 7-inch rod of Q2 ferrite ($\mu_i = 125$) is suitable for a loop core from the broadcast band through 10 MHz. For increased output, the turns may be wound on two rods that are taped together, as shown in **Fig 4**. Loopstick antennas for construction are described later in this chapter.

Maximum response of the loopstick antenna is broadside to the axis of the rod as shown in **Fig 5**, whereas maximum response of the ordinary loop is in a direction at right angles to the plane of the loop. Otherwise the performances of the ferrite-rod antenna and of the ordinary loop are similar. The loopstick may also be shielded to eliminate the antenna effect, such as with a U-shaped or C-shaped channel of aluminum or other form of "trough." The length of the shield should equal or slightly exceed the length of the rod.

Sensing Antennas

Because there are two nulls that are 180° apart in the directional pattern of a loop or a loopstick, an ambiguity exists as to which one indicates the true direction of the station being tracked. For example, assume you take a bearing measurement and the result indicates the transmitter is somewhere on a line running approximately east and west from your position. With this single reading, you have no way of knowing for sure if the transmitter is east of you or west of you.

If there is more than one receiving station taking bearings on a single transmitter, or if a single receiving station takes bearings from more than one position on the transmitter, the ambiguity may be worked out by triangulation, as described earlier. However, it is sometimes desirable to have a pattern

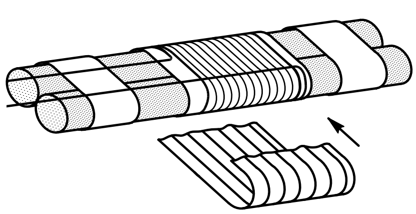

Fig 4—A ferrite-rod or loopstick antenna. Turns of wire may be wound on a single rod, or to increase the output from the loop, the core may be two rods taped together, as shown here. The type of core material must be selected for the intended frequency range of the loop. To avoid bulky windings, fine wire such as #28 or #30 is often used, with larger wire for the leads.

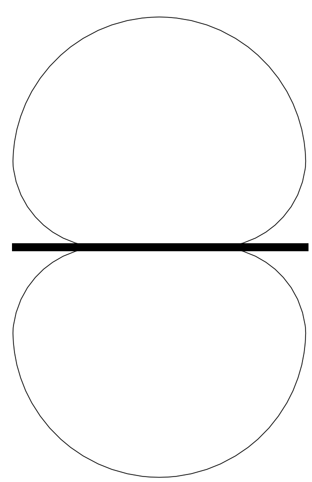

Fig 5—Field pattern for a ferrite rod antenna. The dark bar represents the rod on which the loop turns are wound.

with only one null, so there is no question about whether the transmitter in the above example would be east or west from your position.

A loop or loopstick antenna may be made to have a single null if a second antenna element is added. The element is called a sensing antenna, because it gives an added sense of direction to the loop pattern. The second element must be omnidirectional, such as a short vertical. When the signals from the loop and the vertical element are combined with a 90° phase shift between the two, a cardioid pattern results. The development of the pattern is shown in **Fig 6A**.

Fig 6B shows a circuit for adding a sensing antenna to a loop or loopstick. R1 is an internal adjustment and is used to set the level of the signal from the sensing antenna. For the best null in the composite pattern, the signals from the loop and the sensing antenna must be of equal amplitude, so R1 is adjusted experimentally during setup. In practice, the null of the cardioid is not as sharp as that of the loop, so the usual measurement procedure is to first use the loop alone to obtain a precise bearing reading, and then to add the sensing antenna and take another reading to resolve the ambiguity. (The null of the cardioid is 90° away from the nulls of the loop.) For this reason, provisions are usually made for switching the sensing element in and out of operation.

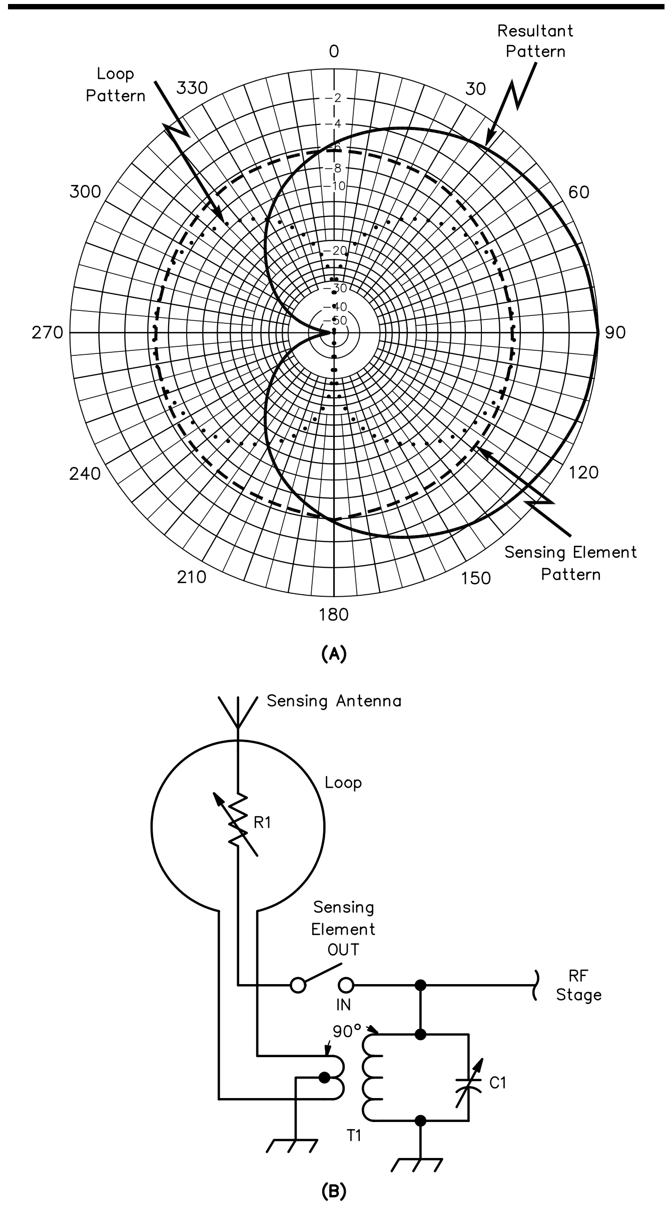

Fig 6—At A, the directivity pattern of a loop antenna with sensing element. At B is a circuit for combining the signals from the two elements. C1 is adjusted for resonance with T1 at the operating frequency.

PHASED ARRAYS

Phased arrays are also used in amateur RDF work. Two general classifications of phased arrays are end-fire and broadside configurations. Depending on the spacing and phasing of the elements, end-fire patterns may exhibit a null in one direction along the axis of the elements. At the same time, the response is maximum off the other end of the axis, in the opposite direction from the null. A familiar arrangement is two elements spaced 1/4 wavelength apart and fed 90° out of phase. The resultant pattern is a cardioid, with the null in the direction of the leading element. Other arrangements of spacing and phasing for an end-fire array are also suitable for RDF work. One of the best known is the Adcock array, discussed in the next section.

Broadside arrays are inherently bidirectional, which means there are always at least two nulls in the pattern. Ambiguity therefore exists in the true direction of the transmitter, but depending on the application, this may be no handicap. Broadside arrays are seldom used for amateur RDF applications.

The Adcock Antenna

Loops are adequate in RDF applications where only the ground wave is present. The performance of an RDF system for sky-wave reception can be improved by the use of an Adcock antenna, one of

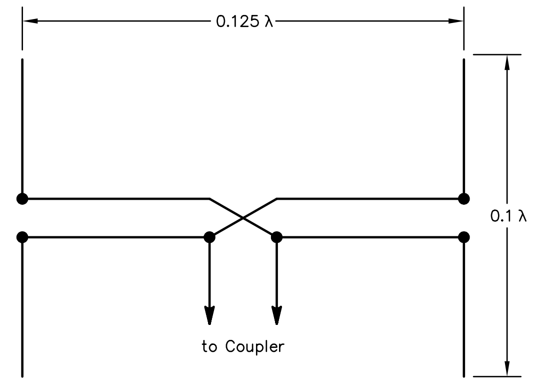

Fig 7—A simple Adcock antenna.

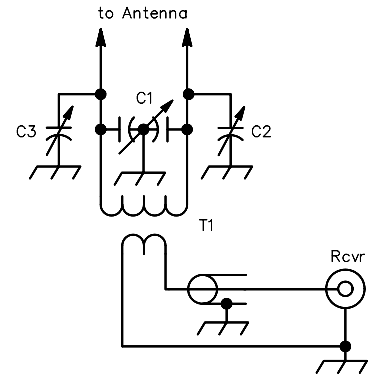

Fig 8—A suitable coupler for use with the Adcock antenna.

the most popular types of end-fire phased arrays. A basic version is shown in **Fig 7**.

This system was invented by F. Adcock and patented in 1919. The array consists of two vertical elements fed 180° apart, and mounted so the system may be rotated. Element spacing is not critical, and may be in the range from 1/10 to 3/4 wavelength. The two elements must be of identical lengths, but need not be self-resonant. Elements that are shorter than resonant are commonly used. Because neither the element spacing nor the length is critical in terms of wavelengths, an Adcock array may be operated over more than one amateur band.

The response of the Adcock array to vertically polarized waves is similar to a conventional loop, and the directive pattern is essentially the same. Response of the array to a horizontally polarized wave is considerably different from that of a loop, however. The currents induced in the horizontal members tend to balance out regardless of the orientation of the antenna. This effect has been verified in practice when good nulls were obtained with an experimental Adcock under sky-wave conditions. The same circumstances produced poor nulls with small loops (both conventional and ferrite-loop models). Generally speaking, the Adcock antenna has attractive properties for amateur RDF applications. Unfortunately, its portability leaves something to be desired, making it more suitable to fixed or semi-portable applications. While a metal support for the mast and boom could be used, wood, PVC or fiberglass are preferable because they are nonconductors and would therefore cause less pattern distortion.

Since the array is balanced, a coupler is required to match the unbalanced input of a typical receiver. **Fig 8** shows a suitable link-coupled network. C2 and C3 are null-clearing capacitors. A low-power signal source is placed some distance from the Adcock antenna and broadside to it. C2 and C3 are then adjusted until the deepest null is obtained. The coupler can be placed below the wiring-harness junction on the boom. Connection can be made by means of a short length of 300-Ω twin-lead.

The radiation pattern of the Adcock is shown in **Fig 9A**. The nulls are in directions broadside to the array, and become sharper with greater element spacings. However, with an element spacing greater

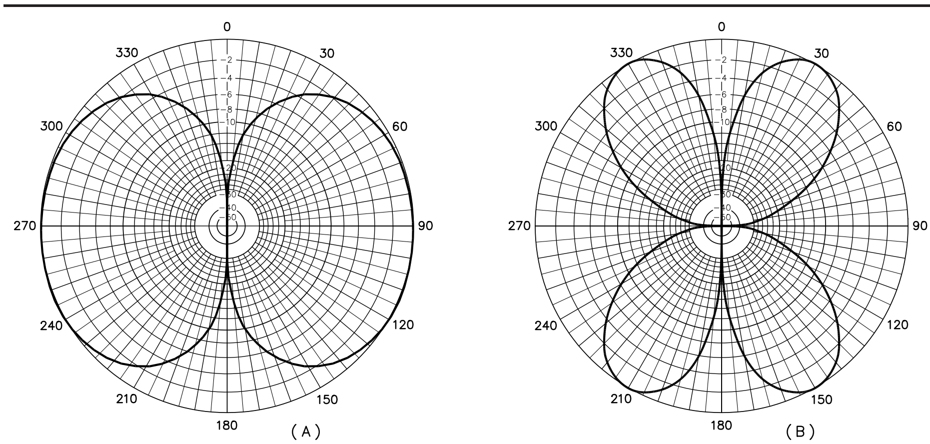

Fig 9—At A, the pattern of the Adcock array with an element spacing of 1/2 wavelength. In these plots the elements are aligned with the horizontal axis. As the element spacing is increased beyond 3/4 wavelength, additional nulls develop off the ends of the array, and at a spacing of 1 wavelength the pattern at B exists. This pattern is unsuitable for RDF work.

than 3/4 wavelength, the pattern begins to take on additional nulls in the directions off the ends of the array axis. At a spacing of 1 wavelength the pattern is that of Fig 9B, and the array is unsuitable for RDF applications.

Short vertical monopoles are often used in what is sometimes called the U-Adcock, so named because the elements with their feeders take on the shape of the letter U. In this arrangement the elements are worked against the earth as a ground or counterpoise. If the array is used only for reception, earth losses are of no great consequence. Short, elevated vertical dipoles are also used in what is sometimes called the H-Adcock.

The Adcock array, with two nulls in its pattern, has the same ambiguity as the loop and the loopstick. Adding a sensing element to the Adcock array has not met with great success. Difficulties arise from mutual coupling between the array elements and the sensing element, among other things. Because Adcock arrays are used primarily for fixed-station applications, the ambiguity presents no serious problem. The fixed station is usually one of a group of stations in an RDF network.

LOOPS VERSUS PHASED ARRAYS

Although loops can be made smaller than suitable phased arrays for the same frequency of operation, the phased arrays are preferred by some for a variety of reasons. In general, sharper nulls can be obtained with phased arrays, but this is also a function of the care used in constructing and feeding the individual antennas, as well as of the size of the phased array in terms of wavelengths. The primary constructional consideration is the shielding and balancing of the feed line against unwanted signal pickup, and the balancing of the antenna for a symmetrical pattern.

Loops are not as useful for skywave RDF work because of random polarization of the received signal. Phased arrays are somewhat less sensitive to propagation effects, probably because they are larger for the same frequency of operation and therefore offer some space diversity. In general, loops and loopsticks are used for mobile and portable operation, while phased arrays are used for fixed-station operation. However, phased arrays are used successfully above 144 MHz for portable and mobile RDF work. Practical examples of both types of antennas are presented later in this chapter.

THE GONIOMETER

Most fixed RDF stations for government and commercial work use antenna arrays of stationary elements, rather than mechanically rotatable arrays. This has been true since the earliest days of radio. The early-day device that permits finding directions without moving the elements is called a *radiogoniometer*, or simply a *goniometer*. Various types of goniometers are still used today in many installations, and offer the amateur many possibilities.

