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Chapter 5

Loop Antennas

A loop antenna is a closed-circuit antenna — that is, one in which a conductor is formed into one or more turns so its two ends are close together. Loops can be divided into two general classes — large loops in which both the conductor length and the loop dimensions are comparable with the wavelength and small loops in which both the total conductor length and the maximum linear dimension of a turn are very small compared with the wavelength.

Material on quad and delta loops is adapted from Chapter 10 of *Low-Band DXing,* 5th edition by John Devoldere, ON4UN. Material on small loops was written by Domenic Mallozzi, N1DM. Additional discussion of loop antennas can be found in these chapters: **Low-Band Antennas**, **Multiband Antennas** and **Receiving and Direction Finding Antennas**.

5.1 LARGE LOOPS

Resonant loop antennas have a circumference of 1 λ. The exact shape of the loop is not particularly important. In free space, the loop with the highest gain, however, is the loop with the shape that encloses the largest area for a given circumference. This is a circular loop, which is difficult to construct. Second best is the square loop (quad), and in third place comes the equilateral triangle (delta) loop (see the reference for Dietrich).

The maximum gain of a 1-λ loop over a λ/2 dipole in free space is approximately 1.35 dB. Delta loops are used extensively on the low bands at apex heights of λ4 to 3λ/8 above ground. At such heights the vertically polarized loops far outperform dipoles or inverted-V dipoles for low-angle DXing, assuming good ground conductivity.

Loops are generally erected with the plane of the loop perpendicular to the ground. Whether or not the loop produces a vertically or a horizontally polarized signal (or a combination of both) depends only on how (or on which side) the loop is being fed.

Another type of large loop antennas comprises the horizontally mounted loops, which have the plane of the loop parallel to the ground. These antennas produce horizontal radiation with takeoff angles determined, as usual, by the height of the horizontal loop over ground.

5.1.1 THE SQUARE OR QUAD LOOP

Belcher, WA4JVE; Casper, K4HKX; and Dietrich, WAØRDX, have published studies comparing the horizontally polarized vertical quad loop with a dipole. (See the References and Bibliography section.) A horizontally polarized quad loop antenna (**Figure 5.1A**) can be seen as two short, end-loaded dipoles stacked λ/4 apart, with the top antenna at λ/4 and the bottom one just above ground level. The total length for a resonant loop is approximately 5 to 6% longer than the free-space wavelength.

There is no broadside radiation from the vertical wires of the quad because of the current opposition in the vertical members. In a similar manner, the vertically polarized quad loop consists of two top-loaded, λ/4 vertical dipoles, spaced λ/4 apart. Figure 5.1 shows how the current distribution along the elements produces cancellation of radiation from certain parts of the antenna, while radiation from other parts (the horizontally or vertically stacked short dipoles) is reinforced.

The square quad can be fed for either horizontal or vertical polarization merely by placing the feed point at the center of a horizontal arm or at the center of a vertical arm. At the higher frequencies in the HF range, where the quads are typically half to several wavelengths high, quad loops are usually fed to produce horizontal polarization, although there is no specific reason for this except maybe from a mechanical standpoint. Polarization by itself is of little importance at HF because of random rotation in the ionosphere.

Quad Loop Impedance

The radiation resistance of an equilateral quad loop in free space is approximately 120 Ω. The radiation resistance

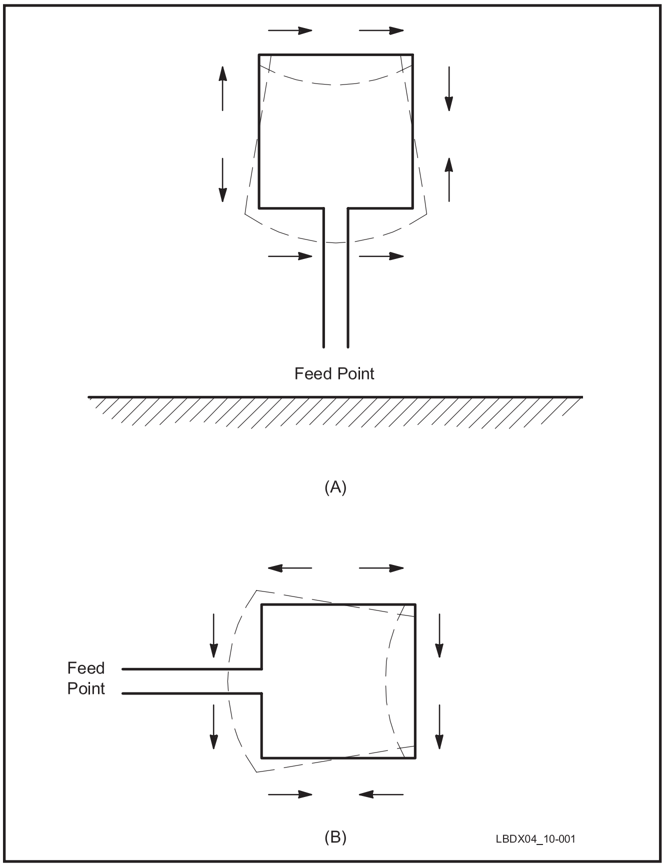

Figure 5.1 — Quad loops with a 1-λ circumference. The current distribution is shown for (A) horizontal and (B) vertical polarization. Note how the opposing currents in the two legs result in cancellation of the radiation in the plane of those legs, while the currents in the other legs are in-phase and reinforce each other in the broadside direction (perpendicular to the plane of the antenna).

for a quad loop as a function of its height above ground is given in **Figure 5.2**. The impedance data were obtained by modeling an equilateral quad loop over three types of ground (very good, average and very poor ground) using *NEC*.

The reactance data can assist you in evaluating the influence of the antenna height on the resonant frequency. The loop antenna was first modeled in free space to be resonant at 3.75 MHz and the reactance data was obtained with those free-space resonant-loop dimensions.

For the vertically polarized quad loop, the resistive part of the impedance changes very little with the type of ground under the antenna. The feed point reactance is influenced by the ground quality, especially at lower heights. For the horizontally polarized loop, the radiation resistance is noticeably influenced by the ground quality, especially at low heights. The same is true for the reactance.

Quad Loop Patterns — Vertical Polarization

The vertically polarized quad loop in Figure 5.1B can be considered as two shortened top-loaded vertical dipoles, spaced λ/4 apart. Broadside radiation from the horizontal elements of the quad is canceled, because of the opposition of currents in the vertical legs. The wave angle in the broadside direction will be essentially the same as for either of the vertical members. The resulting radiation angle will depend on the quality of the ground up to several wavelengths away from the antenna, as is the case with all vertically polarized antennas.

The quality of the reflecting ground will also influence the gain of the vertically polarized loop to a great extent. The quality of the ground is as important as it is for any other vertical antenna, meaning that vertically polarized loops close to the ground will not work well over poor soil.

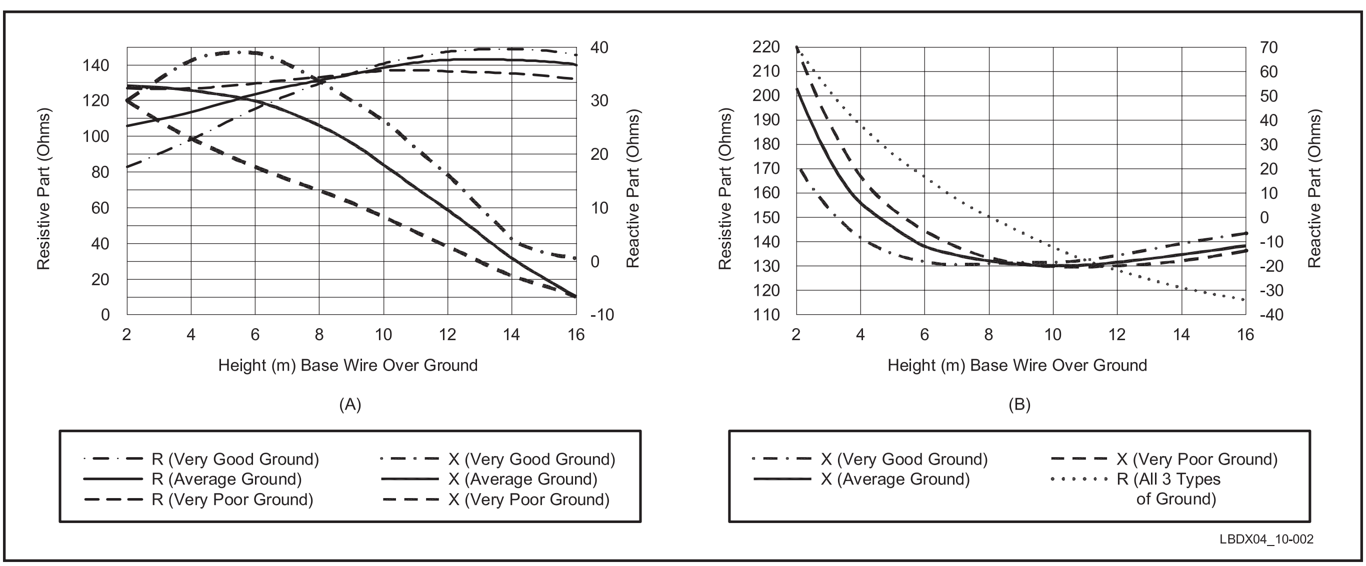

Figure 5.2 — Radiation resistance and feed point resistance for square loops at different heights above real ground. The loop was first dimensioned to be resonant in free space (reactance equal to zero), and those dimensions were used for calculating the impedance over ground. At A, for horizontal polarization, and at B, for vertical polarization. Analysis was with *NEC* at 3.75 MHz.

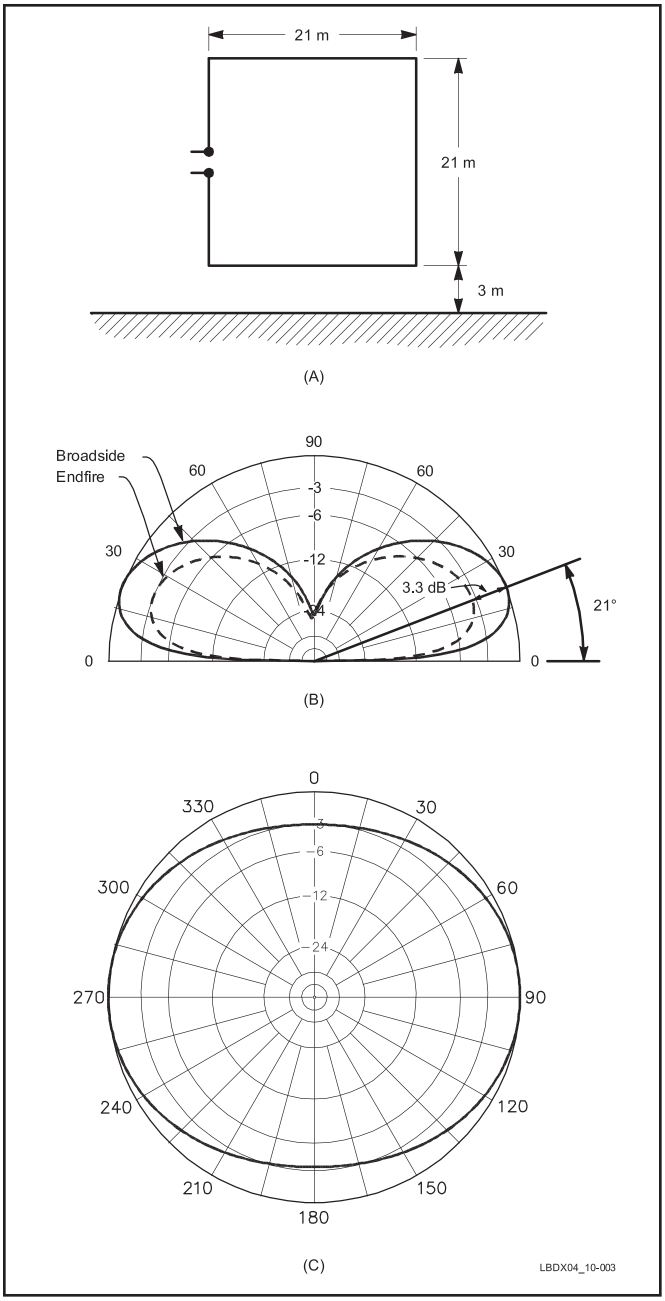

Figure 5.3 — Shown at A is a square loop, with its elevation-plane pattern at B and azimuth pattern at C. The patterns are generated for good ground. The bottom wire is 0.0375 λ above ground (3 meters or 10 feet on 80 meters). At C, the pattern is for a wave angle of 21°.

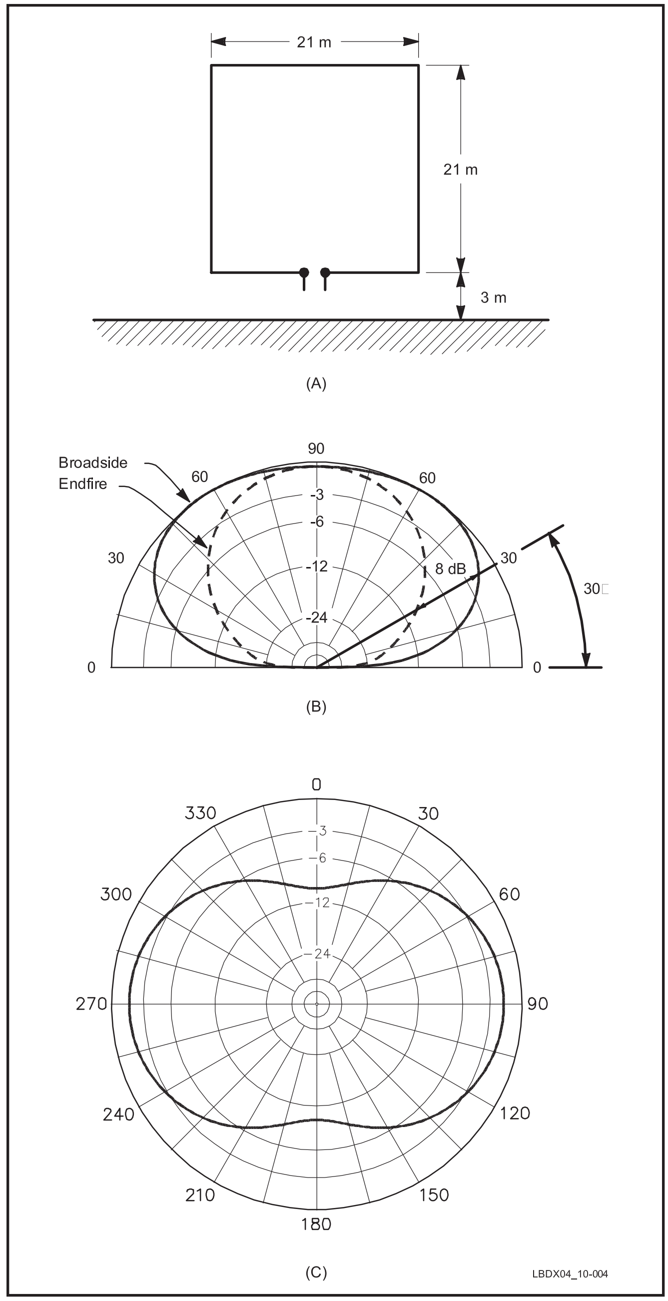

Figure 5.4 — Azimuth and elevation patterns of the horizontally polarized quad loop at low height (bottom wire 0.0375 λ above ground). At an elevation angle of 30°, the loop has a front-to-side ratio of approximately 8 dB.

Figure 5.3 shows both the azimuth and elevation radiation patterns of a vertically polarized quad loop with a top height of 0.3 λ (bottom wire at approximately 0.04 λ). This is a very realistic situation, especially on 80 meters. The loop radiates an excellent low-angle wave (lobe peak at approximately 21°) when operated over average ground. Over poorer ground, the wave angle would be closer to 30°. The horizontal directivity, Figure 5.3C, is rather poor, and amounts to approximately 3.3 dB of side rejection at any wave angle.

