the Quad antenna: part 1, general concepts

A comprehensive study of this popular antenna

This is the first in a series of articles on the Quad antenna family. In this series I will attempt to:

- clarify the concepts of Quad family antenna design.
- set forth Quad theory to the extent needed for practical design.
- provide easily used design data for a range of practical designs, medium frequency (mf) to very high frequency (VHF).
- provide data on practical construction to eliminate current physical weakness problems.

Included are:

- concepts of the loop family
- circular loops; octagonal loops
- circular loop arrays; octagonal arrays
- the Quad loop family
- arrays of Quad loops
- the triangular loop family
- triangular loop arrays
- ground effects on loops and arrays
- multifrequency loop designs
- other loop designs
- loops and array construction techniques

There will be several installments on the elements of theory and design data, each dealing with a single member of the Quad family.

Quad versus Yagi

The Yagi is the most popular type of Amateur directive antenna. Surveys on the hf bands show that over half of all stations use some form of Yagi. Three-element triband designs with traps for band isolation are the most common.

The Quad, second in popularity, is usually a two-element design using the square configuration. Many are single band, others are two or three single-band antennas on a common boom. True multiband Quad elements have been designed, but are rarely used.

The lower portions of the hf band tend to favor delta or triangular loop Quads that need only a single high support. The circular loop is popular on VHF. But total usage is about one-fourth that of the Yagi — some 12 to 15 percent of all installations (this includes all types of antennas, not just Yagis). Commercial use of Quads is limited and they are relatively low sales items on the Amateur market.

The pros and cons of using a Quad are often debated. The most common reason given for using a Quad is that it is a good directive antenna which can be built from locally available materials. It's fun to experiment with and has a reputation for good performance at low height. Long-time Quad users seem to stay with the design because they like the performance.

Three reasons usually given for not using a Quad are: susceptibility to damage during high winds, lack of space, and lack of design data for the high-performance types. In actuality, these are weak reasons for rejecting this antenna. First, the wind damage factor can be reduced by solving aerodynamic and mechanical design problems. Second, for a given gain, the Quad can have a smaller turning radius than a Yagi. This allows it to fit into smaller places, and makes it easier to obtain gain at lower frequencies. Finally, there is an enormous amount of literature covering all elements of Quad theory, design, performance, and construction.

Unfortunately, Quad literature tends to be fragmented. The theory and most precise design and performance data are written by scientists and engineers; the practical construction data appears in Amateur

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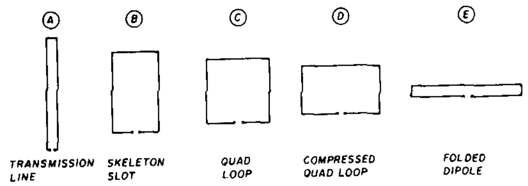

fig. 1. The square (4-sided) Quad family, conceptually formed by separating the sides of a two-wire open transmission line shorted at the far end. As a first approximation, all members behave as a transmission line.

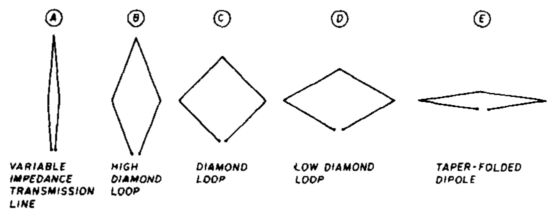

fig. 2. The diamond Quad family, formed by changing the separation of transmission line sides at the midpoint. Again, all members behave as a transmission line. Properties are very close to those of the square Quad family.

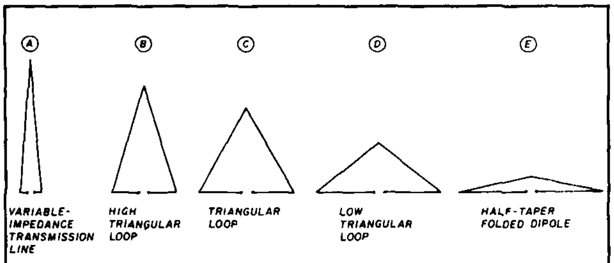

fig. 3. Triangular loop family, formed by changing the transmission line spacing at the feed point. Transmission line behaviour indicates that the performance will be similar to the square and diamond loops.

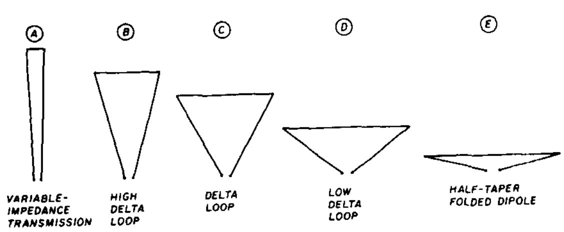

fig. 4. Triangular or the delta-loop family. Transmission-line spacing change is at the far end of the line.

Radio publications. The scientific data are hard to use in a practical sense because computers are needed to derive useful design values.

shapes of the Quad families

One of the easiest ways to approach the Quad concept is to start with a length of open-wire transmission line, shorted at one end and with a generator at the other, as shown at A in **fig. 1**. If the spacing between the sides of the line is progressively increased, the shapes of B to E successively develop. These shapes are representative of the rectangular Quad family. From A to E, the shapes are:

A shorted line
B skeleton slot
C Quad loop
D compressed Quad
E folded dipole

Instead of keeping the sides of the figures parallel, we could choose the midpoint of the sides as the point of inflection and create a second family with diamond-shaped members (**fig. 2** A to E). The center shape is the only one commonly named, the diamond Quad.

When three points of inflection are used instead of four, the result is two families of triangles as shown in **fig. 3**, A to E, and **fig. 4**, A to E. The center triangles in each figure are generally called delta loops, and are distinguished by whether they are fed at an apex or the midpoint of a side.

You can use more than four points of inflection. At the upper limit, the sides become smooth curves — the ellipses and circle of **fig. 5**, A to E. At the extremes, A is still a shorted transmission line section and E is a folded dipole.

It is not required that the shapes remain symmetrical, that the conductor always be along the perimeter of the figure, or that no part of the figure be re-entrant. Three possible shapes are shown in **fig. 6**. A is an acute triangle, B is a bent-side or bat-wing Quad, and C is a "line shortened" Quad.

The element need not be confined to a plane. The G4ZU Birdcage and the Swiss Quad, examples of non-planar elements, are basically variations of the bat-wing element of **fig. 6** with the apex of the bent element pulled out at right angles to the paper.

Finally, simple and symmetrical shapes are not the only ones that may be used. **Figure 7** shows some other designs: A uses a transmission-line section to reduce size, and B and C use a form of capacitive hat for the same purpose. D uses a form of open-wire feed to give choice of polarization.

conceptual approach to Quad performance

The end points of the major Quad families have well-known characteristics, providing a basis for a conceptual approach to Quad performance. Let's start by looking at the shorted transmission line.

First, suppose the generator frequency for the line of **fig. 1A** is varied. At very low frequencies, any practical line is basically a short circuit and has little effect. The resistive component of impedance is small, essentially zero. The reactance is also small, and inductive.

Both resistance and inductive reactance increase with frequency. This increase continues until the line becomes one-quarter wave long. At the frequency where this occurs, the input impedance is very high, and purely resistive. The line acts as a parallel resonant circuit. This is also known as the first resonance point.

For still higher frequencies, the resistance decreases, and the reactance decreases from its infinite value, but is now capacitive. When the line is one-half wave long, the reactance again becomes zero. The input resistance would be zero for a lossless line. This is the first series-resonance point. At slightly higher frequencies, the resistance and reactance increase, and the reactance is (again) inductive.

The pattern of alternating low and high impedance, and inductive and capacitive reactance, repeats at increasing frequencies. **Figure 8** shows the pattern with the peaks and nulls marking additional resonances.

At the other (shape) extreme is the folded dipole of **fig. 1E**. At low frequencies, its input resistance is very low. Its reactance is high, and capacitive. The antenna looks like a small capacitor in series with a small resistor.

Reactance decreases and resistance increases with increasing frequency, until the antenna is somewhat less than a half wavelength overall. At this point the reactance is zero, and the resistance is very nearly 300 ohms, just four times the resistance of a resonant single-wire antenna. This is the first resonance point.

At still higher frequencies, the resistance continues to increase. The reactance also increases, but is inductive in sign. With the antenna just less than a full wave overall, reactance again becomes zero, and impedance is very high.

This pattern also repeats, at close to each half wavelength. The points of low impedance and zero reactance mark the second, third, etc. current-feed resonances, and the high impedance points to the voltage-feed resonances.

frequency/size/pattern relationship

Before going on, let's consider the effect that changing frequency (or size) has on the radiation pattern.

At frequencies small compared to first resonance, the current on all parts of the wire will be nearly equal in magnitude and phase, as indicated for the loop in **fig. 9**. For a point on the loop axis, at right angles to the plane of the paper, the field contributions of the eight points of current shown appear as in the small vector diagram, and add up to zero. In the plane of the paper, the components from the near and far side of the loop have an out-of-phase component, because of the time required for a radio wave to travel across the loop. A doughnut-shaped pattern results. The hole axis is at right angles to the plane of the paper.

These very small loops will radiate well, but will be difficult to feed because they have very low resistance — not much more than the conductor itself. Loss in the matching system will be high.

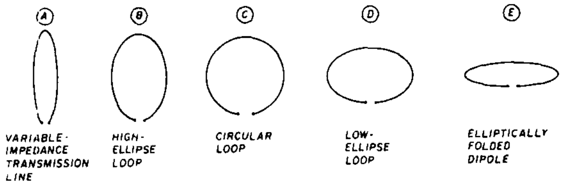

fig. 5. Circular-loop family, formed by smoothly changing the transmission line spacing. For a given length of conductor, the circle has the greatest area, and will show higher gain than the square. (For the same given perimeter, the area of a circle is 27 percent greater than that of a square.-Ed.) However, the figures with greater separation of the current maxima can show still higher gain: this is true for all loops.

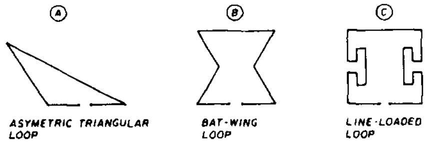

fig. 6. Examples of other possible shapes. In each case, the area in the figure is less than that for a corresponding simple symmetric member. This reduces gain below maximum (possible), but allows attainment of some other objective, such as small size or use of a given support.

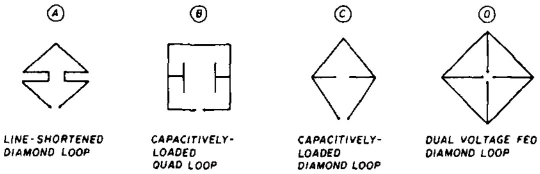

fig. 7. More examples of special shapes, all using some form of loading to reduce antenna size. Line sections can be replaced by inductors, and the capacitive sections by actual capacitors. The fourth shape uses the capacitive lines as the feed point, to allow horizontal or vertical polarization.

