LONG SLOT ANTENNAS

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Abstract.—Slot antennas in which the slot is made as long as possible and to which metal wings are added to control the radiation pattern in the plane perpendicular to the axis of the antenna are treated. Also included is the use of such slot antennas in arrays to obtain directivity characteristics. As an example, the temporary array on the Chrysler Building for the CBS color television transmitter is given.

A CONVENTIONAL slot antenna consists of a resonant half-wave slot in a metal sheet, a cavity enclosing the slot on one side of the sheet and a feeder used to apply a potential between the opposite edges of the slot.

Since most of the previous applications of slot antennas have been to aircraft, the usual problem is to find a means for making the slot as short and as narrow as possible. In this paper we shall consider other applications in which the slot is made as long as possible. Long slots are desirable in applications which require directivity.

I. THEORY OF OPERATION

Consider a slot antenna consisting of a cylinder T in which is milled a longitudinal slot S as shown in Fig. 1. A concentric feeder F is brought into the cylinder through metal plate P_1. The outer conductor of feeder F is connected to the cylinder on one side of slot S. The inner conductor of the concentric feeder is connected to the opposite side of slot S. The potential between the inner and outer conductors of the concentric line is applied across the slot at the center of one slot.

The edges of slot S act as conductors of a balanced transmission line which is loaded by a distributed shunt inductive reactance. The phase velocity of propagation along such a transmission line is greater than the velocity of light. Experiment shows that the phase velocity of propagation along the slot is controlled by the inside cross-sectional area A of cylinder T. As this area A is decreased the velocity of propagation increases to about four times the velocity of light. When area A is decreased still farther the propagation along the slot changes to exponential. The transition between the two forms of propagation takes place gradually and in the intermediate voltageregion the voltage and phase distributions along the slot are as in Fig. 2.

This condition is obtained when the cylinder T is about 2 wavelengths long and its inner diameter is about 0.14 wavelength.

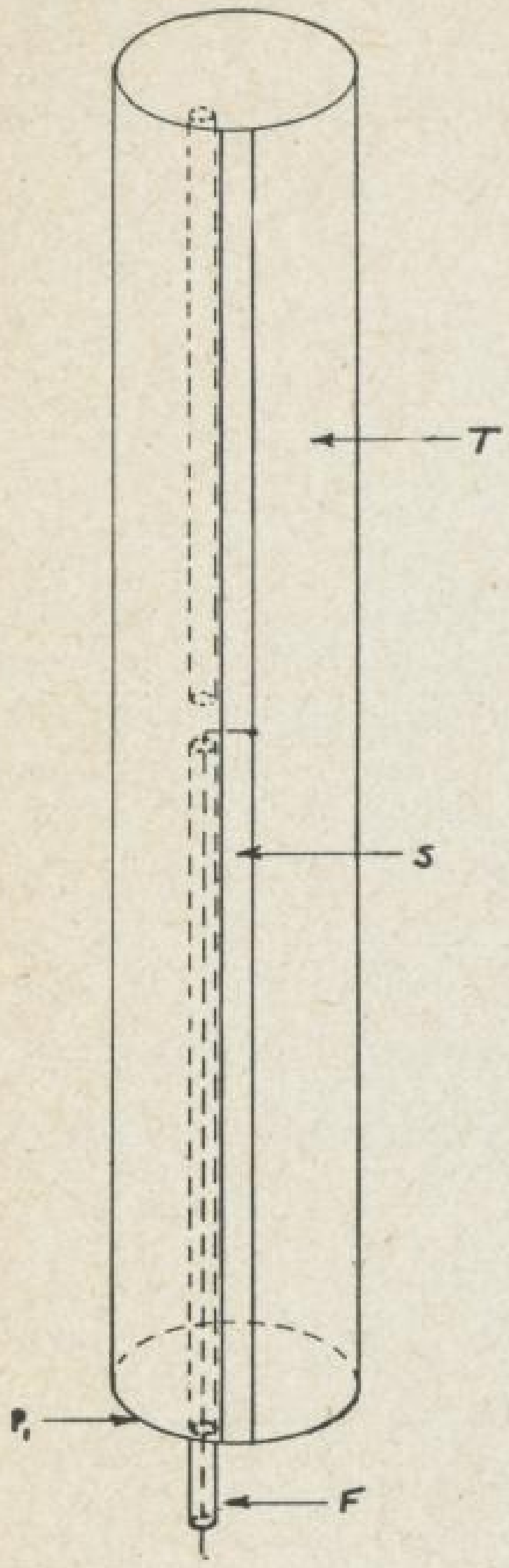

Fig. 1—Slotted cylinder antenna.

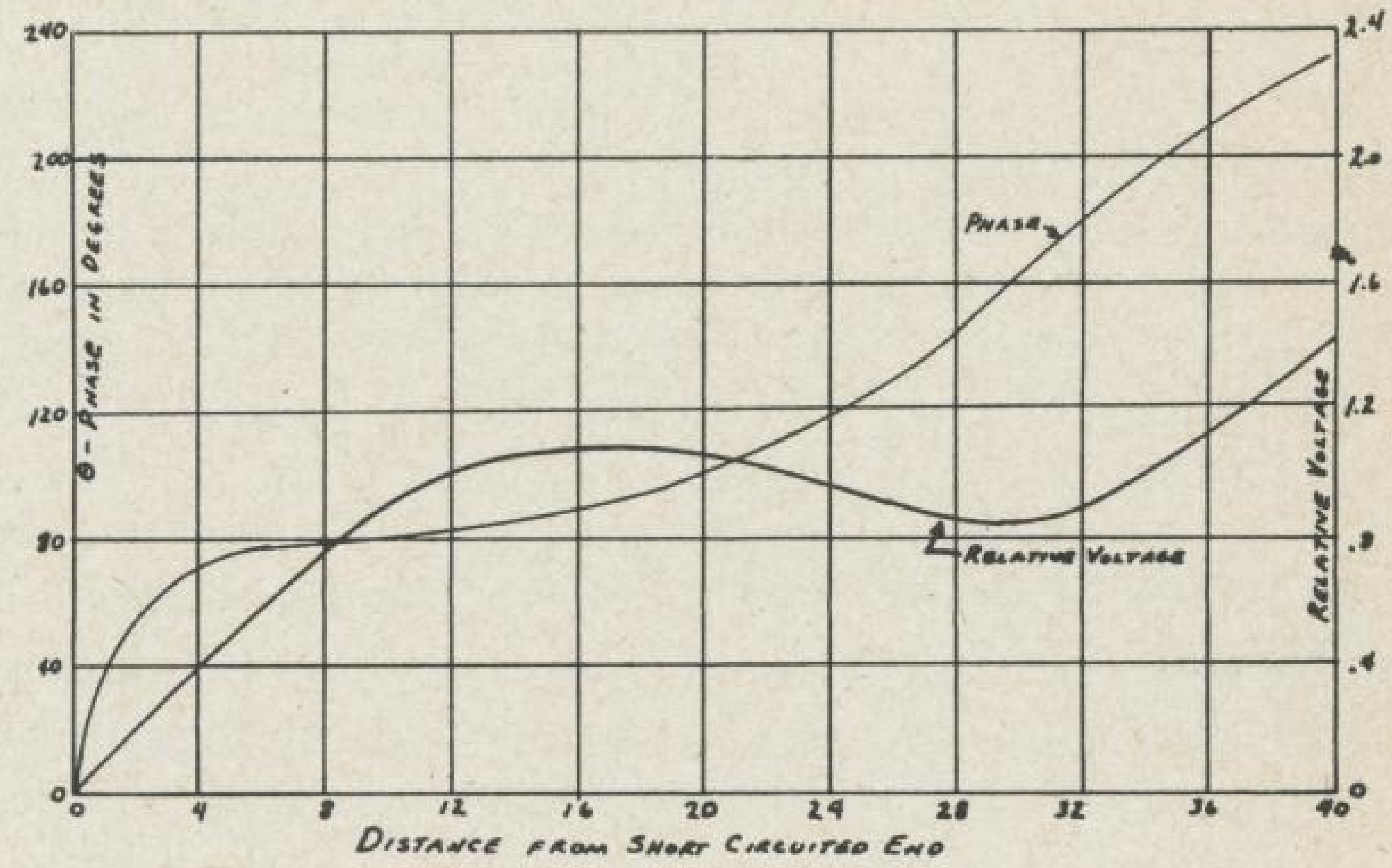

Fig. 2—Voltage and phase distribution along slot.

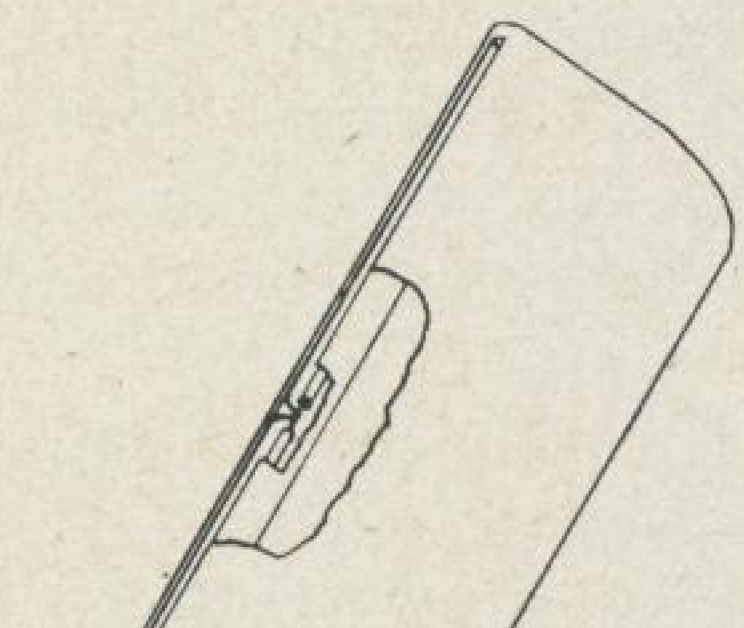

Fig. 3—Antenna with wings wrapped around large cylinder.