The early style of goniometer is a special form of RF transformer, as shown in **Fig 10**. It consists of two fixed coils mounted at right angles to one another. Inside the fixed coils is a movable coil, not shown in Fig 10 to avoid cluttering the diagram. The pairs of connections marked A and B are connected respectively to two elements in an array, and the output to the detector or receiver is taken from the movable coil. As the inner coil is rotated, the coupling to one fixed coil increases while that to the other decreases. Both the amplitude and the phase of the signal coupled into the pickup winding are altered with rotation in a way

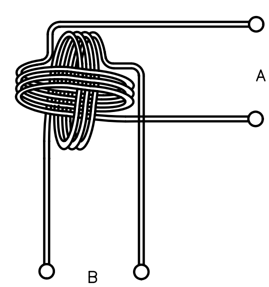

Fig 10—An early type of goniometer that is still used today in some RDF applications. This device is a special type of RF transformer that permits a movable coil in the center (not shown here) to be rotated and determine directions even though the elements are stationary.

that corresponds to actually rotating the array itself. Therefore, the rotation of the inner coil can be calibrated in degrees to correspond to bearing angles from the station location.

In the early days of radio, the type of goniometer just described saw frequent use with fixed Adcock arrays. A refinement of that system employed four Adcock elements, two arrays at right angles to each other. With a goniometer arrangement, RDF measurements could be taken in all compass directions, as opposed to none off the ends of a two-element fixed array. However, resolution of the four-element system was not as good as with a single pair of elements, probably because of mutual coupling among the elements. To overcome this difficulty a few systems of eight elements were installed.

Various other types of goniometers have been developed over the years, such as commutator switching to various elements in the array. A later development is the diode switching of capacitors to provide a commutator effect. As mechanical action has gradually been replaced with electronics to "rotate" stationary elements, the word *goniometer* is used less frequently these days. However, it still appears in many engineering reference texts. The more complex electronic systems of today are called beam-forming networks.

Electronic Antenna Rotation

With an array of many fixed elements, beam rotation can be performed electronically by sampling and combining signals from various individual elements in the array. Contingent upon the total number of elements in the system and their physical arrangement, almost any desired antenna pattern can be formed by summing the sampled signals in appropriate amplitude and phase relationships. Delay networks are used for some of the elements before the summation is performed. In addition, attenuators may be used for some elements to develop patterns such as from an array with binomial current distribution.

One system using these techniques is the *Wullenweber* antenna, employed primarily in government and military installations. The Wullenweber consists of a very large number of elements arranged in a circle, usually outside of (or in front of) a circular reflecting screen. Depending on the installation, the circle may be anywhere from a few hundred feet to more than a quarter of a mile in diameter. Although the Wullenweber is not one that would be constructed by an amateur, some of the techniques it uses may certainly be applied to Amateur Radio.

For the moment, consider just two elements of a Wullenweber antenna, shown as A and B in **Fig 11**. Also shown is the wavefront of a radio signal arriving from a distant transmitter. As drawn, the wavefront strikes element A first, and must travel somewhat farther before it strikes element B. There is a finite time delay before the wavefront reaches element B.

The propagation delay may be measured by delaying the signal received at element A before summing it with that from element B. If the two signals are combined directly, the amplitude of the resultant signal will be maximum when the delay for element A exactly equals the propagation delay. This results in an in-phase condition at the summation point. Or if one of the signals is inverted and the two are summed, a null will exist when the element-A delay equals the propagation delay; the signals will combine in a 180° out-of-phase relationship. Either way, once the time delay is known, it may be converted to distance. Then the direction from which the wave is arriving may be determined by trigonometry.

By altering the delay in small increments, the peak of the antenna lobe (or the null) can be steered in azimuth. This is true without regard to the frequency of the incoming wave. Thus, as long as the

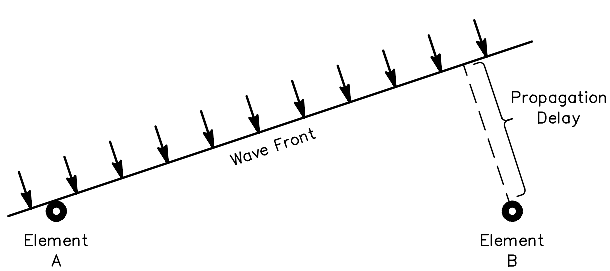

Fig 11—This diagram illustrates one technique used in electronic beam forming. By delaying the signal from element A by an amount equal to the propagation delay, the two signals may be summed precisely in phase, even though the signal is not in the broadside direction. Because this time delay is identical for all frequencies, the system is not frequency sensitive.

delay is less than the period of one RF cycle, the system is not frequency sensitive, other than for the frequency range that may be covered satisfactorily by the array elements themselves. Surface acoustic wave (SAW) devices or lumped-constant networks can be used for delay lines in such systems if the system is used only for receiving. Rolls of coaxial cable of various lengths are used in installations for transmitting. In this case, the lines are considered for the time delay they provide, rather than as simple phasing lines. The difference is that a phasing line is ordinarily designed for a single frequency (or for an amateur band), while a delay line offers essentially the same time delay at all frequencies.

By combining signals from other Wullenweber elements appropriately, the broad beamwidth of the pattern from the two elements can be narrowed, and unwanted sidelobes can be suppressed. Then, by electronically switching the delays and attenuations to the various elements, the beam so formed can be rotated around the compass. The package of electronics designed to do this, including delay lines and electronically switched attenuators, is the beam-forming network. However, the Wullenweber system is not restricted to forming a single beam. With an isolation amplifier provided for each element of the array, several beam-forming networks can be operated independently. Imagine having an antenna system that offers a dipole pattern, a rhombic pattern, and a Yagi beam pattern, all simultaneously and without frequency sensitivity. One or more may be rotating while another is held in a particular direction. The Wullenweber was designed to fulfill this type of requirement.

One feature of the Wullenweber antenna is that it can operate at 360° around the compass. In many government installations, there is no need for such coverage, as the areas of interest lie in an azimuth sector. In such cases an in-line array of elements with a backscreen or curtain reflector may be installed broadside to the center of the sector. By using the same techniques as the Wullenweber, the beams formed from this array may be slewed left and right across the sector. The maximum sector width available will depend on the installation, but beyond 70 to 80° the patterns begin to deteriorate to the point that they are unsatisfactory for precise RDF work.

USING RDF ANTENNAS FOR COMMUNICATIONS

Because of their directional characteristics, RDF antennas would seem to be useful for two-way communications. It has not been mentioned earlier that the efficiency of receiving loops is poor. The radiation resistance is very low, on the order of 1 Ω, and the resistance of wire conductors by comparison is significant. For this reason it is common to use some type of preamplifier with receiving loops. Small receiving loops can often be used to advantage in a fixed station, to null out either a noise source or unwanted signals.

A loop that is small in terms of a wavelength may also be used for transmitting, but a different construction technique is necessary. A thick conductor is needed at HF, an inch or more in diameter. The reason for this is to decrease the ohmic losses in the loop. Special methods are also required to couple power into a small loop, such as links or a gamma match. A small loop is highly inductive, and the inductance may be canceled by inserting a capacitor in series with the loop itself. The capacitor must be able to withstand the high RF currents that flow during transmissions. Construction information for a small transmitting loop is contained in Chapter 5.

On the other hand, the Adcock antenna and other phased arrays have been used extensively for transmitting. In this application maximum response is off the ends of the Adcock, which is 90° away from the null direction used for RDF work.

RDF SYSTEM CALIBRATION AND USE

Once an RDF system is initially assembled, it should be "calibrated" or checked out before actually being put into use. Of primary concern is the balance or symmetry of the antenna pattern. A lopsided figure-8 pattern with a loop, for example, is undesirable; the nulls are not 180° apart nor are they at exact right angles to the plane of the loop. If this fact was not known in actual RDF work, measurement accuracy would suffer.

Initial checkout can be performed with a low-powered transmitter at a distance of a few hundred feet. It should be within visual range and must be operating into a vertical antenna. (A quarter-wave vertical or a loaded whip is quite suitable.) The site must be reasonably clear of obstructions, especially steel and concrete or brick buildings, large metal objects, nearby power lines, and so on. If the system operates above 30 MHz, trees and large bushes should also be avoided. An open field makes an excellent site.

The procedure is to "find" the transmitter with the RDF equipment as if its position were not known, and compare the RDF null indication with the visual path to the transmitter. For antennas having more than one null, each null should be checked.

If imbalance is found in the antenna system, there are two options available. One is to correct the imbalance. Toward this end, pay particular attention to the feed line. Using a coaxial feeder for a balanced antenna invites an asymmetrical pattern, unless an effective balun is used. A balun is not necessary if the loop is shielded, but an asymmetrical pattern can result with misplacement of the break in the shield itself. The builder may also find that the presence of a sensing antenna upsets the balance slightly. Experimenting with its position with respect to the main antenna may lead to correcting the error. You will also note that the position of the null shifts by 90° as the sensing element is switched in and out, and the null is not as deep. This is of little concern, however, as the intent of the sensing antenna is only to resolve ambiguities. The sensing element should be switched out when accuracy is desired.

The second option is to accept the imbalance of the antenna and use some kind of indicator to show the true directions of the nulls. Small pointers, painted marks on the mast, or an optical sighting system might be used. Sometimes the end result of the calibration procedure will be a compromise between these two options, as a perfect electrical balance may be difficult or impossible to attain.

The discussion above is oriented toward calibrating portable RDF systems. The same general suggestions apply if the RDF array is fixed, such as an Adcock. However, it won't be possible to move it to an open field. Instead, the array is calibrated in its intended operating position through the use of a portable or mobile transmitter. Because of nearby obstructions or reflecting objects, the null in the pattern may not appear to indicate the precise direction of the transmitter. Do not confuse this with imbalance in the RDF array. Check for imbalance by rotating the array 180° and comparing readings.

Once the balance is satisfactory, you should make a table of bearing errors noted in different compass directions. These error values should be applied as corrections when actual measurements are made. The mobile or portable transmitter should be at a distance of two or three miles for these measurements, and should be in as clear an area as possible during transmissions. The idea is to avoid conduction of the signal along power lines and other overhead wiring from the transmitter to the RDF site. Of course the position of the transmitter must be known accurately for each transmission.

FRAME LOOPS

It was mentioned earlier that the earliest style of receiving loops was the frame antenna. If carefully constructed, such an antenna performs well and can be built at low cost. **Fig 12** illustrates the details of a practical frame type of loop antenna. This antenna was designed by Doug DeMaw, W1FB, and described in *QST* for July 1977. (See

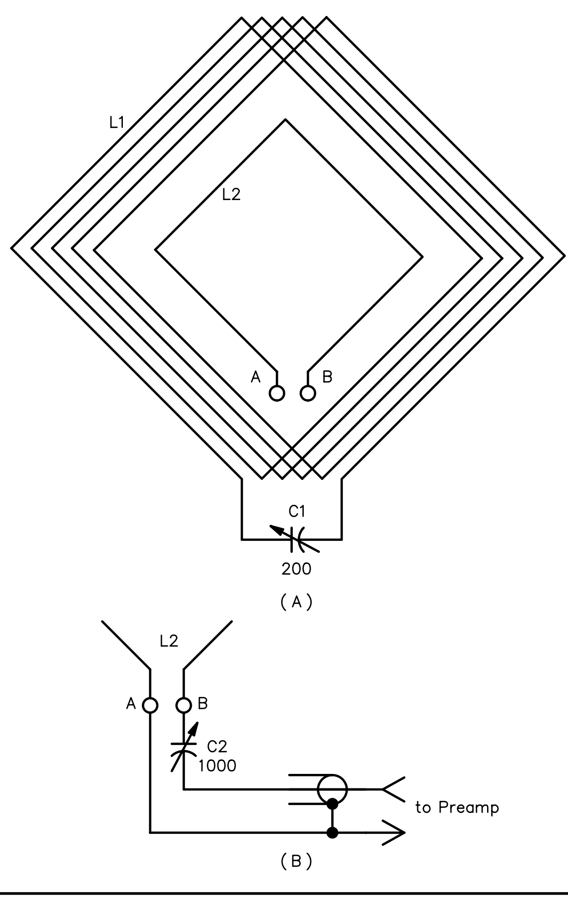

Fig 12—A multiturn frame antenna is shown at A. L2 is the coupling loop. The drawing at B shows how L2 is connected to a preamplifier.

the Bibliography at the end of this chapter.) The circuit at A is a five-turn system which is tuned to resonance by C1. If the layout is symmetrical, good balance should be obtainable. L2 helps to achieve this objective by eliminating the need for direct coupling to the feed terminals of L1. If the loop feed was attached in parallel with C1, which is common practice, the chance for imbalance would be considerable.

L2 can be situated just inside or slightly outside of L1; a 1-inch separation works nicely. The receiver or preamplifier can be connected to terminals A and B of L2, as shown at B of Fig 12. C2 controls the amount of coupling between the loop and the preamplifier. The lighter the coupling, the higher is the loop Q, the narrower is the frequency response, and the greater is the gain requirement from the preamplifier. It should be noted that no attempt is being made to match the loop impedance to the preamplifier. The characteristic impedance of small loops is very low—on the order of 1 Ω or less.

A supporting frame for the loop of Fig 12 can be constructed of wood, as shown in **Fig 13**. The dimensions given are for a 1.8-MHz frame antenna. For use on 75 or 40 meters, L1 of Fig 12A will require fewer turns, or the size of the wooden frame should be made somewhat smaller than that of Fig 13.

SHIELDED FRAME LOOPS

If electrostatic shielding is desired, the format shown in **Fig 14** can be adopted. In this example, the loop conductor and the single-turn coupling loop are made from RG-58 coaxial cable. The number of loop turns should be sufficient to resonate with the tuning capacitor at the operating frequency. Antenna resonance can be checked by first connecting C1 (Fig 12A) and setting it at midrange. Then connect a small three-turn coil to the loop feed terminals, and couple to it with a dip meter remember that the pickup coil will act to lower the frequency slightly from actual resonance.

In the antenna photographed for Fig 14, the one-turn coupling loop was made of #22 plastic-insulated wire. However, electrostatic noise pickup occurs on such a coupling loop, noise of the same nature that the shield on the main loop prevents. This can be avoided by using RG-58 for the coupling loop. The shield of the coupling

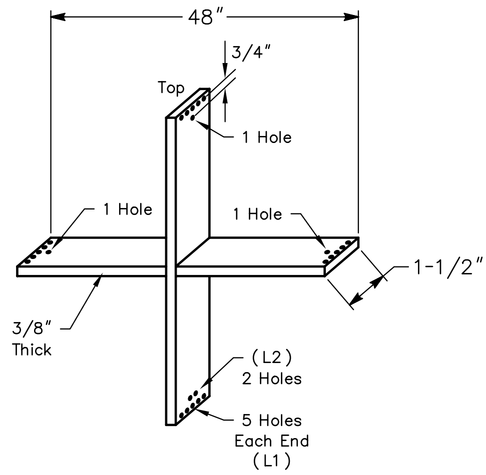

Fig 13—A wooden frame can be used to contain the wire of the loop shown in Fig 12.