Quad Loop Patterns — Horizontal Polarization

A horizontally polarized quad-loop antenna (two stacked short dipoles) produces a wave angle that is dependent on the height of the loop. The low horizontally polarized quad (top at 0.3 λ) radiates most of its energy right at or near zenith angle (straight up).

Figure 5.4 shows directivity patterns for a horizontally polarized loop. The horizontal pattern, Figure 5.4C, is plotted for a takeoff angle of 30°. At low wave angles (20° to 45°),

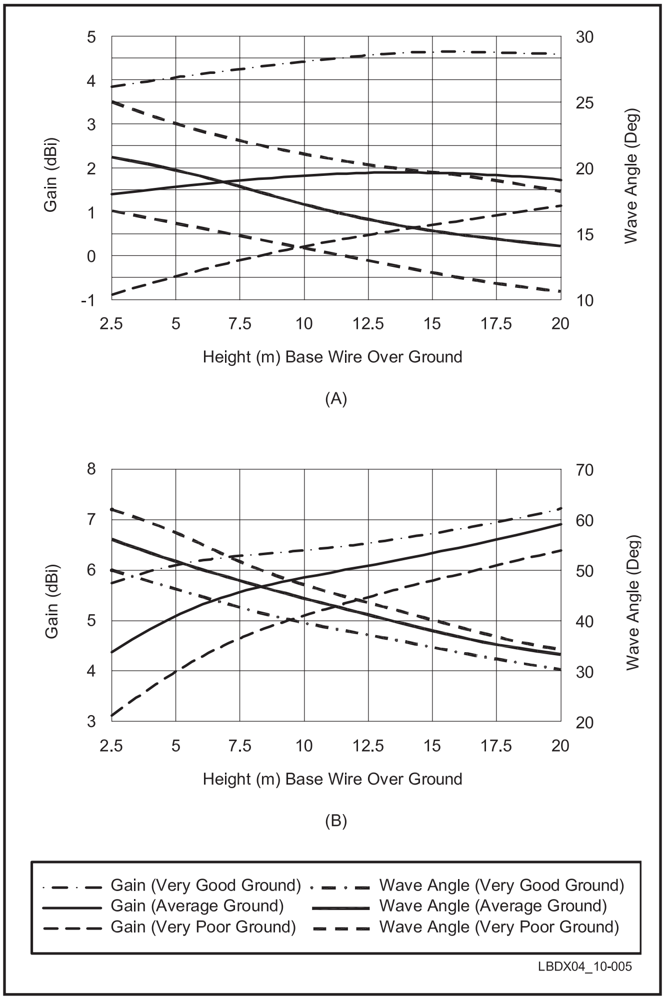

Figure 5.5 — Radiation angle and gain of the horizontally and the vertically polarized square loops at different heights over good ground. At A, for vertical polarization, and at B, for horizontal polarization. Note that the gain of the vertically polarized loop never exceeds 4.6 dBi, but its wave angle is low for any height (14 to 20°). The horizontally polarized loop can exhibit a much higher gain provided the loop is very high. Modeling was done over average ground for a frequency of 3.75 MHz, using *NEC*.

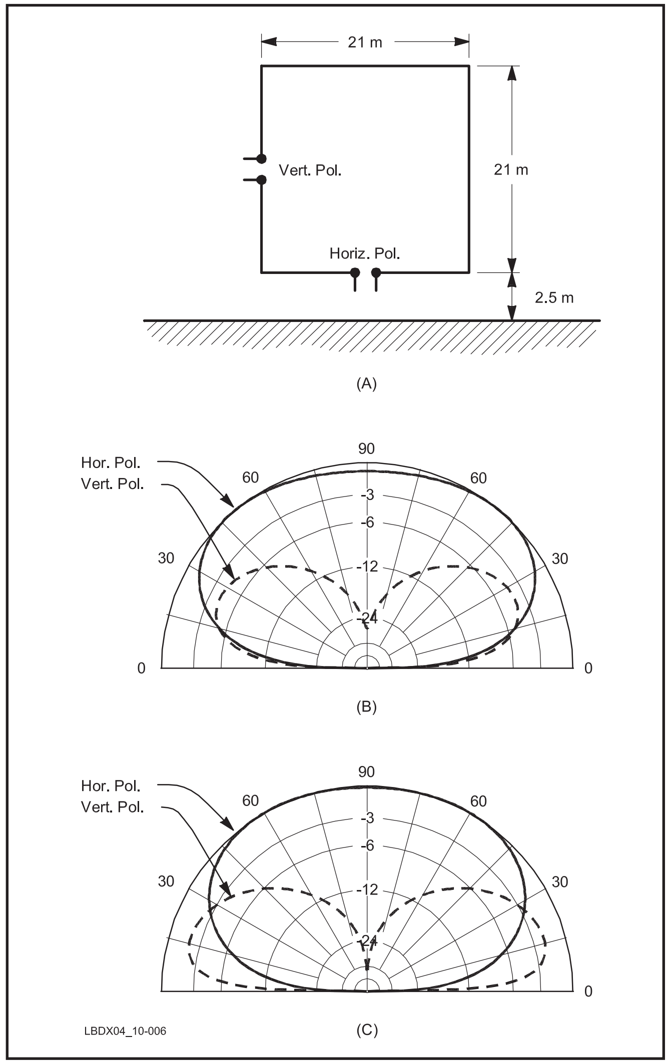

Figure 5.6 — Superimposed patterns for horizontally and vertically polarized square quad loops (shown at A) over very poor ground (B) and very good ground (C). In the vertical polarization mode the ground quality is of utmost importance, as it is with all verticals.

the horizontally polarized loop shows more front-to-side ratio (5 to 10 dB) than the vertically polarized rectangular loop.

Vertical versus Horizontal Polarization — Quad Loops

Vertically polarized loops should be used only where very good ground conductivity is available. From **Figure 5.5A** we see that the gain of the vertically polarized quad loop, as well as the wave angle, does not change very much as a function of the antenna height. This makes sense, since the vertically polarized loop is in the first place two phased verticals, each with its own radial.

However, the gain is drastically influenced by the quality of the ground. At low heights, the gain difference between very poor ground and very good ground is a solid 5 dB! The wave angle for the vertically polarized quad loop at a low height (bottom wire at 0.03 λ) varies from 25° over very poor ground to 17° over very good ground. Vertically polarized delta loops at low height always require a good ground screen underneath the antenna (unless they are over excellent or perfect ground), exactly in the same way that a vertical with only one or two radials requires a good ground underneath the radials.

With a horizontally polarized quad loop the wave angle is very dependent on the antenna height, but not so much on the quality of the ground. At very low heights, the main wave angle varies between 50° and 60° (but is rather constant all the way up to 90°). As far as gain is concerned, there is a 2.5-dB gain difference between very good and very poor ground, which is only half the difference we found with the vertically polarized loop. Comparing the gain to the gain of the vertically polarized loop, we see that at very low antenna heights the gain is about 3-dB better than for the vertically polarized loop. But this gain exists at a high wave angle (50° to 90°), while the vertically polarized loop at very low heights radiates at 17° to 25°.

Figure 5.6 shows the vertical-plane radiation patterns for both types of quad loops over very poor ground and over very good ground on the same dB scale.

Rectangular Quad Loops

A rectangular quad loop with unequal side dimensions can be used with very good results on the low bands. The vertical and the horizontal radiation patterns for this quad loop over good ground are shown in **Figure 5.7**. The horizontal directivity is approximately 6 dB (front-to-side ratio).

Even in free space, the feed point impedance of the two configurations of this rectangular loop is not the same. When fed in the center of a short side, the radiation resistance of the antenna in Figure 5.7 at resonance is 44 Ω. When fed in the center of one of the long sides, the resistance is 215 Ω. Over real ground the feed point impedance is different in both configurations as well; depending on the quality of the ground, the impedance can vary by 40 to 90 Ω.

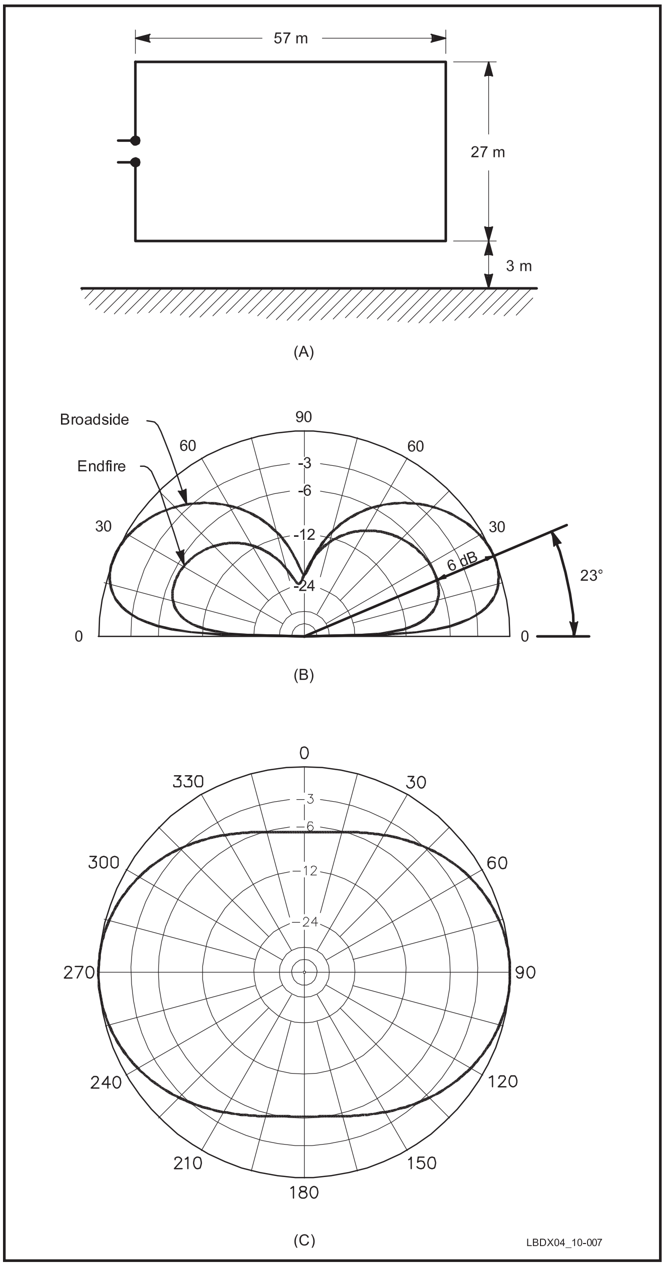

Figure 5.7 — At A, a rectangular loop with its baseline approximately twice as long as the vertical height. At B and C, the vertical and horizontal radiation patterns, generated over good ground. The loop was dimensioned to be resonant at 1.83 MHz. The azimuth pattern at C is taken at a 23° elevation angle.

Feeding the Quad Loop

The quad loop feed point should be in the middle of the vertical or the horizontal wire. A balun should be used as described in the **Transmission Line System Techniques** chapter. Alternatively, you could use open-wire feeders (for example, 450-Ω line). The open-wire-feeder alternative has the advantage of being a lightweight solution. With a tuner you will be able to cover a wide frequency range with no compromises. (See Feeding Large Loops following the section on Delta Loops.)

5.1.2. TRIANGULAR OR DELTA LOOPS

Because of its shape, the delta loop with the apex on top is a very popular antenna as it needs only one support. As for the quad configuration, the length of the resonant delta loop is approximately 1.05 to 1.06 λ.

In free space the equilateral triangle produces the highest gain and the highest radiation resistance for a three-sided loop configuration. As we deviate from an equilateral triangle toward a triangle with a long baseline, the effective gain and the radiation resistance of the loop will decrease for a bottom corner-fed delta loop. In the extreme case (where the height of the triangle is reduced to zero), the loop has become a half-wavelength-long transmission line that is shorted at the end, which shows a zero-Ω input impedance (radiation resistance), and thus zero radiation.

Just as with the quad loop, we can switch from horizontal to vertical polarization by changing the position of the feed point on the loop. For horizontal polarization the loop is fed either at the center of the baseline or at the top of the loop. For vertical polarization the loop should be fed on one of the sloping sides, at λ/4 from the apex of the delta. **Figure 5.8** shows the current distribution in both cases.

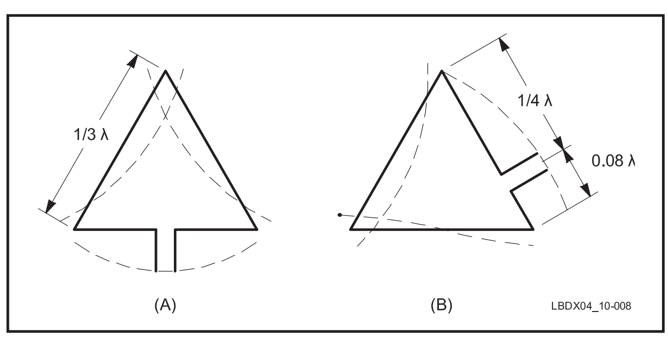

Figure 5.8 — Current distribution for equilateral delta loops fed for (A) horizontal and (B) vertical polarization.

Delta Loop Patterns — Vertical Polarization

As shown in **Figure 5.9**, in the vertical-polarization mode the delta loop can be seen as two sloping quarter-wave verticals (their apexes touch at the top of the support), while the baseline (and the part of the sloping section under the feed point) takes care of feeding the "other" sloping section with the correct phase. The top connection of the sloping verticals can be left open without changing anything about the operation of the delta loop. The same is true for the baseline, where the middle of the baseline could be opened without changing anything. These two points are the high-impedance points of the antenna. Either the apex or the center of the baseline must be shorted, however, in order to provide feed voltage to the other half of the antenna. Normally, of course, we use a fully closed loop in the standard delta loop, although for single-band operation this is not strictly necessary.

Assume we construct the antenna with the center of the horizontal bottom wire open. Now we can see the two half baselines as two λ/4 radials, one of which provides the necessary low-impedance point for connecting the shield of the coax. The other radial is connected to the bottom of the second sloping vertical, which is the other sloping wire of the delta loop. This is similar to a λ/4 vertical using a single elevated radial. The current distribution in the two quarter-wave radials is such that all radiation from these radials is effectively canceled.

The vertically polarized delta loop is really an array of two λ/4 verticals, with the high-current points spaced 0.25 λ to 0.3 λ, and operating in phase. The fact that the tops of the verticals are close together does not influence the performance to a large degree. The reason is that the current near the apex of the delta is at a minimum (it is current that creates radiation!). You can open the apex and move the vertical wires apart if you have a very tall support, in which case you will increase the gain of the antenna somewhat.

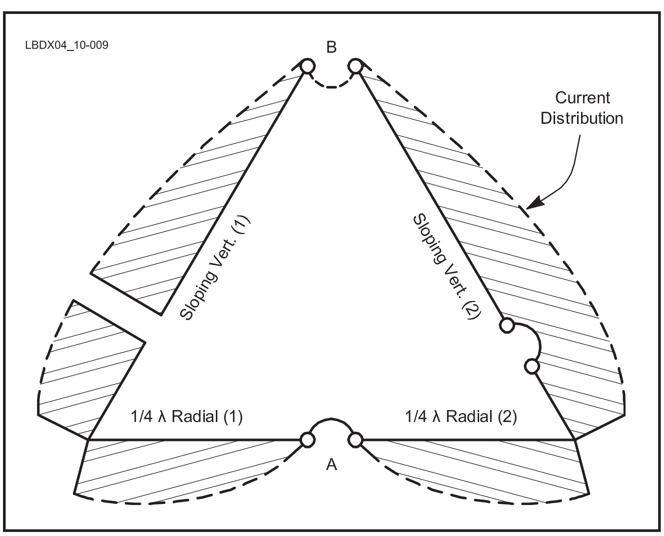

Figure 5.9 — The delta loop can be seen as two λ/4 sloping verticals, each using one radial. Because of the current distribution in the radials, the radiation from the radials is effectively canceled.