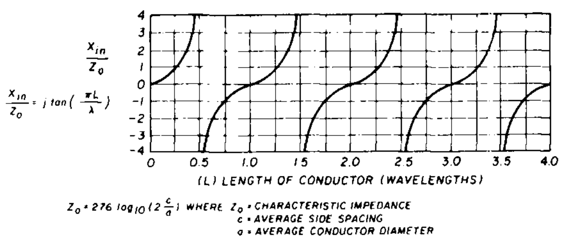

fig. 8. Generalized terminal reactance of a two-wire transmission line. The characteristic impedance is determined by wire size and spacing. From the standard formula, $Z_o = 276 \log (2\frac{c}{a})$, c being the separation and a the wire diameter. Use the average separation for nonparallel-sided lines. Lacking other data, use this curve to give (approximately) the feed-point reactance for any member of the Quad family of loops.

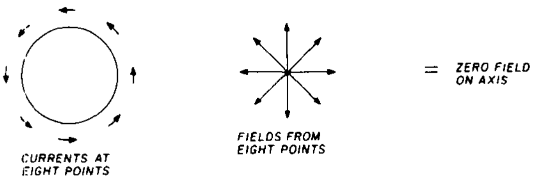

fig. 9. Vector field pattern of small loop, showing that the fields from individual wire segments cancel for on-axis radiation. The resultant field is doughnut shaped.

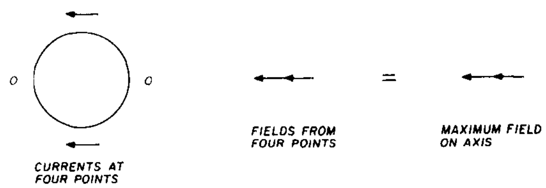

fig. 10. Vector field pattern for a one-wavelength loop. Components from the loop top and bottom add to form a major lobe on axis. The components at 45 degrees do not completely cancel, so there is a small doughnut pattern of vertically polarized radiation.

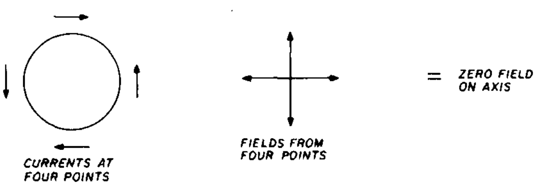

fig. 11. Vector-field pattern for a two-wavelength loop. Components on axis cancel, but add to form a double cone-shaped pattern. Cancellation of on-axis radiation occurs for wire lengths of three or more integral wavelengths also.

At frequencies close to first resonance, maximum current will occur at the feedpoint and half-way around the loop from it, as shown in **fig. 10**. The major field components from the upper and lower parts of the loop, on axis and at right angles to plane of the paper, are now in phase. In the plane of the paper, the components on the line of maximum current are out of phase. Maximum radiation is at right angles to the loop, and is horizontally polarized.

There are small components of current on the vertical parts of the loop. These are equal and opposite in phase and form a vertically polarized pattern. Most Quad analyses neglect this component, since it is much smaller than the main lobe. Its practical importance is not clear, but it may be responsible for creating the reputation of the Quad as a good performer at low heights and under marginal conditions.

For frequencies close to second resonance, maximum currents occur at each one-quarter point around the loop (**fig. 11**). Because currents on opposite sides are equal but opposite in phase, there is no net radiation on the loop axis. Maximum radiation occurs in the plane of the paper, with lobes of 90 degrees each. This is the general pattern for all resonances higher than the first, with the number of lobes equal to twice the order of the resonance. The pattern is the same for all simple shapes.

The considerations above indicate that the primary area of interest for the Quad family of **figs. 1** through **6** will be at or near first resonance, where the lobe structure is simple and on the axis of symmetry. For all of these shapes, the total conductor length is very close to one wavelength.

Quads with conductor lengths of two or more wavelengths don't have useful radiation patterns at right angles to the loop plane. One exception occurs if the basic transmission line is open circuited (**fig. 12**). The first, or serial, resonance point isn't too useful. The next (or parallel) one gives a simple lobe structure on the axis of the loop, which is useful in itself or as a switched open/shorted two-frequency loop. This was the basis of the now rarely used bi-square beam.

drive resistance relationship

The input resistance of a shorted one-half wave transmission line is almost zero (see discussion referring to **fig. 1**). For the folded dipole, the drive resistance is about 300 ohms. Considering that the currents in two wire segments interact less the further they are apart, we expect the input resistance of the intermediate shapes to fall between these limits. For the shapes designated as C, the input resistance should be near 150 ohms. The resistance will be lower for the skeleton slot, or B types, and higher for the squashed D types. The exact pattern of variation must be worked out.

drive reactance and resonance relationship

Antenna resonance is defined by zero input reactance. All of the shape variations will have a specific point or points of resonance, and we can't expect them to be independent of conductor shape. For a shorted, air-insulated line, resonance will be very close to the physical half-wavelength point. The resonant frequency of a folded dipole will be some 5 percent lower. Because we don't know the current change due to variations in the separation of current points, we must determine the effect of changing shapes.

The magnitude of reactance change in moving away from resonance involves cosine functions. For small deviations from resonance, it is reasonable to expect that the reactance can be approximated by a simple linear function. The reactance, then, can be specified by two values — the frequency of resonance and the slope of the reactance curve. We must see if an additional simple function for shape can be developed.

gain relations near resonance

We can look at the gain from two viewpoints. The first is based on element separation. The gain of the shorted line section is zero, because the radiating section is approximately zero length. As we move toward other shapes, the radiating length increases, but the spacing between the two high-current sections decreases. As the shape approaches that of the skeleton slot, there will be two well-separated high-current sections of reasonable length. The gain should approach twice that of a simple dipole.

At the other extreme, the gain of the folded dipole is the same as a simple dipole. Thus, we expect a gain decrease when going from the very tall, narrow slot toward the dipole. Overall, the gain should increase slowly as the sides of the dipole are pulled apart, reaching a maximum at some separation, and then falling to zero gain. However, without some other guidance, we cannot state the gain of intermediate shapes.

A second way of looking at this gain variation is from the view of the effective area. Considering just the high-current part, the area measured in average amperes times electrical degrees of length will be nearly zero for the shorted line, unity on a per unit scale for the folded dipole, and basically two for the shapes (C). Thus we expect the gain of an optimum member of the Quad family to approach 3 dB above an isotropic. The circular loop should have the best gain, the rectangular one slightly lower, and the delta loop lower still. However, all nearly symmetrical shapes should show some gain with respect to a dipole.

Further consideration of the same area indicates that the gain of the resonant open-circuited (two wavelength) square should approach 6 dB above an isotropic at parallel resonance. We would expect many of the odd and re-entrant shapes to have gain, but the ones with small area will show a loss compared to a dipole.

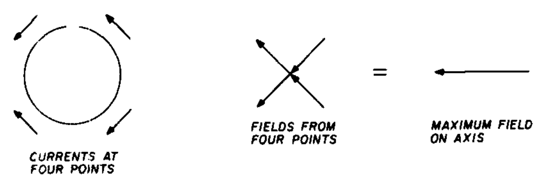

fig. 12. Vector field pattern for a two-wavelength loop formed from an open transmission line. The components add to produce an on-axis lobe. This lobe exists for longer wires also, but there are also added lobes.

Quad elements in beams

Any of the above shapes can be used in either a driven or parasitic beam. One way of looking at such beams is to assume that the radiation effect of each element is the same as if it comes from a point source located at the center of electrical symmetry of the element. This leads to the concept of pattern multiplication, where the overall pattern is the product of the element pattern and an array pattern, as determined by the relative spacing, current, and phase.

Because array patterns are well known (and quite simple in many cases), beam patterns will be easy to develop when the element patterns are worked out. There is, however, a corollary to this. Any unusual benefit from the Quad family will have to come from the elements themselves and not from the fact that they are assembled into an array.

In this simplified consideration, some gain above a dipole has appeared. It is expected that a Quad array can be shorter than an array of dipoles (Yagi) and still achieve the same gain. Although the vertical height is much greater, the horizontal span and the turning radius are less. For a given gain, Quads require less space.

neglected factors

A number of implicit assumptions were made in the preceding paragraphs. One is that the conductor has no loss, and is very thin. Currents were assumed to be sinusoidal. Small pattern factors, like the lobes in the plane of the elements, were ignored. These are important in a detailed analysis, but should represent only variations from simply derived values and not major changes.

Part 2 will cover the theory of circular elements and the beams constructed from them.

ham radio

the Quad antenna: part 2,

circular and octagonal loops

Analysis shows good performance with similar data

Although there is a contradiction in terms, it is convenient to consider the circular loop, and arrays built of loops, as the first members of the Quad family. One reason is that all other versions can be regarded as departures from the "ideal" circular figure. To the extent this is true, the performance of circular-loop antennas is thus representative of the performance of the entire family.

Another reason is that the theoretical anaylsis of the circular loop is far more advanced than for the other shapes. Extensive tables of calculated characteristics have been published, some with comparisons of measured performance. In contrast, while there are theories of square Quad loop and array performance, their complexity makes them impractical for calculation, even on mainframe computers.

theoretical basis of circular-loop analysis

As shown in **fig. 1**, only two quantities are necessary to specify the circular-loop antenna: the conductor size, usually given as its radius; and the loop size, also described by radius. It is often more convenient to use two derived descriptive quantities in theoretical discussion. The first is the normalized circumference of the loop at the specific frequency of interest given by the quantity kb, where k is defined as

$$k = 2\pi/\lambda,$$

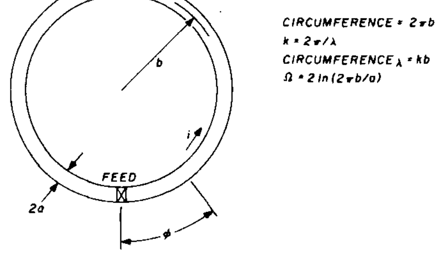

fig. 1. A circular loop can be described by two quantities, the radius of the conductor (a) and the radius of the loop (b). For work, it is convenient to use two derived quantities, a conductor thickness factor (omega) and the circumference in wavelengths at the operating frequency (kb).

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λ being the wavelength. The quantity kb is therefore the circumference of the loop in wavelengths. Conductor size is usually given by the relationship

$$\Omega = 2ln\left(\frac{2\pi b}{a}\right)$$

where ln is the natural logarithm, equal to 2.3 times the more common log_{10} value. The value of omega is given in **fig. 2** as a function of the ratio 2πb/a, or loop circumference to conductor radius. Values less than 10 represent very large conductor diameters, and those over 20 very small conductors. High-frequency antennas will usually have values in the range 20-25, and self-supporting ultrahigh frequency antennas values of 10-15.

The loop is assumed to be fed at one point, usually taken as the angle reference. This induces a current, *i*, in the loop at angle zero which, in turn, creates a field at the point designated by R,01, for example. The total field at this point is the sum of the fields produced by all points on the loop.

The field components also induce current flow in the loop. When equilibrium is reached (after a few rf cycles) the field close to the conductor must lie only at right angles to it. (If there had been a tangential component, a change in the current would have been induced, so equilibrium would not yet have been attained.) This observation plus standard field equations give the conditions for calculating current distribution, and therefore the drive impedance and radiation pattern.

While the concept is relatively simple, the mathematical operations are difficult. See the references, especially Storer,[1] for details. For our purposes it is sufficient to note that the current distribution is given by:

$$I(\emptyset) = \frac{V}{(j \cdot \pi \cdot 377)}\left[\frac{1}{A_0} + 2 \cdot sum\frac{Cos\,(n \cdot \emptyset)}{A_n}\right]$$

where the sum is for all values of N from 1 to infinity. This result was derived by Hallen.[2]

This equation is simple, but its evaluation is complex. The quantities A involve series for which exact solutions are unknown. Even approximate solutions require further assumptions, two being that the conductor diameter is small compared to loop diameter and to operating wavelength. This restriction is satisfied by practical antennas.