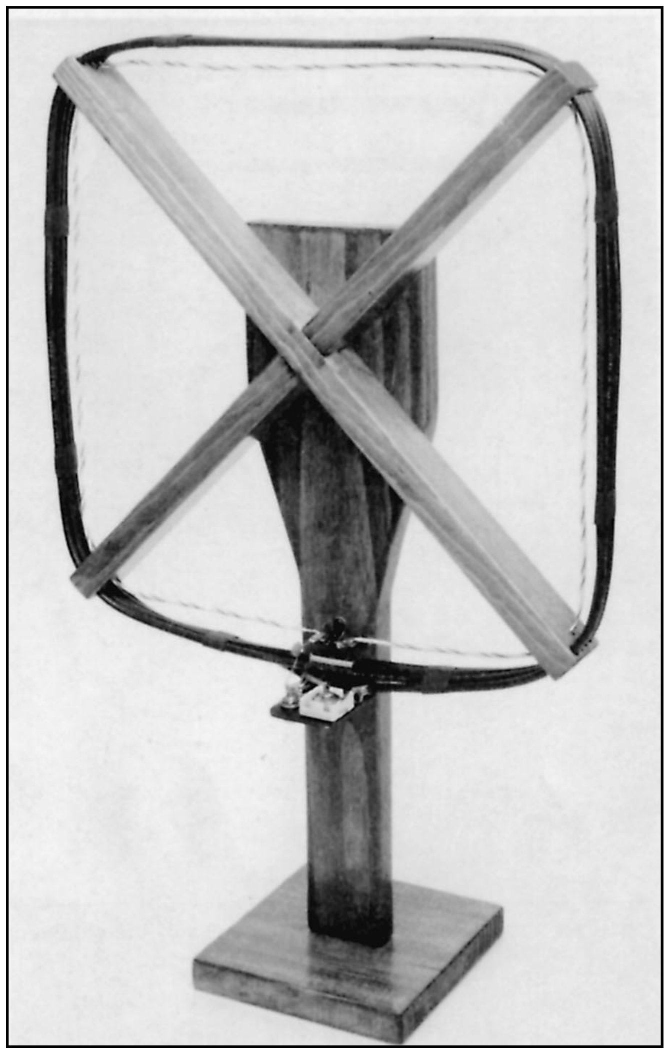

Fig 14—An assembled table-top version of the electrostatically shielded loop. RG-58 cable is used in its construction.

loop should be opened for about one inch at the top, and each end of the shield grounded to the shield of the main loop.

Larger single-turn frame loops can be fashioned from aluminum-jacketed Hardline, if that style of coax is available. In either case, the shield conductor must be opened at the electrical center of the loop, as shown in **Fig 15** at A and B. The design example is based on 1.8-MHz operation.

In order to realize the best performance from an electrostatically shielded loop antenna, it must be operated near to and directly above an effective ground plane. An automobile roof (metal) qualifies nicely for small shielded loops. For fixed-station use, a chicken-wire ground screen can be placed below the antenna at a distance of 1 to 6 feet.

FERRITE-CORE LOOPS

Fig 16 contains a diagram for a rod loop (loopstick antenna). This antenna was also designed by Doug DeMaw, W1FB, and described in *QST* for July 1977. The winding (L1) has the appropriate number of turns to permit resonance with C1 at the operating frequency. L1 should be spread over approximately 1/3 of the core center. Litz wire will yield the best Q, but Formvar magnet wire can be used if desired. A layer of 3M Company glass tape (or Mylar tape) is recommended as a covering for the core before adding the wire. Masking tape can be used if nothing else is available.

L2 functions as a coupling link over the exact center of L1. C1 is a dual-section variable capacitor, although a differential capacitor might be better toward obtaining optimum balance (not tried). The loop Q is controlled by means of C2, which is a mica compression trimmer.

Electrostatic shielding of rod loops can be effected by centering the rod in a U-shaped aluminum, brass or copper channel which extends slightly beyond the ends of the rod loop (1 inch is suitable). The open side (top) of the channel can't be closed, as that would constitute a shorted-turn condition and render the antenna useless. This can be proved by shorting across the center of the channel with a screwdriver blade when the loop is tuned to an incoming signal. The shield-braid gap in the coaxial loop of Fig 15 is maintained for the same reason.

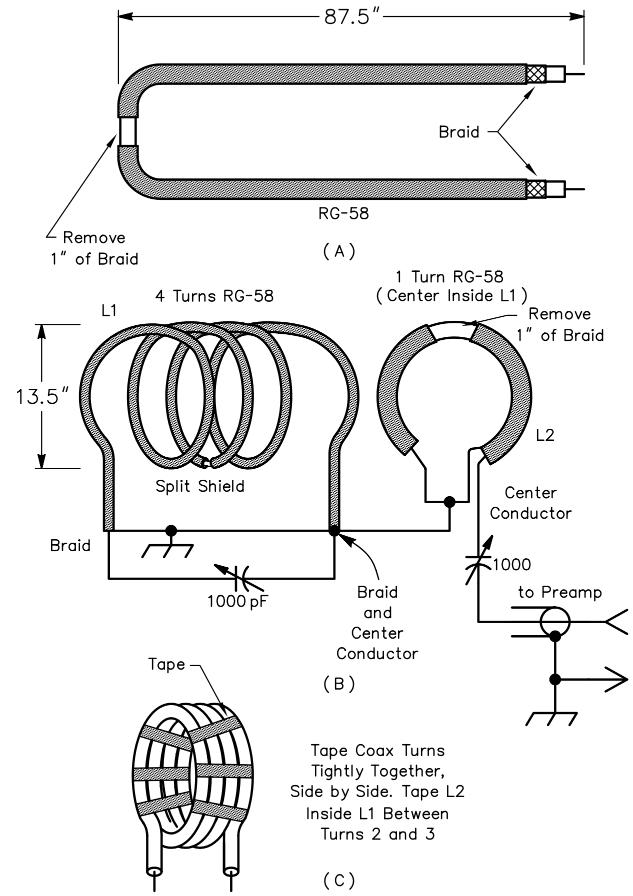

Fig 15—Components and assembly details of the shielded loop shown in Fig 14.

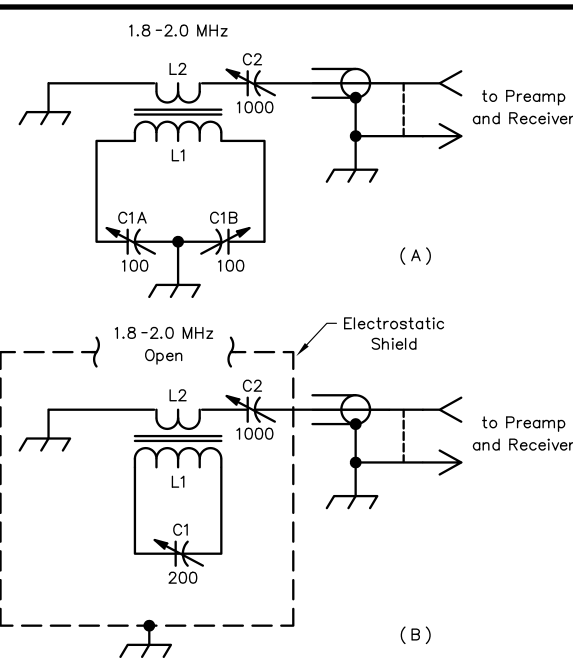

Fig 16—At A, the diagram of a ferrite loop. C1 is a dual-section air-variable capacitor. The circuit at B shows a rod loop contained in an electrostatic shield channel (see text). A suitable low-noise preamplifier is shown in Fig 19.

Fig 17 shows the shielded rod loop assembly. This antenna was developed experimentally for 160 meters and uses two 7-inch ferrite rods which were glued end-to-end with epoxy cement. The longer core resulted in improved sensitivity during weak-signal reception. The other items in the photograph were used during the evaluation tests and are not pertinent to this discussion. This loop and the frame loop discussed in the previous section have bidirectional nulls, as shown in Fig 1A.

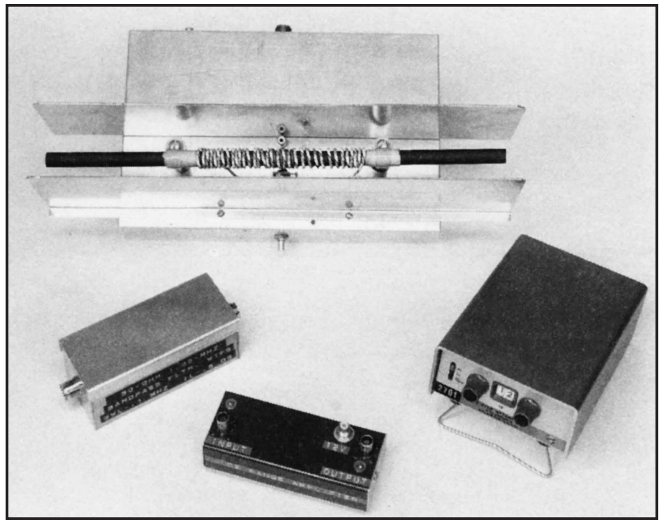

Fig 17—The assembly at the top of the picture is a shielded ferrite-rod loop for 160 meters. Two rods have been glued end to end (see text). The other units in the picture are a low-pass filter (lower left), broadband preamplifier (lower center) and a Tektronix step attenuator (lower right). These were part of the test setup used when the antenna was evaluated.

Obtaining a Cardioid Pattern

Although the bidirectional pattern of loop antennas can be used effectively in tracking down signal sources by means of triangulation, an essentially unidirectional loop response will help to reduce the time spent when on a "hunting" trip. Adding a sensing antenna to the loop is simple to do, and it will provide the desired cardioid response. The theoretical pattern for this combination is shown in Fig 1D.

Fig 18 shows how a sensing element can be added to a loop or loopstick antenna. The link from the loop is connected via coaxial cable to the primary of T1, which is a tuned toroidal transformer with a split secondary winding. C3 is adjusted for peak signal response at the frequency of interest (as is C4), then R1 is adjusted for minimum back response of the loop. It will be necessary to readjust C3 and R1 several times to compensate for the interaction of these controls. The adjustments are repeated

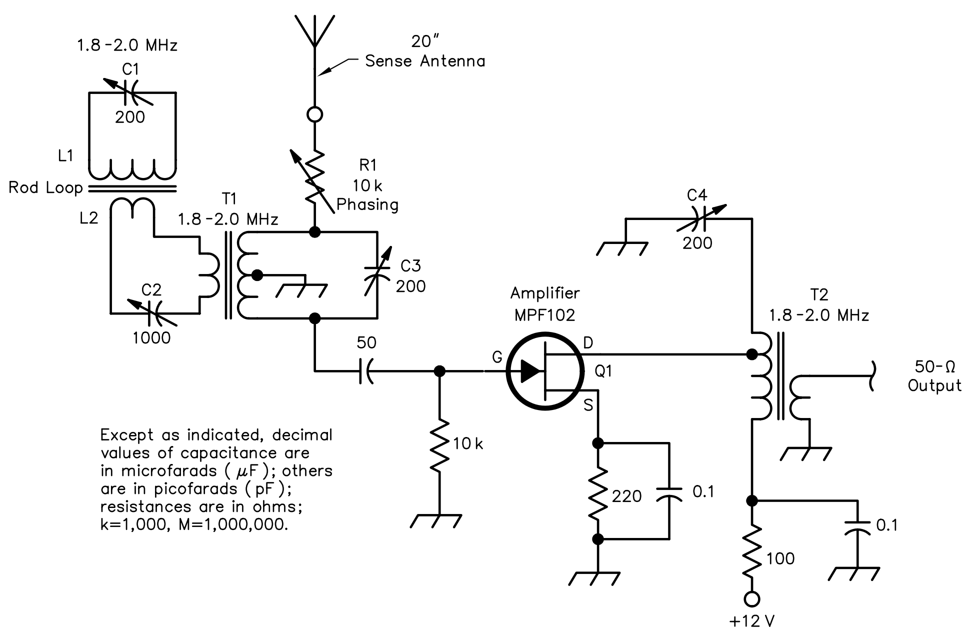

Fig 18—Schematic diagram of a rod-loop antenna with a cardioid response. The sensing antenna, phasing network and a preamplifier are shown also. The secondary of T1 and the primary of T2 are tuned to resonance at the operating frequency of the loop. T-68-2 to T-68-6 Amidon toroid cores are suitable for both transformers. Amidon also sells ferrite rods for this type of antenna.

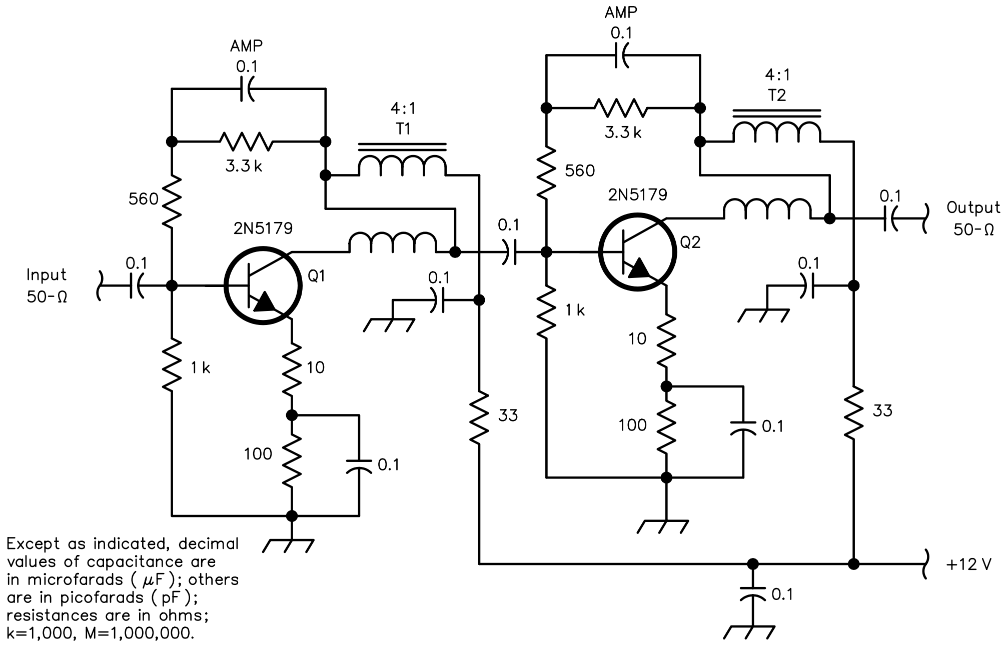

Fig 19—Schematic diagram of a two-stage broadband amplifier patterned after a design by Wes Hayward, W7ZOI. T1 and T2 have a 4:1 impedance ratio and are wound on FT-50-61 toroid cores (Amidon) which have a μ_i of 125. They contain 12 turns of #24 enam wire, bifilar wound. The capacitors are disc ceramic. This amplifier should be built on double-sided circuit board for best stability.

until no further null depth can be obtained. Tests at ARRL HQ showed that null depths as great as 40 dB could be obtained with the circuit of Fig 18 on 75 meters. A near-field weak-signal source was used during the tests.