Considering a pair of phased verticals, we know from the chapter **Effects of Ground** that the quality of the ground will be very important as to the efficient operation of the antenna. This does not mean that the delta loop requires radials. It has two elevated radials that are an integral part of the loop and take care of the return currents. The presence of the (lossy) ground under the antenna is responsible for near-field losses, unless we can shield it from the antenna by using a ground screen or a radial system, which should not be connected to the antenna.

As with all vertically polarized antennas, the quality of

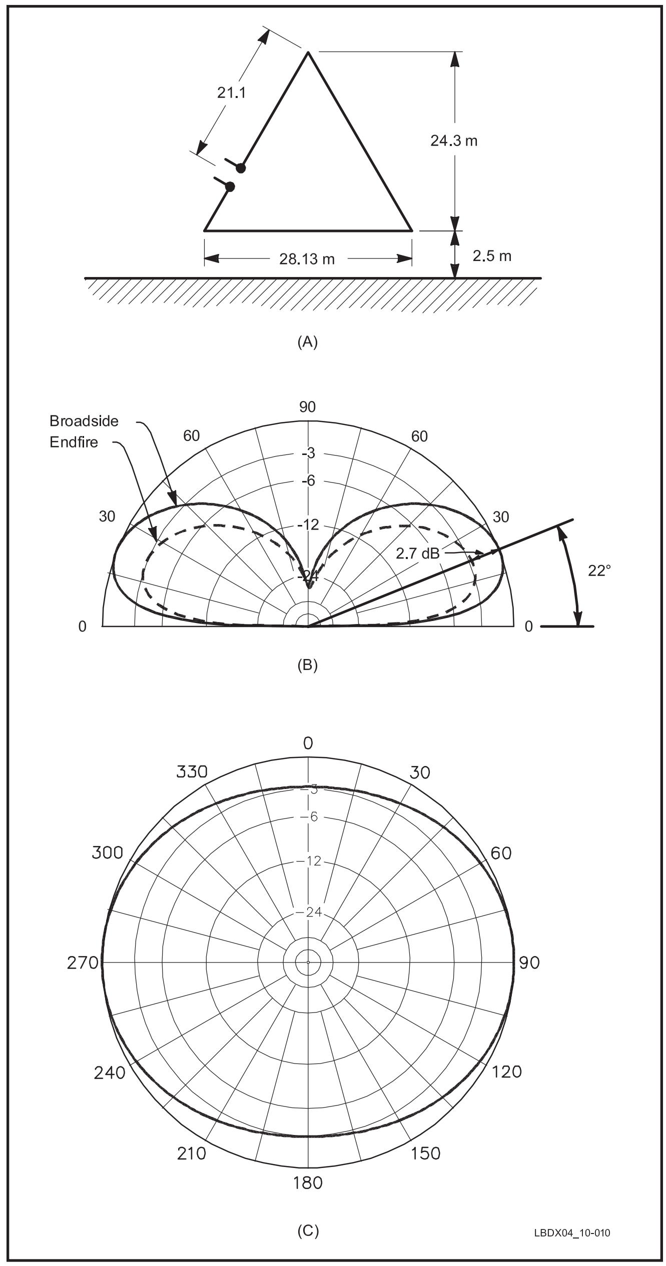

Figure 5.10 — Configuration and radiation patterns for a vertically polarized equilateral delta loop antenna. The model was calculated over good ground, for a frequency of 3.8 MHz. The elevation angle for the azimuth pattern at C is 22°.

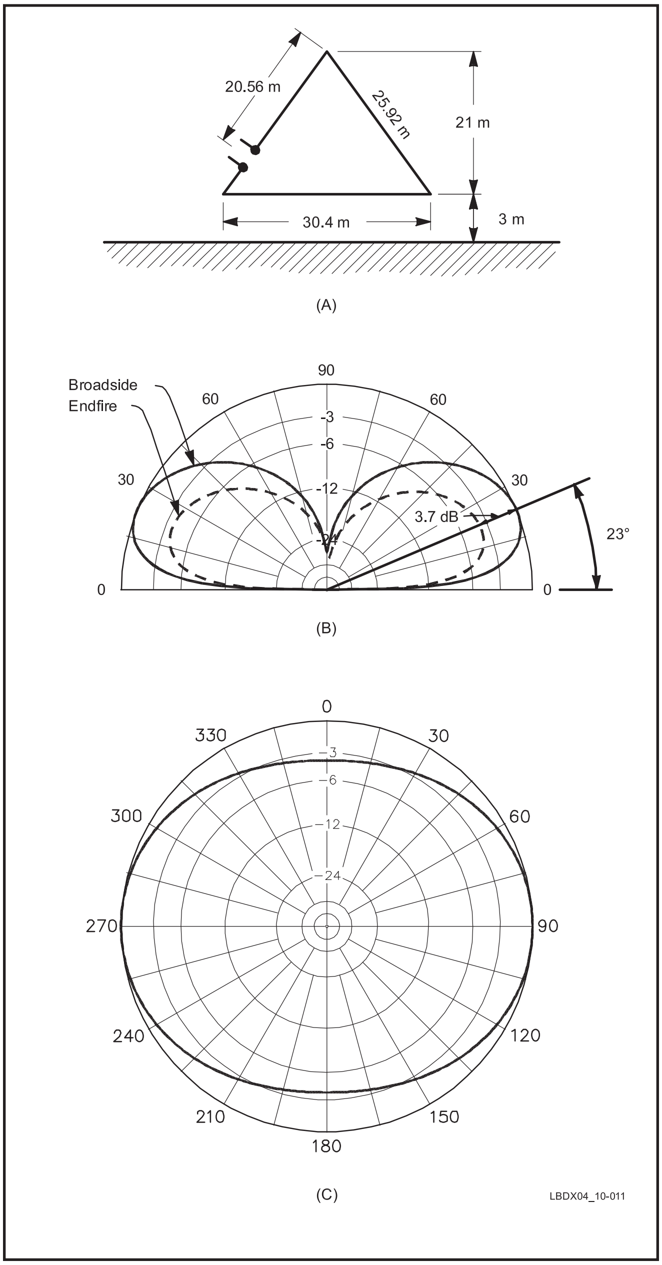

Figure 5.11 — Configuration and radiation patterns for the "compressed" delta loop, which has a baseline slightly longer than the sloping wires. The model was dimensioned for 3.8 MHz to have an apex height of 24 meters and a bottom wire height of 3 meters. Calculations are done over good ground at a frequency of 3.8 MHz. The azimuth pattern at C is for an elevation angle of 23°. Note that the correct feed point remains at λ/4 from the apex of the loop.

the ground within a radius of several wavelengths will determine the low-angle radiation of the loop antenna.

The Equilateral Triangle

Figure 5.10 shows the configuration as well as both the broadside and the end-fire vertical radiation patterns of the vertically polarized equilateral-triangle delta loop antenna. The model was constructed for a frequency of 3.75 MHz.

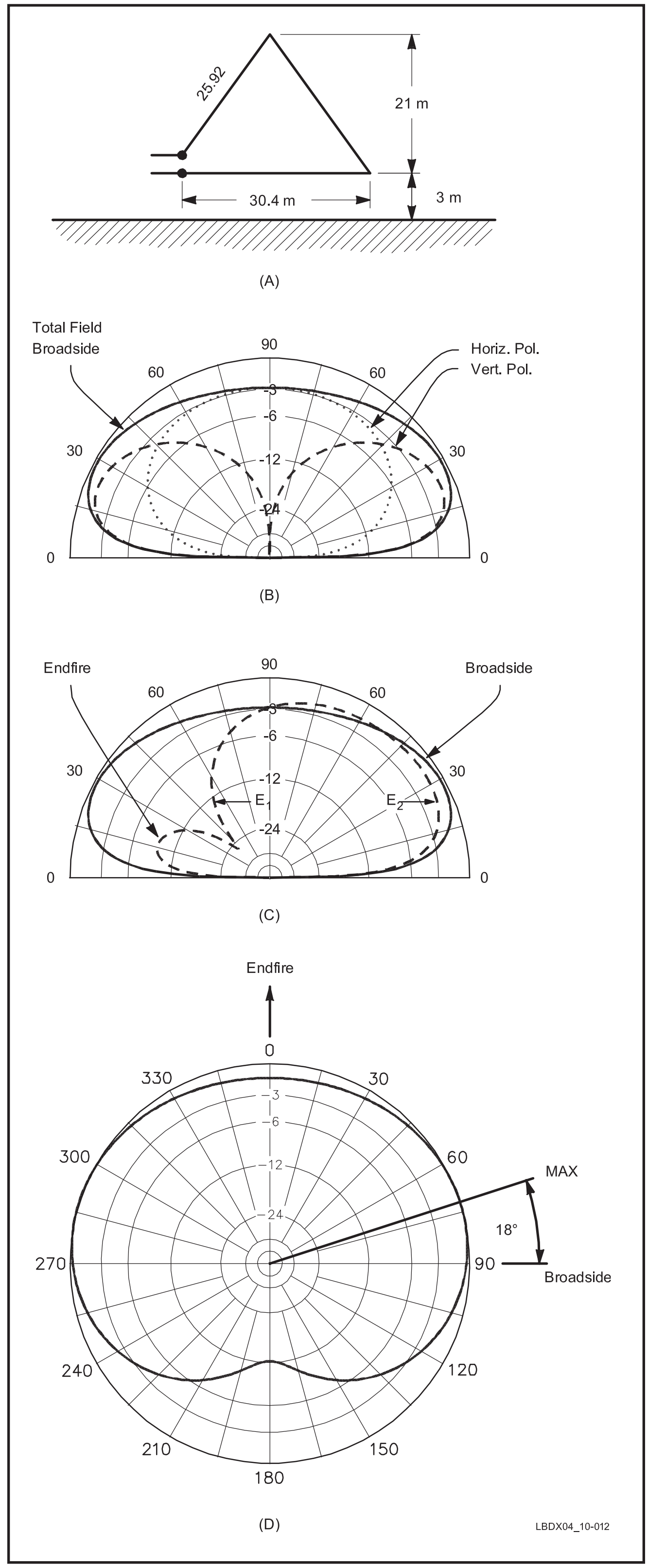

Figure 5.12 — Configuration and radiation patterns for the compressed delta loop of Figure 5.11 when fed in one of the bottom corners at a frequency of 3.75 MHz. Improper cancellation of radiation from the horizontal wire produces a strong high-angle horizontally polarized component. The delta loop now also shows a strange horizontal directivity pattern (at D), the shape of which is very sensitive to slight frequency deviations. This pattern is for an elevation angle of 29°.

The baseline is 2.5 meters above ground, which puts the apex at 26.83 meters. The model was made over good ground. The delta loop shows nearly 3 dB front-to-side ratio at the main wave angle of 22°. With average ground the gain is 1.3 dBi.

The Compressed Delta Loop

Figure 5.11 shows an 80 meter delta loop with the apex at 24 meters and the baseline at 3 meters. This delta loop has a long baseline of 30.4 meters. The feed point is again located $\lambda/4$ from the apex.

The front-to-side ratio is 3.8 dB. The gain with average ground is 1.6 dBi. In free space the equilateral triangle gives a higher gain than the "flat" delta. Over real ground and in the vertically polarized mode, the gain of the flat delta loop is 0.3 dB better than the equilateral delta, however. This must be explained by the fact that the longer baseline yields a wider separation of the two "sloping" verticals, yielding a slightly higher gain.

For a 100-kHz bandwidth (on 80 meters) the SWR rises to 1.4:1 at the edges. The 2:1 SWR bandwidth is approximately 175 kHz.

The Bottom-Corner-Fed Delta Loop

Figure 5.12 shows the layout of the delta loop being fed at one of the two bottom corners. The antenna has the same apex and baseline height as the compressed delta loop. Because of the "incorrect" location of the feed point, cancellation of radiation from the base wire (the two "radials") is not 100% effective, resulting in a significant horizontally polarized radiation component. The total field has a very uniform gain coverage (within 1 dB) from 25° to 90°. This may be a disadvantage for the rejection of high-angle signals when working DX at low wave angles.

Due to the "incorrect" feed point location, the end-fire radiation (radiation in line with the loop) has become asymmetrical. The horizontal radiation 2pattern shown in Figure 5.12D is for a wave angle of 29°. Note the deep side null (nearly 12 dB) at that wave angle. The loop actually radiates its maximum signal about 18° off the broadside direction. This feed point configuration (in the corner of the compressed loop) is to be avoided, as it really degrades the performance of the antenna.

Delta Loop Patterns — Horizontal Polarization

In the horizontal polarization mode, the delta loop can be seen as an inverted-V dipole on top of a very low dipole with its ends bent upward to connect to the tips of the inverted V. The loop will act as any horizontally polarized antenna over real ground; its wave angle will depend on the height of the antenna over the ground.

Figure 5.13 shows the vertical and the horizontal radiation patterns for an equilateral-triangle delta loop, fed at the center of the bottom wire. As anticipated, the radiation is maximum at the zenith. The front-to-side ratio is around 3 dB for a 15 to 45° wave angle. Over average ground the gain is 2.5 dBi. So far we have only spoken about relative patterns. What about real gain figures from the vertically and the horizontally polarized delta loops?

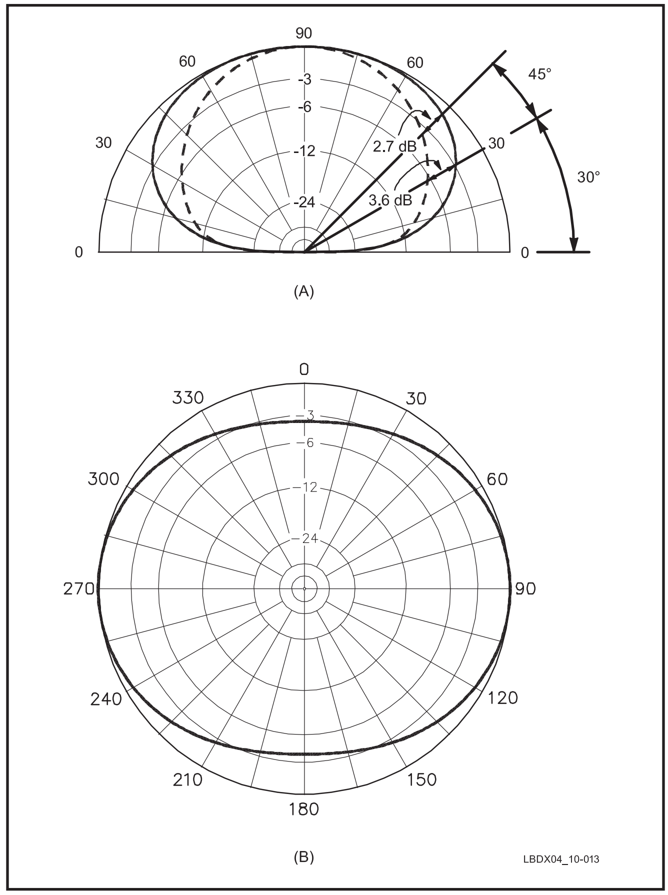

Figure 5.13 — Vertical and horizontal radiation patterns for an 80 meter equilateral delta loop fed for horizontal polarization, with the bottom wire at 3 meters. The radiation is essentially at very high angles, comparable to what can be obtained from a dipole or inverted-V dipole at the same (apex) height.

Vertical versus Horizontal Polarization — Delta Loops

Figure 5.14 shows the superimposed elevation patterns for vertically and horizontally polarized low-height equilateral triangle delta loops over two different types of ground (same dB scale).

Over very poor ground, the horizontally polarized delta loop is better than the vertically polarized loop for all wave angles above 35°. Below 35° the vertically polarized loop takes over, but quite marginally. The maximum gain of the vertically and the horizontally polarized loops differs by only 2 dB, but the big difference is that for the horizontally polarized loop, the gain occurs at almost 90°, while for the vertically polarized loop it occurs at 25°.

One might argue that for a 30° elevation angle, the horizontally polarized loop is as good as the vertically polarized loop. It is clear, however, that the vertically polarized antenna gives good high-angle rejection (rejection against local signals), while the horizontally polarized loop will not.

