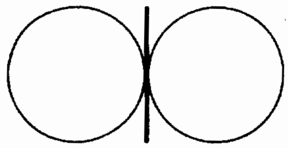


FIG. 1
Pattern of horizontal half-wave antenna

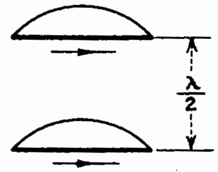


FIG. 2
Two half-wave antennas ½λ apart

FIG. 3
Half-wave array

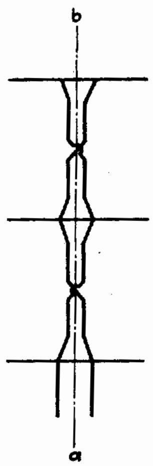


FIG. 4
Feed line

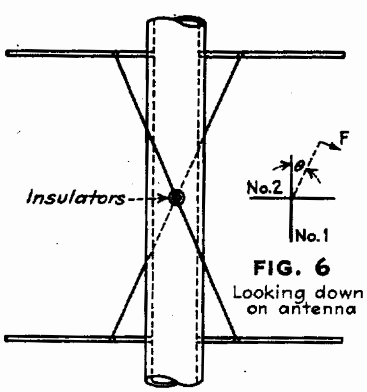


FIG. 5
Antenna wires and feed lines

FIG. 6
Looking down on antenna

The "Turnstile"

A new ultra-high frequency radiating system which economizes energy by concentrating it in a horizontal plane equally in all directions

By **GEORGE H. BROWN**
RCA Manufacturing Co., Inc.
Camden, New Jersey

ANTENNAS operated at short wave lengths can have dimensions of the order of several wave lengths without becoming unwieldy in actual physical size. A great many arrangements can be used which direct the radiated energy in some one particular direction. This concentration thus yields a greater field strength than does, for example, a single half-wave antenna operated at the same power. If the signal strength in the remaining directions is of no consequence, the arrangement of a few wires in a directional array has accomplished the same result as building a more powerful transmitter. Now that the ultra-high frequencies are being used for broadcast purposes, the directional arrays are not always desirable. If the antenna is located in the heart of a city, it is desirable to radiate equal signals in all directions in a horizontal plane. It is still possible to rob energy from the high angles and concentrate it near the horizon. An investigation was undertaken to develop an antenna for ultra-high frequency use which embodied the following features.

1. The antenna should give a circularly symmetrical radiation pattern.
2. The antenna should concentrate the energy in the vertical plane so that the signal strength toward the horizon for a given power input will be considerably greater than that obtained from a single half-wave vertical antenna with the same input power.
3. The antenna must be structurally possible where high winds occur and should preferably be a rather simple structure not liable to damage easily.
4. If possible, the antenna should be supported by a single mast.

One system which immediately suggests itself is the "Franklin" antenna which consists of half-wave elements placed vertically, one above the other, and connected with phase shifting devices so that the currents in all the elements are in phase. This antenna fulfills the first two conditions, but it seems very difficult to meet the last two conditions.

Arrangements which use horizontal elements usually do not fulfill the first condition stated, since each horizontal element yields a "Figure 8" as the horizontal pattern.

The antenna which was finally developed uses horizontal elements and fulfills the four conditions outlined.

Theoretical Development

Let us first examine the action of a horizontal half-wave antenna in free space. In the horizontal plane which passes through the antenna, the field strength is horizontally polarized. The horizontal pattern has the shape of a "Figure 8" with the maximum intensity occurring in a direction normal to the axis of the antenna (Fig. 1).

Suppose that another half-wave antenna is placed parallel to the first, and one-half wave length above the first antenna (Fig. 2). The antennas are both excited so that the currents in each antenna are equal and in phase. This arrangement still yields a "Figure 8" pattern in the horizontal plane, but the magnitude of the horizontal pattern has increased since energy has been robbed from high angles and sent out horizontally.

