MULTI-ELEMENT ANTENNA ARRAYS

finished July 19, 1959

25RC

NATIONAL RADIO INSTITUTE
ESTABLISHED 1914
WASHINGTON, D. C.

STUDY SCHEDULE NO. 25

For each study step, read the assigned pages first at your usual speed, then reread slowly one or more times. Finish with one quick reading to fix the important facts firmly in your mind, then answer the Lesson Questions for that step. Study each other step in this same way.

☐ 1. Collinear Directive Arrays .... Pages 1-7

The properties of this type of antenna, and its applications in standard broadcast and high-frequency transmission are discussed. Answer Lesson Questions 1 and 2.

☐ 2. Complex Directive Arrays .... Pages 7-14

In this section you learn how broadside and end-fire antennas work, and how they can be combined with collinear arrays to form Sterba, lazy H, 8JK, and other highly directive antennas. Answer Lesson Question 3.

☐ 3. Long-Wire Directive Arrays .... Pages 15-19

This section tells how directivity can be obtained by using antennas with elements that are several wavelengths long. V beam and rhombic antennas that use long-wire elements are discussed. Answer Lesson Question 4.

☐ 4. Parasitic Arrays .... Pages 19-23

Elements that have no direct connection to the transmitter, but obtain their power parasitically from a driven element, can be used to increase directivity. Answer Lesson Questions 5 and 6.

☐ 5. Power-Fed Reflectors and Directors .... Pages 24-28

To prevent interference between broadcast stations, some stations must have unusual radiation patterns. They can be obtained by using two or more driven elements by adjusting the phase and the amplitude of the currents to each element. Answer Lesson Questions 7, 8, and 9.

☐ 6. Ultra-High Frequency Arrays .... Pages 29-36

This section considers the special problems of FM and television antennas, and the types of antennas that are used for these services. Answer Lesson Question 10.

☐ 7. Start Studying the Next Lesson.

FM1M856 1956 Edition Printed in U.S.A.

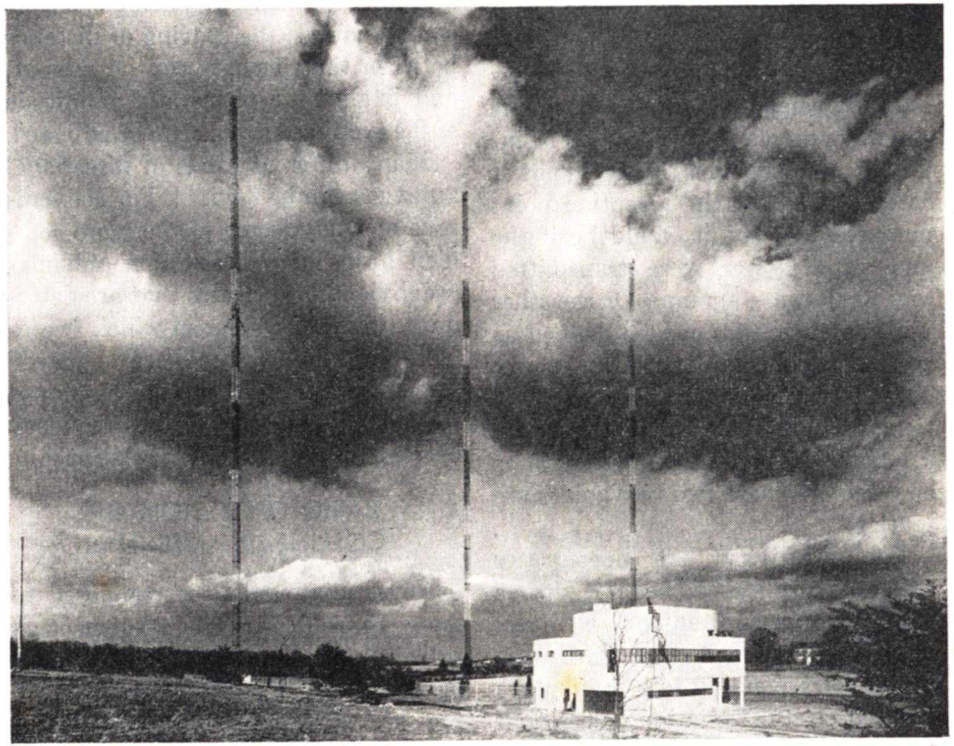
MULTI-ELEMENT ANTENNA ARRAYS

Collinear Directive Arrays

IN THE last few Lessons we studied the behavior of simple antennas, and several methods of feeding radio-frequency power to them. We now come to the interesting problems associated with more complicated antennas, such as those composed of more than one radiating element.

There is only one reason for constructing complex antennas, and that is to build some degree of radiation directivity into the antenna systems.

In point-to-point communication, high directivity is desirable in both vertical and horizontal planes. A very sharp horizontal-plane radiation pattern, or beam, is advantageous, because the only useful power is that which is



Courtesy Western Electric Co.

This is a view of the antenna array used by WTOP (formerly WJSV), Washington, D. C. It consists of three vertical radiators each 340 ft. tall, equally spaced, and in a straight line. The desired directivity pattern is obtained by dividing the 50 kw. of power between the three elements, and by controlling the relative phase of the r.f. applied to each of them.

radiated directly toward the reception point. Increase of vertical plane directivity is also useful, for it allows the concentration of radiation at the optimum angle of elevation when using a sky wave over a definite skip distance.

There are two advantages in the control of the direction of maximum antenna radiation: (1) An increase in the sharpness of the radiation pattern gives proportionately more power in one or more desired directions at the expense of the other directions. (2) Such radiation control offers the possibility of transmitting relatively less power toward a neighboring service area, so that higher transmitter power can be used without producing interference.

► As a measure of their directivity, the performance of complex antennas is usually compared to that of a simple half-wave dipole in free space. For instance, antenna gain is the signal power increase in db at the reception point compared to what it would be if the same total power were transmitted from a half-wave antenna. On the other hand, antenna gain can be defined as the increase in total transmitter power that it is necessary to radiate from the standard half-wave antenna in order to achieve the same signal strength at the receiver. These two viewpoints are identical.

High directivity that concentrates radio energy in a sharp beam is always the result of several antenna elements interfering with each other. In the direction corresponding to a major lobe of radiation, the radiation fields of all the elements are in phase, so that they add together, and result in a strong signal. In all other directions, the separate fields are out of phase, so that they cancel each other, and the resultant field is either reduced to a low intensity, or dropped to zero. *No matter how complex an antenna becomes, the radiation directivity it possesses is a direct result of this destructive and constructive interference between the fields of the separate elements.*

The relative phases of two or more radiation fields at any reception point depend on not only the phases and amplitudes of the antenna currents generating the fields, but also on the respective distances of the antenna elements from the reception point. We see from this that radiation patterns can be changed in several ways: The number of antenna radiating elements can be varied; the spacing or distance between the elements can be altered; and finally, the phase and amplitude of the exciting currents can be adjusted.

Many different kinds of directional antennas can be devised. For convenience of study, some of the more common forms of multi-section antennas are divided into classes that are determined by the manner in which two or more radiation elements are "stacked" into an array, and the means employed to feed them with radio-frequency currents of definite phase relationship.

BASIC OPERATION OF COLLINEAR ANTENNAS

Any radiator that is composed of more than one antenna element is called an "antenna array." The simplest type of array is that shown in Fig. 1A, where there are two elements lying in line. When the elements of an array all lie on the same straight line, it is called a "collinear" array. There may be two or more elements of any length, and they need not be adjacent.

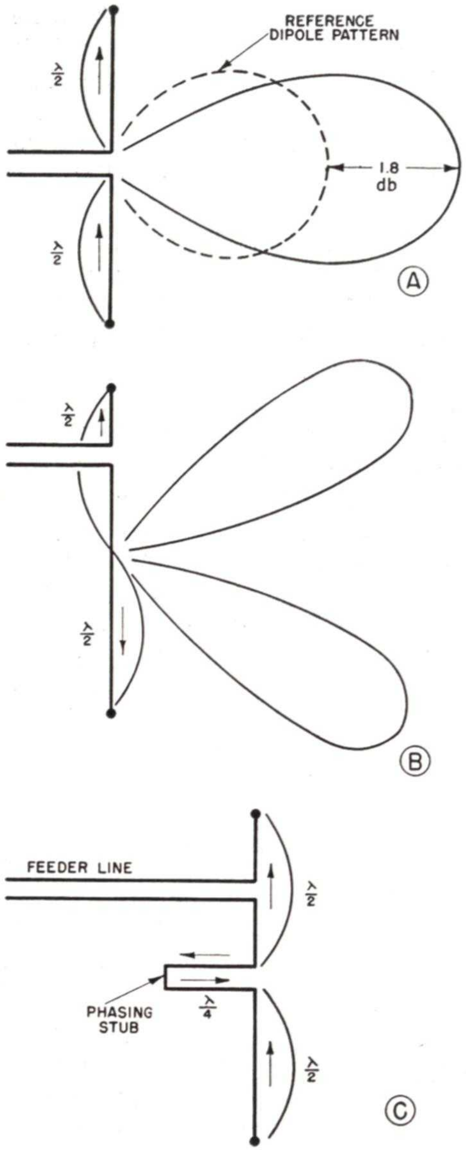


FIG. 1. Two half-wave collinear elements fed in phase, as at A, give a gain of 1.8 db as compared to the output of a single half-wave dipole. Note that a high-impedance feed is used. If a low-impedance feed is desired, it is necessary to feed at the center of one of the half-wave sections. However, if this is done as at B, the radiation pattern splits in two, because of the current phase reversal in the lower element. Low-impedance feed can be used, as in C, if the phasing stub is inserted to restore proper phasing.

The array in Fig. 1A is a two-element collinear array that is composed of half-wave elements, spaced at a half wavelength—the distance between the centers of the elements. As indicated by the arrows, the separate elements are excited with currents that are in phase, which results in a radiation pattern that is slightly sharper than a simple dipole, and there is an antenna gain of about 1.8 db. For comparison, the approximate pattern of the reference dipole is shown by the dashed lines.

Although the radiation lobe is drawn on only one side of the antenna, the radiation occurs in all directions that are perpendicular to the antenna. In a three-dimensional view, this radiation pattern looks like a slightly flattened doughnut with the antenna running through the hole.

The feedpoint of the array in Fig. 1A has a high impedance, since it is being fed into nodes of theoretical zero current. This high input impedance can be matched to a low-impedance transmission line by inserting a quarter-wave matching section of proper characteristic impedance, as outlined for the Q antenna in a previous Lesson; or, it is possible to use a quarter-wave matching stub.

Stub Phasing. If we try to feed this array at a low-impedance current loop, as shown in Fig. 1B, we obtain two major radiation lobes. This is caused by the phase reversal of the current in the lower half of the array.

It is possible to use low-impedance feed, and still obtain a single radiation lobe, if we insert a phase-reversing stub in the center of the antenna as shown in Fig. 1C. This stub reverses the phase, because it is one-half wavelength in length. It is a half-wave section that is folded so that it does not radiate. The gain of this array is still 1.8 db, and the radiation pattern is identical to that shown in Fig. 1A.

Ways of Increasing Gain. By increasing the element lengths from 0.5 wavelength to 0.64 wavelength, we can increase the sharpness of the radiation pattern, and raise the gain of the two-element collinear array from 1.8 db to approximately 3 db.

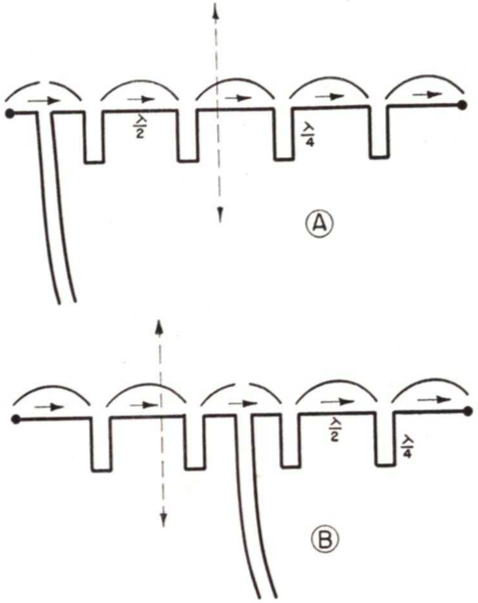


FIG. 2. Five-element collinear arrays giving a gain of 5.3 db. Maximum radiation is in the direction of the dotted arrows. Both feeder line connections are low-impedance, but the method in B gives more uniform power distribution, because the current and the voltage distribution is symmetrical with regard to the center of the antenna.

The gain of this array can also be increased by increasing the spacing between the elements. The theoretical gain for two half-wave elements, spaced three-quarters wave-length, is 3.2 db as compared to the 1.8 db for half-wave spacing. Raising the gain in this manner, however, introduces difficulties in constructing a non-radiating phase-reversing stub that spans the gap between the two radiating elements.