Over very good ground, the same thing that happens with any vertical happens with a vertically polarized delta: The performance at low angles is greatly improved with good ground. The vertically polarized loop is still better at any wave angle under 30° than when horizontally polarized. At a 10° radiation angle, the difference is as high as 10 dB.

In conclusion, over very poor ground, vertically polarized loops do not provide much better low-angle radiation when compared to the horizontally polarized loops. They have the advantage of giving substantial rejection at high angles, however. Over good ground, Figure 5.14 shows that the vertically polarized loop will give up to 10 dB and more gain at low radiation angles as compared to the horizontally polarized loop, in addition to its high-angle rejection.

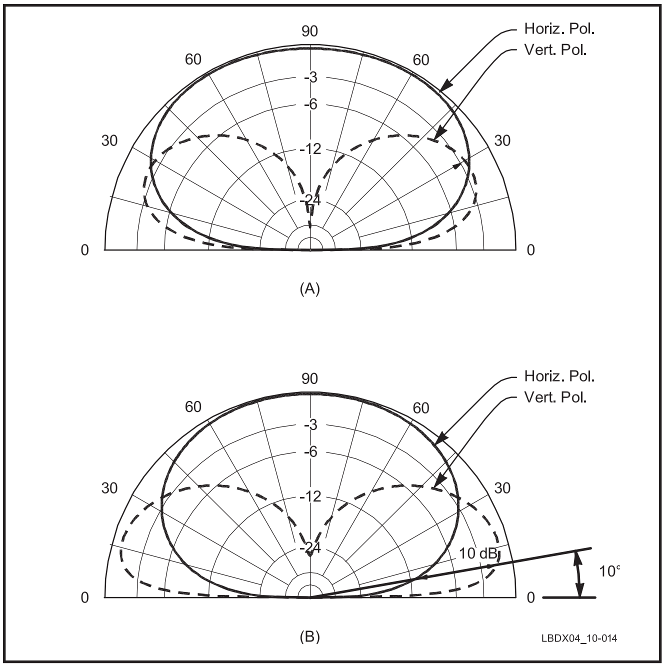

Figure 5.14 — Radiation patterns of vertically and horizontally polarized delta loops on the same dB scale. At A, over very poor ground, and at B, over very good ground. These patterns illustrate the tremendous importance of ground conductivity with vertically polarized antennas. Over better ground, the vertically polarized loop performs much better at low radiation angles, while over both good and poor ground the vertically polarized loop gives good discrimination against high-angle radiation. This is not the case for the horizontally polarized loop.

Feeding the Delta Loop

The feed point of the delta loop in free space is symmetrical. At high heights above ground the loop feed point is to be considered as symmetrical, especially when we feed the loop in the center of the bottom line (or at the apex), because of its full symmetry with respect to the ground.

Figure 5.15 shows the radiation resistance and reactance for both the horizontally and the vertically polarized equilateral delta loops as a function of height above ground. At low heights, when fed for vertical polarization, the feed point is to be considered as asymmetric, whereby the "cold" point is the point to which the "radials" are connected. The center conductor of a coax feed line goes to the sloping vertical section. Many users have, however, used (symmetric) open-wire line to feed the vertically polarized loop (for example, 450-Ω line).

Delta Loop Gain and Radiation Angle

Figure 5.16 shows the gain and the main-lobe radiation angle for the equilateral delta loop at different heights. The values were obtained by modeling a 3.8-MHz loop over average ground using *NEC*.

Cunningham, K6SE (SK), investigated different configurations of single element loops for 160 meters, and came up with the results listed in **Table 5.1** (modeling done with *EZNEC* over good ground). These data correspond surprisingly well with those shown in Figure 5.16 (where the ground was average), which explains the slight difference in gain.

5.1.3 FEEDING LARGE LOOPS

Most practical 1 λ loops present a feed point impedance between 50 and 150 Ω, depending on the exact geometry and

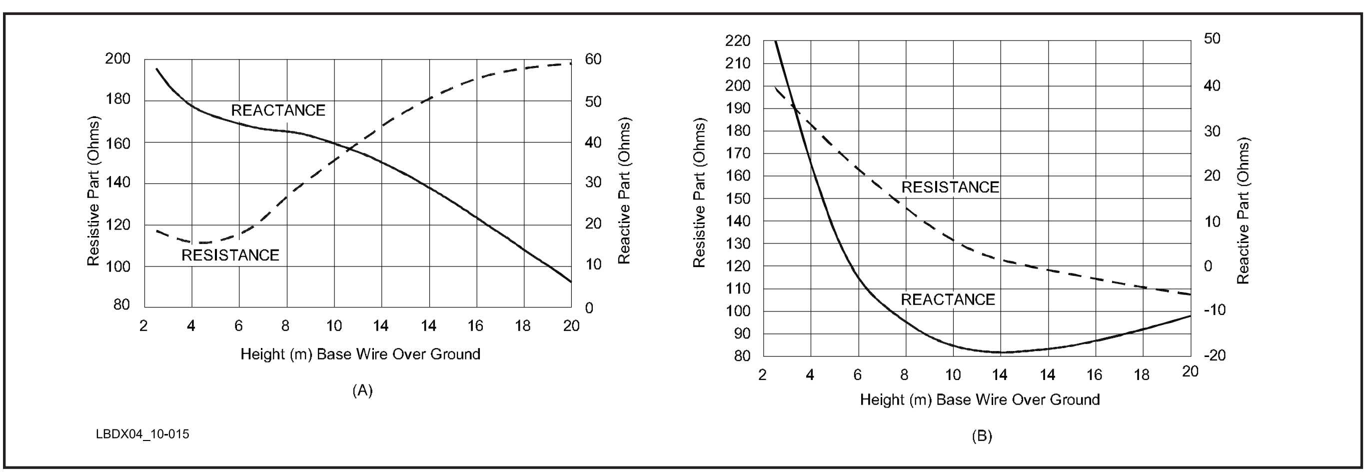

Figure 5.15 — Radiation resistance of (A) horizontally and (B) vertically polarized equilateral delta loops as a function of height above average ground. The delta loop was first dimensioned to be resonant in free space (reactance equals zero). Those dimensions were then used for calculating the impedance over real ground. Modeling was done at 3.75 MHz over good ground, using *NEC*.

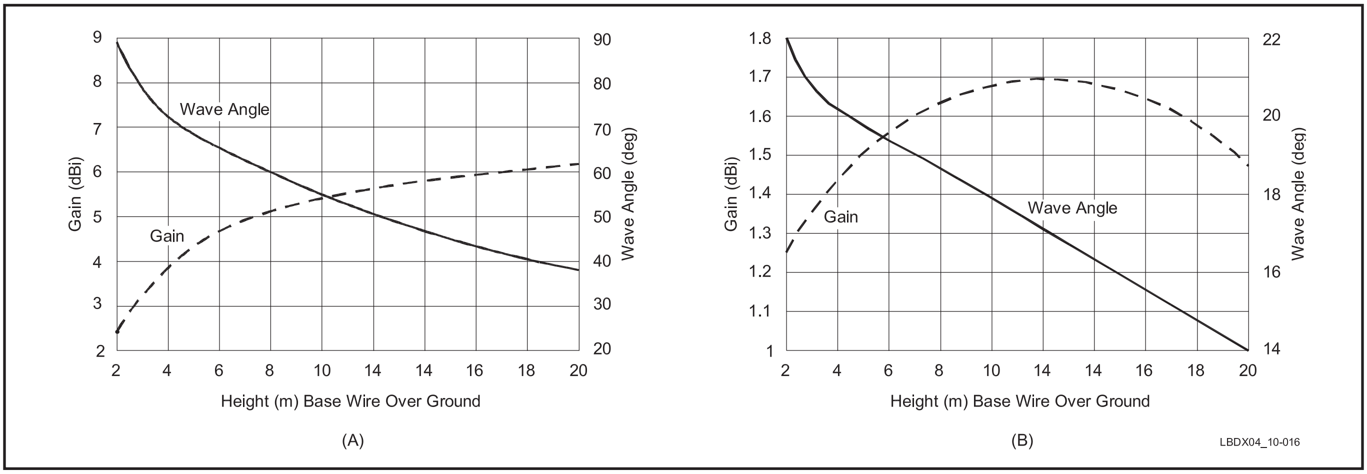

Figure 5.16 — Gain and radiation angle of (A) horizontally and (B) vertically polarized equilateral delta loops as a function of the height above ground. Modeling was done at 3.75 MHz over average ground, using *NEC*.

coupling to other antennas. Delta loops tend to have impedances at the low end of the range and quads somewhat higher. The shape of the loop and proximity to the ground will affect the feed point impedance.

Measure the feed point impedance using a noise bridge or antenna analyzer connected directly to the antenna terminals. A section of feed line that is λ/2 long (or an integer multiple of λ/2) connected to the feed point will also allow direct measurement of feed point impedance if the feed point can't be reached directly.

If the impedance exceeds 50 to 70 Ω, a λ/4 feed line transformer can be used to reduce the feed point impedance to a more acceptable value (see the **Transmission Line System Techniques** chapter). If the impedance is much higher than 150 Ω, feeding via 450 Ω open-wire feeders may be warranted. Alternatively, you could use an unun (unbalanced-to-unbalanced) transformer, which can be made to cover a very wide range of impedance ratios.

To keep RF current from flowing on the outside of the coaxial feed line, use a balun or current choke at the loop feed point. RF current flowing on the feed point can distort the pattern of the loop and result in unnecessary noise pickup. For details on ununs, baluns, and common mode chokes see the **Transmission Line System Techniques** chapter.

5.1.4 HORIZONTAL LOOPS

A large loop, installed horizontally over ground and in **Figure 5.17** is an excellent multiband antenna. A 1-λ circumference loop installed at a height of λ/2 or lower has a radiation pattern similar to a λ/2 dipole at the same height — omnidirectional, high-angle radiation. As the frequency of operation increases the current distribution around the loop and the radiation pattern become more complex. The radiation lobes peak at lower elevation angles, generally approximating the angle of peak radiation for a dipole at the same electrical height.

The exact performance of the loop depends on shape, height, and frequency of use. DeMaw, W1FB (SK), analyzed a square, horizontal loop cut for resonance at 1.9 MHz. Peak gain varied from 0.28 dBd at 1.9 MHz (at an elevation angle of 90°) to a maximum of 7.00 dBd at 21.0 MHz (at an elevation angle of 14°). **Figure 5.18** shows the azimuth and elevation patterns for DeMaw's loop at 14 MHz, typical of this type of loop when operated above the loop's lowest resonant frequency. Cebik, W4RNL (SK), also analyzed large, horizontal loops at different frequencies and obtained similar results. (See the References for articles by DeMaw and Cebik.)

Feed point impedance on the 1-λ resonant frequency is approximately 100 Ω and rises to a few hundred ohms or higher at higher frequencies. Because of the varying feed

Table 5.1
Loop Antennas for 160 Meters

Description	*Feeding Method*	*Gain (dBi)*	*Elevation Angle (degrees)*
Diamond loop, bottom 2.5 meters high	Fed in side corner	2.15	18.0
Square loop, bottom 2.5 meters high	Fed in center of one vertical wire	2.06	20.5
Inverted equilateral delta loop (flat wire on top)	Fed λ/4 from bottom	1.91	20.9
Regular equilateral delta loop	Fed λ/4 from top	1.90	18.1

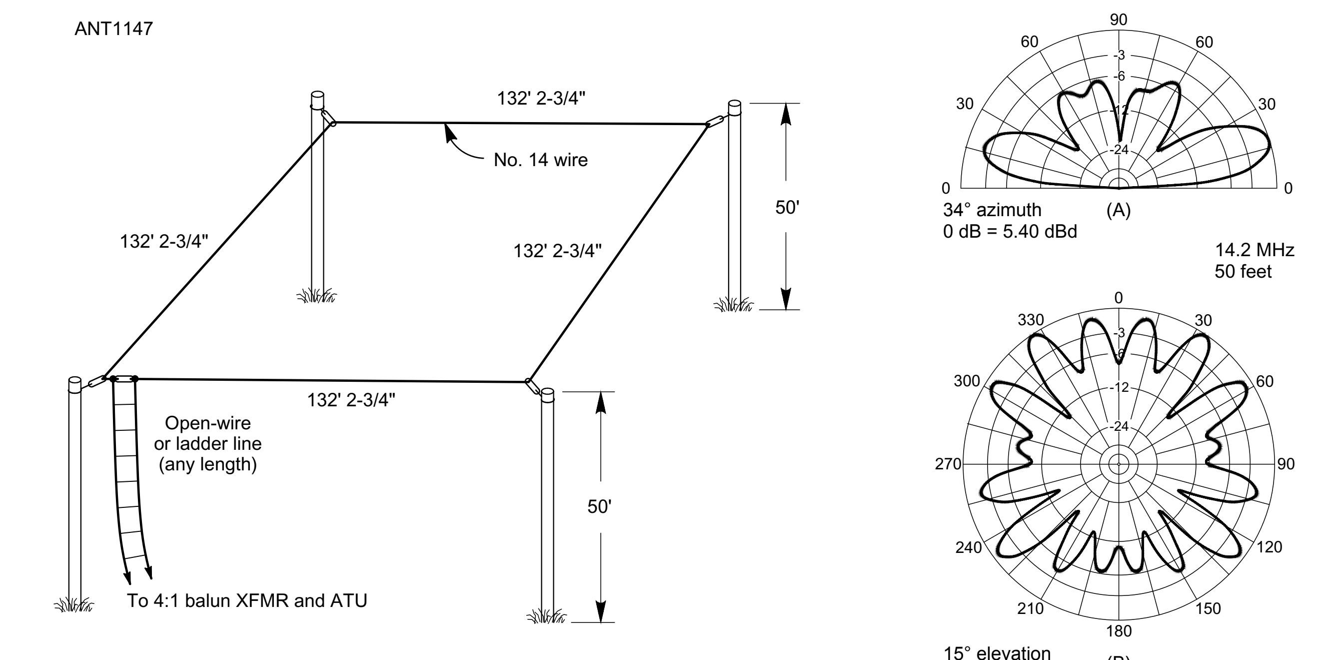

Figure 5.17 — Construction of the W1FB full-wave 1.9-MHz loop. The antenna can be fed with any length of open-wire or ladder line from 300 to 600 Ω. The elevation (A) and azimuth (B) patterns are also given for the antenna at 14.2 MHz.

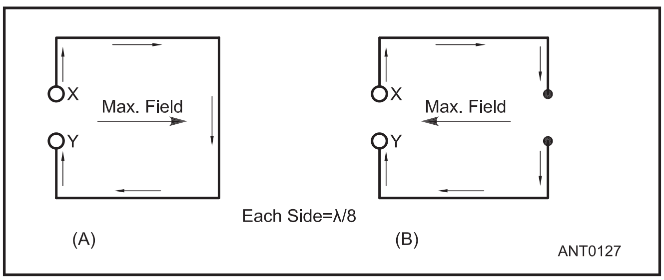

Figure 5.18 — Half-wave loops, consisting of a single turn having a total length of ½ λ.

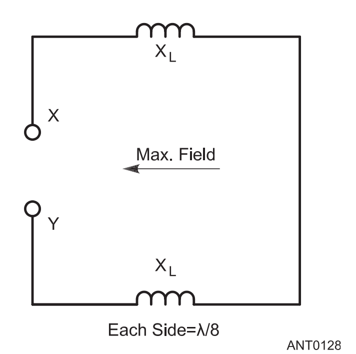

Figure 5.19 — Inductive loading in the sides of a ½-λ loop to increase the directivity and gain. Maximum radiation or response is in the plane of the loop, in the direction shown by the arrow.

point impedance, it is recommended that the antenna be fed with parallel conductor transmission line to reduce feed line loss.