Additionally, the infinite series in the equation tends

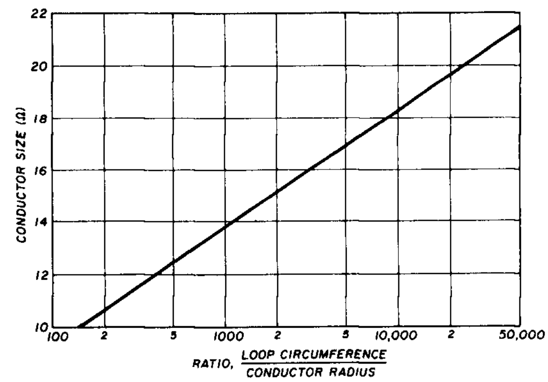

fig. 2. Values of the thickness factor (omega) as a function of the ratio of loop to conductor radius (or diameter). Practical self-supporting loops need an omega around 10-12 to have sufficient strength. Wire cage elements may be used to secure low omega factors at low frequencies.

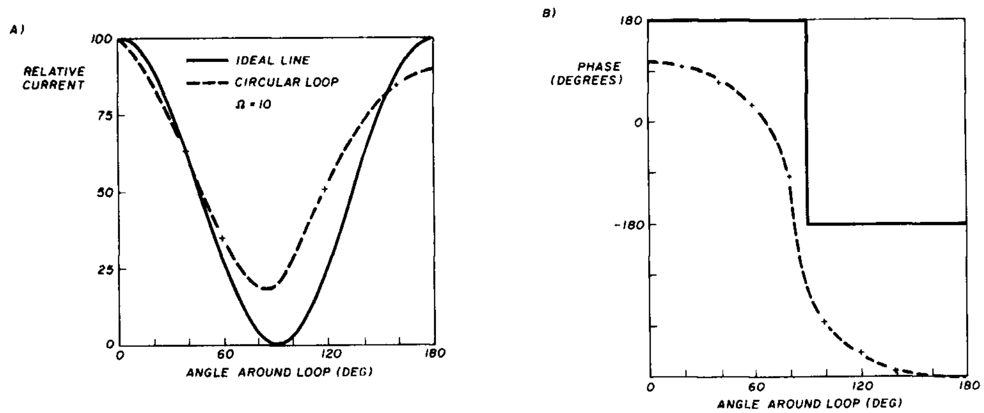

fig. 3. Current magnitude and phase on a large conductor circular loop one wavelength in circumference as derived by Storer.[3,1] The loop is below resonance. The current on a conductor of essentially 0 radius is shown for comparison. Derived from transmission line theory, this is the first approximation to the current on any loop of the same circumference.

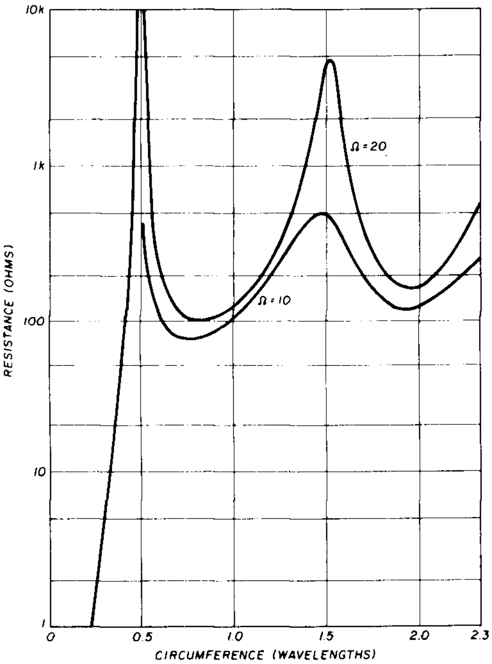

fig. 4A. Feedpoint or self-resistance of one-wavelength circumference loops — one with a large conductor radius, the other small. The drive resistance is sensitive to conductor size around the points of parallel resonance, at 0.5, 1.5, 2.5, etc. wavelengths circumference. These curves may be used as approximations for any loop of equal circumference and radius.

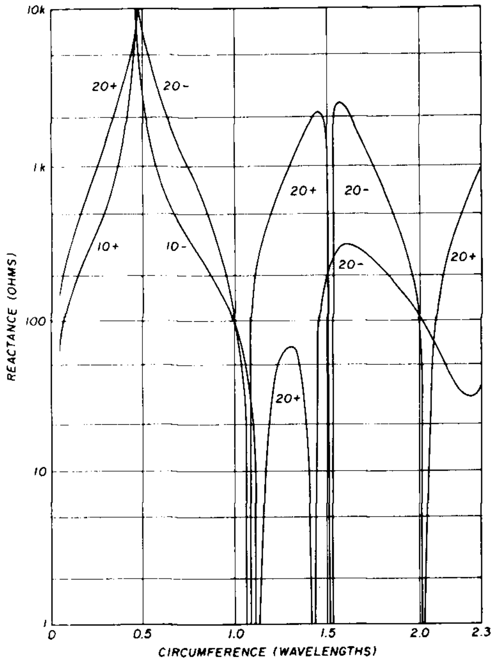

fig. 4B. Feedpoint or self-reactance of one-wavelength circumference loops. High reactance denotes the parallel resonances, low reactance the series resonances. Both series and parallel resonances are sensitive to conductor size. Series resonance is generally at wavelengths greater than integral values. Parallel resonances are at wavelengths less than odd multiples of 0.5 wavelength.

to become divergent when the number of terms is reduced for reasonable scale of calculation. Storer[3,1] developed a method of calculation by keeping the first four terms of the series and replacing the remainder by an integral. He also published a set of ten curves giving the real and imaginary components of the series. With these, evaluation of the current distribution and drive impedance is reduced to some simple (but tedious) curve measuring and complex-number algebra. Unfortunately, the curves cannot be reduced to simple equation form, so this can't be avoided.

Rather than presenting these curves and usage details here, I will give only the results of examination of some specific loop designs. Subsequent analyses have given a table of drive impedances, which is more accurate for most work. These values are covered later.

For values outside the range given here, or to obtain the current distribution, you will need the Storer curves. (The **reference 3** version is best, and is available at reasonable cost from Cruft Laboratory Library, Harvard University, Cambridge, Massachusetts.)

A simpler solution for small circular loops is available.[4] Here "small" covers the range from 0 to 0.3 wavelength circumference. This restriction allows

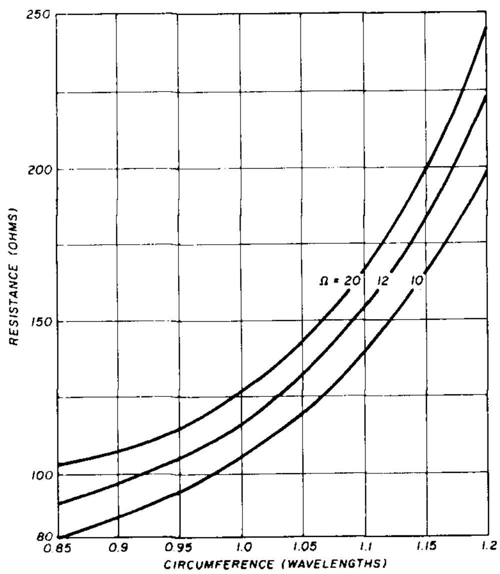

fig. 5A. Feedpoint or self-resistance of three loops around one-wavelength circumference.

simplification of the general equation above, with only three terms giving adequate accuracy. Approximate equations for each are given, and are easily handled by small computers. Note that the reactance for these small antennas is determined almost entirely by the loop circumference, with almost no effect on conductor size. In contrast, the input resistance varies with both.

current distribution on a circular loop

Figure 3 shows the magnitude of the current on a one-wavelength circular loop as calculated by Storer, together with the current magnitude on an ideal shorted transmission line made from one wavelength of conductor. **Figure 3B** shows the phase with respect to the driving voltage for both cases.

A number of important factors concerning the entire Quad family show on these curves. The first is that a one-wavelength loop is not resonant, as indicated by the fact that the angle of the drive impedance is not zero. Since the loop appears as a capacitance, it is below resonance. Unlike dipoles, loops must be longer than a wavelength to be resonant.

A second factor is that there is no point on the loop where the current goes to zero. Associated with this is the fact that the current at 180 degrees from the feedpoint is appreciably less than at the driving point. Similarly, these two currents are not 180 degrees out of phase, but somewhat more. The point of phase reversal is not at 90 degrees to the line of symmetry through the feedpoint.

One reason for the differences between the loop and the ideal shorted line is the greater separation of the sides. Currents are not constrained to be equal because of tight coupling, as in the ideal shorted line. Further, power is being radiated, causing a reduction in current when moving away from the feedpoint. (In a practical antenna, the current differences would be somewhat greater, as the analysis assumes zero ohms loss.)

These current curves show that the usual evaluation of a Quad — two separated dipoles with ends bent to touch — can't fully describe the performance. This simple concept is useful in verbal descriptions, and can be a valuable tool in approximate analysis. But it must be remembered that numerical results are probably in error by a factor *at least as large as the current error*, or at least 20 percent. The effect of the error should be smallest for pattern calculations and drive resistance, but is likely to be sizeable for drive reactance and resonant frequency.

These detail current calculations are for loops with relatively large conductors, $\Omega = 10$. Other studies, plus the tables presented later, show that the current magnitude and angle move progressively toward the curve for the ideal transmission line as the conductor radius becomes smaller. This means that the two-dipole approximation is likely to be better at high frequency than at ultrahigh frequency because omega is large for practical conductor sizes. The current distribution for some other loops is also given in **references 1, 3, 5,** and **6.**

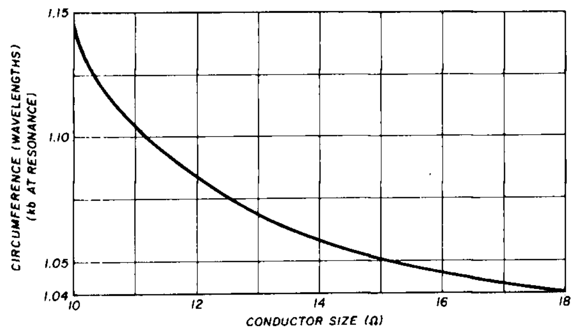

fig. 6. Resonant frequency of a circular loop derived from *fig. 5B*, as the frequency of 0 reactance. A simple linear relationship of reactance versus wavelength (or frequency) can be developed using two figures. However, the curves are usually less time consuming to use.