Gain can also be increased by adding elements. The five-element array in Fig. 2A, for example, has a gain of approximately 5.3 db. The currents of all the elements are in phase, and the maximum radiation as indicated, occurs broadside (that is, at right angles) to the line of the array. Because of ohmic losses along the array, the elements that are farthest removed from the feeder line do not receive full current. It is preferable, therefore, to feed near the center of the system, as shown in Fig. 2B, in order to maintain a more uniform distribution of power among the elements.

For other collinear arrays of various numbers of elements, the theoretical gains for one-half and three-quarter wave spacing are given in Table I.

TABLE I
Theoretical Gain of Collinear Half-Wave Antennas

Spacing between centers of adjacent half waves	Number of half waves in array versus gain in decibels				
	2	3	4	5	6
$\lambda/2$	1.8	3.3	4.5	5.3	6.2
$3\lambda/4$	3.2	4.8	6.0	7.0	7.8

The Franklin Antenna. In constructing collinear arrays for broadcast frequencies, it often happens that the length of the phasing stubs is too long for convenience. It is possible to replace the phasing stubs with loading coils that reverse the current phase between elements equally well. This was done in a vertical antenna that was developed by C. S. Franklin of the British Marconi Company in order to obtain a vertical collinear array that is operated against ground. Three different arrays of this type are shown in Fig. 3. Such arrangements give intense radiation along the ground, but radiate very little sky wave.

The chief disadvantage of the Franklin antenna is the expense of building the necessary high towers. For example, an antenna that has only two half-wave elements is 1970 feet at 500 kc., 985 feet at 1000 kc., and 660 feet at 1500 kc.

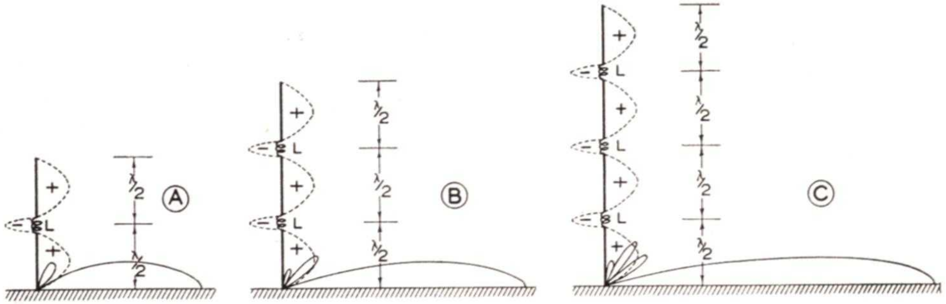


FIG. 3. Franklin vertical collinear arrays of two, three, and four elements. Loading coils are used for proper phasing. As indicated, these broadcast antennas have a very strong ground wave with very little sky-wave radiation.

These figures show that this type of antenna is more practical as the frequency is increased. At ultra-high frequencies, the dimensions are reduced to reasonable values, and in such use the array can take the form that is shown in Fig. 4A.

UHF COLLINEAR ARRAY

The ultra-high frequency array shown in Fig. 4A, is particularly interesting, not only because it is an efficient antenna, but also because it exemplifies several common practices in antenna and feeder design. In the first place, we note that the half-wave elements are only 95% of a half wavelength. In practice, the "end-effects" cause an antenna to be resonant when it is 5% shorter than the theoretical resonant length.*

We next notice that each half-wave radiating element is composed of a quarter wave along the 3-inch shield pipe, and another quarter wave along a larger diameter metal "skirt." The purpose of this method of construction is illustrated in Fig. 5A where we have a single half-wave element, or "flagpole" antenna that is driven by a 73-ohm coaxial line. By attaching the cable shield to the metal skirt that is folded back over the line, we not only complete the radiating portion of the

---

*In any practical antenna, the insulators at the ends of the antenna cause some capacitance at these points. Because r.f. current flows into these capacitors, the current at the ends of the antenna must not drop to zero. Therefore, the antenna elements must be shortened (generally about 5%), so that the standing waves of current at the ends of the antenna do not decrease to zero.

antenna, but we also form a quarter-wave stub that is made up of the inside of the skirt and the shield of the cable itself. Since this quarter-wave stub has a high impedance at the lower end of the skirt, it acts as a bazooka, and prevents r.f. currents from flowing down the remainder of the cable shield. As an additional feature, by dropping the point of connection to the cable inner conductor, the stub can also be used as a quarter-wave matching stub to match a 440-ohm line to the antenna elements. A modified form of a flag-pole antenna that is using this type of matching is illustrated in Fig. 5B.

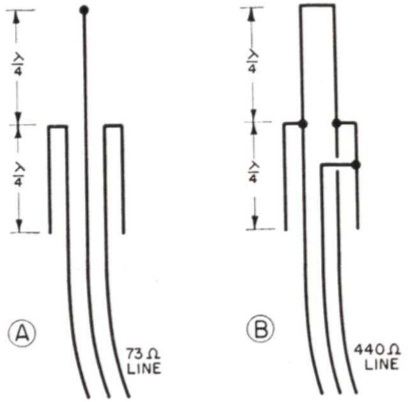


FIG. 5. In the flag-pole antenna, a quarter-wave skirt is folded back over the cable shield to form a bazooka-type section that prevents r.f. current from flowing down the coaxial line. By tapping down, as at B, the skirt can also be used as a matching stub to match a higher impedance line.

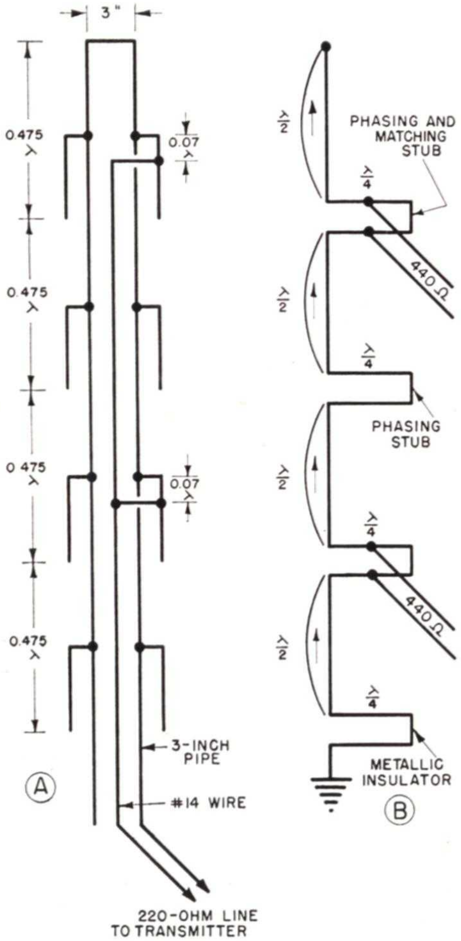


FIG. 4. At left, an ultra-high frequency version of the Franklin four-element collinear vertical array. Bazooka-type skirts are used for both phasing and impedance-matching. At right, is the linear equivalent of this directive array.

Referring to Fig. 4A, we now see that the array is four collinear half-wave elements that are separated by quarter-wave stubs. In linear form, the equivalent of this array looks like that shown in Fig. 4B. In this arrangement we can see that the quarter-wave stubs perform several functions: The one at the bottom serves as a "metallic" insulator to insulate the entire antenna; two of the others serve as impedance-matching stubs, and all of them behave as phasing stubs.

Theoretically, it is satisfactory to feed the array, shown in Fig. 4A, at one 440-ohm point only, but for good power distribution it is better to feed simultaneously at the two points shown. Since the feed point of the topmost section in Fig. 4A is a multiple of a half wave away from the lower feed point, it presents a second 440-ohm load to the coaxial line at this latter point. Thus, the coaxial feed line sees two 440-ohm loads in parallel, or 220 ohms, and the combination of a 3-inch pipe and a #14 wire is chosen because it has a surge impedance of approximately 220 ohms to match this load. There is actually a slight mismatch, since the two feed points are not exactly a half wave apart, but the effects of this slight discrepancy are practically negligible.

Notice that in collinear arrays, the center of the elements are generally spaced one-half wavelength. In practice, if the spacing is different from one-half wavelength, it is difficult to feed in-phase currents to each of the radiating elements.

Complex Directive Arrays

In addition to the collinear type of directional antenna just discussed, there are two other basic types: The "broadside" and the "end-fire" arrays. Let us study these types in detail for we will meet them later, combined with collinear arrays to form complex directive arrays. Both of these arrays consist of two or more radiating elements, all lying in the same plane as shown in Fig. 6. The only difference between the two systems is the phase of the currents in the individual elements.

BROADSIDE AND END-FIRE ARRAYS

In the *broadside* array shown in Fig. 6A, all the elements are one-half wavelength apart, and these are excited with

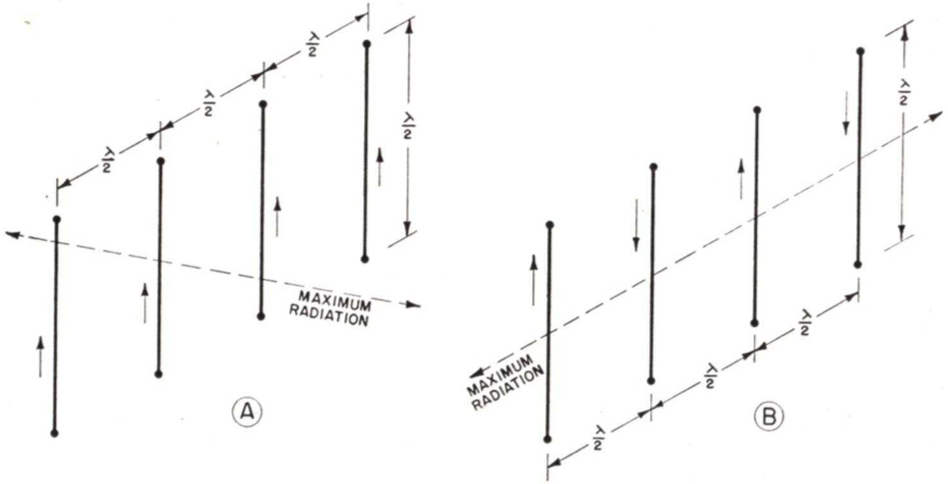


FIG. 6. In the broadside array at left, currents in all elements are in phase so that maximum radiation occurs perpendicular to the plane of the array. When currents in adjacent elements are out of phase, as at right, we have an end-fire array that concentrates the radiation off the ends of the array.

currents that are *in phase.* For a radio wave in space, there is a phase shift of 180° for every half wavelength of travel. This means that radiation leaving one element, flows *along the line of the array* and arrives at the next element at the proper time, and in the exact phase to be cancelled by the radiation from the second element. This cancellation between elements continues for the entire length of the array, so that the resultant radiation off the ends of the array is reduced to virtually zero. On the other hand, a side view of the array shows that all the elements are fed in phase, and are practically the same distance from the observer. For this reason the radiation waves are in phase, and add together as though all the elements were parallel. Thus, this type of array with this phasing leads to strong radiation in a direction that is perpendicular to the plane of the array.

TABLE II
Theoretical Gain of Broadside Half-Wave Elements at Different Spacings

Separation in fractions of a wavelength	Gain in decibels
1/8	0.3
1/4	1.0
3/8	2.4
1/2	4.0
5/8	4.6
3/4	4.8

For the *end-fire* array in Fig. 6B, alternate elements are excited with currents that are *180° out of phase.* A side view of this arrangement shows that the radiation from half the elements is out of phase, and hence cancels the radiation from the remaining elements. The radiation in a broadside direction, therefore, is very low. *Along the plane of the array,* the radiation from one element arrives at the next element in the proper phase to be reinforced. Accordingly, the radiation of all the elements adds together, and becomes a maximum off the ends of the array.

Gain of the Broadside. In practical broadside arrays, the elements are kept a half wavelength long (except for the 5% shortening correction), but the spacing between elements is not always a half wavelength. Like the collinear array, greater spacing of the elements gives higher gain. This is particularly useful if only two elements can be accommodated in a given space. For a broadside, using two half-wave elements, the theoretical gain varies with the spacing, as shown in Table II.

If ample space is available, the gain is increased by using more than two elements. For half-wave spacing, the gain versus the number of elements in a broadside is presented in Table III.

TABLE III
Theoretical Gain Versus Number of Broadside Elements with Half-Wave Spacing

Number of elements	Gain in decibels
2	4.0
3	5.5
4	7.0
5	8.0
6	9.0

By increasing both the spacing and the number of elements, greater gain can be obtained. In practice, however, this is not done for it is difficult, as we will later see, to feed in-phase currents to more than two antenna elements when the spacing between the elements is not λ/2. For this reason then, if more than two elements are used in an array, the spacing between them is generally λ/2.

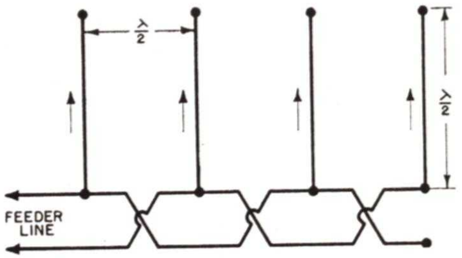


FIG. 7. Proper phasing for a broadside array, using half-wave spacing, can be accomplished by transposing the feeder line between the elements.