5.1.5 HALF-WAVE LOOPS

The smallest size of "large" loop generally used is one having a conductor length of ½ λ. The conductor is usually formed into a square, as shown in **Figure 5.19**, making each side ⅛ λ long. When fed at the center of one side, the current flows in a closed loop as shown in Figure 5.19A. The current distribution is approximately the same as on a ½ λ wire, and so is a maximum at the center of the side opposite the terminals X-Y, and a minimum at the feed point. This current distribution causes the field strength to be a maximum in the plane of the loop and in the direction looking from the low-current side to the high-current side. (See the referenced article by Cebik for additional discussion of this configuration.)

If the side opposite the feed point is opened at the center as shown in Figure 5.19B (strictly speaking, it is then no longer a loop because it is no longer a closed circuit), the direction of current flow remains unchanged but the maximum current flow and lowest impedance occurs at the feed point. This reverses the direction of maximum radiation.

The radiation resistance at a current maximum (which is also the resistance at X-Y in Figure 5.19B) is on the order of 50 Ω. The impedance at the feed point in Figure 5.19A is a few thousand ohms. This can be reduced by using two identical loops side by side with a few inches spacing between them and applying power between terminal X on one loop and terminal Y on the other.

Unlike a ½ λ dipole or a small loop, there is no direction in which the radiation from a loop of the type shown in Figure 5.19 is zero. There is appreciable radiation in the direction perpendicular to the plane of the loop, as well as to the "rear" — the opposite direction to the arrows shown. The front-to-back (F/B) ratio is approximately 4 to 6 dB. The small size and the shape of the directive pattern result in a loss of about 1 dB when the field strength in the optimum direction from such a loop is compared with the field from a ½ λ dipole in its optimum direction.

The ratio of the forward radiation to the backward radiation can be increased, and the field strength likewise increased at the same time to give a gain of about 1 dB over a dipole, by using inductive reactances to "load" the sides joining the front and back of the loop. This is shown in **Figure 5.20**. The reactances, which should have a value of approximately 360 Ω, decrease the current in the sides in which they are inserted and increase it in the side with the feed point. This increases the directivity and thus increases the efficiency of the loop as a radiator. Lossy coils can reduce this advantage greatly.

5.1.6 *PROJECT:* NESTED LOOP ANTENNAS FOR MULTIPLE BANDS

The following nested loop array for the 20, 17, 15, 12, and 10 meter bands can be used as a permanent station antenna or for portable operation. The design was originally described in the *QST* article "Nested Loop Antenna" by Scott Davis, N3FJP, which is included on this book's CD-ROM.

The square loops are constructed as in **Figure 5.20** according to the dimensions in **Table 5.2**. The loops hang in the vertical plane in a diamond shape and are fed at the bottom corner to radiate with horizontal polarization. The perimeter, P, of each loop is calculated by dividing 1005 feet by the frequency in MHz. Table 5.2 shows the loop dimensions for 20 through 10 meters.

The PVC pipe horizontal cross support spans between opposite loop corners, and is 1.41 times the largest loop side length, S. Brass screws are used to hold the PVC together. If the horizontal PVC pipe sags excessively, reinforce it with lengths of 1 × 2 inch pressure-treated wood taped to the pipe.

To construct the antenna, start with

Table 5.2
Nested Loop Antenna Dimensions
75 Ω Matching Section Cable with 0.66 Velocity Factor (VF)

Band	*Freq (MHz)*	*Perimeter, P (ft)*	*Side, S (ft)*	*Cross Support (ft)*	*Distance From Center, D (ft)*	*Length, L of 75 Ω cable (ft)*
20 m	14.175	70.9	17.8	24.8	12.4	11.5
17 m	18.118	55.5	13.9	19.4	9.7	9.0
15 m	21.225	47.4	11.8	16.6	9.3	7.7
12 m	24.940	40.3	10.1	14.1	7.1	6.5
10 m	28.500	35.3	8.8	12.3	6.2	5.7

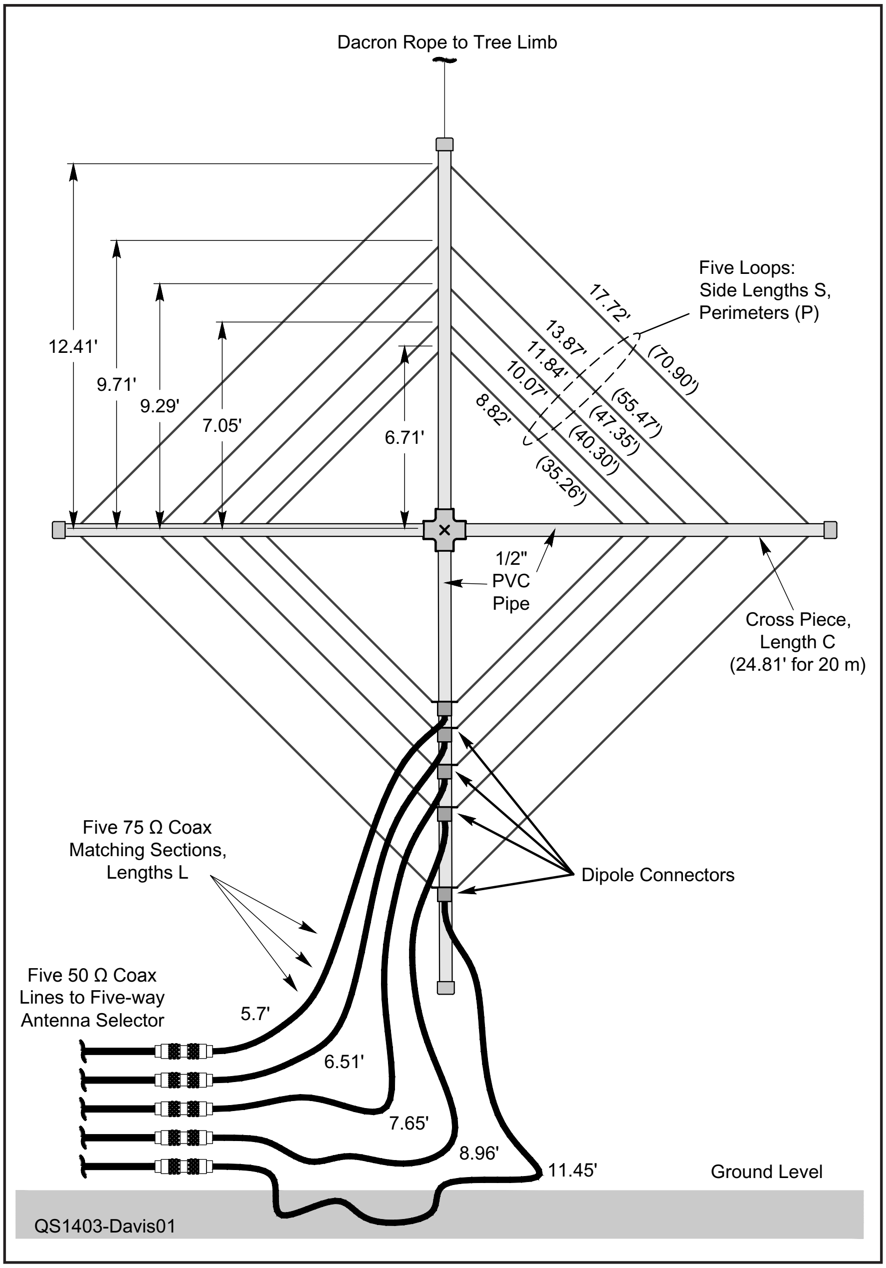

Figure 5.20 — The five-band version of the nested loops with construction notes. See the CD-ROM article for more construction details and a parts list.

the largest loop (20 meters). Cut a 70.9 foot piece of wire for the loop perimeter and divide it by 4 to determine the length, S, of each side. Arrange the wire on the PVC structure, temporarily taping it to find where the wire should pass through the PVC pipe. Drill holes through the pipe for the loop wire. After you run the wire through the holes, wrap a bit of electrical tape on each side of the wire next to the pipe to keep the wire from sliding and to give the pipe additional support. Repeat for each band in sequence from large to small loop perimeter.

At the feed point, rather than sliding the wires through the PVC pipe, use brass wood screws into the PVC to secure the ends of the wires. An SO-239 can be installed at this point or pigtails on the feed line can be attached to the loop wire. Be sure to waterproof this connection.

The loop feed point impedance is about 100 Ω, so individual λ/4 matching sections of 75 Ω coax (RG-59 or RG-11) can be used convert the impedance to 50 Ω. Table 5.2 gives the matching section lengths, taking into account velocity factor VF = 0.66 for solid polyethylene coaxial cable. The formula for the matching sections is L = (246 × VF)/f (MHz). A multiposition remote coax switch can be used to use a single feed line to the antenna with the matching sections connected between the loops and the switch.

5.2 SMALL LOOP ANTENNAS

A "small" loop can be considered to be simply a rather large coil, and the current distribution in such a loop is the same as in a coil. That is, the current has the same phase and the same amplitude in every part of the loop. To meet this condition, the total length of conductor in the loop must not exceed about 0.1 λ.

The electrically small loop antenna has existed in various forms for many years. Probably the most familiar form of this antenna is the ferrite *loopstick* found in portable AM broadcast-band receivers. Amateur applications of the small loop include direction finding, low-noise directional receiving antennas for 1.8 and 3.5 MHz, and small transmitting antennas. Because the design of transmitting and receiving loops requires some different considerations, the two situations are examined separately in this section. Applications of small loops are presented in the **Receiving and Direction-Finding Antennas** and the **Stealth and Limited-Space Antennas** chapters.

5.2.1 THE BASIC SMALL LOOP

What is and what is not a small loop antenna? By definition, the loop is considered electrically small when its total conductor length is less than 0.1 λ — 0.085 is the number used in this section. This size is based on the fact that the current around the perimeter of the loop must be in phase. When the winding conductor is more than about 0.085 λ long, this is no longer true. This constraint results in a very predictable figure-eight radiation pattern, shown in **Figure 5.21**.

The simplest loop is a 1-turn untuned loop with a load connected to a pair of terminals located in the center of one of the sides, as shown in **Figure 5.22**. How its pattern is developed is easily pictured if we look at some "snapshots" of the antenna relative to a signal source. **Figure 5.23** represents a loop from above, and shows the instantaneous radiated voltage wave. Note that points A and B of the loop are receiving the same instantaneous voltage. This means that no current will flow through the loop, because there is no current flow between points of equal potential. A similar analysis of **Figure 5.24**, with the loop turned 90° from the position represented in Figure 5.23, shows that this position of the loop provides maximum response. Of course, the voltage derived from the passing wave is small because of the small physical size of the loop. Figure 5.21 shows the ideal radiation pattern for a small loop.

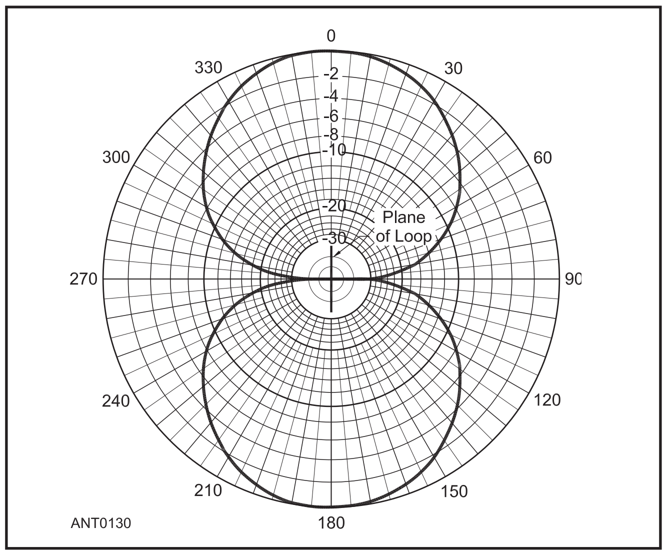

Figure 5.21 — Calculated small loop antenna radiation pattern.

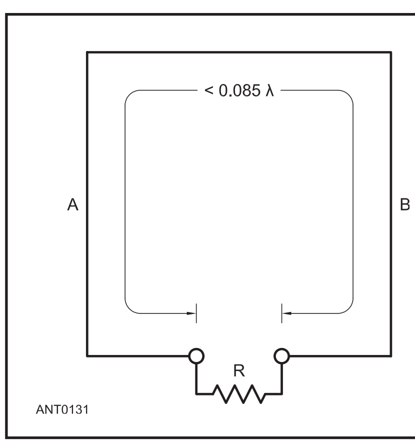

Figure 5.22 — Simple untuned small loop antenna.

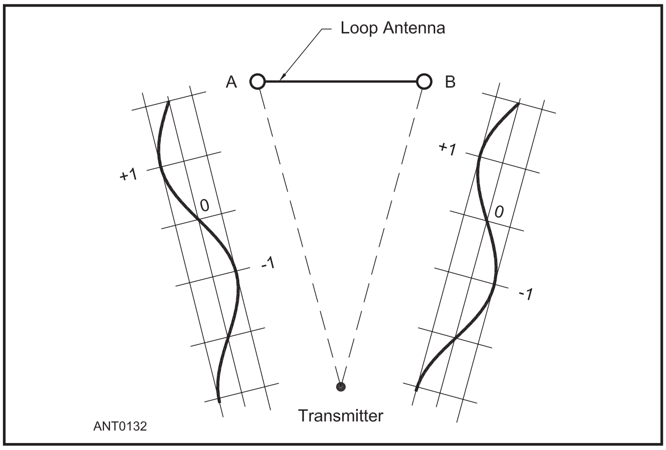

Figure 5.23 — Example of orientation of loop antenna that does not respond to a signal source (null in pattern).

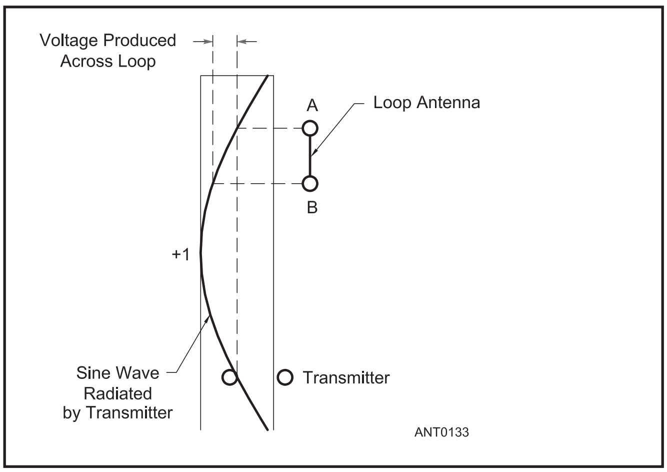

Figure 5.24 — Example of orientation of loop antenna for maximum response.

The voltage across the loop terminals is given by

$$V = \frac{2 \pi A N E \cos\theta}{\lambda} \qquad \text{(Eq 1)}$$

where

V = voltage across the loop terminals
A = area of loop in square meters
N = number of turns in the loop
E = RF field strength in volts per meter
θ = angle between the plane of the loop and the signal source (transmitting station)
λ = wavelength of operation in meters

This equation comes from a term called *effective height*. The effective height refers to the height (length) of a vertical piece of wire above ground that would deliver the same voltage to the receiver. The equation for effective height is

$$h = \frac{2 \pi N A}{\lambda} \qquad \text{(Eq 2)}$$

where h is in meters and the other terms are as for Eq 1.

A few minutes with a calculator will show that, with the constraints previously stated, the loop antenna will have a very small effective height. This means it will deliver a relatively small voltage to the receiver, even with a large transmitted signal.

5.2.2 TUNED LOOPS

We can tune the loop by placing a capacitor across the antenna terminals. This causes a larger voltage to appear across the loop terminals because of the Q of the parallel resonant circuit that is formed.

The voltage across the loop terminals is now given by

$$V = \frac{2 \pi A N E Q \cos\theta}{\lambda} \qquad \text{(Eq 3)}$$

where Q is the loaded Q of the tuned circuit, and the other terms are as defined above.

Most amateur loops are of the tuned variety. For this reason, all comments that follow are based on tuned-loop antennas, consisting of one or more turns. The tuned-loop antenna has some particular advantages. For example, it puts high selectivity up at the “front” of a receiving system, where it can significantly help factors such as dynamic range. Loaded Q values of 100 or greater are easy to obtain with careful loop construction.