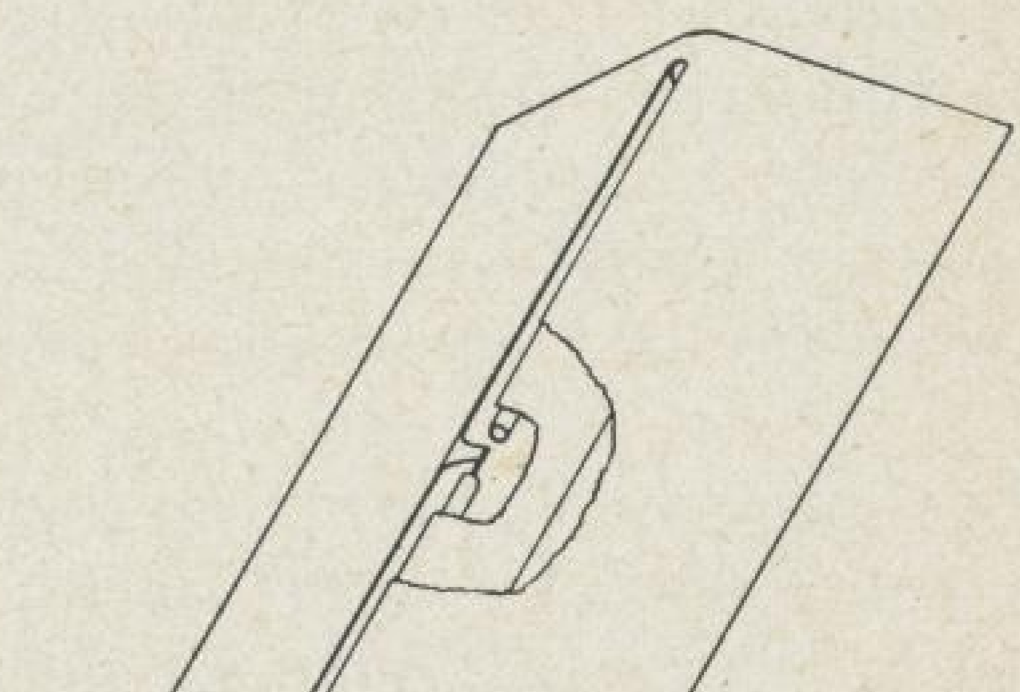

Fig. 4—Antenna with wings, angle between wings 225°.

The potential between the opposite edges of the slot produces circumferential currents on the outer surface of cylinder *T*. Since these currents are very nearly co-phasal the overall behaviour of the cylinder is similar to that of an array of small closely stacked loops about two wavelengths high.

The radiation patterns of the antenna of Fig. 1 in the plane perpendicular to the antenna axis may be controlled so as to conform with the shape which may be desired for a particular service. This is accomplished by the addition of metal "wings" as is shown in Figs. 3, 4 and 5. It is an odd property of the antenna of Fig. 1 that the addition of such metal wings has only a small effect on the velocity of propagation along the slot and that with or without wings this velocity is still controlled by the cross-sectional area *A* of cylinder *T*, provided that the angle between the wings is not too small.

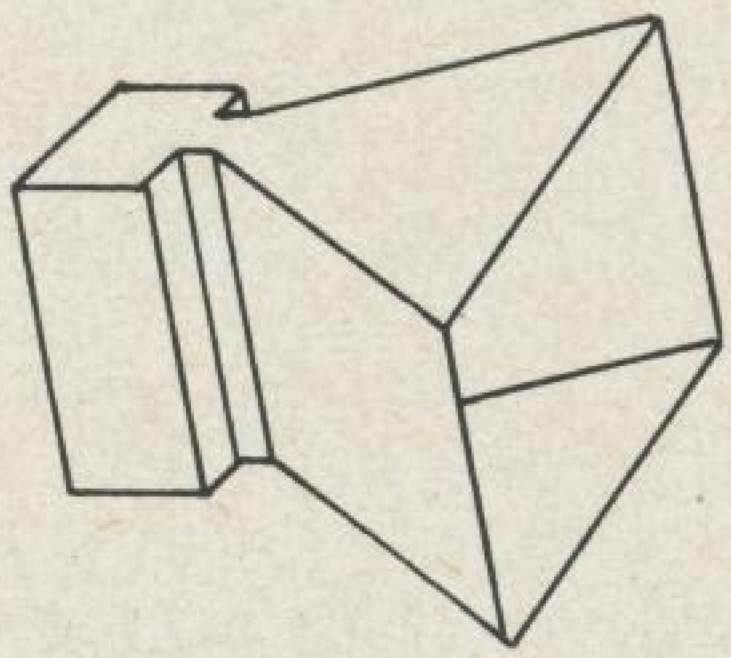

FIG. 5—Antenna with wings, angle between wings 80°.

The main effect of the wings is to intercept the current which normally flows around the cylinder and to force it into the wings. Figures 6, 7, 8 and 9 show the cross sectional views of several types of wings and the corresponding radiation patterns.

One common characteristic of all of these antennas is the distribution of radiation in planes through the long axis of the slot. The radiation patterns in these planes depend on the active length of the slot. The sharpest patterns are obtained with slots about two wavelengths long. As slots are made still longer the patterns first become wider at the base and then develop minor lobes. These effects may be explained with the aid of Fig. 2 which shows the distribution of amplitude and phase of the potential across the slot. When one half of the slot length is less than the virtual half wavelength $\lambda_{s/2}$ along the slot the phase of the voltage along the slot is nearly uniform. When the half-length of the slot is made longer than the virtual half wavelength the phase of the voltage at the center of the slot leads the phase of the voltage at other points. The resulting wavefront is bowed out and the radiation pattern becomes broader. The sharpest patterns are obtained when one half of the slot length is slightly less than the virtual half wavelength.

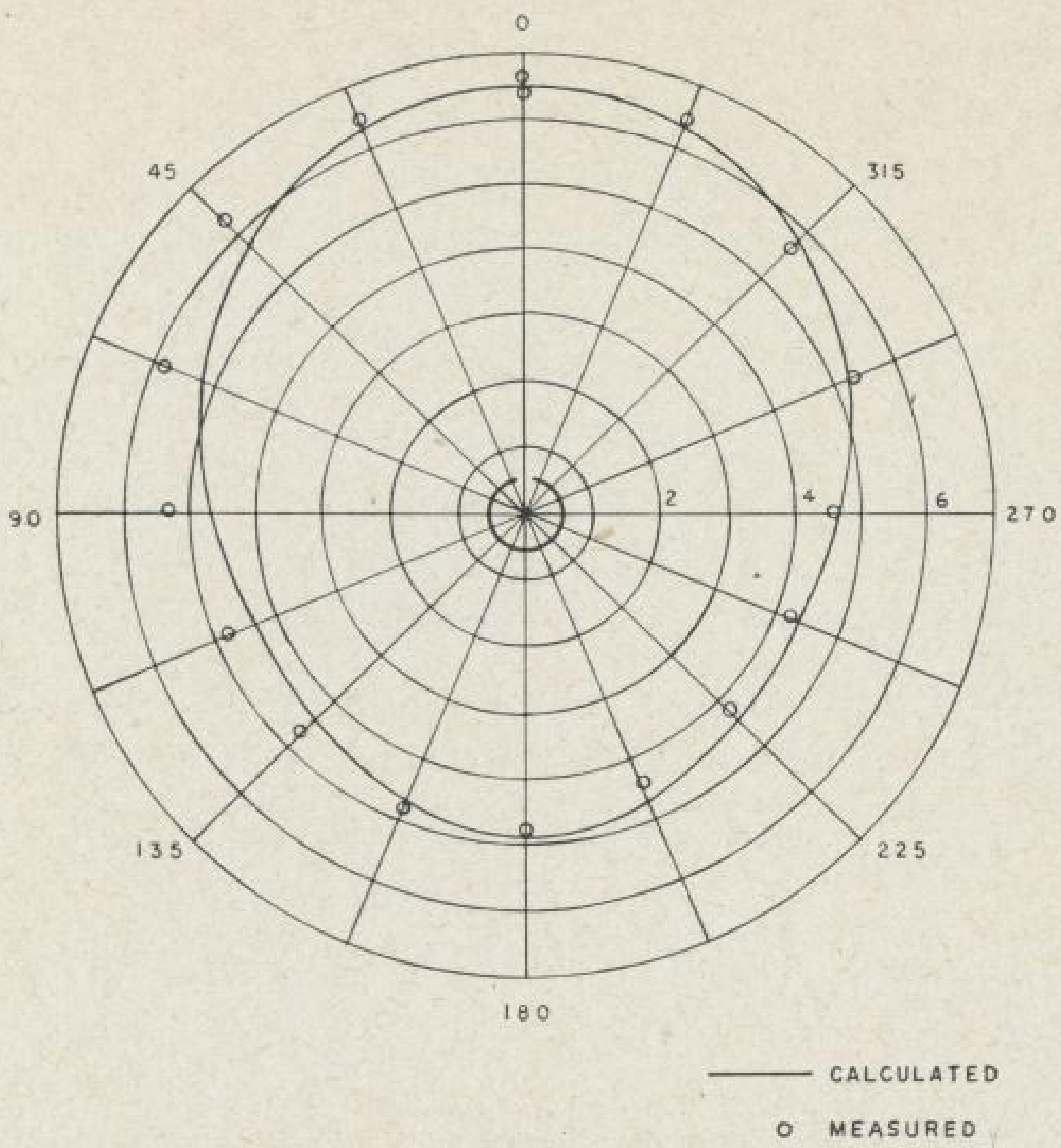

Fig. 6—Horizontal pattern of antenna of Fig. 1.

This simple picture is somewhat complicated by the fact that in reality there are two parameters which control the pattern:

1) The ratio of slot length to virtual wavelength S/λ_s and

2) The ratio of the virtual wavelength to wavelength in space λ_s/λ_o

The second parameter is important because it is directly related to the attenuation along the slot. If $\lambda\ /\ \lambda_o$ is less than 1.5 the attenuation is small. When

