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CIRCUIT DESIGN FOR LOW-FREQUENCY RADIO RANGES

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Circuit Design for Low-Frequency Radio Ranges

SUMMARY

This report presents a discussion of the circuit theory involved in the design of the radio range coupling system, and a description of the equipment employed in the latest type of radio-range station. Particular emphasis is laid upon the theory of the coupling system because it is the most important part of the entire equipment, and also because its function is perhaps the least understood by those who do not have direct contact with the problems of radio range operation. Some of the theoretical work is new as far as the literature on the subject is concerned, and the results are presented here for the first time in published form.

INTRODUCTION

During the past four years the airways radio range has assumed a position of increasing importance as an aid to air navigation. This has been brought about chiefly by the rapid growth of instrument and "over-the-top" flying in which the pilot must rely almost entirely upon ground radio aids for directional guidance and position fixing.

In order to keep pace with the rapid technical advancement in the fields of both aviation and radio, the Radio Development Section has engaged in a continuous program of investigation looking toward the improvement of radio range facilities.

Experience gained with the earlier forms of equipment has pointed the way to many improvements in design and methods of operation. It has, however, been impossible in most cases to incorporate improved design features in existing equipment without completely rebuilding it.

On July 1, 1937, the Bureau of Air Commerce entered upon an extensive program of airway modernization and construction, involving the procurement of approximately one hundred sets of radio range equipment. An opportunity was thus afforded to specify and obtain complete equipment for each station, the component parts of which were designed for coordinated operation with each other. This involved a desirable departure from former procurement procedure which, because of limited finances, required that only a few items of equipment be purchased at a time as the need for them arose.

In specifying the electrical characteristics of the equipment for the new stations, a number of important changes from past practice have been made. These changes result in a simplification of the adjustments necessary for the tuning process, and the alignment and stabilization of the courses. We will discuss here the general theory of operation of the new equipment without, however, entering into a comparative study of the advantages of the new over the old.

GENERAL DESCRIPTION AND PRINCIPLES OF OPERATION

In Fig. 1 is shown a polar diagram of the distribution of electromagnetic field intensity about a four-course airway radio range. By transmitting the two figure-of-eight patterns alternately, and keying one with the Morse character *A* (—) and the other with the character *N* (—) in such a way that these complementary signals interlock, it is possible to make a direct aural comparison of the received intensities of the two signals. In flying the range, the pilot follows the course defined by the equisignal line passing through one of the intersections of the field patterns. Deviation to right or left of the course is indicated by predominance of one or the other of the *A* or *N* signals in the headphones. When on course, a continuous unvarying tone is heard, interrupted only by transmission of station identification signals at 24-second intervals. The identification signals are also transmitted once in each figure-of-eight so that the ratio of their intensities is the same as that of the *A*–*N* signals

Theoretically the courses are defined by the equisignal lines which are conceived as having no width Actually, because of the inability of the human ear to detect changes in signal level of less than about 0 5 decibel, the courses appear to have a finite width of approximately 3 degrees under ideal conditions In mountainous country it is not possible to realize the ideal performance which may be obtained from radio ranges located in level terrain Reflection of energy from large vertical obstacles, such as mountains, distorts the radiation patterns so that they may intersect at more than one point, and thus produce multiple courses This is an entirely natural phenomenon and is not to be associated in any way with malfunctioning of the equipment itself

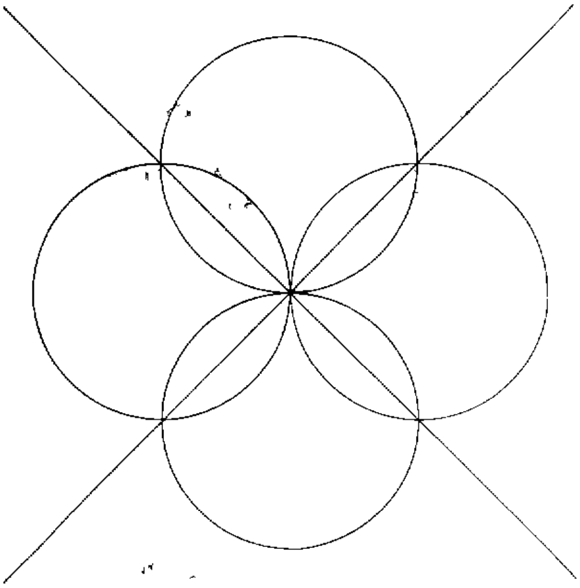

Figure 1 —Field Intensity Distribution of a Four Course Radio Range

Two types of antenna systems are in current use at the various radio ranges, both of which have the directional characteristics illustrated in Fig 1 One of these consists of two crossed loops intersecting at their centers with their planes at right angles The other is the modified Adcock antenna, the present version of which consists of four vertical steel tower radiators symmetrically disposed at the corners of a square, and excited from a centrally located transmitter Since the loop system is subject to severe course swinging during the hours of darkness, it has been largely superseded by the Adcock system which is free from this defect Accordingly, in this report, we shall limit our discussion entirely to those ranges employing the Adcock antenna system

The simultaneous range and broadcast stations require, in addition to the modified Adcock system, a fifth central antenna for the transmission of carrier energy and speech A discussion of the operation of this type of range has been given elsewhere [1] and will not be repeated here However, the contents of this report will apply equally to either the simultaneous station or to the older type of range because there is no fundamental difference in the circuit arrangements between the two

With the modified Adcock system, a symmetrical figure-of-eight field pattern is radiated when two diagonally opposite antennas are excited in such a way that their currents are equal in magnitude and 180° out of phase If the phase differs from 180°, within certain limits, the pattern still retains the general form of the figure of eight, but becomes unsymmetrical with one lobe larger than the other If all four radiators of the system are excited simultaneously, a figure-of-eight pattern is produced the axis of which assumes a position with respect to the radiators dependent upon the relative current amplitudes in the two diagonally opposite pairs By making the proper adjustments of the phase between opposite radiators, the relative currents in diagonal pairs, and the ratio of powers supplied during *A* and *N* transmissions, it is possible to produce, alternately, two figure-of-eight patterns at right angles, which intersect on any arbitrarily assigned alignment of courses This is illustrated in Fig 2

In Fig 3 is shown a simplified schematic diagram of the coupling system in use at the new radio range stations Let us trace through the operation of the system, considering separately the function of each item of equipment

Starting at the output terminal of the trans-

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[1] W E Jackson & D M Stuart Proc I R E Vol 25 No 3

mitter, the first element of the coupling circuit encountered is the link circuit relay. The function of this relay is to switch the radio-frequency output of the transmitter from one goniometer primary to the other. In physical construction, the relay is of the polar type, designed for rapid change-over. It is energized by an automatic, motor-driven keying device not shown on the diagram. In operation, the armature moves to the left contact and remains there during the dash of the letter N, then to the right contact making the dot of the letter A, back to the left to make the dot of the N, and finally to the right to make the dash of the A after which the entire sequence is repeated. In order to obtain a smooth interlock of the two signals, the relay contacts are adjusted so that no appreciable gap occurs in the sequence of operations.

The goniometer is a variable coupling transformer used to regulate the relative energy supplied to the two diagonally opposite pairs of antennas. It consists of two mutually perpendicular primary windings inductively coupled to two mutually perpendicular secondary windings in such a way that when the primary windings are rotated relative to the secondary windings the mutual inductance follows the law

$$M_1 = M_o \cos G \text{ for Secondary \#1}$$
$$M_2 = M_o \sin G \text{ for Secondary \#2}$$

where M_o is the mutual inductance at maximum coupling, and G is the angle between the primary winding under consideration and #1 secondary winding. For the other primary winding we have, of course,

$$M_1' = M_o \sin G \text{ for Secondary \#1}$$
$$M_2' = M_o \cos G \text{ for Secondary \#2}$$

If energy is applied to the N or left primary, the voltage applied to the transmission lines to antennas 1 and 2 will be

$$E_{12} = E_s \cos G$$

while that applied to the lines to antennas 3 and 4 will be

$$E_{34} = E_s \sin G$$

The resulting field pattern, assuming all lines to be of equal length, and proper adjustment of the antennas, would be a symmetrical figure of eight with axis inclined at an angle G to the line of antennas 1 and 2. With energy applied to the other primary we would have

$$E_{12}' = E_s \sin G$$
$$E_{34}' = E_s \cos G$$

and the field pattern would be identical to the first except rotated by 90 degrees in space.

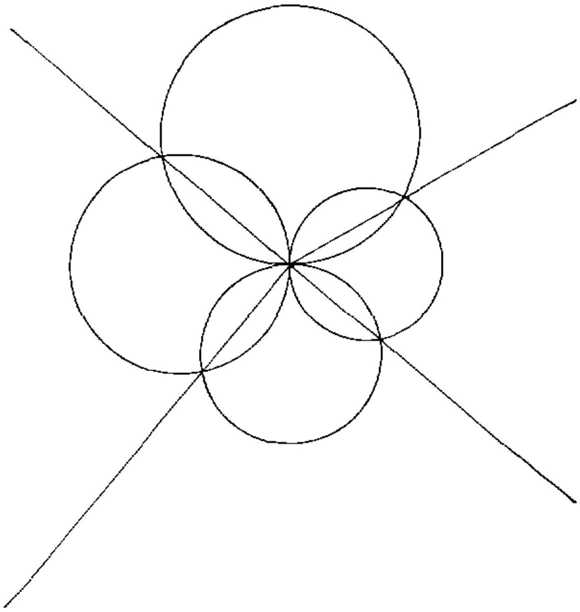


Figure 2. —Field Intensity Distribution for Producing a Nonreciprocal Course Alignment

The courses produced by this arrangement would be 90 degrees apart and aligned at angles of 45 degrees ± G to the diagonal tower lines. It is obvious that rotation of the goniometer windings through a given angle will rotate the range courses through the same angle under the above outlined conditions. The L pad connected in one of the primary circuits is used to regulate the relative power applied to the primaries, and thus control the relative field intensities of the figure-of-eight patterns. Its use is avoided insofar as is practicable, but it is essential in securing so-called squeezed courses.