The greater the null depth, the lower the signal output from the system, so plan to include a preamplifier with 25 to 40 dB of gain. Q1, as shown in Fig 18, will deliver approximately 15 dB of gain. The circuit of **Fig 19** can be used following T2 to obtain an additional 24 dB of gain. In the interest of maintaining a good noise figure, even at 1.8 MHz, Q1 should be a low-noise device. The sensing antenna can be mounted 6 to 15 inches from the loop. The vertical whip need not be more than 12 to 20 inches long. Some experimenting may be necessary in order to obtain the best results. Optimization will also change with the operating frequency of the antenna.

A SHIELDED LOOP WITH SENSING ANTENNA FOR 28 MHz

Fig 20 shows the construction and mounting of a simple shielded 10-meter loop. The loop was designed by Loren Norberg, W9PYG, and described in *QST* for April 1954. (See the Bibliography at the end of this chapter.) It is made from an 18-inch length of RG-11 coax (solid or foam dielectric) secured to an aluminum box of any convenient size, with two coaxial cable hoods (Amphenol 83-1HP). The outer shield must be broken at the exact center. C1 is a 25-pF variable

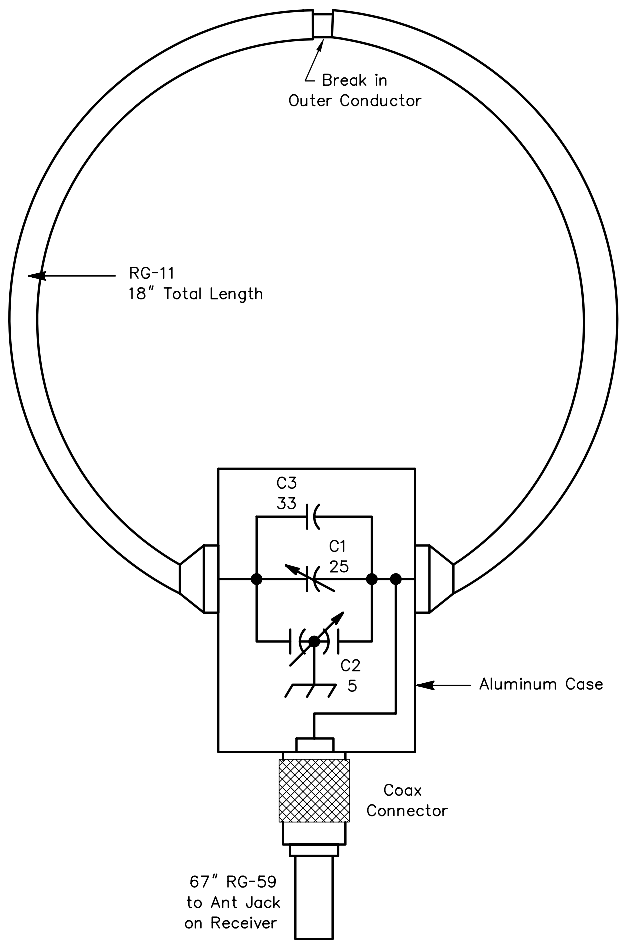

Fig 20—Sketch showing the constructional details of the 28-MHz RDF loop. The outer braid of the coax loop is broken at the center of the loop. The gap is covered with waterproof tape, and the entire assembly is given a coat of acrylic spray.

capacitor, and is connected in parallel with a 33-pF mica padder capacitor, C3. C1 must be tuned to the desired frequency while the loop is connected to the receiver in the same way as it will be used for RDF. C2 is a small differential capacitor used to provide electrical symmetry. The lead-in to the receiver is 67 inches of RG-59 cable (82 inches if the cable has foamed dielectric).

The loop can be mounted on the roof of the car with a rubber suction cup. The builder might also fabricate some kind of bracket assembly to mount the loop temporarily in the window opening of the automobile, allowing for loop rotation. Reasonably true bearings may be obtained through the windshield when the car is pointed in the direction of the hidden transmitter. More accurate bearings may be obtained with the loop held out the window and the signal coming toward that side of the car.

Sometimes the car broadcast antenna may interfere with accurate bearings. Disconnecting the antenna from the broadcast receiver may eliminate this trouble.

Sensing Antenna

A sensing antenna can be added to Norberg's loop to check on which of the two directions indicated by the loop is the correct one. Add a phono jack to the top of the aluminum case shown in Fig 20. The insulated center terminal of the jack should be connected to the side of the tuning capacitors that is common to the center conductor of the RG-59 coax feed line. The jack then takes a short vertical antenna rod of a diameter to fit the jack, or a piece of #12 or #14 solid wire may be soldered to the center pin of a phono plug for insertion in the jack. The sensing antenna can be plugged in as needed. Starting with a length of about four times the loop diameter, the length of the sensing antenna should be pruned until the pattern is similar to that of Fig 1D.

THE SNOOP LOOP—FOR CLOSE-RANGE RDF

Picture yourself on a hunt for a hidden 28-MHz transmitter. The night is dark, very dark. After you take off at the start of the hunt, heading in the right direction, the signal gets stronger and stronger. Your excitement increases with each additional S unit on the meter. You follow your loop closely, and it is working perfectly. You're getting out of town and into the countryside. The roads are unfamiliar. Now the null is beginning to swing rather rapidly, showing that you are getting close.

Suddenly the null shifts to give a direction at right angles to the car. With your flashlight you look carefully across the deep ditch beside the road and into the dark field where you know the transmitter is hidden. There are no roads into the field as far as you can see in either direction. You dare not waste miles driving up and down the road looking for an entrance, for each tenth of a mile counts. But what to do—your radio equipment is mobile, and requires power from the car battery.

In a brief moment your decision is made. You park beside the road, take your flashlight, and plunge into the veldt in the direction your loop null clearly indicated. But after taking a few steps, you're up to your armpits in brush and can't see anything forward or backward. You stumble on in hopes of running into the hidden transmitter—you're probably not more than a few hundred feet from it. But away from your car and radio equipment, it's like the proverbial hunt for the needle in the haystack. What you really need is a portable setup for hunting at close range, and you may prefer something that is inexpensive. The Snoop Loop was designed for just these requirements by Claude Maer, Jr, WØIC, and was described in *QST* for February 1957. (See the Bibliography at the end of this chapter.)

The Snoop Loop is pictured in **Fig 21**. The loop itself is made from a length of RG-8 coax, with the shield broken at the top. A coax T connector is used for convenience and ease of mounting. One end of the coax loop is connected to a

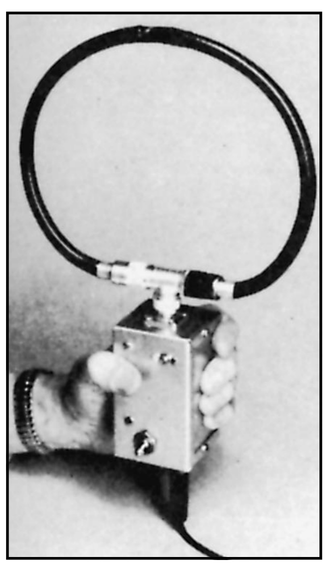

Fig 21—The box containing the detector and amplifier is also the "handle" for the Snoop Loop. The loop is mounted with a coax T as a support, a convenience but not an essential part of the loop assembly. The loop tuning capacitor is screwdriver adjusted. The on-off switch and the meter sensitivity control may be mounted on the bottom.

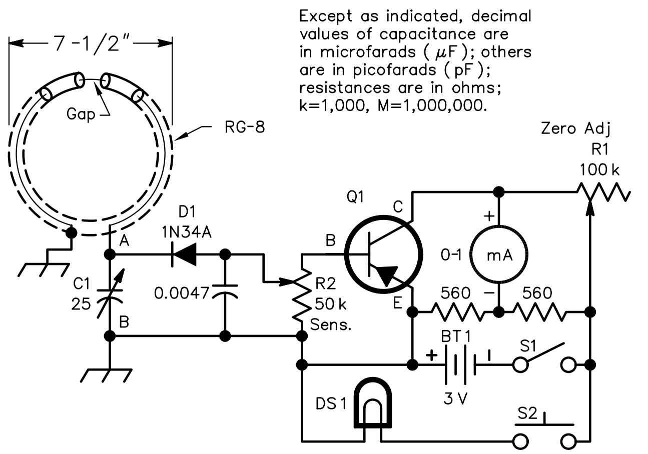

Fig 22—The Snoop Loop circuit for 28-MHz operation. The loop is a single turn of RG-8 inner conductor, the outer conductor being used as a shield. Note the gap in the shielding; about a 1-inch section of the outer conductor should be cut out. Refer to Fig 23 for alternative connection at points A and B for other frequencies of operation.

BT1—Two penlight cells.
C1—25-pF midget air padder.
D1—Small-signal germanium diode such as 1N34A or equiv.
DS1—Optional 2-cell penlight lamp for meter illumination, such as no. 222.
Q1—PNP transistor such as ECG102 or equiv.
R1—100-kΩ potentiometer, linear taper. May be PC-mount style.
R2—50-kΩ potentiometer, linear taper.
S1—SPST toggle.
S2—Optional momentary push for illuminating meter.

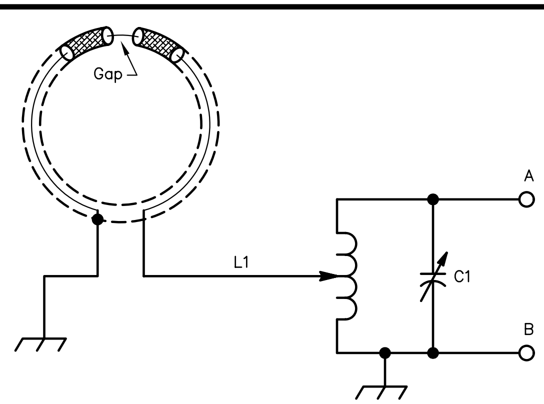

Fig 23—Input circuit for lower frequency bands. Points A and B are connected to corresponding points in the circuit of Fig 22, substituting for the loop and C1 in that circuit. L1-C1 should resonate within the desired amateur band, but the L/C ratio is not critical. After construction is completed, adjust the position of the tap on L1 for maximum signal strength. Instead of connecting the RDF loop directly to the tap on L1, a length of low impedance line may be used between the loop and the tuned circuit, L1-C1.

male plug in the conventional way, but the center conductor of the other end is shorted to the shield so the male connector at that end has no connection to the center prong. This results in an unbalanced circuit, but seems to give good bidirectional null readings as well as an easily detectable maximum reading when the grounded end of the loop is pointed in the direction of the transmitter. Careful tuning with C1 will improve this maximum reading. Don't forget to remove one inch of shielding from the top of the loop. You won't get much signal unless you do.

The detector and amplifier circuit for the Snoop Loop is shown in **Fig 22**. The model photographed does not include the meter, as it was built for use only with high-impedance headphones. The components are housed in an aluminum box. Almost any size box of sufficient size to contain the meter can be used. At very close ranges, reduction of sensitivity with R2 will prevent pegging the meter.

The Snoop Loop is not limited to the 10-meter band or to a built-in loop. **Fig 23** shows an alternative circuit for other bands and for plugging in a separate loop connected by a low-impedance transmission line. Select coil and capacitor combinations that will tune to the desired frequencies. Plug-in coils could be used. It is a good idea to have the RF end of the unit fairly well shielded, to eliminate signal pickup except through the loop. This little unit should certainly help you on those dark nights in the country. (Tip to the hidden-transmitter operator—if you want to foul up some of your pals using these loops, just hide near the antenna of a 50-kW broadcast transmitter.)

A LOOPSTICK FOR 3.5 MHz

Figs 24 through **26** show an RDF loop suitable for the 3.5-MHz band. It uses a construction

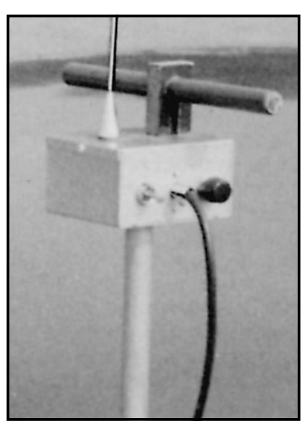

Fig 24—Unidirectional 3.5-MHz RDF using ferrite-core loop with sensing antenna. Adjustable components of the circuit are mounted in the aluminum chassis supported by a short length of tubing.

technique that has had considerable application in low-frequency marine direction finders. The loop is a coil wound on a ferrite rod from a broadcast-antenna loopstick. The loop was designed by John Isaacs, W6PZV, and described in *QST* for June 1958. Because it is possible to make a coil of high Q with the ferrite core, the sensitivity of such a loop is comparable to a conventional loop that is a foot or so in diameter. The output of the vertical-rod sensing antenna, when properly combined with that of the loop, gives the system the cardioid pattern shown in Fig 1D.

To make the loop, remove the original winding on the ferrite core and wind a new coil as shown in Fig 25. Other types of cores than the one specified may be substituted; use the largest coil available and adjust the winding so that the circuit resonates in the 3.5-MHz band within the range of C1. The tuning range of the loop may be checked with a dip meter.

The sensing system consists of a 15-inch whip and an adjustable inductance that will resonate the whip as a quarter-wave antenna. It also contains a potentiometer to control the output of the antenna. S1 is used to switch the sensing antenna in and out of the circuit.

The whip, the loopstick, the inductance, L1, the capacitor, C1, the potentiometer, R1, and the switch, S1, are all mounted on a 4×5×3-inch box chassis as shown in Fig 26. The loopstick may be mounted and protected inside a piece of $^1/_2$-inch PVC pipe. A section of $^1/_2$-inch electrical conduit is attached to the bottom of the chassis box and this supports the instrument.