Feeding the Broadside. The simplest way to feed a broadside array is to run a transmission line along the array, connecting each element to the line. If the spacing is a half wavelength, the phase of the voltage on the line reverses every half wave, so we connect alternate elements to opposite sides of the line to excite the elements in phase. This is easily done by transposing the line between the elements as shown in Fig. 7. This is called a high-impedance feed system because the transmission line feeds into a high impedance point.

As illustrated in Fig. 8, there are two ways of feeding a two-element broadside array. A high-impedance feed to an array is shown in Fig. 8A. This array has one-half the number of elements of the array shown in Fig. 7. The direction of the current flow in the elements and the transmission line is indicated by the arrows. In contrast, the arrangement in Fig. 8B is a low-impedance feed system (so called because the transmission line feeds into a low-impedance point) in which the two elements are fed in parallel, each through a quarter-wave section of line. Here, too, the current flow is indicated by arrows, and as far as the radiating elements are concerned, their currents are still in phase.

The low-impedance feed broadside array can be expanded into the symmetrical four-element array of Fig. 9. This construction is an improvement over that shown in Fig. 7, for it allows

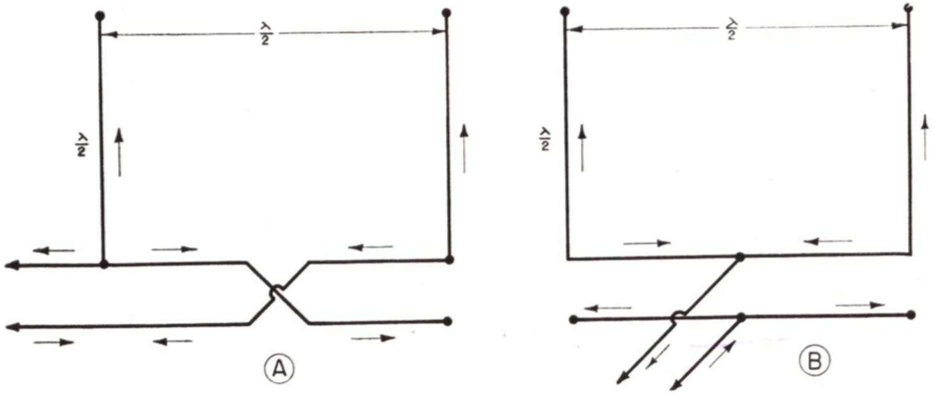


FIG. 8. The two-element broadside may be fed in two different ways. At left, a high-impedance system, and at right, a low-impedance arrangement.

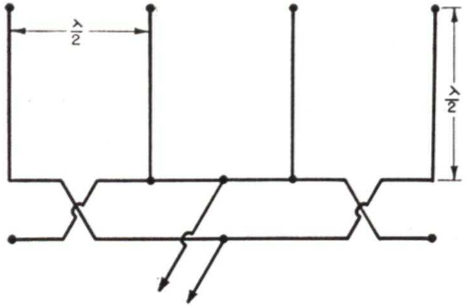


FIG. 9. A symmetrical four-element broadside array that has a low-impedance feed and a uniform power distribution between the elements.

the use of a low-impedance line, and the power distribution between the elements is made more uniform.

A modified version of the broadside is illustrated by the Bruce array of Fig. 10. This scheme used quarter-wave elements that are spaced a quarter wavelength apart. As shown by the arrows, in all vertical elements the loops of maximum current occur in phase, so that most of the radiation comes from these vertical parts. On the other hand, current nodes occur on the horizontal wires, and the small currents that flow are out of phase, so that the radiation from the horizontal members is very low. The array can be fed at either end for high-impedance feed; or for better power distribution, one of the medium-impedance feeds of Figs. 10B and 10C can be applied at the center element of the array.

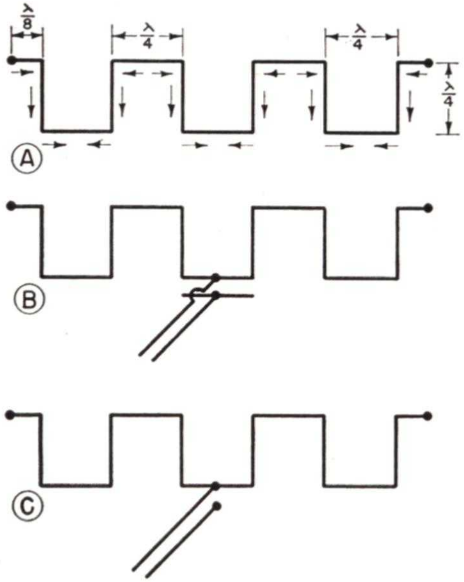


FIG. 10. The Bruce broadside array takes advantage of the current distribution on a resonant wire. Fed at either end, the array has a high impedance. For better power distribution, the medium-impedance feeds shown in B and C are preferred.

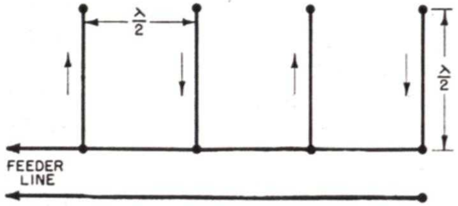


FIG. 11. Proper phasing for end-fire operation is automatically obtained when all elements of this array are connected to the same side of the feeder line.

Using the End-fire Array. Almost any of the broadside arrangements can be made into an end-fire array by feeding alternate elements with *out-of-phase* currents, instead of *in-phase* currents. Thus, the antenna system shown in Fig. 7 can be changed to an end-fire array, by connecting all the elements to the *same* side of the transmission line. This gives us the array shown in Fig. 11. Since the phase of the voltage reverses every half-wave distance down the feed line, the currents in consecutive elements are 180° out of phase as desired. As a matter of fact, end-fire phasing is achieved automatically for *any* element spacing. This is because the phase shift along the transmission line is nearly the same as that encountered by a wave travelling in space along the line of the array; consequently, no matter what the element spacing may be, the waves travelling toward the ends of the array are reinforced at every element.

For the simple two-element end-fire array with half-wave spacing, we can use the high-impedance feed of Fig. 12A, or the low-impedance connection shown in Fig. 12B. Note that these arrangements are very similar to the broadside arrays that are shown in Fig. 8. The only difference is that the feed methods are interchanged so that the elements are driven out of phase.

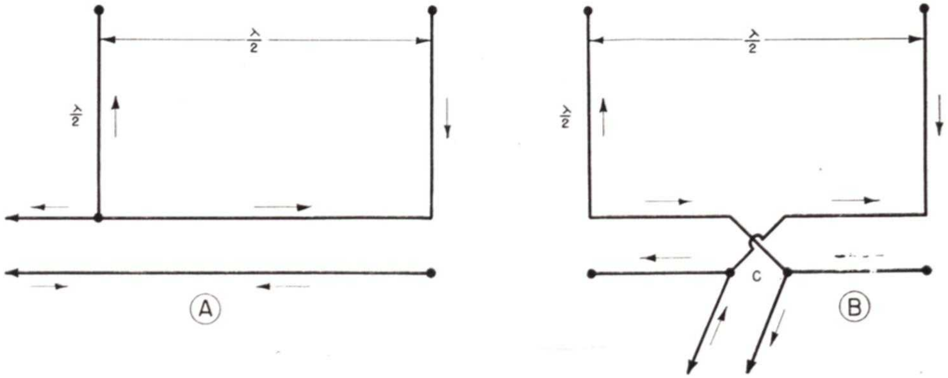


FIG. 12. At left, a high-impedance feed for the two-element end-fire array. At right, a method of feeding with a low-impedance transmission line.

Like the two-element broadside array, the gain of the two-element end-fire array depends on the spacing of the elements. For two elements that are driven 180° out of phase, the gain varies with their separation as shown in Table IV. Note that, unlike the broadside array, the gain increases with the spacing up to a certain point only, and then it decreases. Maximum directivity is realized for comparatively close spacing; a convenient type of array to use where space is limited.

A closely spaced two-element end-fire array, however, cannot be fed by the methods shown in Fig. 12 where the 180° phasing depends on the element half-wave spacing. Nevertheless, by connecting two elements to opposite sides of a transmission line, as shown in Fig. 13, they are driven out of phase. When a resonant transmission line is used to feed such a two-element array, high-impedance feed, as shown in Fig. 13A, can be used. If desired, an untuned line may be used, if the elements are tapered to form a part

TABLE IV
Theoretical Gain of End-Fire Half-Wave Elements (180° out of phase)

Spacing in fractions of a wavelength	Gain in decibels
1/20	4.1
1/8	4.3
1/4	3.8
3/8	3.0
1/2	2.2
5/8	1.7

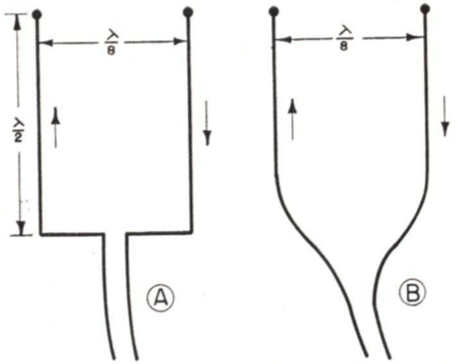


FIG. 13. For 180° phasing, the two elements in a close-spaced end-fire array are connected to opposite sides of the feeder line. A resonant line is used with the arrangement at the left. For an untuned line, the elements may be tapered to form a part of the feed line as at the right.

of the transmission line as shown in Fig. 13B. This latter method prevents standing waves on the feed line by eliminating abrupt impedance changes in a way similar to the delta feed that was described in earlier Lessons.

COMBINATION ARRAYS

The three basic types of arrays discussed so far are the collinear, the broadside, and the end-fire. From what we have already learned, we are able to combine these to construct complex arrays of mixed forms, some of which can be derived quite simply.

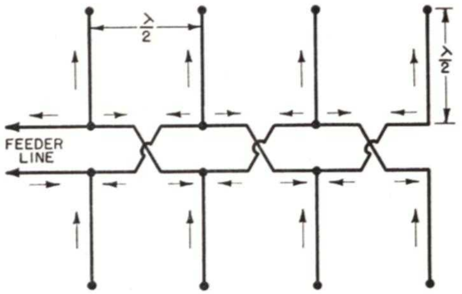


FIG. 14. A complex broadside array, made by adding collinear duplicates to the simple four-element broadside array of Fig. 7.

In the broadside array of Fig. 7, the number of elements can be increased without increasing the length of the array by adding duplicates of the first set of elements on the other side of the line as shown in Fig. 14. We can also think of this array as consisting of four collinear elements added together to make a broadside array.

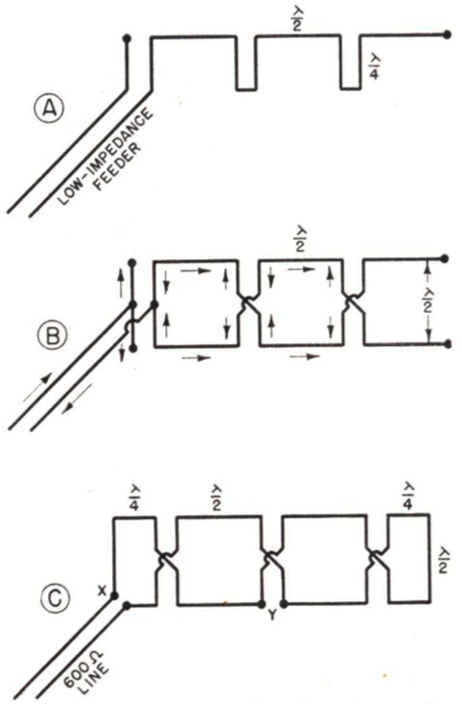


FIG. 15. Two collinears like those in A, when combined in broadside make the sterba array in B. This may be modified as in C to have a closed circuit through which direct current may be passed for deicing purposes.

Sterba Antenna. We can arrive at a different version of mixed broadside and collinear structures by starting with the collinear array of Fig. 15A, and combining it in broadside with another array of this type in order to get the array that is shown in Fig. 15B. This is often called a "Sterba" array. In modified form it appears as shown in Fig. 15C where there is a closed circuit through which direct current may be superimposed upon the radio frequency for deicing purposes. Feeding at point X gives a fair match for a 600-ohm line. Closing the circuit at X, and feeding at Y, however, results in a high-impedance feed.

Lazy-H Antenna. Still another common array is made by starting with a two-element broadside, and duplicating it with collinear elements, or by beginning with two collinear half waves, and then broadsiding them. In either case, we arrive at the lazy-H array of Fig. 16. This is a compact array of fairly high directivity, and is very adaptable as a rotatable beam for ultra-high frequency use.