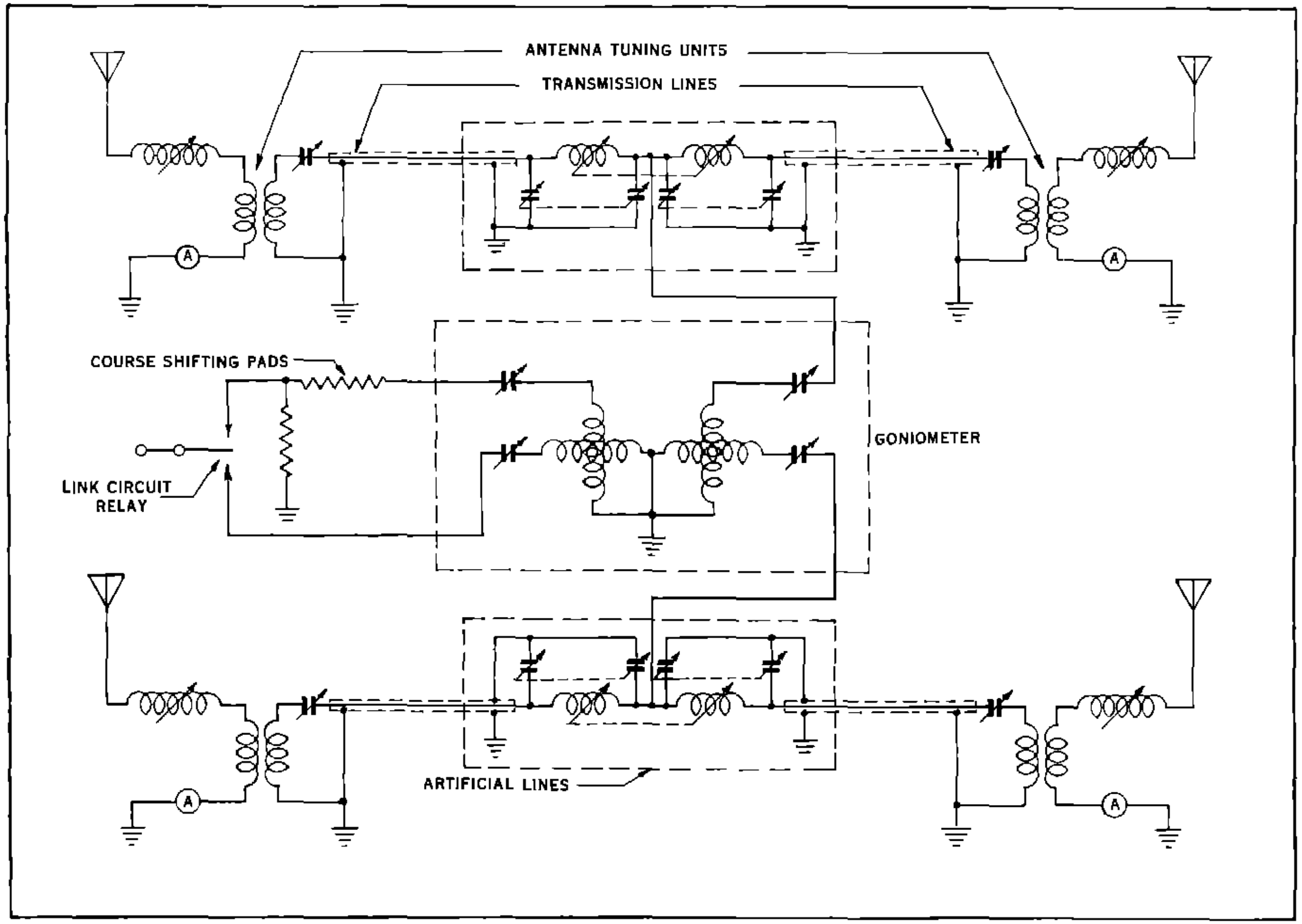


Figure 3.—Schematic Diagram of Radio Range Coupling System

The π section artificial lines inserted in the circuit between the goniometer secondaries and the real lines are adjustable phase shifting networks, and are used only when the course alignment requires that opposite towers operate at phase differences of other than 180 degrees. The real transmission lines which deliver energy to the antenna circuits are of the concentric conductor variety and are usually buried in the ground.

The antenna tuning unit consists of a loading inductance to adjust the reactance of the antenna circuit, and a variable coupling transformer to match the antenna impedance to that of the line. Provisions are made for varying the reactance of the primary winding of the transformer by means of a series variable condenser, and for reversing the phase of the antenna current by rotation of the secondary winding to either side of the zero coupling position.

The radiating elements of the modified Adcock antenna are insulated, self-supporting steel towers, 125 feet in height. At the frequencies employed (200–400 kc.) these towers have an electrical length of only 9° to 18° and are equivalent to a lumped capacity in series with a resistance. The total resistance of the antenna circuit, exclusive of the loading coil, is approximately 1.5 ohms. The equivalent lumped capacity of the tower is approximately 845 micromicrofarads. At 300 kilocycles then, the impedance of the antenna is 1.5–j629 ohms. It is evident that if the reactive component of this impedance is resonated by means of the loading coil in the tuning unit, the resultant impedance of the circuit will vary widely for small changes in antenna capacity. The problem presented by this circumstance forms the basis for the discussion in the following section.

THEORETICAL ANALYSIS OF RADIO RANGE CIRCUITS

It has been pointed out that the location of the courses emanating from a radio range depends upon the phase and amplitude of the currents flowing in the various radiating elements of the antenna system. In general, then, it is to be expected that variations in antenna constants will alter the established current relations and thereby cause a shift in the position of the courses. It is obviously impossible to prevent small variations of the electrical constants of any practical antenna system which is subject to the effects of changing weather and ground conditions. However, it is possible by means of special circuit arrangements to minimize the effect of antenna detuning upon course alignment. Since these circuits comprise such an important part of the radio range coupling system, and perform such an essential function, they will be discussed here at some length.

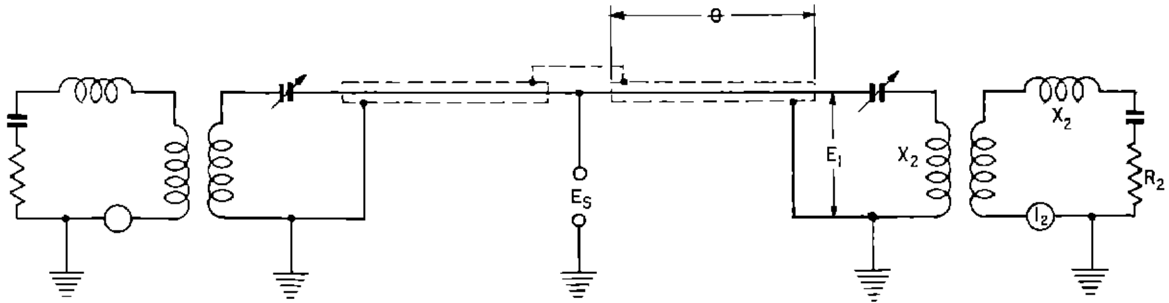


Figure 4.—Schematic Diagram of Coupling System Involved in Exciting One Pair of Diagonally Opposite Antennas

In Fig. 4 is shown a schematic diagram of the transmission lines and antenna tuning units involved in supplying power to a pair of diagonally opposite antenna towers. In this diagram, the electrical constants of the towers are represented by their lumped circuit equivalents. In what follows we will first idealize the transmission line and coupling transformer primary by assuming that the former has no attenuation and that the latter has no resistance. For an efficient coupling system, these assumptions are justified, and lead to results which are a very close approximation to the truth After illustrating the theory under these assumptions, the effects of circuit losses on the system will be considered We will adhere to the use of the following symbols for designation of the most important electrical parameters, and will introduce and define additional symbols in the text as the need arises

Θ=Electrical length of transmission line
Z_O=Characteristic impedance of transmission line
Z_S=Driving point impedance of transmission line
Z_1=Self impedance of primary circuit
Z_{11}=Total impedance of primary circuit (self impedance plus reflected impedance)
Z_M=Mutual impedance between goniometer windings at maximum coupling
Z_{P1}=Impedance of goniometer primary #1
Z_{P2}=Impedance of goniometer primary #2
Z_2=Impedance of secondary circuit
E_s=Transmission line driving point voltage
E_1=Voltage applied to primary circuit
I_1=Current in primary circuit
I_2=Current in secondary or antenna circuit
I_s=Transmission line driving point current
Ψ=Phase angle of antenna circuit

At the coupling transformer of antenna *A* we have

$$\begin{aligned} E_1 &= I_1 Z_1 + I_2 Z_{12} \\ 0 &= I_1 Z_{12} + I_2 Z_2 \end{aligned} \qquad (1)$$

from which

$$I_2 = -\frac{E_1 Z_{12}}{Z_1 Z_2 - Z^2_{12}} \qquad (2)$$

$$I_1 = -\frac{I_2 Z_2}{Z_{12}} \qquad (3)$$

In our notation the voltage at the sending end of the transmission line is given in terms of the receiving end voltage and current by

$$E_s = E_1 \cos\Theta + jI_1 Z_o \sin\Theta \qquad (4)$$

Using (2) and (3) in (4), we obtain for the transfer impedance relating the antenna current to the line sending end voltage

$$Z_{s2} = \frac{E_s}{I_2} = Z_{12}\cos\Theta - \frac{Z_2}{Z_{12}}(Z_1\cos\Theta + jZ_o\sin\Theta) \qquad (5)$$

From inspection of (5), it may be seen that Z_{s2} will become independent of the antenna impedance Z_2 if we make

$$Z_1 \cos\Theta + jZ_o \sin\Theta = 0 \qquad (6)$$

Solving (6) for Z_1, we obtain

$$Z_1 = -jZ_o \tan\Theta \qquad (7)$$

or, since we are neglecting primary resistance

$$X_1 = -Z_o \tan\Theta$$

and

$$Z_{s2} = jX_{12}\cos\Theta \qquad (8)$$

By satisfying equation (7), we establish a constant-voltage constant-current relation between the sending end of the line and the antenna circuit The line and coupling equipment may then be looked upon as comprising a modification of one of the networks associated with the name of Boucherot, the properties of which are well known It may be shown from the theory of ideal transmission lines that the reactance $-Z_o \tan\Theta$ is exactly the amount required to tune a short circuited line of electrical length Θ to series resonance This fact is made use of, as we shall describe, in the practical adjustment of equipment in the field

Equation (7) represents a physically realizable condition except for $\Theta=90°$ in which case an infinite value of primary circuit reactance would be required In practice, however, the electrical lengths of the transmission lines are always sufficiently removed from 90° to prevent such a difficulty from arising Suppose now that the primary reactance at Antenna *A* in Fig 4 is adjusted to equal $-Z_o \tan\Theta$ Then as the tuning of the antenna circuit is varied, the ratio $\frac{E_s}{I_2}$ remains constant as given by 8 Since the voltage E_s is common to the transmission lines to both diagonal antennas, the ratio of the currents in the two antennas remains constant Thus if the primary circuit at each of the four antennas is adjusted in accordance with (7), the established phase and amplitude relations of the currents in opposite pairs will be preserved even though the antennas may become detuned by random variations in capacity or resistance

In addition to satisfying (7) at each antenna tuning unit, it is desirable that the total impedance presented by each primary circuit should be adjusted to match the line impedance in order to obtain an efficient transfer of power, and eliminate standing waves from the line. It may be shown from (2) and (3) that the total primary impedance is given by

$$Z_{11}=Z_1-\frac{Z_{12}^2}{Z_2} \qquad (9)$$

which is equivalent to

$$Z_{11}=\frac{X_{12}^2R_2}{R_2^2+X_2^2}+j\left(X_1-\frac{X_{12}^2X_2}{R_2^2+X_2^2}\right) \qquad (10)$$

Since the characteristic impedance of our line is a pure resistance, it is required that

$$\frac{X_{12}^2R_2}{R_2^2+X_2^2}=Z_0 \qquad (11)$$

and

$$X_1-\frac{X_{12}^2X_2}{R_2^2+X_2^2}=O \qquad (12)$$

If we define the phase angle of the antenna circuit as

$$\psi=\tan^{-1}\frac{X_2}{R_2} \qquad (13)$$

we may rewrite (11) and (12) as

$$X_{12}=\frac{\sqrt{Z_0R_2}}{\cos\ \Theta} \qquad (11.1)$$

$$\tan\psi=-\tan\Theta \qquad (12.1)$$

which are the circuit relations which must obtain in order that the line impedance will be matched.