To produce an output having only one null there must be a 90° phase difference between the outputs of the loop and sensing antennas, and the signal strength from each must be the same. The phase shift is obtained by tuning the sensing antenna slightly off frequency by means of the slug in L1. Since the sensitivity of the whip antenna is greater than that of the loop, its output is reduced by adjusting R1.

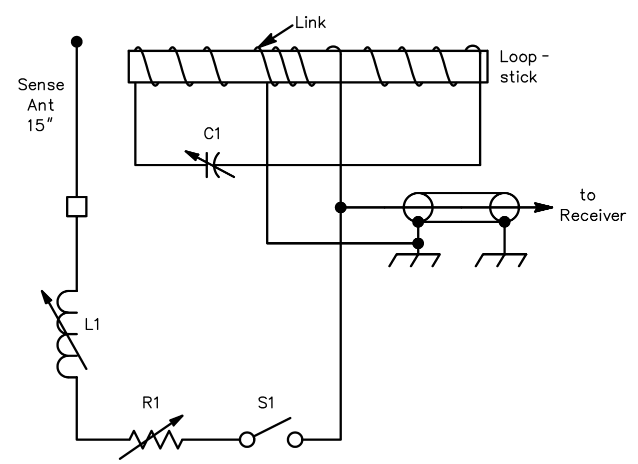

Fig 25—Circuit of the 3.5-MHz direction finder.

C1—140 pF variable (125-pF ceramic trimmer in parallel with 15-pF ceramic fixed.

L1—Approx. 140 μH adjustable (Miller No. 4512 or equivalent).

R1—1-kΩ carbon potentiometer.

S1—SPST toggle.

Loopstick—App. 15 μH (Miller 705-A, with original winding removed and wound with 20 turns of #22 enam.) Link is two turns at center. Winding ends secured with Scotch electrical tape.

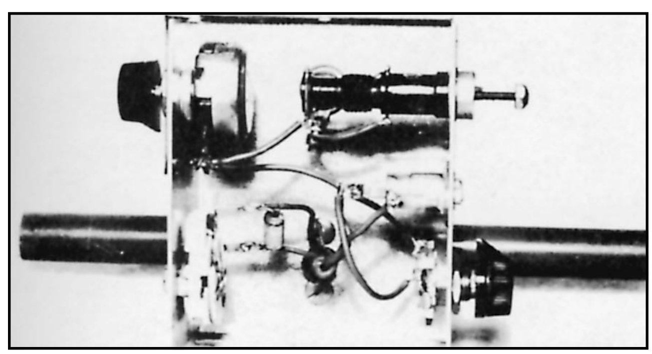

Fig 26—Components of the 3.5-MHz RDF are mounted on the top and sides of a Channel-lock type box. In this view R1 is on the left wall at the upper left and C1 is at the lower left. L1, S1 and the output connector are on the right wall. The loopstick and whip mount on the outside.

Adjustment

To adjust the system, enlist the aid of a friend with a mobile transmitter and find a clear spot where the transmitter and RDF receiver can be separated by several hundred feet. Use as little power as possible at the transmitter. (Remove your own transmitter antenna before trying to make any loop adjustments and remember to leave it off during transmitter hunts.) With the test transmitter operating on the proper frequency, disconnect the sensing antenna with S1, and peak the loopstick using C1, while watching the S meter on the receiver. Once the loopstick is peaked, no further adjustment of C1 will be necessary. Next, connect the sensing antenna and turn R1 to minimum resistance. Then vary the adjustable slug of L1 until a maximum reading of the S meter is again obtained. It may be necessary to turn the unit a bit during this adjustment to obtain a larger reading than with the loopstick alone. The last turn of the slug is quite critical, and some hand-capacitance effect may be noted.

Now turn the instrument so that one side (not an end) of the loopstick is pointed toward the test transmitter. Turn R1 a complete revolution and if the proper side was chosen a definite null should be observed on the S meter for one particular position of R1. If not, turn the RDF 180° and try again. This time leave R1 at the setting which produces the minimum reading. Now adjust L1 very slowly until the S meter reading is reduced still further. Repeat this several times, first R1, and then L1, until the best minimum is obtained.

Finally, as a check, have the test transmitter move around the RDF and follow it by turning the RDF. If the tuning has been done properly the null will always be broadside to the loopstick. Make a note of the proper side of the RDF for the null, and the job is finished.

A 144-MHz ANTENNA FOR RDF

Although there may be any number of different antennas that will produce a cardioid pattern, the simplest design is depicted in **Fig 27**. Two $^1/_4$-wavelength vertical elements are spaced one $^1/_4$-wavelength apart and are fed 90° out of phase. Each radiator is shown with two radials approximately 5% shorter than the radiators. This array was designed by Pete O'Dell, KB1N, and described in *QST* for March 1981.

During the design phase of this project a personal computer was used to predict the impact on the antenna pattern of slight alterations in its size, spacing and phasing of the elements. The results suggest that this system is a little touchy and that the most significant change comes at the null. Very slight alterations in the dimensions caused the notch to become much more shallow and, hence, less usable for RDF. Early experience in building a working model bore this out.

This means that if you build this antenna, you will find it advantageous to spend a few minutes to tune it carefully for the deepest null. If it is built using the techniques presented here, then this should prove to be a small task which is well worth the extra effort. Tuning is accomplished by adjusting the length of the vertical radiators, the spacing between them and, if necessary, the lengths of the phasing harness that connects them. Tune for the deepest null on your S meter when using a signal source such as a moderately strong repeater. This should be done outside, away from buildings and large metal objects. Initial indoor tuning on this project was tried in the kitchen, which revealed that reflections off the appliances were producing spurious readings. Beware too of distant water towers, radio towers, and large office or apartment buildings. They can reflect the signal and give false indications.

Construction is simple and straightforward. Fig 27B shows a female BNC connector (Radio Shack 278-105) that has been mounted on a small piece of PC-board material. The BNC connector is held "upside down," and the vertical radiator is soldered to the center solder lug. A 12-inch piece of brass tubing provides a snug fit over the solder lug. A second piece of tubing, slightly smaller in diameter, is telescoped inside the first. The outer tubing is crimped slightly at the top after the inner tubing is installed. This provides positive contact between the two tubes. For 146 MHz the length of the radiators is calculated to be about 19 inches. You should be able to find small brass tubing at a hobby store. If none is available in your area, consider brazing rods. These are often available in hardware sections of discount stores. It will probably be necessary to solder a short piece to the top since these come in 18-inch sections. Also, tuning will not be quite as convenient. Two 18-inch radials are added to each element by soldering them to the board. Two 36-inch pieces of heavy brazing rod were used in this project.

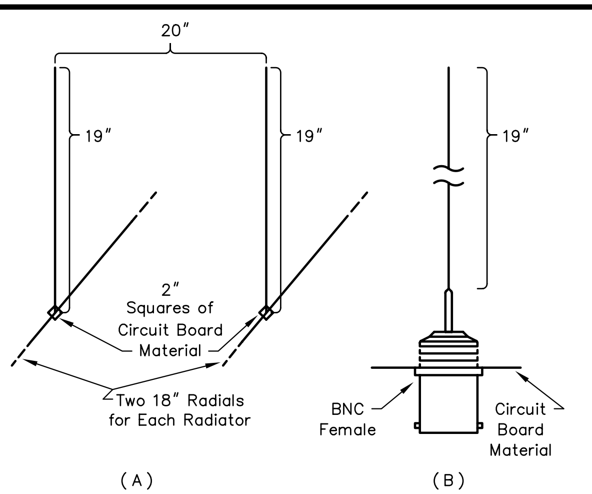

Fig 27—At A is a simple configuration that can produce a cardioid pattern. At B is a convenient way of fabricating a sturdy mount for the radiator using BNC connectors.

The Phasing Harness

As shown in **Fig 28**, a T connector is used with two different lengths of coaxial line to form the phasing harness. This method of feeding the antenna is superior over other simple systems toward obtaining equal currents in the two radiators. Unequal currents tend to reduce the depth of the null in the pattern, all other factors being equal.

The 1/2-wavelength section can be made from either RG-58 or RG-59 because it should act as a 1-to-1 transformer. With no radials or with two radials perpendicular to the vertical element, it was found that a 1/4-wavelength section made of RG-59 75-Ω coax produced a deeper notch than a 1/4-wavelength section made of RG-58 50-Ω line. However, with the two radials bent downward somewhat, the RG-58 section seemed to outperform the RG-59. Because of minor differences in assembly techniques from one antenna to another, it will probably be worth your time and effort to try both types of coax and determine which works best for your antenna. You may also want to try bending the radials down at slightly different angles for the best null performance.

The most important thing about the coax for the harness is that it be of the highest quality (well shielded and with a polyethylene dielectric). The reason for avoiding foam dielectric is that the velocity factor can vary from one roll to the next—some say that it varies from one foot to the next. Of course, it can be used if you have test equipment available that will allow you to determine its electrical length. Assuming that you do not want to or cannot go to that trouble, stay with coax having a solid polyethylene dielectric. Avoid coax that is designed for the CB market or do-it-yourself cable-TV market. (A good choice is Belden 8240 for the RG-58 or Belden 8241 for the RG-59.)

Both RG-58 and RG-59 with polyethylene dielectric have a velocity factor of 0.66. Therefore, for 146 MHz a quarter wavelength of transmission line will be 20.2 inches × 0.66 = 13.3 inches. A half-wavelength section will be twice this length or 26.7 inches. One thing you must take into account is that the transmission line is the total length of the cable *and the connectors*. Depending on the type of construction and the type of connectors that you choose, the actual length of the coax by itself will vary somewhat. You will have to determine that for yourself.

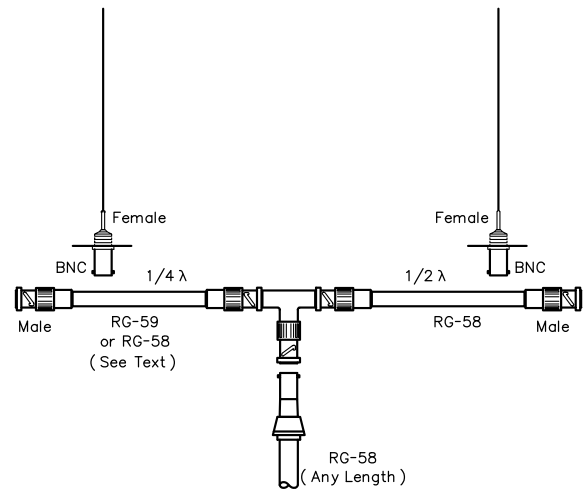

Fig 28—The phasing harness for the phased 144-MHz RDF array. The phasing sections must be measured from the center of the T connector to the point that the vertical radiator emerges from the shielded portion of the upside-down BNC female. Don't forget to take the length of the connectors into account when constructing the harness. If care is taken and coax with polyethylene dielectric is used, you should not have to prune the phasing line. With this phasing system, the null will be in a direction that runs along the boom, on the side of the 1/4-wavelength section.

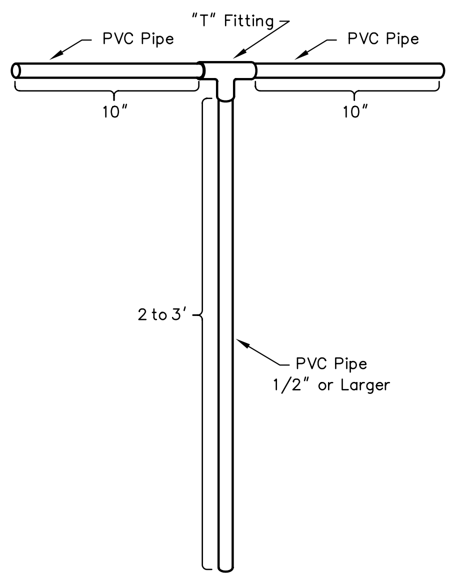

Fig 29–A simple mechanical support for the DF antenna, made of PVC pipe and fittings.

Y connectors that mate with RCA phono plugs are widely available and the phono plugs are easy to work with. Avoid the temptation to substitute these for the T and BNC connectors. Phono plugs and a Y connector were tried. The results with that system were not satisfactory. The performance seemed to change from day to day and the notch was never as deep as it should have been. Although they are more difficult to find, BNC T connectors will provide superior performance and are well worth the extra cost. If you must make substitutions, it would be preferable to use UHF connectors (type PL-259).

Fig 29 shows a simple support for the antenna. PVC tubing is used throughout. Additionally, you will need a T fitting, two end caps, and possibly some cement. (By not cementing the PVC fittings together, you will have the option of disassembly for transportation.) Cut the PVC for the dimensions shown, using a saw or a tubing cutter. A tubing cutter is preferred because it produces smooth, straight edges without making a mess. Drill a small hole through the PC board near the female BNC of each element assembly. Measure the 20-inch distance horizontally along the boom and mark the two end points. Drill a small hole vertically through the boom at each mark. Use a small nut and bolt to attach each element assembly to the boom.

Tuning

The dimensions given throughout this section are those for approximately 146 MHz. If the signal you will be hunting is above that frequency, then the measurements should be a bit shorter. If you are to operate below that frequency, then they will need to be somewhat longer. Once you have built the antenna to the rough size, the fun begins. You will need a signal source near the frequency that you will be using for your RDF work. Adjust the length of the radiators and the spacing between them for the deepest null on your S meter. Make changes in increments of 1/4 inch or less. If you must adjust the phasing line, make sure that the 1/4-wavelength section is exactly one-half the length of the half-wavelength section. Keep tuning until you have a satisfactorily deep null on your S meter.

THE DOUBLE-DUCKY DIRECTION FINDER

For direction finding, most amateurs use antennas having pronounced directional effects, either a null or a peak in signal strength. FM receivers are designed to eliminate the effects of amplitude variations, and so they are difficult to use for direction finding without looking at an S meter. Most modern portable transceivers do not have S meters.

This "Double-Ducky" direction finder (DDDF) was designed by David Geiser, WA2ANU, and described in *QST* for July 1981. It works on the principle of switching between two nondirectional antennas, as shown in **Fig 30**. This creates phase modulation on the incoming signal that is heard easily on the FM receiver. When the two antennas are exactly the same distance (phase) from the transmitter, **Fig 31**, the tone disappears.

In theory the antennas may be very close to each other, but in practice the amount of phase modulation increases directly with the spacing, up to spacings of a half wavelength. While a half-wavelength separation on 2 meters (40 inches) is pretty large for a mobile array, a quarter wavelength gives entirely satisfactory results, and even an eighth wavelength (10 inches) is acceptable.