Consider a situation where the inherent selectivity of the loop is helpful. Assume we have a loop with a loaded Q of 100 at 1.805 MHz. We are working a DX station on 1.805 MHz and are suffering strong interference from a local station 10 kHz away. Switching from a dipole to a small loop will reduce the strength of the off-frequency signal by 6 dB (approximately one S unit). This, in effect, increases the dynamic range of the receiver. In fact, if the off-frequency station were further off frequency, the attenuation would be greater.

Another way the loop can help is by using the nulls in its pattern to null out on-frequency (or slightly off-frequency) interference. For example, say we are working a DX station to the north, and just 1 kHz away is another local station engaged in a contact. The local station is to our west. We can simply rotate our loop to put its null to the west, and now the DX station should be readable while the local will be knocked down by 60 or more dB. This obviously is quite a noticeable difference. Loop nulls are very sharp and are generally noticeable only on ground-wave signals (more on this later).

Of course, this method of nulling will be effective only if the interfering station and the station being worked are not in the same direction (or in exact opposite directions) from our location. If the two stations were on the same line from our location, both the station being worked and the undesired station would be nulled out. Luckily the nulls are very sharp, so as long as the stations are at least 10° off axis from each other, the loop null will be usable.

A similar use of the nulling capability is to eliminate local noise interference, such as that from a light dimmer in a neighbor’s house. Just point the null at the offending light

Table 5.3
Inductance Equations for Short Coils (Loop Antennas)

Triangle:

$$L\,(\mu H) = 0.006\,N^2\,s\left[\ln\left(\frac{1.1547\,s\,N}{(N+1)\,\ell}\right) + 0.65533 + \frac{0.1348\,(N+1)\,\ell}{s\,N}\right]$$

Square:

$$L\,(\mu H) = 0.008\,N^2\,s\left[\ln\left(\frac{1.4142\,s\,N}{(N+1)\,\ell}\right) + 0.37942 + \frac{0.3333\,(N+1)\,\ell}{s\,N}\right]$$

Hexagon:

$$L\,(\mu H) = 0.012\,N^2\,s\left[\ln\left(\frac{2\,s\,N}{(N+1)\,\ell}\right) + 0.65533 + \frac{0.1348\,(N+1)\,\ell}{s\,N}\right]$$

Octagon

$$L\,(\mu H) = 0.016\,N^2\,s\left[\ln\left(\frac{2.613\,s\,N}{(N+1)\,\ell}\right) + 0.75143 + \frac{0.07153\,(N+1)\,\ell}{s\,N}\right]$$

where
N = number of turns
s = side length in cm
ℓ = coil length in cm

dimmer, and the noise should disappear.

Now that we have seen some possible uses of the small loop, let us look at the details of its design. First, the loop forms an inductor having a very small ratio of winding length to diameter. The equations for calculating inductance given in most radio handbooks assume that the inductor coil is longer than its diameter. However, F. W. Grover of the US National Bureau of Standards has provided equations for inductors of common cross-sectional shapes and small length-to-diameter ratios. (See the Bibliography at the end of this chapter.) Grover's equations are shown in **Table 5.3**. Their use will yield relatively accurate numbers; results are easily worked out with a scientific calculator or home computer.

The value of a tuning capacitor for a loop is easy to calculate from the standard resonance equations. The only matter to consider before calculating this is the value of distributed capacitance of the loop winding. This capacitance shows up between adjacent turns of the coil because of their slight difference in potential. This causes each turn to appear as a charge plate. As with all other capacitances, the value of the distributed capacitance is based on the physical dimensions of the coil. An exact mathematical analysis of its value is a complex problem. A simple approximation is given by Medhurst (see Bibliography) as:

$$C = HD \qquad \text{(Eq 4)}$$

Table 5.4
Values of the Constant H for Distributed Capacitance

Length to Diameter Ratio	*H*
0.10	0.96
0.15	0.79
0.20	0.78
0.25	0.64
0.30	0.60
0.35	0.57
0.40	0.54
0.50	0.50
1.00	0.46

where
C = distributed capacitance in pF
H = a constant related to the length-to-diameter ratio of the coil (**Table 5.4** gives H values for length-to-diameter ratios used in loop antenna work.)
D = diameter of the winding in cm

Medhurst's work was with coils of round cross section. For loops of square cross section the distributed capacitance is given by Bramslev (see Bibliography) as

$$C = 60S \qquad \text{(Eq 5)}$$

where
C = the distributed capacitance in pF
S = the length of the side in meters

If you convert the length in this equation to centimeters, you will find Bramslev's equation gives results in the same order of magnitude as Medhurst's equation.

This distributed capacitance appears as if it were a capacitor across the loop terminals. Therefore, when determining the value of the tuning capacitor, the distributed capacitance must be subtracted from the total capacitance required to resonate the loop. The distributed capacitance also determines the highest frequency at which a particular loop can be used, because it is the minimum capacitance obtainable.

5.2.3 ELECTROSTATICALLY SHIELDED LOOPS

Over the years, many loop antennas have incorporated an electrostatic shield. This shield generally takes the form of a tube around the winding, made of a conductive but nonmagnetic material (such as copper or aluminum). Its purpose is to maintain loop balance with respect to ground, by forcing the capacitance between all portions of the loop and ground to be

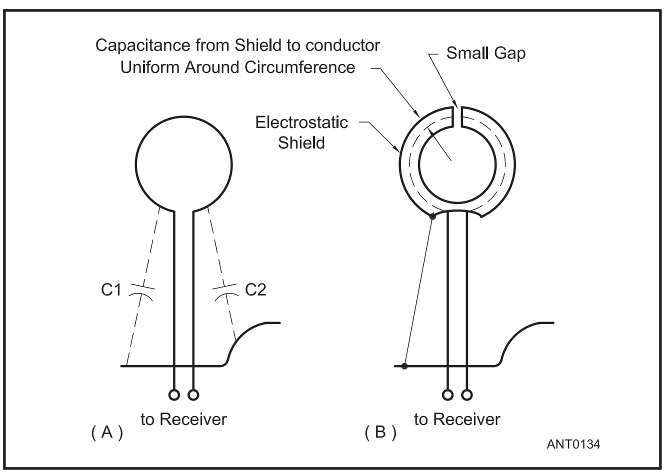

Figure 5.25 — At A, the loop is unbalanced by capacitance to its surroundings. At B, the use of an electrostatic shield overcomes this effect.

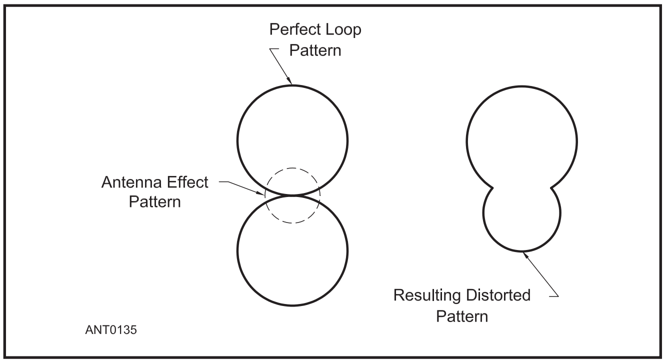

Figure 5.26 — Distortion in loop pattern resulting from antenna effect.

identical. This is illustrated in **Figure 5.25**. It is necessary to maintain electrical loop balance to eliminate what is referred to as the *antenna effect*. When the antenna becomes unbalanced it appears to act partially as a small vertical antenna. This vertical pattern gets superimposed on the ideal figure-eight pattern, distorting the pattern and filling in the nulls. The type of pattern that results is shown in **Figure 5.26**.

Adding the shield has the effect of somewhat reducing the pickup of the loop, but this loss is generally offset by the increase in null depth of the loops. Proper balance of the loop antenna requires that the load on the loop also be balanced. This is usually accomplished by use of a balun transformer or a balanced input preamplifier. One important point regarding the shield is that it cannot form a continuous electrical path around the loop perimeter, or it will appear as a shorted coil turn. Usually the insulated break is located opposite the feed point to maintain symmetry. Another point to be considered is that the shield should be of a much larger diameter than the loop winding, or it will lower the Q of the loop.

Various construction techniques have been used in making shielded loops. Genaille located his loop winding inside aluminum conduit, while True constructed an aluminum shield can around his winding. Others have used pieces of hardline to form a loop, using the outer conductor as a shield. DeMaw used flexible coax with the shield broken at the center of the loop conductor in a multi-turn loop for 1.8 MHz. Goldman uses another shielding method for broadcast receiver loops. His shield is in the form of a barrel made of hardware cloth, with the loop in its center. (See Bibliography for above references.) All these methods provide sufficient shielding to maintain the balance. It is important to consider the effect of the shield configuration on antenna Q. A short letter by N1DM in *QEX* (July/Aug 1998, see References) discusses the Q of a loop antenna with a U-type shield versus a full box shield. His data shows between 54% and 89% degradation of Q for the full box case on an otherwise identical antenna configuration.

Use of coax cable to construct the shield may add some additional capacitive components which will limit the loop's higher frequency tuning range. Those designing a loop of this type should consider this fact when selecting the loop inductance the need to take this parasitic capacitance (in addition to the distributed capacitance) to obtain the desired higher frequency tuning point.

It is possible, as Nelson shows, to construct an unshielded loop with good nulls (60 dB or better) by paying great care to symmetry.

5.2.4 LOOP Q

As previously mentioned, Q is an important consideration in loop performance because it determines both the loop bandwidth and its terminal voltage for a given field strength. The loaded Q of a loop is based on four major factors. These are (1) the intrinsic Q of the loop winding, (2) the effect of the load, (3) the effect of the electrostatic shield, and (4) the Q of the tuning capacitor.

The major factor is the Q of the winding of the loop itself. The ac resistance of the conductor caused by skin effect is the major consideration. The ac resistance for copper conductors may be determined from

$$R = \frac{0.996 \times 10^{-6} \sqrt{f}}{d} \qquad \text{(Eq 6)}$$

where

R = resistance in ohms per foot
f = frequency in Hz
d = conductor diameter in inches

The Q of the inductor is then easily determined by taking the reactance of the inductor and dividing it by the ac resistance. If you are using a multi-turn loop and are a perfectionist, you might also want to include the loss from conductor proximity effect. This effect is described in detail later in this chapter, in the section on transmitting loops.

Improvement in Q can be obtained in some cases by the use of Litz wire (short for *Litzendraht*). Litz wire consists of strands of individual insulated wires that are woven into bundles in such a manner that each conductor occupies each location in the bundle with equal frequency. The Litz wire has a reduced ac resistance when compared to an equivalent cross section solid or stranded wire by taking into account the skin depth of conductors as frequency increases. Litz wire's improvement in ac resistance is due to the fact that the insulated individual strands result in more area of the total cross section of the conductor being in the skin depth region than for an equivalent diameter solid or stranded wire. (Stranded wire at ac acts the same as a solid wire of the same outside diameter.) Over 60% of the ac current is in this skin depth region. Therefore skin depth is more important to the calculation of ac resistance than the total conductor diameter.

Figure 5.27 shows an example of the skin depth of a solid conductor with radius R and a piece of Litz wire with an equivalent radius R. By examining the figure you can see that the cross sectional area of the current carrying skin effect region is double that of the solid wire. Litz wire is available in many configurations and the determining factor for the selection of a particular Litz wire starts with determining the optimum diameter of the individual insulated wire strands

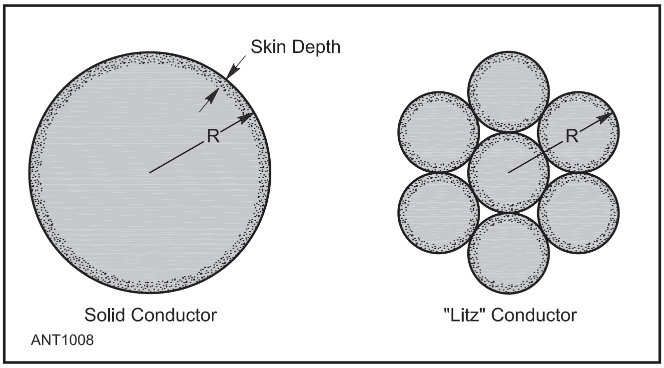

Figure 5.27 — Comparison of skin depth between conventional (A) and Litz wire (B).

Table 5.5
Optimum Sizes of Individual Wires Used in Litz Wire

Frequency Range	*Optimum AWG*
60 Hz to 1 kHz	28
1 kHz to 10 kHz	30
10 kHz to 20 kHz	33
20 kHz to 50 kHz	36
50 kHz to 100 kHz	38
100 kHz to 200 kHz	40
200 kHz to 350 kHz	42
350 kHz to 850 kHz	44
850 kHz to 1.4 MHz	46
1.4 MHz to 2.8 MHz	48

(After Table 2 from New England Wire Technologies “Litz Wire Technical Information”)

used in the construction of the particular cable. **Table 5.5** gives the values of optimum wire size based on frequency of use. When properly selected, Litz wire results in improved Q over solid or stranded wire of equivalent size, up to about 2.8 MHz. Above 2.8 MHz other effects quickly reduce the advantage of Litz wire. When using Litz wire it is important to realize that the ends of the Litz wire must be properly prepared so that all the strands of the wire are soldered to the connections of the capacitor and output connector. For those interested in the use of Litz wire the most common modern application is in high efficiency transformers and inductors in the kHz and low MHz range. Technical journals on transformer and magnetic design still present articles on the use of Litz wire with some regularity.

The Q of the tuned circuit of the loop antenna is also determined by the Q of the capacitors used to resonate it. In the case of air variables or dipped micas typically used this is not usually a problem. But if variable-capacitance diodes are used to remotely tune the loop, pay particular attention to the manufacturer’s specification for Q of the diode at the frequency of operation. The tuning diodes can have a significant effect on circuit Q.

Now we consider the effect of load impedance on loop Q. In the case of a directly coupled loop (as in Figure 5.22), the load is connected directly across the loop terminals, causing it to be treated as a parallel resistance in a parallel-tuned RLC circuit. Obviously, if the load is of a low value, the Q of the loop will be low. A simple way to correct this is to use a transformer to step up the load impedance that appears across the loop terminals. In fact, if we make this transformer a balun, it also allows us to use our unbalanced receivers with the loop and maintain loop symmetry. Another solution is to use what is referred to as an inductively coupled loop, such as DeMaw’s four-turn electrostatically shielded loop. A one-turn link is connected to the receiver. This turn is wound with the four-turn loop. In effect, this builds the transformer into the antenna.

Another solution to the problem of load impedance on loop Q is to use an active preamplifier with balanced input and unbalanced output. This method also has the advantage of amplifying the low-level output voltage of the loop to where it can be used with a receiver of even mediocre sensitivity.

There has been a significant amount of technical interest in this area over the last 20 years driven by low band DXers and AM band DXers. They have discovered that one of the critical issues to maximize performance of a loop/preamp combination is the dynamic range of the preamp. A poorly designed preamp may overload from local broadcast stations or have a poor noise figure itself which limits the ultimate performance observed with the loop antenna. Chris Trask, N7ZWY, has covered this in some detail with regards to the shortwave bands. Trask’s excellent two-part article in the July/Aug and Sep/Oct 2003 issues of *QEX* (see References) includes a discussion of preamp requirements in Part 2. His design resulted in a noise figure of less than 2 dB from 6 to 14 MHz while obtaining a third order intercept of +5 dBm. The interested experimenter should consult that article.

In fact, the Q of the loop when used with a balanced preamplifier having high input impedance may be so high as to be unusable in certain applications. An example of this situation would occur where a loop is being used to receive a 5 kHz wide AM signal at a frequency where the bandwidth of the loop is only 1.5 kHz. In this case the detected audio might be very distorted. The solution to this is to put a Q-degrading resistor across the loop terminals to match the antennas bandwidth to the signal. The chapter **Receiving and Direction-Finding Antennas** also contains information about preamplifiers for use with loop antennas.