In applying the results of the foregoing analysis to the actual adjustment of equipment in the field, it is only necessary to carry out the following simple procedure.

After the transmitter is adjusted to operate on the assigned station frequency, each winding of the goniometer is carefully resonated by means of the series variable condenser provided for this purpose. Next, the sending ends of the transmission lines are effectively short-circuited by a resistance of one ohm or less, and a small radio-frequency voltage is applied across this resistance. With the antenna circuit opened, the condenser in series with the transformer primary at each antenna tuning unit is adjusted until resonance of the entire transmission line is indicated by a thermogalvanometer inserted in series with the primary winding. Since this adjustment is made to satisfy (7), it is clear that if artificial lines are to be used they must be included in the circuit at the time of the adjustment. Without disturbing the setting of the primary condenser, the antenna circuit reactance and the mutual inductance of the transformer are next adjusted so that the impedance presented by the primary matches the characteristic impedance of the transmission line. This establishes the circuit conditions specified by (11.1) and (12.1). During the antenna tuning operation, all of the towers except the one under adjustment should be grounded in order to avoid the effects of their mutual impedances. While this procedure is recognized as being not strictly correct, it does not result in any serious misadjustment in the present case and is recommended for its simplicity.

After the tuning procedure has been completed, the goniometer, artificial lines, and course shifting pad may be adjusted to previously calculated settings to secure the desired course alignment. The method of making these calculations is well known, and will not be described here. It may be said, however, that very accurate results may be obtained, and the time required to align the courses reduced to a minimum if the calculations are carefully made and applied.

It must be mentioned at this point that when (7) is satisfied, we are limited to operating opposite antennas at a phase difference of exactly 180 degrees, since the transfer impedance given by (8) is a pure imaginary, indicating 90 degrees phase difference between line voltage and antenna current. Under this condition, course alignments would be restricted to those in which opposite courses are 180 degrees apart. If it is desired to depart from this reciprocal bearing relation in course alignment, opposite antennas must be operated at phase differences other than 180 degrees in which case it is impossible to satisfy (7). The transfer impedance Z_{02} will no longer be independent of antenna tuning, and it is to be expected that variations in tower constants will alter the phase of the antenna currents and thereby shift the courses For this reason, it is to be emphasized that a non-reciprocal course alignment can only be obtained by an unstable adjustment of the equipment and is to be avoided wherever possible

Let us consider now a radio range adjusted in accordance with the above outlined procedure and having a reciprocal alignment of courses Suppose the goniometer to be set on zero degrees so that one pair of towers is excited only during the N and the other pair excited only during the A If one of the towers becomes detuned let us say one of those which radiates during the A signal the current in both of the A towers will fall off equally while the current in the N towers will be unaffected The field intensity of the A lobes will be reduced, and the location of all of the courses will be shifted This occurs regardless of our constant current network because of the necessarily imperfect regulation of the voltage source Suppose now that under the same conditions the goniometer is set on 45 degrees Both of the goniometer secondaries are then equally coupled to each of the primaries and the induced secondary voltages are at all times equal Since the secondary windings have been tuned to exact resonance, the entire secondary voltage appears across the transmission lines so that the sending end voltages on each pair of lines are always equal regardless of the impedance presented by the lines If then any one of the antennas becomes detuned, the currents must drop equally in all four and the course alignment will be unaffected It is thus seen that maximum course stability is obtained when the goniometer is set at 45 degrees and that any departure from this setting involves a sacrifice in stability

In order that the goniometer may be set on 45 degrees the course alignment must be known prior to the time the towers are erected so that they may be properly oriented It has been the policy to locate the towers for optimum stability wherever possible, and it is therefore considered highly desirable that the originally established course alignment be adhered to in order that this stable condition may be preserved

It has been pointed out that for goniometer settings other than 45 degrees, the degree of course shifting which occurs when an antenna becomes detuned is a function of the regulation of the power source or transmitter Let us investigate the effect of antenna tuning upon the various impedances of the coupling system in an effort to determine this functional relationship

It may be shown from transmission line theory that the input impedance to one of the lines will be given in our notation by

$$Z_s = Z_o \frac{Z_{11}\cos\Theta + jZ_o\sin\Theta}{Z_o\cos\Theta + jZ_{11}\sin\Theta} \qquad (14)$$

Putting $Z_{11} = Z_1 - \frac{Z^2_{12}}{Z_2}$ and letting $Z_1 = -jZ_o\tan\Theta$

we obtain

$$Z_s = -\frac{Z_oZ^2_{12}\cos^2\Theta}{Z_oZ_2 - jZ^2_{12}\sin\Theta\cos\Theta} \qquad (15)$$

Since the line is to be matched initially, the value of mutual impedance of the coupling transformer will be given by (11 1), i e ,

$$Z^2_{12} = -X^2_{12} = -\frac{Z_oR_2}{\cos^2\Theta} \qquad (11\ 2)$$

It is to be noted that the value of R_2 prevailing at the time when the antenna is originally tuned governs the value of Z_{12} However when Z_{12} is once established, it is not subject to random variations since its value depends only on the geometry of the transformer The type of antenna which we are considering is subject to rather large changes in capacity accompanied by only very minor variations in resistance Therefore, in what follows it will be assumed that only the reactive term of the impedance Z_2 is variable Substituting (11 2) in (15) we obtain after some manipulation

$$Z_s = \frac{Z_o}{1 + j(\tan\Psi + \tan\Theta)} \qquad (16)$$

Equation (16) gives the input impedance to a single transmission line in terms of the phase angle of the antenna circuit The impedance presented to the goniometer secondary by the two lines in parallel under the condition where only one antenna has been detuned is

$$Z'_s=\frac{Z_o}{2+j(\tan\Psi+\tan\Theta)} \qquad (17)$$

If the mutual impedance between one secondary and one primary of the goniometer at maximum coupling is given by $Z_M=jX_M$, and the goniometer setting is G, we will have for the primary impedances when all goniometer circuits are self-resonant

$$\begin{aligned} Z_{P_1}&=\frac{2X^2_M}{Z_o}+jX^2_M\cos^2 G\,(\tan\Psi+\tan\Theta)\\ Z_{P_2}&=\frac{2X^2_M}{Z_o}+jX^2_M\sin^2 G\,(\tan\Psi+\tan\Theta)\end{aligned} \qquad (18)$$

It is interesting to note that under condition (7), the resistive component of the goniometer primary impedance is independent of antenna tuning When an antenna becomes detuned, the effect is merely that of introducing a reactive term in the primary circuit as indicated by (18) As would be expected, when $G=45°$ the two primaries have the same impedance under all conditions of antenna tuning

The curve of Fig 5 illustrates the way in which antenna current varies with antenna tuning under typical operating conditions In plotting this curve from equations (18), it was assumed that $G=O$ and the impedance of the generating source was 25% of the primary resistance of the goniometer It is apparent that the higher the resistance of the antenna circuit or of the generating source, the more nearly the current will remain constant with changes in antenna reactance

In the preceding analysis, as was stated at the outset, the coupling circuits have been assumed to be resistanceless The results obtained under this assumption are an accurate representation of the true state of affairs as far as indicating the correct adjustment of the various circuits is concerned It becomes necessary, however, to take account of the losses in the transmission lines, and the antenna coupling unit primary circuit in order to arrive at a quantitative estimate of the degree of dependence of the transfer impedance Z_{S2} upon the antenna impedance Z_2

In considering the effect of line attenuation and transformer primary resistance, it is convenient for purposes of analysis to replace the coupling transformer by its equivalent circuit as shown in Fig 6 Since the resistance of the transformer secondary merely adds to the

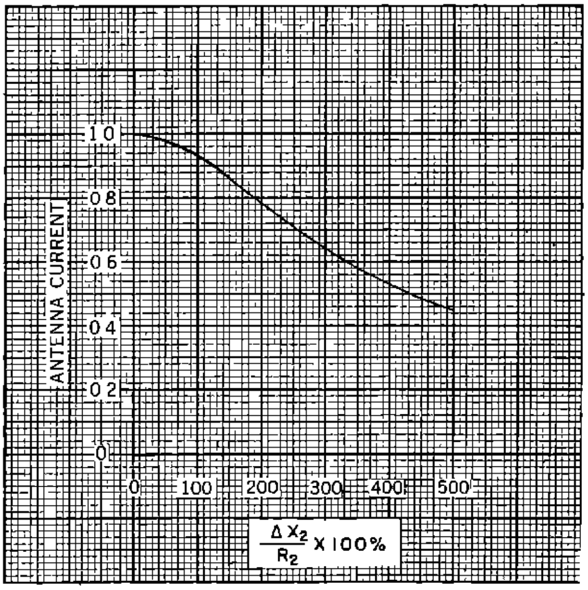
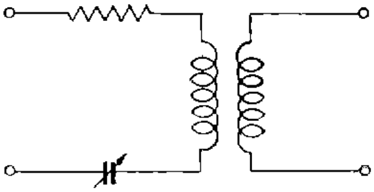
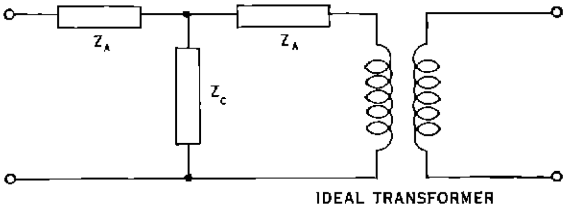


Figure 5 —Curve Showing the Variation of Antenna Current with Antenna Tuning When (7) is Satisfied