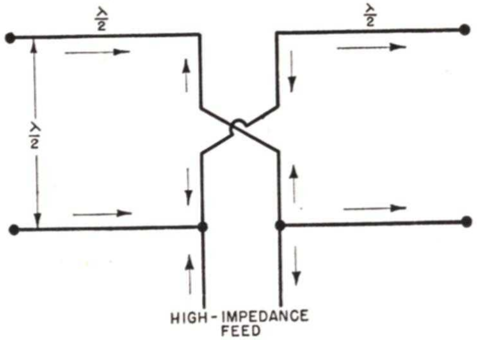


FIG. 16. The lazy-H directive array is made by adding collinear elements to the two-element broadside.

W8JK Antenna. A closely spaced end-fire array can be built up into a complex directive antenna system in a way similar to that of the lazy-H antenna. If we take the end-fire array shown in Fig. 17A, and add its collinear duplicate, we obtain the arrangement shown in Fig. 17B. This antenna is frequently used at ultra-high frequencies for its directivity in a horizontal plane by mounting it on its side on top of a rotating mast. As such, it is often called the "flat-top beam." This antenna is also called a W8JK, after the call letters of the amateur who popularized it.

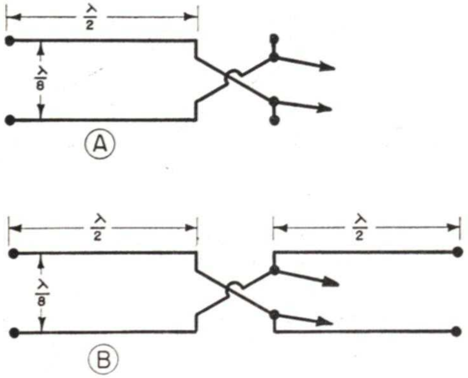


FIG. 17. The two-element close-spaced end-fire array at A, when expanded by adding its collinear duplicate, becomes the flat-top beam or the W8JK array at B.

GAIN OF COMPLEX ARRAYS

These combinations of collinear and broadside or end-fire arrays give increased directivity in *both* vertical and horizontal planes, because additional radiators have been added to the array height as well as to its breadth.

Since the collinearity of elements in a complex array usually sharpens the radiation pattern in one plane only, and the broadsiding or end-firing increases directivity in the other plane that is perpendicular to the first, the total directivity of these combined structures can be computed approximately as the sum of the gain of the collinear part of the array, plus the gain caused by the broadsiding or end-firing of the array.

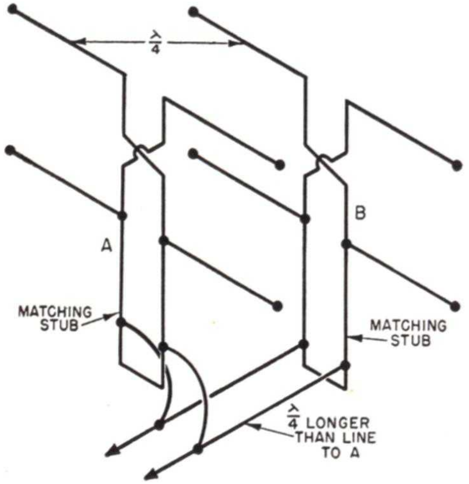


FIG. 18. An end-fire array made by combining two lazy H's and exciting them 90° out of phase. This combination is unidirectional in the direction A through B.

For example, let us consider again the four-element broadside array of two-element collinears shown in Fig. 14. From Table III we find that the broadsiding gives us a gain of 7 db, and from Table I we find that the collinearity raises the gain 1.8 db. Thus, the array in Fig. 14 is an over-all directivity gain of 8.8 db. This is not exactly correct because of the coupling between the various elements, but it is adequate for practical purposes.

In a similar manner, the Sterba array of Fig. 15B has three collinear elements that are giving a gain of 3.3 db as determined by Table I; besides this, the two sets in broadside array with half-wave spacing, as seen in Table II, give an additional gain of 4 db. The total gain of this array, therefore, is approximately 7.3 db.

For the flat-top beam antenna shown in Fig. 17B, Table IV shows that the end-firing gives a gain of 4.3 db, and the collinearity (from Table I) increases this 1.8 db which results in a total of 6.1 db increase in directivity.

ARRAYS OF ARRAYS

Complex antennas that combine collinearity with broadsiding or end-firing can be interpreted in a slightly different manner. We can consider the arrangements of Figs. 14, 15 and 16 as collinear arrays using broadside arrays as elements, or as broadside arrays of collinear elements. We realize that the elements of an array need not be simple radiators, but can be arrays themselves. Thus we can increase the gain of a simple array by making an "array of arrays."

For example, the lazy H array of Fig. 16 can be used as an element of an end-fire array by placing two lazy H's in line a quarter wavelength apart as shown in Fig. 18. Matching stubs are used to match the elements to a split untuned line, and the feed line to one Lazy H is made one-quarter wavelength longer than the other in order to drive the Lazy H's 90° out of phase. If the elements A and B are fed at, let us say 600 ohms, then the main feeder line coming from the transmitter to the junction of the two 600-ohm lines must be a 300-ohm line, since it is feeding two 600-ohm loads in parallel.

► With this arrangement, the antenna radiation pattern has only one major lobe, hence the system is unidirectional in the direction A through B. By reversing one feed line at the transmitter, the system may be made unidirectional in the opposite direction.

Long-Wire Directive Arrays

You recall that the radiation pattern of a free-space half-wave doublet consists of two main lobes that are at right angles to the line of the antenna as shown in Fig. 19A. Such a half-wave radiator is the standard with which all directive antennas is compared.

If we increase the length of the single-wire radiator, so that it becomes a full wave, three half waves, or two full waves, etc., we obtain radiation patterns that are more complex, like those shown in Figs. 19B, 19C, 19D, etc. Note that although the number of lobes is increased, these points of maximum radiation begin to lean toward the ends of the long wire. Furthermore, these lobes are much sharper than those from a simple half-wave antenna, that is, a larger fraction of the total radiated power is concentrated in the direction of these lobes.

Since we can realize some directivity gain by using a long wire antenna, what about the possibility of a simple *array* of long wires? Fig. 19E shows that the lobes of maximum radiation from a free-space five wavelength wire occur at an angle of 22.5° with respect to the antenna itself. Let us suppose that we combine two such wires in the form of a V, having a 45° angle between them as shown in Fig. 20. We now find that the four 22.5° lobes of one antenna reinforce the four lobes of the other antenna to give a resultant radiation pattern of only two lobes for the composite antenna. Notice that lobes A-B combine with lobes E-F to produce most of the directivity that is shown in lobes K-L. The energy that is radiated to the sides of the antenna by lobe D is cancelled by G, and that of C is cancelled by H. However, the energy that is radiated forward by C and H combines to form L, and that of D and G combines to form K. This produces a high-gain beam with maximum radiation occurring in both directions along the center line of the V.

Such V-beam antennas can be used as elements for more complex arrays to obtain even greater directivity. For example, two V's can be broadsided, forming a W-shaped structure. Or again, we can make an end-fire combination by placing one V a quarter wave behind the other, and exciting them 90° out of phase in the same manner as the two lazy H's shown in Fig. 18. This latter arrangement has the advantage of giving a single-lobed

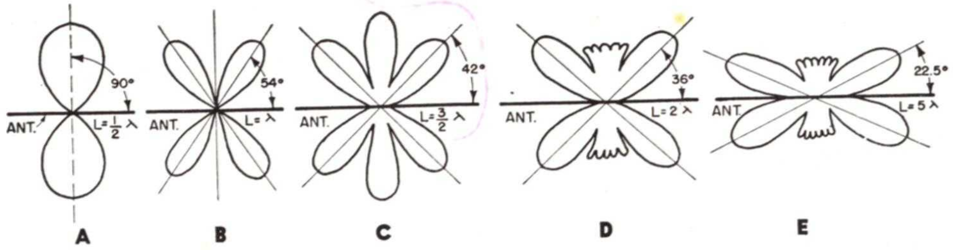


FIG. 19. The radiation patterns for single-wire antennas from one-half to five wavelengths long.

unidirectional pattern, instead of a bidirectional one. There are, however, better ways of improving the directivity of the V-beam antenna.

THE TERMINATED V-BEAM

In earlier Lessons we found that standing waves on a long wire are the direct result of an original electric wave, travelling from the transmitter to the end of the wire, and a second reflected wave, travelling from the wire termination back to the transmitter.

An electric wave on a wire radiates predominantly in directions near that in which it is travelling. If in considering the radiation pattern of the two-wavelength wire in Fig. 19D, for example, we assume that the r.f. energy is coming from a transmitter on the left side of the figure, and we can see that the two main lobes, pointing to the right, are caused by the *original wave* that is travelling from left to right along the antenna wire, and that the other two main lobes are caused by the *reflected wave* that is travelling in the opposite direction. Both of these waves make up the standing waves that are normally present on the antenna length. We thus see that we are able to reduce the number of radiation lobes by eliminating the reflected wave.

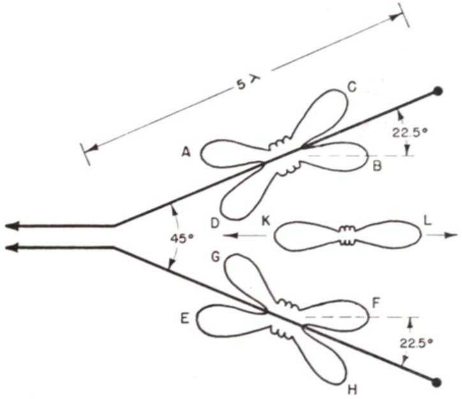


FIG. 20. The V-beam antenna in which, by proper choice of included angle, the major lobes of two long-wire antennas are aligned to give a sharp bidirectional beam.

If, for example, we use a two-wavelength wire as shown in Fig. 21, and terminate the end of the wire in a resistance R that is equal to its characteristic impedance so that no wave reflection occurs, we have a radiation pattern with only *two* major lobes. In comparing this with the radiation pattern of a non-terminated wire of the same length, as shown in Fig. 19D, we see that the pattern appears to be cut in half. *We have actually taken that power that normally would have been radiated by the reflected wave, and "thrown it away" as heat in the terminating resistor.*

From this behavior of a terminated long wire, we see that the performance of the V-beam antenna shown in Fig. 20, can be improved by loading the ends of the wires with appropriate resistors. Such a terminated V-beam antenna is shown in Fig. 22. Here we have the two-lobed pattern of wire A, combined with that of wire B to give the sharp high-gain beam at C, which indicates that there is practically no backward radiation.

The terminating resistors R, must be capable of dissipating one-half the transmitter power that is fed into the antenna. For stable operation, it is imperative that the lower end of these resistors are connected to a low-resistance ground.

To adjust such an antenna, the resistors R, which are normally about 600 ohms, are varied slightly, until the standing waves are reduced to a minimum along the 600-ohm transmission feed line.

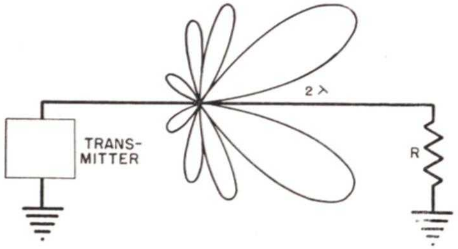


FIG. 21. A long wire that is terminated in a resistance is equal to its characteristic impedance so that no reflections occur, radiates predominantly in the same direction that the original energy from the transmitter is travelling.

Actually, the efficiency of a terminated V antenna is the same as that for a non-terminated one, since the power that is lost in the terminating resistors is the same power that is normally radiated in the "backward" beam. This improvement in directivity is a distinct advantage. In transmission, for instance, the unidirectionality prevents power from being radiated in a direction that may interfere with other services. When the antenna is used for reception, interfering signals that would otherwise come in from the backside of the antenna are greatly attenuated.

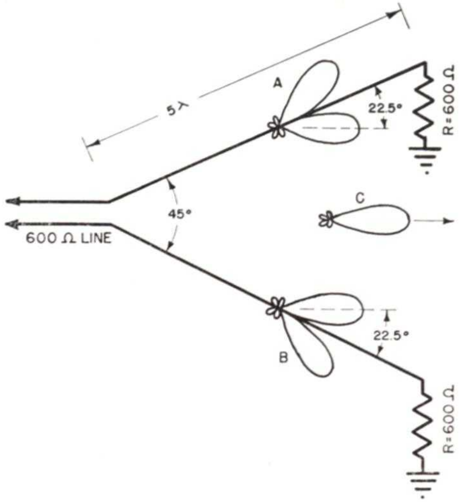


FIG. 22. By terminating the wires in a V beam with resistors, the energy normally radiated in a backward beam is absorbed. This leaves a sharp beam in one direction only.