5.3 FERRITE-CORE LOOP ANTENNAS

The ferrite-core loop antenna is a special case of the air-core receiving loops considered up to now. Because of its use in every AM broadcast-band portable radio, the ferrite-core loop is, by quantity, the most popular form of the loop antenna. Broadcast-band reception is far from its only use; it is commonly found in radio-direction-finding equipment and low-frequency-receiving systems (below 500 kHz) for time and frequency standard systems. In recent years, design information on these types of antennas has been a bit sparse in the amateur literature, so the next few paragraphs are devoted to providing some details.

Ferrite-loop antennas are characteristically very small compared to the frequency of use. For example, a 3.5-MHz version may be in the range of 15 to 30 cm long and about 1.25 cm in diameter. Earlier in this chapter, effective height was introduced as a measure of loop sensitivity. The effective height of an air-core loop antenna was given by Eq 2.

If an air-core loop is placed in a field, in essence it cuts the lines of flux without disturbing them (**Figure 5.28A**). On the other hand, when a ferrite (magnetic) core is placed in the field, the nearby field lines are redirected into the loop (Figure 5.28B). This is because the reluctance of the ferrite material is less than that of the surrounding air, so the nearby flux lines tend to flow through the loop rather than through the air. (*Reluctance* is the magnetic analogy of resistance, while *flux* is analogous to current.) The reluctance is inversely proportional to the permeability of the rod core, μ_{rod}. (In some texts the rod permeability is referred to as effective permeability, μ_{eff}). This effect modifies the equation for effective height of a ferrite-core loop to

$$h = \frac{2 \pi N A \mu_{rod}}{\lambda} \qquad \text{(Eq 7)}$$

where
- h = effective height (length) in meters
- N = number of turns in the loop
- A = area of loop in square meters
- μ_{rod} = permeability of the ferrite rod
- λ = wavelength of operation in meters

This obviously is a large increase in "collected" signal. If the rod permeability were 90, this would be the same as making the loop area 90 times larger with the same number of turns. For example, a 1.25-cm diameter ferrite-core loop would have an effective height equal to an air-core loop 22.5 cm in diameter (with the same number of turns).

By now you might have noticed we have been very careful to refer to rod permeability. There is a very important reason for this. The permeability that a rod of ferrite exhibits is a combination of the material permeability or μ, the shape of the rod, and the dimensions of the rod. In ferrite rods, μ is sometimes referred to as initial permeability, μ_i, or toroidal permeability, μ_{tor}. Because most amateur ferrite loops are in the form of rods, we will discuss only this shape.

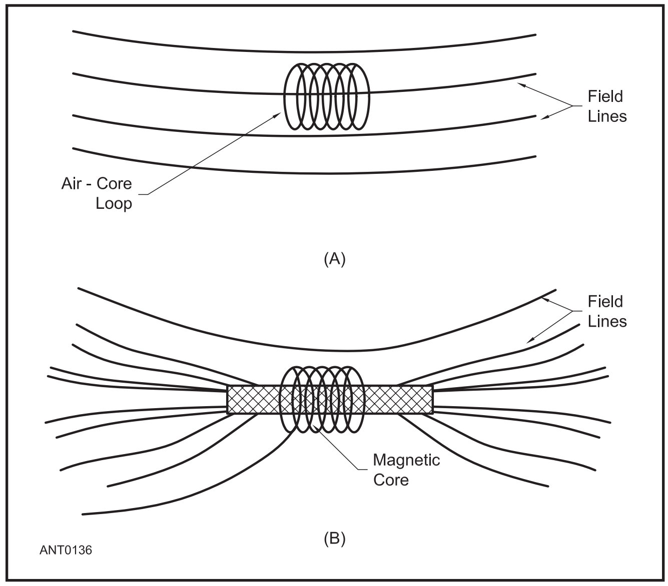

Figure 5.28 — At A, an air-core loop has no effect on nearby field lines. B illustrates the effect of a ferrite core on nearby field lines. The field is altered by the reluctance of the ferrite material.

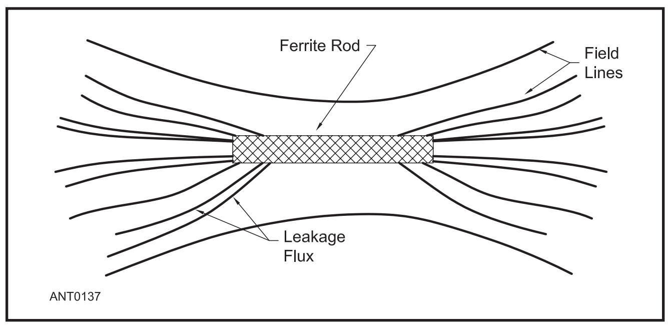

Figure 5.29 — Example of magnetic field lines near a practical ferrite rod, showing leakage flux.

The reason that μ_{rod} is different from μ is a very complex physics problem that is well beyond the scope of this book. For those interested in the details, books by Polydoroff and by Snelling cover this subject in considerable detail. (See Bibliography.) For our purposes a simple explanation will suffice. The rod is in fact not a perfect director of flux, as is illustrated in **Figure 5.29**. Note that some lines impinge on the sides of the core and also exit from the sides. These lines therefore would not pass through all the turns of the coil if it were wound from one end of the core to the other. These flux lines are referred to as *leakage flux*, or sometimes as flux leakage.

Leakage flux causes the flux density in the core to be non-uniform along its length. From Figure 5.29 it can be seen that the flux has a maximum at the geometric center of the

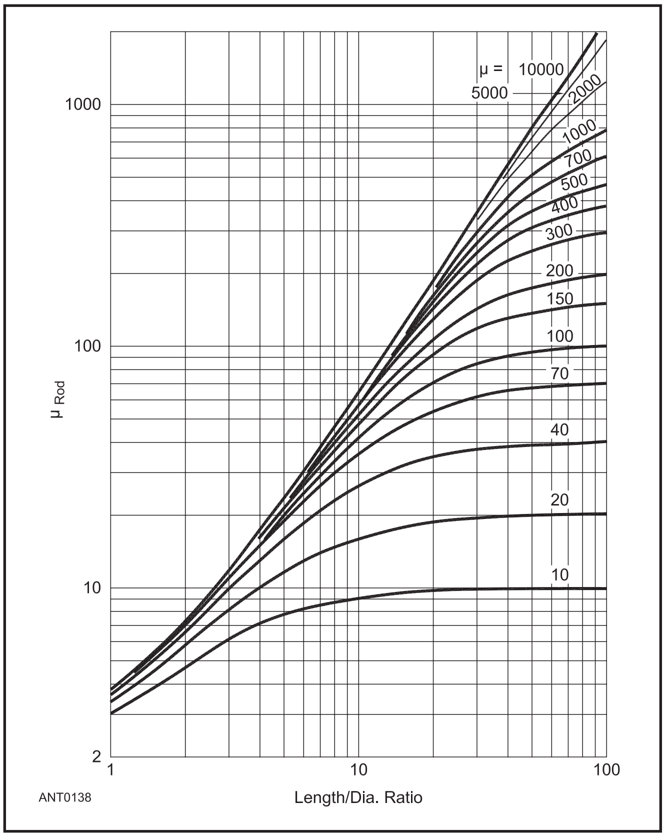

Figure 5.30 — Rod permeability, μ_{rod}, versus material permeability, μ, for different rod length-to-diameter ratios.

length of the core, and decreases as the ends of the core are approached. This causes some noticeable effects. As a short coil is placed at different locations along a long core, its inductance will change. The maximum inductance exists when the coil is centered on the rod. The Q of a short coil on a long rod is greatest at the center. On the other hand, if you require a higher Q than this, it is recommended that you spread the coil turns along the whole length of the core, even though this will result in a lower value of inductance. (The inductance can be increased to the original value by adding turns.) **Figure 5.30** gives the relationship of rod permeability to material permeability for a variety of values.

The change in μ over the length of the rod results in an adjustment in the term μ_{rod} for its so called "free ends" (those not covered by the winding). This adjustment factor is given by

$$\mu' = \mu_{rod}\sqrt{a / b} \qquad \text{(Eq 8)}$$

where
- μ' = the corrected permeability
- a = the length of the core
- b = the length of the coil

This value of μ' should be used in place of μ_{rod} in Eq 7 to obtain the most accurate value of effective height.

All these variables make the calculation of ferrite loop antenna inductance somewhat less accurate than for the air-core version. The inductance of a ferrite loop is given by

$$L = \frac{4\pi N^2 A \mu_{rod} \times 10^{-4}}{\ell} \qquad \text{(Eq 9)}$$

where
- L = inductance in μH
- N = number of turns
- A = cross-sectional area of the core in square mm
- μ_{rod} = permeability of the ferrite rod
- ℓ = magnetic length of core in mm

Experiments indicate that the winding diameter should be as close to that of the rod diameter as practical in order to maximize both inductance value and Q. By using all this information, we may determine the voltage at the loop terminals and its signal-to-noise ratio (SNR). The voltage may be determined from

$$V = \frac{2\pi A N \mu' Q E}{\lambda} \qquad \text{(Eq 10)}$$

where
- V = output voltage across the loop terminals
- A = loop area in square meters
- N = number of turns in the loop winding
- μ' = corrected rod permeability
- Q = loaded Q of the loop
- E = RF field strength in volts per meter
- λ = wavelength of operation in meters

Lankford's equation for the sensitivity of the loop for a 10 dB SNR is

$$E = \frac{1.09 \times 10^{-10} \lambda \sqrt{f L b}}{A N \mu' \sqrt{Q}} \qquad \text{(Eq 11)}$$

where
- f = operating frequency in Hz
- L = loop inductance in henrys
- b = receiver bandwidth in Hz

Similarly, Belrose gives the SNR of a tuned loop antenna as

$$SNR = \frac{66.3 N A \mu_{rod} E}{\sqrt{b}} \sqrt{\frac{Qf}{L}} \qquad \text{(Eq 12)}$$

From this, if the field strength E, μ_{rod}, b, and A are fixed, then Q or N must increase (or L decrease) to yield a better SNR. Higher sensitivity can also be obtained (especially at frequencies below 2000 kHz) by bunching ferrite cores together to increase the loop area over that which would be possible with a single rod. Bowers and Bryant have built both 4 and 8-foot long ferrite loops for broadcast band DX'ing by using multiple ferrites cores bunched together and stacked lengthwise. Their 8-foot loop used over 100 pounds of ferrite cores. Marris, G2BZQ, also adopted the multiple core approach on 160 and 80 meters, constructing a 18 inch long multiple core ferrite loop using twelve ferrite rods each 6 inches long and ½ inch in diameter. He reported that there was no need for a preamp even when used for transatlantic reception. Marris noted that it is important to prepare the ends of the rods or cores before bonding them together. From a magnetic design point of view this is important to reduce the physical length of the air gaps between the individual lengthwise rods. This will maintain the best magnetic path (and maintain apparent permeability) for the antenna rods.

High sensitivity is important because loop antennas are not the most efficient collectors of signals, but they do offer improvement over other receiving antennas in terms of SNR. For this reason, you should attempt to maximize the SNR when using a small loop receiving antenna. In some cases there may be physical constraints that limit how large you can make a ferrite-core loop.

After working through Eq 11 or 12, in many cases you might find you still require some increase in antenna system gain to effectively use your loop. In these cases the addition of a low noise, high dynamic range preamplifier may be quite valuable even on the lower frequency bands where they are not commonly used.

The electrostatic shield discussed earlier with reference to air-core loops can be used effectively with ferrite-core loops. The question of how big this shield should be is hard to answer without some experimentation. A good starting point is found in Langford-Smith's book in which he recommends the shield diameter be at least twice the outside diameter of the coil. As in the air-core loop, a shield will reduce electrical noise and improve loop balance.

5.4 LOOP ANTENNA ARRAYS

Arrays of loop antennas, both in combinations with each other and with other antenna types, have been used for many years. The arrays are generally used to cure some "deficiency" in the basic loop for a particular application, such as a 180° ambiguity in the null direction, low sensitivity, and so forth.

5.4.1 A SENSING ELEMENT

For direction-finding applications the single loop suffers the problem of having two nulls that are 180° apart. This leads to an ambiguity of 180° when trying to find the direction to a transmitting station from a given location. A sensing element (often called a *sense antenna*) may be added to the loop, causing the overall antenna to have a cardioid pattern and only one null. The sensing element is a small vertical antenna whose height is equal to or greater than the loop effective height. This vertical is physically close to the loop, and when its omnidirectional pattern is adjusted so that its amplitude and phase are equal to one of the loop lobes, the patterns combine to form a cardioid. This antenna can be made quite compact by use of a ferrite loop to form a portable DF antenna for HF direction finding. The chapter **Receiving and Direction-Finding Antennas** contains additional information and construction projects using sensing elements.

5.4.2 PHASED ARRAYS OF LOOPS

A more advanced array that can develop more diverse patterns consists of two or more loops. Their outputs are combined through appropriate phasing lines and combiners to form a phased array.

5.4.3 CROSSED LOOPS

Two loops mounted perpendicular to each other can also be formed into an array that can be rotated without physically turning the loops themselves. This method was developed by Bellini and Tosi in 1907 and performs this apparently contradictory feat by use of a special transformer called a *goniometer*. The goniometer is basically has three coils, two fixed coils at right angles to each other which are connected to the appropriate loop antennas and a rotating coil centered on the other two. The two fixed coils can basically be thought of as transferring the signals from the antenna to the rotating coil The rotating coil then couples to these and based on the signal strength on each coil can determine the actual direction of the incoming signal. The goniometer is described in more detail in the chapter **Receiving and Direction Finding Antennas**. For those with an experimental bent Anderson published a construction article for a 160 meter crossed loop system including goniometer in Volume 1 of the *ARRL Antenna Compendium*. He used a completely balanced system using shielded twisted pair transmission line to a receiver with balanced inputs and also noted the better performance of these loops when electrostatically shielded.

5.4.4 SPACED LOOP ARRAYS

The use of multiple tuned loops in arrays is practical. In most cases these arrays use phasing lines to create a pattern with a deep notch in a desired direction. AM band DXers use this technique to null out nearby stations to allow reception of DX. Tuned arrays use techniques similar to those used in phasing vertical antennas with delay lines. Of course the fact that a loop antenna is not radiating equally in all azimuths as a vertical antenna must be accounted for in designing these arrays and calculating the resulting antenna patterns.

5.4.5 APERIODIC LOOP ARRAYS

The aperiodic loop array is a wide-band antenna. This type of array is useful over at least a decade of frequency, such as 2 to 20 MHz. Unlike most of the loops discussed up to now, the loop elements in an aperiodic array are un-tuned. Such arrays have been used commercially for many years. One loop used in such an array is shown in **Figure 5.31**. This loop is quite different from all the loops discussed so far in

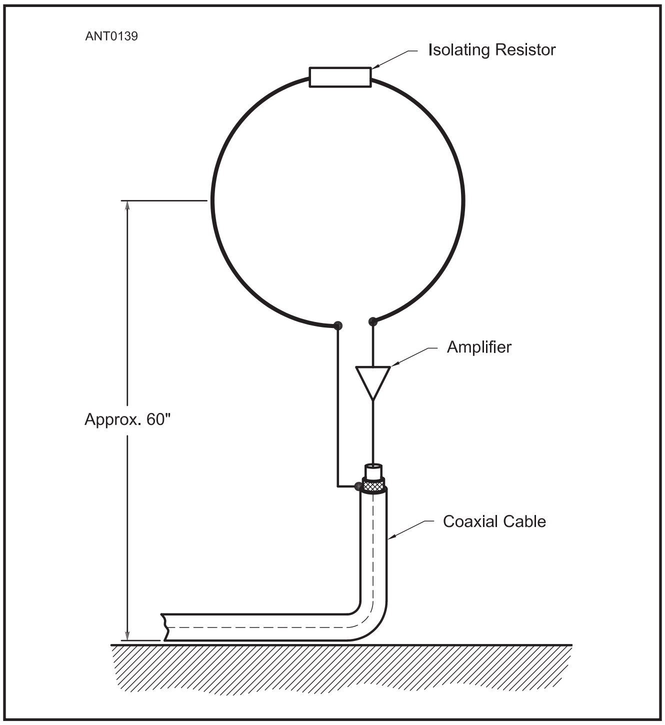

Figure 5.31 — A single wide-band loop antenna used in an aperiodic array.