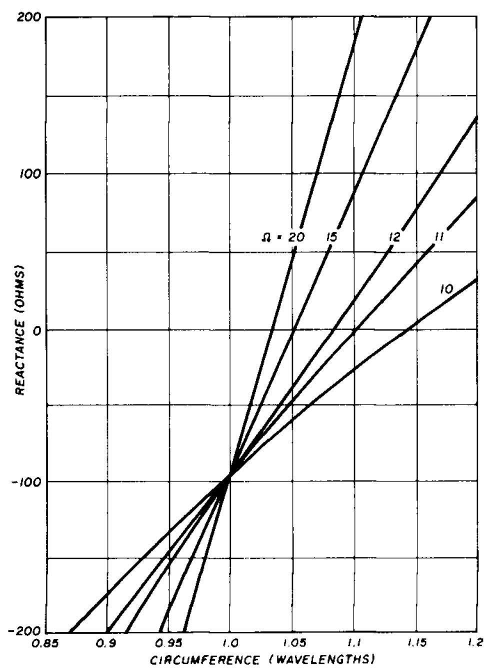

fig. 5B. Feedpoint or self-reactance of five loops around one-wavelength circumference. The reactance for all conductor sizes is equal to −95 ohms for a circumference of one wavelength. This may be compared with dipole reactance which shows the same characteristic, with a reactance of 35 ohms at 0.94 wavelength as the common point.

As a first approximation, the current distribution can always be assumed to be that of an ideal transmission line of the same conductor length. A second approximation can be sketched by "rounding all sharp corners," and decreasing the current away from the feedpoint. Greater accuracy will require tedious evaluation using Storer's curves or the MININEC technique (to be discussed).

drive-point impedance

Get the drive-point impedance by dividing the drive-point voltage by the drive current calculated above. Storer[3,1] gives tables of this impedance for loops from 0.05 to 2.5 wavelengths in circumference, and for omega values from 8 to 12 (large diameter conductors).

In considering the general problem of loop antennas, Wu[7] developed another method for solving Hallen's equation. This gives the same values for resistance components as Storer, but the reactance values are quite different and agree more closely with measurements on real antennas. King, Harrison, and Tingley[8,9] have used Wu's theory to calculate loop-drive admittances for sizes from 0.05 to 2.5 wavelengths and for omega from 10 to 20. For those who have forgotten, or never had occasion to work with admittances,

$z = R + jX$

$y = 1/Z$

$y = g + jb$

(See also **reference 10.**)

Figures 4A and **4B** show feed resistance (R) and reactance (X), respectively, for loops from 0.05 to 2.5 wavelengths circumference. The two values of omega shown, 10 and 20, are representative of very high frequency and high-frequency loops.

Over this range of loop diameters, three high-impedance or parallel resonance points are noted, corresponding to 0.5, 1.5, and 2.5 wavelengths circumference. For $\Omega = 20$, the low-impedance, zero-reactance points correspond to serial resonances at about 1.0 and 2.0 wavelengths circumference. For $\Omega = 10$, there is also a serial resonance at 1.0 wavelength circumference. There is no true serial resonance for a circumference of 2.0 wavelengths. Instead, the reactance becomes low and remains low and capacitive. This is the case for all values of omega less than 11, and for all but the first serial resonance.

The resistance at the serial resonance point changes markedly with the value of omega. For omega that is large (20 or so), the resistance also varies markedly with loop diameter. But for $\Omega = 10$, the resistance change is much smaller. (For $\Omega = 8$, the change is less than 2:1 for any circumference greater than 0.6 wavelength.)

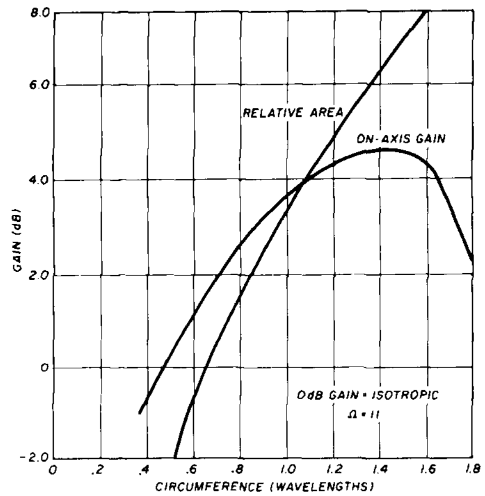

fig. 7. Gain of a circular loop in dB above isotropic, as derived by Ito el al.[11] Maximum gain occurs for a loop circumference of 1.4 wavelengths. Gain is less for smaller sizes due to less radiating area. On-axis gain, the value shown, is less at larger sizes because of lobe splitting. However, the gain of the main lobe increases as circumference increases. The associated curve shows the relative area of the loop.

These characteristics mean that thick loops are inherently broadband antennas and relatively easy to match. However, the pattern changes described in part 1 affect the desirability of this broadband operation, as discussed later.

Figures 5A and **5B** show the feed resistance and reactance for frequencies of greatest interest (those close to the first series resonance) for loops from 0.8 to 1.2 wavelengths circumference. **Figure 6** is derived from **fig. 5B**, and shows the resonant frequency as a function of conductor size. These three curves give the information needed to design practical loop antennas and arrays and to calculate their performance. Their use is covered further on.

gain of loop antennas

In considering loop gain, it was noted that gain should increase as loop size increases and that there are pattern changes as size increases. Specifically, gain on the axis of symmetry becomes zero for all loops with 2, 3, or more wavelengths in conductor length.

These two effects are shown in the calculated gain curve of **fig. 7** (see **reference 11**). For a circumference of 1 wavelength, the on-axis gain is 3.4 dB above isotropic, or about 1.4 dB above a dipole. (Based on measurements, Lindsay[12] quotes approximately 4.0 dB, and Appel-Hansen[13] quotes 3.4 dB above isotropic.)

Figure 7 shows that larger loops are superior from the viewpoint of gain. A calculated gain value of 4.5 dB occurs for a loop circumference of 1.5 wavelengths. Above this circumference, the gain decreases, as the on-axis lobe splits. Remember, there is no radiation on axis for a circumference of 2 wavelengths.

In smaller sizes, the on-axis gain decreases as the circumference becomes less than a wavelength, and as the pattern changes toward the doughnut pattern of a small loop. The gain is about equal to that of a dipole at a circumference of about 0.65 wavelength, and about 1.5 dB poorer than that of a dipole for a circumference of 0.5 wavelength.

This brings up two important points. First, from the view of gain, the circular loop should be designed to operate away from resonance. Considering the factors of gain, lobe shape, and feed impedance, Ito et al.[11] recommend a design circumference of 1.2 wavelengths, for a gain of 4.2 dB.

Second, a loop has good gain performance over a wide range of frequences. For example, a 14-MHz loop would be slightly better than a dipole on 10 MHz, and about 1.5 dB poorer on 7 MHz. The gain would be near maximum on 21 MHz, better than a dipole on 18 MHz, and about as good on 24 MHz. The on-axis gain would be poor on 28 MHz, but there would be usable radiation in two lobes.

The acceptability of operation away from resonance is affected by the difficulty encountered in feeding the loop. From **fig. 4**, feeding a large loop on high frequency does not appear to be an unusual problem. The feed resistance would increase, but a matching section or transformer is needed. There would be an inductive component, easily compensated by a stub. Depending on conductor size, a very high frequency loop might require only a matching transformer.

Wideband operation would be a greater problem.

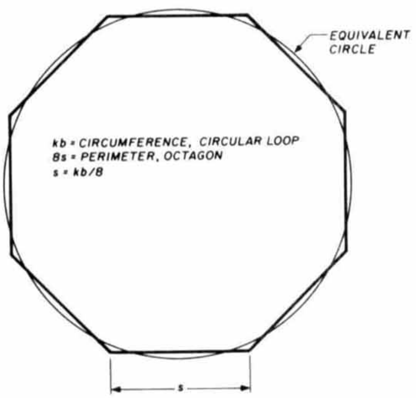

fig. 8. Relative geometry of a circle and an octagon. The difference in area for the same conductor length is very small.

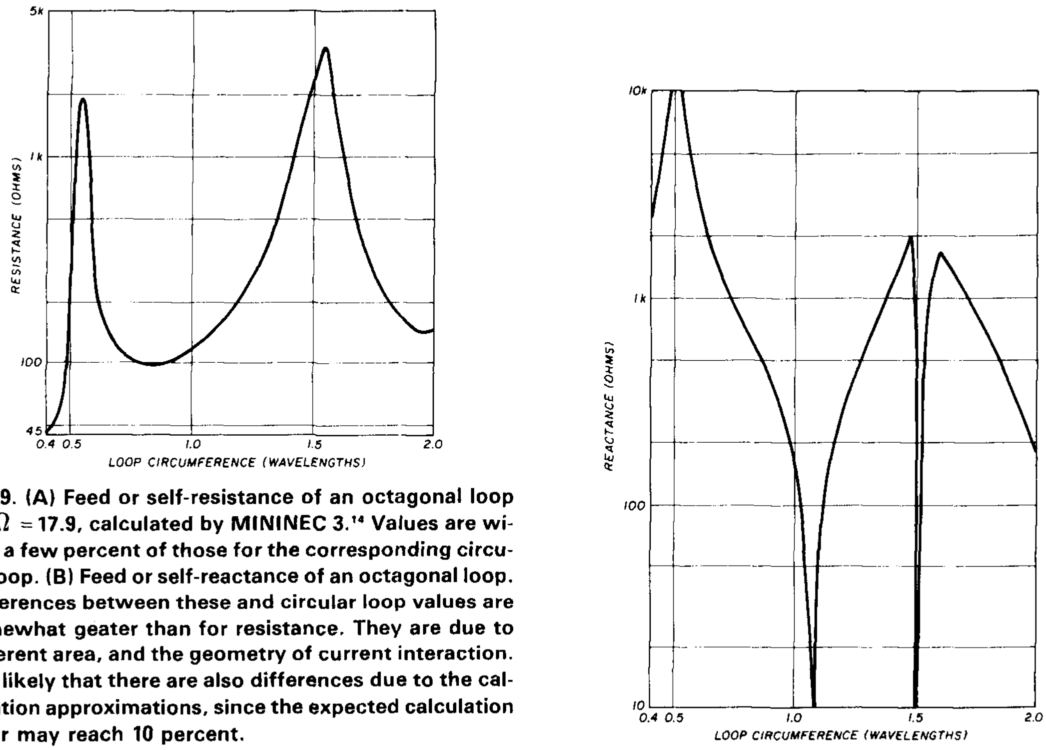

fig. 9. (A) Feed or self-resistance of an octagonal loop for $\Omega = 17.9$, calculated by MININEC 3.[14] Values are within a few percent of those for the corresponding circular loop. (B) Feed or self-reactance of an octagonal loop. Differences between these and circular loop values are somewhat geater than for resistance. They are due to different area, and the geometry of current interaction. It is likely that there are also differences due to the calculation approximations, since the expected calculation error may reach 10 percent.

You'd need a complex matching section at the antenna, or your transmission line would have appreciable VSWR. The combination of open-wire line and a wide-range "Match Box" would give excellent performance. This is especially interesting as the basis of a 3.5/7/10-MHz fixed-loop design.

I have made use of this wideband capability on many occasions. A 14-MHz loop is regularly used on bands from 7 to 28 MHz. Much of my 10, 18, and 24-MHz experimental work (KK2XJM) used this antenna. Other than Teflon™ insulated 75-ohm feedline and a pi-section tuner, no special precautions were taken.

circular-loop radiation patterns

Published data on radiation patterns of loop antennas varies from sparse to nonexistent. The equations needed to calculate the currents and patterns are solvable on a small computer only with a lot of programming and computing time. It has been necessary to approximate further to develop the pattern data which follows.

the MININEC antenna program

The chosen calculation technique (sometimes called "the method of moments") is the public domain program "MININEC," from Logan and Rockway,[14] currently in its third version. It uses essentially the same initial assumptions as the Hallen[2] approach above. But instead of applying the geometry exactly and then making simplifying assumptions, assume that the radiator is composed of a series of straight-line sections carrying constant current.