THE RHOMBIC ANTENNA

A better unidirectional antenna can be made by placing two V antennas back-to-back as indicated in Fig. 23. This diamond-shaped array, or "rhombic" antenna, as it is usually called, gives higher directivity gain than other types of antennas, except a few that require more elaborate construction. Its extremely sharp unidirectional pattern of maximum radiation to the right is the result of adding the forward lobe of the left-hand V to the backward lobe of the right-hand V. As with the single terminated V-beam antenna, the terminating resistor R absorbs the power that otherwise goes into a lobe that radiates to the left.

The rhombic antenna is ordinarily

used to produce directivity in a horizontal plane, and in such cases the array is constructed by suspending all four legs from the same height above ground.

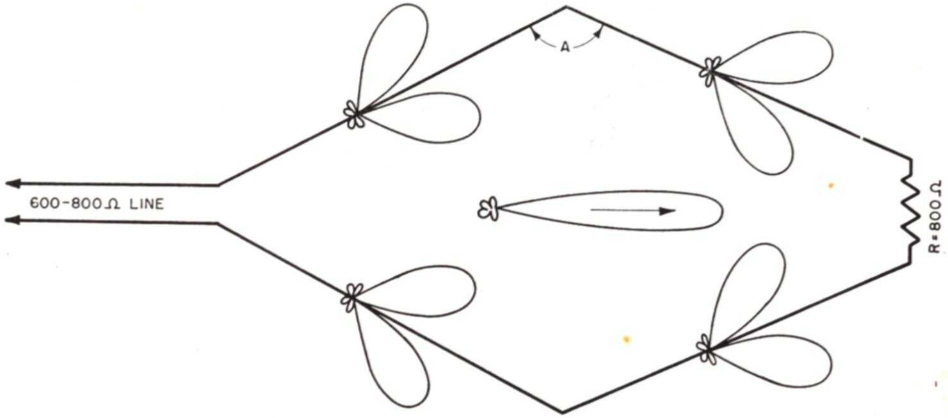


FIG. 23. The rhombic antenna made up of two V-beam antennas arranged back-to-back so that the forward lobe of one combines with the backward lobe of the other, is one of the most sharply directive antennas that it is possible to build.

Since the terminating resistor prevents reflections at the ends of the wires, there are no standing waves on a rhombic array, and it is entirely non-resonant. As a consequence, it is not necessary to cut each leg of the array to some resonant length, for rhombics may be made with legs of any length, from as few as two to as many as eight wavelengths long. However, the construction must be such that angle A has very definite value to insure that radiation lobes from all four legs reinforce each other to give a sharp over-all beam.

The non-resonant characteristic of the rhombic array makes possible several other operative advantages. When properly terminated with a resistor R of about 800 ohms, the input impedance of a rhombic is approximately 800 ohms, and this impedance remains substantially constant over a wide frequency range. This means that such an antenna can be operated over widely separated frequencies without the necessity of changing the coupling adjustment at the transmitter. Furthermore, the transmission line stays matched over this same range of frequencies, thereby maintaining high efficiency in the transmission line itself.

In practice, wave reflections from the ground come into play so that the beam from a horizontal rhombic does not leave the array on a line that is parallel to the earth's surface, but instead it is concentrated into the sky at an angle. This wave angle can be selected to be any desired value by proper choice of array height above ground as well as the length of the legs and the included angle A between the wires of the antenna. This property makes the rhombic particularly useful for high-frequency point-to-point work, where it is desirable to use a sharp sky beam for transmission over a definite skip distance.

THE TILTED-WIRE ANTENNA

The "tilted-wire" antenna in Fig. 24 is a modified version of the rhombic. It is made by supporting a single long wire on one supporting pole, and terminating the remote end of the radiator by a loading resistor R to ground. Actually, the tilted wire forms only half a rhombic laid on its edge, the second half is made by the reflected image of the radiating wire.

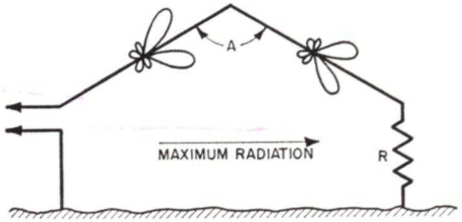


FIG. 24. The tilted-wire antenna, in conjunction with its image, appears as a modification of the rhombic array.

The sharp, unidirectional pattern is the result of a radiation lobe of the left half of the wire lying in line, in order to reinforce a lobe of the right half. As with all terminated antennas, the resistor R serves to absorb the power that is otherwise radiated in a backward direction.

Like the rhombic array, the legs of the tilted-wire antenna can be almost any desired length. Here, too, however, it is necessary that the tilt angle A be a definite, specific value in order to obtain optimum lobe alignment, and a maximum gain in directivity.

Parasitic Arrays

Up to this point we have considered antenna arrays that have power fed directly into the radiating elements by the driving transmitter. It is possible, however, to construct directive arrays in which some of the radiating elements have no metallic connection to the driving source.

Let us suppose, for instance, that we have a simple half-wave dipole, as shown in Fig. 25, that is being excited in any ordinary manner. If we bring a section of wire, approximately a half wavelength long close to the antenna, some of the antenna energy is absorbed by it. This absorbed energy causes a current to flow in this section of the wire, but once such a current starts to flow, the absorbed energy once more radiates into space. This re-radiated energy combines with the energy that is directly radiated by the antenna in such a way that it modifies the directional pattern of the antenna. The free wire is parasitically excited, and for this reason it is called a "parasitic" element. In conjunction with a driven antenna, parasitic elements can be used to form effective directive systems. Antenna systems that use these parasitic elements are popular because of their adaptability to rotatable installations.

REFLECTORS AND DIRECTORS

It is characteristic of a parasitic array to show a unidirectional radiation pattern rather than a bidirectional one. When the action of a single parasitic element increases the radiation from the antenna in the direction that is *through* the parasitic element, it is called a "director." This is the direction A, shown in Fig. 25. On the other hand, when the effect of the parasitic element increases the radiation in the opposite direction, that is, away from itself, as at B in Fig. 25, it is called a "reflector."

Whether a parasitic element behaves as a director or as a reflector depends on its spacing from the antenna, and on the phase of its current compared with that in the antenna. This phase relationship is also determined by the spacing, and by the tuning of the parasitic element. Elements are usually tuned by adjusting their length so that they are slightly above or below resonance, but they can be tuned by the usual tuning means.

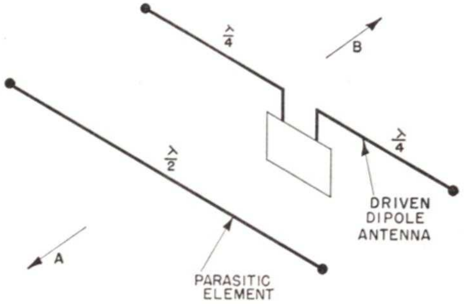


FIG. 25. A resonant element placed near an antenna absorbs energy, and reradiates it to change the antenna radiation pattern.

If, for any given spacing between an antenna and one parasitic element, we tune the element for maximum gain as a *reflector,* we obtain the highest gain that is possible to realize with a single reflector at this spacing. If we try a number of different spacings, taking care each time to tune the parasitic reflector for maximum gain, and then measure the gain that we obtain for different conditions, we can plot a curve like the heavy line shown in Fig. 26.

On the other hand, if we try different spacings, but tune the element each time for optimum performance as a *director,* we obtain a curve like the dotted line shown in Fig. 26.

These curves reveal that the maximum gain that can be realized from a director or a reflector is very nearly the same; the director giving slightly more gain at a slightly closer spacing.

► To obtain the curves of Fig. 26, we find that for maximum gain, a *reflector* must be tuned *below resonance,* that is, to a frequency *lower* than the operating frequency, at all spacings that are less than a quarter wavelength. Similarly, a *director* that is adjusted for maximum gain must be detuned toward a *higher-than-operating* frequency for spacings that are greater than 0.1 wavelength.

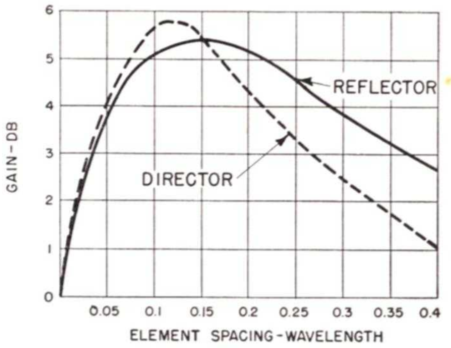


FIG. 26. Variation of the maximum possible gain from a reflector or director as the spacing between the antenna and the parasitic element is changed.

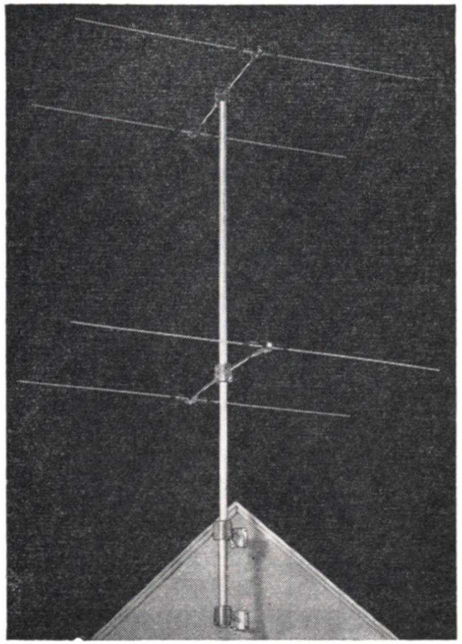
In practice, a reflector is usually spaced 0.15 wavelength from the antenna, and is made about 5% longer than a half wavelength. This causes it to be resonant at a lower frequency, to be slightly inductive, and to have a lagging current phase. For a director, a spacing between 0.1 and 0.15 wavelength is used, and its length is made about 4% shorter than it is for exact resonance. A director, therefore, is resonant at a higher-than-operating frequency, is slightly capacitive, and has a leading current phase.

FRONT-TO-BACK RATIOS

The adjustments that give the greatest forward gain from an antenna array and a parasitic element do not make the system completely unidirectional; instead, there is left a minor radiation lobe that is directed toward the rear. The ratio of the forward gain to the backward gain, or the front-to-back discrimination ratio, can be made much greater by using adjustments that are slightly different from those used for maximum forward gain.

The front-to-back ratio is increased by detuning the director or the reflector more than is required for a maximum forward gain. The tuning condition of the parasitic element, as determined by its length, that gives maximum attenuation to the rear is more critical than the tuning condition for maximum forward gain. It is possible, therefore, to secure good front-to-back ratios without sacrificing more than a small part of the forward directivity.

In general, backward radiation can be reduced to a lower value by using an element as a director rather than as a reflector. With the optimum director spacing of 0.1 wavelength, and the element tuned for maximum forward gain, the front-to-back ratio is only 5.5 db. This means that the power that is radiated forward is only 3½ times greater than that radiated backward. By proper director tuning, however, the front-to-back ratio can be increased to 17 db at a sacrifice of only 1 db in forward gain. Under these circumstances, 50 times more power is radiated forward than is radiated backward, and the absolute power to the front is reduced only about 25%.



A commercial directive antenna array used for the reception of television signals. This is a good example of how two element antennas can be stacked to obtain more gain.

RADIATION RESISTANCE OF PARASITIC ARRAYS

Since a parasitic element is quite close to the antenna, and actually absorbs energy from the intense electric field, it is reasonable to expect that the added element has an effect upon the radiation resistance of the antenna.

In general, the presence of a parasitic element lowers the antenna resistance markedly. When a director or reflector is adjusted to give the maximum gains illustrated by the curves in Fig. 26, the antenna radiation resistance varies with the same spacings as those shown in Fig. 27. Notice that at spacings from 0.1 to 0.2 wavelength, corresponding to those for highest gain from a reflector or director, the antenna resistance lies between 14 and 40 ohms. This is considerably lower than the 73 ohms of an ordinary half-wave doublet.

This reduction of antenna resistance leads to three disadvantages. First, the antenna radiation efficiency goes down, because more power is lost in heating the fixed ohmic losses of the antenna, and less power is radiated in the lower radiation resistance. Second, the selectivity of the antenna system increases so that optimum performance can be secured over a comparatively narrow band of frequencies only. Third, the number of suitable feeder systems becomes limited, and the adjustment of the feeder lines and the coupling networks becomes more critical.

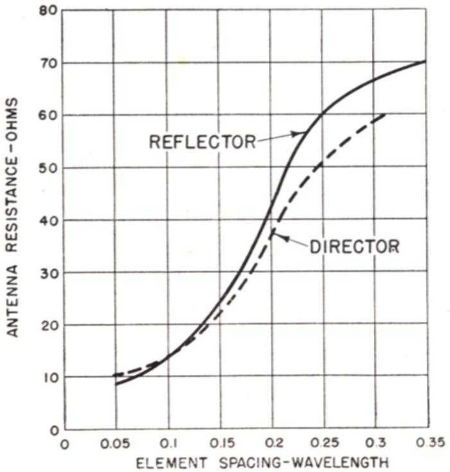


FIG. 27. Curves showing the sharp decrease in antenna radiation resistance as the spacing between antenna and a parasitic element is decreased.

