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Report on

The Medium Frequency Adcock Direction Finder

and

A Resistance Goniometer

by

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NAVAL RESEARCH LABORATORY

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Report

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The Medium Frequency Adcock Direction Finder
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NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
WASHINGTON, D. C.

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ABSTRACT

This report covers the work done thus far in investigating a satisfactory solution for the medium frequency, polarization error free, shore navigational direction finder problem. There is described the fixed Adcock direction finder which was designed, installed, and studied for this purpose. Following this, mathematical analyses and criteria are given for the degree of stability and balance required for good bearings in such a system. Quantitative analyses of the effects of unbalance and the simple method utilized for measuring small variations of antenna impedance (unbalance) with great accuracy as given herein may be used in conjunction with a suggested method for determining the suitability of fixed Adcock direction finder sites and ground networks. Also reported are the unsatisfactory results obtained with a new goniometer of the resistance bridge type despite the design used to realize high resolving power in the Laboratory constructed model. In addition, the behavior of the minimum while taking bearings on stations, the pick-up factor obtained and the highly objectionable precipitation static observed with the Adcock direction finding system are discussed.

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AUTHORIZATION

1. This problem was authorized by Bureau of Engineering letter C-S67/69(7-28-R8) of 30 July 1938 to the Naval Research Laboratory, and its present status is herewith reported upon.

STATEMENT OF PROBLEM

2. The object of this investigation was:

(a) To study the fixed Adcock direction finder in the medium frequency range (300 - 1000 kilocycles);

(b) To use the information as a means for determining the performance required of a "Shore Navigational Direction Finder," with a view of developing a direction finder approaching such requirements; and

(c) To investigate the performance of a new type of goniometer which utilizes the resistance bridge principle.

3. The increasing necessity for accurate and reliable radio direction finding has focused more and more attention upon the Adcock direction finder as a means for overcoming the serious "night" and "airplane" errors inherent in direction finders of the "loop" type. (Space separated loops can be arranged to balance out polarization error.) A fixed Adcock installation was made at the Naval Research Laboratory for use in the 300 - 1000 kilocycle range, and the results given in this report are based upon the studies made of it.

KNOWN FACTS BEARING ON THE PROBLEM

4. The frame aerial (loop) direction finder, while extensively employed for marine and navigational purposes, is fundamentally limited by polarization error (see (a) in bibliography) (often referred to as "night effect") which makes reliable direction finding difficult and sometimes impossible at night except for relatively short distances. Polarization error is also encountered both by day and night when bearings are taken from the ground on aircraft; it is then commonly referred to as "airplane effect."

5. In August 1918, F. Adcock[(b)] disclosed an arrangement of spaced vertical antenna for the elimination of "aeroplane effect" in radio direction finding. Although the working principle of the Adcock collector system is basically simple, its large spacing and its application to practice involved so many serious difficulties that for a number of years it was almost completely neglected.

6. In 1921, the theory of "night effect" was published by T. L. Eckersley[(c)] who, in the course of obtaining more conclusive evidence as to the cause of bearing variations, showed that pick-up by the loop of the horizontal component of the radio wave's electric vector was responsible for polarization errors. During 1926, the English described a method[(d)]

for using Adcock's aerial system as a means for overcoming polarization error. Their work has been responsible for the renewed interest in the Adcock system of direction finding. The Adcock spaced aerials (i.e., a pair of space separated vertical antennas) act in part as an open "loop" aerial, whose top member has been omitted and whose lower member is rendered ineffective to pick up. In this manner, the desirable* directive properties of the "loop" are retained and the aerial system responds only to the vertical, polarization error free, component of the radio waves' electric vector. The large spacing required by the Adcock aerials makes its rotation difficult and slow, but by utilizing a goniometer in conjunction with crossed open "loops" (i.e., two pair of space-separated vertical antennas) a fixed stationary Adcock system(e)(f)(g)(h) is obtained which can be made to closely simulate the performance of a rotating Adcock system of equivalent spacing.

THEORETICAL CONSIDERATIONS

7. Theoretical Limitations of Radio Direction Finding. The demand for more reliable and more accurate radio bearings has resulted in the active development of better direction finders. Practical limitations, however, have prevented radio direction finding accuracy and reliability from approaching the theoretical limits set by optical considerations. For example, the deviations caused by the vicinity immediate to the direction finder and the non-linearities(i)(j) of the medium traversed by the wave; namely, the ground and the ionosphere, become limiting factors. In particular, scattering (direction of propagation change) of the radio wave by random ionic clouds probably restricts the ultimate accuracy of all types of radio direction finders at distances where the sky wave dominates the ground wave. "Limitations of Radio Direction Finding,"(k) the title of an article previously published by the Naval Research Laboratory, treats this subject in greater detail.

8. Polarization, Diversity, and Instrument Error Limitations. Much before the theoretical limitations are reached, scattering effect, variable electrical characteristics of the medium traversed by the radio wave, polarization error and instrument error enter; these prevent the theoretical limits of accuracy from being reached.

8. (a) Polarization error:

(1) Propagation and Polarization Phenomena: Assuming that an observer could instantaneously follow the electrical mechanism of radio wave propagation, he might notice that as a radio wave emanated from a distant radiating element toward him, that it generally consisted of two propagated components. One of these components (or rays) would appear to have traveled the expected optical path (earth's curvature neglected) from the radiating element, while the other ray would appear to have been optically reflected from some surface above the intervening space which acted in the nature of a mirror. If the observer could compare the propagation behavior of the two rays, he would notice first, that the direct

*Refer to Fig.3, reference (f), for a more complete comparison of the response patterns obtained with the "loop" and Adcock system of collectors.

or ground ray was attenuated more rapidly with distance than the reflected ray; second, that the reflected ray underwent multiple reflections with respect to the upper mirror and the ground as a lower mirror, thereby giving a relatively simple interference pattern on the earth's surface; third, that the simple interference pattern is made complicated by the presence of the ground wave, the non-linearity of the sky mirror (ionosphere) and the discontinuities of the ground mirror (terrain) traversed; fourth, that close to the radiating element the ground wave predominated, while at remote distances the sky wave alone was responsible for the interference pattern on the earth's surface. If the observer could distinguish between the forces responsible for each ray's propagation, he would notice that both waves possessed an electric as well as a magnetic force which were constantly oscillating in the plane of the wave front, and that these forces were always in time phase and space quadrature with respect to one another.

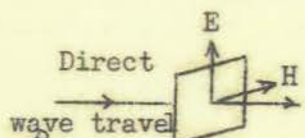
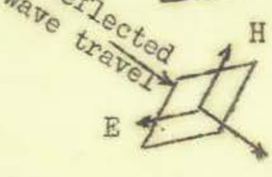
Were he to compare the orientations of the electric forces in the two waves he would observe that:

(1) In the ground wave, the electric force was usually vertical in the plane of the wave front.

(2) In the reflected wave, the position of the electric force varied each time it was reflected and depended upon the angle of reflection.

(3) The particular position of an electric vector could be considered as the resultant of a vertical and a horizontal electric vector, both of which were in the plane of the wave front.

In references (a) and (1) it is shown that the position of the electric vector affects the accuracy of "loop" type direction finders and determines the type of polarization possessed by the wave. The principal positions assumed by this vector and the type of polarization resulting are listed below.

Type Polarization Designation	Type Polarization Description	Position of Forces in Wave Front Electric=E	Position of Forces in Wave Front Magnetic=H	Position of Forces in Wave Front Graphic Representation	Wave Types Generally Found In
A	Normal	Vertical	Horizontal		Direct or Ground.
B*	Normal	Vertical	Horizontal		Direct and Reflected.
C*	Abnormal	Horizontal	Vertical		Reflected.

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*NOTE:

(1) The presence of a "C" component simultaneously with an "A" or "B" component gives rise to a resultant elliptically polarized wave. Reflected waves generally contain the "B" and "C" components, therefore are usually elliptically polarized.

(2) The time phase difference between the electric vectors in the "A", "B", and "C" components can cause fading of the resultant electric vector, depending upon their relative phase and amplitude differences.

(2) Night Effect: It can be readily shown[a] that the presence of components "A" and "B" permits satisfactory direction finding accuracy, but that the presence of the "C" components can introduce as much as 90° error in the "loop" type direction finders, depending upon the instantaneous magnitudes of the three components. Since the ground ray is more rapidly attenuated than the reflected wave, particularly as the frequency is increased (i.e., ground losses increase with frequency), one may expect greater bearing errors with the "loop" type collector at higher frequencies and greater distances because, the probability of the presence of the "C" component has increased and because the reflected wave becomes more intense during nocturnal transmissions. Bearing errors introduced at these times have commonly been termed "due to night effect." The "C" component differs from the other components in that its plane of polarization has been rotated 90 space degrees; it has become more accurately defined as the "Abnormally Polarized Wave," whose existence may be evident at day and which is generally much stronger at night.

(3) Airplane Effect: Direct waves from radiating elements remote from the ground (airplane transmission) are known to propagate "abnormally" as well as "normally" polarized[a] components, unless special precautions are taken with the radiator. As a consequence, polarization bearing errors observed with airplane transmissions are sometimes termed "due to a airplane effect."