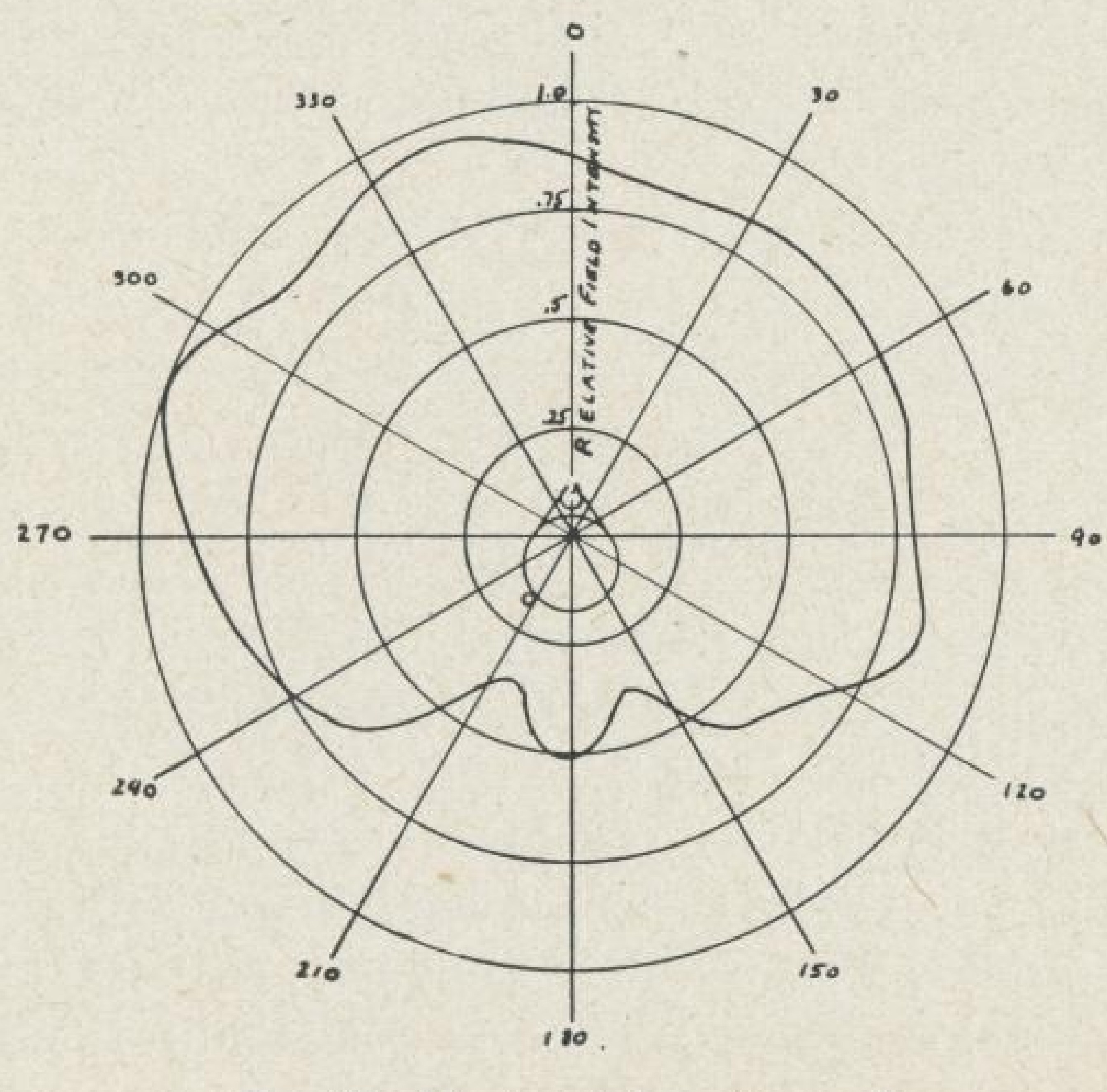

Fig. 7—Horizontal pattern of antenna of Fig. 3

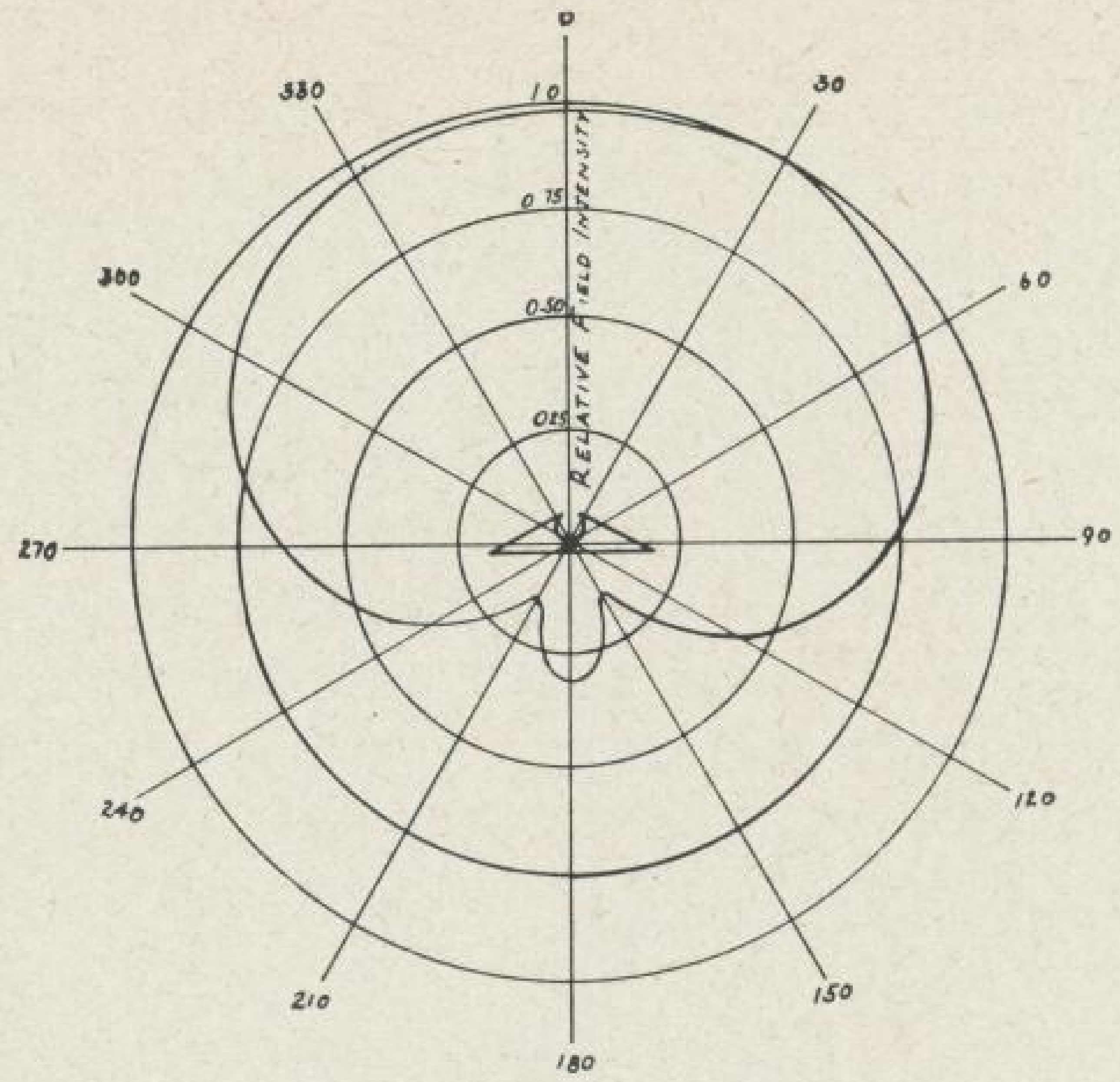

FIG. 8—Horizontal pattern of antenna of Fig. 4.

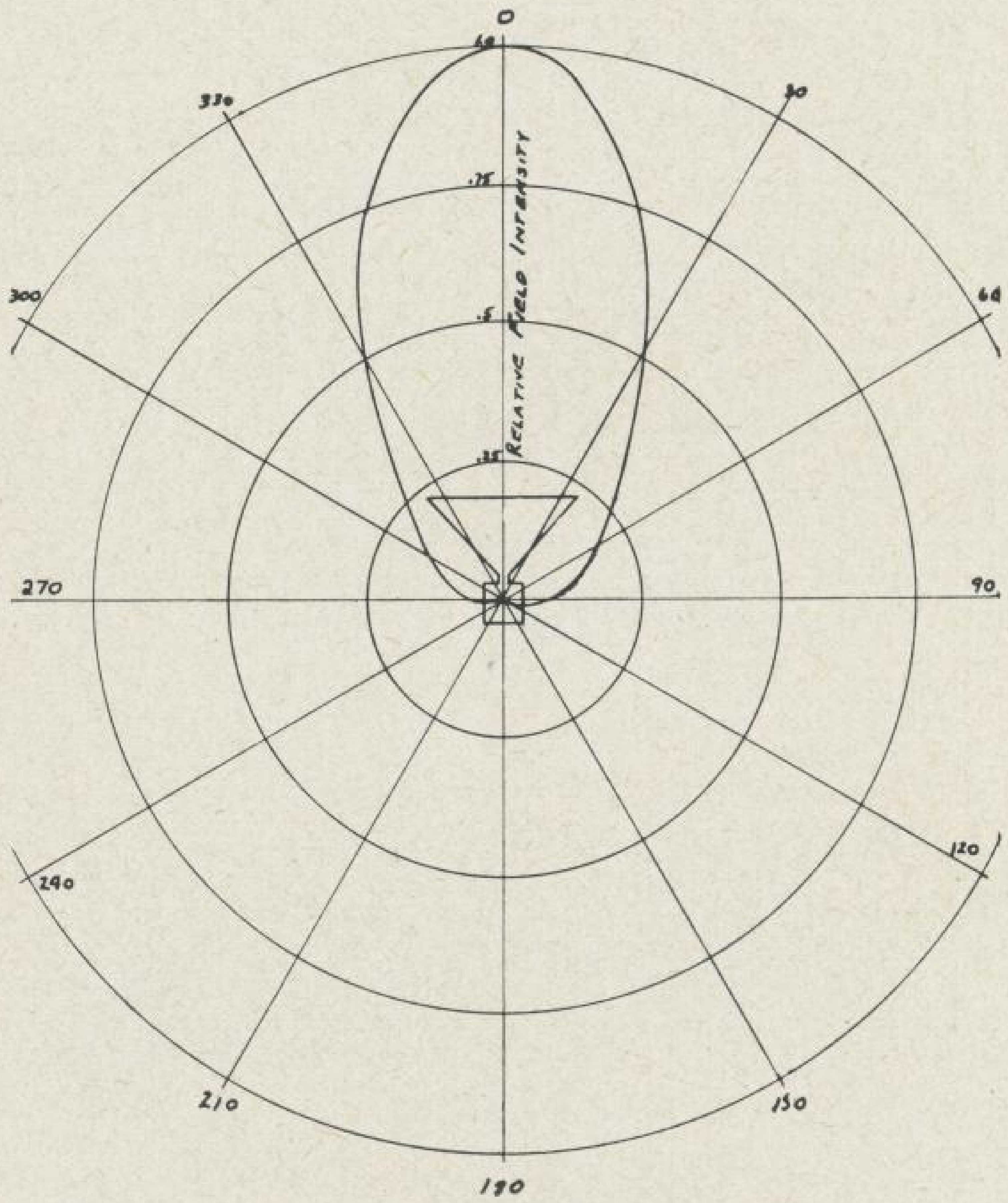

FIG. 9—Horizontal pattern of antenna of Fig. 5.

λ_s/λ_o is above 2.3 the attenuation is so great that the flat portion of the phasecurve is very short and it is no longer possible to obtain a co-phasal distribution along a long slot.