If still more elements are placed in the array, Fig. 3, each one-half wave from its neighbor and excited

Antenna

Avoiding directional effects, the antenna is ideally suited for broadcast service on frequencies below 10 meters

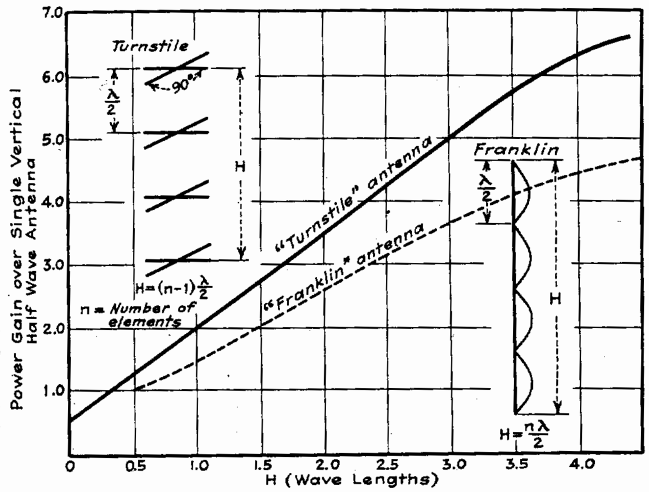


Fig. 7—Theoretical power gain of Turnstile and Franklin antennas

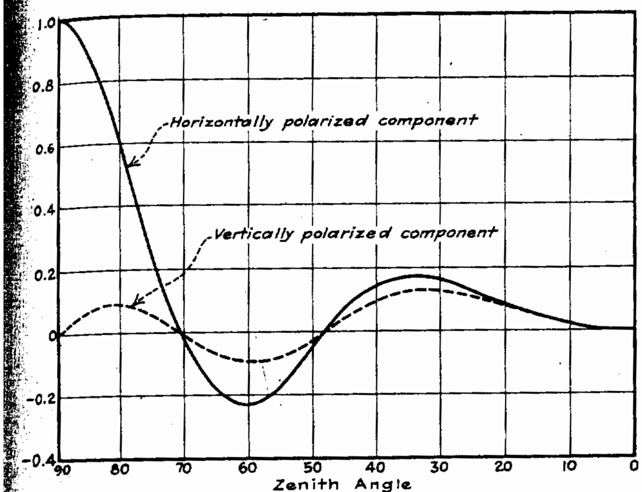


Fig. 8 — Vertical radiation of 6-element Turnstile antenna

all in phase, the horizontal signal is still further increased, but the horizontal pattern still remains "Figure 8" in shape. For the time being, we will ignore this latter fact and consider means of constructing the arrangement of Fig. 3.

Suppose that the elements are supported in space in some fashion. Then the elements can be excited in the proper phase and current magnitude by means of a single two-wire transmission line transposed once between each pair of elements. The half-wave length of transmission line gives a phase reversal of voltage along the line so that the single transposition returns the voltages on adjacent elements to the in-phase condition.

In Fig. 4, the line *a-b* lies in a neutral plane with respect to the antenna elements and the transmission line. Thus if this line were a wire or piece of metal, there would be no voltage induced in it due to the radiating system. This fact makes it possible to replace the line *a-b* by a metal shaft or flag pole, thus affording a supporting structure for the system. Each half-wave antenna, instead of running through the pole, can consist of two quarter-wave rods screwed into opposite sides of the pole. The transmission lines, instead of having an abrupt transposition, twist continuously around the pole. It is possible to do this if supporting insulators are placed on the pole midway between the elements (Fig. 5). This arrangement now fulfills all the conditions imposed except that of the circularly symmetrical horizontal pattern.

On our flag pole, let us put a second system of radiators and transmission line identical with the first, but so placed that the two sets of radiators are at right angles and corresponding elements are at the same level on the pole. Thus with two sets of identical elements on the pole, we have two separate transmission lines coming down the pole to the transmitter. These two transmission lines are so fed, with equal power into each line, so that the currents in one set of radiators are in time quadrature with the currents in the other set which is at right angles in space with the first set. Figure 6 shows a view of the antenna looking down from the top. Then the field in the horizontal plane due to Set No. 1 is

$$F_1 = I \sin (\omega t) \sin \theta \qquad (1)$$

where θ is the angle indicated on Fig. 6

The field due to Set No. 2 is

$$F_2 = I \cos (\omega t) \cos \theta \qquad (2)$$

The sum of (1) and (2) gives the total resultant field.

$$F_t = F_1 + F_2 = I \cos (\omega t\text{-}\theta) \qquad (3)$$

Thus the total field is constant in magnitude and changes in phase as θ changes, giving us a circularly symmetrical horizontal pattern.

As mentioned previously, the signal strength toward the horizon increases with the number of antenna elements. The ordinates of Fig. 7 show the ratio of the power into the single vertical half-wave antenna to the power into the array in question to achieve the same field strength.