(4) Overcoming Polarization Error with the Adcock Type Collectors: In paragraph 6, a rotatable open "loop" collector system is described which is non-responsive to the "C" or "abnormally polarized" component. It is named after Adcock, one of the early workers among the British pioneers in this field. In addition to its non-responsiveness to the "C" component, the Adcock collectors discriminate* against the "B" component of the reflected wave in such a manner that it responds in direct proportion to the sine of the angle which the reflected wave makes with the exposed length of the antenna; thus the efficiency of the Adcock collectors on tilted waves is reduced and becomes zero for a wave of vertical descent. Since the sky wave is more intense than the ground wave at the higher frequencies, such discrimination becomes more evident and objectionable due to the substantial loss in Adcock direction finder sensitivity for waves of appreciable elevation angle at these frequencies. The high frequency rotatable Adcock direction finder, Model DT-2, developed by the Laboratory, successfully overcomes this "discrimination effect" by providing means for tilting its collectors with respect to the elevation angle of the sky wave.

Refer to note, bottom of page 2.

8. (b) Diversity errors: Assuming that a system responds only to the "A" and "B" components, it is shown in reference (m) that a Rotatable Adcock Collector is theoretically free from bearing errors, and that the resulting current in such an Adcock collector system responding to a direct and reflected wave is, (Refer to Fig.A, Plate 10):

$$I_R = E_G \sin\left(\frac{\pi D}{\lambda} \cos\phi\right) \cdot \cos\left(\omega t + \frac{2\pi D_o}{\lambda}\right)$$

$$+ E_A \sin\left(\frac{\pi D}{\lambda} \cos\phi \sin\theta\right) \cos\left(\omega t + \frac{2\pi D_1}{\lambda}\right) \qquad (1)$$

Where I_R = Resultant current in pick up coil (same as I_A in ref.(m).)

$E_G \approx$ The electric intensity of the direct or ground wave.

$E_A \approx$ The electric intensity of the sky wave.

λ = Wave length of the wave in meters.

D = Spacing between the antennas in meters.

D_o = Optical path of the transmitted direct (ground) wave measured to center of the antennas, in meters.

D_1 = Optical path of the transmitted sky (atmospheric) wave measured to center of the antennas, in meters.

ϕ = Horizontal or azimuth angle of wave in degrees (relative to antenna plane) assumed to be the same for the ground and sky wave.

θ = Vertical or incidence angle of the sky wave in degrees. (relative to the vertical).

$\omega = 2\pi f$ = Angular velocity of wave in radians.

Thus whatever the magnitude of E_G or E_A, I_R (the resultant current due to a rotating Adcock system) goes to zero whenever the azimuth angle of the wave, $\theta = \pi/2$ or $3\pi/2$. Hence the rotating Adcock system gives the correct bearing in the presence of the direct wave or the sky wave or both, provided both waves have the same azimuth.

For a Fixed Adcock System, using an inductive goniometer, the resultant search coil current, I'_R, is obtained as follows:

Referring to Fig. B of Plate 10:

Let I_A = The current flowing in fixed coil L_A due to antenna pair AA'

I_B = The current flowing in fixed coil L_B due to antenna pair BB'

From equation (1), the resultant current due to one antenna pair (A-A') making an angle ϕ with the direction of the approaching wave is

$$I_A = I_R$$

Similarly, the resultant current due to another antenna pair (B-B') making an angle $(\pi/2 - \phi)$ with the direction of the approaching wave is:

$$I_B = E_G \sin\left(\frac{\pi D}{\lambda}\sin\phi\right)\cos\left(\omega t + \frac{2\pi D_o}{\lambda}\right)$$

$$+ E_A \sin\left(\frac{\pi D}{\lambda}\sin\phi\,\sin\theta\right)\cos\left(\omega t + \frac{2\pi D_1}{\lambda}\right) \qquad (2)$$

when $\sin\phi$ is substituted for $\cos(\pi/2 - \phi)$

From the inductive goniometer law derived in paragraph 8(c) 4(a), it can be shown that the resultant search coil current I'_R due to I_A and I_B is:

$$I'_R \approx I_B \cos\psi - I_A \sin\psi$$

where ψ is the goniometer azimuth angle or the angle between the axis of the search coil and fixed coil L_B.

Substituting the values of I_A and I_B :

$$I'_R \approx E_G\left\{\cos\psi\,\sin\left(\frac{\pi D}{\lambda}\sin\phi\right) - \sin\psi\,\sin\left(\frac{\pi D}{\lambda}\cos\phi\right)\right\}\cos\left(\omega t + \frac{2\pi D_o}{\lambda}\right)$$

$$+ E_A\left\{\cos\psi\,\sin\left(\frac{\pi D}{\lambda}\sin\phi\,\sin\theta\right) - \sin\psi\,\sin\left(\frac{\pi D}{\lambda}\cos\phi\,\sin\theta\right)\right\}$$

$$\cos\left(\omega t + \frac{2\pi D_1}{\lambda}\right) \qquad (3)$$

If ψ_1 is the observed bearing (goniometer azimuth angle) in the presence of the ground wave alone (i.e. $E_A = 0$) then for $I'_R = 0$ equation (3) reduces to:

$$\cos\psi_1\,\sin\left(\frac{\pi D}{\lambda}\sin\phi\right) = \sin\psi_1\,\sin\left(\frac{\pi D}{\lambda}\cos\phi\right) \qquad (4)$$

or

$$\tan\psi_1 = \frac{\sin\left(\frac{\pi D}{\lambda}\sin\phi\right)}{\sin\left(\frac{\pi D}{\lambda}\cos\phi\right)} \qquad (5)$$

[redacted]

When, however, $\frac{\pi D}{\lambda} \ll 1$, then $\sin\left(\frac{\pi D}{\lambda}\sin\phi\right) = \left(\frac{\pi D}{\lambda}\sin\phi\right)$ (6)

$\therefore \tan\psi_1 = \tan\phi$ and $\sin\left(\frac{\pi D}{\lambda}\cos\phi\right) = \left(\frac{\pi D}{\lambda}\cos\phi\right)$ (7)

and $\psi_1 = \phi$ (8)

If ψ_2 is the observed bearing in the presence of the sky wave alone (i.e. $E_G = 0$) then for $I'_R = 0$ equation (3) reduces to:

$$\cos\psi_2 \sin\left(\frac{\pi D}{\lambda}\sin\phi\sin\theta\right) = \sin\psi_2 \sin\left(\frac{\pi D}{\lambda}\cos\phi\sin\theta\right) \quad (9)$$

or

$$\tan\psi_2 = \frac{\sin\left(\frac{\pi D}{\lambda}\sin\phi\sin\theta\right)}{\sin\left(\frac{\pi D}{\lambda}\cos\phi\sin\theta\right)} \quad (10)$$

When, however, $\frac{\pi D}{\lambda} \ll 1$, then $\sin\left(\frac{\pi D}{\lambda}\sin\phi\sin\theta\right) = \left(\frac{\pi D}{\lambda}\sin\phi\sin\theta\right)$ (11)

and $\sin\left(\frac{\pi D}{\lambda}\cos\phi\sin\theta\right) = \left(\frac{\pi D}{\lambda}\cos\phi\sin\theta\right)$

$$\therefore \tan\psi_2 = \frac{\pi D/\lambda \sin\theta}{\pi D/\lambda \sin\theta} \cdot \frac{\sin\phi}{\cos\phi} = \tan\phi \quad (12)$$

and $\psi_2 = \phi$ (13)

If, however, $\pi D/\lambda$ is no longer $\ll 1$ then a comparison of equations (5) and (10) shows that $\tan\psi_2$ differs from $\tan\psi_1$ by an amount depending upon D/λ (the aerial spacing factor) and θ, the vertical or incidence angle of the wave. The error introduced by $\tan\psi_2 \neq \tan\psi_1$ may be termed "due to diversity effect."

For $D/\lambda < 0.1$, the probability of large diversity error is small. When $D/\lambda = 0.1$ there are certain distances from the transmitter which can give rise to large values of θ and consequently diversity errors as large as 1° may be encountered in many areas, depending upon the intensities and particularly the phases of the E_G and E_A components (refer to equation (3)). When $D/\lambda = 0.3$ the probability of large diversity error has increased and there are distances from the transmitter which can give rise to diversity errors as great as 5° and in some very narrow areas to 20° or more. Calculations(m) indicate that the phase differences of the E_G and E_A components are large when $0.3 < D/\lambda < 0.1$.

Under these conditions fading and blurring of the minimum occur which makes the presence of diversity effect apparent to the operator. Unfortunately, fading and blurred minimums are not so evident when $0.1<D/\lambda < 0.3$. Under these conditions, large bearing errors due to diversity effect may go undetected.

8. (c) Instrument Error:

(1) Aside from polarization and diversity error, there remain those deviations due to the site and those due to the elements linking the collectors to the search coil. Deviations due to the site in general are fixed and can usually be corrected by suitable calibration. Variable deviations in fixed Adcocks, however, are essentially localized in the antenna impedance changes. As analyzed in Appendix II, Plates 15, 16, and Tables 2,3, these give rise to errors and uncertain (blurred minimum) bearings. In order to keep the antenna impedance variations as small as possible, the fixed Adcock systems are operated non-resonant, thus allowing the large untuned antenna reactance to literally "swamp" small changes in resistance and capacitance.

