SECTION 3

SPECIALIZED BROADCAST RADIO ENGINEERING

BROADCAST ANTENNA SYSTEMS—PART II

315E

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BROADCAST ANTENNA SYSTEMS—PART II

SCOPE OF ASSIGNMENT

The preceding assignment discussed in some detail the problems concerned with the selection of the proper type of broadcast antenna, the location of the antenna and the means by which maximum antenna efficiency could be obtained. The discussion now will be continued with a view of determining the solution of the problem in which the simple non-directional radiating system is inadequate.

First will be studied the characteristics and patterns that can be obtained for two antenna elements by varying their spacing, current amplitudes, and phase. Then the methods of obtaining such relationships will be taken up, with particular attention to transmission lines and phase-shifting networks, as well as measuring equipment.

Next the calculations for the pattern of a two-element array will be studied, and a typical calculation made. This will be followed by the methods of making field intensity measurements, and will conclude with a description of a typical field intensity meter.

DIRECTIONAL ANTENNAS

NEED FOR DIRECTIONAL ANTENNAS.—There are two principal reasons for the use of directional antennas in broadcasting: First, consider the case of a transmitter to be located to the eastward of a large metropolitan area adjacent to the Atlantic sea coast. If this station radiates, for example, 50 kw of power with a non-directional antenna, a large proportion of the transmitted energy will be radiated over the Atlantic Ocean where it will serve no useful purpose. If the eastward radiation can be suppressed, and that equivalent energy added to the energy radiated westward and along a north and south line, the result will be increased signal intensity over the desired area with a minimum waste of power.

The second, and probably more important use for the directional antenna is in the suppression of radiation in such directions which point toward the service areas of stations on the same or adjacent channels. Suppression of radiation in the interfering direction by means of a directional antenna array will allow a station to increase its power and hence its useful service area without increasing the amount of interference it would cause to another station.

PRINCIPLE OF OPERATION.—Directional antenna arrays operate on the principle of wave interference in which, by proper spacing and phasing of two or more antenna systems, the electromagnetic waves are caused to combine in one direction in such polarity that the radiated fields cancel each other and in another direction in such phase and amplitude that the several signals reinforce each other.

The principle of wave interference probably has been known for several centuries. The first thorough treatment of the subject was made by Sir Thomas Young in 1802. In 1886 Hertz invoked the use of this principle in proving the existence of electromagnetic waves. He made use of parabolic mirrors for both transmitting and receiving, these mirrors having directional characteristics very similar to those sometimes used in present-day radio transmission. Hertz found that parallel wires stretched over a frame were quite as effective as a reflector as a continuous sheet of metal of similar dimensions providing the wires were kept parallel to the lines of electric force of the arriving wave.

In recent years Southworth, working with long directional arrays for both transmitting and receiving, has found that the directional characteristics of the array depend to a very large extent on the total length of the array and to a much lesser extent on the spacing and number of radiators making up the array. The experiments of Hertz were conducted on very short waves which made the use of directional systems and reflectors practical. From the time of Marconi's first work until the early 1920's most radio development proceeded along the lines of lower frequencies and higher power. At the low frequencies directional arrays usually are somewhat impractical due to the dimensions required, and in the earlier days of radio there were not sufficient stations in operation to make interference a serious problem.

The present trend, of course, is all in the opposite direction; that is, toward higher and higher frequencies, more and more stations within a given band of frequencies, and a consequent requirement of more efficient use of the radio spectrum. A principal contribution toward meeting this requirement is the use of directional arrays which permit the maximum utilization of power output with minimum interference to other stations and services.

The principle of operation of the directional array will be explained by reference to Fig. 1. In Fig. 1, A_1 is a vertical antenna and A_2 is a similar vertical radiator which acts as a parasitic reflector spaced exactly one-quarter wavelength (90°) behind A_1. A_1 and A_2 are tuned to the same resonant frequency. A_1 is excited or driven by the transmitter through a coaxial transmission line.

As power is supplied to A_1 energy is radiated, which at a time period 90° later reaches A_2 and induces current in A_2 opposite in direction to the original current in A_1. Due to this induced current, energy is re-radiated from A_2. 90° later some of the energy radiated from A_2 reaches A_1. It will be seen that from the start of one alternation of current in A_1 to the completion of that alternation (180° later) radiated energy has reached from A_1 to A_2, been re-radiated and traveled back to A_1. The polarity of the field due to re-radiation is opposite in phase to that of the original field radiated from A_1. At the instant energy begins to reach A_1 from A_2 in opposite polarity to the original field radiated from A_1, the current from A_1 begins to reverse and A_1 again radiates energy but in opposite polarity to the original radiated field. Thus by the time the energy reaches A_1 from A_2 the two fields combine in like polarity and reinforce each other in the direction away from A_2, which in Fig. 1 is shown as "direction of radiation."

On the other hand, around reflector A_2 the re-radiated field is opposite in polarity and very nearly equal in amplitude to the field causing the induced current, so that these fields tend to cancel and the field is suppressed in the direction behind the reflector. Due to the time of transit of the field of the antenna to the reflector (90°) the induced current in A_2 lags the current in A_1 by 90° but since the current in A_2 is opposite in polarity to that in A_1, there is another 180° to be added to the above 90° angle, which finally results in the current in A_2 leading that in A_1 by 90°. Because of the losses in A_2 the re-radiated energy can never quite equal the intensity of the field causing the reflector current and complete backward suppression by this type of reflector can never be accomplished.

For zero radiation directly backward the current in the antenna and the reflector must be of equal amplitude, have exactly 90° difference in phase, and the spacing between A_1 and A_2 be exactly 90°. Of course, such a condition is impossible to obtain with a free reflector. For best addition of the wave amplitude in a forward direction the phase angle between currents should be equal to $2\pi S/\lambda$ where S is spacing. In practice, in order to have definite control of the current amplitude and phase in both antenna and reflector, it is customary to drive both A_1 and A_2 by transmission lines from the transmitter and to use phase-shifting networks by means of which the phase relation between the two currents can be accurately adjusted.

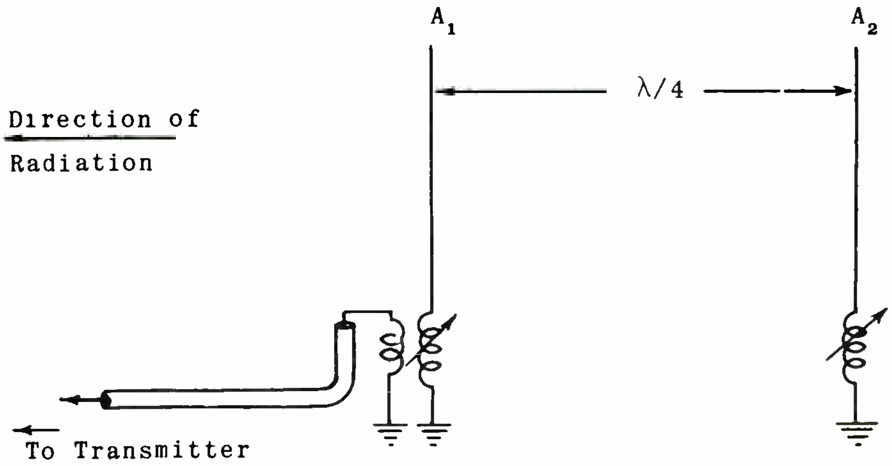


Fig. 1.—Two vertical antennas spaced one-quarter wavelength apart, with one parasitically excited by the other and acting as a reflector.

VARIOUS PATTERNS POSSIBLE FOR A TWO-ELEMENT ARRAY.—The condition of 90° spacing and 90° phase angle as shown in Fig. 1 is only one of an almost infinite number of combinations that can be used. The interference pattern resulting from two or more sources of waves, such as antennas, is dependent on the spacing between the radiating elements and the magnitudes and relative phases of the currents in the radiators. By proper selection of these three factors almost any type of radiation field strength pattern can be provided. Fig. 2(a) and (b), shows the field intensity pattern produced by two antennas spaced one-half wavelength apart and energized by currents of equal phase and equal amplitude. 2(a) shows the manner in which the fields interfere both in combination and in opposition to produce the figure 8 pattern in 2(b).

In Fig. 2(b) and Fig. 3(b) the ratio of the area of the outer circle to the area enclosed within the field intensity pattern expresses the GAIN RATIO of the directional antenna over a single non-directional antenna radiating the same amount of total power. It will be seen that the gain in 3(b) is approximately 2 to 1. This same method of showing the gain ratio will be used in other diagrams illustrating the patterns of directional antenna arrays.

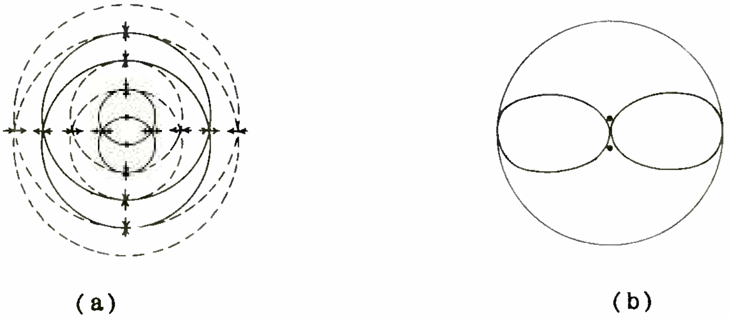
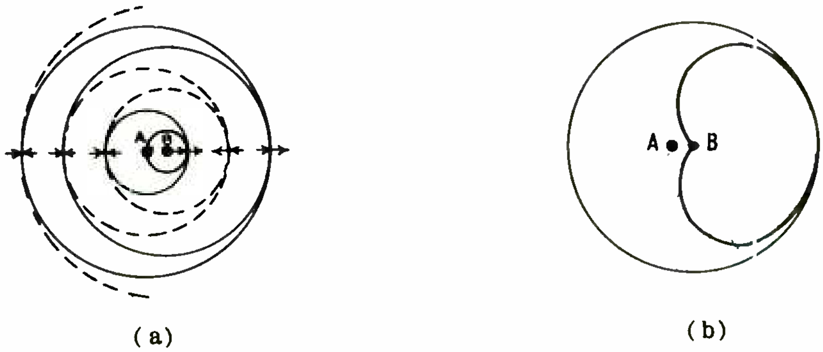

(a) (b)

Fig. 2.—Pattern produced by two antennas spaced one-half wavelength apart and energized by currents of equal phase and magnitude.

It is seen that the direction of maximum radiation of each lobe is perpendicular to the line connecting the two towers.

Fig. 3(a) and (b), shows the interference pattern and the corresponding radiation field intensity pattern for two radiators spaced 90° as in Fig. 1 and energized by currents of equal amplitude but 90° difference in phase. This is similar to the condition of Fig. 1 except that both antenna and reflector are energized directly from the transmitter and the two currents are made equal in amplitude.

An almost unlimited number of combinations of spacing, current amplitude and phase relation can be used to produce the various patterns that may be desired. In addition to this, other combinations involving more than two radiators can be employed. Fig. 4 shows a number of combinations of field intensity patterns which can be obtained by the use of a two-element array for various spacing of elements and phasing of currents of equal amplitude. For example, item b in this figure shows the pattern of Fig. 3 obtained with .25 λ spacing and 90° phase difference. Modifications of these patterns can be obtained for a given spacing by varying either the phase relation between currents or the amplitude relation between currents, or both. It should be noted in connection with Fig. 4 that the line connecting the two antennas is assumed in all cases to be horizontal.



(a)

(b)

Fig. 3.—Pattern produced by two antennas one-quarter wavelength apart and energized by currents of equal amplitudes but 90° apart in phase.

As a practical use or application of these patterns consider the problem previously discussed in which a 50 kw transmitter was assumed to be located to the eastward of a large metropolitan section along the Atlantic sea coast. It is desired in this case to have minimum radiation eastward but good signal intensity up and down the coast and westward into the metropolitan area. Consider the figure represented by a spacing of 3/8 λ and current phase relation of 1/8 λ or 45°. A pair of towers spaced 3/8 λ along a line east and west would produce a good signal up and down the coast and westward into the metropolitan area. If a small eastward lobe were desired with somewhat stronger westward radiation and slightly decreased radiation along the north and south line, the same spacing of 3/8 λ might be used with a current phase relation of 90°.

It will be seen that where a directional array is involved the engineer has all the problems as explained in the preceding assignment regarding the selection of the antenna location and the type of antenna, plus the selection of the proper field pattern to serve best the desired area with adequate attenuation of the signal in the direction that would cause interference with another station. It is suggested that the student take a large scale map of any city with which he is familiar, select a city several hundred miles away which must be protected by the use of a directional array, and then tentatively locate his transmitter on the large scale map and select a combination from Fig. 4 which will provide the proper protection and most efficiently serve his local area. The solution, of course, must include the spacing of the towers, the phase relation of the currents, and the orientation of the towers with regards to a north-south line.