The ohmic losses of any antenna, however, can be decreased by using lower resistance conductors in construction. At ultra-high frequencies, where parasitic arrays are frequently used, the decrease in ohmic losses is accomplished by using large diameter conductors of aluminum or copper tubing. With a half inch, or larger, tubing, the loss resistance in any two-element antenna is negligible.

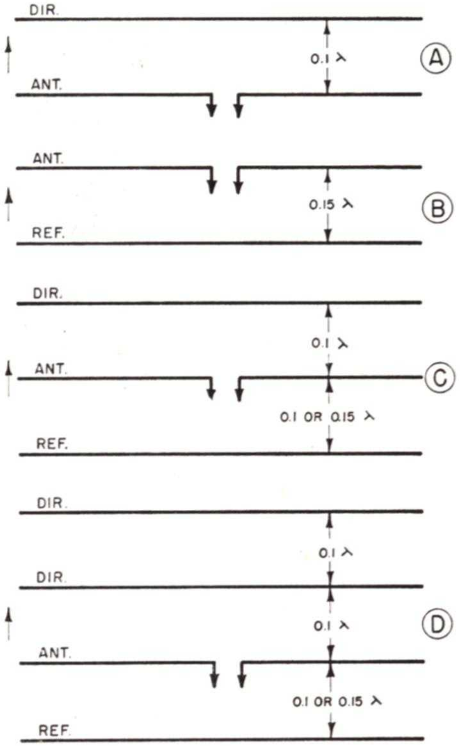


FIG. 28. Several methods of combining reflectors and directors in multiple parasitic arrays.

The use of mechanically rigid conductors also offers other advantages. It is relatively easy, for instance, to devise adjustable sliding sections for tuning by changing the length; since the members can be made largely self-supporting, they are well adapted to the design of rotary antenna assemblies.

MULTI-ELEMENT PARASITIC ARRAYS

Higher forward gain, and greater front-to-back ratios can be obtained by using more than one parasitic antenna element. Instead of a single reflector or director, one of each can be used. If more elements are desirable, it is better to use them as additional directors, and employ only one reflector. Practical combinations are shown in Fig. 28.

To illustrate the methods usually employed in adjusting a parasitic array, let us consider the array of one reflector and two directors shown in Fig. 28D. The antenna itself is coupled to the transmitter through a line of approximately 5-ohms impedance since the radiation resistance of the complete array is about 5 ohms. A higher impedance line with a suitable matching network can be used.

Optimum adjustment of each parasitic element is determined by reading a simple field-strength meter; ordinarily this is a short receiving antenna that is coupled to a resonant-tuned circuit, rectifier, and d.c. milliammeter.

The field strength meter is first placed at the rear of the array (in the direction of the reflector), and the reflector is removed, or open-circuited at its center. The length of the director that is nearest the antenna is then adjusted for a *minimum* meter reading that indicates a minimum backward radiation. (Remember that the rules for determining the lengths of parasitic elements are only approximate. The exact lengths must be determined experimentally as described here.) The second director is then adjusted to make the backward radiation even smaller. After this is accomplished, the reflector is reconnected at its center, and its length is also adjusted for a still lower backward radiation.

The forward gain of the antenna array is now peaked. If the antenna is a rotary one, it is rotated 180°; if not, the field-strength meter is carried around, and set up in front of the array. The reflector should not be readjusted. The directors, however, are readjusted slightly to give a maximum forward radiation.

TABLE V
Forward Gain and Front-to-Back Ratios of Multi-Element Parasitic Arrays

Number of elements	Forward gain—db	Front-to-back ratio—db
2	4 to 5	10 to 15
3	6 to 7	15 to 25
4	7 to 9	20 to 30

When all tuning adjustments are complete, this four-element array, using two directors and one reflector, can give a forward gain of 7 to 9 db. The front-to-back ratio should be between 20 to 30 db.

Under normal conditions, the average forward gains, and the front-to-back ratios that can be expected from parasitic arrays of different numbers of elements are given in Table V. These figures assume that there is careful adjustment of the parasitic elements.

Power-Fed Reflectors and Directors

Parasitic arrays are very useful for ultra-high frequency communication where it is desirable to have the unidirectional beam symmetrical and uniform. They are not suitable, however, for special services where it is necessary to use some peculiar odd-shaped radiation pattern to cover a given service area, and yet prevent interference with other services that are close to the transmitting point.

We learned that the patterns of a parasitic array are dependent upon the relative magnitudes and phases of the currents in the various elements, and on the physical spacing between these elements. Unfortunately, the spacing itself determines to a great degree the current that flows in each element. Since we cannot adjust the current and the spacing so that they are independent of each other, it is possible to obtain only a limited number of radiation patterns from a parasitic array.

On the other hand, if we do not rely on parasitic excitation of reflectors or directors, but drive them directly by feeding power to them from the transmitter, a much better control over the performance can be realized. With an independent element excitation, we are at liberty to choose not only the magnitude and the phase of current in each element, but also the spacing between the elements as well. Furthermore, it is not necessary that all elements be in a line, or a row, but they may have almost any conceivable physical relationship. This arrangement gives a wider choice of radiation patterns.

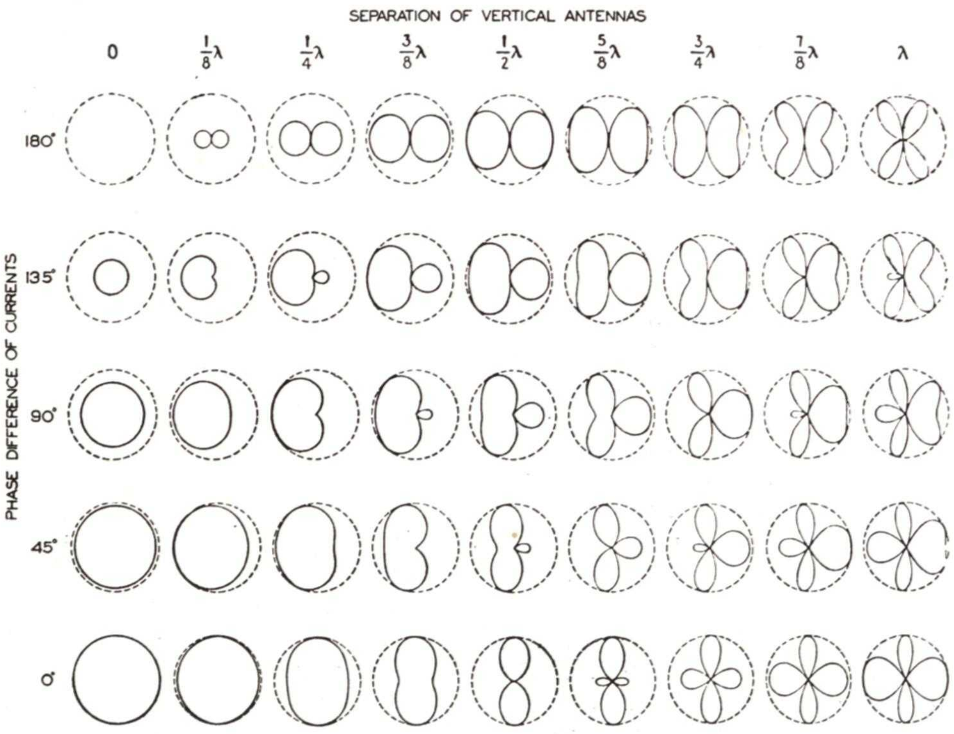


FIG. 29. Radiation patterns in the horizontal plane, as obtained with two vertical antennas spaced varying distances apart and carrying currents having various phase relations, are shown here in solid lines.

To illustrate, in Fig. 29 is shown the patterns, in a horizontal plane, that can be obtained for different spacings of only *two* parallel vertical elements that are carrying *equal* currents of various phases. If we vary the magnitude of the current in one or both elements, the number of patterns can be greatly increased; if we add a *third* radiating element, the number of possible patterns becomes almost unlimited.

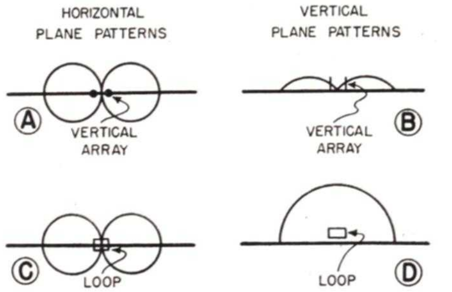


FIG. 30. Although the two-element vertical array and the loop antenna have identical patterns in the horizontal plane, only the former has sharp directivity in the vertical plane, and hence is not subject to sky-wave pickup or radiation.

A TWO-ELEMENT LOOP ARRAY

The radiation patterns, shown in Fig. 29, for two radiating elements that are fed 180° out of phase, and are spaced less than a half wavelength apart, are approximately two circles, and approach two perfect circles as the spacing between the elements becomes smaller. An example of how this principle is put into use is shown in Fig. 30A.

These circles form the same pattern in a horizontal plane as the pattern obtained from a vertical loop antenna. For comparison, the conventional loop pattern is given in Fig. 30C. This identical action can be expected since the two vertical elements can be considered as the two vertical sides of a loop in which the two horizontal sides are missing. As far as vertically-polarized waves and the horizontal radiation pattern are concerned, the two closely spaced vertical elements and a loop antenna behave alike.

There is, however, considerable difference in the respective radiation patterns in a *vertical* plane. For the loop antenna, as shown in Fig. 30D, the horizontal top and bottom come into use so that the radiation directly upward is equal to the maximum radiation in a horizontal plane, and this pattern forms part of a circle. On the other hand, the array of two vertical elements has no radiation directly upward. The vertical pattern of this array, as given in Fig. 30B, is sharper than the horizontal pattern.

The two-element vertical array, shown in Fig. 30, is as directional in a horizontal plane as the conventional loop antenna, and has the advantage of the sky wave being greatly attenuated. As a matter of fact, there is a "zone of silence" directly over the radiating antenna. This array, therefore, is extremely useful in radio beacon work where loop antennas sometimes give trouble from sky-wave effects.

RADIATION NULLS

All the two-element patterns of Fig. 29 are symmetrical about an imaginary line that joins the two antennas. The patterns shown have as many as four nulls, or directions of negligible radiation. If a given transmitting station is using a two-element array, it is possible that the service areas of four other stations can be protected, provided the other stations are properly located in the directions of the nulls. This, however, is not often the case.

When it is necessary to set up a peculiar-shaped radiation pattern to prevent undue interference, it is usually accomplished by adding a third element that need not be in a straight line with the other two.

Let us suppose, for example, that we have a two-element array that makes it possible to concentrate the radiation in the desired direction, and at the same time protect another station. If we add a third element, located in the direction of the second station to be protected, and excite it with a current of the proper magnitude and phase, we can produce a null in this direction. Unfortunately, the radiation from this third element now gives a strong signal in the direction of the first station, which previously had been protected. Thus, we have produced a new null in the direction of the second station, but lost the null for the first station.

If, on the other hand, we adjust the original two-element array so that it gives equal interference at the two stations, and if this interference is in the same phase, we can locate the third element in a direction half-way between the two stations, and compensate both signals at the same time.

To arrange the three elements so that all the desired directions can be protected simultaneously, and yet preserve good coverage in some other specified direction presents a complicated problem. In all cases mathematical analysis is necessary to determine the proper arrangement of the antenna elements, and the magnitudes and phases of the currents with which they are excited in order to fulfill the particular requirements. Let us study a specific example of final design as it is worked out by an engineer. The duties of a maintenance man are to assist the engineer in these adjustments, so it is helpful to know what the engineer has to do.

Let us suppose that a station, operating on a power of 500 watts, increases the power to 1000 watts. The main service area lies west of the station, with areas of secondary importance lying east and south of the station. Three other stations, on the same or adjacent frequency channels, must be protected. Station A lies due north, and Station B is located forty degrees south of west, and Station C is forty-five degrees south of east.

By mathematical analysis, a horizontal three-element array that gives the desired radiation pattern is shown in Fig. 31A. The necessary values of current excitation are: $I_2 = I_1$ where I_2 and I_1 have the same phase, and $I_3 = I_1/2$ where I_3 lags I_1 by 90°.

The resulting radiation pattern from this array, as shown in Fig. 31B, comes close to the requirements. There is not only excellent protection for Station C, but there is also entirely adequate protection for Stations A and B. The nulls in the directions of these latter stations can be improved by making minor changes in the element positions, and in the currents in each of them.