ACTUAL CIRCUIT



EQUIVALENT CIRCUIT

Figure 6 —Actual and Equivalent Circuits of Antenna Tuning Unit Coupling Transformer

resistance of the antenna circuit and has no effect upon the transfer impedance we may write for the equivalent circuit parameters

$$Z_A=R_1+jX_1-jX_{12}\sqrt{\frac{R_1+jX_1}{jX_2}} \qquad (19)$$

$$Z_C=jX_{12}\sqrt{\frac{R+jX_1}{jX_2}}$$

The characteristics of the T section may be obtained from the well-known relation

$$\cosh\gamma=1+\frac{Z_A}{Z_C}=\frac{\sqrt{R_1+jX_1}\sqrt{jX_2}}{jX_{12}}=\rho\epsilon^{j\delta} \qquad (20)$$

where

$$\rho=\frac{\sqrt{X_2\sqrt{R^2{}_1+X^2{}_1}}}{X_{12}}$$

and

$$\delta=\frac{1}{2}\tan^{-1}-\frac{R_1}{X_1},\quad \gamma=\alpha+jb$$

the real and imaginary parts of which are the attenuation and phase constants respectively. We have, then, expanding $\cosh\gamma$ and equating reals and imaginaries

$$\cosh\alpha\cos b=\rho\cos\delta \qquad (21)$$

$$\sinh\alpha\sin b=\rho\sin\delta$$

from which

$$\cos b=\sqrt{\frac{1+\rho^2\pm\sqrt{(1+\rho^2)^2-4\rho^2\cos^2\delta}}{2}} \qquad (22)$$

and

$$\sinh\alpha=\frac{\rho\sin\delta}{\sqrt{\frac{1+\rho^2\pm\sqrt{(1+\rho^2)^2-4\rho^2\cos^2\delta}}{2}}} \qquad (23)$$

In a practical system such as the one under discussion, the following approximations are always valid

$$X^2{}_1>>R^2{}_1 \qquad (24)$$

$$\delta<1.0^0$$

We may write then with negligible error

$$\cos\delta=1.0 \qquad (25)$$

$$\rho=\frac{\sqrt{X_1X_2}}{X_{12}}$$

Using (7), (11.1), and (12.1) in (25) we obtain the result

$$\rho=\sin\Theta \qquad (26)$$

and from (22) we have

$$\cos b=\sin\Theta \qquad (27)$$

The angles b and Θ are thus shown to be complementary.

To the degree of approximation which we have adopted (23) reduces to

$$\sinh\alpha=-\frac{R_1}{2X_1}\tan\Theta=\frac{R_1}{2Z_o} \qquad (28)$$

and since in practice $\frac{R_1}{2Z_o}$ is very small we may put

$$\alpha=\frac{R_1}{2Z_o}$$

Summarizing our analysis up to this point, we have determined that the propagation constant of the T section of our equivalent circuit is given by

$$\gamma=\alpha+jb$$

$$\alpha=\frac{R_1}{2Z_o}$$

$$b=90^\circ-\Theta$$

In arriving at these results, it has been assumed that the actual coupling circuit is adjusted so that (7), (11), and (12) are satisfied. The angle Θ is the electrical length of the real line which would be used with the coupling system, as adjusted, to satisfy (7).

Considering now the composite circuit formed by the real transmission line, the T section, and the ideal transformer coupled to the antenna, we will have for the transfer impedance

$$Z_{s2}=Z_2n\cosh P+\frac{Z_o}{n}\sinh P \qquad (29)$$

where

n^2=impedance transformation ratio for the ideal transformer

P=propagation constant for the composite line

Since from (27) the total electrical length of the composite line is shown to be 90°, (29) becomes

$$Z_{s2}=jnZ_2\sinh\alpha+j\frac{Z_o}{n}\cosh\alpha \qquad (30)$$

where

$$\propto = \propto_1 + \alpha$$

$\propto_1$ being the attenuation constant for the real line. Putting $Z_2 = R_2 + jX_2$ we may write

$$Z_{s2} = \frac{(Z_o \cosh^2\propto + n^4(R^2_2 + X^2_2)\sinh^2\propto + 2n^2 Z_0 R_2 \sinh\propto \cosh\propto)^{\frac{1}{2}} \epsilon^{j\Phi}}{n} \tag{31}$$

$$\Phi = \tan^{-1} - \frac{Z_0 \cosh\propto + n^2 R_2 \sinh\propto}{n^2 X_2 \sinh\propto} \tag{32}$$

In practice the antenna reactance is subject to so much wider variations than is the resistance that we may consider the resistance as a constant and write

$$Z_{s2} = \frac{(Z^2_0(\cosh\propto + \sinh\propto)^2 + n^4 X^2_2 \sinh^2\propto)^{\frac{1}{2}} \epsilon^{j\Phi}}{n} \tag{31.1}$$

$$\Phi = \tan^{-1} - \frac{Z_0(1 + \coth\propto)}{n^2 X_2} \tag{32.1}$$

It may easily be demonstrated that variation of the magnitude of Z_{s2} with changes of X_2 is only of minor importance in its effect upon course alignment as compared with variations in the phase, Φ. Let us then focus our attention upon the relation (32.1).

It is seen that if $\propto = 0$

$$\Phi = \tan^{-1}(-\infty) = 90°$$

and is entirely independent of the value of X_2. Thus the lower we make the attenuation of the composite circuit, the more nearly we may approach this ideal condition. The curves of Fig. 7 show the phase angle Φ as a function of X_2 for various line attenuations. In Fig. 8, similar information is presented in a slightly different manner. Here the phase shift and course shift which may be expected to occur with a fixed amount of antenna detuning are plotted against the attenuation of the line being used. These curves illustrate forcefully the necessity for using transmission lines and coupling transformers having the lowest possible losses.

Up to this point we have studied the behavior of our circuits, always under the assumption that they were adjusted to satisfy (7). Let us consider now the effects of departing from (7) as is necessary in securing nonreciprocal course alignments.

We will assume that our coupling transformer is adjusted so that its transfer impedance is given, to the degree of approximation adopted in the preceding work, by $\frac{Z_0}{n}\epsilon^{jb}$. When this is operated in conjunction with a transmission line of electrical length Θ, we will have then for the phase angle of the transfer impedance referred to the sending end of the line

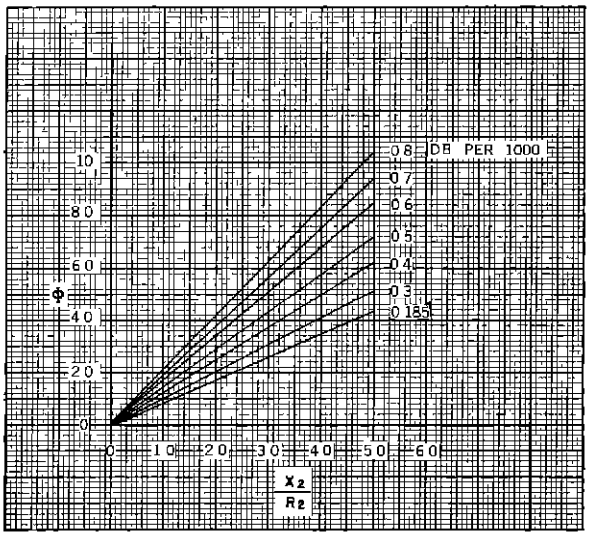


Figure 7.—Curves Showing the Variation of Phase Between a Pair of Antennas as a Function of Antenna Tuning for Various Transmission Line Attenuations

$$\Theta' = b + \Theta$$

Since we are not now restricted by (27), we must determine the value of our transfer impedance from (29) by inserting

$$P = \propto + j\Theta'$$

We have

$$Z_{s2} = n(R_2 + jX_2)\cosh(\propto + j\Theta') + \frac{Z_0}{n}\sinh(\propto + j\Theta') \tag{30}$$

Putting

$$n^2 R_2 = Z_0$$

$$n^2 X_2 = Z_0 \tan\Psi$$

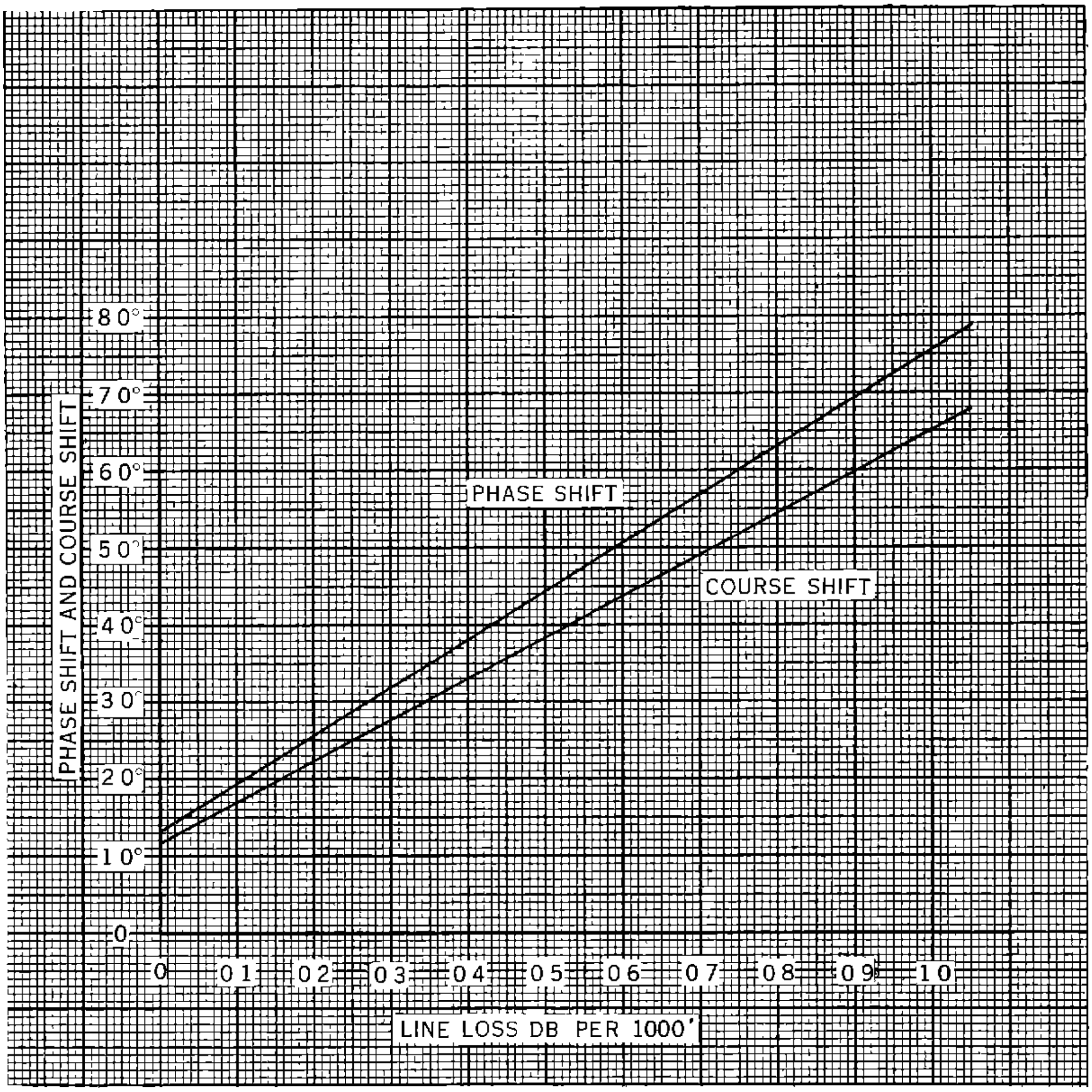


Figure 8.— Curves Showing the Phase Shift and Course Shift Which May be Expected to Occur for a Fixed Antenna Detuning $\left(\frac{X_2}{R_2}=3.0\right)$ as a Function of Line Attenuation. These Curves do not Pass Through the Origin Because of the Losses in the Transformer Primary