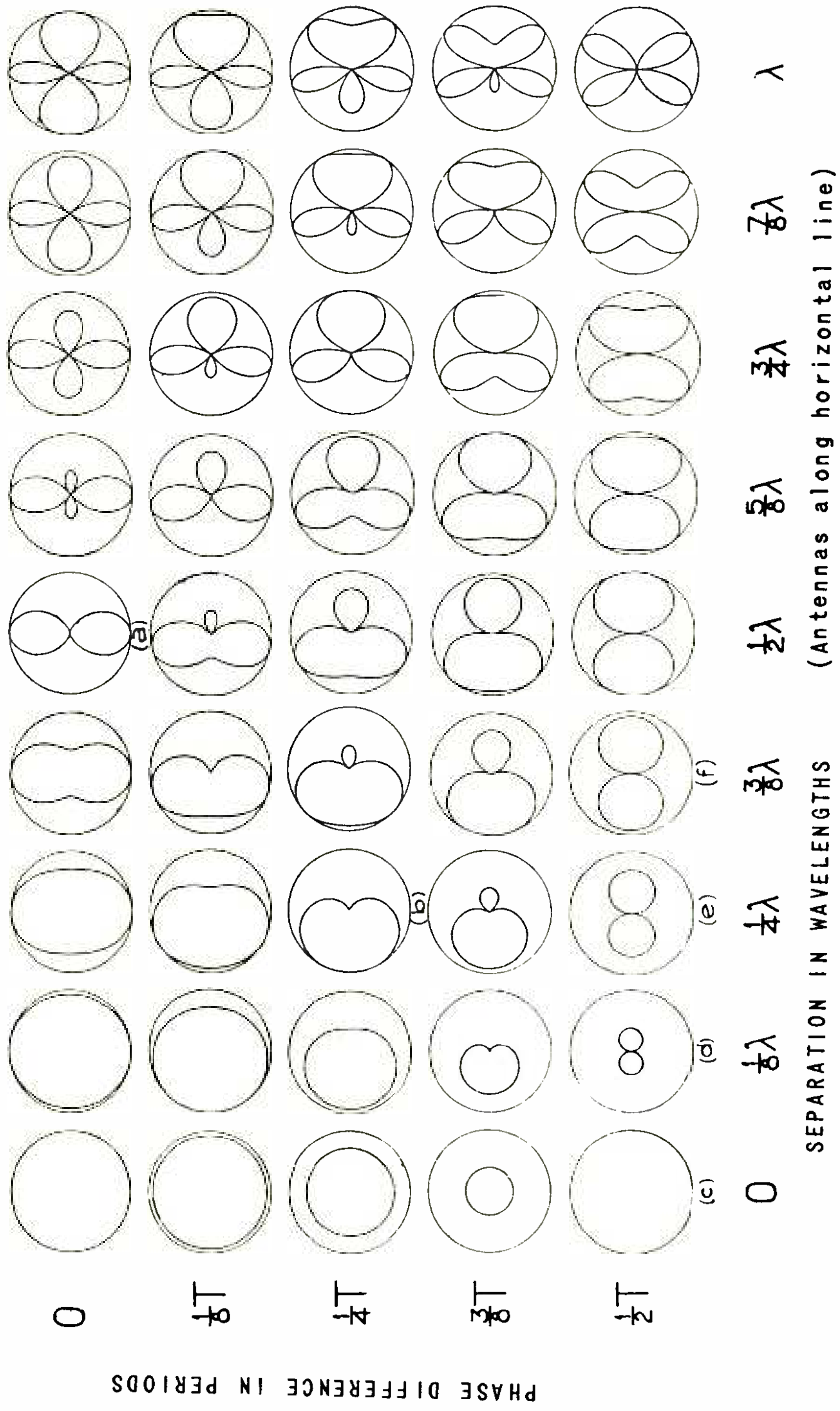


Fig. 4.—Directive amplitude diagrams for an array of two antennas.

TRANSMISSION LINES AND PHASE-SHIFTING NETWORKS

ILLUSTRATIVE EXAMPLE.—Consider an actual installation to operate at frequency of 1000 KC/s. Assume that the field intensity pattern desired is that of a two-element array with tower spacing of 3/8 λ, and the phasing such that the current in the reflector lags the current in the antenna by 45°.

A most simple and symmetrical arrangement is shown in Fig. 5. At each tower is a small house or box for the antenna coupling circuit. Exactly midway between the towers is a house for the phase shifting network and for coupling lines 2 and 3 to 1 from the transmitter. At 1000 KC/s the wavelength is 300 meters. Therefore the spacing of the towers at 3/8 λ = 112.5 meters = 369 feet.

Line 1 may be any desired length. Line 1 terminates in a coupling circuit by means of which lines 2 and 3 are coupled in parallel to line 1 with the proper impedance matching arrangement. Since lines 2 and 3 are identical in length and connected in an identical manner to line 1, the current in the antenna and reflector will be in phase. Now if an "artificial line" having an electrical length of +45° is added in series with line 3 to the reflector the current in the reflector will be caused to lag the current in the antenna by that many degrees and the desired phase shift will be accomplished.

The design of the phase shifting network is greatly simplified by the symmetrical arrangement of Fig. 5 in

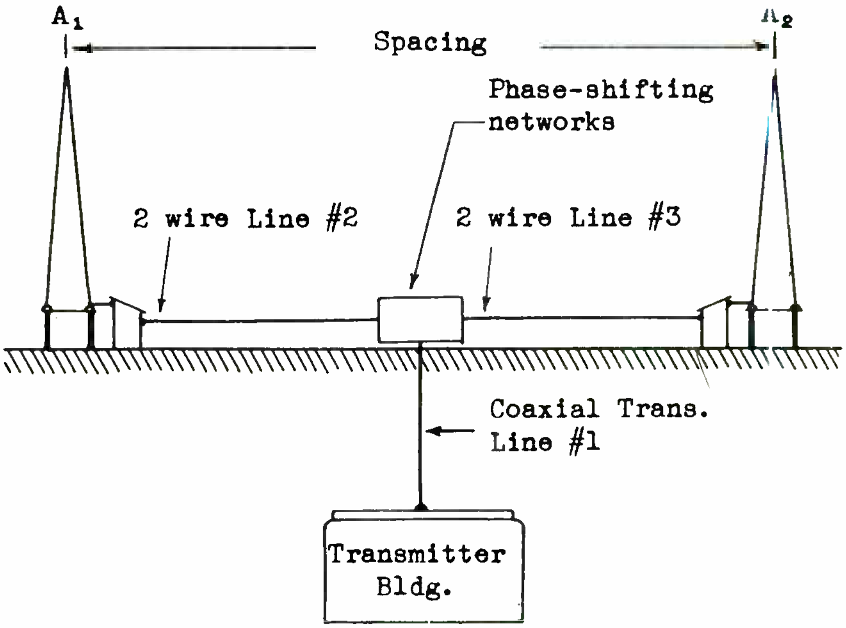
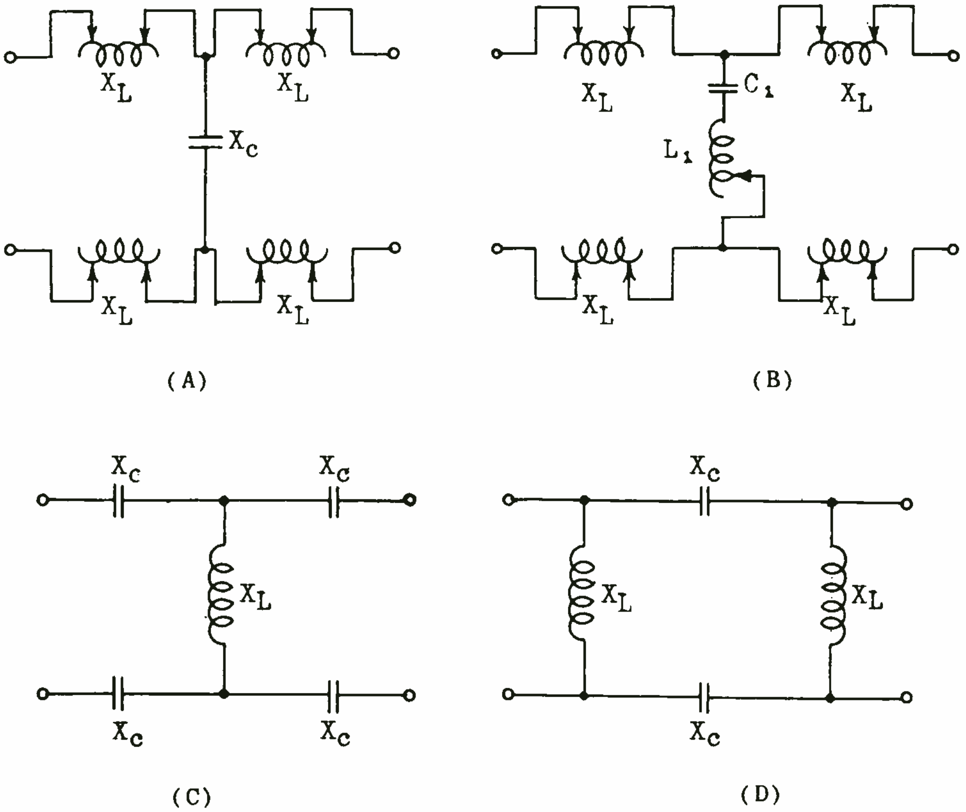


Fig. 5.—Actual installation of a two-element array.

which lines 2 and 3 are identical in length because then the velocity of propagation over the line itself does not have to be considered. The electrical length of a transmission line is a function of several factors. For a single wire overhead line the velocity of propagation is almost as great as through space, a correction factor of about .96 being used for broadcast frequencies. In the case of a two wire cable or a concentric line, due to the concentrated capacity the velocity of propagation is much slower and will vary with different types of cable. Thus if lines 2 and 3 are not of identical length the velocity correction factor for the particular type of line must be known in order to be able to calculate the electrical length of each line in degrees. When they are of identical length and connected in parallel to the driving circuit it is not necessary to know their actual electrical length.

It is assumed here that lines 2 and 3 are equal in length and that an additional electrical length of 45° is to be introduced into line 3. It is now necessary to consider the design and calculation for artificial lines.

ARTIFICIAL LINES.— An artificial line consists of lumped values of inductance and capacity and may be



(A) (B)

(C) (D)

Fig. 6.—Various types of artificial lines.

designed to **EITHER LENGTHEN OR SHORTEN** an existing line. Fig. 6(A) and (B) show circuits of artificial lines which add to the length of an existing line. Fig. 6, (C) and (D) illustrate circuits used in artificial lines which shorten the electrical length of an existing line. In (A) and (B) all values of X_L must be identical. Similarly in (C) all values of X_c must be identical and in (D) the two X_L's must be identical in value as are the X_c's.

Before starting the artificial line calculation it is necessary to know the characteristic impedance (Z_o) of the line which is to be artificially lengthened, the required length of artificial line in degrees (θ) and the operating frequency in KC/s.

Assume that the artificial line of Fig. 6(A) is to be used; that in Fig. 5 the two-wire lines used have Z_o of 400 ohms; and that the operating frequency is to be 1000 KC/s.

The equations for Fig. 6(A) are:

$$X_L = \frac{Z_o}{2} \tan \frac{\theta}{2}$$

$$X_c = \frac{-Z_o}{\sin \theta}$$

$$Z_o = 400 \text{ ohms}$$

$$\theta = 45^\circ$$

$$F = 1000 \text{ KC/s}$$

where θ is taken as positive. Then

$$X_L = \frac{400}{2} \tan \frac{45^\circ}{2} = 200 \tan 22.5^\circ$$

$$= 82.8 \text{ ohms}$$

$$L = \frac{X_L}{2\pi F} = \frac{82.8}{6.28 \times 10^6} = 13.2 \times 10^{-6}\text{H}$$

$$= 13.2 \ \mu\text{H}.$$

$$X_c = \frac{400}{\text{Sin } 45^\circ} = \frac{400}{.707} = 566 \text{ ohms}$$

$$C = \frac{1}{2\pi F X_c} = \frac{1}{6.28 \times 10^6 \times 566} = 282 \ \mu\mu\text{F}.$$

Thus an artificial line as shown in Fig. 6(A) made up of four series inductance elements of 13.2 μH each and a shunt capacity of 282 μμF is the equivalent of a two-wire cable having a characteristic impedance of 400 ohms and a length of 45° at 1000 KC/s.

Assume that it is desired to use the circuit of Fig. 6(B) with fixed capacity C_1 of .00025 μF. To calculate L_1. Each value of X_L will be 13.2 μH as calculated for Fig. 6(A). The effective reactance of the shunt arm must be 566 ohms and capacitive. C_1 is fixed at .00025μF.

$$X_{c1} = \frac{1}{2\pi FC} = \frac{1}{6.28 \times 10^6 \times 2.5 \times 10^{-10}}$$

$$= 636 \text{ ohms}$$

But

$$X_c = X_{c1} - X_{L1} = 566 \text{ ohms}$$

and

$$X_{L1} = X_{c1} - X_c = 636 - 566 = 70 \text{ ohms}$$

$$L_1 = \frac{X_L}{2\pi F} = \frac{70}{6.28 \times 10^6} = 11.16 \ \mu\text{H}$$

In other words, at a frequency of 1000 KC/s the shunt arm of Fig. 6(B), consisting of C_1 = .00025 μF and L_1 = 11.16 μH in series, offers exactly the same capacitive reactance as does the shunt arm in Fig. 6(A) which consists of a single larger capacitor.

This method of varying the effective capacity of a circuit by means of a fixed capacitor and variable inductance in series is very convenient where the frequency range and the required capacity change are limited. At a given frequency as the inductance is increased the effective capacity is decreased and vice-versa.

However, this method will be useful only under certain conditions. The size of capacitor chosen must be smaller than that normally required to give the capacitive reactance indicated. But if it be chosen too small then the required inductance will be unduly and unnecessarily large. Furthermore, the current flow will be the same as for the proper size, larger capacitor used alone.

But such a current flowing through the actual smaller capacitor will set up a higher voltage across it. Of course this voltage is cancelled in part by the coil (incipient resonance phenomena) so that the overall voltage is the same as that for a capacitor alone, but the fact that there is a higher voltage across the actual capacitor means that the voltage rating of this unit will have to be higher, and the losses will be greater. In addition, there will be losses in the coil. As a consequence, this method is only employed to permit the use of a smaller standard size capacitor and to afford a more convenient and practical means of adjusting the shunt reactance.

There are occasionally installations where it is impractical to make the lines feeding the two towers from the junction box the same length, or where three or more towers may be used to get a distinctive pattern and it is not practical to place the junction box equi-distant from all of the towers. In such cases the desired phase relation may be such that one or more of the lines must be shortened in electrical length. In that case an artificial line similar to the one in Fig. 6(C) or (D) may be used. The necessary calculations for X_L and X_c for these two circuits are shown below.

For Fig. 6(C).

$$X_c = \frac{Z_o}{2} \tan \frac{\theta}{2}$$

$$X_L = \frac{-Z_o}{\sin \theta}$$

For Fig. 6(D).

$$X_c = \frac{Z_o}{2} \tan \theta$$

$$X_L = \frac{-Z_o}{\sin \frac{\theta}{2}}$$

where, for either figure, θ is taken as negative.

It should be noted that these equations are identical to those for Fig. 6(A) except that the series and shunt reactances are changed from L to C and from C to L respectively.

The only difference in the arrangement of Fig. 6(C) and (D) is that in (D) the capacity of the single capacitor X_c is less than that of each capacitor in (C) because the single capacitor replaces the other two in series. On the other hand, each inductance in (D) is larger than the single inductance in (C) because in (D) the two inductances are in parallel across the line. The desired capacitive reactance of each capacitor in (D) may be obtained by the use of a fixed capacitor with a variable inductance in series as explained for (B).

A somewhat lower loss circuit will be obtained if instead variable capacitors are used, because the losses in the series capacitor will be considerably less than in series inductance. The fact that the negative artificial line is inherently lower loss than the positive artificial line is one reason why a line arrangement in which negative artificial lines are used should tend to be somewhat more stable than one employing positive lines. However, in practice the difference is very small.