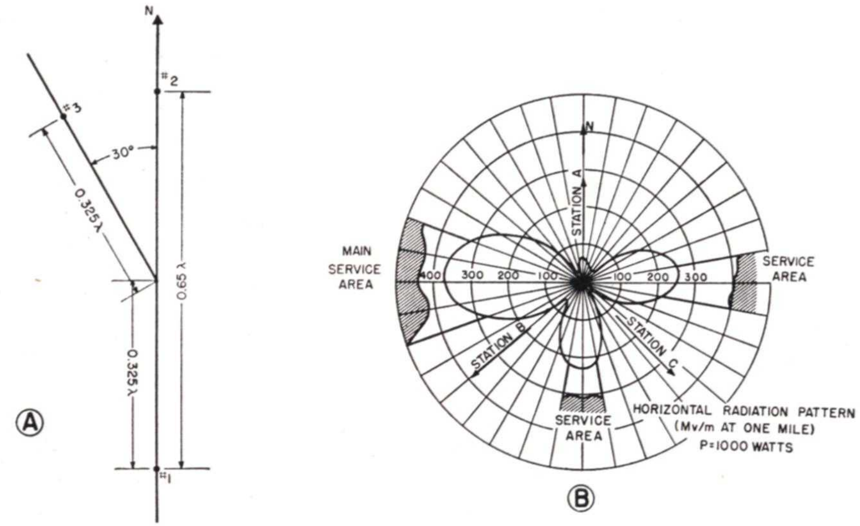


FIG. 31. A special three-element array and its made-to-measure radiation pattern giving three nulls for the protection of other stations.

COMPLEX-ARRAY ADJUSTMENT

Any given array like the one just discussed requires an enormous amount of "cut-and-try" computation in order to obtain the appropriate magnitudes and phases of the individual element currents, but after this has been done there remains the practical problem of exciting the antennas in the particular manner specified. This is not as easy as it may seem, because of coupling between the elements.

Let us suppose, for example, that we adjust an array by first detuning all the antenna elements but one, and then adjust the coupling circuit of this remaining antenna element so that the transmission feeder line has no standing waves. Next, we make the same kind of adjustment on a second antenna element with the first one disconnected. Then, when both antenna elements are fed power simultaneously, we find that the coupling circuits are no longer in tune, and the lines are improperly terminated so that standing waves may develop. The reason for this behavior is that the current in each element is modified in both magnitude and phase by parasitic pickup from the other elements. In fact, both the resistance and the reactance in any of the elements are affected by the currents in the other elements. We cannot, therefore, correctly adjust the input to one element, unless the other elements are already properly excited. Any cut-and-try procedure becomes hopelessly involved.

In actual practice, this trouble is avoided by first measuring the input resistance and the reactance of each antenna element with the other elements detuned or disconnected. Next the coupling between the elements is measured in order to determine how the separate input impedances are changed by the final current in each element. Finally, from these measurements, the input impedances that can be expected for each element, when the whole array is properly adjusted, are calculated.

These computations give definite values of resistance and reactance, and three separate *dummy antennas* are made by using these values. To tune the complex array, all the radiating elements are disconnected, and the dummy antennas are substituted for them. In this way the tuning and coupling adjustments of each transmission line are made independent of each other, and carried out one at a time. The dummy antennas are removed after all these adjustments are made, and the real radiating elements are connected again to the feed lines.

All the measurements and calculations just described, however, do not solve the problem of feeding several currents of specified magnitudes and phase differences. The proper magnitude of exciting current in any element can be adjusted easily by changing the transmission line coupling to that particular element. For proper phasing, each element can be fed through a separate length of actual transmission line, or by using an "artificial" transmission line. In the actual transmission line, the individual feeder lines have differences in length that correspond to the desired phase differences. (Thus, a line that is a quarter wavelength longer than a second one, can feed its load with current lagging 90° behind the current in the first load, if the inputs to two lines are fed in parallel.) An artificial line consists of a complex LC network, adjusted in such a way that the amount of phase shift that is produced is equivalent to an appreciable length of line, but occupying less space.

► In order to maintain the desired directivity pattern, the FCC requires that the ratio of the amplitude of the currents to the various elements is maintained within 5 per cent of the licensed value.

Ultra-High Frequency Arrays

We learned that two parallel antenna elements that are separated by a half wavelength, and excited out of phase make an end-fire array. A somewhat similar arrangement of an antenna and a parasitically-excited reflector give a unidirectional end-fire arrangement. Neither of these schemes provide for the reduction of the spread of the beam, that is, they both radiate considerable power in the directions to either side of the desired beam. If additional elements are incorporated, as shown in Fig. 32, to eliminate or reduce this sideway leakage of power, higher gain in the desired direction results.

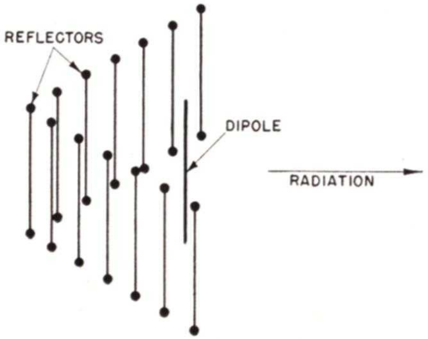
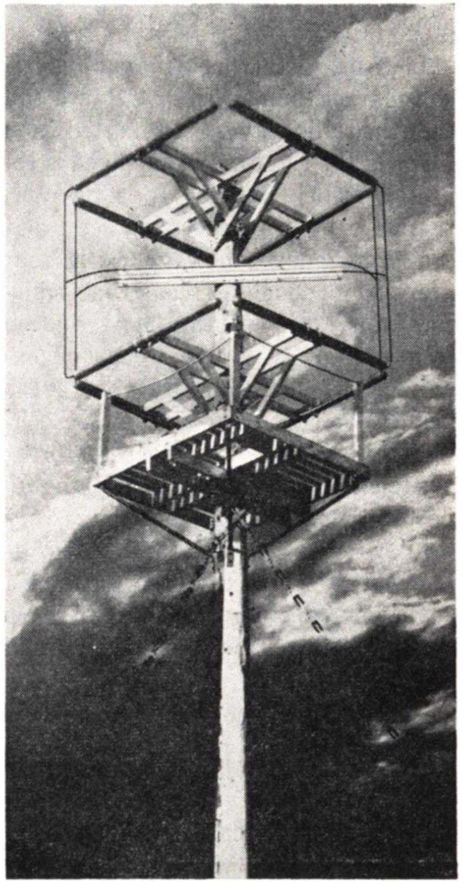


FIG. 32. The corner reflector makes a parasitic array with a forward gain of about 10 db, and a front-to-back ratio of approximately 35 db.

This type of directive array is known as the "corner reflector." It has a forward gain of approximately 10 db. The front-to-back ratio is about 35 db, and the front-to-side ratio is approximately 25 db.

The reflectors are not interconnected, and the spacing between them is not critical. Normally, a reflector element is placed every 1/10 wavelength along the line of the elements. The use of fewer reflectors reduces the efficiency somewhat, and the use of more reflectors gives only a little increase in gain, and greatly increases the complexity and expense of the array.



Courtesy General Electric Co.

A cubical antenna using eight radiating elements used by General Electric for television broadcasting from experimental station W2XB in the Helderberg mountains of New York State. Two of these arrays are used, one for the video signal, and one for the accompanying sound transmission.

METALLIC REFLECTORS

If we add more reflector elements to the corner reflector, and space them closer together in order to keep the over-all dimensions fixed, it eventually becomes almost two sheets of metal. This is the most practical way to construct a reflector array in the microwave region where wavelengths are very short, and it is not necessary for the metal sheets to be inconveniently large.

If we use metal sheets that are physically larger than a wavelength, we find that the radio waves are reflected from them in the same way that light is reflected from a mirror. It is possible, therefore, by using sheets of metal that are large enough, or wavelengths that are short enough to construct "mirrors" for radio waves. The radiation from microwave radar sets, for example, is focussed into a very sharp beam that is somewhat like a searchlight by placing a dipole radiator at the focal point of a metal parabolic reflector. See Fig. 33. The action is very similar to that of an automobile headlamp that is placed at the focus of a silvered reflector. Extremely sharp beams can be obtained in this way, and gains of 30 db or more are quite common.

► Even at low radio frequencies, a flat sheet of metal behind a radiating antenna causes the radiation to be more directive, for the metal sheet acts as a reflector, and thus directs the energy away from the wall.

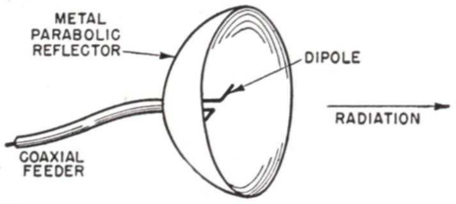


FIG. 33. A microwave dipole placed at the focus of a metal parabolic reflector makes an extremely sharp beam, gains of 30 db or more are quite common.

FM ARRAYS

The directional characteristics that are required for FM antennas are somewhat different from those previously discussed. A sharp beam is undesirable, and there is seldom need for protection of other station areas, because of the short range of the service area and the comparatively few transmitters. It is usually desirable to obtain as uniform coverage as possible in all directions from the transmitting station. This means that a uniform radiation pattern is necessary in the horizontal plane. In the vertical plane, however, the pattern can be quite sharp, which keeps most of the energy close to the ground, so that little power is lost in a sky wave that ordinarily is useless at such frequencies.

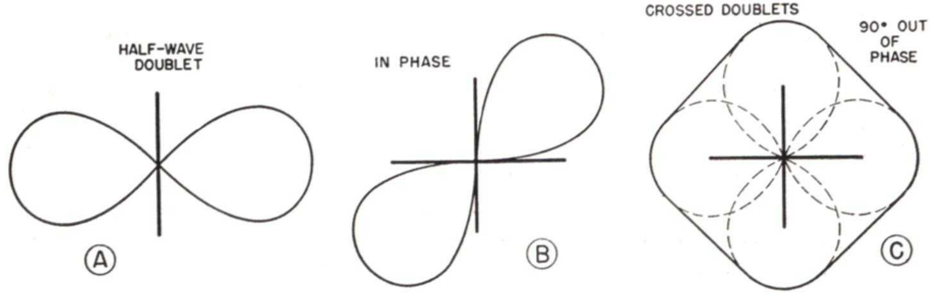


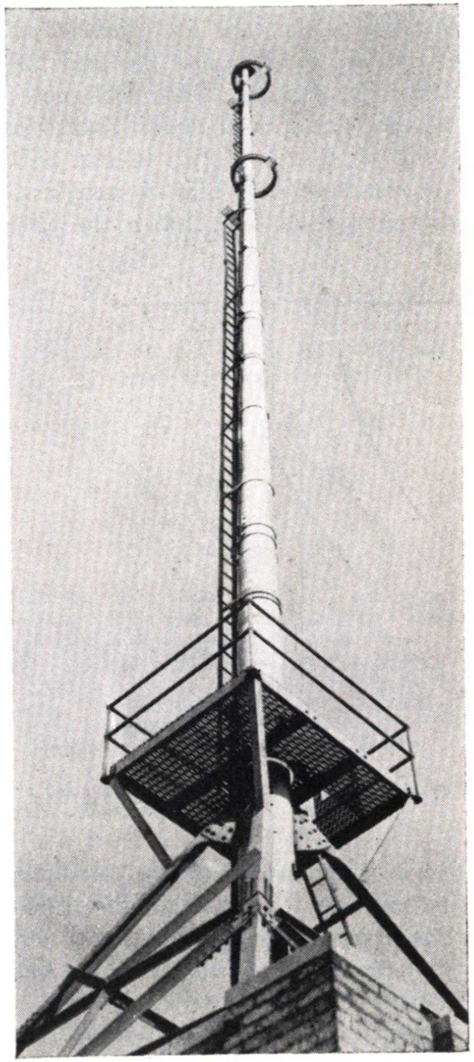
FIG. 34. The radiation patterns from a single doublet and crossed doublets excited in and out of phase.

In addition to the radiation pattern requirements, horizontal polarization is preferable to vertical polarization for FM broadcasting. Accordingly, a good FM array is one that not only has uniform signal strength in all directions, but also possesses radiating elements that lie parallel to the ground, so that the radiated waves are predominantly horizontally polarized.

A single half-wave doublet gives a figure-eight radiation pattern like that shown in Fig. 34A. If we mount two such doublets at right angles, as indicated in Fig. 34B, and then excite them in phase, the resulting radiation pattern is rotated, and appears as though it had a single doublet mounted at a 45° angle. If, on the other hand, we excite the two doublets with currents that are 90° out of phase, we get the fairly uniform radiation pattern of Fig. 34C.

Turnstile Antenna. This combination of two crossed doublets driven 90° out of phase is called a "turnstile" element. A number of such elements that are mounted one above the other, and excited as a broadside array, give high directivity in the vertical plane, and essentially uniform coverage in the horizontal plane. Such an arrangement is known as a turnstile array.

The turnstile array has convenient mechanical features as well as its desirable radiation pattern. Since the center of each doublet is at zero potential, it can be grounded. Thus, all turnstile elements may be mounted directly on a metal supporting mast, and each one is then shunt-excited from a trans-



This is a General Electric two-bay circular antenna used by the Columbia Broadcasting System for f.m. coverage of New York City. It is mounted 100 ft. above the roof of a 700-ft. building. Provision has been made to add two more bays to increase the effective gain of this array.

mission line in a manner similar to the grounded center doublet shown in Fig. 35A.