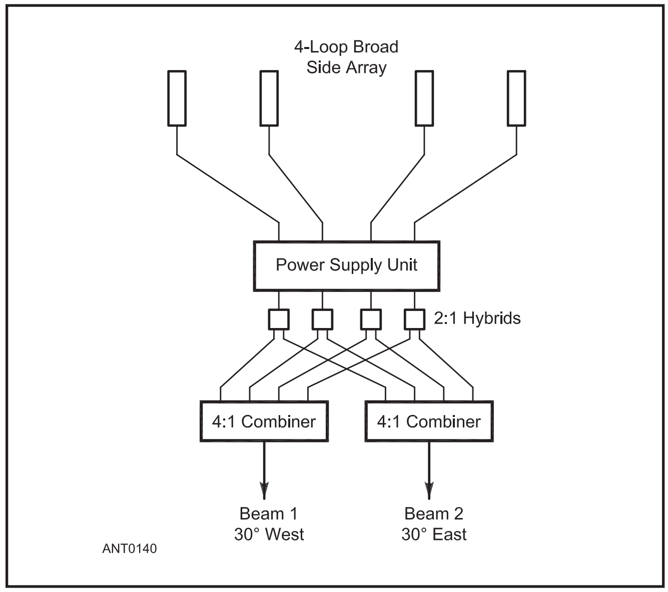

Figure 5.32 — Block diagram of a four-loop broadside array with dual beams separated by 60° in azimuth.

this chapter because its pattern is not the familiar Figure-8. rather, it is omnidirectional.

The antenna is omnidirectional because it is purposely unbalanced, and also because the isolating resistor causes the antenna to appear as two closely spaced short monopoles. The loop maintains the omnidirectional characteristics over a frequency range of at least four or five to one. These loops, when combined into end-fire or broadside phased arrays, can provide quite impressive performance. A commercially made end-fire array of this type consisting of four loops equally spaced along a 25-meter baseline can provide gains in excess of 5 dBi over a range of 2 to 30 MHz. Over a considerable portion of this frequency range, the array can maintain F/B ratios of 10 dB. Even though the commercial version is very expensive, an amateur version can be constructed using the information provided by Lambert. One interesting feature of this type of array is that, with the proper combination of hybrids and combiners, the antenna can simultaneously feed two receivers with signals from different directions, as shown in **Figure 5.32**. This antenna may be especially interesting to one wanting a directional receiving array for two or more adjacent amateur bands.

For those with a interest in the more exotic antennas an array can be constructed with a non-uniform spacing to enhance a particular parameter of the array. For example, Collins has described a professional direction finding array which uses the log function for setting spacing between loops (this is analogous to the spacing of the elements in a log periodic dipole array). In his design the array of loops are used to form a multi-direction rosette consisting of six arms in which each arm uses log periodic spacing of the loop antennas from a central point. This leads to a more uniform antenna gain over the frequency range of the antenna array as opposed to the periodic gain and front to back ratio for arrays made from antennas spaced uniformly along an axis.

5.5 SMALL TRANSMITTING LOOP ANTENNAS

The electrically small transmitting-loop antenna involves some different design considerations compared to receiving loops. Unlike receiving loops, the size limitations of the antenna are not as clearly defined. For most purposes, any transmitting loop whose physical circumference is less than ¼ λ can be considered "small." In most cases, as a consequence of their relatively large size (when compared to a receiving loop), transmitting loops have a non-uniform current distribution along their circumference. This leads to some performance changes from a receiving loop.

The transmitting loop is a parallel-tuned circuit with a large inductor acting as the radiator. As with the receiving loop, the calculation of the transmitting-loop inductance may be carried out with the equations in **Table 5.6**. Avoid equations for long solenoids found in most texts. Other fundamental equations for transmitting loops are given in Table 5.6.

In the March 1968 *QST*, Lew McCoy, W1ICP, introduced the so-called "Army Loop" to radio amateurs. This was an amateur version of a loop designed for portable use by Patterson of the US Army and described in 1967. The Army Loop is diagrammed in **Figure 5.33A**, showing that this is a parallel tuned circuit fed by a tapped-capacitance impedance-matching network.

The Hart "high-efficiency" loop was introduced in the June 1986 *QST* by Ted Hart, W5QJR. It is shown schematically in Figure 5.33B and has the series-tuning capacitor separate from the matching network. The Hart matching network is basically a form of gamma match. Other designs have used a smaller loop connected to the transmission line to couple into the larger transmitting loop as shown in Figure 5.33C. In addition, Steve Yates, AA5TB, has published a website (**www.aa5tb.com/loop.html**) with a great deal of information on these small antennas and links to many designs.

The approximate radiation resistance of a loop in ohms is given by

$$R_R = 3.12 \times 10^4 \left(\frac{N\,A}{\lambda^2} \right)^2 \qquad \text{(Eq 13)}$$

where

N = number of turns
A = area of loop in square meters
λ = wavelength of operation in meters

The radiation resistance of a small transmitting loop is usually very small. For example, a 1-meter diameter, single-turn circular loop has a radius of 0.5 meters and an enclosed area of $\pi \times 0.5^2 = 0.785$ m^2. Operated at 14.0 MHz, the free-space wavelength is 21.4 meters and this leads to a computed radiation resistance of only $3.12 \times 10^{-4} (0.785/21.4^2)^2 = 0.092\ \Omega$.

Unfortunately the loop also has losses, both ohmic and from skin effect. By using this information, the radiation efficiency of a loop can be calculated from

$$\eta = \frac{R_R}{R_R + R_L} \qquad \text{(Eq 14)}$$

where

η = antenna efficiency
R_R = radiation resistance in Ω
R_L = loss resistance in Ω, which includes the loop's conductor loss plus the loss in the series-tuning capacitor.

A simple ratio of R_R versus R_L shows the effects on the efficiency, as can be seen from **Figure 5.34**. The loss resistance is primarily the ac resistance of the conductor. This can be calculated from Eq 6. A transmitting loop generally requires the use of copper conductors of at least ¾ inch in diameter in order to obtain reasonable efficiency. Tubing is as useful as a solid conductor because high-frequency currents flow only along a very small depth of the surface of the conductor; the center of the conductor has almost no effect on current flow.

Note that the R_L term above also includes the effect of the tuning capacitor's loss. Normally, the unloaded Q of a capacitor can be considered to be so high that any loss in the tuning capacitor can be neglected. For example, a very high-quality tuning capacitor with no mechanical wiping contacts, such as

Table 5.6
Transmitting Loop Equations

$$X_L = 2\,\pi\,f\,L \text{ ohms}$$

$$Q = \frac{f}{\Delta f} = \frac{X_L}{2(R_R + R_L)}$$

$$R_R = 3.12 \times 10^4 \left(\frac{NA}{\lambda^2} \right)^2 \text{ ohms}$$

$$V_C = \sqrt{P\,X_L Q}$$

$$I_L = \sqrt{\frac{PQ}{X_L}}$$

where

X_L = inductive reactance in ohms
f = frequency in Hz
Df = bandwidth in Hz
R_R = radiation resistance in ohms
R_L = loss resistance in ohms (see text)
N = number of turns
A = area enclosed by loop in square meters
l = wavelength at operating frequency in meters
V_C = voltage across capacitor
P = power in watts
I_L = resonant circulating current in the loop

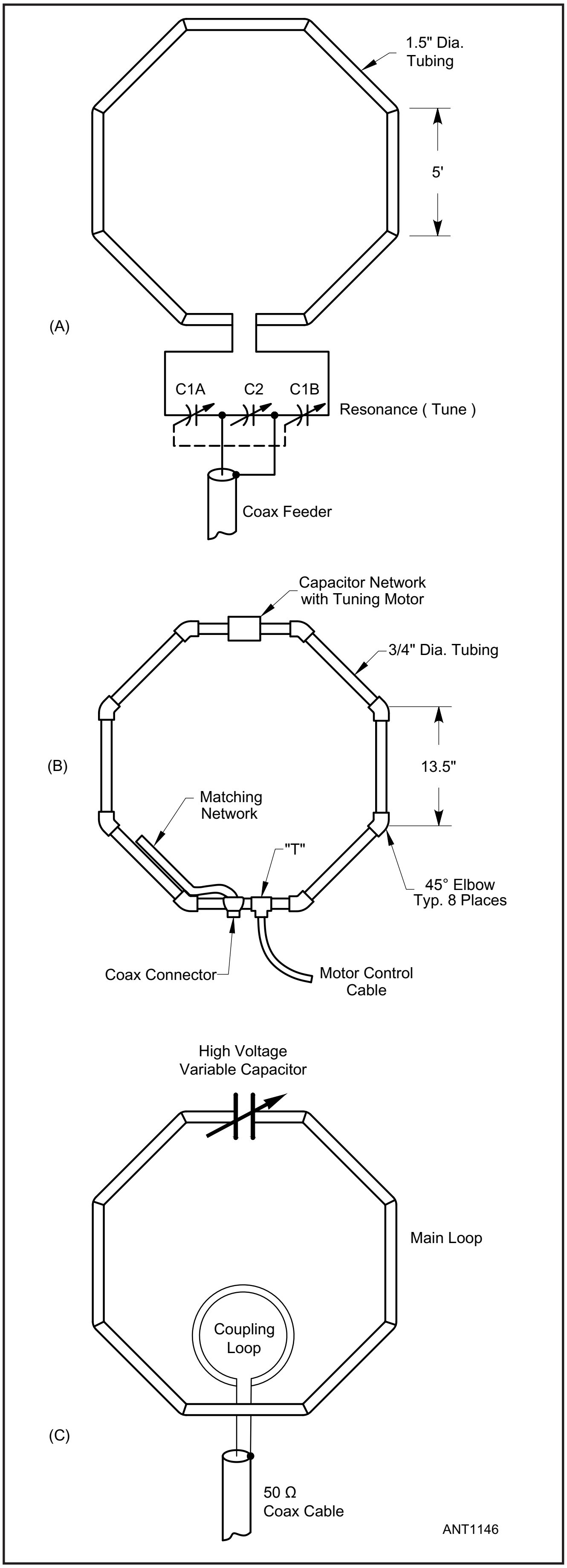

Figure 5.33 At A, a simplified diagram of the Army Loop. At B, the W5QJR loop. At C, using a smaller loop connected to the transmission line to couple into the larger transmitting loop.

a vacuum-variable or a transmitting butterfly capacitor, might have an unloaded Q of about 5000. This implies a series loss resistance of less than about 0.02 Ω for a capacitive reactance of 100 Ω. This relatively tiny loss resistance can become significant, however, when the radiation resistance of the loop is only on the order of 0.1 Ω! Practical details for curbing capacitor losses are covered later in this chapter.

At this point you may ask the question, what radiation efficiency can reasonably be expected from a small loop. Austin, Boswell, and Perks published a short paper discussing loss mechanisms for small loops (see the Bibliography) recognizing the extremely low radiation resistance made any resistive losses a major factor in antenna efficiency. Losses in the tuning capacitor contacts were found to be a major source of resistive loss. Ground losses were found to decrease rapidly as the loop was raised above ground and inconsequential above 0.1 λ. Those authors also used a toroidal coupling transformer to couple to the loop.

In addition, Boswell, Tyler and White published an article in a professional journal which considers the efficiency of a simple 1 meter diameter loop made from (22 mm diameter copper tube) over 80 through 30 meters. Their results were 0.25 percent on 80 meters and 18 percent on 30 meters. The low numbers should not preclude considering the loop as in many cases this is the only reasonable solution to transmitting for the amateurs in a restricted space antenna situation. It is important to note that small transmitting loops (like their receiving cousins) have narrow 2:1 SWR bandwidth, meaning if you wish to change frequency across a wide range of frequencies, expect to have to do some tuning. In commercial loops this is usually done remotely using a small stepper or gear motor to rotate an appropriate capacitor.

In the case of multi-turn loops there is an additional loss related to a term called *proximity effect*. The proximity effect occurs in cases where the turns are closely spaced (such as being spaced one wire diameter apart). As these current-carrying conductors are brought close to each other, the

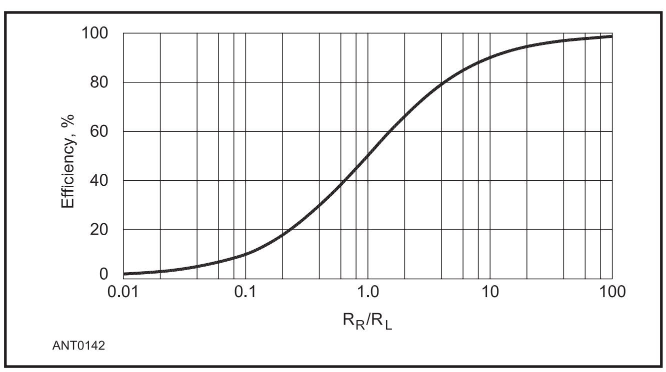

Figure 5.34 — Effect of ratio of R_R/R_L on loop efficiency.

current density around the circumference of each conductor gets redistributed. The result is that more current per square meter is flowing at the surfaces adjacent to other conductors. This means that the loss is higher than a simple skin-effect analysis would indicate, because the current is bunched so it flows through a smaller cross section of the conductor than if the other turns were not present.

As the efficiency of a loop approaches 90%, the proximity effect is less serious. But unfortunately, the less efficient the loop, the worse the effect. For example, an 8-turn transmitting loop with an efficiency of 10% (calculated by the skin-effect method) actually only has an efficiency of 3% because of the additional losses introduced by the proximity effect. If you are contemplating construction of a multi-turn transmitting loop, you might want to consider spreading the conductors apart to reduce this effect. G. S. Smith includes graphs that detail this effect in his 1972 IEEE paper and Trask, N7ZWY, examined the details of this loss for receiving antennas and recommends spacing turns at least five wire diameters to reduce this effect. His recommendation also applies to the transmitting variety of the loop antenna.

The components in a resonated transmitting loop are subject to both high currents and voltages as a result of the large circulating currents found in the high-Q tuned circuit formed by the antenna. This makes it important that any fixed capacitors have a high RF current rating, such as transmitting micas or the Centralab 850 series. Be aware that even a 100-W transmitter can develop currents in the tens of amperes, and voltages across the tuning capacitor in excess of 10,000 V. This consideration also applies to any conductors used to connect the loop to the capacitors. A piece of #14 AWG may create more loss than the rest of the loop conductor!

It is therefore best to use copper strips or large diameter wire to make any connections. Make the best electrical connection possible, using soldered or welded joints. Using nuts and bolts should be avoided, because at RF these joints generally have high resistance, especially after being subjected to weathering. Trask has also noted that some flexible copper tubing is made from a lead/copper alloy. This should be avoided due to increased resistivity. Trask recommended rigid copper tubing, refrigeration tubing or large copper wire be used.

An unfortunate consequence of having a small but high-efficiency transmitting loop is high loaded Q, and therefore limited bandwidth. This type of antenna may require retuning for frequency changes as little as 5 kHz. If you are using any wide-band mode such as AM or FM, this might cause fidelity problems and you might wish to sacrifice a little efficiency to obtain the required bandwidth.

A special case of the transmitting loop is that of the ferrite-loaded loop. This is a logical extension of the transmitting loop if we consider the improvement that a ferrite core makes in receiving loops. Unfortunately the transition to a transmitting antenna for the ferrite loaded loop is not a minor issue. Among the concerns is the saturation of the magnetic core. This often leads to defining the need for a rather large core that is larger than typical commercial ferrites available.). Recently Simpson and collaborators have been working on transmitting loops using egg-shaped ferrite cores with volumes of 2.2 cubic feet for use in a 2 MHz transmitting application. They have reported some success but the efficiency of these antennas is not high (<3%) and the cores are very heavy (622 pounds) for a power rating of 5 W. Along with the problem of having a very limited bandwidth this may limit the practical application of this type of antenna for amateurs in the foreseeable future.

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