Fig. 7 shows a possible arrangement of the coupling equipment and phase shifting network at the point where the three lines are coupled together. Line 1 is a conventional concentric line which is terminated

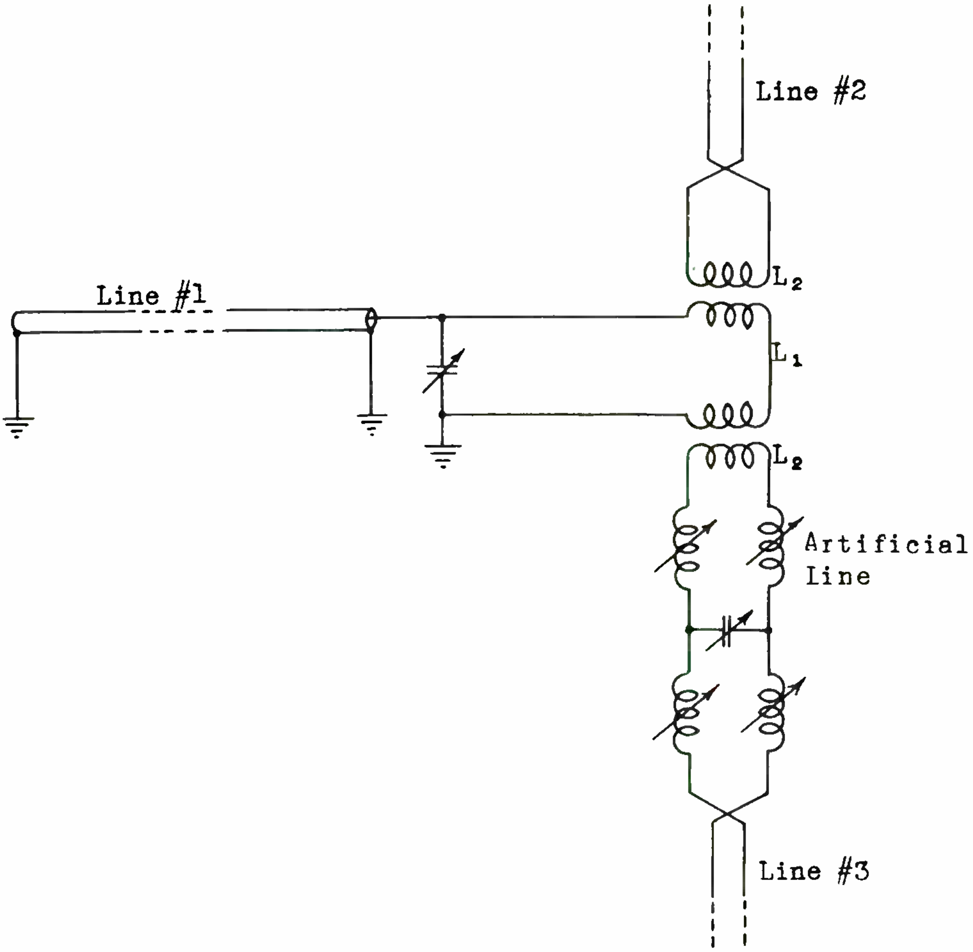


Fig. 7.—Arrangement of coupling equipment and phase-shifting network at a point where three lines are coupled together.

in a tuned circuit. Coupling between L_1 and L_2 is made such that line 1 is terminated by a pure resistance equal to the characteristic impedance of line 1. The two two-wire lines are connected in parallel across L_2 and the artificial line inserted in series with line 3. Lines 2 and 3 in this case are assumed to be ordinary rubber covered two-wire cables which may be run through shielding conduit or under ground. The reason for the use of a two-wire line in which neither side is grounded is to allow the use of a symmetrical artificial line. If it is desired to use 2 and 3 in the form of concentric lines in which the outer conductor is grounded, it will be necessary to use a T-type artificial line. The only change which need be made in that case is to ground the variable plates of the shunt capacitor and combine the two inductances on each side of the capacitor into a single inductance having twice the reactance as calculated for Fig. 6(A). This arrangement would be preferable for use with a transmitter having a power output capacity beyond that which could be safely carried by duplex high voltage cable.

SIMPLE PHASE MEASUREMENTS.—It must not be understood that the adjustments of the artificial line from calculations as shown above are exact. All curves, calculations, correction factors, etc. as used in antenna transmission line work simply allow approximate adjustments to be made. This applies, of course, to design and adjustments of all radio frequency circuits. Also there is a tendency in all circuits of this type to be somewhat unstable with regard to current, phase and amplitude under adverse atmospheric conditions, snow and ice on the towers, etc., which tend to detune the antennas.

In the case of a directional antenna array the problem is further complicated by the coupling (mutual reactance) between the towers. For example, if Tower 2 were not excited directly from the antenna it would still have a fairly large current flow due to its being cut by the field of Tower 1. Tower 1 likewise is energized by the radiation field of Tower 2. Additional complication is introduced by the fact that the spacing of the towers in degrees may be different from the phase difference between the antenna currents in degrees.

The mutual coupling between towers affects both the amplitude and phase of both currents and hence requires adjustments of both phase and amplitude which must be made during operating conditions. Therefore, it is essential that actual measurement be made of the phase angle between the currents in the two towers. For this purpose a radio frequency phase meter can be obtained and will be described later. At this point a simple method of measuring and calculating the phase angle between the currents will be described.

First select a location several hundred feet away and EQUI-DISTANT from the two radiators for a measuring point. (In the case of a symmetrical transmitter and antenna arrangement as shown in Fig. 5 the measuring point could be at the transmitter building itself). At the measuring point erect some sort of pickup device which in the case of Fig. 5 could be a receiving antenna connected from the top of the building to ground. Provide means for tuning this circuit to the resonant frequency of the antenna and connect in series to ground an r-f milliammeter; (0 - 125 mils is satisfactory). Next terminate the transmission line of tower A_2 (transmission line number 3) with a resistance equal to the line impedance and disconnect tower A_2 from the circuit. Adjust the transmitter to low power. When power is now applied only antenna A_1 is energized. Energize antenna A_1 and tune the pickup circuit to maximum current in the milliammeter. (As a precaution a shunt should be used with the r-f milliammeter until it is determined that the current is not excessive.) Carefully note the current reading of the milliammeter. Call this current reading A.

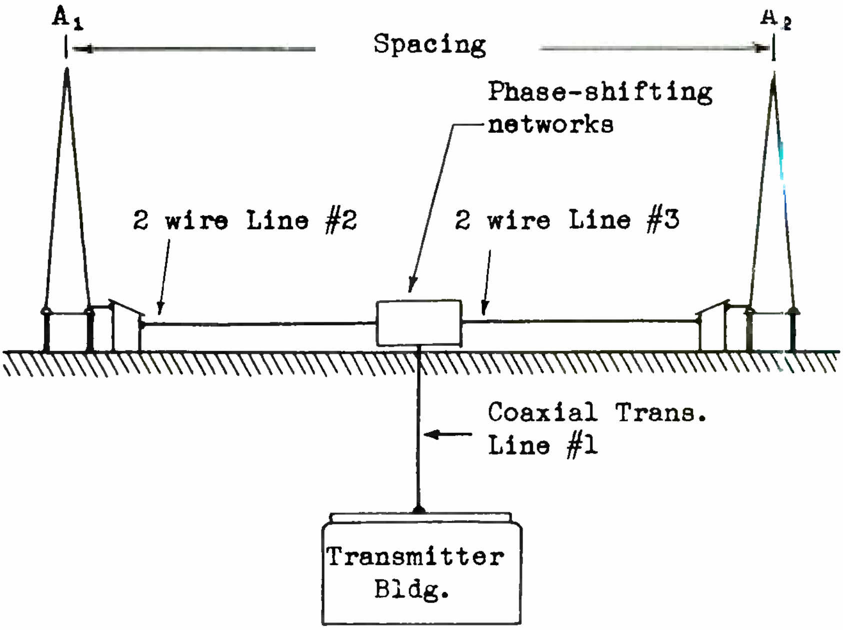


Fig. 5.—Actual installation of a two-element array.

Remove the load resistance from line 3 and connect this line back to antenna A_2 as for normal operation. Disconnect antenna A_1 and terminate transmission line 2 with the resistor previously used on line 3. Energize antenna A_2 keeping the power output exactly as for the preceding measurement and again carefully note the current reading of the milliammeter. Call this reading R.

Next energize both antennas A_1 and A_2; observe and carefully note the current reading of the milliammeter. Call this current reading C.

Draw a triangle to scale using the sides A, R, and C as shown in Fig. 8. The phase relation between the currents of towers A_1 and A_2 is equal to 180° minus the angle ϕ. In other words $\theta = 180^\circ - \phi$. Since the measuring point is equi-distant from radiators A_1 and A_2 and since the currents in the two towers, when properly adjusted, are equal, then if I_{A1} and I_{A2} are 180° out of phase the two radiation fields at the measuring point must be equal in amplitude and opposite in phase and under that condition C = 0. If I_{A1} and I_{A2} are exactly in phase then C = A + R. In that event the angle as shown in Fig. 8 would increase to 180°.

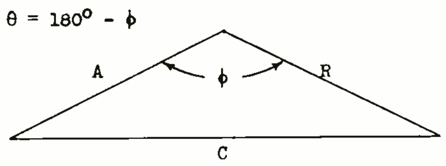


Fig. 8.—Vector diagram of antenna currents.

It is evident that for this measurement to be correct the current in the two towers must be identical. In some types of broadcast antenna arrays the desired field pattern is obtained with unequal currents in the two radiators. In that case it would be necessary, if this method of measurement were to be employed, to adjust the currents to equality in the two towers in order to make the phase measurement. This may be done by adding resistance in the antenna circuit normally having the larger current to reduce that current to equality with that of the lower current circuit. IT PARTICULARLY MUST BE EMPHASIZED THAT THE CURRENT IN THE TOWER MUST NOT BE REDUCED BY DETUNING THE ANTENNA CIRCUIT OF THAT TOWER AS THAT IN ITSELF WOULD CHANGE THE PHASE OF THE CURRENT IN THAT RADIATOR. Thus the two precautions to be observed are:

1. Be sure that the pickup and measuring point is exactly equidistant from both radiators.
2. Be sure that the radiation fields of the radiators are identical.

THE RADIO-FREQUENCY PHASE METER.—As pointed out earlier in this assignment it is very desirable that the station on which a directional array is used have means for frequently checking the phase relation of the currents in the two or more radiators. Typical of such equipment is the RCA Type 300-A radio-frequency phase meter as shown in Fig. 9. This instrument is capable of measuring all phase angles from 0 to 360 degrees at any frequency between 200 and 1600 KC/s. It also can be used for directly measuring the phase angle of an artificial line and for other purposes.

The arrangement of the apparatus in the phase meter is as shown in Fig. 10. It consists essentially of two resistance-coupled radio frequency amplifiers which feed the two sets of deflection plates of a cathode ray tube as shown in the diagram. One of the amplifiers contains a calibrated phase-shifting network which may be adjusted to secure an indication of in-phase condition on the oscilloscope screen. The amount of phase shift introduced by this device is then equal to the phase difference between the two in-phase signals and is read directly from the dial scale. In this operation the phase meter utilizes the ability of a cathode ray tube to indicate with considerable accuracy the condition of two voltages being directly in phase or 180° out of phase. Either of these conditions results in a straight line pattern on the oscilloscope screen while other phase relations produce an elliptical pattern.


Fig. 9.—RCA Type 300 Radio Frequency Phase Meter.

The phase meter is installed as shown in Fig. 11. To measure the phase relation in a directional array the antenna currents are "sampled" by means of small pickup coils and small amounts of energy are sent through concentric transmission lines to a central point where the phase meter is located. If the concentric lines all have equal length no correction need be made for time delay occurring in the line. However, when the line lengths are unequal the time delay or phase

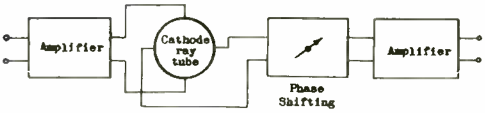


Fig. 10.—Arrangement of the apparatus in the phase meter.

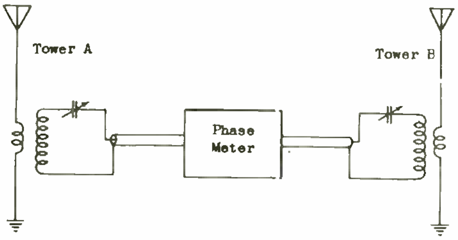


Fig. 11.—Method of connecting the phase meter.

shift of the line becomes an important factor and must be measured and taken into consideration in the interpretation of the readings obtained. In a two-element array as shown in Fig. 5 where all dimensions are symmetrical the phase meter could be located in the transmitter building and lines of equal length run to the two towers for the sampling voltages.

In view of the fact that the adjustment of the phase meter to determine the phase angle is concerned only with getting a straight line indication on the cathode ray tube, it is apparent that the currents in the two antennas do not have to be identical as for the other method of measuring the phase angle previously discussed. Also the amplitude of the picked up voltage, which is a function of the antenna current, does not have to be uniform so that the actual measurement can be made during operating conditions with or without modulation.

Fig. 12 illustrates the manner in which the phase meter can be used to measure the time delay introduced by a T type artificial line. One amplifier of the phase meter is connected across the input of the artificial line and the other phase meter amplifier is connected across the output of the artificial line. Energy is supplied at the operating frequency and the phase delay of this device is measured directly by the meter.

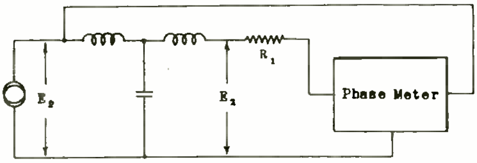


Fig. 12.—Measuring the phase delay for a T type artificial line.

The input impedance of this particular phase meter is approximately 80 ohms to match low impedance cables. Where the phase meter is to be used as in Fig. 12, and where the circuit under measurement is designed for insertion in a higher impedance line, then resistance R_1 should be inserted between the output of the artificial line and the phase meter so that the total resistance of R_1 plus the phase meter input resistance across the output of the artificial line is equal to the impedance into which the artificial line is to operate. It is assumed in Fig. 12 that the input to the artificial line is its normal source of energy and hence no further impedance matching device is required.