and expanding the hyperbolic functions we obtain

$$Z_{s2}=\frac{Z_0}{n}(\cosh\alpha\cos\Theta'-\tan\Psi\sinh\alpha\sin\Theta'$$
$$+\sinh\alpha\cos\Theta')+j\frac{Z_0}{n}(\sinh\alpha\sin\Theta'$$
$$+\tan\Psi\cosh\alpha\cos\Theta'+\cosh\alpha\sin\Theta')$$

which may be written

$$Z_{s2}=\frac{Z_0}{n}[(\cosh\alpha+\sinh\alpha)^2+\sin 2\Theta'\tan\Psi$$
$$+(\sinh^2\alpha\sin^2\Theta'$$
$$+\cosh^2\alpha\cos^2\Theta')\tan^2\Psi]\epsilon^{\frac{1}{2}j\Phi} \qquad (31.2)$$

where $$\Phi=\tan^{-1}\frac{\sin\theta'+\dfrac{\tan\Psi\cos\theta'}{1+\tanh\alpha}}{\cos\theta'-\dfrac{\tan\Psi\sin\theta'}{1+\coth\alpha}} \qquad (32.2)$$

Since we are primarily interested in the rate at which Z_{s2} and Φ vary with Ψ, let us form the derivatives of these functions and study their behavior. It may be shown that

$$\frac{d\Phi}{d\Psi}=\frac{\sec^2\Psi\left(\dfrac{\sin^2\theta'}{1+\coth\alpha}+\dfrac{\cos^2\theta'}{1-\tanh\alpha}\right)}{1+\sin 2\theta'\tan\Psi\left(\dfrac{\coth\alpha-\tanh\alpha}{2+\tanh\alpha+\coth\alpha}\right)+\tan^2\Psi\left(\dfrac{\sin^2\theta'}{(1+\coth\alpha)^2}+\dfrac{\cos^2\theta'}{(1+\tanh\alpha)^2}\right)} \qquad (33)$$

and

$$\frac{d|Z_{s2}|}{d\Psi}=\frac{Z_o\sin 2\theta'\sec^2\Psi+2\tan\Psi\sec^2\Psi(\sinh^2\alpha\sin^2\theta'+\cosh^2\alpha\cos^2\theta')}{2n[(\cosh\alpha+\sinh\alpha)^2+\sin 2\theta'\tan\Psi+(\sinh^2\alpha\sin^2\theta'+\cosh^2\alpha\cos^2\theta')\tan^2\Psi]^{\frac{1}{2}}} \qquad (34)$$

Evaluating these at $\Psi=0$ which is the proper antenna tuning for our transformer equivalent circuit, we obtain simply

$$\frac{d\Phi'}{d\Psi}_{\Psi=0}=\frac{\sin^2\theta'}{1+\coth\alpha}+\frac{\cos^2\theta'}{1+\tanh\alpha} \qquad (35)$$

$$\frac{d|Z_{s2}|}{d\Psi}=\frac{Z_o}{2n}\,\frac{\sin 2\theta'}{\cosh\alpha+\sinh\alpha} \qquad (36)$$

(35) and (36) are shown graphically in Figs. 9 and 10, respectively. The numerical value of these differential coefficients is a measure of the degree of dependence of the transfer impedance upon the impedance of the antenna circuit. As would be expected, each of the curves passes through a minimum at $b+\theta=90°$ which is the phase angle at which (7) is satisfied. It is interesting to note that for $b+\theta=90°$ the amplitude of Z_{s2} is absolutely independent of Ψ for small variations, while the phase is still dependent to a slight degree on Ψ because of losses in the line and coupling system.

EQUIPMENT

In specifying the equipment for the new ranges special attention has been devoted to securing well coordinated operation of all of the component parts in accordance with the foregoing theory. The principal aim has been to provide for maintenance of the established course alignments within a tolerance of 1.5 degrees under all reasonable operating conditions. In order to insure continuity of service those items of equipment in which failure is most likely to occur have been installed in duplicate with provisions for switching to the standby unit in the event of a breakdown of the regular equipment. Standby engine driven generators are installed in the range building to take over in case of a failure in the commercial power source.

In Fig. 11 is shown a photograph of the transmitter. This is a dual unit with two independent radio-frequency channels operating on frequencies differing by 1020 cycles. One of the channels delivers 400 watts of carrier power, which may be modulated 70% by speech, to the center antenna. The other delivers 275 watts of unmodulated energy through the coupling system to the four corner antennas. The audible tone signals at the receiving end are produced by the 1020 cycle beat between the carrier, and the single sideband radiated from the corner antennas. This beat note is maintained by the frequency difference of two matched A-cut quartz plates which supply the primary excitation to the two channels of the transmitter.

The coupling unit shown in Figs. 12 and 13 includes two link circuit relays, two keying devices, a course shifting pad, the goniometer, and the artificial lines, together with the necessary tuning condensers and other auxiliary equipment. The relays and keying devices are provided in duplicate as a standby measure, and to simplify the switching operations in changing from one transmitter to the other.

In the design of a goniometer, one of the most important considerations is that of obtaining a variation of mutual inductance with rotation which approximates very closely to a sinusoidal function under operating conditions. In the

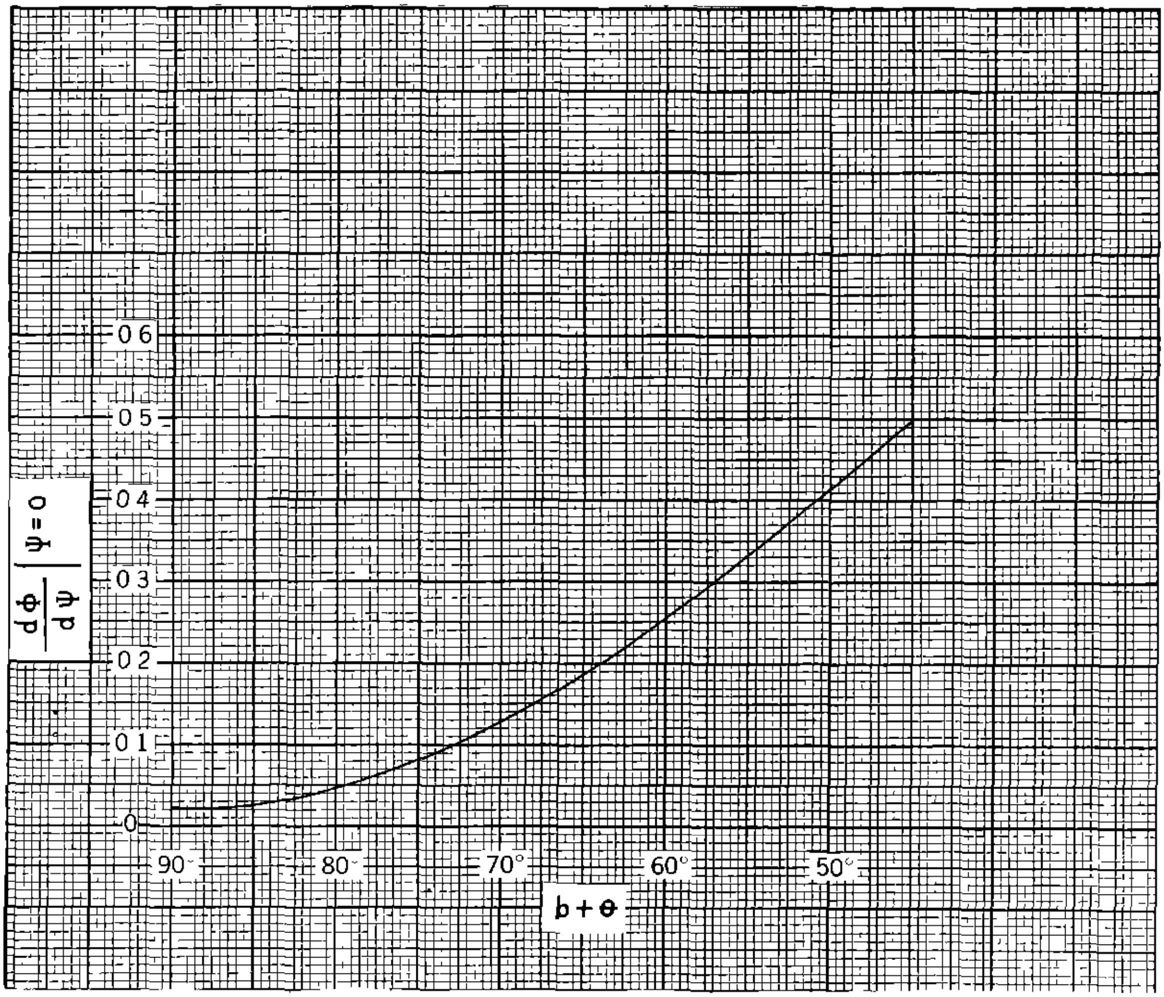


Figure 9.—Curve Showing the Rate at Which the Phase Between a Pair of Antennas Changes with the Phase of one Antenna Circuit as a Function of the Total Transmission Line and Terminating Network Phase Angle. The Condition $B+\Theta=90°$ is Equivalent to (7).

present equipment it was required that the mutual inductance should follow the law

$$M = M_0 \sin G$$

within a tolerance specified by

$$\frac{M - |M_0 \sin G|}{M_0} < .04$$

with the further restriction that

$$\frac{M(at\ 0°)}{M_0} < .01$$

The margin by which these minimum requirements have been exceeded is illustrated by the experimentally determined goniometer characacteristic of Fig. 14. The value of M_0, the mutual inductance at maximum coupling has been chosen such that the impedance appearing at the primary terminals during normal operation is from 50 to 200 ohms depending upon the operating frequency. It has been determined that this range of impedances permits efficient loading of the transmitter and is optimum for the reduction of arcing at the contacts of the link circuit relay.

The goniometer rotor is mounted on a shaft which is supported at each end by ball bearings. A large scale dial, attached directly to the shaft at the front panel, permits setting of the goniometer within approximately one quarter degree.