Since the attenuation also depends on the loading, that is, on the capacitance per unit length of the slot, the above stated limits of λ_s / λ_o apply only to slots formed by edges of metal tubes of usual thickness. With capacity loaded edges the attenuation is lower for the same values of λ_s / λ_o. The attenuation, however, is increased by the action of wings when they make a relatively small angle with one another as in Fig. 5. Such increase in attenuation may be offset by increasing the capacitance between the edges of the slot. This was done in the case of the slot of Fig. 5.

Figures 10 and 11, show the types of patterns which may be obtained with long slots in the planes which pass through the long axis of the slots.

Pattern A in Fig. 10 is considerably broader than pattern B in Fig. 10 because of the relatively short length of the slot.

The input impedances of long slot antennas have suitable values for

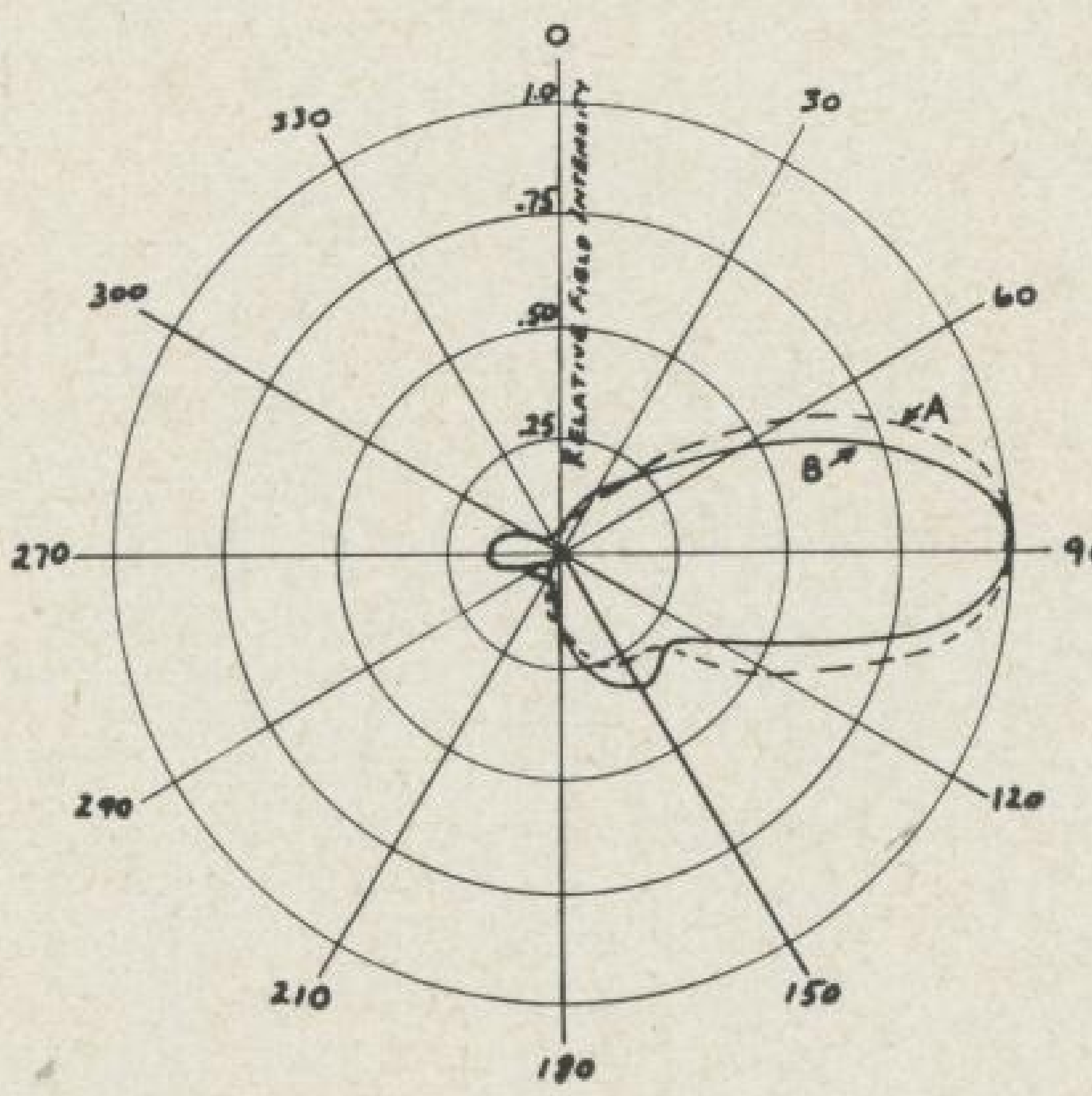

FIG. 10—Vertical patterns of slotted cylinder.
Curve A—Slot length of 34 inches and a frequency of 490 mc.
Curve B—Slot length 38 inches and a frequency of 490 mc.

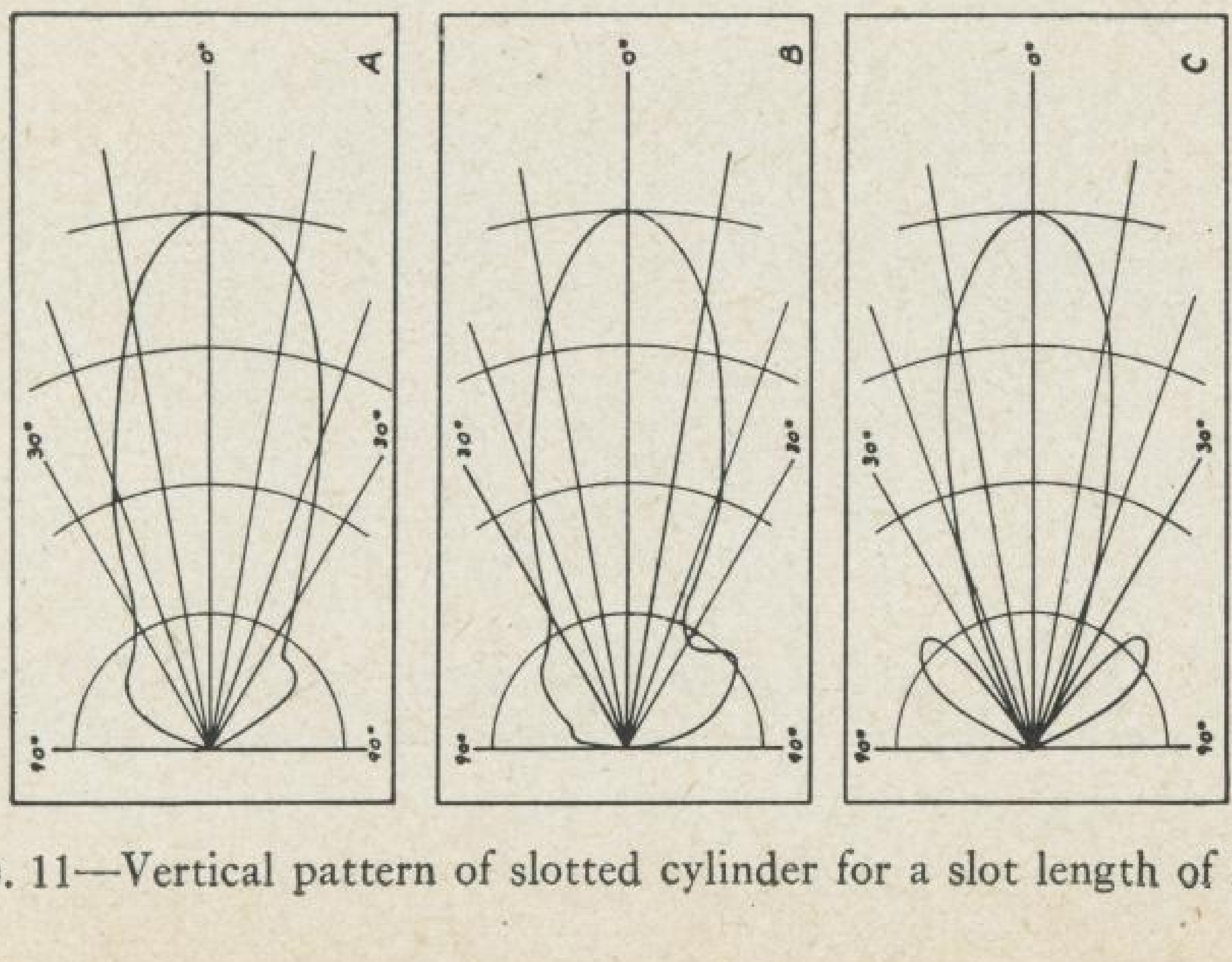

FIG. 11—Vertical pattern of slotted cylinder for a slot length of 2 λ.

many applications. The exact value of the impedance of a particular long slot radiator depends on λ_s / λ_o, on the length of the slot, on the capacitive loading of the slot and on the shape of the wings. The input impedance of a long slot antenna without wings with a slot 2′ long is very nearly a pure resistance of around 250 ohms.

A typical input impedance of a long slot antenna with wings is shown in Figs. 12 and 13.