The Western Electric Company has developed a Type 2-A phase monitor which serves the same purpose as the instrument previously described and which further has means for indicating the relative amplitude of the currents in the two or more antennas. This instrument is shown in Fig. 13. In Fig. 14 is shown the block schematic diagram of the method by which the phase difference and relative amplitudes of the currents are measured.

The combined system consists of the measuring apparatus as shown in Fig. 13 connected to a sampling loop on each tower by coaxial transmission lines as shown in Fig. 14. The sampling loops consist of a single turn loop which is fastened to each antenna at a point sufficiently high above the ground to insure an accurate sample of the current flowing in the antenna. The dimensions of the loop as well as its points of attachment must be identical for both antennas. The top of the loop is directly connected to the antenna while the bottom is insulated and is connected to the center conductor of a coaxial line leading to the measuring equipment. The two transmission lines are made to have identical overall characteristics; that is, equal characteristic impedance and equal length.

At the measuring equipment the lines are connected to radio-frequency milliammeters (M_1 and M_2 in Fig. 14) which indicate the magnitude of the two currents supplied to the input of a vacuum tube voltmeter. Between milliammeter M_2 and the voltmeter on one of the lines is a phase-shifting network which permits the phase of the current in that circuit to be shifted until it is the same as that supplied by the other line.

The circuit is so arranged that when this condition is reached the vacuum tube voltmeter will give a minimum reading and the amount of phase shift required to bring the two currents into phase is indicated by the dial controlling the phase-shifting network. Since the magnitude and phase of the currents required to give the desired field distribution pattern are known, it is only necessary to adjust the line branching and phase-shifting networks in the main lines to the antenna until those known values are indicated on the measuring equipment.

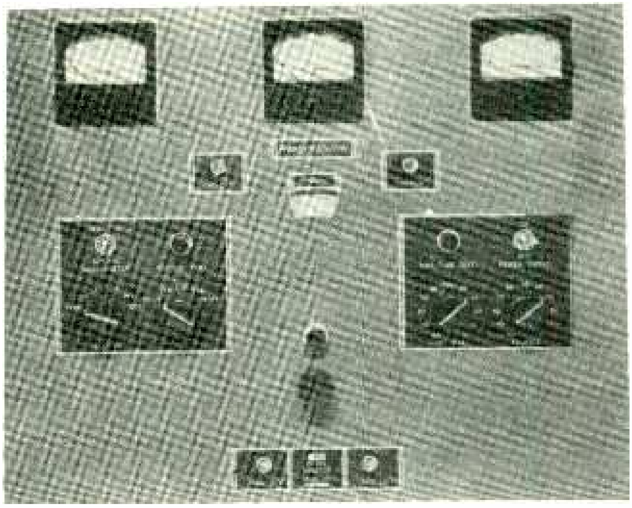


Fig. 13.—Western Electric Type 2-A phase monitor.

When the desired relative amplitude of the currents has been obtained together with the proper phase relation between the currents, which can be done of course at low power, the transmitter output can be brought up to the proper value. Field strength measurements are then made as previously explained to assure that the field pattern conforms to that specified by the construction permit.

combinations of pairs of towers. Three possible combinations, of course, can be obtained.

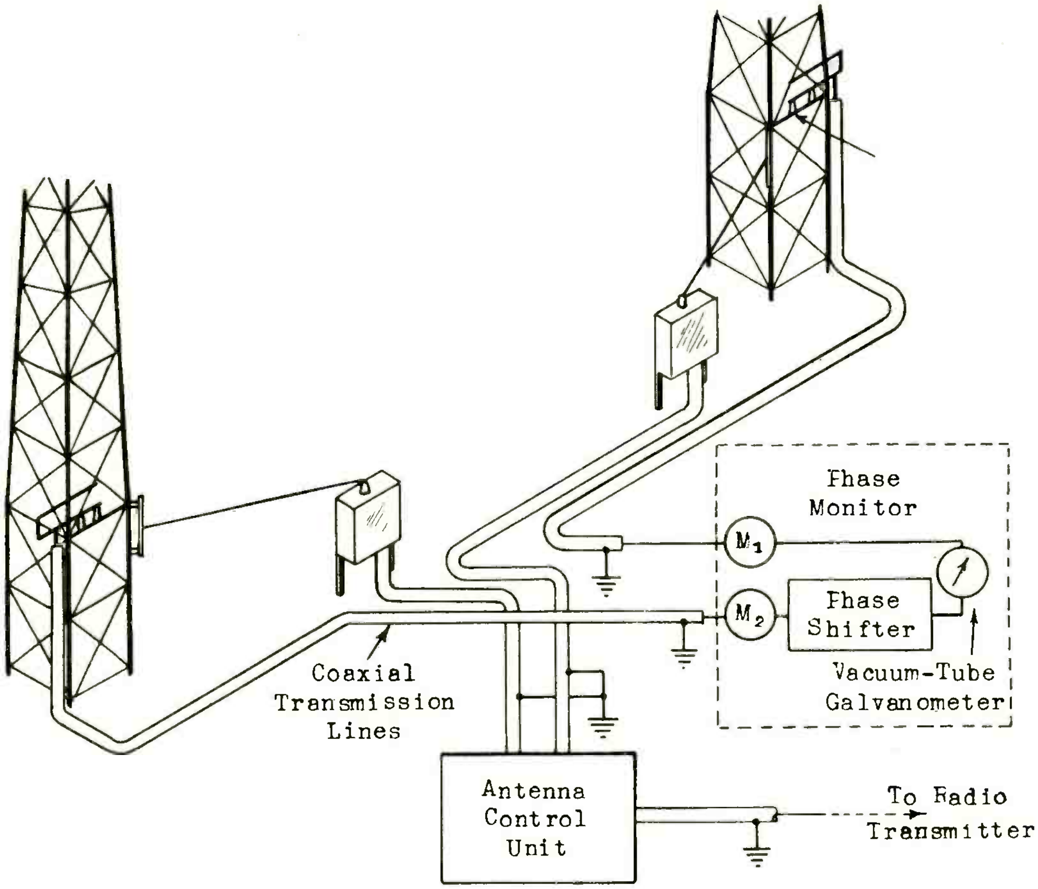


Fig. 14.—Setup employing phase monitor for measuring phase difference and relative amplitudes of the antenna currents.

Normally this phase monitor will be installed permanently as a part of the station equipment so that the station routine measurements should include a check of the current phase and relative amplitude. The equipment includes connections and switching for three incoming coaxial lines so that in a three tower array the procedure would be to check the relation between the

DESIGN OF DIRECTIONAL ANTENNA

PRELIMINARY CONSIDERATIONS.— The installation of a directional broadcast antenna is a somewhat involved problem:

1). It is necessary to select the site for the antenna as explained in the preceding assignment.

2). The approximate field

strength pattern required must be selected with relation to the primary area to be served and the service areas of other stations which are to be protected.

3). Before a construction permit will be granted by the Federal Communications Commission, the station must submit the complete design of the array to be installed and calculated performance data prepared by a properly qualified engineer; the data must include the formulas and mathematical calculations.

4). After the antenna array is installed it must be adjusted according to calculated requirements of Item 3.

5). Complete field strength measurements must be made along sufficient radials (at least eight) to clearly show the directional pattern and these data correlated as previously explained to show the antenna performance in terms of field intensity at one mile and the RMS field at one mile.

6). Further adjustments undoubtedly will be required to coordinate the measured data with the predicted performance upon the basis of which the construction permit was granted.

This appears to be, and usually is, a lengthy procedure. Unfortunately the best of practical antenna design calculations cannot predict accurately the many factors which will influence the actual performance of an antenna. Ground conductivity ordinarily is not uniform in all directions around the array; there will be greater absorption in one direction than in another; etc. Thus the sixth item above is often the most troublesome and in some installations will require several weeks of adjustments and many groups of measurements to make the results obtained coincide with the desired calculated performance. This job can be done satisfactorily only by experienced engineers with adequate equipment.

CALCULATION OF ARRAY PERFORMANCE.—In order to discuss mathematically the performance of a directional antenna, it is necessary to understand the electrical relation between the several elements of the array. There are several methods of calculating the field intensity at any point from a given radiating system, some of the methods being quite involved. The most direct approach is through the mutual impedance between the elements of the array. In this method it is customary to employ curves plotted from calculated data.

For the purpose of this discussion refer to curves in Figs. 15 and 16 which have been prepared from data taken from curves by G. H. Brown. Fig. 15 shows the magnitude of the mutual impedance between identical vertical antennas, calculated for three antenna heights. Just as the mutual inductance of two coils coupled together is a function of the coil dimensions and spacing, so is the mutual impedance of two antennas a function of their dimensions and the distance between them.

With quite closely coupled coils the coupling, due to the lumped inductance, is mostly inductive although in some cases the capacitive coupling may be sufficient to become troublesome. In the case of two antennas, the radiation field reaching each from the other is made up of equal components of electric and magnetic energy; also due to the time required for the field to

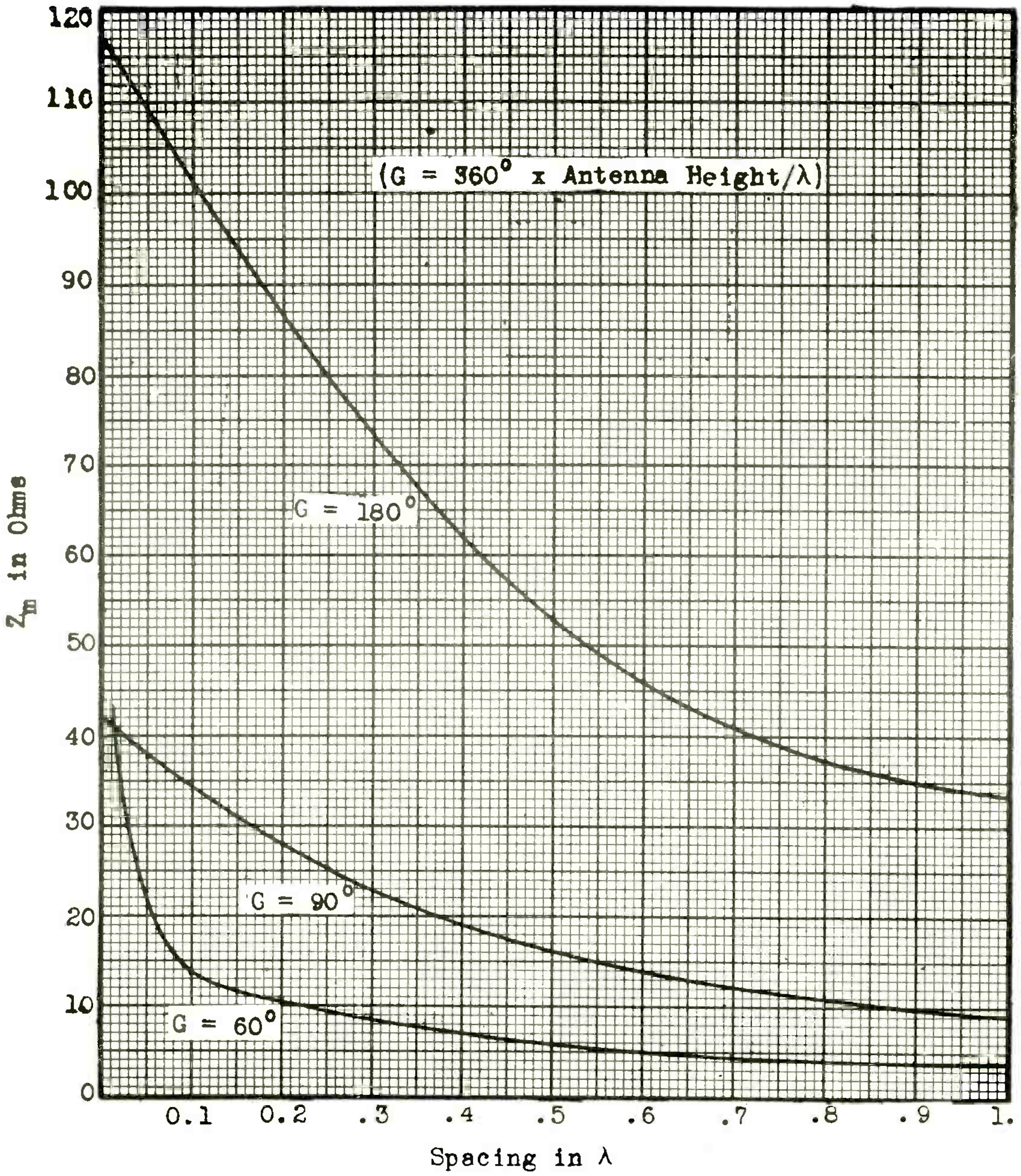


Fig. 15.—Mutual impedance between identical vertical antennas, for three heights.

proceed from one antenna to the other, the induced voltage may differ by any phase angle from the inducing voltage, depending upon the distance in wavelengths and to some extent upon the height of the antennas. This is shown in Fig. 16.

For example, from Fig. 15 it is found that if two .25 λ (90°) antennas are spaced .25 λ (90°), their mutual impedance will be 25 ohms. From Fig. 16, it is found that under this condition the phase angle of Z_m is -32°. In the study of coupled circuits it has been shown that when two tuned circuits are coupled together the effective resistance and reactance of both are changed. Further, if the two circuits are individually driven and if the two circuit currents are subject to external phase control, the resultant field around the two circuit coupling coils and the resultant circuit resistances will be quite complex.

Such is the condition when two vertical antennas are coupled together in a typical directional array. By the spacing of the radiators and by adjustments of the relative phase and amplitudes of the two currents, a complex resultant radiation field is developed which produces the desired field strength pattern.