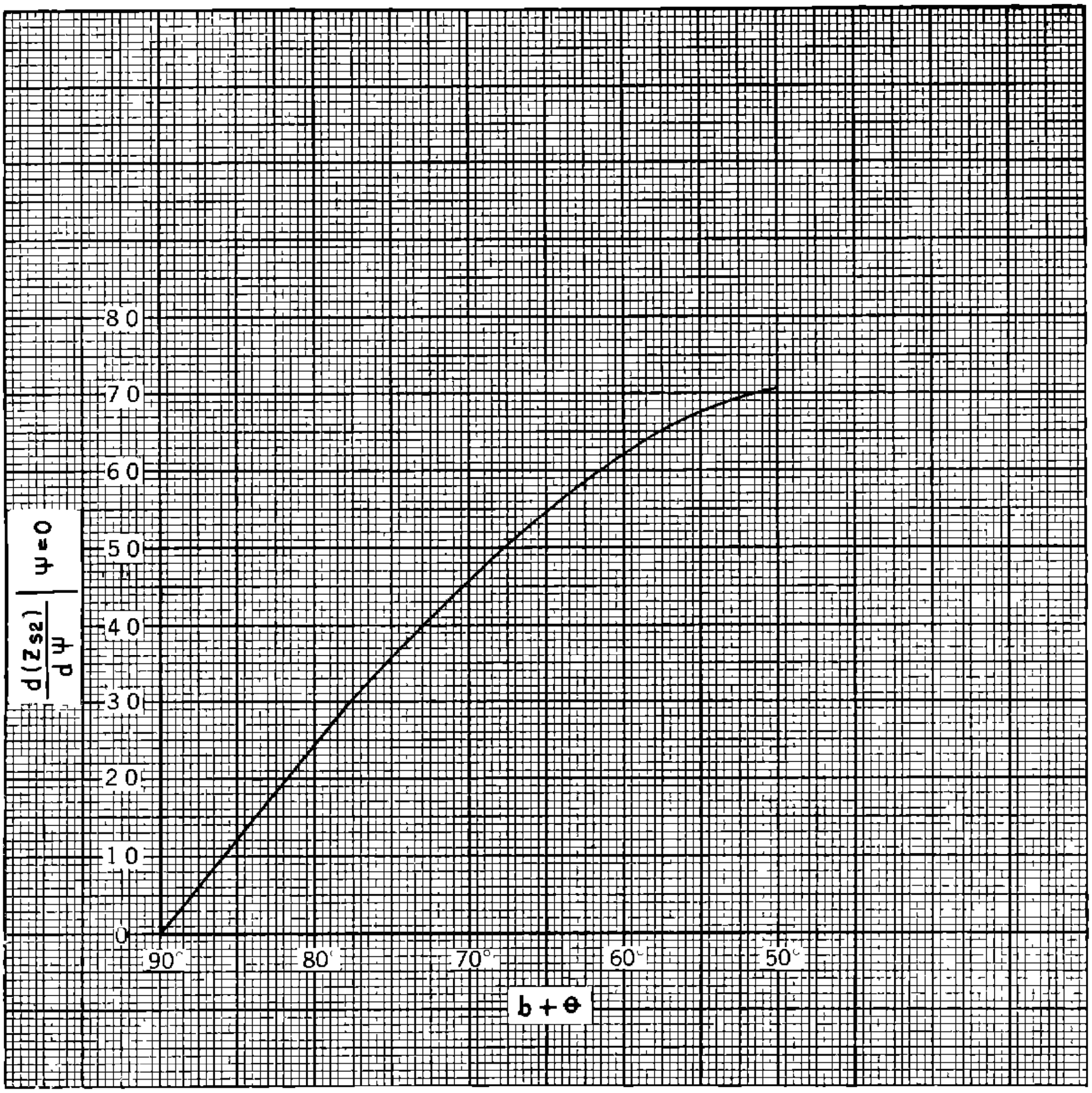


Figure 10.—Curve Showing the Rate of Change of the Magnitude of Transfer Impedance with Antenna Phase as a Function of the Total Transmission Line and Terminating Network Phase Angle

The artificial lines employ a variable inductance of the sliding contact type in the series arms, and rotating plate variable condensers in the shunt arms. The controls are ganged so that when the length of one line is increased, the length of the opposite line is automatically decreased a like amount. This maintains the electrical center of the system at the sending ends of the lines where power is applied. It is possible to set the lines to any desired length, and the correct characteristic impedance, by the adjustment of three dials for each pair of lines in accordance with calibration curves which are supplied with the equipment.

In selecting transmission lines for use at the new stations, our theoretical proof of the effect of attenuation upon course stability was the guiding principle. A further requirement was that the line should have no external field, and should be adaptable to installation under

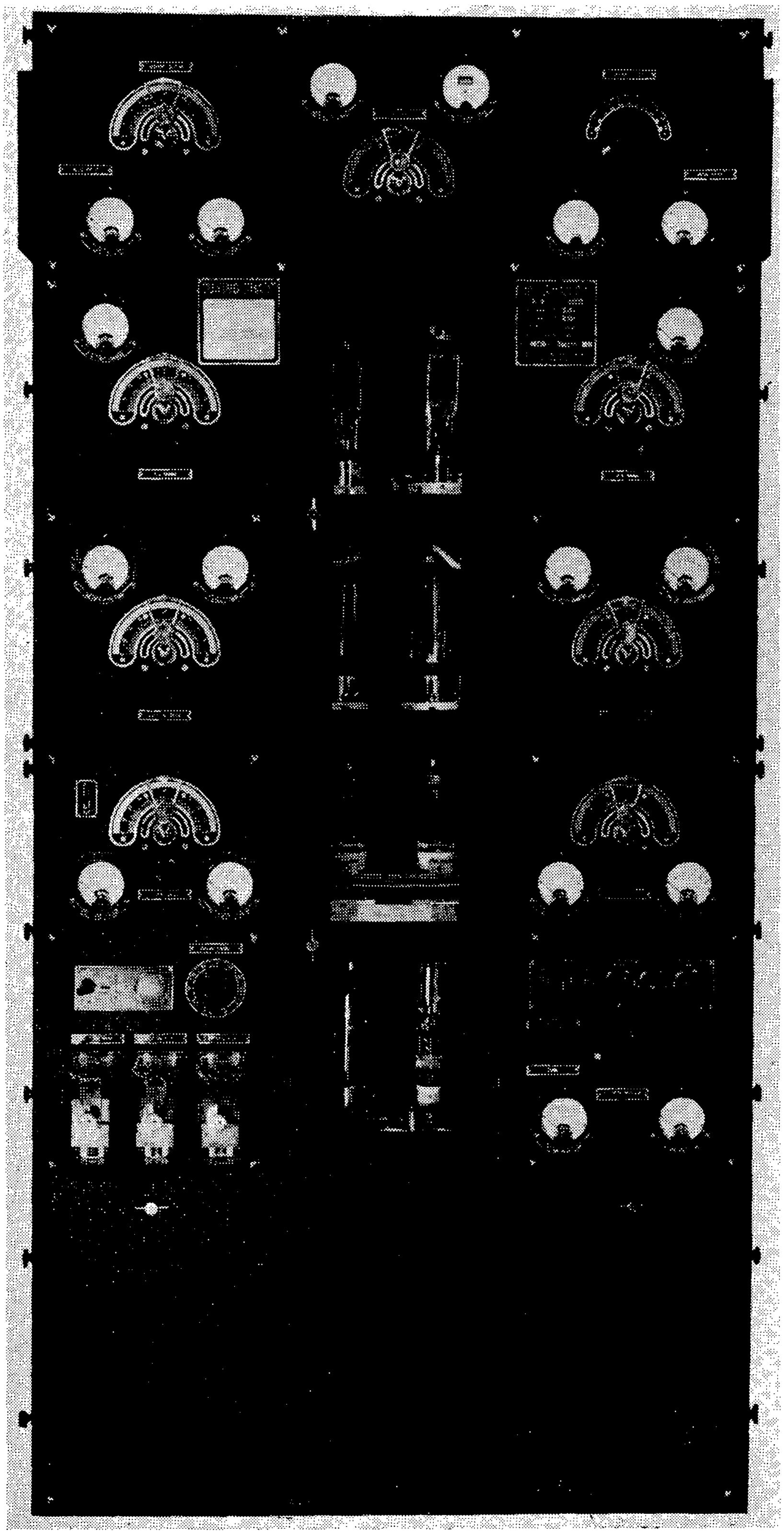


Figure 11.—Front View of Two-Channel Simultaneous Range and Broadcast Transmitter.

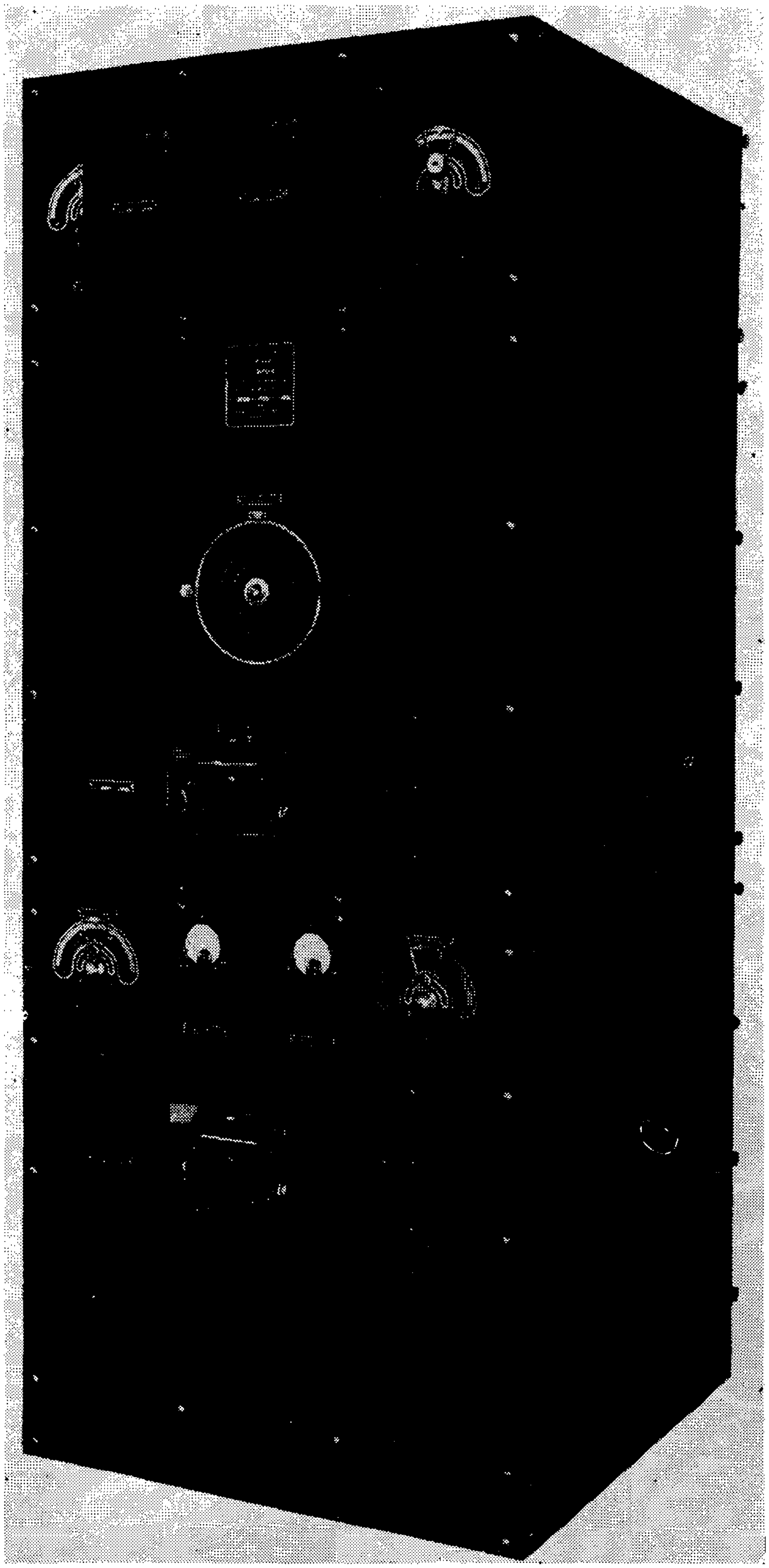


Figure 12.—Front View of Radio Range Coupling Unit.