Experience with mechanical design of these antennas has shown that it is convenient to use six antenna elements in each set. Then the distance from the bottom radiator to the top radiator is 2.5 wave lengths.

The vertical radiation characteristic of this antenna is made up of a horizontally polarized component and a vertically polarized component. The vertically polarized component becomes zero in the horizontal plane. Figure 8 shows these two components as a function of the angle measured from the zenith, when the antenna consists of six elements per set.

While this antenna layout looked very good on paper, it was neces-

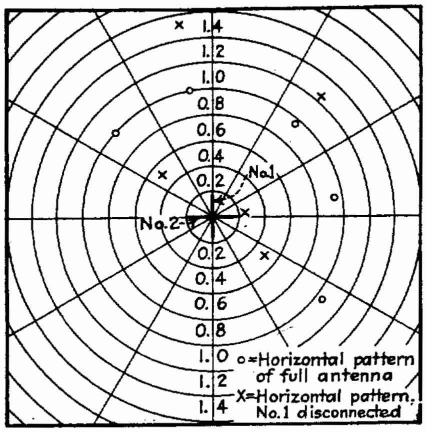


Fig. 9—Result of field measurements

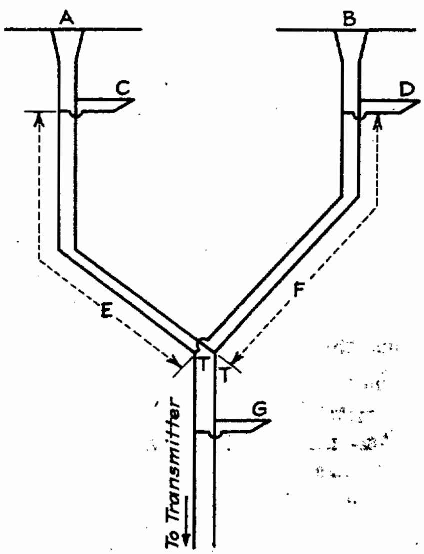


Fig. 10—Transmission line arrangement

sary to verify the results experimentally. The experimental method was also used to determine certain optimum dimensions. Accordingly, a model was built to operate on a wave length of 3.0 meters. The flag pole used was 42 feet long and 3 inches in diameter. The six-element antenna was chosen. The radiators were one-quarter inch brass rods, each one-quarter wave length long. These rods were threaded and screwed into the steel flag pole. The insulators for supporting the transmission lines were porcelain stand-off insulators, fastened to the pole by means of stud bolts in their bases. The quadrature phase relation between sets of radiators was accomplished by means of transmission lines of the proper lengths.

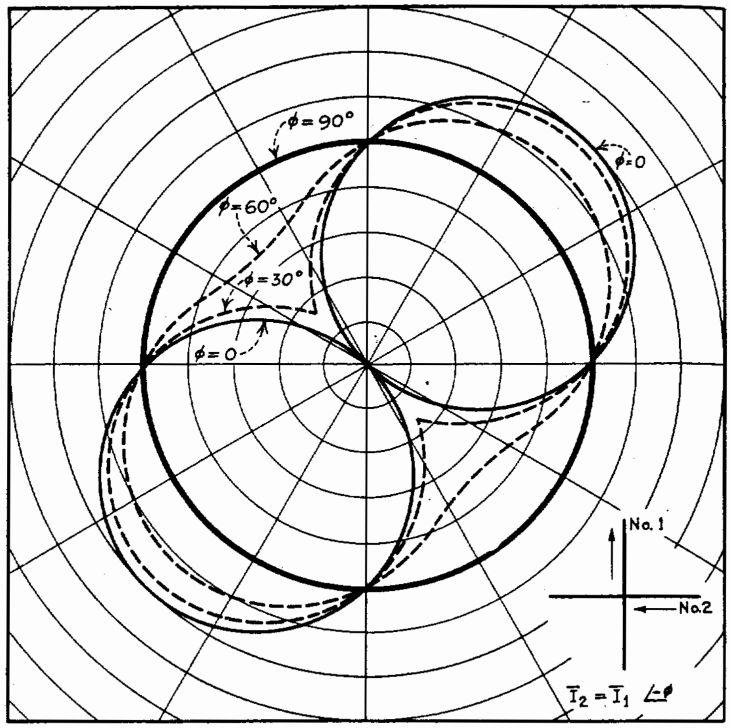
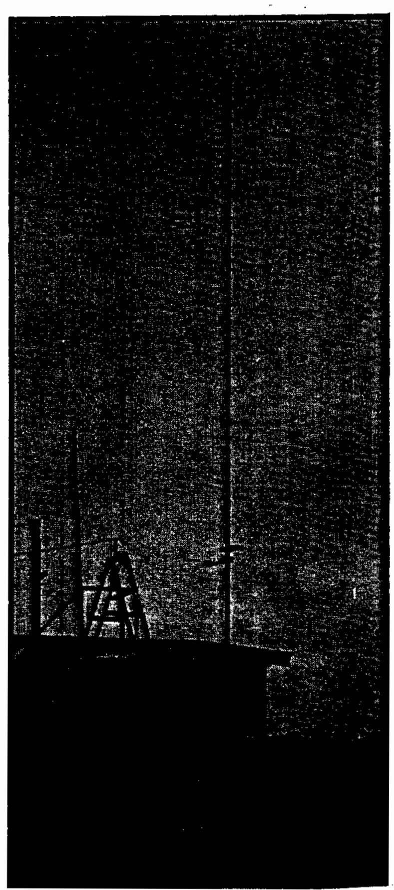