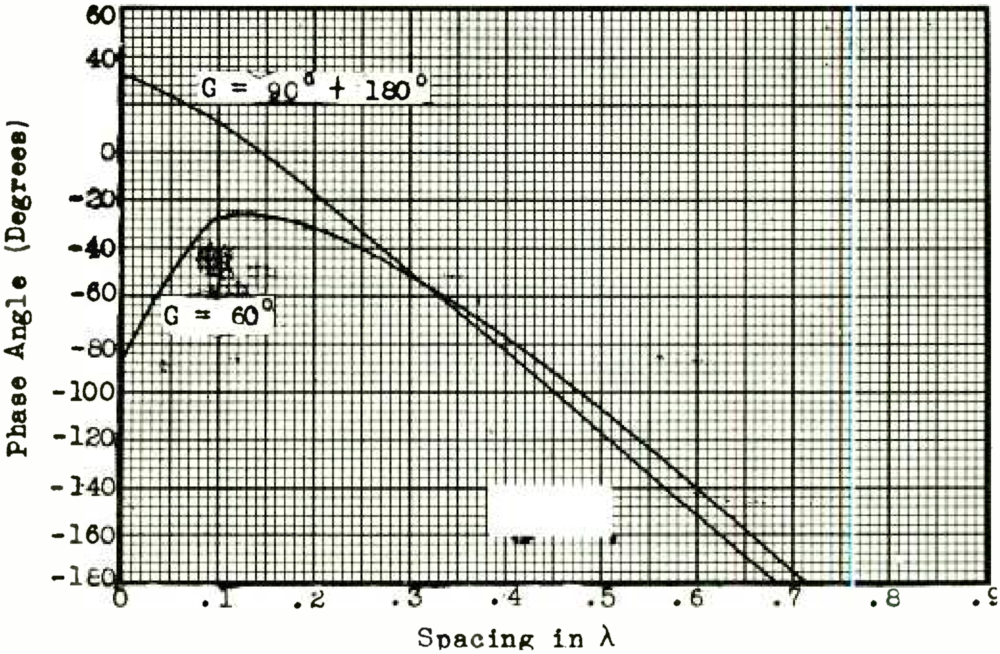


Fig. 16.—Phase angle of voltage induced in one antenna by another, spaced from it as shown.

There are a number of methods of calculating the performance of the directional array, all of which produce similar results. The calculation procedure to be used in the following typical design problems is straight-forward and not too involved. Consider a typical problem.

Assume that for a given installation it is determined that pattern (b) from Fig. 4, when properly oriented with respect to the desired service area and the other station to be protected, is the most desirable. This pattern is produced with 90° spacing of towers (S = 90°) and with a 90° phase lead of current in the rear tower. It is decided to use .25 λ (90°) radiators. The arrangement is shown schematically in Fig. 17. The currents in A_1 and A_2 are equal and the current in A_2 leads the current in A_1 by 90°.

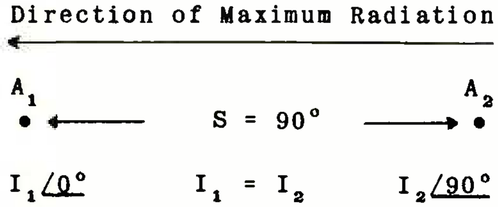


Fig. 17.—Two towers spaced by 90° and excited by equal currents in quadrature.

The radiation resistance R_a of a .25 λ antenna can be shown to be 36.6 ohms (ideal conditions). This would be the resistance if a single antenna were used. With two antennas in an array the resistance of both will be changed by the effect of the resistance component of mutual impedance Z_m.

From Fig. 15, Z_m for two 90° antennas spaced .25 λ is 25 ohms. From Fig. 16, the phase angle (θ_m) of Z_m for the conditions specified is -32°. Thus

$$Z_m = 25 \qquad \theta_m = -32°$$

M = ratio I_2/I_1. In this example M = 1.

$$R_1 = R_a + MZ_m \text{Cos}(S + \theta_m)$$

$$= 36.6 + 25 \text{ Cos}(90° - 32°)$$

$$= 36.6 + 25 \text{ Cos } 58° = 36.6 + 13.2$$

$$= 49.8 \text{ ohms.}$$

$$R_2 = R_a + \frac{Z_m}{M} \text{Cos } (-S + \theta_m) \qquad M = 1$$

$$= 36.6 + 25 \text{ Cos } (-90° - 32°)$$

$$= 36.6 + 25 \text{ Cos } (-122°)$$

$$= 36.6 - 13.2 = 23.4 \text{ ohms.}$$

Considering the array on the basis of coupled circuits, a figure which may be called the "Gain" of the array is determined.

$$\text{Gain} = \sqrt{\frac{R_a}{R_1 + MR_2}}$$

(In this case M = 1)

$$\text{Gain} = \sqrt{\frac{36.6}{49.8 + 23.4}} = .7$$

$$E = e \times \text{Gain} \times \overline{f(\phi) \sqrt{(1)^2+(M)^2+2M\text{Cos}(S\text{Cos}\phi\text{Cos}\theta+\theta_a)}}$$

e = field intensity at one mile from a single radiator.

E = field intensity at one mile at any specified vertical and horizontal angle.

Gain = .7

(As calculated above for this particular case).

ϕ = vertical angle of elevation with respect to ground.

θ = horizontal angle with respect to line of towers.

θ_a = Phase angle of I_2 with respect to I_1. (In this case 90° lead).

M = ratio I_2/I_1. (In this case 1)

$$f(\phi) = \frac{\text{Cos } (90° \text{ Sin } \phi)}{\text{Cos } \phi}$$

S = Spacing of towers in degrees. (In this case 90°).

Where only the horizontal pattern at ground is required, the formula is simplified by the removal of the vertical components and becomes,

$$E = e \times \text{Gain}\ \sqrt{(1)^2 + (M)^2 + 2M \operatorname{Cos}(S \operatorname{Cos}\theta + \theta_a)}$$

which in this problem reduces to

$$E = .7e\sqrt{2 + 2 \operatorname{Cos}(90^\circ \operatorname{Cos}\theta + 90^\circ)}$$

Assume that measurements and experience indicate that the field intensity at one mile from a single radiator installed in the selected location should be 200 MV/meter. Then,

$$e = 200 \qquad \text{Gain} = .7$$

and

$$E = 140\sqrt{2 + 2 \operatorname{Cos}(90^\circ \operatorname{Cos}\theta + 90^\circ)}$$

The calculations are made and tabulated as shown in Table 1. The mean value of G^2 (column H, Table 1) becomes:

$$(G^2)_{ave} = 508{,}693 \div 13 = 39{,}130$$

$$G_{RMS} = \sqrt{39{,}130} = 197$$

The resulting horizontal pattern is shown in Fig. 18. It is seen that directly back of the array along the line of towers (0°) the radiation is practically entirely suppressed. (Actually of course, while calculations indicate complete suppression, due to conditions which in practice cannot be made ideal, total backward suppression is not obtained). At angles between 0° and 90° and 0° and 270°, the radiated field is reduced considerable over that to be expected from a single radiator. At all angles between 90° and 270°, the field strength exceeds that from a single radiator with maximum intensity at 180°. For all practical purposes the range of maximum signal intensity may be considered constant with this type of pattern from 140° to 220°.

Calculation shows that the signal voltage gain in the direction of maximum signal is 280/197 = 1.41. Since the power required to produce any increase in signal voltage is a function of E^2, $(P = E^2/R)$, the gain in the direction of maximum signal is equivalent to doubling the transmitter power output in that direction. $(1.41^2 = 2)$. Thus by properly selecting the transmitter site and properly orienting the array, the interfering signal in that direction of the station to be protected can be made negligible and the signal in the area which it is most desired to cover can be increased by the equivalent of doubling the transmitter power.

It has been shown that the vertical angle of radiation is important. In broadcasting it is desirable to increase the radiation at low angles and to reduce high angle radiation so as to increase the distance from the transmitter at which serious fading begins. The vertical field pattern is calculated as follows:

$$E = e \times \text{Gain} \times f(\phi) \times \sqrt{(1)^2 + M^2 + 2M \operatorname{Cos}(S \operatorname{Cos}\theta \operatorname{Cos}\phi + \theta_a)}$$

In this example the equation becomes,

$$E = 140 \times f(\phi) \times$$

$$\sqrt{2 + 2 \text{ Cos } (90^\circ \text{ Cos } \theta \text{ Cos } \phi + 90^\circ)}$$

where θ = horizontal angle with respect to line of towers.

ϕ = vertical angle with respect to ground.

$$f(\phi) = \frac{\text{Cos } (90^\circ \text{ Sin } \phi)}{\text{Cos } \phi}$$

The calculation for the vertical pattern may be made along any horizontal angle. With this type of array the particular interest will be in the vertical pattern along the line of maximum signal, in this case 180°. For that horizontal angle,

$$90^\circ \text{ Cos } \theta = -90^\circ$$

The equation becomes,

$$E = \frac{140 \times f(\phi)}{\sqrt{2 + 2 \text{ Cos } (-90^\circ \text{ Cos } \phi + 90^\circ)}}$$

The vertical pattern plotted from the figures in column 1 is shown on Fig. 18, the third set of angles on the graph applying to the vertical pattern. The dashed curve corresponds to the vertical pattern which would be produced with the same amount of power radiated from a single .25 λ antenna. It should be noted that in the horizontal direction of maximum signal there is some

TABLE I

A	B	C	D	E	F	G	H
θ	$90^\circ \text{Cos}\theta$	B + 90°	2 Cos C	2 + D	$\sqrt{E}$	$140\ \sqrt{E}$	G^2
0	90°	180°	-2	0.	0	0	0
15	87°	177°	-1.998	0.002	0.04	5.6	31
30	78°	168°	-1.956	0.004	0.209	29.2	853
45	63.6°	153.6°	-1.791	0.209	0.45	63.	3969
60	45°	135°	-1.41	0.59	0.77	107.8	11620
75	23.3°	113.3°	- .792	1.208	1.09	152.6	23290
90	0°	90°	0	2	1.41	197.4	38960
105	-23.3°	66.7°	.792	2.792	1.67	233.8	54660
120	-45°	45°	1.41	3.41	1.84	257.6	66360
135	-63.6°	26.4°	1.792	3.792	1.95	273.	74530
150	-78°	12°	1.956	3.956	1.99	278.6	77620
165	-87°	3°	1.998	3.998	2.	280.	78400
180	-90°	0	2	4	2	280	78400
							508693

2.00
2
1.846
1.38
.147
1.11
1.0526
200
1.38

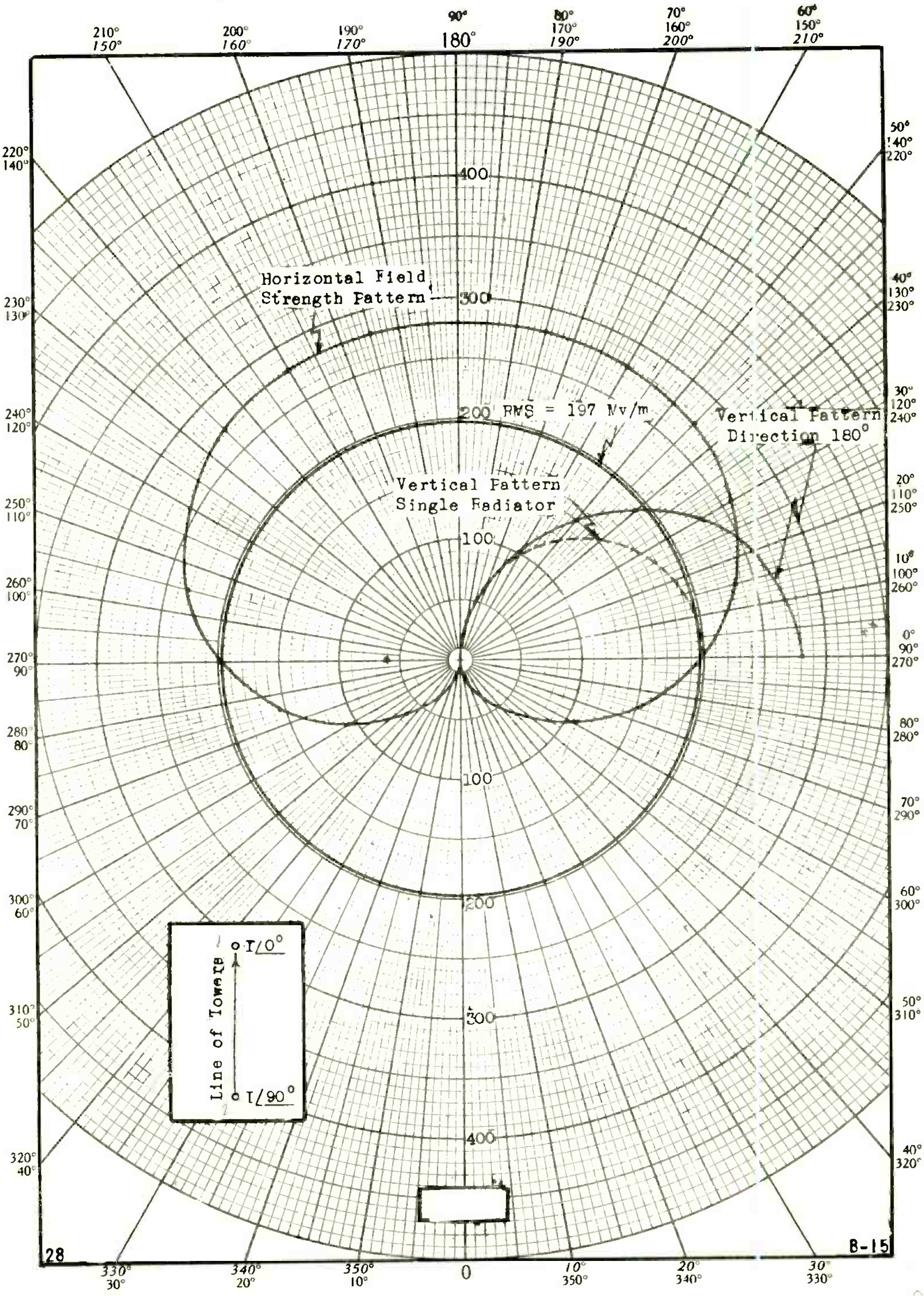


Fig. 18.—Pattern for antenna array having characteristics shown.

improvement in the shape of the vertical pattern; that is, the proportion of high angle radiation is somewhat less with the directional array than with a single radiator.

TABLE 2

A	B	C	D	E	F	G	H	I
ϕ	90°Cosϕ	90° − B	2CosC	2 + D	$\sqrt{E}$	f(ϕ)	F · G	140H
0	90°	0°	2.	4	2	1	2	280
10	88.65	1.35	1.999	3.999	1.99	.976	1.94	272
20	84.6	5.4	1.991	3.991	1.99	.913	1.82	255
30	77.9	12.1	1.956	3.956	1.989	.818	1.63	228
40	68.9	21.1	1.866	3.866	1.96	.696	1.36	190
50	57.8	32.2	1.692	3.692	1.92	.559	1.07	150
60	45.	45.	1.414	3.414	1.85	.418	.773	108
70	30.8	59.2	1.024	3.024	1.74	.276	.48	67
80	15.7	74.3	.541	2.541	1.6	.137	.219	31
90	0	90	0	2	1.41	0	0	0

DISCUSSION OF RESULTS.—In plotting the performance data as shown in Fig. 18 for presentation to the F.C.C. for a construction permit for the antenna array, it is necessary to show the array of towers and the horizontal pattern oriented with respect to true north. The direction of true north shall be shown at zero azimuth. Thus in Fig. 18, if true north is taken as zero azimuth, the azimuth angle of maximum signal intensity is 180° or due south.