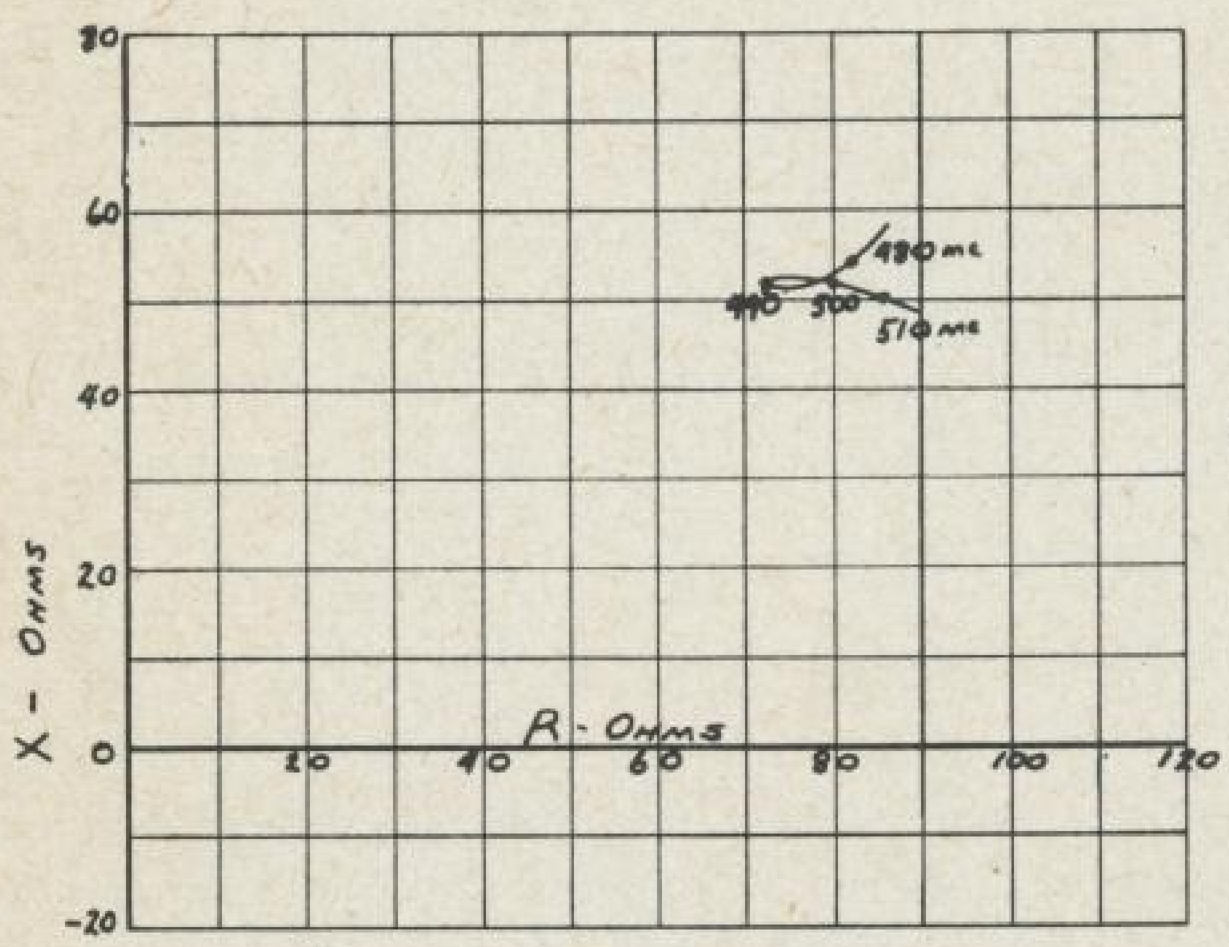

Fig. 12—Impedance characteristic of antenna of Fig. 3 for a slot length of 44 inches.

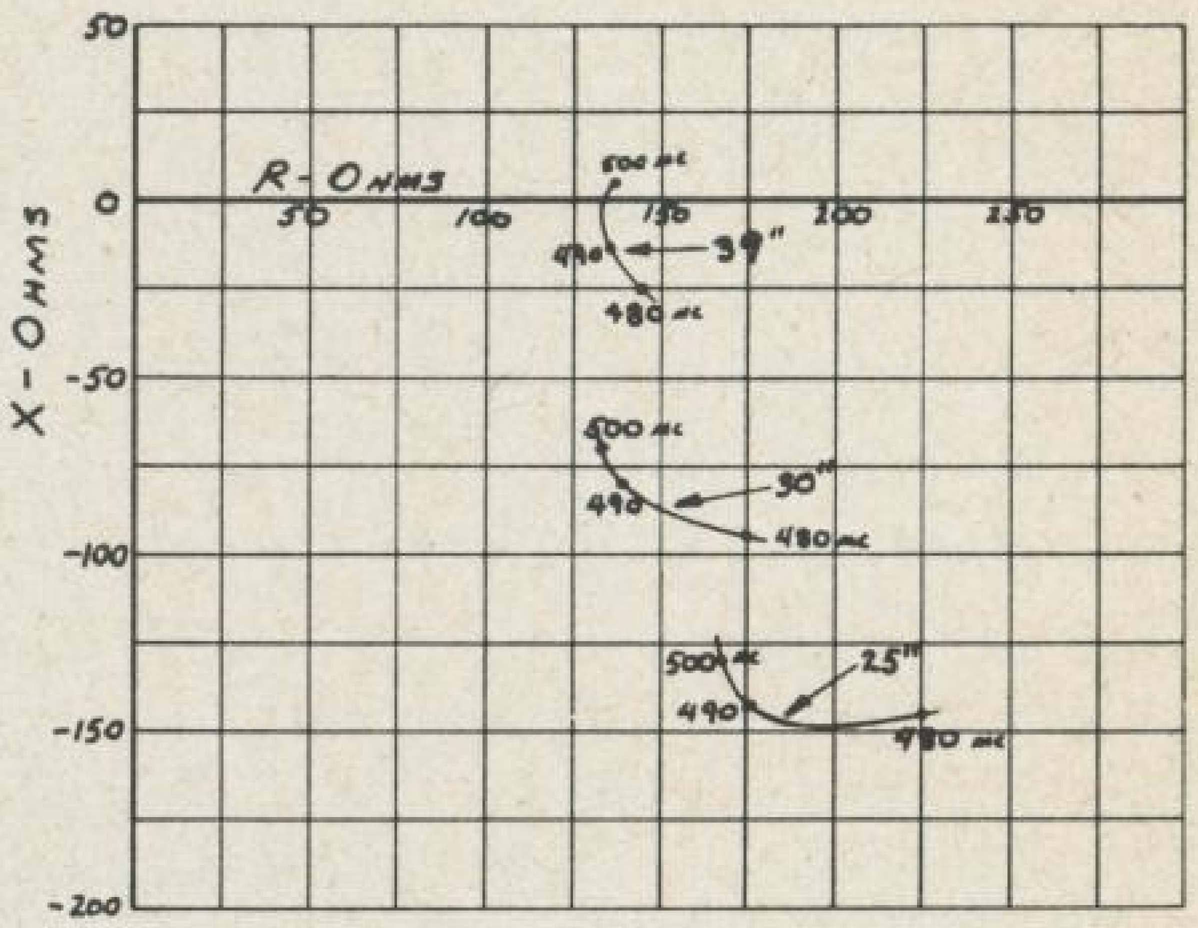

Fig. 13—Impedance characteristic of antenna of Fig. 4 for slot lengths indicated.

The input impedance of a slot radiator with horn-shape wings and with a capacity-loaded slot is shown in Fig. 14. When this impedance is compensated by means of a short-circuited section of 52 ohms the standing-wave-ratio on a 52-ohm feeder is as shown in Fig. 15.

One of the useful applications of long slot antennas is to UHF and VHF broadcasting. Long slot antennas without wings have a reasonable size at

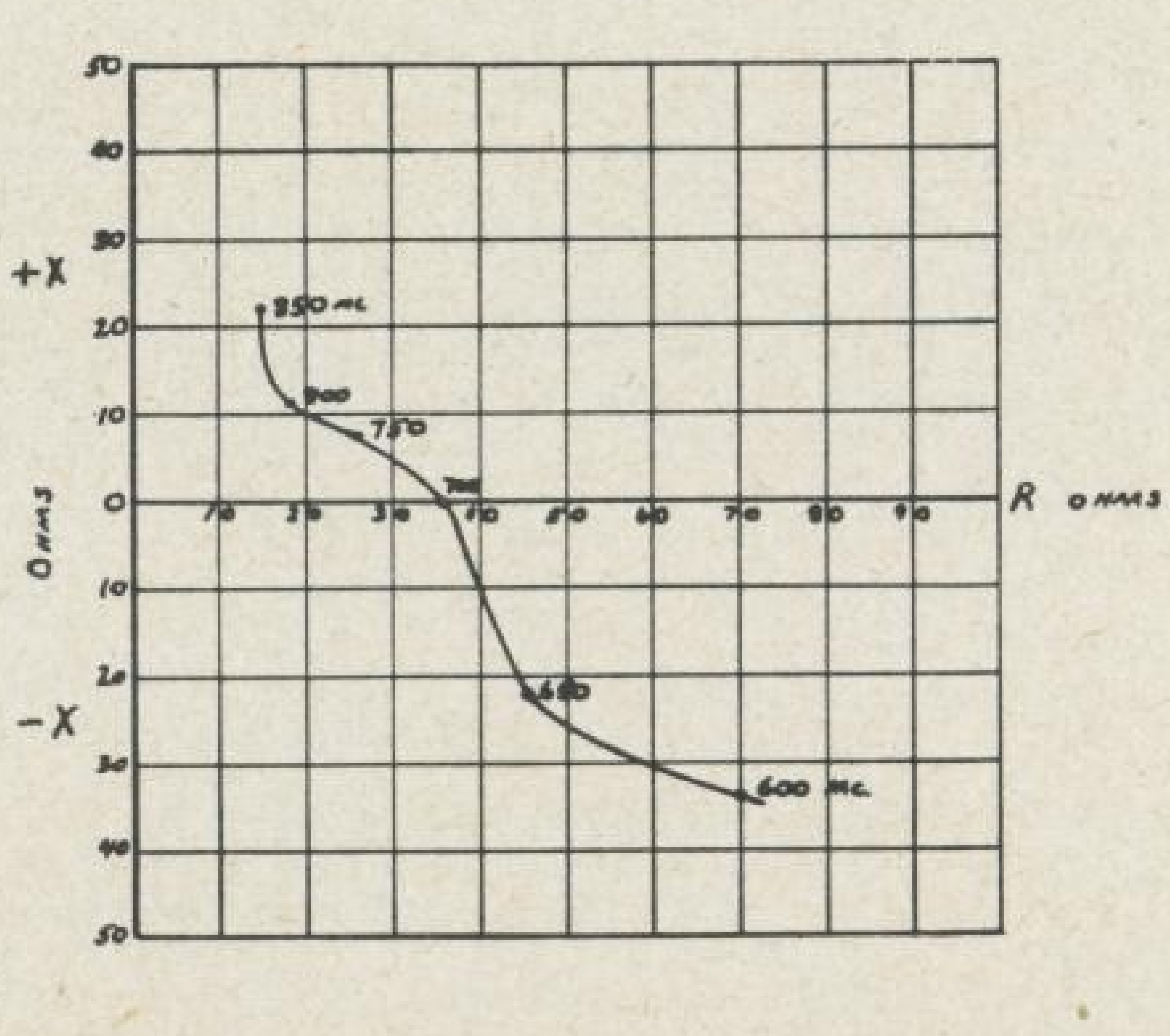

Fig. 14—Impedance characteristic of antenna of Fig. 5.

frequencies above 80 mc, that is, at frequencies in the new FM band and in the upper portion of the television band. Antennas with wings are particularly well adapted for use in the UHF television band 480 mc to 920 mc.

The property which makes the long slot antennas desirable for use as transmitting antennas is the fact that they have a relatively high gain per feeder. This property is particularly convenient when it is desired to build an antenna with high gain that must be obtained by confining the radiation to angles near the horizon.