Fig. 11—Horizontal radiation pattern—currents of equal magnitude but varying in phase

After all critical adjustments were made, a check was made of the horizontal pattern to determine how circular it was. A horizontal half-wave antenna was mounted on the end of a bamboo pole. This pole was 26 feet long. A transmission line connected this antenna with a detector placed at the base of the pole. Readings were taken on the circumference of a circle whose radius was 175 ft. with the axis of the flag pole as the origin of the circle. The circles on Fig. 9 show the results of this test.

Experimental model of the Turnstile antenna



Next, the elements pointing east and west were disconnected to determine the expected "Figure 8" pattern. The crosses on Fig. 9 show the measured results. This test indicates the necessity of using two sets of elements if it is desired to send equal signals in all directions.

A measure of the field strength was made at a fixed point. Then the flag pole was replaced by a single vertical half-wave antenna excited with the same power. The field strength from this arrangement was slightly less than one-half that obtained with the array, indicating a power gain for the array of approximately four to one. From Fig. 7, we find the theoretical figure to be 4.27 to 1.

Constructional Details

The first full scale antenna was constructed for operation at 45 megacycles. The supporting pole ex-

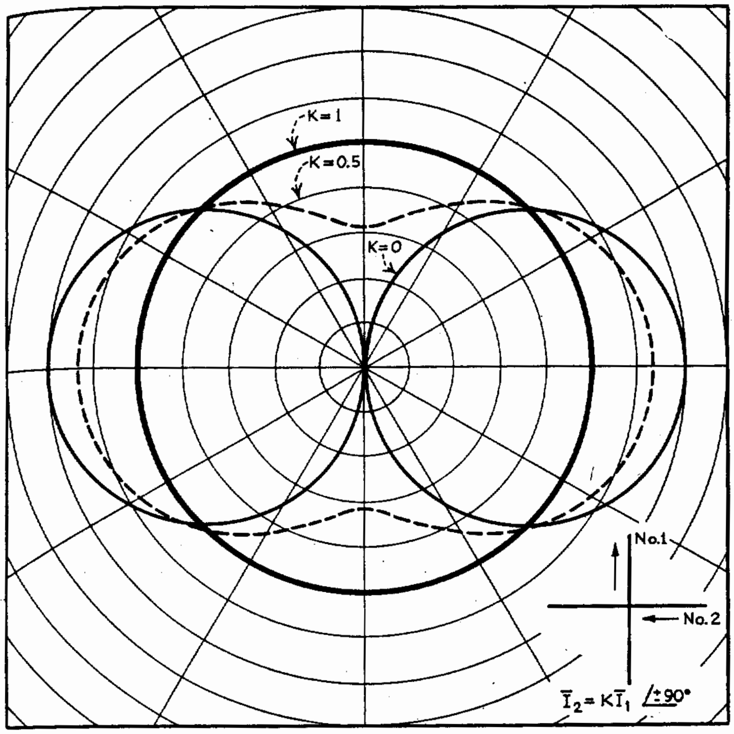
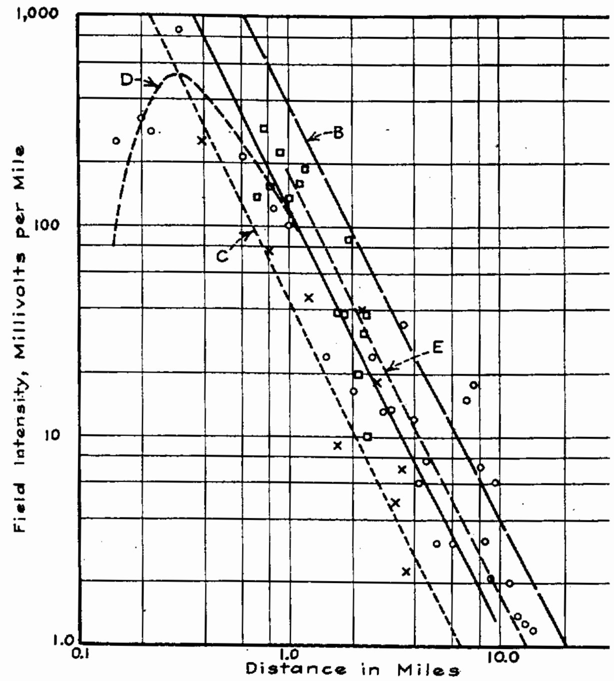