Think in terms of two antenna elements with fixed spacing. Mount them on a ground plane and rotate that ground plane. The ground plane held

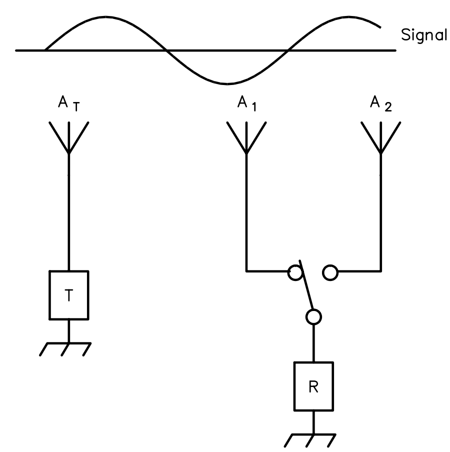

Fig 30—At the left, A_T represents the antenna of the hidden transmitter, T. At the right, rapid switching between antennas A_1 and A_2 at the receiver samples the phase at each antenna, creating a pseudo-Doppler effect. An FM detector detects this as phase modulation.

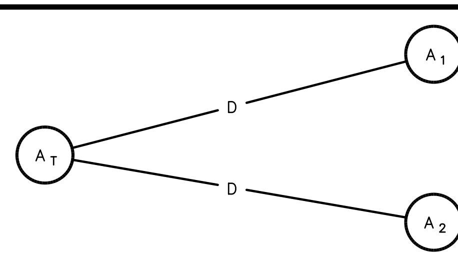

Fig 31—If both receiving antennas are an equal distance (D) from the transmitting antenna, there will be no difference in the phase angles of the signals in the receiving antennas. Therefore, the detector will not detect any phase modulation, and the audio tone will disappear from the output of the detector.

above the hiker's head or car roof reduces the needed height of the array and the directional-distorting effects of the searcher's body or other conducting objects.

The DDDF is bidirectional and, as described, its tone null points both toward and away from the signal origin. An L-shaped search path would be needed to resolve the ambiguity. Use the techniques of triangulation described earlier in this chapter.

Specific Design

It is not possible to find a long-life mechanical switch operable at a fairly high audio rate, such as 1000 Hz. Yet we want an audible tone, and the 400 to 1000-Hz range is perhaps most suitable considering audio amplifiers and average hearing. Also, if we wish to use the transmit function of a transceiver, we need a switch that will carry perhaps 10 W without much problem.

A solid-state switch, the PIN (positive-intrinsic-negative) diode, has been developed within the last several years. The intrinsic region of this type of diode is ordinarily bare of current carriers and, with a bit of reverse bias, looks like a low-capacitance open space. A bit of forward bias (20 to 50 mA) will load the intrinsic region with current carriers that are happy to dance back and forth at a 148-MHz rate, looking like a resistance of an ohm or so. In a 10-W circuit, the diodes do not dissipate enough power to damage them.

Because only two antennas are used, the obvious approach is to connect one diode "forward" to one antenna, to connect the other "reverse" to the second antenna and to drive the pair with square-wave audio-frequency ac. **Fig 32** shows the necessary circuitry. RF chokes (Ohmite Z144, J. W. Miller

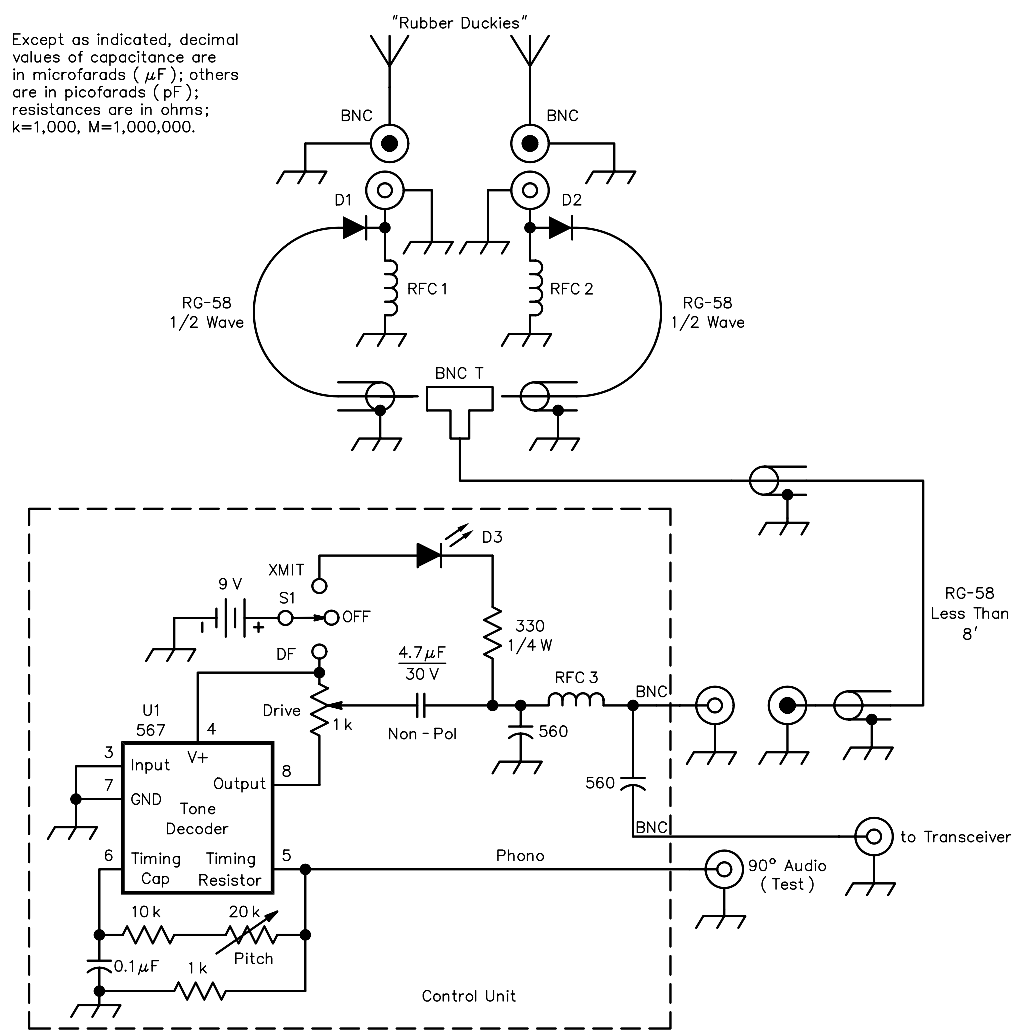

Fig 32—Schematic diagram of the DDDF circuit. Construction and layout are not critical. Components inside the broken lines should be housed inside a shielded enclosure. Most of the components are available from Radio Shack, except D1, D2, the antennas and RFC1-RFC3. These components are discussed in the text.

RFC-144 or similar VHF units) are used to let the audio through to bias the diodes while blocking RF. Of course, the reverse bias on one diode is only equal to the forward bias on the other, but in practice this seems sufficient.

A number of PIN diodes were tried in the particular setup built. These were the Hewlett-Packard HP5082-3077, the Alpha LE-5407-4, the KSW KS-3542 and the Microwave Associates M/A-COM 47120. All worked well, but the HP diodes were used because they provided a slightly lower SWR (about 3:1).

A type 567 IC is used as the square-wave generator. The output does have a dc bias that is removed with a nonpolarized coupling capacitor. This minor inconvenience is more than rewarded by the ability of the IC to work well with between 7 and 15 V (a nominal 9-V minimum is recommended).

The nonpolarized capacitor is also used for dc blocking when the function switch is set to XMIT. D3, a light-emitting diode (LED), is wired in series with the transmit bias to indicate selection of the XMIT mode. In that mode there is a high battery current drain (20 mA or so).

S1 should be a center-off locking type toggle switch. An ordinary center-off switch may be used but beware. If the switch is left on XMIT you will soon have dead batteries.

Cables going from the antenna to the coaxial T connector were cut to an electrical $^{1}/_{2}$ wavelength to help the open circuit, represented by the reverse-biased diode, look open at the coaxial T. (The length of the line within the T was included in the calculation.)

The length of the line from the T to the control unit is not particularly critical. If possible, keep the total of the cable length from the T to the control unit to the transceiver under 8 feet, because the capacitance of the cable does shunt the square-wave generator output.

Ground-plane dimensions are not critical. See **Fig 33**. Slightly better results may be obtained with a larger ground plane than shown. Increasing the spacing between the pickup antennas will give the greatest improvement. Every doubling (up to a half wavelength) will cut the width of the null in half. A 1° wide null can be obtained with 20-inch spacing.

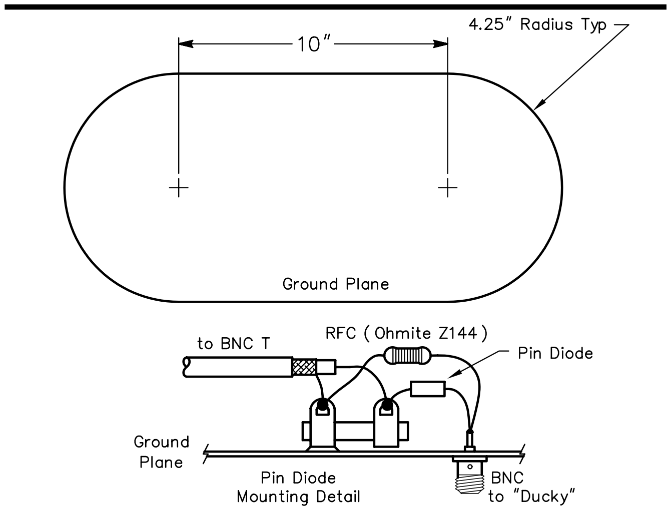

Fig 33—Ground-plane layout and detail of parts at the antenna connectors.

DDDF Operation

Switch the control unit to DF and advance the drive potentiometer until a tone is heard on the desired signal. Do not advance the drive high enough to distort or "hash up" the voice. Rotate the antenna for a null in the fundamental tone. Note that a tone an octave higher may appear. The cause of the effect is shown in **Fig 34**. In Fig 34A, an oscilloscope synchronized to the "90° audio" shows the receiver output with the antenna aimed to one side of the null (on a well-tuned receiver). Fig 34B shows the null condition and a twice-frequency (one octave higher) set of pips, while C shows the output with the antenna aimed to the other side of the null.

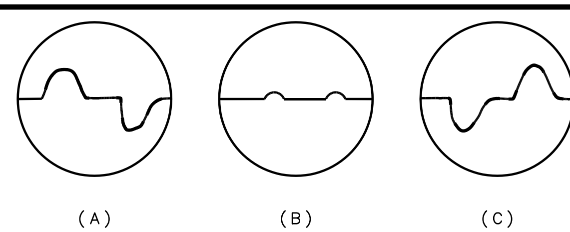

Fig 34—Typical on-channel responses. See text for discussion of the meaning of the patterns.

If the incoming signal is quite out of the receiver linear region (10 kHz or so off frequency), the off-null antenna aim may present a fairly symmetrical AF output to one side, **Fig 35A**. It may also show instability at a sharp null position, indi-

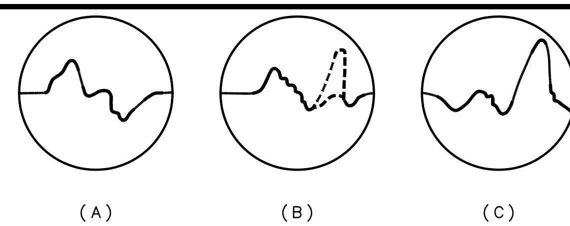

Fig 35—Representative off-channel responses. See text for discussion of the meaning of the patterns.

cated by the broken line on the display in Fig 35B. Aimed to the other side of a null, it will give a greatly increased AF output, Fig 35C. This is caused by the different parts of the receiver FM detector curve used. The sudden tone change is the tip-off that the antenna null position is being passed.

The user should practice with the DDDF to become acquainted with how it behaves under known situations of signal direction, power and frequency. Even in difficult nulling situations where a lot of second-harmonic AF exists, rotating the antenna through the null position causes a very distinctive tone change. With the same frequencies and amplitudes present, the quality of the tone (timbre) changes. It is as if a note were first played by a violin, and then the same note played by a trumpet. (A good part of this is the change of phase of the fundamental and odd harmonics with respect to the even harmonics.) The listener can recognize differences (passing through the null) that would give an electronic analyzer indigestion.

DIRECTION FINDING WITH AN INTERFEROMETER

In New Mexico, an interferometer RDF system is used by the National ELT Location Team to aid in locating downed aircraft. The method can be used for other VHF RDF activities as well. With a little practice, you can take long-distance bearings that are accurate to within one degree. That's an error of less than 2000 feet from 20 miles away. The interferometer isn't complicated. It consists of a receiver, two antennas, and two lengths of coaxial cable. The system and techniques described here were developed by Robert E. Cowan, K5QIN, and Thomas A. Beery, WD5CAW, and were described in *QST* for November 1985.

Interferometer Basics

The theory of interferometer operation is simple. Signals from two antennas are combined out of phase to give a sharp null in signal strength when the antennas are located on a line of constant phase. **Fig 36** shows that if you know the location of two points on a line of constant phase, you can get an accurate fix on the transmitter.

Most DF bearings are taken several miles from the transmitter. At these distances, the equal-phase circles appear as straight lines. As shown in **Fig 37A**, if you put the antennas at points A and B on a line of

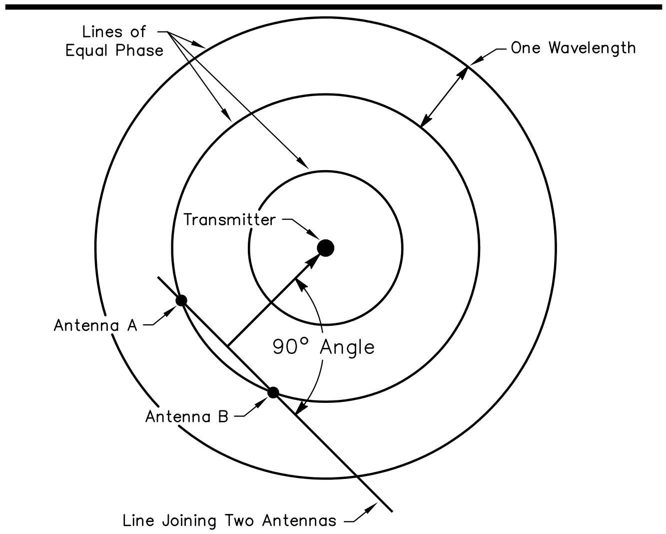

Fig 36—The transmitter is at a right angle to the center of the line that joins two points of equal phase.