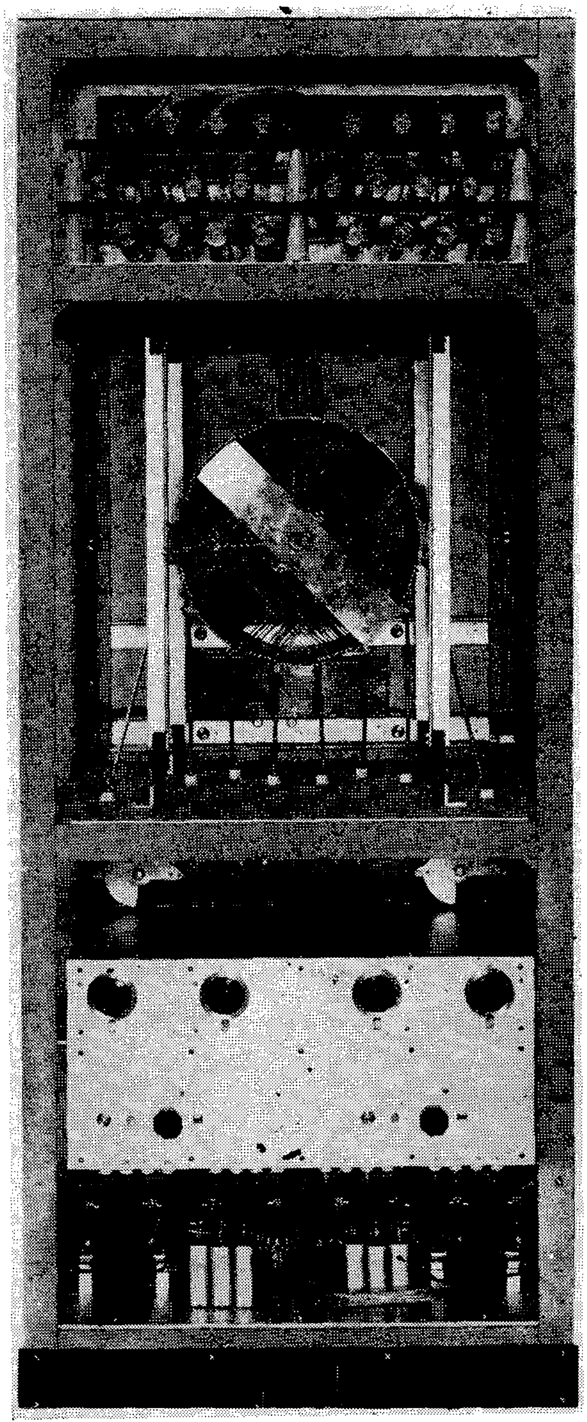


Figure 13.—Rear View of Radio Range Coupling Unit.

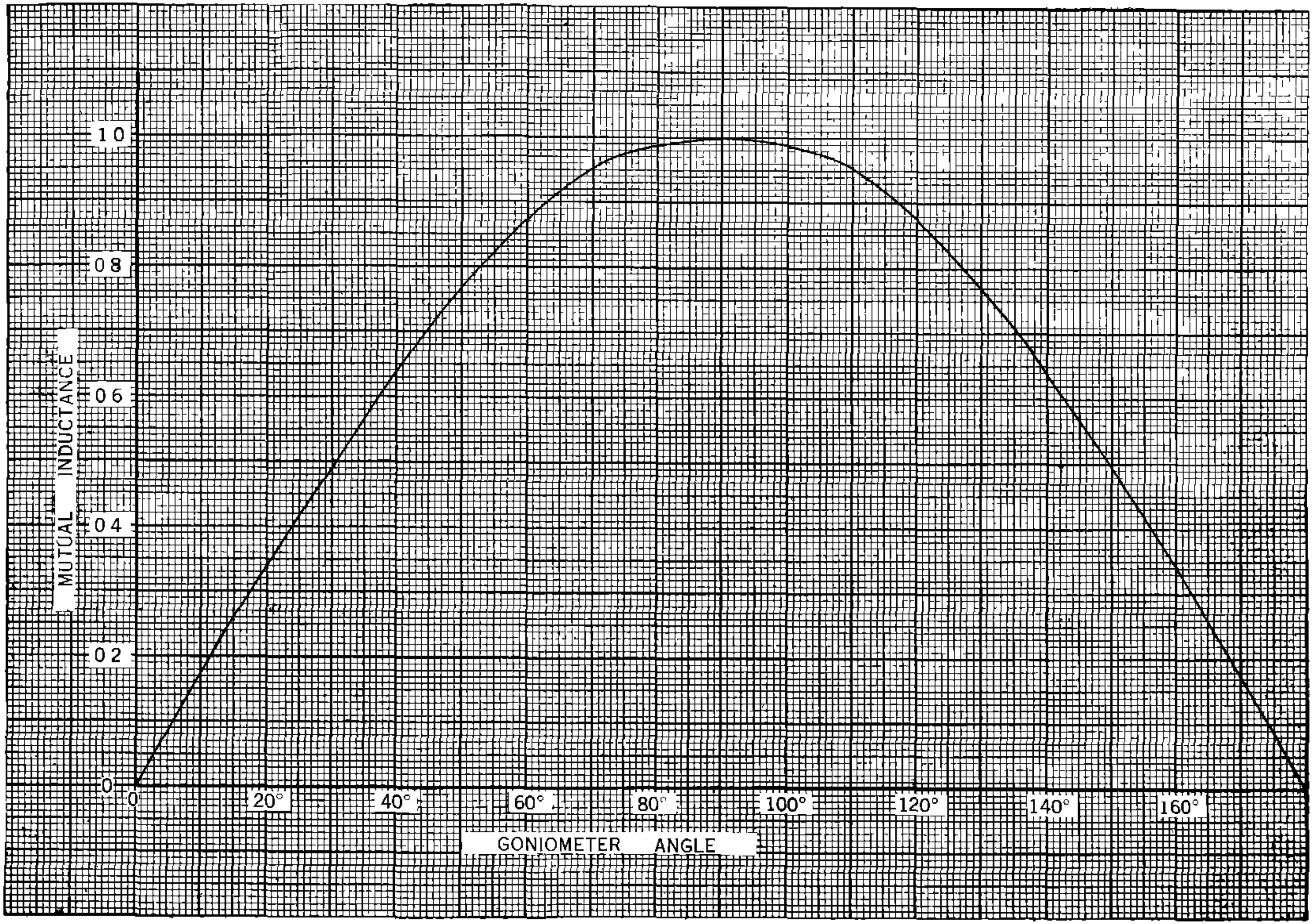


Figure 14 —Experimentally Determined Goniometer Characteristic

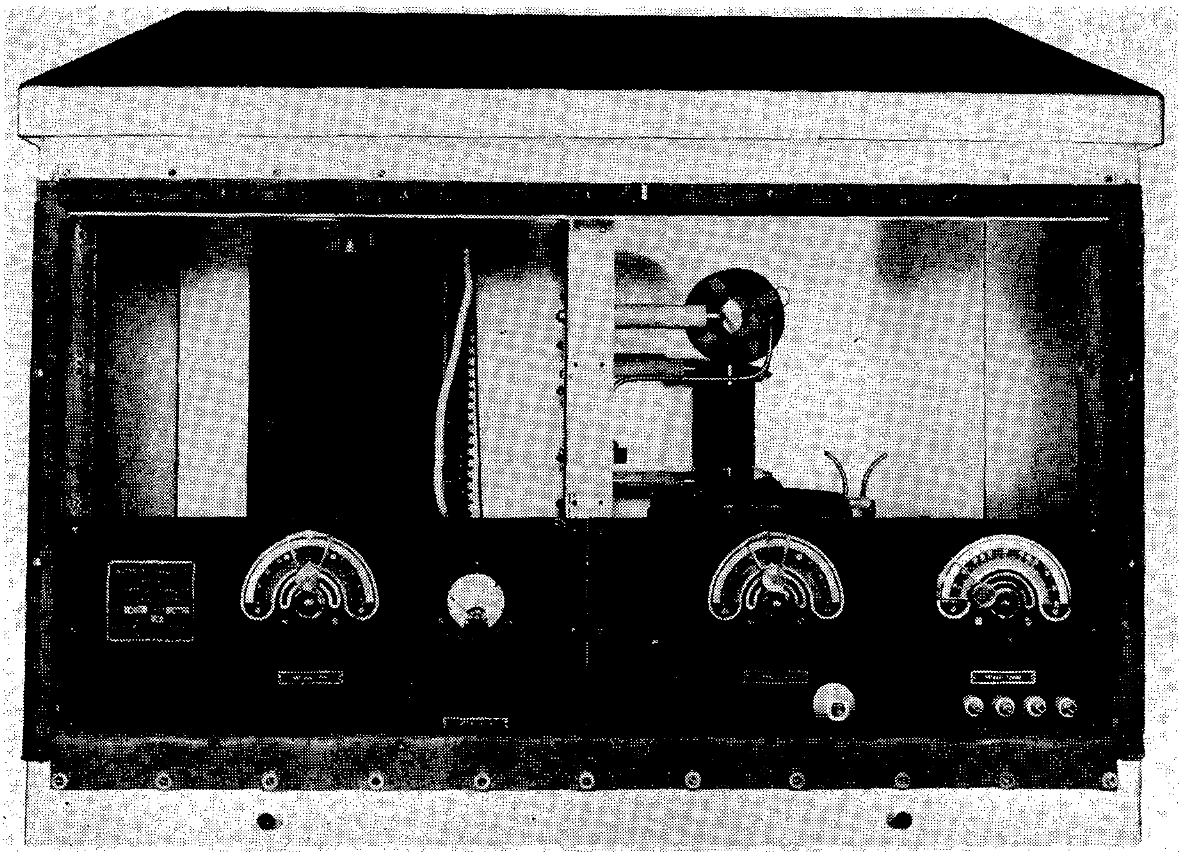


Figure 15.—Antenna Tuning Unit, Cover and Shields Removed.

ground. The concentric conductor type of line meets both of these criteria satisfactorily, and has accordingly been adopted. In effecting a compromise between cost and attenuation, it appeared that the ⅞-inch size of line was optimum. In physical construction, this line consists of a ⅞-inch outer conductor of hard drawn copper tubing with a wall thickness of .045 inch, and a ¼-inch inner conductor supported concentrically by isolantite doughnut-shaped insulators spaced every 6 inches. The calculated value of characteristic impedance is 68.5 ohms. Actually, because of the presence of the insulators, the measured value is 65.3 ohms. The attenuation at 300 kilocycles has been determined by measurement to be 0.185 decibel per thousand feet, and the phase constant at this frequency is 115.0 degrees per thousand feet which corresponds to a velocity of propagation of 0.955 times the free space velocity. At the older range stations, two-conductor parkway cable, having an attenuation at 300 kilocycles of approximately 1.0 decibel per thousand feet was used. The improvement in course stability resulting from the use of the new lines as compared to the old lines may be seen by reference to Fig. 8.