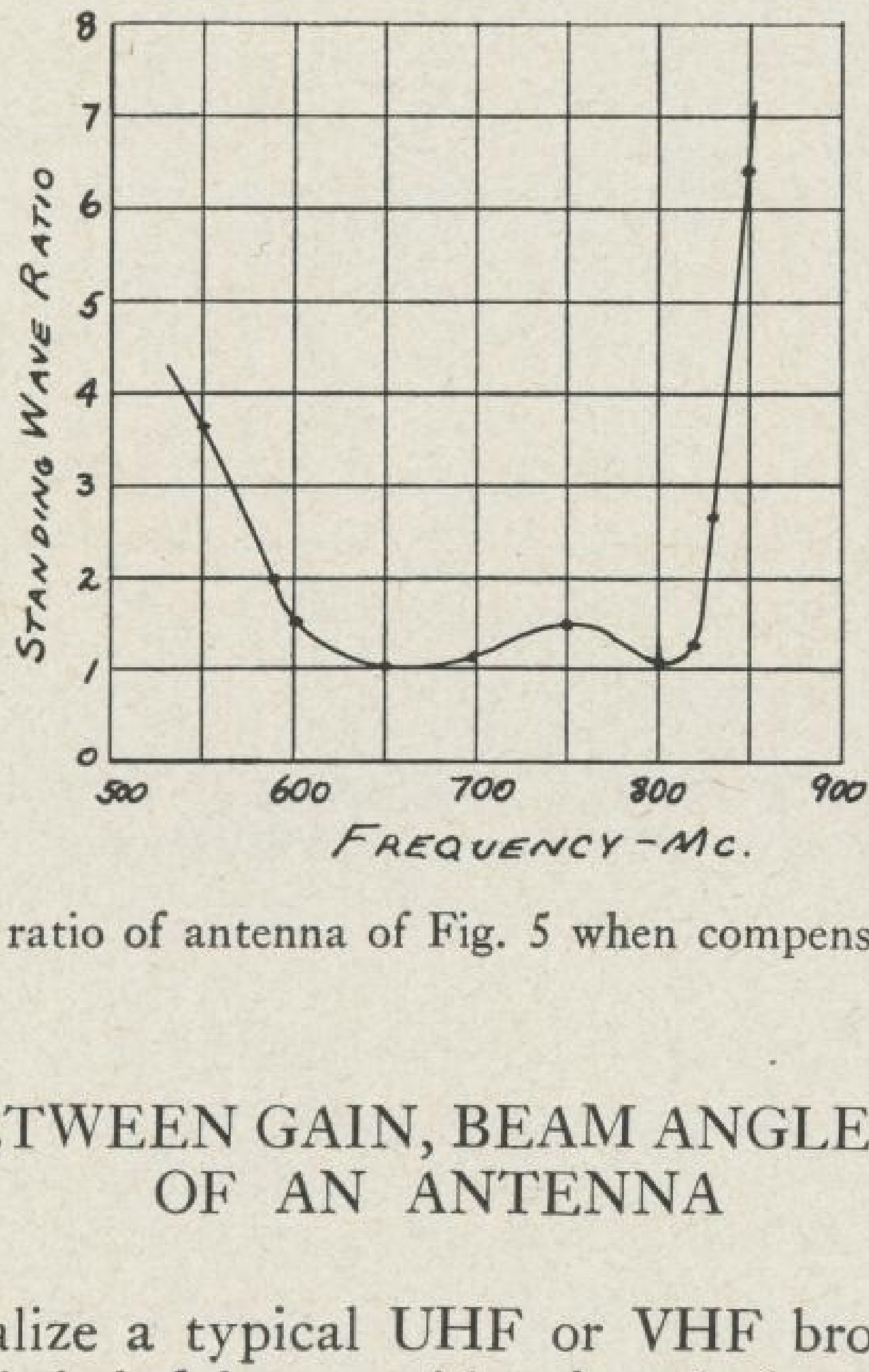

Fig. 15—Standing-wave ratio of antenna of Fig. 5 when compensated by a shunt section.

II. RELATION BETWEEN GAIN, BEAM ANGLE AND APERTURE OF AN ANTENNA

In order to visualize a typical UHF or VHF broadcast transmitting antenna problem it is helpful to consider the relations which exist between the gain, the beam angle and the overall vertical span or the "aperture" of an antenna. The following calculation, based on a somewhat idealized case, gives a fair approximation of these relationships. Consider a linear array of Fig. 16 consisting of a large number of identical radiating elements in which each individual element radiates a field distributed in the form of a figure of eight with maximum along the horizon. The field of one radiating element is

$$f = \frac{1}{r}\cos\theta\cos\omega t$$

If the phases are referred to the center of the array the combined field of all elements of the array at a distant point is

$$F = \frac{1}{r}\int_{-a}^{+a}\cos\theta\cos\left(\omega t - \frac{2\pi}{\lambda}z\sin\theta\right)dz = 2\frac{\cos\theta}{k\sin\theta}\sin(ka\sin\theta)\cos\omega t$$

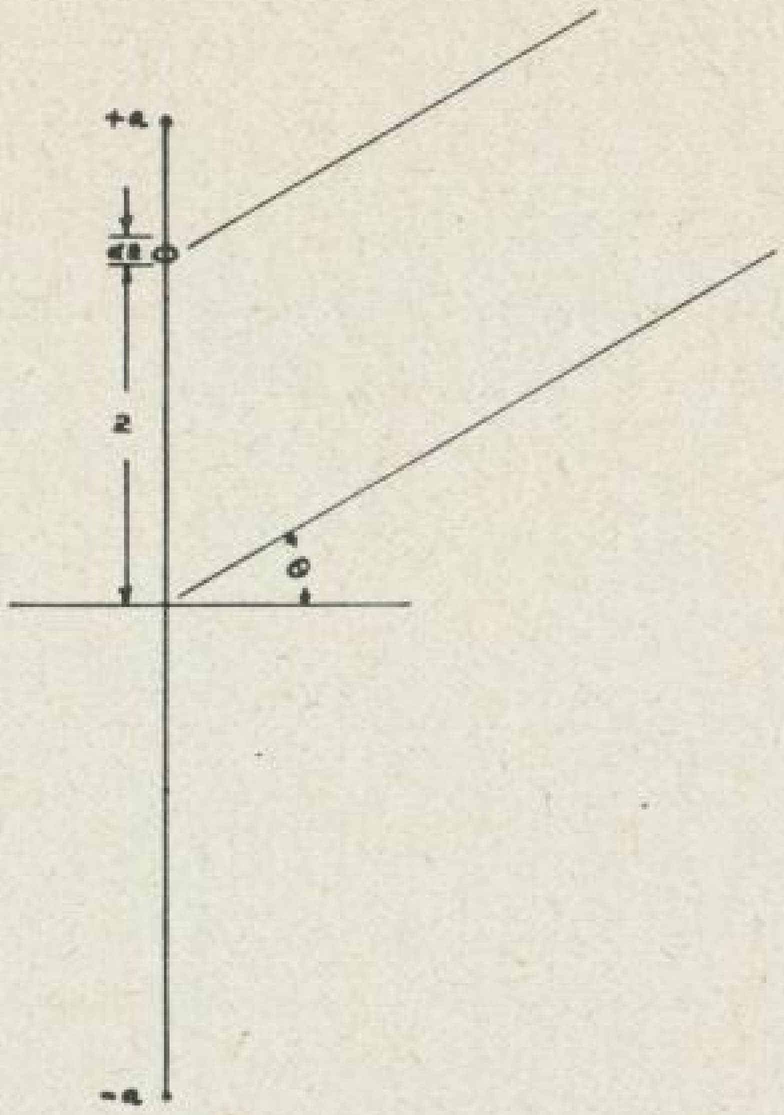

FIG. 16—Linear array with uniform current distribution.

The total power P radiated through a large sphere of diameter r is

$$P = \frac{c}{8\pi} 2\pi \int_{-90}^{+90} 4 \frac{\cos^2 \theta}{\sin^2 \theta} \sin^2(ka \sin \theta) \cos \theta \, b\, \theta = c \left\{ -2 + \cos(2\,ka) + \right.$$

$$\left. \frac{\sin 2\,ka}{2\,ka} + 2\,k\,a \int_{o}^{2ka} \frac{\sin u}{u}\, du \right\}$$

and the corresponding power gain G is therefore given by $G = \frac{F^2}{p} \times \frac{CK^2}{2}$

The curve in Fig. 17 shows the relation between G and the array. For comparison small circles in Fig. 17 show the power gain of arrays consisting of loops spaced one wavelength apart. The crosses in the same figure show the gain of arrays consisting of loops spaced a half wavelength apart. From inspection of Fig. 17 it is clear that the gain of an array is primarily a function of the total aperture and that for longer arrays it makes little difference when the "illumination" is not continuous but is in the form of descrete sources spaced for example one wavelength apart. Similar results are obtained when a long array consists of several nearly uniformly illuminated sections with or without some spaces between them. This is the case when each of the elements is a long slot antenna. For example, two long slot antennas each 2.1 wavelength long with an overall aperture of 4.2 wavelengths has a gain of about 7.35. An array consisting of four long slot elements, each two wavelengths long has a gain of 16.4. The aperture-gain relations which correspond to these arrays are indicated by small triangles in Fig. 17.

Since the number of elements in an array is directly related to the required number of branch feeders, transformers, and other fittings it is obvious that, other things being equal, a few long elements are preferable to a large number of small elements. This is particularly true at the higher