A solution's accuracy increases as the number of sections for a given geometry is increased. While the complexity of the solution is not greatly affected, the time required for the solution increases as the square of the number of segments. An IBM PC may take several hours to run the program; a very small computer like the Commodore 64 may need 12 to 24. Even so, this approach is the best generally available, and is quite practical.

The original MININEC[15] was written for the Apple computer. I have translated it for the C-64 and the Amiga; KA4WDK has done the same for the PC. The third version was written for the PC, and I translated it for the Amiga; it also runs on the Macintosh.

MININEC originators used various conditions to examine calculation accuracy, including analysis of loops. One series used a ten-sided polygon approximation of a circle, with two current segments per side plus three for the feed side. Agreement with theory was to within 10 percent.

A second series approximated the circle using the circumscribed polygon. This shows good agreement (±6 percent) for susceptance, down to four sides. Equally good agreement for conductance required 16 sides. With 22 sides, agreement was within 6 percent for sizes from 0.1 to 2.0 wavelengths. MININEC solutions are found to be unreliable for circumferences less than about 0.01 wavelength.

The inscribed polygon approximation is not an ideal check of solution accuracy as the number of segments decreases. It introduces two added factors which change the results. One is the loss of area. (For eight sides this amounts to about 3 percent.) This reduces the gain by about the same amount. More important, the total conductor length decreases as the number of segments decreases, by about the same percentage. This change in wire length introduces a change in reactance near the series-resonant points, and a change in resistance near parallel-resonant points. Both may be relatively large.

A better approximation occurs when the conductor length is kept constant. It is not easy to evaluate the precise error this causes, but it appears that it is no greater than the sum of the inherent error of MININEC plus the area error in the approximation.

It also appears that the inherent error will be around 5 to 10 percent if two simple rules are followed in setting up a MININEC analysis:

- use a minimum of two segments per section of conductor,
- use a minimum of four segments per halfwave of conductor.

Practically, MININEC gives extremely good accuracy. An antenna can easily depart from its ideal value by 20 percent or more because of neglected factors like supports, tower location, and feed-antenna interaction.

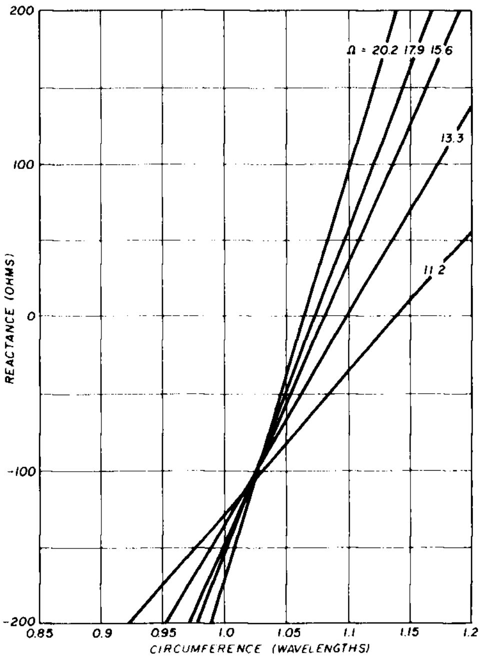

fig. 10. Feed or self-reactance of an octagon for circumferences around one wavelength. The point of equal values occurs at the same reactance as the circular loop but at a greater circumference. Curve slopes are almost identical.

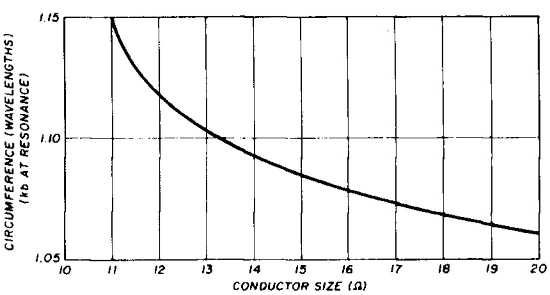

fig. 11. Resonant wavelength of an octagonal loop as a function of conductor thickness. The curve is similar to that of a circular loop, but differs by as much as ±6 percent.

octagonal loop

Calculated values for an octagonal loop should be a good approximation of circular-loop values. The octagon is also a useful antenna by itself. Probably the best-known type is the "Army Loop" — really a loop operating well below resonance, incorporating both a matching system and low-loss construction. **Figure 8** shows the basic factors involved, and allows visualization of the small area difference from the circular loop.

The properties of the octagon for conductor lengths close to 1 wavelength are summarized by **figs. 9A** and **9B** for drive resistance and reactance. These should be compared with **figs. 4A** and **4B** to see the validity of the octagon approximation to a circular loop. As expected from previous discussions, the agreement

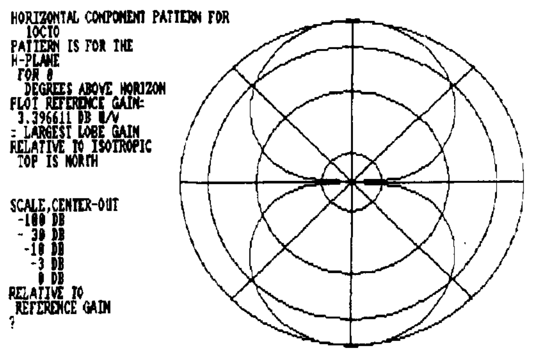

fig. 12. Horizontal radiation pattern for an octagon lying in a vertical plane and fed at the bottom. Only the horizontally polarized component is shown. The pattern is very similar to that of a dipole, but the gain is higher by about 1.25 dB.

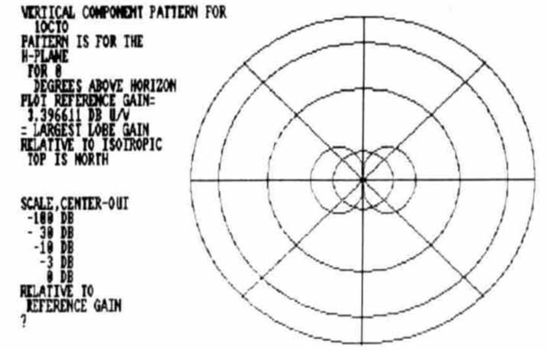

fig. 13. Vertical radiation pattern for the total radiation from an octagon in the plane of the loop. Maxima are along the line of maximum current. The minima represent the expected side radiation. (kb = 1.0, Ω = 17.9)

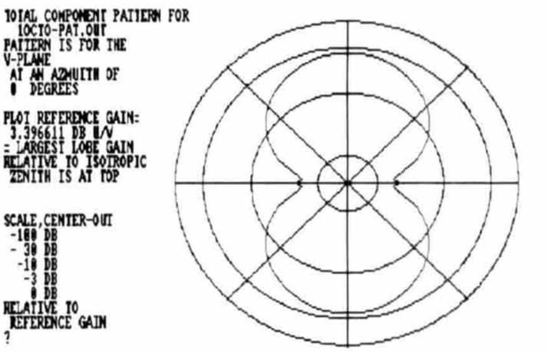

fig. 14. Horizontal radiation pattern for the vertically polarized component of an octagon lying in a vertical plane and fed at the bottom. This component is about 20 dB below the main lobe because of the currents on the vertical and inclined parts of the octagon.

for resistance is good — no more than a few percent difference. The agreement for reactance is not quite as good; this is the usual finding. However, neither error is beyond the expected range.

If you build a practical octagon antenna, use **figs. 10** and **11** if the antenna is to be resonant or nearly so. If it is away from resonance, the values from **table 1** give a good approximation. For best accuracy, the table values should be interpolated for the actual conductor diameter and equivalent radius. Alternatively, MININEC can be used to obtain values within 5 to 10 percent error.

patterns of circular/octagonal loops

Because the octagon has been found to be a good approximation to the circle, we can use its pattern as a close approximation to those of circular loops.

Figure 12 shows the MININEC calculated horizontal plane pattern for a 1-wavelength octagon fed at the center of the bottom segment — that is, with horizontal polarization. The lobes are very nearly the same as those of a dipole, but are slightly narrower to produce gain. The gain is 3.4 dB, essentially that of a circular Quad.

Figure 13 shows the vertical plane pattern in the plane of the loop, for the total radiation. **Figure 14** shows the horizontal plane pattern for vertical polarization. There is a major difference from dipole patterns in these two figures. The loop has an appreciable vertically polarized component, zero on axis and maximum at right angles to this. This component is not present with dipoles and its importance is not clear. It may have an adverse effect because of interference received on the vertically polarized side lobes (and back lobe in beams), or it may tend to reduce fading due to variation of incoming signals and path splitting. The component may also be a factor in the reputation of Quad loops as good performers at low height. More aspects of these questions will be discussed in other parts of this series.

Figure 15, provided for comparison, shows the calculated current on an octagon. Because the example is for a relatively thin conductor, there is close resemblance to the distribution for a transmission line.

Figure 16 compares the calculated gain of an octagon and a circular loop. Some of the variation is due to the difference in areas. The rest appears to be related to differences in the calculation method. Practically, the difference is negligible.

General conclusions from this comparison of circular and octagonal loops are that both have good performance, and that the data from one can be used for the other with little error.

We will use this last finding in part 3, which is devoted to arrays composed of circular and octagonal loops. Design data for arrays of two to twelve elements will be given.

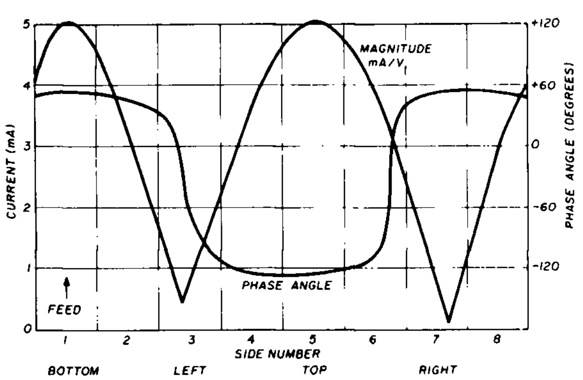

fig. 15. Current distribution on an octagon. Because of the small conductor size, the distribution approaches that of an ideal transmission line.

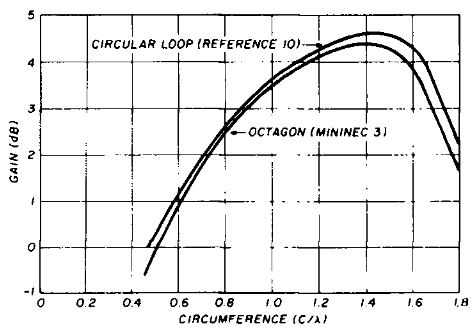

fig. 16. Calculated gain of a circular loop and an octagon. The difference is small — partly real and partly due to differences in the calculation technique. The curves do confirm the extra gain of a loop as compared with a dipole, and also indicate the added gain possible with off-resonance operation.

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ham radio

PART 3 — COMING UP IN OUR JULY ISSUE.