Fig. 12—Pattern with varying currents but with constant phase difference of 90°

Fig. 13—Field intensity measurements based on 1,000 watts into antenna



tended 70 feet above the roof. The radiators were nickel-steel tubes, copper plated. These tubes were made with sufficient wall thickness to allow a slight taper. This taper is supposed to avoid possible fracture due to vibration of the tubes. The stand-off insulators are 8 inches in length. The transmission lines are made up of No. 8 hard drawn wire. The antenna elements are placed slightly less than one-half wave length apart so that the transmission line length between elements is exactly one-half wave.

To achieve the proper phase shifts, the antenna is fed by an arrangement of transmission lines as shown in Fig. 10. If the lines have a characteristic impedance of 500 ohms, the following dimensions will hold *approximately*.

1. The distance from *c* or *d* to the lowest antenna element is 0.355 wave lengths (plus any integral number of half-wave lengths desired).

2. The length of *c* (or *d*) from line connection to shorting bar is 0.085 wave lengths.

3. *e* is any convenient length.

4. *f* equals *e* plus one-quarter wave length.

5. The distance from *T-T* to point of connection of *g* is 0.4 wave lengths.

6. The length of *g* is 0.15 wave lengths.

Four strain insulators are placed at the top of the pole to neutralize the pull on the top elements due to the transmission lines.

The transmission lines are connected to the antenna elements by means of clamps placed 0.06 wave lengths from the surface of the supporting pole.

Small metal pads are fabricated to the pole to insure firm horizontal mounting for the insulators and radiating rods.

In designing a particular antenna, consideration should be given the highest recorded wind velocity, the possibility of the formation of sleet on the antenna, and the possibility of excessive corrosion due to proximity to salt water.

Factors Affecting Horizontal Radiation Pattern

The design of the turnstile antenna has been based on the premise that it is most desirable to have a circularly symmetrical horizontal radiation pattern. It is, however, conceivable that such an antenna might be located in the heart of a city which is oblong in shape. In this event, it would be desirable to have a horizontal pattern which is elongated. This may be accomplished by controlling the phase relation between currents in the two perpendicular sets of radiators or by controlling the ratio of the currents in these two sets.

Figure 11 shows what happens to the horizontal radiation pattern when the currents in the two sets of elements are held equal in magnitude but the phase relation is shifted. We see that the pattern can be elongated along a line which bisects the angle formed by the two sets of radiators. Figure 12 shows similar results when the current ratio is varied but the currents are held in quadrature. Here the elongation points along the axis of one of the antenna elements. By choosing the proper phase and current ratios, it is possible to make the elongation occur at any angle in the horizontal plane.

Field Intensity Measurements

As stated previously, the first full scale antenna was constructed for operation at 45 megacycles. This antenna was located on the roof of a building in an urban district. The

[*Continued on page 48*]

"Turnstile" Antenna

[*Continued from page 17*]

top of the turnstile antenna is 470 feet above sea level and 310 feet above grade. Before the antenna was placed in operation, the probable field strength as a function of distance was estimated from the formula

$$E = \frac{88\ ha\ \sqrt{WK}}{3\,\lambda\, r^2}$$

where

- E = field intensity in volts per meter
- λ = wave length (meters)
- r = horizontal distance (meters)
- h = height of transmitting antenna (meters)
- a = height of horizontal receiving antenna above ground (meters). It was known that this dimension would be 8 meters for the measuring equipment.
- W = power into the antenna (watts)
- K = power gain factor from Fig. 7.