(2) From Plates 11, 12, and 13 it is seen that even the non-resonant antenna undergoes sufficient capacitance and resistance change to cause impedance variations* of the order of 2 per cent in magnitude and 0.14** per cent in phase. This is partially reduced by the compensating devices described in paragraph 10 (e). Moreover, polarization errors can enter into the instrument if the horizontal feeders are unbalanced and otherwise respond to the "C" component of the radio wave. As a rule, perfect balance cannot be retained mechanically or electrically for long intervals and even in well shielded feeders the walls of the shield are other than zero impedance (particularly at the higher frequencies), thus they themselves respond to the "C" component, induce corresponding potentials upon the unbalanced feeders, and cause bearing error.

(3) In references (e)(n) the results given for various arrangements most effective in reducing the polarization error show that a balanced coupled system with four transposed lines for each feeder lead gives the lowest polarization error. The modified form of balanced coupled system utilized in the Naval Research Laboratory installation (see Plate 1) is considered a rational compromise between the best system for reducing polarization error and one not too difficult to install and maintain in a balanced state. The investigation of the Adcock system as reported herein has not concerned itself with the magnitude of polarization error as measured by means of the standard wave(n) since its approximate value could be determined from the literature and because it was masked by the larger instrument errors described above. It is expected that an investigation of polarization error will be made at a later date.

*In general, the variations between antennas are smaller since the cause responsible for the change in one antenna changes the others similarly.

**A 0.13 degree phase shift out of a possible 90 degree shift = 0.14%.

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(4) Goniometer Law:

(a) Inductive Goniometer: An inductive goniometer is generally used for resolving the currents from two fixed directional antennas by utilizing a fixed coil (or split coils) for each directive antenna. The fixed coils are made equal and are arranged to give uniform mutually perpendicular magnetic fields, thus allowing a rotatable third coil to couple to them in such a manner that it reproduces the directional characteristic of the directive antenna. The goniometer coils are wound so that the mutual inductances of the fixed coils to the rotatable search coil follows the law: (Refer to Fig. A of Plate 14.)

$$M_{1-3} \approx L_1 \sin \psi \qquad (14)$$

$$M_{2-3} \approx L_2 \cos \psi \approx L_1 \cos \psi \qquad (15)$$

where $L_1 = L_2$ = Self inductance of fixed coil.

L_3 = Self inductance of search coil.

ψ = Goniometer azimuth angle = angle between the axes of L_2 and L_3.

M_{1-3} = Mutual inductance between L_1 and L_3.

M_{2-3} = Mutual inductance between L_2 and L_3.

In appendix I, equation (54) shows that when $D/\lambda \ll 1$, the resultant voltage due to a pair of antennas (A-A') arranged for directional response is:

$$E_R = K \cos \phi$$

A fixed and symmetrical system of two pairs of balanced antennas (A-A' and B-B') arranged in space quadrature relationship (e.g., see Plate 3) would therefore be:

$$E_{R_1} = K \cos \phi \qquad \text{(for antenna pair A-A').} \qquad (16)$$

and

$$E_{R_2} = K \cos (\pi/2 - \phi) = K \sin \phi \qquad \text{(for antenna pair B-B').} \qquad (17)$$

where ϕ = the wave azimuth angle with respect to the plane of antenna pair A-A',

and $\pi/2 - \phi$ = the wave azimuth angle with respect to the plane of antenna pair B-B'.

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The current I_1, in the goniometer coil L_1, being proportional to the voltage E_{R_1} applied to it, induces a voltage in the search coil = E_1', such that

$$E_1' = -j\omega M_{1-3} I_1 \quad \text{(normal induction law)} \tag{18}$$

or

$$E_1' \approx -j\omega(L_1 \sin\psi) I_1 \approx \omega(L_1 \sin\psi) E_{R_1} \tag{19}$$

Substituting the value of E_{R_1} from equation (16) and simplifying,

$$E_1' = K' \sin\psi \cos\phi \tag{20}$$

where K' is the proportionality factor which includes the constants K, ω and L_1.

Similarly,

$$E_2' = K' \cos\psi \sin\phi \tag{21}$$

and if the connections to coil L_2 be reversed,

$$E_2' = -K' \cos\psi \sin\phi \tag{22}$$

The total voltage in the search coil is

$$E'_R = E'_1 + E'_2 \tag{23}$$

If L_3 is rotated, bearings are obtained when $E'_R = 0$*

Then $E'_1 = -E'_2$ (24)

and if equations (20) and (22) are substituted in (24) we obtain

$$K' \sin\psi \cos\phi = K' \cos\psi \sin\phi \tag{25}$$

or

$$\tan\psi = \tan\phi \tag{26}$$

and

$$\psi = \phi \tag{27}$$

Equation (27) may be termed the Inductive Goniometer Law since the wave azimuth is reproduced as a goniometer azimuth.

* $E'_R = 0$ for balanced systems only. Refer to Appendix II and Tables 2 and 3 for unbalanced cases.

(b) <u>Resistance Goniometer</u>: A resistance goniometer suggested in reference (o) has been constructed (See Plates 24 and 25) using the resistance bridge principle. It can be shown that if it is coupled to the same space quadrature antenna pairs as described in paragraph 8(c)(4)(a), it too can reproduce the wave azimuth in a manner similar to the inductive goniometer.

For example, assume that the arms A,B of Fig.B, Plate 14, draw no current,* and that the current due to E_{R_1} gives rise to two equal currents I_1 and I'_1. The voltage across arms AB, due to E_{R_1} is:

$$E'_{AB} = I_1 \, (R + R_2) - I'_1 R_1 \tag{28}$$

$$= \frac{E_{R_1}}{2R} \, (R + R_2 - R_1) = E_{R_1}\left(\frac{R_2}{R}\right) \tag{29}$$

where $R = R_1 + R_2$.

$$I_1 = I'_1 = \frac{E_{R_1}}{2R}$$

$$I_2 = I'_2 = \frac{E_{R_2}}{2R}$$

$E_{R_1} = K \cos \phi$ (from equation (16)).

$E_{R_2} = K \sin \psi$ (from equation (17)).

ϕ = The wave azimuth.

ψ = The resistance goniometer azimuth.

In a similar manner, the voltage across arms A B due to E_{R_2} is:

$$E''_{AB} = I_2 \, (R + R_1) - I'_2 \, (R_2) \tag{30}$$

$$= \frac{E_{R_2}}{2R} \, (R + R_1 - R_2) = E_{R_2}\left(\frac{R_1}{R}\right) \tag{31}$$

* Tests show no significant error introduced, when arms A,B be terminated in a high, low, or optimum load impedance, while a residual E'_{AB} is present.

and if the E_{R_2} connections (polarity) are reversed

$$E''_{AB} = - E_{R_2}\left(\frac{R_1}{R}\right) \tag{32}$$

The total voltage across arms A B is:

$$E_{AB} = E'_{AB} + E''_{AB} \tag{33}$$

If the arms A B are rotated and bearings are obtained when $E_{AB} = 0$* then

$$E'_{AB} = - E''_{AB} \tag{34}$$

and if equations (29) and (32) are substituted in (34)

$$E_{R_1}\left(\frac{R_2}{R}\right) = E_{R_2}\left(\frac{R_1}{R}\right) \tag{35}$$

From equations (35), (16), and (17) we obtain:

$$\frac{R_1}{R_2} = \frac{E_{R_1}}{E_{R_2}} = \frac{K \cos \phi}{K \sin \phi} = \cot \phi \tag{36}$$

Let us draw Fig.C as a detail of Fig. B, Plate 14.

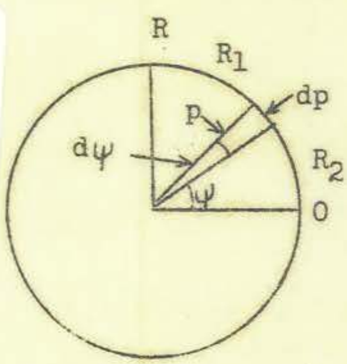

Fig. C

$$\text{if } dp = p\, d\psi \tag{37}$$

$$R = p\int_0^{\pi/2} d\psi = p\,\psi\Big]_0^{\pi/2} = p\left(\frac{\pi}{2}\right) \tag{38}$$

$$\text{and } p = \frac{R}{\pi/2} \tag{39}$$

$$\text{Then } R_2 = p\,\psi = \frac{R}{\pi/2}\,\psi \tag{40}$$

$$\text{and } R_1 = p\left(\frac{\pi}{2} - \psi\right) = \frac{R}{\pi/2}\left(\frac{\pi}{2} - \psi\right) \tag{41}$$

[redacted]

* $E_{AB} = 0$ for balanced systems only. Refer to Appendix II and Table 2 for unbalanced cases.

$$\text{or} \quad \frac{R_1}{R_2} = \frac{\left(\frac{\pi}{2} - \psi\right)}{\psi} \tag{42}$$

Combining equations (36) and (42)

$$\frac{R_1}{R_2} = \cot \phi \quad = \frac{\left(\frac{\pi}{2} - \psi\right)}{\psi} \tag{43}$$

$$\therefore \frac{\left(\frac{\pi}{2} - \psi\right)}{\psi} = \cot \phi$$

$$\text{and} \quad \psi \quad = \frac{\pi/2}{1 + \cot \phi} \tag{44}$$

Equation (44) may be termed the Resistance Goniometer Law since there is a goniometer azimuth angle ψ which follows the wave angle ϕ .

The deviation between ψ and ϕ for the resistance goniometer takes the form of a nearly summetrical sine curve completing four cycles for each goniometer revolution. The maximum or peak deviations are approximately 4 degrees in amplitude. The theoretical resistance goniometer law and actual calibrations obtained using direct current and 190 kilocycles are in close agreement (refer to Plate 6).