Analysis of
multi-element arrays;
all-driven-element design

the Quad antenna part 3, circular-loop and octagonal arrays

An array of two or more circular loops (like any other antenna) can have all elements driven, or some driven and the others self-excited, or parasitic. The special case of one driven element is sometimes called the Yagi-Uda configuration; this really applies only to the configuration of one parasitic reflector, a driven element, and one or more parasitic directors, all elements being dipoles.

Part 3 addresses circular-loop and octagonal arrays — initially with two elements, then with more. This is followed by a limited discussion of a particular all-driven-element design.

theory of two circular-loop arrays

The relationships between two circular loops, parallel and on a common axis, are shown in **fig. 1**. Compare this with the single-loop drawing in part 2, **fig. 1**. The important difference is that two loops contribute to the field, and in turn, to the induced currents. They have the same requirement that the component of the field along the wire be zero.

Computational complexity can be reduced if the current on each loop is assumed to be the sum of two currents, of the form:

I1 = Ia + Ib
I2 = Ia − Ib

Those with power-line engineering training will recognize this as a form of "symmetrical component" analysis used for multiphase power lines.

The assumed currents Ia and Ib are the same on both loops. This allows you to solve for the currents using Hallen's[2] method. Unfortunately, this simplification does not help much in practical calculation.

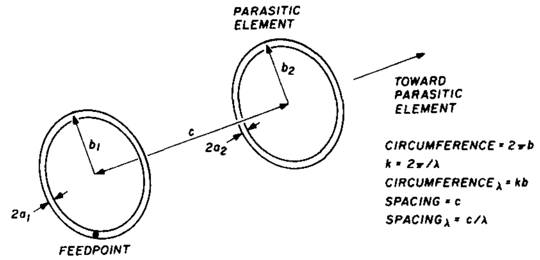

fig. 1. Geometry and nomenclature for a circular loop array. Two quantities are needed to describe each element, and another to specify the spacing, the letter C is used here. For octagons, an added descriptor for the number of sides is needed.

There is no easy way to use the ten curves prepared by Storer[1,3] to derive the currents on the two elements. Theory application is beyond practical small computer use; a large computer is needed. But a number of published results of this theoretical analysis can be applied to practical antennas. These will serve as the basis for some further analyses, for comparison, and also provide some data on the performance of practical designs.

the basic two-loop array

As with the Yagi, the two-loop array with one loop parasitically excited is both a useful antenna and the basis for further array expansion. Practically, these

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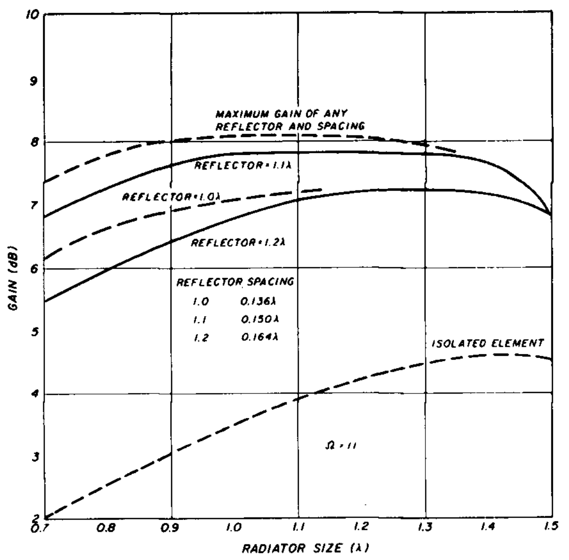

fig. 2. Forward-lobe gain for a reflector-radiator combination, plotted against size of radiator. Separate curves are shown for reflectors of 1.0, 1.1 and 1.2 wavelengths circumference. The top curve shows the maximum gain possible by choice of reflector size and spacing. Gain of an isolated element is shown for comparison. Data from Ito et al.[11]

two-element arrays give the largest increase in performance for a given investment in size and weight.

All the performance data on the designs described here are derived from Ito, Inagaki, and Sekiguchi[11]. Gain values are in dB above isotropic, unless otherwise noted.

gain performance

Figure 2 shows the forward gain performance with the parasitic element tuned as a reflector. The top curve shows the maximum gain with retuning; the nearly parallel curves show the gain for a specific parasitic element size.

For the two-element beam with reflector, the maximum gain is 8.1 dB. The gain is <3 to >5 dB higher than the gain of an isolated radiator of the same size. Over the range of radiator size from 1.0 to 1.25 wavelengths, the optimum gain varies only by 0.1 dB or so. Also, the gain does not vary greatly for changes in reflector size, typically by ±0.6 dB for a change from 1.1 to 1.3 wavelengths loop size. This means that the two-element loop with reflector is a good wideband antenna, with nearly constant forward gain over the wide frequency range of ±15 percent.

Forward gain performance with the parasitic element tuned as a director is shown in **fig. 3**. The top curve shows the maximum gain that can be developed for a given radiating loop size by tuning the director and choosing the best spacing. The nearly parallel curves give the gain for given sizes of the director. Also shown is the gain of a single isolated element.

The maximum two-element gain is 7.3 dB. This represents almost exactly a 3-dB increase over a single loop of the same size. This 3-dB increase is essentially independent of radiator size but is sensitive to director dimension.

The combination of nearly maximum gain and good gain stability led the developers of this data to recommend that the radiator loop be larger than resonant size. Their specific recommendation is 1.2 wavelengths circumference. Some consequences of this are discussed later.

The curves for a 1.2-wavelengths radiator in **figs. 4** and **5** are also useful. The variable for these curves is radiator-parasitic spacing in wavelengths.

As we have seen, maximum gain with the parasitic element as a reflector is 8.1 dB, and for the parasitic element as director it is 7.3 dB. These values show on the curves. Maximum reflector gain occurs at 1.08 wavelengths loop circumference at a spacing of 0.15 wavelength. Maximum director gain occurs at 0.95 loop circumference and a spacing of 0.1 wavelength.

Minimum back radiation with a reflector is −12.1 dB. This nearly occurs over the range of reflector sizes from 1.1 to 1.15 wavelengths circumference, and the range of spacing from 0.1 to 0.25 wavelength. Maximum front-to-back ratio occurs at a circumference of 1.1 wavelengths and a spacing around 0.1 wavelength. It is about 20 dB.

The data in part 1 shows that the optimum director size for minimum back radiation varies markedly with spacing. Minimum back radiation with the parasitic as a director is −3 dB, but this occurs for spacings around 0.6 wavelength, beyond the range of practical use. The forward gain is only 2 dB at this point. The practical minimum backlobe level is essentially 3 dB, occurring over the range 0.8-0.96 wavelength director circumference and a spacing of 0.1 wavelength. The front-to-back ratio is only 4 dB. A director of 0.9 wavelength circumference and 0.15 wavelength spacing will give nearly as good gain and front-to-back ratio.

These data show that the best design values for a two-element circular loop array, and for the radiator-reflector combination for larger arrays, are the same. Maximum performance is obtained from

- Radiator circumference, 1.2 wavelengths.
- Reflector circumference, 1.1 wavelengths.
- Element spacing, 0.15 wavelength.

Radiator circumferences from 1.1 to 1.3 wavelengths give nearly the same performance.

drive impedance

The drive impedance of an isolated loop is a complex function of loop and conductor diameter. These factors apply with a parasitic element present plus the added complexity of the changes introduced by the currents on that element. Because of this there is very little data on feed impedances in scientific or engineering literature. It is necessary to use the limited amount available to develop trends and then depend on measurements to design the antenna feed. Fortunately this is not difficult, given the wideband characteristics of loop antennas.

The paper by Ito, et al.[11] includes a single set of curves that give useful information about the radiator-reflector combination. Data is for a reflector of 1.1 wavelengths circumference, with an element omega of 11, corresponding to a loop-to-conductor radius of 39. This is typical of a self-supporting UHF antenna.

The following values are developed from the curves; resonance, of course, means that the drive reactance is zero:

- Isolated resonant loop
  Radiator circumference = 1.1 wavelengths.
  Drive resistance = 153 ohms.
- Resonant radiator with reflector
  Radiator circumference = 1.08 wavelengths.
  Drive resistance = 139 ohms.
- Resonant radiator with director
  Radiator circumference = 0.87 wavelength.
  Drive resistance = 250 ohms.
- Isolated 1.2-wavelengths loop
  Drive resistance = 215 ohms.
  Drive reactance = 84 ohms.
- 1.2-wavelengths radiator with reflector
  Drive resistance = 158 ohms.

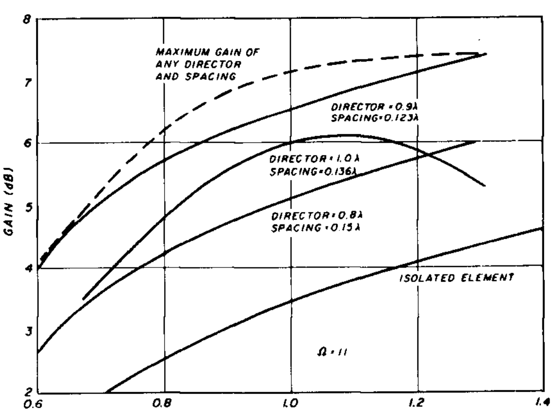

fig. 3. Forward-lobe gain for a director-radiator combination, plotted against radiator size. Separate curves are shown for directors 0.8, 0.9 and 1.0 wavelengths circumference. The top curve shows the maximum gain possible by choice of director size and spacing. Gain of an isolated element is shown for comparison. Data from Ito et al.[11]

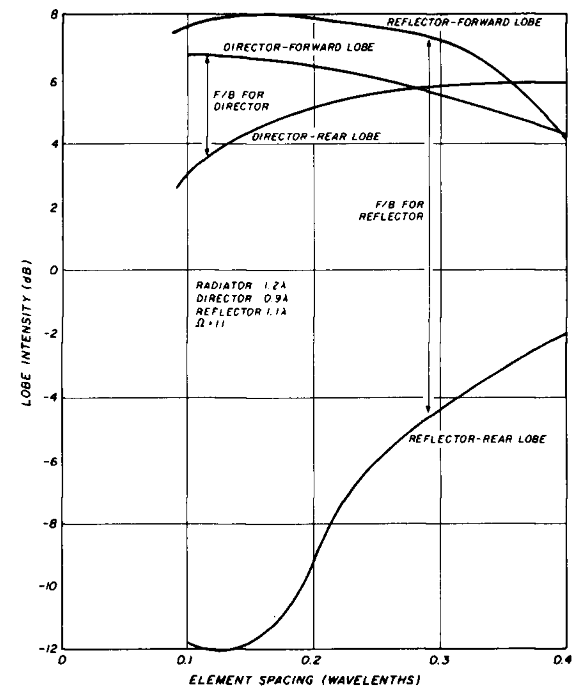

fig. 4. Forward and back lobe intensities for typical radiator-parasitic combinations, plotted against parasitic spacing. As usual for parasitic elements, maximum gain and maximum front-to-back ratio occur for different conditions. For two-element antennas, the reflector at 0.12 wavelength spacing is a good choice. Data from Ito et al.[11]

  Drive reactance = 365 ohms.
- 1.2-wavelengths radiator with director
  Drive resistance = 33.5 ohms.
  Drive reactance = − 132 ohms.