If the station to be protected is located in a northwesterly direction at an aximuth angle of 310° and the transmitter is located northwest of the principal area to be served, the line of towers should be shifted in a counterclockwise direction 50° which would put the line of towers along the 130°-310° line. The calculations would be unchanged.

If any other type of pattern is selected from Fig. 4 as more nearly meeting the particular requirements for a given installation, the spacing of the towers and the relative phase angle of the currents is taken directly from Fig. 4. The performance under the desired operating conditions is calculated with the procedure and formulas exactly as shown above.

Very often the complete null as shown in Fig. 18 is not required, a reduction of signal in the direction of the station to be protected being sufficient. This may be the case where a station has been operating satisfactorily with a non-directional antenna and where a power increase is granted with the provision that the signal in the direction of a certain station IS NOT INCREASED. Such a situation might be taken care of by relocating the transmitter (if necessary), using a directional antenna (possibly of the type illustrated in Figs. 17 and 18), but by making one current larger than the other, that is, by making M other than unity. If M were greater than unity, the pattern of Fig. 18 would have a minimum but not a null in the 0° direction. For example, M might be 1.2. In that case the current I_2 would be $1.2I_1$. All the formulas used above contain provision for making M other than unity. It is suggested that the student work out the problem of Figs. 17 and 18 changing $I_1 = I_2$ to $I_2 = 1.2I_1$.

The current which is to flow in each antenna is a function of the transmitter power. In the problem of Fig. 18,

$$P = I^2R = I^2(R_1 + R_2)$$

$$= I^2(49.8 + 23.4) = 73.2I^2$$

$$I = \sqrt{P/73.2}$$

If the transmitter is licensed for 1000 watts output,

$$I = \sqrt{1000/73.2} = 3.7 \text{ amperes.}$$

$$(I_1 = I_2 = 3.7 \text{ amperes})$$

If M is other than 1, the calculation of the antenna currents becomes,

$$P = I_1^2(R_1 + MR_2)$$

$$I_1 = \sqrt{\frac{P}{R_1 + MR_2}}$$

$$I_2 = MI_1$$

For example, assume that in the problem of Fig. 17 all conditions are unchanged except that $I_2 = 1.2I_1$. Then,

$$R_1 = R_a + MZ_m \text{ Cos } (S + \theta_m)$$

$$= 36.6 + (1.2 \times 25) \text{ Cos } (90^\circ - 32^\circ)$$

$$= 36.6 + 30 \text{ Cos } 58^\circ = 36.6 + 15.9$$

$$= 52.5 \text{ ohms.}$$

$$R_2 = R_a + \frac{Z_m}{M} \text{ Cos } (-S + \theta_m)$$

$$= 36.6 + \frac{25}{1.2} \text{ Cos } (-90^\circ - 32^\circ)$$

$$= 36.6 + 20.8 \text{ Cos } - 122^\circ$$

$$= 36.6 - 11 = 25.6 \text{ ohms.}$$

$$P = I_1^2(R_1 + MR_2)$$

$$= I_1^2(52.5 + [1.2 \times 25.6])$$

$$= I_1^2(52.5 + 30.72) = 83.22I^2$$

$$I_1 = \sqrt{\frac{1000}{83.22}} = 3.46 \text{ amperes.}$$

$$I_2 = MI_1 = 1.2 \times 3.46 = 4.15 \text{ amperes.}$$

It again should be emphasized that the calculations as outlined above merely form a basis upon which to make preliminary adjustments. After the array has been installed and adjusted according to calculations, a complete set of field strength measurements must be made over a sufficient number of radials to show the complete pattern. After the measured values have been plotted as shown in the preceding assignment, the resulting pattern is compared with the calculated pattern upon which the construction permit was granted. The array is then adjusted—phase angle of I_1 and I_2 and the relative value M of I_1 and I_2—until the resultant pattern conforms closely with the desired pattern. This is checked with another group of field strength measurements.

A great deal of time and effort will be saved in final adjustment if in the original calculations as many factors as practical are taken into consideration.

In some cases where more involved field strength patterns are required, it may be desirable to use a three tower array, or even a four tower array. Such calculations will not be discussed here. The student is referred to the Engineering Handbook of the National Association of Broadcasters for formulas and typical calculations.

FIELD INTENSITY MEASUREMENTS

GENERAL DISCUSSION.—Throughout this and the preceding assignment the matters of field intensity and field intensity patterns have been discussed. It is logical at this point to consider in some detail the methods by which field intensity measurements are made. It is believed that the most practical approach to this problem is to study one of the several standard types of high-grade field intensity meters, the theory of its operation and the manner in which it is actually used to measure the field intensity of a given signall The field intensity meter which has been selected for discussion is the Type TMV-75-B.

There are two general methods of making field intensity measurements. The first method is that of comparison in which the signal to be measured is picked up in a loop, amplified by means of a superheterodyne receiver, the output of which is fed to a direct current microammeter. An attenuator in the intermediate frequency amplifier of the superheterodyne may or may not be calibrated and simply is adjusted to a convenient reading on the output meter. The output of an accurately calibrated signal generator is then applied to the receiver in such amplitude that the indication on the output meter of the receiver is exactly the same as that from the signal under measurement. The calibrated signal output is then equal to the signal which is being received.

The second method is to use a similar superheterodyne receiver in which the intermediate frequency amplifier gain is accurately known and in which the intermediate frequency attenuator is carefully calibrated. In conjunction with this receiver there must be associated a calibrating oscillator, the output of which can be adjusted accurately to a predetermined value which will be used as a calibrating voltage. After the instrument is adjusted by means of the calibrating voltage at a given frequency, the signal to be measured is picked up in the receiver, carefully tuned in, and by means of the calibrated attenuator adjustment a convenient reading is obtained on the output meter. By the use of a simple formula which involves the meter reading, the attenuator setting, the frequency in kilocycles, and a predetermined constant which is based on the effective height and other characteristics of the loop antenna, the actual field intensity of the signal measured is easily calculated. The RCA field intensity meter to be discussed employs this second method.

FIELD INTENSITY METER.—The RCA Type TMV-75-B field intensity meter is shown in Fig. 19. This equipment is capable of measuring field strength throughout an intensity range of from 20 microvolts to 5 volts per meter at any frequency within the limits of 515 and 20,000 KC/s. The instrument includes an independent calibration standard which insures results of the greatest possible accuracy. With proper operation of equipment the field intensity measurements should be accurate to within 5 per cent over the entire frequency range. The entire equipment is contained in two carrying cases which may be transported conveniently by one person. One case which weights approximately 30 pounds contains the main instrument. The second case is the battery and accessory box and has a weight of approximately 30 pounds when filled, exclusive of batteries. Several arrangements of batteries may be used, the weight of a set which will allow approximately 15 hours of operation being slightly less than 30 pounds.

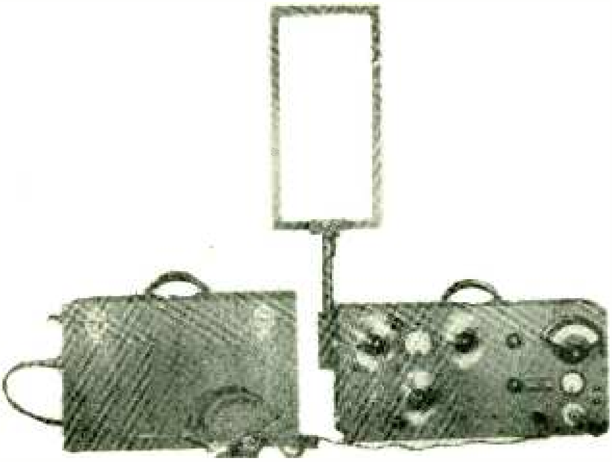


Fig. 19.—RCA Type TMV-75-B Field Intensity Meter.

This equipment can be permanently mounted in a car as shown in Fig. 20. However, measurements will sometimes be made at locations where it is not practical to get an automobile and for that type of measurement the arrangement as shown in Fig. 21 is the more practical.

Fig. 22 shows a block diagram of the complete instrument. The receiver is of the superheterodyne type having three intermediate frequency amplifier stages tuned to a frequency of 300 KC/s. The second detector is designed to serve as a linear output voltmeter. The total gain of the receiver is controlled by means of a continuously-variable gain control in the intermediate frequency amplifier and the calibrated stepped-resistance attenuator located in the input circuit of the i-f amplifier. To facilitate identification of the signal to be measured a set of headphones may be inserted in the output circuit.

The calibrating oscillator is capable of fulfilling all necessary requirements for proper calibration of the instrument. Calibration is required only when there is reason to assume that the resistance of the loop or gain of the i-f amplifier may have changed between readings,

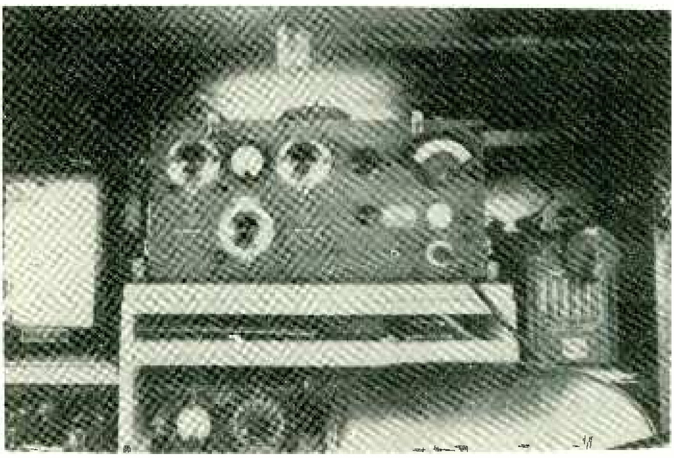


Fig. 20.—Field instenity measuring equipment installed in a car.

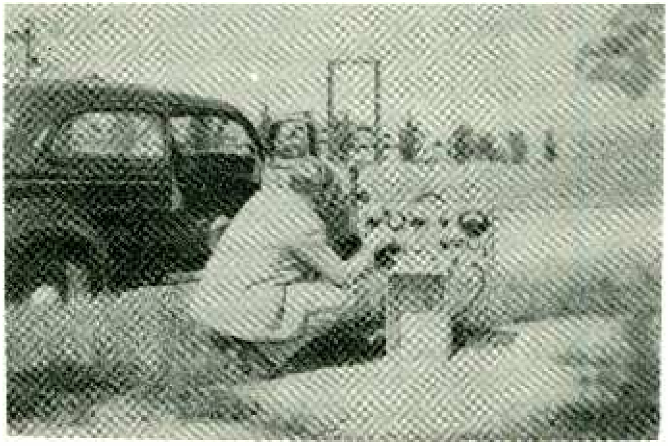


Fig. 21.—Field-Intensity meter set up and in operation.

or when making measurements at different signal frequencies. Coupling to the loop is obtained with a calibrating mutual inductance attenuator which is shielded to eliminate electrostatic and external electromagnetic coupling. The input voltage to the loop from the calibrating oscillator is measured across the primary of the inductor by means of a three-legged thermocouple and a meter whose calibration is independent of frequency. The calibrating attenuator is so designed that the voltage it induces in series with the loop is constant over the entire frequency range for any given setting of the thermo-voltmeter.

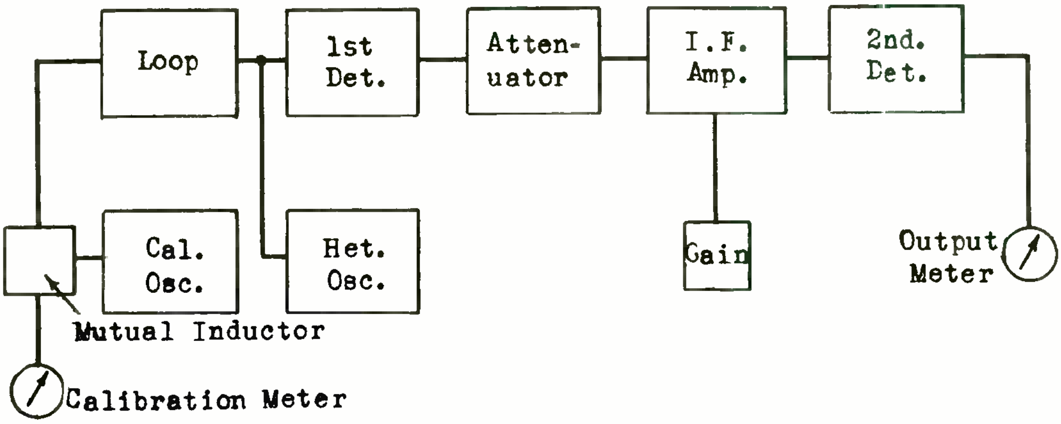


Fig. 22.—Block diagram of Field Intensity meter.

The total frequency range of the instrument is divided into four bands, each band being covered by a separate loop, heterodyne oscillator coil, and calibrating oscillator coil, these components having been so designed as to provide uniform sensitivity on all bands. This condition, however, has not been fully realized because of the extremely small size necessary for the highest frequency loop. The four bands are as follows:

Band A: 515 - 1500 KC/s
Band B: 1500 - 4600 KC/s
Band C: 4600 - 10000 KC/s
Band D: 10000 - 20000 KC/s.