NARRATIVE OF ORIGINAL WORK

9. The following constitutes the original work resulting from the study of the fixed Adcock installation:

(a) Limitations of its present form have been investigated and mathematically analyzed.

(b) Equations have been derived for evaluating the bearing error and bearing spread (blurring of the minimum) caused by different kinds of unbalance in the fixed and rotatable types of Adcock collectors. Graphs are given for the bearing error and bearing spread caused by the upper and lower limits of the different kinds of unbalance that may be expected in fixed Adcock collector systems of the type installed at the Naval Research Laboratory.

(c) A method is suggested for determining the suitability of a fixed Adcock direction finder site.

(d) The analysis and performance of a new, laboratory constructed, high resolving power, resistance goniometer was obtained.

EXPERIMENTAL ADCOCK DIRECTION FINDER INSTALLATION AT THE NAVAL RESEARCH LABORATORY

10. Plates 1 and 17 show the complete Adcock direction finder installation; it is described in greater detail below.

(a) Layout of System

The experimental Adcock direction finder as designed and installed at the Laboratory consists of four 100 foot steel towers anchored at the corner of a true square whose diagonal measures 180 feet. The center of the square is located approximately 300 feet north and to the rear of Naval Research Laboratory Building No. 1 on a line approximately bisecting Laboratory Buildings No. 1 and No. 12. The masts are so oriented that one side of the subtended square has zero azimuth.

(b) Towers

The towers, Plate 18, are commercial "Wincharger" masts insulated from ground and suitably guyed. A series of eight radials (Plate 19) (horizontal wires approximately 2 feet above ground) symmetrically distributed in a 40 foot diameter circle, with outer ends attached to individual ground rods driven 6 feet into the ground) comprise the grounding system associated with each mast.

(c) Hut and Center Antenna

At the center of the antenna system, a 12 foot x 10 foot x 9 foot wooden hut (Plate 20) was constructed and serves to house the central terminating and other radio equipment used with the Adcock system. On top of the hut is a 30 foot guyed telescopic type antenna erected at the exact center of the antenna system. A series of eight ground radials similar to those used at the masts is employed for the local hut ground.

(d) Feeders and Transformers

Two 3/8 inch coaxial gas filled transmission lines comprise a balanced type radio frequency line and two lengths of No. 14 twin conductor lead covered cable extend from the hut to each mast. Plate 21 shows the shielded terminating boxes provided at the antenna end of the transmission lines containing the shielded transformers, which efficiently transfer the energy collected by the antenna and ground to the goniometer via the coaxial transmission lines.

(e) Balancing Circuits

In order to compensate for small inequalities of the masts' electrical constants and effective heights, small adjusting shunt admittances (capacitance and resistance) are connected across the primary of each antenna transformer and are in parallel with the antenna ground connections. This balancing arrangements, shown in Plates 1 and 21, while compensating for electrical differences existing between the different antennas, does not completely correct for all the differences in

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the system. As a consequence, it has been found advantageous to compensate for inequalities (such as may arise during the transmission of the radio frequency voltage from the antennas to the goniometer) by injecting a portion of the voltage induced in the central antenna (see Plates 1, 20, and 22) into the receiver input circuit. Considerable sharpening of the minimum was thus effected.

(f) Receiver

A standard National Company "HRO" receiver (Plate 23) was used to detect for minimum goniometer output voltage; a shielded transformer coupled the goniometer's output to the receiver's input. Battery operation of the receiver was employed to avoid extraneous pick-up.

(g) Resistance Goniometer

The transmission lines terminate at the hut in a totally shielded resistive goniometer, which is used to resolve the voltages derived from the four antennas. The goniometer (Fig.B, Plate 14) consists of a circular and uniformly wound resistance strip arranged in closed mechanical and electrical form. Two rotatable and insulated arms contact the strip diametrically. Carefully shielded permanent connections are made to four equally disposed points along the resistance periphery, while two slip rings permit shielded leads to connect to the rotatable arms. The radio frequency voltage induced in one antenna of a pair is fed by means of a shielded transformer and the balanced transmission line to one pair of oppositely fixed points on the resistance strip of the goniometer, while the radio frequency voltage induced in the opposite antenna is similarly fed to the same pair of fixed points on the resistance goniometer but in opposite polarity. Thus, only the difference of the voltages induced in a pair of antennas appears across a pair of fixed goniometer points. In a similar manner, the difference in voltage induced in the other pair of antennas appears across the other pair of fixed goniometer points. The goniometer rotatable arms are capable of finding a position for which it picks up maximum or minimum resultant voltage. The latter position can be conveniently correlated with the angle of approach of the wave; i.e., with the angular bearing to the source of wave propagation. Approximately ten turns of resistance wire for each angular degree are wound on the 12 inch diameter circular strip to permit a tenth of a degree resolution. Plates 24 and 25 show the finished Laboratory constructed model.

DESCRIPTION OF INVESTIGATIONS

11. (a) General

(1) Direction finding with a fixed Adcock system is primarily a measurement of time, (i.e., "phase") required for the maximum amplitude of the arriving radio wave to pass from one antenna to another. As the system operates in the medium frequency range (300 to 1000 kilocycles) and uses maximum feasible spacing* (i.e., approximately 0.2λ at 1000 kilocycles) between opposite antennas, this time interval varies between 0

* See paragraphs 7 and 8 for a discussion of these limitations.

and 0.2 microsecond (or from 0 to 72 electrical degrees) depending on the frequency and the azimuth angle of the arriving wave. Since scattering* and diversity effect* generally limit the medium frequency Adcock bearing accuracy to about one degree, it is desirable to investigate the stability of the components linking the Adcock collectors in order to determine how their variations may limit the bearing accuracy and usefulness.

(2) It can be shown that the voltage delivered by an Adcock antenna to the goniometer input terminals is proportional to the effective height of the antennas, the admittance of the aerial circuit and depends upon the constants of the transformers and transmission lines linking the antenna to the goniometer. Measurements on the Adcock antenna impedances over many days, see Plates 11, 12, and 13, show that capacity variations of the order of 2** per cent and phase angle changes (principally due to radio frequency ground resistance variations) of about 0.13** degrees (0.14%) may be expected.

(3) To determine the magnitude of bearing error and bearing indefiniteness (blurring of the minimum) introduced by the amounts of antenna impedance change (instabilities) encountered in Adcock systems, a mathematical analysis of the bearing error and bearing spread has been made and is given in Appendix I and II. Evaluations of their magnitudes, for the fixed Adcock system, are plotted in Plates 15 and 16 and summarized in Table 3 for upper and lower limits of unbalance that may be expected in fixed Adcock direction finders of the type installed at the Naval Research Laboratory. A more detailed analysis of voltage unbalance is given in Tables 1, 2, and 3. The transformers and transmission lines, being of high stability, introduce a fixed phase shift only, which may be corrected by suitable matching or circuit compensation.

11. (b) Tests and Methods

(1) Antenna Impedance Measurements. The measurement of small changes in antenna impedance prohibited the presence of an operator at the antenna. A simple method was utilized for measuring these changes with great accuracy and without influencing the results by the operator's presence. The method is shown in Fig. A of Plates 4 and 26. A General Radio Type 516-C radio frequency bridge located in the hut is directly coupled to the antenna impedance by means of the two coaxial transmission lines. The operator while at the hut obtains a bridge balance (i.e., a headset null) when the antenna impedance is in the circuit; he then moves to the antenna, substitutes and adjusts a known impedance; i.e., (a standard capacitance and a compensated resistance unit) until bridge balance is re-established. By extending the telephone cord to the antenna, the operator can accurately determine the point of bridge balance as he personally substitutes and adjusts the standard impedance at the mast.

*See paragraphs 7 and 8 for a discussion of these limitations.

**See notes, bottom of page 8.

The method has proved effective, convenient, and possessed a sensitivity such that the presence of a man 40 to 50 feet from the mast could be detected as $<$ 0.1 μμf change in antenna capacity.

11. (b) (2) <u>Calibration of Resistance Goniometer.</u> The resistance goniometer described in paragraph 10(g) was calibrated with direct and radio frequency currents. The octagonal deviation curve obtained by both calibrations was in close agreement with that inherent in a linear resistance such as is used in the goniometer. The actual calibrations represent a near* symmetrical sine curve completing four cycles in the 360 degree goniometer azimuth scale. The maximum deviations occur at 45 degree intervals and are approximately 4 degrees in amplitude. Calibration with direct and radio frequency currents was accomplished by the (A) and (B) methods shown in Plate 5. Since the simple method (B) did not correspond to the manner in which the goniometer was actually used in practice, a few points taken with the truer but more difficult method (C) were first taken in order to demonstrate the practical equivalence of the two methods. In Plate 6, the theoretical goniometer law* and the calibrated points obtained by method (B) are compared. The range of voltages available from the standard signal generator and those measurable by a direct reading vacuum tube voltmeter made it more convenient to calibrate the resistance goniometer at 190 kilocycles, although aural minimum calibration checks with frequencies from 10 to 1000 kilocycles indicated no significant frequency characteristic.