The change in impedance is greater for the director and this behavior is much the same as for the two-element Yagi. The reason for the increase in drive resistance for the resonant element with director lies partly in the marked change in length needed to cancel the self- and induced reactances.

Remember that a standard method of matching is to change the length of the driven element, then add a stub to cancel the reactance, leaving the resistance at the value that matches the line impedance. You can also do this with loops, but it may require some loss in loop area and therefore loop gain. A gamma match, or stub-transformer sections, would be a better choice.

For most two-element arrays, a good feed is a 4:1 balun at the antenna, used with 50-ohm line. Solid-state transmitters will probably require a better match to obtain rated output, say by use of a transmatch. A possibility is a gamma match, used by at least one commercial design with good results. The simplest alternative is to use low-loss line, say 75-ohm Teflon™

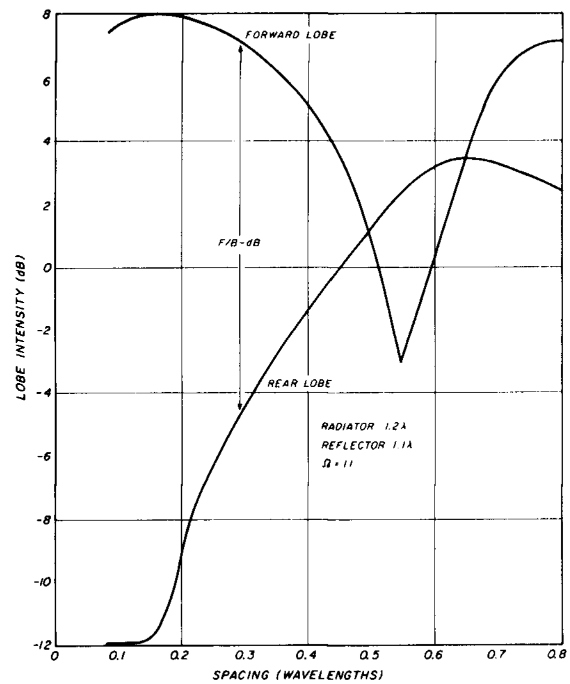

fig. 5. Forward and back-lobe intensities for a reflector-radiator combination over a wide range of spacings. With no change in element size, relative lobe intensities reverse around 0.6 wavelength spacing. Wider spacings can give fair forward lobe performance, but the back lobe remains large. Data from Ito et al.[11]

or foam, or 300-ohm twin lead, plus an appropriate transmatch. A transmatch is a necessity if you want the full advantage of the wideband loop characteristic.

patterns

There is a limited amount of theoretically derived pattern data in current literature. **Figure 6A-C** is replotted from the patterns in Ito et al.[11] which are similar to the corresponding patterns of two-element Yagi antennas[16]. The front-to-back ratio is reasonably good for reflectors in the 1.1-1.2 wavelengths circumference range. Directors of any size give poor front to back, although the forward gain is good, as described above.

None of the theoretical analyses found in the literature show patterns in other planes or for cross-polarization. These will be covered later by approximate analysis.

multi-element arrays

The theory above for two-element antennas has been used to examine the properties of multi-element circular-loop arrays, by Ito et al.[11] and by Shoamanesh and Shafai.[17,18] Experimental work has been reported by Appel-Hansen.[13] Their work is summarized in **figs. 7** and **8** and shows the gain versus array length. Also shown is the theoretical gain of Yagi antennas derived by Lawson.[19]

The gain for the usual Yagi is determined primarily by array length. The first few directors add about 1 dB per director. Thereafter, the gain increases about 3 dB for each doubling of array length.

Information in **table 1** is taken from Shoamanesh and Shafai's[17] theoretical table. All of the entries are for a director spacing of 0.3 wavelength. This gives maximum gain for the number of elements used, and reasonable front-to-back performance. Gain, expected drive impedance, and minor lobe characteristics plus front-to-back ratio are tabulated.

Arrays constructed from the table values should be

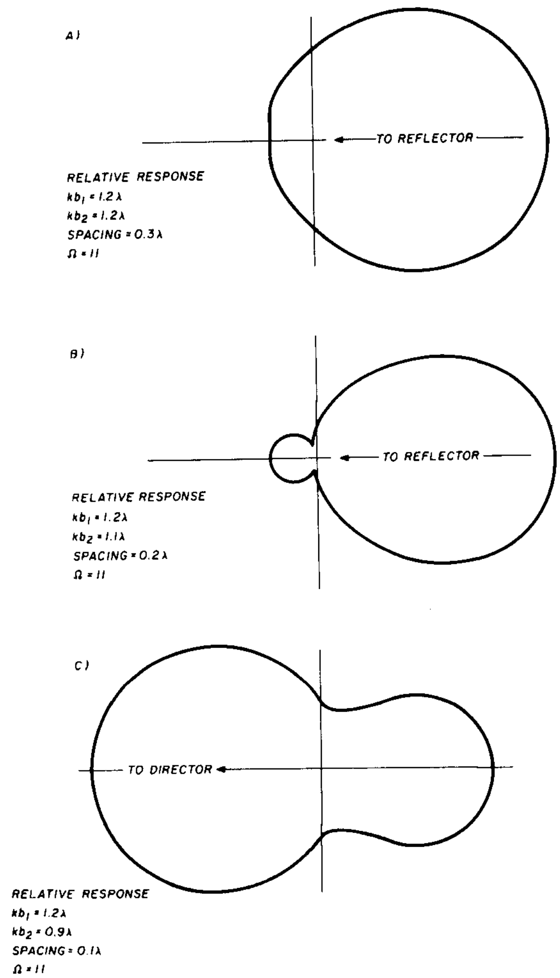

fig. 6. Horizontal plane patterns with horizontal polarization for three selected radiator-parasitic combinations. A and B show patterns with reflectors; C shows a pattern using a director. The front-to-back ratio of a reflector is good for a fairly wide range of conditions. While the director forward gain is also good over a fairly wide range, the front-to-back ratio is always poor. Patterns are scaled from a number plotted by Ito et al.[11]

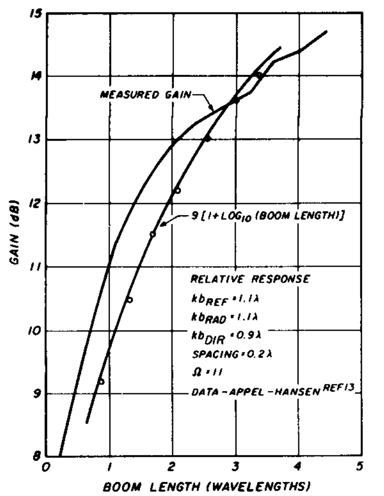

fig. 7. Measured gain of multi-element circular loop arrays, plotted against total boom length. Gain shown is not necessarily the maximum for the boom length given. The arbitrary curve is shown for comparison. Data from Appel-Hansen.[13] See also Lindsay.[12]

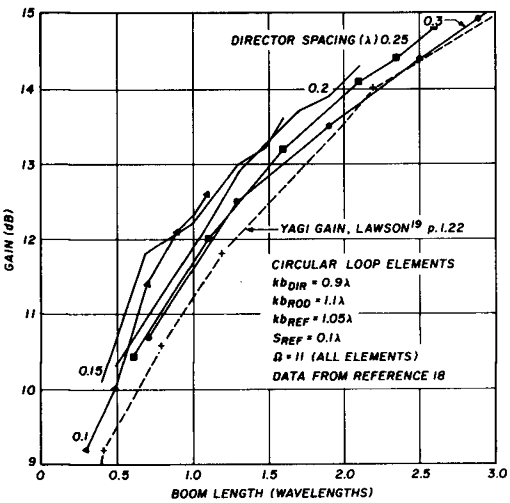

fig. 8. Calculated gain of multi-element circular loop arrays, plotted against boom length. Separate curves are shown for director spacings of 0.1, 0.15, 0.2, 0.25, and 0.3 wavelength spacing. For most boom lengths, a small increase in gain can be attained by using close spacing. There are penalities for this: for example, greater wind load, and usually, smaller bandwidth. Data from Shoamanesh and Shafai.[18]

easy to build in self-supporting form for frequencies in the VHF, UHF, and SHF ranges. By adopting the principle of the bicycle wheel, discussed in a later part of this series, you can build hf designs.

The design values in **table 1** are known to be near optimum for maximum performance. A small increase in gain may be obtained by making some changes in element size and spacing. Unfortunately, there may be appreciable change in minor lobe structure if much retuning is attempted.

The only theoretical data relating to the gain of multi-element circular-loop arrays comes from the same source,[17,18] and is summarized in **fig. 8**. This again shows gain versus boom length, but with individual curves for director spacing. A small but definite increase in gain is usually possible by adding directors, but the limit of improvement is not known. Retuning must be done carefully. Front-to-back ratios vary from about 10 to over 25 dB from one set of spacings to another, and there are probably changes in bandwidth as spacing changes. Shoamanesh and Shafai[17] give some guidelines for design optimization.

The data in Chapers 2 and 3 of Lawson[19] gives more information on results obtainable by optimization. Conversion of this data to loop design conditions is somewhat tedious. First calculate the self- and mutual reactances for the length and spacing data given by Lawson.[19] Then transform these values to loop size and spacing, using the curves and tables given in this series or the references. The basic computational proc-

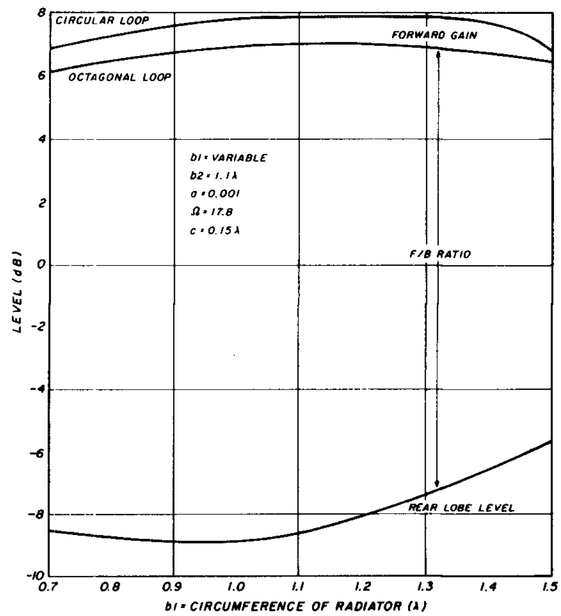

fig. 9. Calculated front and back lobe levels of an octagonal array, plotted against radiator circumference. Radiator circumference is 1.2 and spacing is 0.15 wavelength. The gain of a two-element circular loop is shown for comparison. The variation in gain would be more marked if the size of the reflector were also varied, but this shows again that loop antennas are broadband. The difference in circular and octagonal gain appears to be largely due to calculation technique differences.

Table 1. Calculated performance of multi- and circular-loop arrays.

no. directors	boom wave-lengths	gain (dB)	F/B (dB)	H-B/W (Deg)	E-B/W (Deg)	drive:R (Ohms)	drive:jx (Ohms)
2	.70	10.70	15.20	59.00	54.00	58.50	156.70
4	1.30	12.50	25.80	48.00	44.50	44.20	168.00
6	1.90	13.50	14.20	40.50	38.50	56.00	179.80
8	2.50	14.40	14.20	35.00	32.50	63.60	163.30
9	2.80	14.80	16.40	32.50	30.50	52.00	17.50
10	3.10	15.20	23.00	30.50	30.00	45.60	163.10

Reflector = 1.1, radiator = 1.2, and all directors = 0.9 wavelength circumference. Reflector is spaced 0.15 and directors 0.3 wavelength. The nine-director array needs no matching, the others only a capacitive stub across the feedpoint. A balun is not necessary, but is probably helpful in avoiding feedline and tower radiation.