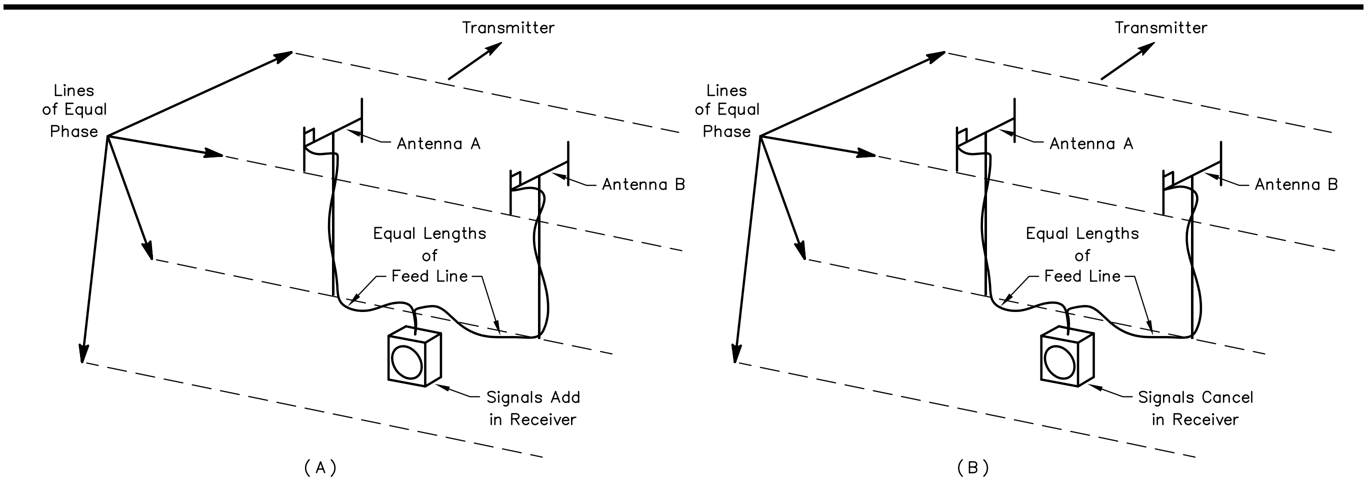

Fig 37—At A, placing two antennas on a line of equal phase and connecting them to a receiver with equal lengths of transmission line causes the signals to add. If the two antennas are placed a half wavelength apart in the direction of the transmitter, as shown at B, the signals cancel to form a null.

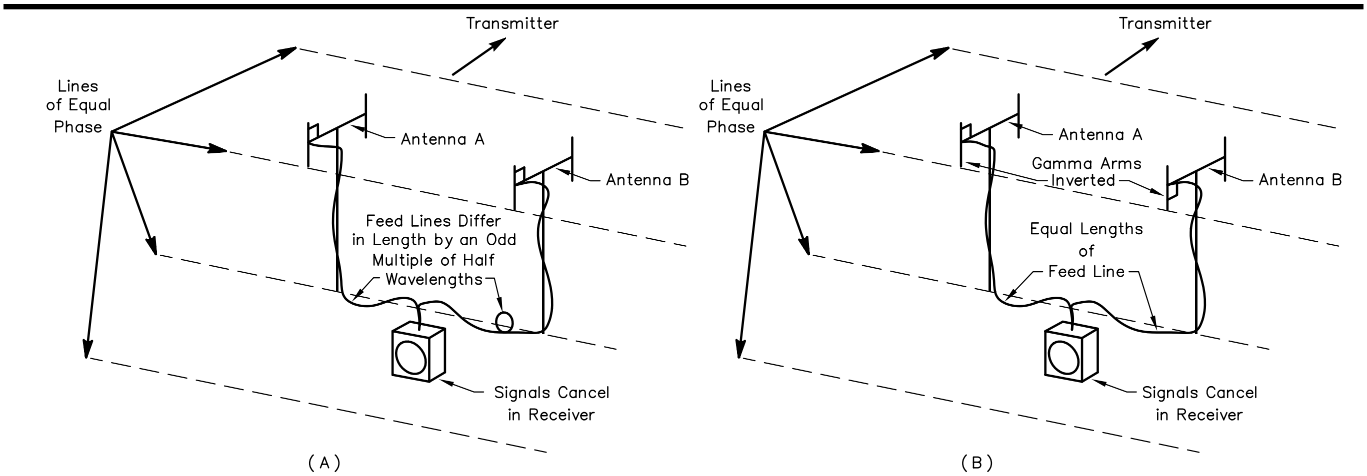

Fig 38—At A, placing two antennas on a line of equal phase and connecting them to a receiver with feed lines that differ in length by an odd multiple of half wavelengths causes the signals to cancel. Another way to obtain signal cancellation, shown at B, is to use equal-length feeders and invert the gamma arm on one of the antennas.

equal phase and connect them to a receiver with equal lengths of transmission line, the signals from the two antennas will add. By moving either one of the antennas back and forth across the equal-phase line, you will notice a broad peak in signal strength. Now if antenna B is moved halfway between two lines of equal phase, as shown in Fig 37B, the signals arriving at the receiver will be exactly out of phase; they will cancel each other completely. A sharp null in signal strength will be noted when either antenna is moved even slightly. This null is very easy to find just by listening to the receiver.

It is this sharp null that you always look for when using the interferometer. However, the setup shown in Fig 37B doesn't put us on a line of equal phase. To do that, you must make the signals at the receiver 180° out of phase. This can be done by having one feed line a half wavelength shorter than the other, as shown in **Fig 38A**. Now you will get a sharp null when the two antennas are on a line of equal phase. Another way of getting the phase reversal is shown in Fig 38B. If the gamma arms of the antennas are reversed (one pointing up, the other pointing down) and equal lengths of feed line are used, the signals will cancel.

After you have located two or more points of equal phase, you can draw a straight line through them. The transmitter will be 90° from this line. By locating an equal-phase line that is 30 to 50 feet long, you can take an accurate compass bearing down the line. This long base line is the secret of the interferometer's accuracy. Other DF systems have a much narrower aperture, and their accuracy is poorer than the interferometer. (Going much beyond 50 feet doesn't improve accuracy unless you have a transit for taking the bearing.) **Fig 39** shows a typical interferometer setup in the field.

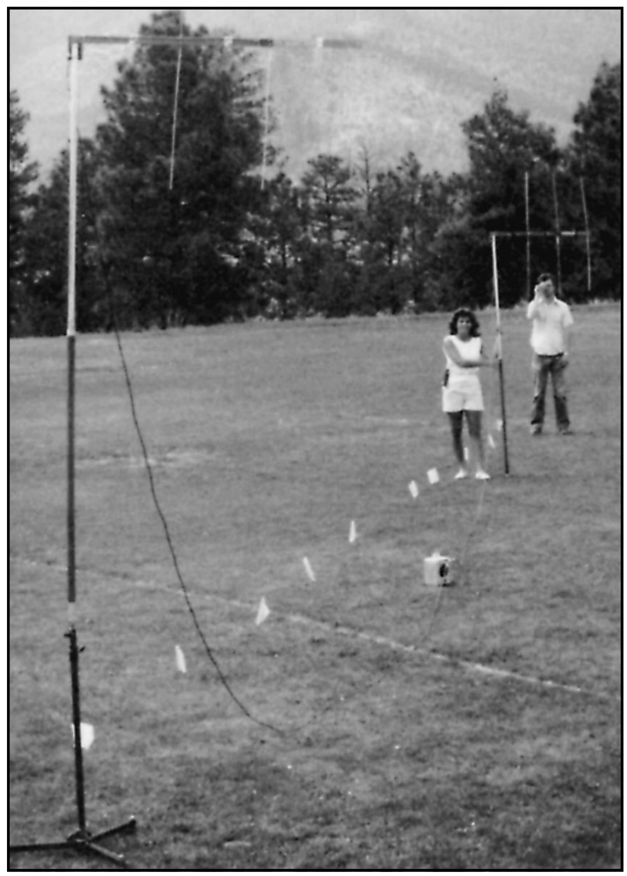

Fig 39—Typical field setup of an interferometer. One antenna is mounted on a stand while the second is moved to find the null locations. A compass bearing is taken down the line of nulls that is marked with surveyor's flags.

Using the Interferometer

To use the interferometer, first connect a receiver to one directional antenna. Rotate it for maximum signal strength to get an approximate bearing to the transmitter. Then add the second antenna to the system using a T connector. Its feed line must be a half wavelength shorter (or longer) than the one connected to the first, unless one of the gamma arms is inverted as shown in Fig 38B. Set up the second antenna about a wavelength away from the first one. The base of the second antenna mast should be at a right angle to the direction in which the first antenna is pointing. Now move the second antenna back and forth in the direction of the transmitter you are hunting, always keeping the mast vertical. As you do this, you will notice a sharp drop in signal strength from the receiver. Find the spot where the signal is weakest and mark its position on the ground.

Now move the second antenna a few steps farther from the first one, and on a line with the first null. Find the null again and mark its position. Continue "walking out the nulls" for 30 to 50 feet. Next take a compass bearing between the two antenna masts or down the line of nulls. The hidden transmitter will be on a line exactly 90° from the bearing. Now move to another location a few miles away and take another interferometer bearing. Plot your locations and bearings on a map. The point where the bearings cross is the transmitter location.

Equipment for the Interferometer

Having an S meter on the interferometer receiver is handy, but by no means necessary. The nulls are a little easier to find if you have a meter to watch.You should have some way of adjusting the receiver sensitivity. An RF or IF gain control is convenient, but an RF attenuator in the feed line also works well. The sensitivity should be adjusted so the maximum incoming signal is about 20 to 30 dB above the noise. If the signal in the receiver is too strong, you may have trouble finding the first null. If it is too weak, the null will be broad and you will find it difficult to position the antenna precisely on the line of constant phase.

Almost any kind of antenna can be used to make an interferometer. Simple dipoles will give the correct null, but because you need to first get an approximate bearing to the transmitter, some sort of directional antenna is preferred. A two or three-element Yagi has adequate directivity, yet is small enough to be carried to the field. It is important that both antennas be constructed alike. In this way their phase centers are the same and you may take a compass bearing between any two similar features on the antennas—the masts, for example.

Reflected signals can cause problems when you are trying to find a good null. Having the interferometer antennas 10 feet or more above the ground helps eliminate reflections from nearby objects such as rocks, cars and people.

Unless you use your antennas with one of the gamma arms inverted, the feed lines that connect the antennas to the receiver must differ in length by an odd multiple of half wavelengths. Don't forget to include the velocity factor of the cable in your calculations. You may want to set your receiver on the ground halfway between the two antennas, as shown in Fig 39. In this case the feeder lengths need be only a half wavelength different.

It is sometimes more convenient to mount your receiver on the mast of the second antenna. In this case one feed line will be only a few feet long and the other may be 40 feet long. This is fine as long as the difference in feed-line length is an odd multiple of half wavelengths. Having one feeder longer than the other creates some amplitude imbalance, but this will not affect your bearing. It is not necessary to be extremely precise when cutting your cables to give a length difference of an odd multiple of half wavelengths. At 146 MHz, a cutting error of a few inches will result in a bearing error of less than one degree.

The two feed lines are connected to the receiver input terminal with a coaxial T connector. Purists will argue that you need an impedance-matching device at this junction. Experiments with both resistive power combiners and Wilkinson hybrids indicate that neither works better than a T connector.

To take full advantage of the interferometer's accuracy, you must be able to take reliable compass bearings. Sighting compasses are the best compromise between hand-held transits and inexpensively priced lensatic compasses. With a moderately priced sighting compass you can take bearings that are accurate to within one degree. Don't forget to account for the magnetic declination of your area when plotting the bearings on a map. If you are unfamiliar with map and compass techniques, consult your local library or bookstore for references on the subject.

Some Fine Points on Interferometer Use

With a little practice, you will find that the interferometer is very easy to use. There are a few things to watch out for, though. Here are some that are based on experience.

Pick your DF site carefully. Although the interferometer works extremely well when reflected signals are present, you can get fooled. The best DF sites are in open terrain and well away from reflecting objects such as buildings, cars, fences and power lines.

Mark your null points on the ground as you find them. Use surveyor's flags, rocks, or other markers to indicate the null points. When you are done, look at this line of nulls. The markers should be in a straight line. Take your compass bearing down this line, and the accuracy will be better than sighting between the antenna masts. This is because you will be averaging several null readings when you take a bearing on the line, whereas a sighting between the masts gives you only a single null reading. Take compass bearings from both directions and average them for best accuracy. If the line has a periodic wiggle to it, this means that you have some reflections at your site. This is discussed later, but the correct sighting line will be down the center of the wiggles.

Beware of DFing pure reflections! Sometimes the only signal to be heard will be a reflection from a mountain or a building. Take two (or more) bearings, go to the area where they cross, and take more bearings to confirm the location. If you are in a critical situation such as locating a downed aircraft, don't commit all your resources until you know for sure that you are not DFing a pure reflection.

The most important thing to remember is that you must get a definite null at each point along the phase front. "Null all the way—okay," is a good rule. If you can't find a null, that means a strong reflection is entering the system. Inevitably it will give you bad information. The best recourse is to pack up the interferometer and move it to a new location. You may need to go a few hundred yards or perhaps a mile, but you will get a good bearing for your efforts. Remember—good nulls give good bearings, and good bearings will locate the transmitter.

Interferometer Radiation Patterns

At this point you have enough information to assemble and operate an interferometer, but some additional information may provide an insight into how it works. When you connect two antennas to a receiver (or transmitter), the two antennas and an out-of-phase feed line combine to form unique radiation patterns. These change dramatically as the two antennas are moved apart. There is always one null that faces the incoming signal. Other nulls are also present, and their location depends on the distance between the antennas. From page 2-16 of Jasik (see Bibliography at the end of this chapter), the equation that is used to calculate the antenna pattern is as follows:

$$E = |\cos(180\, d \cos\theta + \phi/2)| \qquad \text{(Eq 1)}$$

where

E is the relative field strength
d is the spacing between antennas, wavelengths
θ is the angle at which the field strength is calculated, degrees
ϕ is the difference in phase between the two antennas, electrical degrees

Fig 40 shows the relationship of the terms in Eq 1.