11. (b) (3) <u>Balancing of Antenna Prior to Taking Bearings.</u> Before taking bearings on stations, the four antenna collectors and their coupling circuits were balanced close to the frequency for which a station bearing was desired. The balancing procedure (See Fig. B of Plate 4) = exciting the central antenna (which coupled equally to the other four) with a high power well shielded portable oscillator;- With only one pair of antennas connected to the goniometer and the pick-up arms on maximum, the balancing capacitances and resistances described in paragraph 10(e) were adjusted for the best minimum. Using one antenna of this balanced pair as reference, the remaining antennas were individually and carefully balanced against it. As a final check, all collectors were connected to the goniometer in normal manner, and the rotatable arms were turned to determine if the residual unbalance or minimum signal had materially increased. The sensitivity during the balancing of the antenna was such that the unbalance caused by an antenna swaying in a very slight wind would readily be detected. Compensation for the presence of the man adjusting the balancers was adequately effected by over-compensating; i.e., the man adjusted these controls to a value that gave optimum balance when the man completely removed himself from the field.

11. (b) (4) <u>Behavior of Minimum with Bearings on Stations.</u> After balancing the antenna system, say, at 765 kilocycles, bearings were taken on a station of 760 kilocycles (WJZ). It was noticed, however, that although daytime bearings could be obtained on WJZ to within ± 2° (involving an approximate air line distance of 200 miles) the minimum was broader

* See paragraph 8 (c) (4) (b) for derivation of resistance goniometer law.

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than that experienced during the balancing of the antennas as described in paragraph 11 (b) (3). Appreciable sharpening of the bearing minimum to about $\pm 0.2^{\circ}$ was realized by introducing, in suitable phase and magnitude, a balancing voltage collected by the central antenna described in paragraph 10(e). Plate 23 shows the arrangement of the equipment when bearings are taken.

11.(b) (5). Preliminary Calibration of Adcock System and Site. Adcock direction finder bearings* taken on eleven radio stations of various geographical locations gave deviations as much as 7 degrees between the observed and true bearing. A portable "loop" type direction finder exhibitied similar deviations. In order to evaluate the site deviation and the deviation that may be contributed by the Adcock system, the portable oscillator previously employed for balancing the antennas was used to excite a portable antenna erected at several locations having different azimuths at distances of approximately one-half mile or more from the Adcock system. Radio bearings with the Adcock and "loop" direction finders were taken for ten frequencies in the 200 - 1000 kilocycle range for each location of the oscillator. The true bearings to the oscillator were determined with a theodolite. The deviation curves (Plate 7) show the "loop" and Adcock system to be in close agreement, indicating that the deviation observed with the Adcock** is due predominantly to the site.

11. (b) (6). Pick-up Factor. In paragraphs 11 (a)(2) and 11 (a) (3) it was shown how small irregularities in the antenna impedance cause errors and blurred minimum. The difficulty of maintaining phase balance when using tuned circuits makes it inadvisable to tune the antennas. A non-resonant system allows the antenna reactance to "swamp" small variations in its impedance and results in sharper and more stable minima. Non-resonant operation of the antennas, however, means a sacrifice in pick-up factor where pick-up factor may be defined as the ratio of the volts applied across the control grid of the first amplifier to the field strength in volts per meter. It is possible to increase the pick-up factor of the system by resonating** the antennas somewhat below the lowest working frequency of the band. In the Laboratory Adcock installation, the lowest working frequency is 300 kilocycles, and the antenna coupling transformer resonated the antenna at approximately 200 kilocycles. In addition to this arrangement, the pick-up factor may be further increased by proper matching of the goniometer output impedance to the receiver input impedance, and by resonating the goniometer circuit and transmission lines just above the highest working frequency used. The method used in measuring pick-up factor is indicated in Plate 8, while the values obtained are given in Plates 9A, 9B, by the quantity $h\ (E_7/E_0)$, where h is the effective height of the 100 ft. antenna $\approx$ 15 meters.

11. (b) (7). Precipitation Static. While operating the Adcock direction finder during a heavy shower, a very large increase in background noise was observed, and only local radio stations could be received satis-

* Bearings sharpened with fifth antenna balancing voltage.

** The Adcock deviation increases, however, see Plate 7, as antenna resonance (200 kilocycles) is approached. Refer to paragraph 18.

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factorily. Little success was had in obtaining bearings on other than local stations. It was noted that the high background noise was present despite the absence of lightning or thunder. The intensity of the background noise appeared to be constant and of about the same level throughout the 300 to 1,000 kilocycle band. Reference (p) has since been found which also reports this effect in ground Adcock direction finders, while reference (q) includes precipitation static encountered with various aircraft radio antennas.

Because the need and demand for accurate radio bearings usually increases with bad weather, the possible failure of an Adcock direction finder during weather conditions when it may be needed most introduces a serious reliability limitation in such a system. Extensive tests[q] conducted on aircraft antenna during actual and simulated precipitation static conditions show that a plane's vertical antenna responds more to such static than an unshielded loop, while a shielded loop responds less to such static than any of the various forms of antenna tried. Moreover, these results showed that corona discharge was primarily responsible for the static field. When the discharge points were removed five feet from the body of the plane* precipitation static pick-up by the collector was markedly reduced.** The employment of such methods in connection with Adcock collectors may possibly yield a similar improvement. In addition, if the collectors themselves were made of large round and smooth surfaces a further improvement may be realized.

The study of precipitation static should therefore be continued with the object of either reducing its effect in Adcock direction finders or determining the advisability of using a suitably shielded loop collector system for standby purposes. It should be noted that a standby loop direction finder equipment may be conveniently provided by switching the direction finder receiver either to the Adcock or the loop collector system.

DATA OBTAINED

12. The work and data reported in this investigation are given in Appendices I and II, Tables 1, 2, and 3, and Plates 1 to 26 inclusive.

DISCUSSION OF PROBABLE ERRORS

13. The antenna impedance measurements are considered to have an absolute accuracy of approximately 5 per cent, while the relative values (differences between the antennas) are repeatable and accurate to within 0.1 μμf for capacitance and within 1% for resistance. The resistance goniometer calibration measurement accuracy is estimated at about 1 per cent for the direct current measurement and better than 5 per cent for the 190 kilocycle calibration. The pick-up factor accuracy is approximately 10 per cent for measurements made with a given antenna coil in the receiver. Due to the detuning caused by applying a vacuum tube

*Actually, thin wires attached to the ship's body with a suppressor resistor in series.

**Due to the induction field decreasing as the inverse square of the distance between the antenna and source of discharge. Because of the proximity of the aircraft's metallic surface acting as a ground plane a decrease nearly proportional to the inverse cube was reported.

voltmeter to the receivers' first control grid input circuit, the tuning condenser value had to be decreased to re-establish resonance. This shift in tuning capacity at times required the antenna coil of the next band to be used before exceeding the upper frequency limit of the coil when normally used; it is responsible for the E_7 curve (Plate 9) having two discontinuities. The accuracy of the bearings taken are separately discussed under paragraph 17.

RESULTS OF TESTS AND DISCUSSION

14. Under paragraph 11 (b) the significance and results of each test are given.

15. Balance and Stability Requirements. It is of value to emphasize the severity of the balance and stability requirements which are imposed by radio goniometric methods of taking bearings. For example, in Plates 11, 12, and 13 it is seen that capacity variations of the order of 2 per cent and phase angle shifts (due to resistance changes) of the order of 0.13° (0.14 per cent) may sometimes be expected.* For such values of unbalance existing simultaneously in a single antenna, Plates 15 and 16 indicate that about 0.4° bearing error** and ± 1.2° bearing spread ** may be present. The effect of unbalance in other antennas superimposes their effect on the values obtained for the unbalance of a single antenna. Fortunately, however, this is partly offset by the tendency for all the antenna impedances to vary in the same general direction so that the total bearing error and spread in a fixed Adcock system may approximate between 1 and 2-1/2 times that introduced by the variation of a single antenna. It is thus seen that the antenna impedance variations become the limiting stability factor in fixed Adcock systems since they prevent the realization of the one degree theoretical limit of bearing accuracy discussed in paragraph 11 (a) (1).

Since antenna stability criteria are obtained from these unbalance analyses it may be possible to more carefully choose suitable direction finder sites and suitable ground network because the magnitude of instability (variable bearing error and bearing spread) may be predicted from preliminary impedance measurements made on a small portable antenna and ground network suitably placed over the proposed tower sites. Further investigation of this procedure in choosing sites may lead to greater usefulness of the method.

16. Resistance Goniometer Performance.

(a) During the early operation of the resistance goniometer with the Adcock system under actual direction finding conditions, failure of the goniometer occurred. A careful examination revealed that the resistance wire had undergone considerable wear due to the sliding action of the contact arm. The products of wear (minute flakes from the resistance wire)

* See notes, bottom page 8.

** Values are corrected for their wave azimuth characteristic.

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having fallen between adjacent turns had short circuited portions of the resistance strip. The amount of wear was considerable for the small number of hours during which the goniometer was used despite the fact that the contactor had previously been carefully adjusted for a minimum of pressure compatible with good electrical contact and the consideration given during the design of the contactor to a method permitting a minimum of wire wear. A small buffing wheel was used to remove the particles. After readjustment of the contactor for a still lighter pressure, the wire was lubricated with a special grease. The unit operated satisfactorily when reinstalled in the Adcock system, but in a short time a similar failure occurred despite the added caution that was exercised in rotating its arms as little as possible.