Curve A, Fig. 13, shows the curve calculated from this formula, on the basis of 1,000 watts and a power gain of 4. Curves B and C are reference lines placed 10 db above and below A. Curve D is computed from a more exact formula. The points shown on Fig. 13 are the measured points on the basis of 1,000 watts, when the horizontal receiving antenna was 8 meters from the surface of the earth. The points are naturally scattered since the measurements were made through the city.

The theoretical curves show that the field intensity drops off as the inverse square power of the distance, and thus is a straight line with a slope of —2.0 when plotted on log paper. By means of the theory of least squares, an analysis was made of the experimental points for all measurements made at one mile or more. The best straight line on log paper was found to have the equation

$$E = 170/r^{1.98}$$

where E is the field strength in millivolts per meter and r is the distance in miles. Curve E, Fig. 13, shows this equation.

When the 45 megacycle antenna was placed in operation, another striking effect was noticed. Observers reported that, in districts where signals from a single half-wave antenna had fluctuated as much as ten to one due to changes in field distribution due to moving automobiles and possibly elevator cables, the signal from the turnstile only shifted between limits whose ratio was two to one. This effect is probably due to the fact that the transmitting antenna is spread through a space two and one-half wave lengths long, thus giving "diversity" effect.

Directional Antenna Design

[*Continued from page 25*]

null in the ground pattern comes in the line through the radiators, and therefore a lobe of high angle radiation in the same direction results. This undesired lobe may prove troublesome in the service areas of co-channel stations at moderate distances in that direction, and does not permit complete suppression. Fig. 9 shows the familiar $\lambda/4$ (90°), $\phi = 270°$ couplet cardioid pattern for $k = 1.00$ and $k = 0.75$, and the resulting vertical patterns in the plane through the radiators.

When it is desired to suppress simultaneously radiations in two directions, the problem narrows somewhat at the start to those combinations of spacing and phasing which bring the nulls on the desired bearings. The angle between the two directions to be protected, from the proposed location, must first be determined. Call this angle β. In the patterns which have but two null directions, the orientation of the array must be that of the bisector of the angle β. The spacing and phasing for two radiators, to bring two nulls at the desired angles can be found from the following equation:

$$\phi = 180° - s' \cos \frac{\beta}{2} \qquad (5)$$

Here again,

- ϕ is the phase difference between the antenna currents
- s' is the spacing between radiators in electrical degrees
- $\beta/2$ is the angle between a null and the line through the radiators

In many cases it will be found that several space-phase combinations will bring the proper bearing of the nulls.

When dependence is placed on a directive array for effective suppression or elimination of radiation in some direction, the space pattern must be stable. Small changes in the phase angle between the radiator currents cause shifts in the null directions. Some patterns are more sensitive than others to the effects of small phase shifts, which may be due to changes in ground conditions, mis-tuning, etc. It is well to investigate this matter at the time of designing an array by calculating the change in pattern due to small changes in phase. Such a calculation is exhibited in Fig. 10.

Kear and Roder have described methods which are capable of automatically compensating for natural variations in an array, within moderate limits, thus stabilizing the radiation pattern.[2, 3] However, such precautions are required only in the most particular broadcast application.

The effect of sideband frequencies in the directive array may be noticeable sometimes in the vicinity of a sharp null, though it will be seldom of importance at broadcast frequencies. Nevertheless the sideband frequencies farthest removed from the carrier work into different impedances from those at the carrier frequency, with consequent slight departures from the phase relations, current ratio and electrical spacing for the latter. With modulation, therefore, we must visualize a faint quivering in the shape of the radiation pattern. The lower the carrier frequency and the higher the modulating frequency, the greater is the deformation of the radiation pattern during modulation.

[1]Foster, R. M.: B.S.T.J., April, 1926.
Southworth, G. M.: *Proc.* I.R.E., September, 1931.
Radio Engineering Handbook, McGraw-Hill, 1935, 2nd Ed., pp. 744-745.
See also *Electronics* Reference Sheet, page 00, this issue.
[2]Kear, F. G.: *Proc.* I.R.E., July, 1934.
[3]Roder, H.: *Proc.* I.R.E., March, 1934.