The schematic diagram of the field intensity meter is shown in Fig. 23. In the upper left is the loop which is tuned by variable condenser C_1. Connected into the center of the loop is pickup coil L_1 which is coupled through an electrostatic shielding to L_2. By means of L_1L_2 the output of the calibrating oscillator is injected in series with the loop during the calibrating period. During the actual measurement, of course, the calibrating oscillator is turned off. Potentiometer R_3 (lower center) is the calibrating oscillator output adjustment and controls the plate voltage to the Type 30 oscillator tube. Across coil L_2 is connected a thermocouple and microammeter M_1 by which the

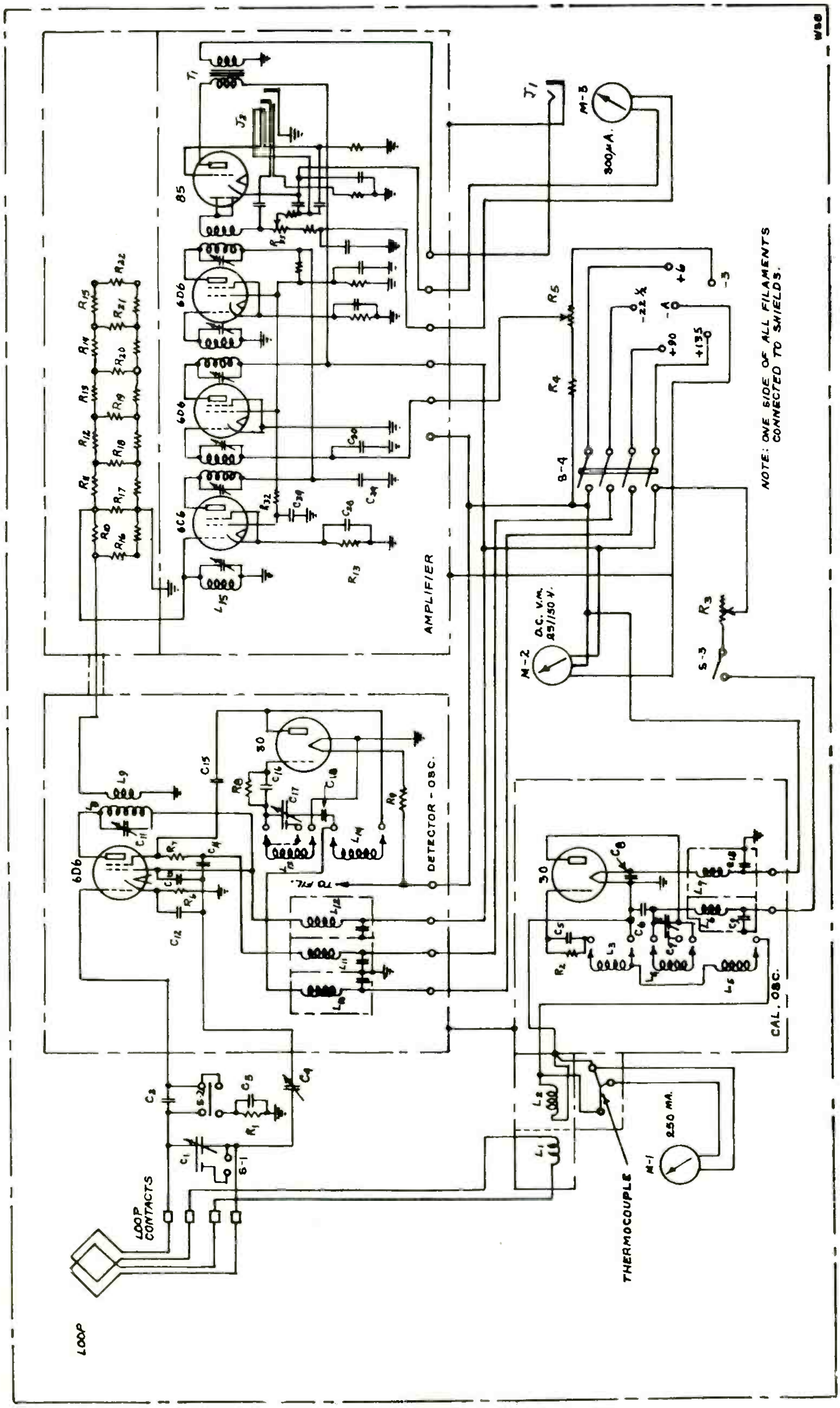


Fig. 23.—Schematic circuit diagram of RCA Type TMV-75-B Field-Intensity Meter.

calibrating oscillator output is indicated. By means of R_3 the calibrated voltage is adjusted to a predetermined reading on M_1.

The signal voltage picked up by the loop is applied to the control grid of the Type 6D6 first detector. The Type 30 heterodyne oscillator tube together with its tuning circuit is shown immediately below the first detector. The output of the first detector at the intermediate frequency of 300 KC/s is applied to the calibrated stepped-resistance attenuator located immediately ahead of the intermediate frequency amplifier. The i-f amplifier has three stages employing one Type 6C6 and two Type 6D6 tubes. The output of the i-f amplifier connects to the two diode units of the Type 85 duplex-diode triode. The rectified output of the Type 85 diodes passes through M_3, a 0 - 300 microammeter which serves as the output meter. M_2 is a d-c voltmeter having scales of 0 - 7.5 and 0 - 150 volts for measuring the filament and plate voltages. The triode section of the 85 tube is excited from the diode output by means of potentiometer R_3 and delivers its output through transformer T_1 to the phone jack J_1. Jack J_2 is used to connect a recorder into the circuit when it is desired to make a permanent record of the measured field intensity over a period of time.

OPERATION OF THE FIELD INTENSITY METER.—To set up the field intensity meter for operation, first connect the instrument to the batteries in the carrying case by means of the battery cable. Next insert the plug-in coils and the loop antenna for the frequency of the signal to be measured. The complete procedure for measurement consists of three steps as follows:

STEP 1. ADJUSTMENT OF RECEIVER TO FREQUENCY: Turn the receiver on. Rotate the loop until the plane of the loop is approximately in the direction of the signal to be received. Tune the receiver to the signal to be measured by means of the loop and heterodyne oscillator tuning control. Headphones may be employed to expedite this procedure using the phone jack on the panel. After the desired signal is located and the receiver accurately tuned, rotate the loop until the signal is at a minimum; then turn on the calibrating oscillator and adjust that oscillator to the frequency for which the receiver is tuned.

STEP 2. CALIBRATION OF THE RECEIVER: Adjust the calibrating knob (R_3 in Fig. 26) to a setting where the calibration meter (M_1 Fig. 26) reads "200". With the i-f attenuator set at "50,000" and the input attenuator switch turned clockwise, adjust the gain of the i-f amplifier with the "gain" control until the output meter M_3 reads "150". (It should be understood that these settings and meter readings are arbitrary values chosen for calibration of this particular instrument and would not be correct for other types or models of field intensity meters).

STEP 3. MEASUREMENT OF FIELD INTENSITY: Turn off the calibrating oscillator and rotate the loop until the signal is again received at the "best" loop position; then adjust the i-f attenuator until the output meter reads a convenient value. The actual measured field strength is then equal to the product of the output meter reading, the attenuator multiplier ratio and a constant derived from a loop measurement, all divided by the frequency in kilocycles at which the measurement is made as shown by the following formula:

$$\text{Field Strength (microvolts/meter)} = \frac{\text{Meter Reading} \cdot \text{Attenuator Setting} \cdot C}{\text{Frequency (KC/s)}}$$

$C = 144.3$ for loop A
$C = 532.$ for loop B
$C = 1687.$ for loop C
$C = 7617.$ for loop D

In practice it will not be necessary to repeat steps 1 and 2 for measurements at a single frequency when the elapsed time between measurements is short and when it is known that the i-f amplifier gain has not been changed.

As a practical example, assume that a measurement is to be made along one of the radials from the antenna of a broadcast transmitter (assume just beyond the first mile radius) at a frequency of 1200 KC/s. At this frequency loop A and coil A will be used and constant "C" in the formula above will be 144.3. Steps 1, 2 and 3 have been performed and with an attenuator setting of 10,000 the output meter reading is 120. The field strength calculation by the formula is shown below.

$$\text{Field Strength } (\mu V/m) = \frac{120 \times 10{,}000 \times 144.3}{1200} = 144{,}300\ \mu V/m = 144.3\ MV/m$$

Thus the field strength of this transmitter at this measuring point is 144,300 µV per meter or 144.3 MV per meter.

Fig. 24 shows a later type field intensity meter manufactured by RCA. This is a direct reading meter, the reading being in microvolts per meter. Shielded loops are used to eliminate pickup voltages due to capacity coupling to the antenna; thus all pickup is magnetic and is due simply to the loop effect and is not influenced by pickup due to the effective height of the loop acting as a vertical antenna.

Figs. 25, 26 and 27 (Courtesy RCA Manufacturing Co.) show the actual procedure in making a field strength measurement.

Fig. 25 shows the first operation after the equipment has been set up and made ready for measurement. First the station to be measured is tuned in by adjusting the single tuning control to the frequency marked on the dial. The loop is then turned for MINIMUM signal.

The next step is shown in Fig. 26. The output voltage from the calibrating oscillator is adjusted. The meter switch is set on "input". The oscillator trimmer is adjusted; then the "cal. input" control is turned until the output meter reads at the red line.

The meter is then calibrated for sensitivity by using the standard signal from the oscillator. The meter switch is placed on "cal. output". The attenuator and multiplier are set from the curve on the instrument lid. The "cal. output" control (shown in Fig. 26 to the right of the control being manipulated) is then turned until the meter reads at the red line.

Fig. 24.—RCA Type 308-A Field Intensity Meter. Available with either a storage battery and vibrator type regulated power supply or dry battery box. The latter type is shown with the battery box below the meter.

Fig. 27 shows the actual measurement of field intensity. The meter switch is set to "measure", the loop is rotated for maximum output reading, and the attenuator with its multiplier (shown in Fig. 27) is adjusted until the meter reads at the red line.

The reading on the attenuator scale is expressed directly in microvolts per meter times the setting of the multiplier switch. In the illustration the attenuator setting is 3.5 and the multiplier is set at 1000. Therefore the reading is 3.5 × 1000 = 3500 microvolts per meter or 3.5 millivolts per meter.

MEASURING TECHNIQUE.—It is important that field intensity measurements be very carefully made. The manufacturer states that with the Type TMV-75-B field intensity measurements properly performed will be accurate to within 5 per cent over the entire frequency range. It is further stated that while a maximum error, excluding that produced by improper tuning is plus or minus 9 per cent (this is made up of all the errors that may accumulate at each part of the circuit) the probability that all of the errors will occur in the same direction is extremely small and the average error should be well within plus or minus 5 per cent. The maximum probable error of the instrument will be within plus or minus 2 per cent. Possible errors resulting from improper tuning may be eliminated during calibration by adjusting the calibrating oscillator to zero beat with the signal being measured.

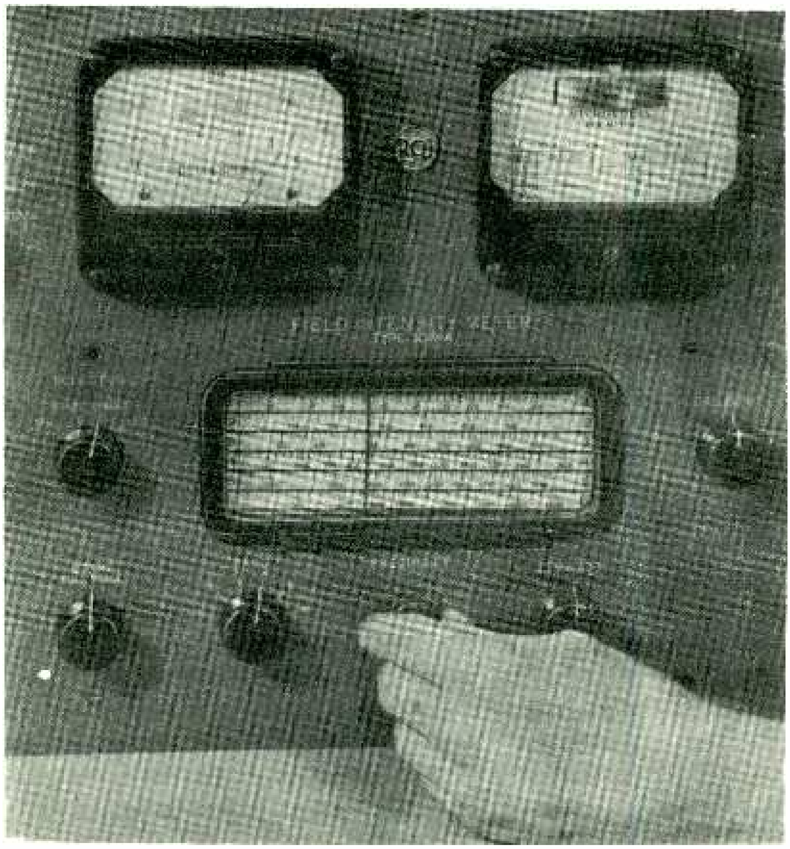


Fig. 25.—The station to be measured is tuned in by adjusting the tuning control to the frequency marked on the dial.

The most likely sources of error in plotted points from field strength measurements do not lie in the instrument itself or even in careless handling of the instrument, but rather in improper selection of the location at which field strength measurements are to be made. A number of these possible errors were pointed out in the preceding assignment.

Errors due to improper location of the measuring points can best be averaged out by taking a large number of measurements over each of a large number of radials from the antenna. If the antenna were located in the middle of a large level plain with no buildings, telephone wires or absorbing objects of any kind within a radius of several miles, very accurate measurements would be possible. The very nature of broadcasting preludes this ideal measurement set-up because broadcast transmitters are located as near as possible to centers of population and from the economic point of view energy must not be radiated to any great extent in non-profitable areas.

Therefore, to get a true picture of the field strength contour a great many measurements must be made often in very inconvenient locations, and the radials over which these measurements are made should be caused to extend at least 15 or 20 miles so that when the points are plotted a smooth curve can be drawn that will average out most of the errors in the measurement and plotting of the points.

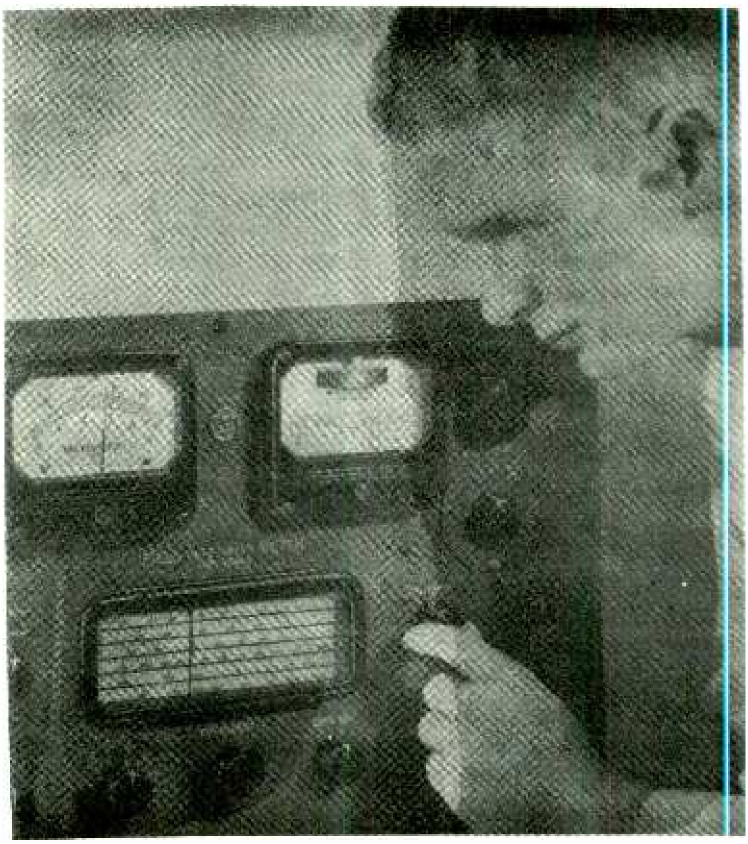


Fig. 26.—Adjusting the output voltage from the calibrating oscillator.