(b) The closed resistance strip in the goniometer was designed to have a diametric impedance of 70 ohms which would just match the combined transmission line characteristic impedances. In order to realize 0.1° resolving power, approximately 10-1/2 turns of wire were wound for each circular degree on a 12 inch diameter circular strip. This required about 3750 turns, which with the small spacing factor allowed per turn necessitated the use of a small wire of high conductivity. The actual wire used was a copper nickel alloy, size #30, with a resistance of 30 ohms per circular mil foot. The latter resistance is 3 times that of copper wire and approaches the latter's comparatively soft composition.

(c) It may be possible to reduce the wear and contact difficulties by using a differently designed resistance strip and contactor. Moreover, the total resistance of the strip may be increased by inserting the necessary impedance matching transformers. The latter, however, introduces at least 6 decibels loss for each transformer required, and is reflected in an undesirable decrease in sensitivity, or signal to noise ratio. Improvements in contactor or hardness of the wire may reduce wear, but there will still remain the sliding contact mechanism which has always been a problem in the service.

(d) A slide wire (single closed turn) type of construction, while inherently capable of yielding excellent electrical resolution, gave severe mechanical difficulties during the preliminary design of the Laboratory resistance goniometer. For example, #40 (.003" dia.) wire was the largest cross section of resistance wire commercially obtainable (assuming a 12" diameter slide wire loop) having a 70 ohm diametric resistance to properly terminate the transmission lines. So fine a wire was considered impractical from a wear standpoint.

Composition or coated types of resistances (for single turn slide wire construction) having the 70 ohm diametric resistance as well as adequate ruggedness, suffer from initial non-uniformity of composition; instability due to temperature, humidity and possibly wear; variable contact resistance and other similar weaknesses.

The Laboratory has suggested a liquid type of resistance goniometer as a possible remedy to the contact and unstable factors arising with the solid types of slide wire construction. Consideration[(o)] has also been given to a commutator type of construction wherein fixed resistances of appropriate value would be connected between adjacent segments. In order to obtain 0.1 degree resolution with the commutator type, 3600 segments would be required which from a construction and maintenance standpoint present many mechanical difficulties.

Development work to ascertain the actual merit of the liquid, commutator, impedance or other types* of similar goniometers over the conventional inductive type appears to lead in the direction of complexity instead of simplicity. Since this nullifies their principal advantage, no further work was done along such lines.

(e) At first glance it may appear that use of a resistive type goniometer gives a much greater energy loss than that obtained with an inductive (relatively dissipationless) type of goniometer. It is important, however, that the transmission lines be properly terminated in order to avoid standing waves and consequential unbalanced voltages being applied to the goniometer. It is conceivable that an inductive goniometer may be designed with sufficient mutual inductive reactance between the fixed and search coils and with proper search coil loading which would satisfactorily and efficiently terminate the transmission lines. Unfortunately, it would be very difficult to maintain such a termination for various positions of the search coil and for various search coil loadings, because in an inductive goniometer the mutual inductance obeys the cosine law (See Equation (14)) its reactance varies with frequency, and the search coil loading varies with the input circuit impedance of the receiver, the frequency and the accuracy of tuning the receiver. This matter appears to have received similar consideration in the Marconi D.F.G. 10, Adcock direction finder[r] where 60 ohm fixed resistances are used to terminate the transmission lines before they are connected to the fixed coils of a tightly coupled inductive type goniometer.

17. Improving the Bearing Minimum. The absolute bearing accuracy on radio stations was not of great interest during the tests; therefore, the site was not completely calibrated. The degree of repeatability of a particular bearing was used instead as a measure of the constancy (i.e., stability) of the system. In paragraph 11 (b) (3), (4) a typical example of the procedure used in taking a bearing is given, and it is shown that despite the fact that the antenna system was balanced at a frequency adjacent to that on which a bearing was to have been taken, it was necessary to utilize a fifth (central) collector in order to sharpen the minimum from a ± 2° width to one of about ± 0.2° width. The central antenna, by means of its circuit, shown in Plate 1, allows a balancing voltage to be introduced in the receiver input circuit, of a phase and magnitude which just overcomes the undesired component E_u' shown in Plate 3. It is important that no other component be introduced at this time, since then it will be added to or subtracted directly from E_D', and the goniometer minimum will be shifted from its true position. The phasing circuit actually used with the central antenna is shown in Plate 1, and practically fulfills these requirements, but if more accurate bearings are required it may be necessary to improve it.

* Cathode ray goniometers have been considered and are to be discussed in a later report.

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18. Antenna Tuning. In paragraph 11 (b) (6), the pick-up factor was discussed and it was shown that it increased as antenna resonance was approached. On the other hand, the closer one approached antenna resonance the greater became the unbalance and error introduced by the antennas. (See Plate 7.) A compromise must therefore be made as to how close one may approach resonance. Similarly, it is necessary to avoid transmission line circuit and other resonances within the working frequency band. In Plates 9A and 9B, both types of resonance are seen to lie at opposite ends of the 300 - 1000 kilocycle band. It is possible to increase the pick-up factor over the band: (a) by better matching of the goniometer impedance to the receiver input impedance (this is suggested in paragraph 11 (b) (6); (b) because the spacing factor D/λ increases with frequency; and (c) because transmission line circuit and other resonances can be approached.

CONCLUSIONS

19. The medium frequency Adcock direction finder is known to give more reliable and more accurate bearings than the "loop" system because it effectively reduces polarization error.

20. Radio goniometric means of using a fixed Adcock direction finder allows a greater spacing and height of antenna than that permitted by the more compact, rotatable "loop" or Adcock systems. The greater induced voltage obtained with the fixed Adcock is offset, however, by the non-resonant method of operating the collectors (as compared to the tuned "loop" system) and by the added complexities introduced in keeping four antennas in balance instead of the two required in the rotatable Adcock, and one (i.e., balancing of antenna effect) for the "loop" system.

21. The variations (instability) of the antenna impedance are primarily responsible for unbalance in the Adcock system. The unbalance severely limits the accuracy and definition of the bearing.

22. The maximum calculated bearing error and bearing spread that may be expected in the Naval Research Laboratory fixed Adcock direction finder, due to instabilities in the antenna impedance are 0.4° and ± 1.2° respectively when based on the maximum variations observed in one antenna. These values may increase to about 1.0° and ± 3.0° respectively when impedance instabilities as observed in all antennas are considered.

23. The reported quantitative analyses of the effects of antenna impedance unbalance upon goniometric bearings together with the simple means employed for measuring small antenna impedance variations with great accuracy may prove to be a convenient and practical method for determining suitable fixed Adcock direction finder sites.

24. A fifth antenna balancing scheme improves the accuracy and definition of bearings.

25. Resonating or partially resonating the collectors increases the pick-up factor but causes greater unbalance. A working compromise allows a material efficiency increase with a tolerable amount of unbalance.

26. The resistance goniometer, while possessing an octagonal deviation of approximately 4° on peaks may have its deviations added to that of the site and thus be simultaneously calibrated.

27. The resistance goniometer, while simple in principle and capable of giving satisfactory electrical performance, involves wear and other sliding contact difficulties that are in common with devices of a similar nature. Since the goniometer is the heart of the direction finder system and because it is constantly in motion while taking bearings, its possible failure and frequent removal for maintenance makes the adoption of the resistance goniometer a first order risk.

RECOMMENDATIONS

28. It is recommended:

(A) That the investigation into a satisfactory solution for the medium wave, polarization error free, shore navigational direction finder problem be continued in the direction of:

(a) Using the fixed Adcock system with its greater permissible height and spacing over the more compact, rotatable, "loop" and Adcock systems.

(b) Obtaining better stabilization and balance of the antenna impedances.

(c) Investigating methods for diminishing the importance of unbalance in the system.

(d) Investigating means for increasing the pick-up factor without introducing excessive unbalance.

(B) That the method proposed in paragraph 15 for choosing a suitable site for fixed Adcock direction finder installations be further investigated.

(C) That the resistance goniometer not be adopted as a standard goniometer for Naval direction finders, in view of paragraph 27.

(D) That the need for continuous direction finding service under precipitation static conditions be determined, its effect on bearing accuracy and spread be further investigated (for purposes of reducing its effect) and the possible advantage of using the shielded "loop" direction finder as a "standby" be studied. The shielded "loop" while subject to the usual polarization errors is least responsive to precipitation static. Standby shielded "loop" direction finding may be conveniently provided by switching the direction finder receiver either to the Adcock or the "loop" collector system.

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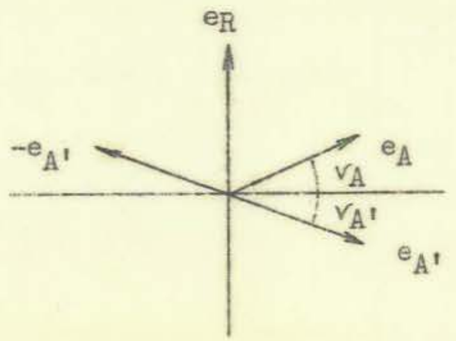
Appendix I

Rotatable Adcock System - Unbalanced Voltage Analysis*

Case 1. Directional characteristics of a balanced system.



In Plate 2,

Let: ϕ = wave azimuth = horizontal angle between antenna plane and direction of wave travel.

D = V radians = antenna spacing in meters.) where $D/\lambda \ll 1$) (i.e., diversity

λ = 2π radians = wave length of wave in meters.) effect neglected)

$\nu_A, \nu_{A'}$ = path differences of wave with respect to fictitious antenna at O.