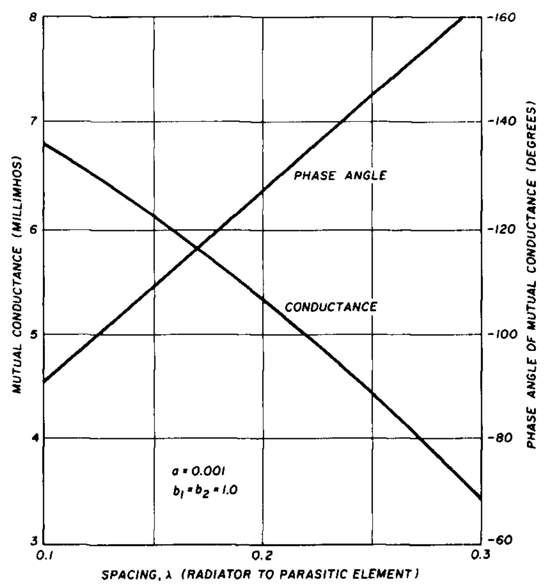

fig. 10. Mutual admittance of two octagonal loops, one wavelength in diameter. For wider separation, the magnitude of the admittance decreases nearly inversely with separation, and the phase linearly. These curves plus the self admittance data given in the second article of the series allow determination of array patterns by use of pattern multiplication techniques.

ess described in Lawson's Chapter 1[19] or in Kraus[20] can be modified for loop anaylsis.

octagonal arrays and loop approximations

Arrays of polygons are not common; circular elements are usually just as easy to build. There is also the matter of added resistance at the joints between segments, if present. The octagonal array data included here is primarily for use in approximating the performance of circular-loop arrays.

Figure 9 is for comparison and gives the gain and front-to-back ratio for a two-element octagonal array. It is very nearly the same as for the two-element circular array of **fig. 2.**

Figure 10 gives the mutual admittances between two 1.0-wavelength elements. Combined with the self-admittance values of **table 1**, these curves allow calculation of the currents in any multi-element array, and in turn the pattern as described by Kraus[20] and used by Lawson.[19] As mentioned above, these curves make the performance data calculated by Lawson[19] useful as an approximation to circular-loop (and other shape) arrays.

patterns of octagonal arrays

Figure 11 shows the MININEC-calculated horizontal-plane pattern of a two-element, bottom-fed array with a parasitic director — an array with nominally horizontal polarization. Radiator and director circumferences are 1.0 and 0.9 wavelengths, and spacing is 0.15 wavelength. The pattern resembles that of an equivalent two-element Yagi, which also shows poor front-to-back ratio. Somewhat more gain could be obtained with a larger radiator and closer spacing.

Figure 12 shows the same calculation for a 1.1-wavelengths reflector. Gain is nearly maximum from this element combination, and the back lobe is reasonably small. This appears to be a good choice for a two-element beam or for the exciter section of a large array.

Figure 13 shows the same calculation for a three-element octagonal array, with 0.9, 1.2, and 1.1 director, radiator and reflector circumferences, with the director spaced at 0.2 and the reflector at 0.15 wavelength. The gain is close to but below the maximum attainable with this boom length. The front-to-back ratio is reasonable. Experience with 2, 10, 15 and 20-meter versions of this combination indicates that better front to back, up to about 30 dB, is possible

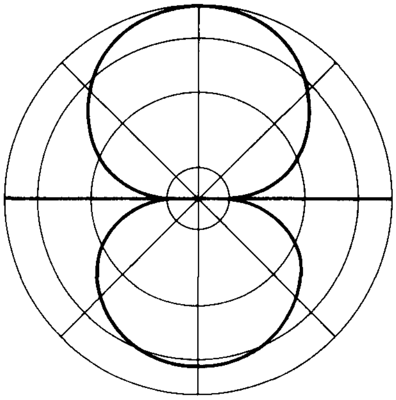

fig. 11. Horizontal plane pattern of the h-polarized component from a bottom-fed director-radiator combination. Circumferences are 0.9 and 1.0 wavelength. Spacing is 0.15 wavelength. Forward gain is reasonable, but the back lobe is large.

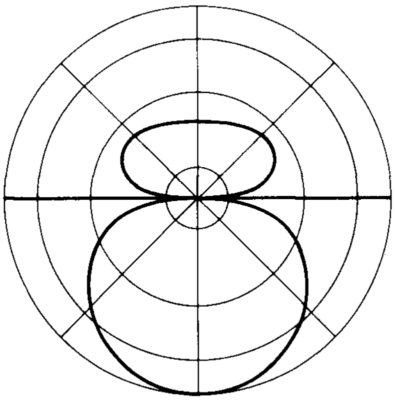

fig. 12. Horizontal plane pattern of a 1.1 wavelength reflector-radiator combination. Other conditions same as in fig. 11. Forward gain is excellent for a two-element antenna. The front-to-back ratio of about 13 dB is good.

with element tuning. **Figure 8** shows that the gain could be increased about 1 dB by a second director at 0.1-wavelength spacing.

Figure 14 shows another pattern for the same beam for the total radiation component. Because of the small cross-polarized component present in loops, the sides of the pattern are filled in, so the front-to-side ratio is poor.

It is my experience that the filled-in pattern is correct for high-angle or E-layer radiation. However, low-angle radiation, typical of F2-layer DX, shows the high front-to-side discrimination of **fig. 13**. Under good conditions, an S9+ signal can be dropped to the noise level if the signal is placed on the 90-degree null. This results in a reduction of 40 dB or more. The same characteristic is noted on 15 meters when E-layer skip is present. Published theoretical analyses shed no light on this performance difference. It appears to be associated with ground reflection. We will return to this subject later in this series.

all-driven arrays

As with dipole elements, loops can be used in driven arrays. Driven arrays are not common in Amateur use because of space requirements. The few occasionally encountered are typically two-element designs. These are also used in place of a single radiator element in some high-performance arrays, partly for gain and front-to-back improvement, but also to improve the effective bandwidth.

Figure 15 shows the MININEC-calculated gain for two 1.0-wavelength loops spaced 0.12 wavelength,

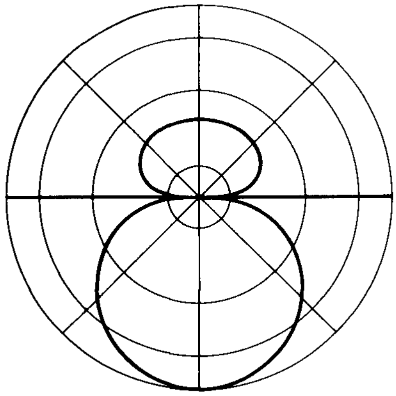

fig. 13. Horizontal plane pattern of a bottom-fed, three-element octagonal array. Circumferences are director = 0.9, radiator = 1.2 and reflector = 1.1 wavelengths. Director spacing is 0.2 and reflector 0.15 wavelength.

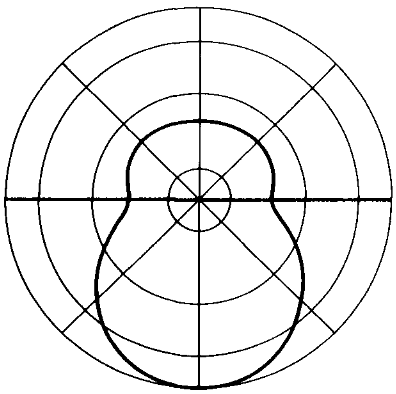

fig. 14. Total component radiation pattern for the array of fig. 13. The vertical component fills in the side-lobe area. See text for practical experience with an antenna of this type.

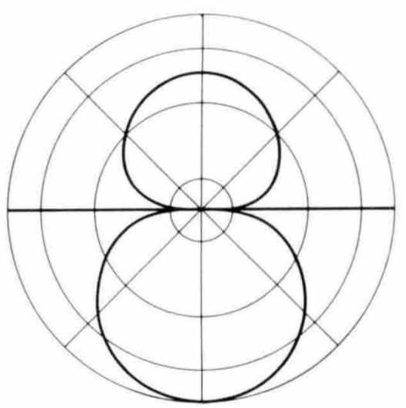

fig. 15. Horizontal component pattern for two one-wavelength loops separated 0.12 wavelength and bottom fed 135 degrees out of phase. The antenna is related to the "ZL-Special", and is useful by itself. The technique is also useful as the feed of large arrays, to give better front-to-back and gain.

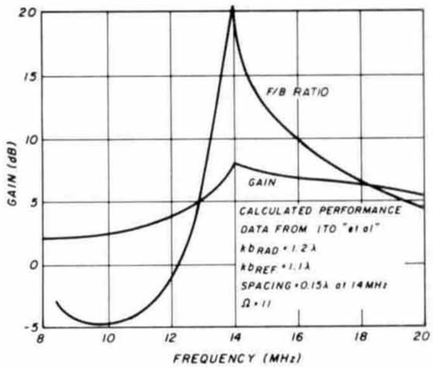

fig. 16. Calculated gain and front-to-back ratio of a two-element array designed for 14 MHz, but operated over the range 8-22 MHz. Forward lobe gain exceeds that of a dipole over the entire range. The back lobe can even be larger than the main lobe, but effective interference reduction is usually possible by rotating the antenna to place the interference in a null. Any antenna of the Quad family is a useful wide-band antenna for occasional operation on other than designated bands. Based on data from Ito et al.[11]

and fed 135 degrees out of phase, like the "ZL-Special" antenna. The gain performance is good, but the back lobe is rather large. Antennas of this type will be studied further when we discuss rectangular loops.

super-wideband operation

Figure 16 shows the calculated performance of a 20-meter two-element array from 8.5 to 20 MHz. The gain curve shows that this parameter exceeds that of a dipole over the entire range. In fact, the performance is reasonable over 7 to 30 MHz, although there is lobe splitting on the higher bands, and main-lobe reversal on the lower ones. Front-to-back ratio is high only near the design frequency, however.

The secret of using this wide bandwidth lies in the transmission-line matching technique used. I prefer Teflon-insulated 75-ohm cable. Open-wire line or twin lead is also good. A matchbox is a necessity. (I think that a matchbox should always be used to simplify using the entire band and to reduce harmonic radiation.) One fact seems clear: if you are using a Quad, you can have multiband operation without a lot of real estate for an antenna farm.

Part 4 deals with the square or Quad loop and some of its close relatives.

references

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17. A. Shoamanesh and L. Shafai, "Properties of Coaxial Yagi Loop Arrays," IEEE Transactions Antenna Propagation, July 1978.

18. A. Shoamanesh and L. Shafai, "Design Data for Coaxial Yagi Array of Circular Loops," IEEE Transactions Antenna Propagation, September 1979.

19. James L. Lawson, *Yagi Antenna Design*, ARRL, Newington, Connecticut, 1986.

20. John D. Kraus, *Antennas*, McGraw-Hill, New York, 1950.

*References 1-15 are found in part 1.

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