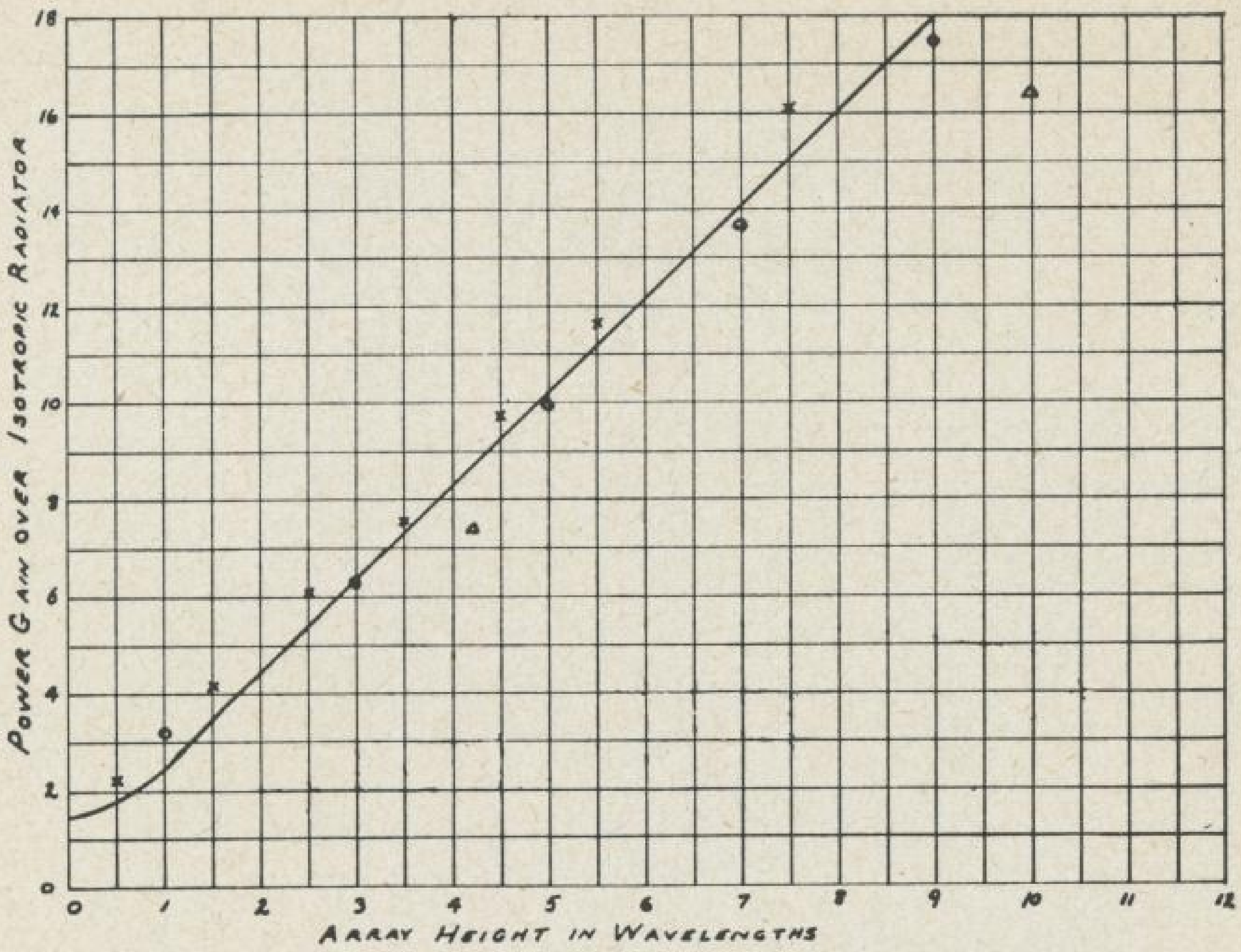

FIG. 17—Power gain of long slot array versus array length for uniform illumination. O—Loops spaced 1 wavelength. X—Loops spaced ½ wavelength.

frequencies where a large number of transmission line fittings is undesirable. It is at these higher frequencies that the long slot radiators have convenient dimensions and therefore offer what seems to be a practical method for reducing the number of elements in high gain arrays.

One example of an antenna of long slot type has already been reported in some detail at the IRE convention January, 1946. This antenna consists of a slotted cylinder about one wavelength long without wings. The slot is open circuited at the upper end and is shortcircuited at the lower end. The operating frequency of this antenna is 99.7 mc. It has now been in use by station WGHF in New York city for a period of about eight months.

A number of similar antennas but with slots about two-wavelengths long have been completed, and are now awaiting erection.

III. THE CBS SLOT ANTENNA FOR COLOR TELEVISION

An array of long slot antennas with wings has been erected for temporary use with the CBS color television transmitter installed on Chrysler building in New York. This array consists of two sections, one mounted on the north and another on the south wall of the Chrysler building. Each section of the array is composed of 4 long-slot elements with wings as shown in Fig. 18A. A photograph of one element mounted on a rotating mount for taking the vertical pattern is shown in Fig. 18B. One feature not shown in this photograph are the two short-circuiting bars used to short-circuit portions of the slot. The vertical and horizontal patterns of the element are as given in Fig. 10. The impedance of this element is shown in Fig. 13. Because of the very short time during which these arrays were designed constructed and erected the optimum slot lengths were not used because some time could

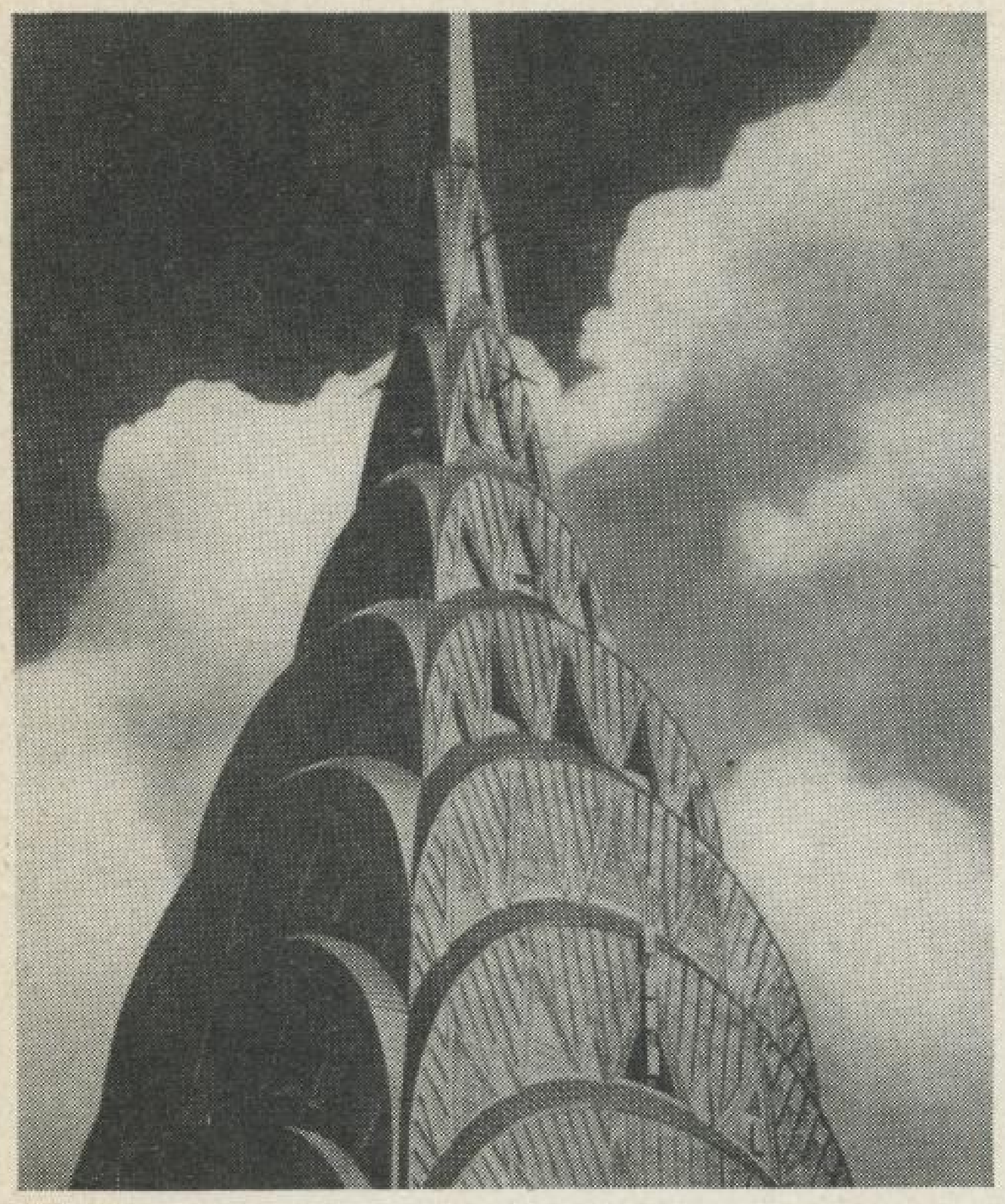


FIG. 18A—Photograph of Chrysler building 4—element UHF television array.
FIG. 18B—One element of the Chrysler building television array set up for test.

be saved by making the slots about 1.6 wavelengths long which resulted in the input impedance being a pure resistance. The vertical pattern of each individual radiator is thus substantially broader than the pattern which would be obtained with a longer slot.

In view of the fact that the vertical pattern of an array of four such elements energized in the same phase results in a beam about 5° wide between half-power points with deep nulls on each side of the beam it was feared that there would be ring-like zones of low signal around the transmitter. Assuming that the antenna is located 800 feet above the surrounding terrain, the first null zone would intersect the ground at about 1¾ miles from the transmitter. Other low signal zones would be closer to the transmitter.

In order to make certain that the signal in the service area in the neighborhood of the transmitter does not fall to a low value, the feeding arrangement of the array was so arranged that the phase of the currents in the two center elements of the array was made to lead the phase of the currents in the end elements by about 39°. Furthermore, the spacing between the elements was made non-uniform. The resulting vertical pattern is such that the field in the first null falls to about 1/5th and in the second "null" to about 1/10th of the maximum value. It is probable that the "null" between the lobes need not be filled in to this extent.

When the array was originally designed it was expected that the two sections of the array would give satisfactory coverage over 300° of the total 360°. Two sectors of interference, one west and another east of the antenna, were expected. Later tests with an 8000-mc model indicated that the sectors of serious interference should be only about half as wide as originally expected. So far, however, the interference nulls have not been observed during the field survey.

IV. OTHER SLOT ANTENNA ARRAYS

A number of tests have been made with another long slot array consisting of elements of the type shown in Fig. 3. This element has a horizontal radiation pattern which is well suited for installation at a downtown station in Chicago. The shape of the wings is such that the major portion of the wing is the heavy supporting steel mast. Figure 19 shows a photograph of