$e_o = E_o \sin \omega t$ or $E_o e^{j\omega t}$ = instantaneous voltage induced in antenna at O.

$e_A, e_{A'}$ = instantaneous voltage induced in antenna A and A'.

$E_o, E_A, E_{A'}, E_R$ = maximum values of $e_o, e_A, e_{A'}$ and e_R.

$$c = 2 E_o \cos \omega t = 2 j E_o \sin \omega t = 2 j e_o.$$

$$k = \frac{2\pi D}{\lambda} \cdot c = \frac{2\pi D}{\lambda} \cdot 2 j e_o = V \cdot c \quad \text{(see equation 45)}$$

$$K = \frac{4\pi D}{\lambda} E_o = \text{maximum value of } k.$$

* The unbalanced voltage analyses made in Appendices I and II are based on unbalance in the collector system only and consider the approaching wave as traveling along the ground. If the wave does not travel along the ground then $V_1 = \frac{2\pi D}{\lambda} \sin \theta$ must be substituted for V where θ is the incidence angle of the wave measured from the vertical.

From Plate 2:

$$V{:}D = 2\pi : \lambda \quad \text{or} \quad V = \frac{2\pi D}{\lambda} \tag{45}$$

$$\therefore \quad \nu_A = \nu_{A'} = \nu = V \cos\phi = \frac{2\pi D}{\lambda} \cos\phi \tag{46}$$

For antennas having equal effective heights,

$$E_o = E_A = E_{A'}$$

$$e_o = E_A \sin \omega t \text{ or } E_A e^{j\omega t} \tag{47}$$

$$e_A = E_A \sin(\omega t + \nu) \text{ or } E_A e^{j(\omega t + \nu)} = e_o e^{j\nu} \tag{48}$$

$$e_{A'} = E_A \sin(\omega t - \nu) \text{ or } E_A e^{j(\omega t - \nu)} = e_o e^{-j\nu} \tag{49}$$

If the collector system is balanced, then we may neglect the effect of the connecting circuit and the resultant voltage across the coupling coil is:

$$e_R = (e_A - e_{A'}) = e_o \left\{ e^{j\nu} - e^{-j\nu} \right\} = 2 e_o \sinh\nu = 2 j e_o \sin\nu = c \sin\nu \tag{50}$$

where $2 e_o \sinh\nu = 2 e_o \left\{ \frac{e^{j\nu} - e^{-j\nu}}{2} \right\} = e_o \left\{ \cos\nu + j \sin\nu - \cos\nu + j \sin\nu \right\}$

$$= 2 j e_o \sin\nu = c \sin\nu \tag{51}$$

when $\frac{D}{\lambda} \ll 1$, then $\sin\nu = \sin \frac{2\pi D}{\lambda} \cos\phi = \frac{2\pi D}{\lambda} \cos\phi$

$$= V \cos\phi \tag{52}$$

and $$e_R = c \sin\nu = (V \cdot c) \cos\phi = \underline{\underline{k \cos\phi}} \tag{53}$$

or $$E_R = \underline{\underline{K \cos\phi}} \tag{54}$$

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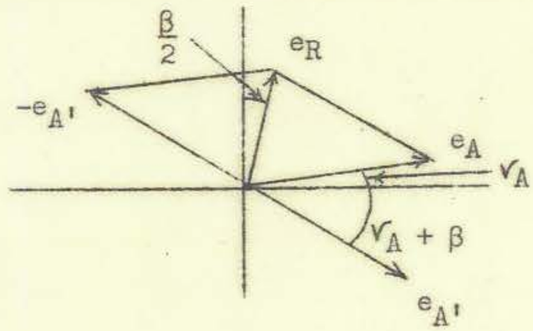
Case 2. Analysis of phase unbalanced system.



Assume that a voltage unbalance (in the Adcock antenna system of case 1) retards the phase of $e_{A'}$ an amount = β radians. Equations (47), (48), (49) and (50) now become:

$$e_o = E_A\, e^{j\omega t}, \quad e_A = e_o\, e^{j\nu},$$

$$e_{A'} = e_o\, e^{-j(\nu + \beta)} \qquad (55)$$

and

$$e_R = (e_A - e_{A'}) = e_o \left\{ e^{j\nu} - e^{-j(\nu + \beta)} \right\} =$$

$$e_o\, e^{-j\frac{\beta}{2}} \left\{ e^{j\left(\nu + \frac{\beta}{2}\right)} - e^{-j\left(\nu + \frac{\beta}{2}\right)} \right\} \qquad (56)$$

$$= 2\, e_o\, e^{-j\frac{\beta}{2}} \sinh \left(\nu + \frac{\beta}{2}\right) = 2\, j\, e_o\, e^{-j\frac{\beta}{2}} \sin \left(\nu + \frac{\beta}{2}\right) \qquad (57)$$

$$= c\, e^{-j\frac{\beta}{2}} \sin \left(\nu + \frac{\beta}{2}\right) \qquad (58)$$

if $\left(\nu + \frac{\beta}{2}\right) \ll 1$, then $\sin \left(\nu + \frac{\beta}{2}\right) = \left(\nu + \frac{\beta}{2}\right) = \left(V \cos \phi + \frac{\beta}{2}\right)$ (59)

and $e_R = \left\{ (V \cdot c) \cos \phi + \frac{\beta \cdot c}{2} \right\} e^{-j\left(\frac{\beta}{2}\right)} = k \cos \phi + \frac{\beta \cdot c}{2}\, e^{-j\left(\frac{\beta}{2}\right)}$ (60)

$$e_R = k \left(\cos \phi + \frac{\beta}{2\, V}\right) e^{-j\left(\frac{\beta}{2}\right)} \qquad (61)$$

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Examining equation (61),

For phases in balance: $\beta = 0$ and $e_R = 0$ (a null) when

$$\phi = \frac{\pi}{2} \text{ or } \frac{3\pi}{2}$$

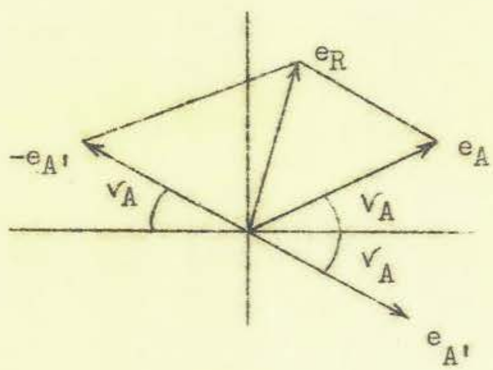
For phases unbalanced:
- $\beta \neq 0$, and $e_R = 0$ (a null) when

$$\phi = \cos^{-1}\left(-\frac{\beta}{2V}\right) \approx \pi/2 - \frac{\beta}{2}$$

- When $\beta \ll V$, Note that $\frac{\beta}{2V}$ is the bearing error introduced; since e_R can be made a null, no blurring exists.

Case 3. Analysis of an amplitude unbalanced system.

Assume that a voltage unbalance (in the Adcock antenna system of Case 1) decreases the amplitude of $e_{A'}$ by an amount = m. Equations (47), (48), (49), and (50) now become:



$$e_o = E_A e^{j\omega t}, \quad e_A = e_o e^{jV},$$

$$e_{A'} = (1 - m)\, e_o e^{-jV} = e_o e^{-jV} - m e_o e^{-jV} \tag{62}$$

$$\text{and } e_R = (e_A - e_{A'}) = \left\{ e_o e^{jV} - e_o^{-jV} + m e_o e^{-jV} \right\} \tag{63}$$

substituting the value of $e_o (e^{jV} - e^{-jV}) =$

$c \sin V$ from equation (50) and simplifying,

$$e_R = c \sin V + m e_o e^{-jV} = c \sin V - j \frac{c}{2} m e^{-jV} \tag{64}$$

$$\text{since by definition, } c = 2 j e_o \text{ and } e_o = \frac{c}{2j} = -j \frac{c}{2} \tag{65}$$

if $D/\lambda \ll 1$, then as in equation (52) $\sin \nu = V \cos \phi$

and

$$e_R = (V \cdot c) \cos \phi - j \frac{c}{2} m e^{-j\nu} = k\left(\cos \phi - j \frac{m}{2V} e^{-j\nu}\right) =$$

$$k \left(\cos \phi - j \frac{m}{2V} e^{-j V \cos \phi}\right) \qquad (66)$$

Examining equation (66)

For amplitude balanced: $m = 0$ and $e_R = 0$ (a null) when $\phi = \pi/2$ or $3\pi/2$

For amplitude unbalanced: $m \neq 0$, and $e_R = \frac{m}{2V}$ (a minimum) when $\phi = \pi/2$ or $3\pi/2$

Thus amplitude unbalance while causing no error, does blur the minimum, which is reflected in bearing spread or indefinite bearings.

Appendix II

Fixed Adcock System - Unbalanced Voltage Analysis*

(Using Inductive Goniometer)

Case 1. <u>Analysis of a balanced system.</u>

In paragraph 8 (c) (4) (a) it is shown in equations (16) to (27) inclusive that the goniometer azimuth angle ψ reproduces the wave angle ϕ without error or blurring the minimum.

Case 2. <u>Analysis of a phase unbalanced system</u>.