As a broadside array is made up of parallel elements that are excited in phase, it is convenient to mount the turnstile elements a half wavelength apart, and to transpose the feed line for proper phasing. When constructed in this manner, the completed turnstile array appears as shown in Fig. 35B. For clearness, only half of each turnstile element has been drawn; the other half is at right angles to those pictured, and these are fed from a similar transmission line carrying a current 90° out of phase with the current in the line shown.

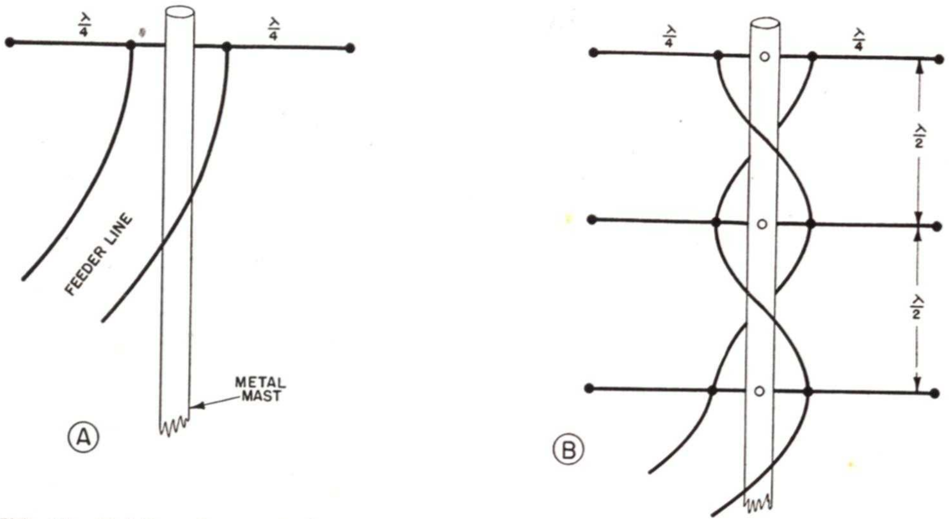


FIG. 35. At left, a shunt-excited, grounded center doublet. At right, how these are crossed and stacked to make the turnstile array.

Horizontal Loop Antenna. Another type of horizontal element that gives a uniform horizontal radiation pattern is a small loop that has a uniform current distribution. You recall that a vertical loop has a uniform vertical pattern. In radio beacon work, this is a disadvantage. In an FM array, however, use is made of this characteristic by placing the loop in a horizontal plane.

In order to have a uniform current distribution on the loop its perimeter must be kept below a quarter-wavelength. It is, therefore, necessary to employ tuning in order to bring the loop to resonance, and to operate efficiently. This can be done as illustrated in Fig. 36A. A more practical arrangement is the "folded loop" of Fig. 36B, which allows the center of the loop to be grounded to the supporting mast. The theory of this folded design is similar to that of the folded dipole discussed in an earlier Lesson.

Several elements of this folded-loop type can be stacked one above the other to make a broadside array; such a construction gives a higher gain per layer than the turnstile array. Nevertheless, in order to keep the mutual impedance between the layers at a low point, the elements are placed a full wavelength apart so that the gain in decibels per foot of height is less than it is with the turnstile array.

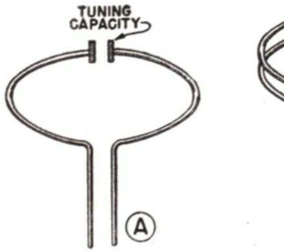


FIG. 36. The simple one-turn loop at left has uniformly distributed current, and hence a uniform radiation pattern. The folded loop at right allows grounding of its center for support of the assembly.

Both the turnstile and the loop arrays are mounted on tall metal masts. If the building, or tower, on which the array is mounted can support such an arrangement, one of these arrays is normally used. Frequently, however, it is necessary to install an FM array on an existing tower that is not designed to carry the extra load of a vertical mast. For such cases "square-loop" elements have been designed.

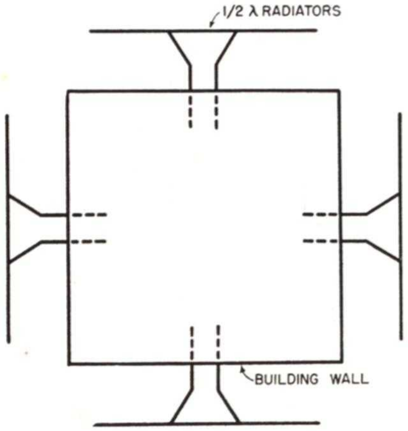


FIG. 37. By mounting half-wave radiators on the four sides of a building, the effect of a square-loop antenna is obtained.

Square-loop elements generally consist of four half-wave radiators that are arranged in the form of a square, and are excited in phase to give a radiation pattern that is fundamentally the same as that of the turnstile element. Figs. 37 and 38 show two common forms of such elements.

The construction in Fig. 38 is particularly interesting, for the shorting bars on the quarter-wave phasing stubs are at ground potential, and hence can be used as supporting points for the entire element.

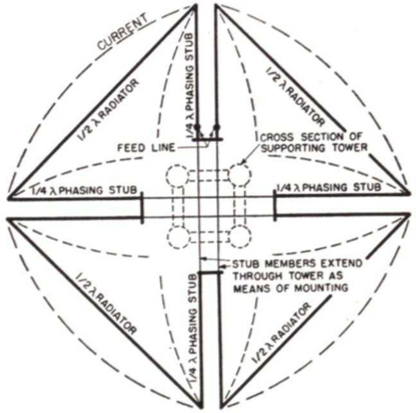


FIG. 38. On a tower mounting, a square-loop antenna can be obtained by mounting a series of half-wave elements as shown here. The shorted quarter-wave phasing stubs act as supports and serve to insulate the antenna array from the tower. The feed line is attached to one stub at a point giving the proper impedance match. The dashed lines show the current distribution.

TELEVISION ARRAYS

When we consider the construction of television antennas, we have not only all the radiation pattern problems of an FM antenna, but also the additional requirement that the antenna elements have very broad resonance curves in order to accommodate the extreme bandwidths that are necessary for satisfactory picture transmission.

One successful solution to the many problems that are involved, is exemplified by the development of the television turnstile array that is used on top of the Empire State Building.

The individual radiator elements that make up this array were developed originally from a dipole of the flagpole type as illustrated in Fig. 5A, and repeated in Fig. 39A for convenience.

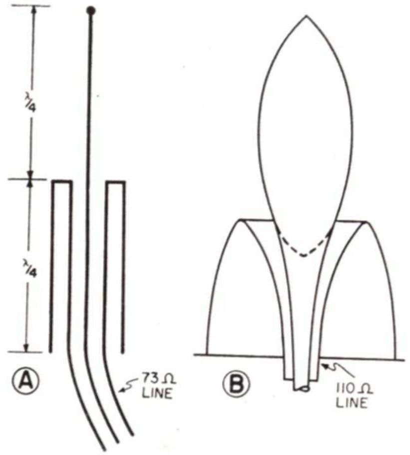


FIG. 39. At left, the flag-pole dipole. At the right is one element of a flared wide-band antenna that has been used by RCA in the television turnstile array on top of the Empire State Building.

The simple arrangement of Fig. 39A is too selective for television purposes, because for frequencies that are slightly removed from resonance, the dipole impedance changes so rapidly that considerable reflection occurs, and sets up standing waves along the transmission line.

In an earlier Lesson, you remember, we learned that when the diameter of the conductors in a dipole is increased, it becomes a wide-band radiator. We learned also that the bi-cone antenna is merely a dipole in which the conductors are "flared" to large diameters, and it possesses a much broader resonance than a simple doublet.

By applying this same flaring principle to the flagpole antenna of Fig. 39A, we find that the ellipsoidal modification, shown in a cross-sectional view in Fig. 39B, has a sufficiently wide response characteristic to accommodate all the sideband frequencies that are encountered in television transmission. Included in the design is a tapered "throat" that serves to match the dipole impedance to the concentric feed line.

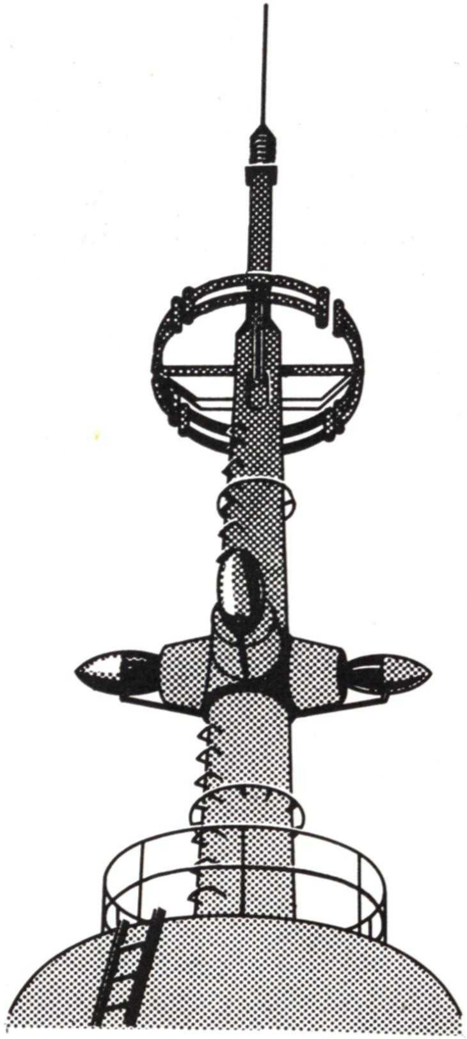


FIG. 40. Complete assembly for both television and sound antenna formerly used by RCA in the Empire State Building installation. The television antenna shown here is an array of flared wide-band elements such as the one drawn in Fig. 39. The sound antenna above is a set of folded dipoles.

To make up the complete array, four of these ellipsoidal elements are "laid on their sides," and fitted together to form a turnstile element, so that a relatively uniform horizontal radiation pattern can be obtained. The complete assembly is shown in the lower part of Fig. 40.

The circular array that is directly above the television antenna is the sound antenna. This resembles some of the elements that were previously de-

Courtesy National Broadcasting Co.

This is the new antenna array on top of the Empire State Building in New York City used by NBC for standard television, standard frequency modulation broadcast, and experimental television services. The lower three sets of four radiating elements are used for channel four television broadcasting. Above that are six dipoles used for f.m. broadcasting, and the radiators on top of the mast are used for 288-mc. experimental television.

scribed for FM arrays, and it is composed of four folded dipole sections that are arranged to form a circular loop that carries approximately uniformly distributed current. The advantage of this type of element over a simple turnstile lies in the very small coupling between it and the vision antenna, even when the two channels have a small frequency separation.

Lesson Questions

Be sure to number your Answer Sheet 25RC.

Place your Student Number on *every* Answer Sheet.

Most students want to know their grade as soon as possible, so they mail their set of answers immediately. Others, knowing they will finish the next Lesson within a few days, send in two sets of answers at a time. Either practice is acceptable to us. However, don't hold your answers too long; you may lose them. Don't hold answers to send in more than two sets at a time or you may run out of Lessons before new ones can reach you.

1. What type of antenna is used as the reference in measuring the gain of directive antennas?

2. Why are multi-element arrays, such as shown in Fig. 2B, generally fed at their physical center?

3. Draw a simple diagram of a lazy H array.

4. The V-beam antenna is terminated in a 600-ohm resistor *to increase its efficiency; to make it transmit equally in all directions;* or *to improve the directivity.*

5. How is the radiation resistance of an antenna affected by the presence of a parasitic element?

6. A parasitic element, used as a director, is *about 4% shorter, 5% longer,* or *the same length* as the driven half-wave element.

7. In what way is the two-element end-fire array an improvement over the simple loop antenna for radio beacon work?

8. What two kinds of coupling lines can be used to feed the elements of a power-fed array with currents of different phases?

9. To what per cent of the licensed value must the ratio of the currents in a directive array be held?

10. If a half-wave element is placed parallel to a metal wall, will the radiating energy be *absorbed, directed away from,* or *in no way affected* by the wall?

ACTION SPEAKS FOR ITSELF

Be sure you are right, then go ahead—this has been the motto of many of the world's great men.

In most cases you know instinctively what is right, your decision being based upon your past training, your experience, your common sense, and your conscience. In these cases, *act!* Waste no valuable time arguing with others who know less than you; waste no time trying to "pound" your ideas into a cynical world—take the initiative yourself.

It is a thousand times better to *do things* and let your deeds speak for themselves than to spend time explaining why your proposed course of action is right. Friends can hinder your success if you take time to justify your actions to each one of them.

If you need advice—if you are not exactly certain you are right, then go to men who are capable of giving authoritative answers to your questions. You'll find that successful men are glad to answer serious, well-planned questions. Analyze their advice in connection with your own experiences make your decision, then act!

Give this plan a tryout. You will accomplish a great deal more work, and you will be a lot happier.

J. E. SMITH