The antenna tuning unit shown in Fig. 15 is constructed in a weatherproof aluminum house and one unit is mounted at the base of each tower upon a framework of steel angles. The loading inductance is continuously variable over the range 0–900 microhenries by means of taps, and an adjustable rotor coil. The coupling transformer has a primary inductance of 200 microhenries, and a maximum mutual inductance of 60 microhenries. The primary is wound with heavy litz to reduce losses to a minimum since losses in this circuit affect the course stability. The primary Q at 300 kilocycles is 350, which corresponds to a resistance of approximately 1.0 ohm. The variable primary tuning condenser has a capacity of 0.001 microfarad, and a plate spacing of ⅜″ which gives it a peak rating of 4,500 volts. Fixed condensers are provided to operate in parallel with the variable condenser to give a total continuous range of capacity of from 0 to 0.005 microfarad.

In addition to the antenna tuning equipment, each tuning house includes choke coils for tower lighting and a lightning arrester to protect the equipment in case the antenna is struck. The method of lighting employed is a single wire system in which the tower itself acts as the return circuit. The tower is effectively grounded by the lighting choke as far as power frequencies are concerned, but retains a high impedance to ground at radio frequencies.

In choosing a tower radiator for radio range operation in the 200–400 kilocycle band, a number of factors must be taken into account. From the standpoint of radiation efficiency a very high tower is indicated. However, since radio ranges are generally located in the vicinity of air terminals, the towers must not be so high as to constitute a hazardous obstruction to aircraft. Economic considerations are also a factor tending to limit the height of the antenna. As the best all around compromise, the towers which are used are 125 feet high, and taper from a 6-foot square cross section at the base to a 1-foot square section at the top. The four legs of the tower rest on porcelain compression insulators, and are held down by means of tie rods running to a fifth insulator at the center of the base. The entire insulated tower is supported on an 8-foot steel substructure which in turn is anchored into a reinforced concrete pier rising approximately 2 feet above ground level. Each tower base is surrounded by a wire mesh counterpoise supported at a level 2 feet below the insulators by structural steel columns. The function of the counterpoise is to minimize the possibility of variations in antenna capacity with changing conditions of the earth and vegetation in the immediate vicinity of the tower base.

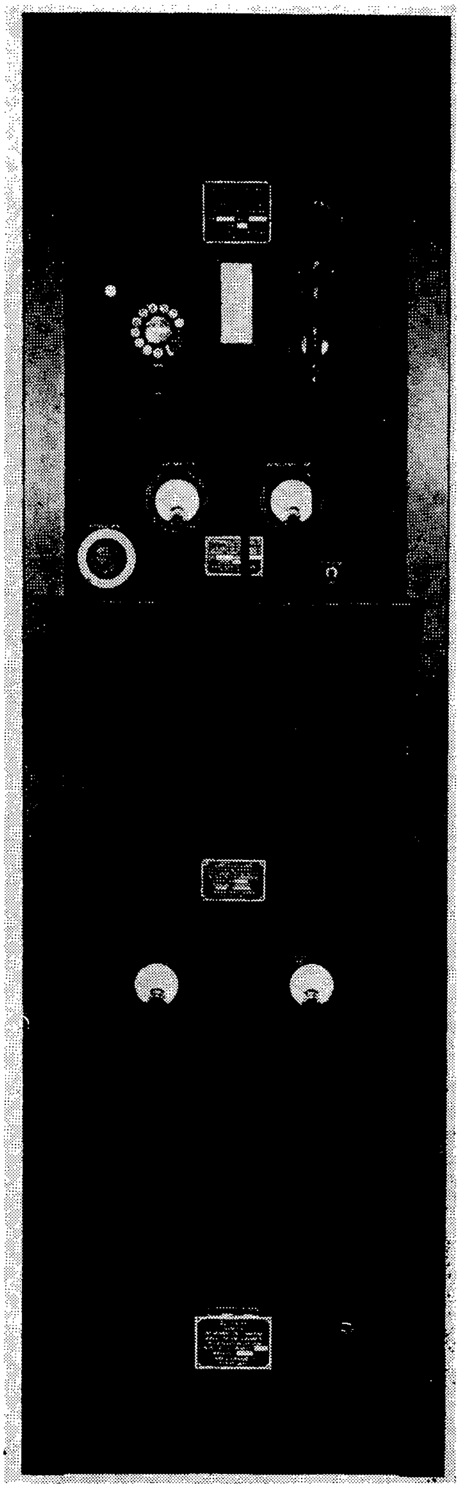


Figure 16.—Station Remote Control Rack.

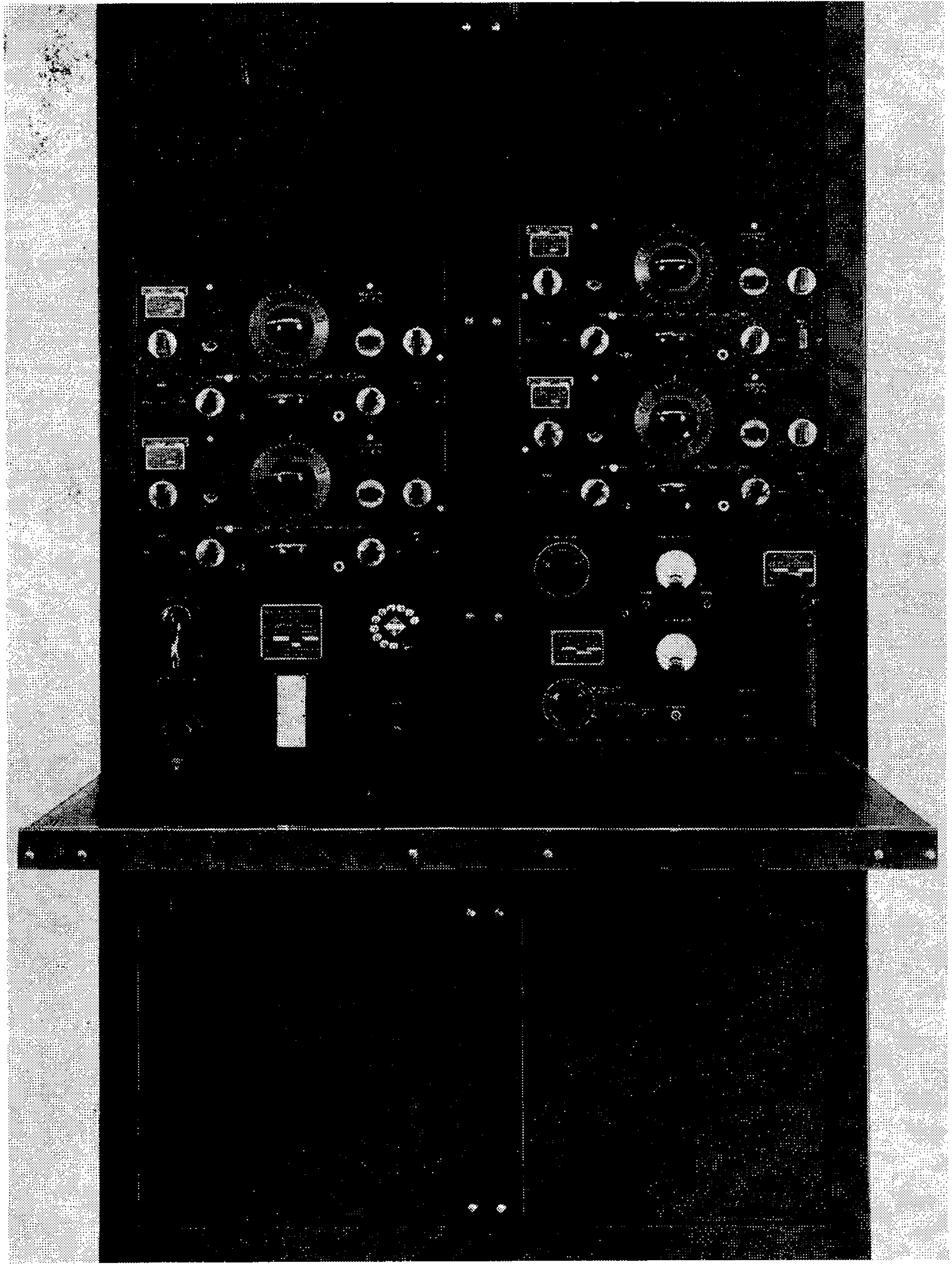


Figure 17.—Operator's Remote Control Racks and Desk.

Fig. 16 shows the range station control rack which contains all of the switching and auxiliary equipment required for the operation of the range. The upper panel carries the intercommunicating phone and a two-motion Strowger machine switch which controls all of the switching operations at the station, and may be operated by either the local dial or over a telephone line by a remote dial. The next lower panel is a constant level amplifier which prevents overmodulation of the carrier during speech broadcasts and holds the average modulation at a relatively high level. Below the desk is installed a band-elimination filter which eliminates frequencies in the neighborhood of 1020 cycles from the voice during broadcasts, and thus reduces interference between speech and range signals. A line equalizer which corrects the frequency characteristic of the telephone line to the remote-control quarters is located immediately below the filter panel. The lower compartment contains a voltage regulator and a rectifier which supplies power for operation of the various relays of the control system.

The operator's rack at the remote-control quarters is shown in Fig. 17. The control equipment consists of the interphone and dial mounted in the left rack, and the microphone to line amplifier and monitoring unit located in the right-hand rack. All of the other space in the racks is taken up by receivers for two-way communication with aircraft.