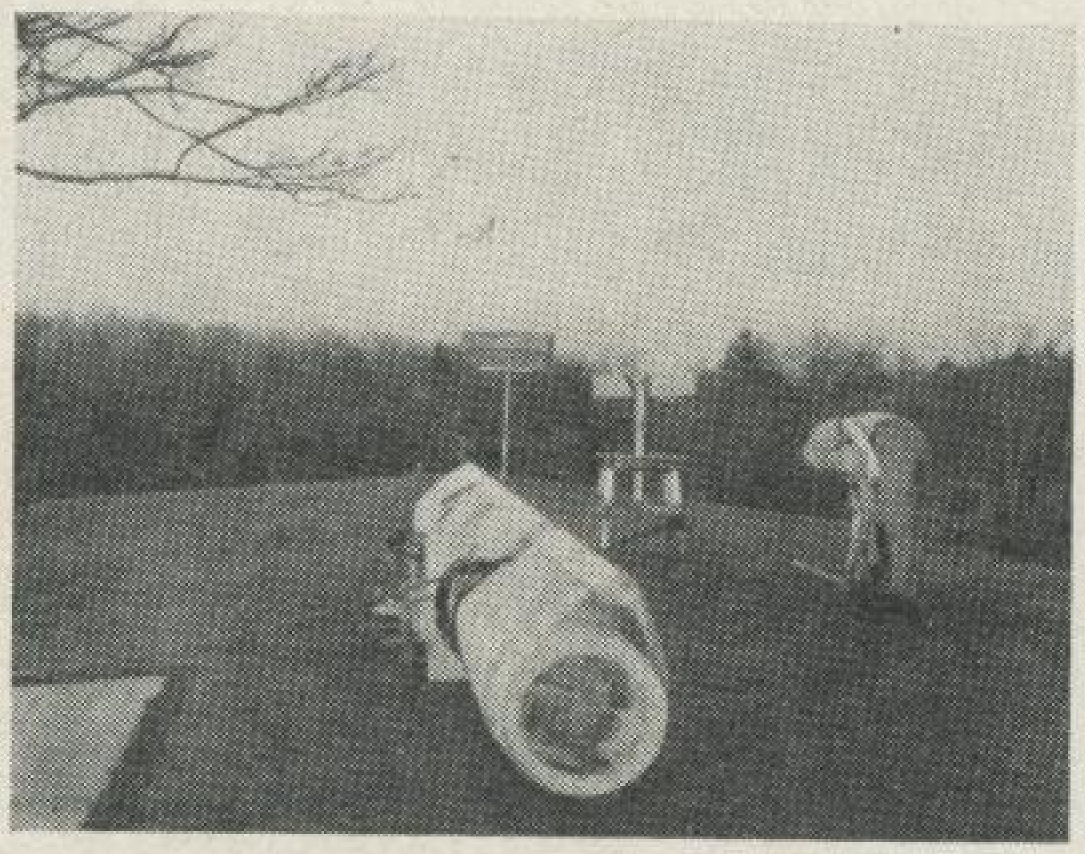

FIG. 19—Experimental 490-mc array with elements of type shown in Fig. 3.

a full scale model of a 490 mc array which was constructed of metal mesh. A vertical pattern of this model is illustrated in Fig. 20. The assymmetry of the pattern is believed to be due to the fact that the wing dimensions were made to conform to the dimensions of an existing stell mast which varies in diameter between 21 inches at the lower end of the array and 16 inches at the upper end. When the mechanical design was studied in detail it was found that it was more convenient to build up the mast with thin cylindrical sections so that all wings would be alike. This should result in a symmetrical vertical pattern because there are no other sources of assymmetry in the array.

Still another array has been studied for use at frequencies at between 490 mc and 920 mc. This array is intended for omnidirectional coverage. The array consists of two sets of long-slot elements with wings mounted back to back on the opposite sides of a mast. The type of horizontal patterns which may be obtained with this array is shown in Fig. 21.

An important point which should be mentioned in connection with the design of transmitting arrays for frequencies between 490 mc and 920 mc

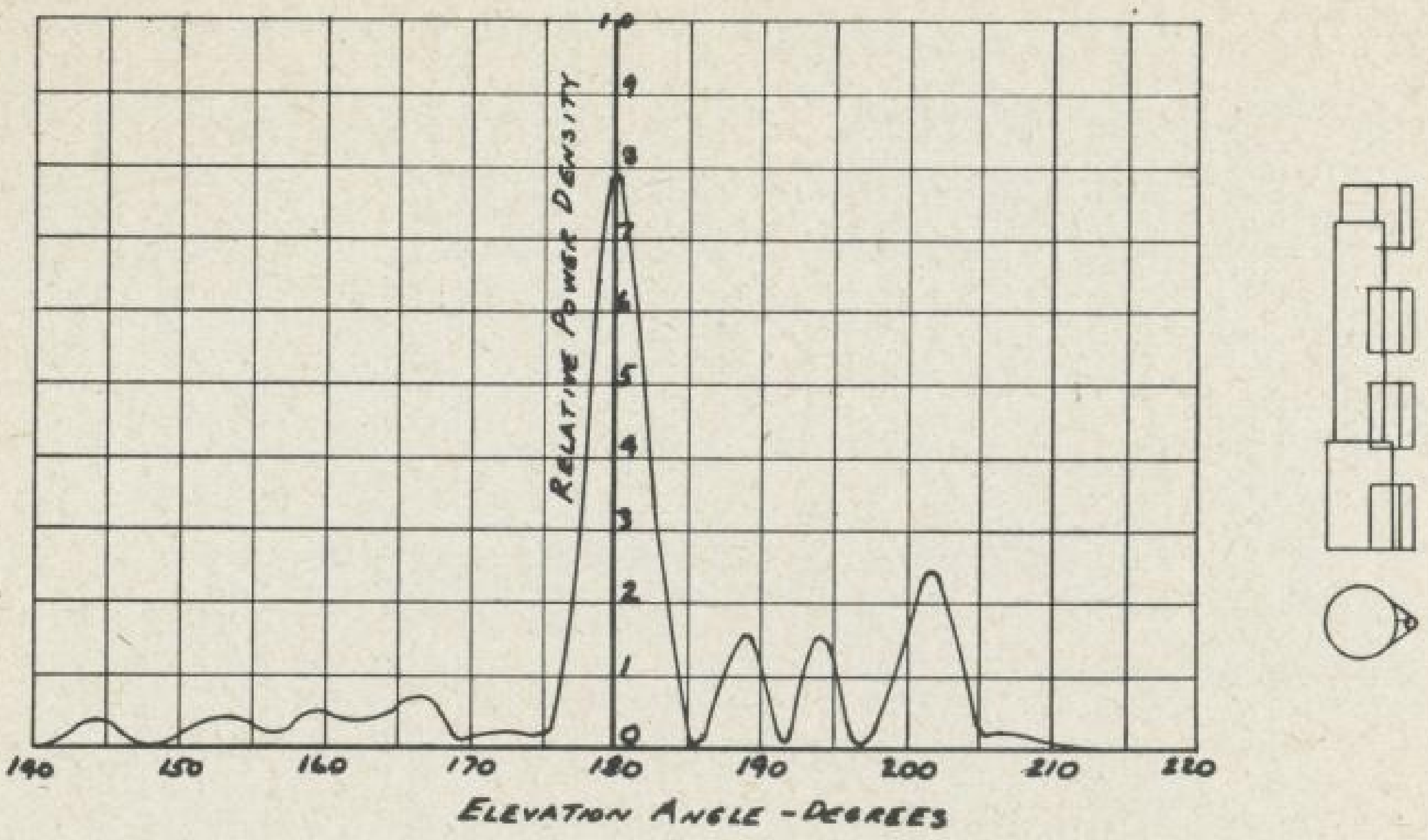

FIG. 20—Vertical pattern of array of Fig. 19.

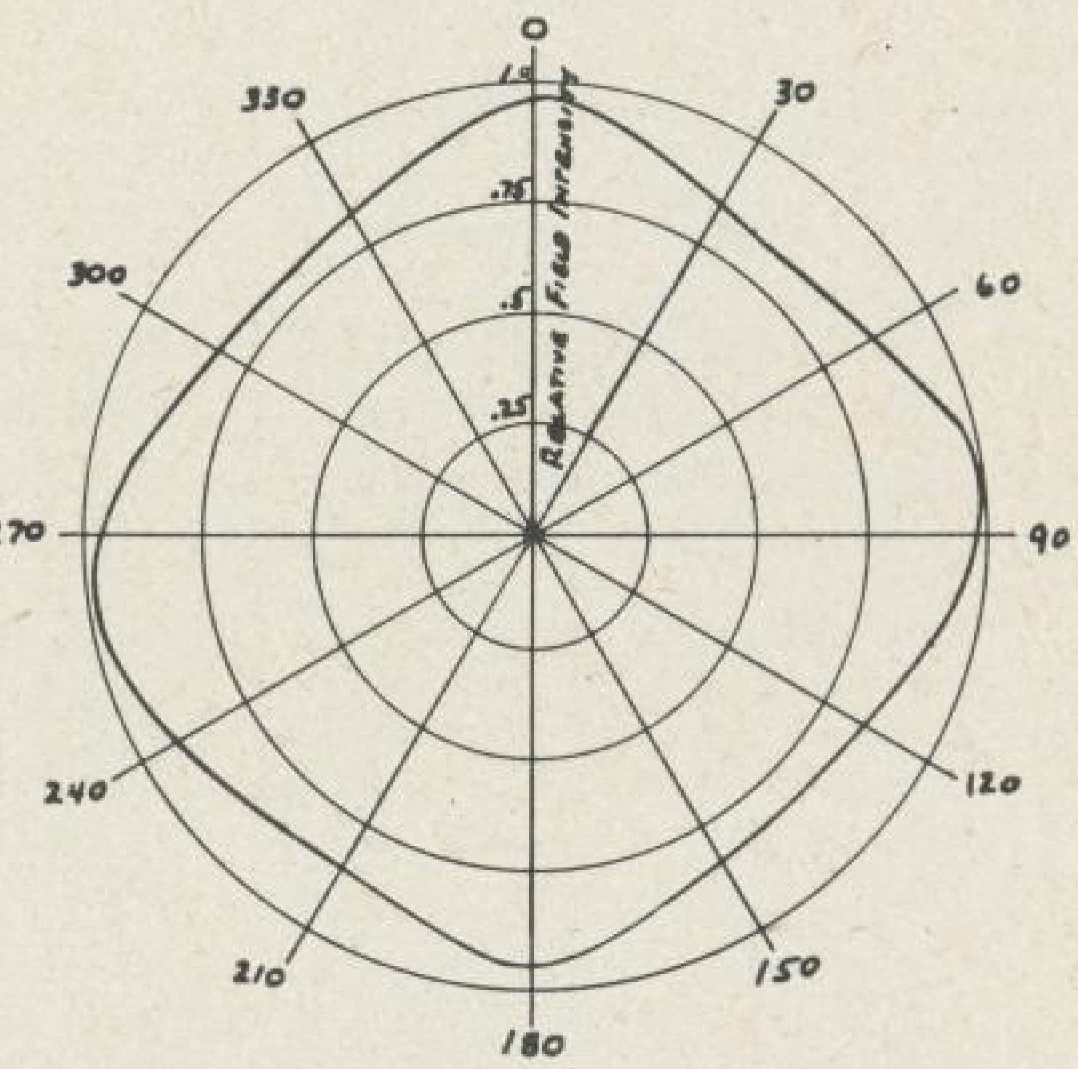

FIG. 21—Horizontal pattern of array composed of two elements of Fig. 4 placed back to back.

is that a number of metal objects such as steel ladder, hangers for transmission lines and other details which at lower frequencies are not important, must be taken into account. This fact sometimes adds considerable complications in the design. All arrays mentioned above have been provided with suitable steel ladders which were included either on full scale or in model measurements.

Antennas of the long slot type may be designed for use over a substantial band of frequencies. A relatively broad band antenna of this type has been constructed for use as a receiving antenna for UHF television signals. This antenna consists of two elements of the type shown in Fig. 5. The characteristic of each element of a model of this antenna are given in Figs. 9 and 14. The two element broadside array has power gain of 14.