Antenna patterns for an interferometer using vertical dipole antennas are shown in **Fig 41**. Note that one null always faces the incoming signal, indicated by 0° azimuth on the plots. This null becomes sharper as the antenna spacing is increased. The pattern also contains lobes and other nulls. In a field setup, the lobes and nulls change position as the antenna spacing is varied. Interfering signals that arrive at an angle from the main signal will be attenuated differently as these lobes and nulls change position with different antenna spacings. If

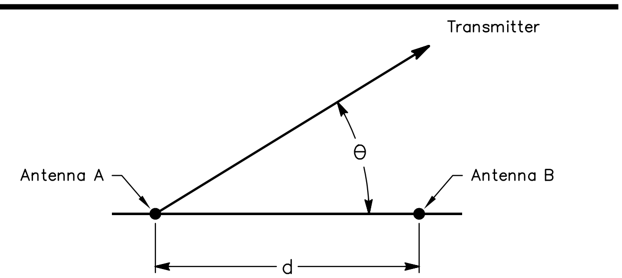

Fig 40—The relationship of the terms used in Eq 1 to calculate interferometer patterns. θ is expressed in degrees, d in wavelengths.

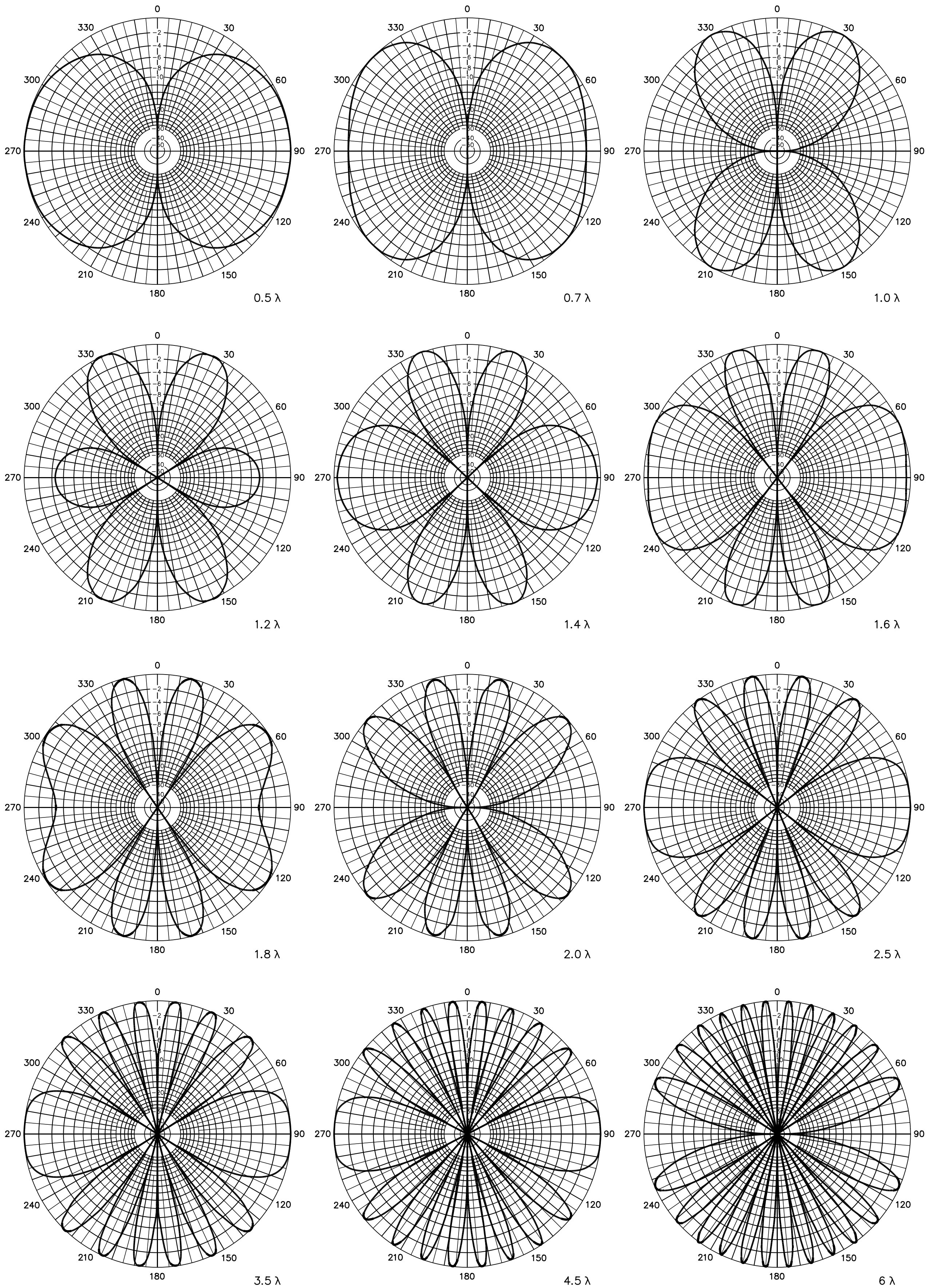

Fig 41—Interferometer radiation patterns with vertical dipole antennas spaced 1/2 to 6 wavelengths apart. The antennas are placed on the horizontal axis.

directional antennas are used in the interferometer, the pattern will be modified by the pattern of the individual antennas.

Effect of Reflected Signals on the Interferometer

All RDF systems are affected by multipath signals. The interferometer works better in multipath situations than any other system tried. Two effects are noticed when reflected signals are present. The first is a periodic curvature, or wiggle, of the apparent phase front. The second is a change in the depth of the nulls that are encountered. These two effects are caused by vector addition of the main signal and a reflected signal in the interferometer system.

If the amplitude of the reflected signal is low, you will be able to find the nulls and mark their positions on the ground. This is shown in **Fig 42**. The nulls are marked with surveyor's flags, and a compass bearing is being taken down the center of the wiggles. Surveyor's tape is used to mark the exact line of bearing. A drawing of the null locations obtained with multipath signals is shown in Fig 43. Notice, as indicated in **Fig 43**, that at some points you will obtain deep nulls, while only shallow nulls can be obtained at other points.

If you can successfully find all of the nulls in a multipath situation, you can easily determine the direction from which the reflected signal is arriving. To do this, first measure the period of the wiggle with a tape measure (the value of P as shown in Fig 43). The angle of the reflected signal with respect to the main signal can then be calculated from the equation

$$\theta = \arcsin P/\lambda \qquad \text{(Eq 2)}$$

where

θ is the angle of reflected signal with respect to main signal, degrees

P is the period of the wiggles, feet

λ is the length of 1 wavelength at the frequency you are using, feet, from the equation

$$\lambda = 984/\text{frequency (MHz)}$$

Eq 2 doesn't tell you whether the reflected signal is to the right or left of the main signal. Generally, though, you can resolve this because your directional antenna will point somewhere between the two signals.

If you try to use the interferometer in a location where the reflected signal is very strong, there will

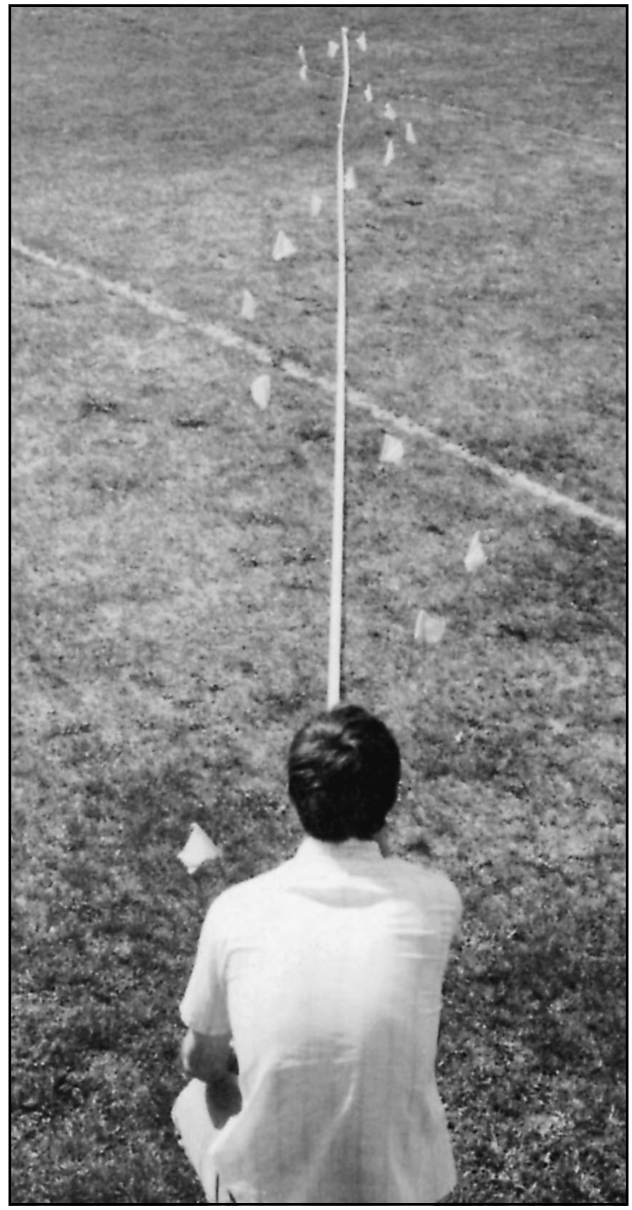

Fig 42—Null locations obtained with a reflected signal are marked with flags. A compass bearing is being taken on a line through the center of the wiggles, marked with a surveyor's tape.

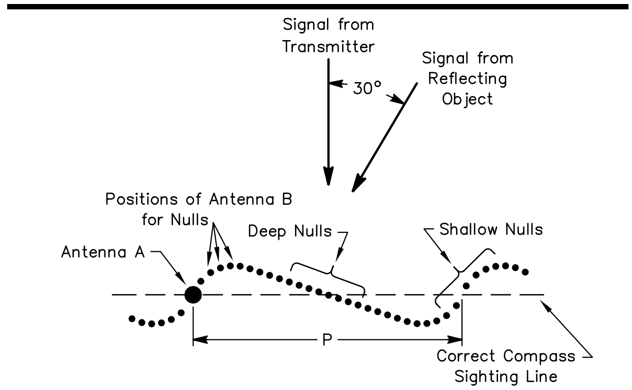

Fig 43—The interferometer pattern of the null markers, obtained in the presence of a direct signal and a reflected signal.

be certain antenna spacings where you just can't find a null, yet at other spacings the nulls will be quite deep. If you take lots of time, you might be able to figure out the proper bearing in the case of severe multipath, but generally it's not worth the effort. Moving the interferometer a short distance may allow you to find a "null all the way" and to take a good bearing.

DF Strategy Using the Interferometer

Locating transmitters with the interferometer is best done as a team effort. Several two-person teams can take bearings and send their data to one location where plotting is done. The person doing the map plotting can then direct the teams to the area where the bearings cross. This point will usually be within a half mile or less of the transmitter location. You can then home in on the transmitter using signal-strength techniques or hand-held DF units. The interferometer is a very useful tool to add to your collection of DF techniques. With a little practice, it can provide long-distance bearings that will quickly lead you to the hidden transmitter.

AN ADCOCK ANTENNA

Information in this section is condensed from an August 1975 *QST* article by Tony Dorbuck, K1FM, ex-W1YNC. Earlier in this chapter it was mentioned that loops are adequate in applications where only the ground wave is present. But the question arises, what can be done to improve the performance of an RDF system for sky-wave reception? One type of antenna that has been used successfully for this purpose is the Adcock antenna. There are many possible variations, but the basic configuration is shown in **Fig 44**.

The operation of the antenna when a vertically polarized wave is present is very similar to a conventional loop. As can be seen from Fig 44, currents I1 and I2 will be induced in the vertical members by the passing wave. The output current in the transmission line will be equal to their difference. Consequently, the directional pattern will be identical to the loop with a null broadside to the plane of the elements and with maximum gain occurring in end-fire fashion. The magnitude of the difference current will be proportional to the spacing, d, and the length of the elements. Spacing and length are not critical, but somewhat more gain will occur for larger dimensions than for smaller ones. In an experimental model, the spacing was 21 feet (approximately 0.15 wavelength at 7 MHz) and the element length was 12 feet.

Response of the Adcock antenna to a horizontally polarized wave is considerably different from that of a loop. The currents induced in the horizontal members (dotted arrows in Fig 44) tend to balance out regardless of the orientation of the antenna. This effect is borne out in practice, since good nulls can be obtained under sky-wave conditions that produce only poor nulls with small loops, either conventional or ferrite-loop models. Generally speaking, the Adcock antenna has very attractive properties for fixed-station RDF work or for semi-portable applications. Wood, PVC tubing or pipe, or other non-conducting material is preferable for the mast and boom. Distortion of the pattern may result from metal supports.

Since a balanced feed system is used, a coupler is needed to match the unbalanced input of the receiver. It consists of T1, which is an air-wound coil with a two-turn link wrapped around the middle. The combination is then resonated to the operating frequency with C1. C2 and C3 are null-clearing capaci-

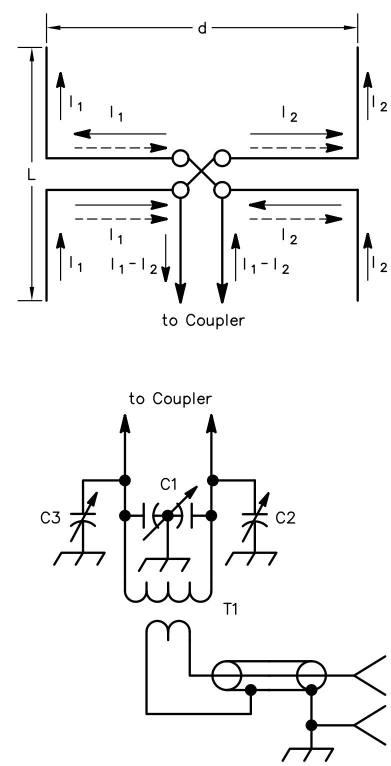

Fig 44—A simple Adcock antenna and suitable coupler (see text).

tors. A low-power signal source is placed some distance from the Adcock antenna and broadside to it. C2 and C3 are then adjusted until the deepest null is obtained. The coupler can be placed on the ground below the wiring-harness junction on the boom and connected by means of a short length of 300-Ω twin-lead. A length of PVC tubing used as a mast facilitates rotation and provides a means of attaching a compass card for obtaining bearings.

Tips on tuning and adjusting a fixed-location RDF array are presented earlier in this chapter. See the section, "RDF System Calibration and Use."

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