Particular care must be employed

in making a field strength survey where a directional array is involved. The Federal Communications Commission requires that proof of performance of a directional antenna system be submitted before any operation during the regular broadcast day may be permitted. These data must show that the pattern obtained is essentially the same as that predicted by the application and required by the terms of the authorization and that any specific requirements set out in the authorization are fully met.

Fig. 27.—The field intensity of the station is measured.

To establish this performance, measurements shall be made as previously explained along a sufficient number of radials to establish the effective field for the antenna system. In the case of a relatively simple directional antenna pattern approximately eight radials in addition to the radials in the direction in which the field intensity values are specified by the authorization are sufficient. However, when more complicated patterns are involved, that is, patterns having several or sharp lobes or nulls, measurement shall be taken along as many additional radials as necessary to definitely establish the pattern.

In cases where the authorization requires a showing that actual field intensities of specified values be obtained in the various portions of the service area sufficient measurements throughout these areas shall be made to show that at least the values specified are obtained.

It is not attempted within the scope of this assignment to discuss all problems in connection with the use of field strength measurements or the requirements in this respect of the Federal Communications Commission. Every engineer who has any responsibility in connection with the design, location, adjustments, or measurements of broadcast antennas should have and carefully study "Standards of Good Engineering Practice Concerning Standard Broadcast Antennas (550-1600 KC/s)" prepared by the Federal Communications Commission. The Commission lays down very specific rules about the manner in which data presented before the Commission shall be obtained and presented. Ordinarily a great deal of time and money will be saved by getting together all of the necessary material and presenting it in the specified manner the first time.

RESUME

This concludes the assignment on broadcast antenna systems. It was shown here how to design a two-element array, from which the extension to three - and more element arrays should be apparent. Even two-element array affords a large number of useful patterns, and the reason for a higher number of elements is to obtain narrower lobes and sharper nulls in the directions where other stations lie that have to be protected.

The next topic was that of transmission lines and phase-shifting networks, which enable actual lines to be artificially lengthened or shortened and the phase of the currents in the elements to be varied as desired. In conjunction with this a simple method of measurement was described for determining the relative phase of two antenna currents by means of their vector relations. However, a phase meter for accomplishing such measurement was also described.

After the antenna is installed, measurements must be made to "prove its performance." Readings of the field intensity must therefore be made along various radials from the antenna, and for this purpose a field intensity meter is employed. The assignment concludes with a description of such a meter and its method of use.

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BROADCAST ANTENNA SYSTEMS—PART II

EXAMINATION

1. (A) Name two reasons for using a directional antenna. Explain.

   (B) In feeding the towers of an array, what is the advantage of making the lines from a common feed point to all towers equal in length?

2. (A) Describe the method of measuring the phase angle between the currents in two towers without the use of a phase meter.

2.

(B) What are three particular precautions to be observed in using this method?

3. What is the basic principle of operation of both the RCA Type 300 and the WE Type 2-A phase monitors?

4. Discuss the use of a series inductance to obtain the proper capacitive reactance for a circuit such as described relative to Fig. 7, include effect of voltage drop across the capacitor.

5. (A) Upon what principle is the operation of an array based?

(C) In the example cited under "Calculation of Array Performance" in this assignment, namely, two quarter wave antennas spaced 90° with currents equal but 90° displaced in phase and 1000 watts into the array, is the antenna power the same for each antenna? If not, what are the two powers?

6. Reference Problem 5(C), plot the vertical radiation pattern for azimuth angle zero. Show your values in tabular form.

7. (A) A broadcast antenna has an impedance at the base feed point of 392 - j110 ohms at 1000 KC/s. What is the current flowing at the base for an antenna power of 50 KW?

(B) In order to conserve tubes during the war emergency, the Federal Communications Commission has reduced the output power of stations 1 DB. What is the new antenna current for war time operation?

8. (A) Reference Problem 7(A). Design an L-section to match this antenna to a 100 ohm coaxial transmission line

8.

(B) Suppose the nearest available capacitor capacity to the one required is 500 μμf.

(a) What size corrective series element is required to make use of this capacitor?

8. (b) What must be the capacitor voltage rating under this condition?

(c) How does this compare to the voltage rating required for the correct size capacitor?

9. (A) A three element array operating at 1000 KC/s is employed with towers in a line spaced 864 feet between adjacent elements. Current in end tower A is $I_A = I_o \underline{/-112^\circ}$, center tower current $I_B = 21_o \underline{/0^\circ}$, and end tower current $I_c = I_o \underline{/+112^\circ}$. A phase monitor is used to measure currents and current phases of the towers, the phases being measured with respect to the center of tower B. The sampling loop lines are *coaxial* and of 70 ohms surge impedance; the sampling circuit from tower A is 1450 ft. long, that from tower B is 580 feet long, and that from tower C is 770 ft. long. The propagation velocity in the lines is 92 per cent of that in air. With antenna properly adjusted and no corrective networks in the sampling circuit lines, what are the phase monitor readings of I_A and I_C with respect to I_B?

9.

(B) Design phasing sections to be inserted in the sampling circuit lines of problem 9(A) to make the phase monitor read $I_A/I_B = \underline{/-112^\circ}$ and $I_C/I_B = \underline{/+112^\circ}$.

9.

10. The relative horizontal pattern of the array of problem 9 is given as a function of $(2 + 2\ \mathrm{Cos}(a + S\ \mathrm{Cos}\ \theta))$ where:

S is the spacing, in degrees, between adjacent tower elements.

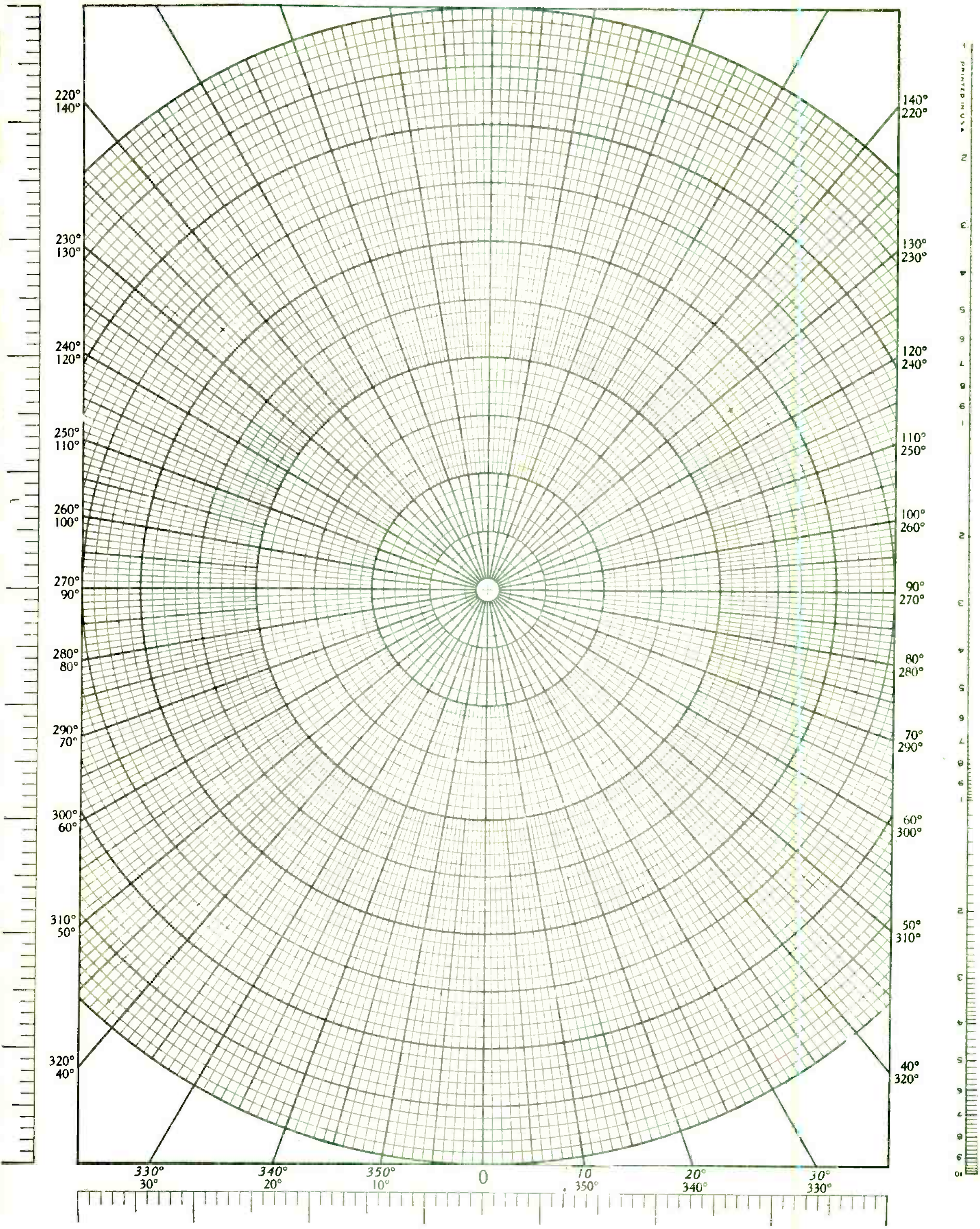
a is the phase relation, in degrees, of the end towers with respect to the center tower. (end tower currents assumed plus and minus the same angle, a).

θ is the azimuth angle of the direction in question. θ is measured from the line through the center tower and the one of leading current; this line is defined as $\theta = 0°$.

10. (A) Calculate and plot the horizontal pattern of any two adjacent towers of the array. Tabulate your answers.

10.

10. (B) Suppose the frequency is changed to 1030 KC/s; what readjustment of tower phases would be necessary to keep the principal nulls (between major lobes) in the same direction? Give the phase in degrees.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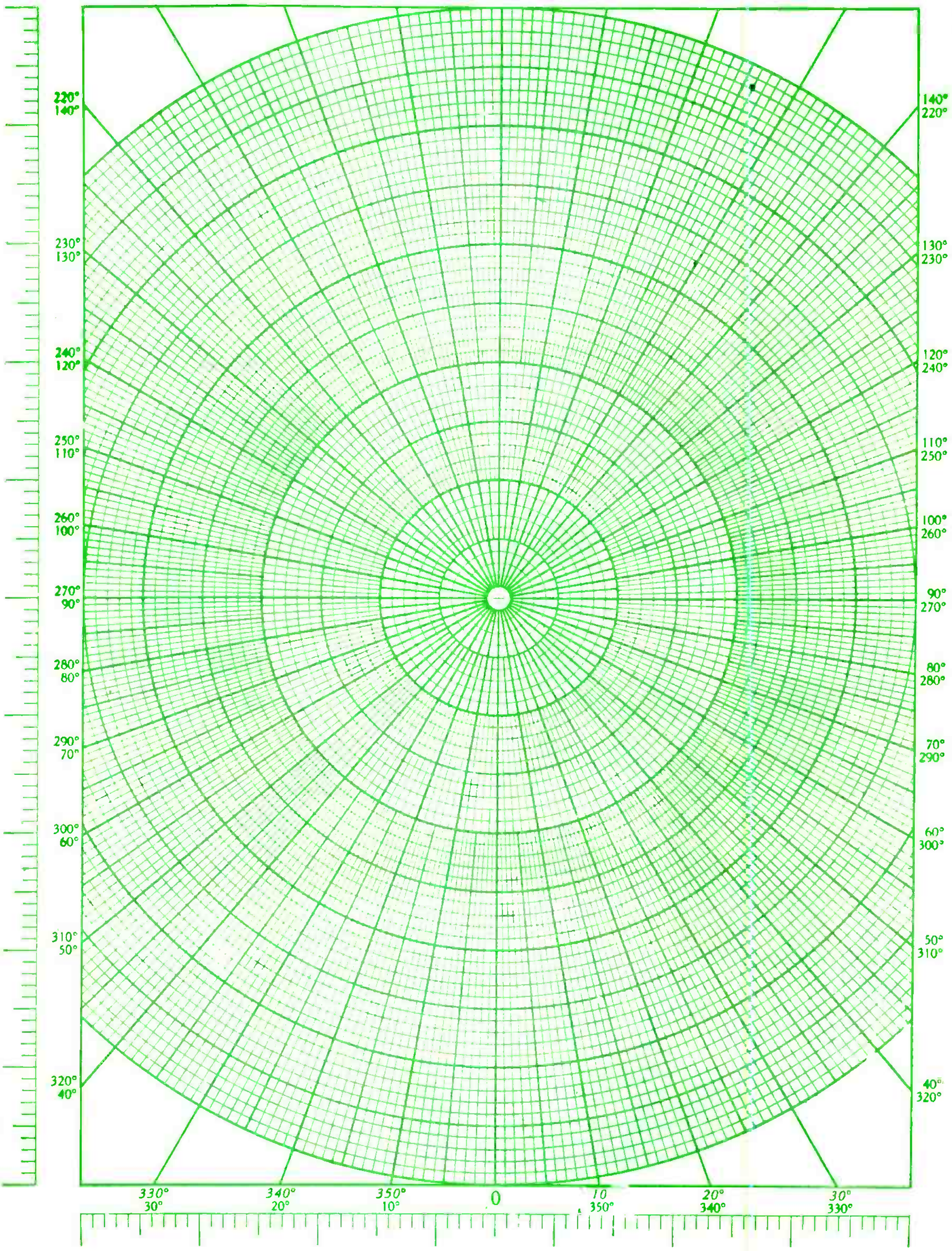
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