Assume that in the Adcock collector system shown in Plate 3, antenna pair A - A' is balanced while antenna B' of pair B - B' is unbalanced; e.g., is <u>retarded</u> in phase by an amount = β <u>radians</u>, then

$$e_{R_1} = k \cos \phi \quad \text{from equations (16) or (53)}$$

$$e_{R_2} = k \left(\sin \phi + \frac{\beta}{2\,V}\right) e^{-j\left(\frac{\beta}{2}\right)} \quad \text{from equations (17) and (61)} \qquad (67)$$

Also,

$$e'_1 = k' \cos \phi \ \sin \psi \quad \text{from equations (20) and (53)} \qquad (68)$$

$$e'_2 = -k' \left(\sin \phi + \frac{\beta}{2\,V}\right) e^{-j\left(\frac{\beta}{2}\right)} \cdot \cos \psi \quad \text{from equations (22) and (67)} \qquad (69)$$

from equation (23):

$$e'_R = (e'_1 + e'_2) = k' \left\{ \cos \phi \ \sin \psi - \left(\sin \phi + \frac{\beta}{2V}\right) e^{-j\left(\frac{\beta}{2}\right)} \cos \psi \right\} \qquad (70)$$

$$= \left\{ \tan \psi - \left(\tan \phi + \frac{\beta}{2\,V \cos \phi}\right) e^{-j\left(\frac{\beta}{2}\right)} \right\} k' \cos \phi \ \cos \psi \qquad (71)$$

$$= \left\{ \tan \psi - \left(1 + \frac{\beta}{2\,V \sin \phi}\right) e^{-j\left(\frac{\beta}{2}\right)} \tan \phi \right\} k' \cos \phi \ \cos \psi \qquad (72)$$

Examining equation (72)

For phases in balance: $\beta = 0$; and $e'_R = 0$ (a null) when $\psi = \phi$

* See note, bottom of page 1, Appendix I.

For phases unbalanced:

- $\beta \neq 0$; and $e'_R \neq 0$ when $\psi = \phi$.
- Since $e^{-j\left(\frac{\beta}{2}\right)}$ contains a real and an imaginary component, there is no value of ψ which will make $e'_R = 0$. When ψ is adjusted for a minimum e'_R, bearing error and blurred minimum will be present in amounts depending upon β and ϕ.

Case 3. <u>Analysis of an amplitude unbalanced system.</u>

Assume that in the Adcock collector system shown in Plate 3, antenna pair A - A' is balanced, while antenna B' of pair B - B' is unbalanced; e.g., is <u>decreased</u> in voltage amplitude by an amount = <u>m</u> .

Then $e_{R_1} = k \cos\phi$ from equations (16) or (53)

$$e_{R_2} = k\left(\sin\phi - \frac{m}{2V}\, j\, e^{-j\gamma'}\right) \text{ from equations (17) and (66)} \qquad (73)$$

where $$\gamma' = V \sin\phi = 2\frac{\pi D}{\lambda} \sin\phi \qquad (73a)$$

also $$e'_1 = k' \cos\phi \sin\psi \text{ from equations (20) and (53)} \qquad (74)$$

$$e'_2 = -k'\left(\sin\phi - \frac{m}{2V}\, j\, e^{-j\gamma'}\right)\cos\psi \text{ from equations (22) and (73)} \qquad (75)$$

$$e'_R = (e'_1 + e'_2) = k'\left\{\cos\phi \sin\psi - \left(\sin\phi - \frac{m}{2V}\, j\, e^{-j\gamma'}\right)\cos\psi\right\} \text{ from equation (23)} \qquad (76)$$

$$= \left\{\tan\psi - \left(\tan\phi - \frac{m}{2V\cos\phi}\, j\, e^{-j\gamma'}\right)\right\} k' \cos\phi \cos\psi \qquad (77)$$

$$= \left\{\tan\psi - \left(1 - \frac{m}{2V\sin\phi}\, j\, e^{-j\gamma'}\right)\tan\phi\right\} k' \cos\phi \cos\psi \qquad (78)$$

Examining equation (78)

For amplitudes in balance: $m = 0$; and $e'_R = 0$ (a null) when $\psi = \phi$

For amplitude unbalance:

- $m \neq 0$, and $e'_R \neq 0$ when $\psi = \phi$.
- Since $j\,e^{-j\gamma}$ contains a real and an imaginery component, there is no value of ψ which will make $e'_R = 0$. When ψ is adjusted for a minimum e'_R, bearing error and blurred minimum will be present in amounts depending upon m and ϕ.

Case 4. Behavior of bearing minimum in a phase unbalanced system.

A. Bearing error introduced.

From equation (72), case 2

$$e'_R = \left\{\tan\psi - \left(1 + \frac{\beta}{2V\sin\phi}\right)\tan\phi\; e^{-j\frac{\beta}{2}}\right\} k'\cos\phi\cos\psi =$$

$$\left\{\tan\psi - A\,e^{-j\frac{\beta}{2}}\right\} k'' \qquad (79)$$

$$\text{where } k'' = k'\cos\phi\,\cos\psi \qquad (80)$$

$$\text{and}\quad A = \left(1 + \frac{\beta}{2V\sin\phi}\right)\tan\phi = \left(\tan\phi + \frac{\beta}{2V}\sec\phi\right) \qquad (81)$$

$$\text{or}\quad e'_R = \left\{\tan\psi - A\left(\cos\frac{\beta}{2} - j\sin\frac{\beta}{2}\right)\right\} k'' \qquad (82)$$

$$= \left\{\tan\psi - A\left(1 - j\frac{\beta}{2}\right)\right\} k'' \quad \text{when } \frac{\beta}{2} \ll 1 \qquad (83)$$

Now, let ψ_1 = the goniometer azimuth obtained when e'_R = a minimum

(this corresponds to the real part of equation (83) = 0)

then $\delta_1 = \psi_1 - \phi$ = the bearing error present due to phase unbalance β.

$$\text{for } e'_R = \text{a minimum},\quad \left\{\tan\psi_1 - A\right\} k'' = 0 \quad\text{and}\quad \tan\psi_1 = A. \qquad (84)$$

$$\therefore\quad \psi_1 = \phi + \delta_1 = \tan^{-1} A = \tan^{-1}\left(\tan\phi + \frac{\beta}{2V}\sec\phi\right) \qquad (85)$$

$$\text{and}\quad \delta_1 = \left\{\tan^{-1} A\right\} - \phi = \left\{\tan^{-1}\left(\tan\phi + \frac{\beta}{2V}\sec\phi\right)\right\} - \phi \qquad (86)$$

B. <u>Bearing spread introduced due to blurring of the minimum.</u>

Let ψ_2 = the goniometer azimuth for which e'_R is 3 decibels (or 1.4 times) greater than its minimum value. (This corresponds to the real part of equation (83) having the same magnitude as its imaginery part.)

then $\delta_2 = \psi_2 - \psi_1$ = <u>one-half</u> the bearing spread or the change in ψ_1 necessary to increase e'_R 3 decibels over its minimum value.

For e'_R to increase 3 decibels, $(\tan \psi_2 - A) \equiv \frac{\beta}{2} A$ (87)

Simplifying, and substituting equation (84)

$$\text{and } \psi_2 = \tan^{-1}\left(1 + \frac{\beta}{2}\right) A = \tan^{-1}\left\{\left(1 + \frac{\beta}{2}\right) \tan \psi_1\right. \tag{88}$$

$$\therefore \quad \delta_2 = \psi_2 - \psi_1 = \left\{\tan^{-1}\left(1 + \frac{\beta}{2}\right) \tan \psi_1\right\} - \psi_1 \tag{89}$$

Case 5. <u>Behavior of bearing minimum in an amplitude unbalanced system.</u>

A. <u>Bearing error introduced.</u>

From equation (77) case 3,

$$e'_R = \left\{\tan \psi - \left(\tan \phi - j \frac{m}{2V \cos \phi} e^{-j\gamma'}\right)\right\} k' \cos \phi \cos \psi$$

$$= \left\{\tan \psi - \tan \phi + j \frac{m}{2V \cos \phi} \left(\cos \gamma' - j \sin \gamma'\right)\right\} k'' \tag{90}$$

Where k'' is obtained from equation (80) and $\gamma' = V \sin \phi$, from equation (73a)

But, when $\frac{D}{\lambda} \ll 1$, $\gamma' \ll 1$ and $\cos \gamma' \doteq 1$ and $\sin \gamma' \doteq \gamma'$

$$\therefore \; e'_R = \left\{ \tan\psi - \tan\phi + j\,\frac{m}{2V\cos\phi}\,(1 - j\gamma') \right\} k'' \qquad (91)$$

$$= \left\{ \tan\psi - \tan\phi + j\,\frac{m}{2V\cos\phi} + \frac{m\gamma'}{2V\cos\phi} \right\} k'' \qquad (92)$$

$$= \left\{ \tan\psi - \tan\phi + \frac{m\,V\sin\phi}{2V\cos\phi} + j\,\frac{m}{2V\cos\phi} \right\} k'' \qquad (93)$$

$$= \left\{ \tan\psi - \left(1 - \frac{m}{2}\right)\tan\phi + j\,\frac{m}{2V\cos\phi} \right\} k'' \qquad (94)$$

let ψ_3 = the goniometer azimuth when e'_R = a minimum.

(This corresponds to the real part of equation (94) = 0.)

then $\delta_3 = \psi_3 - \phi$ = the bearing error present due to amplitude unbalance m .

$$\text{for } e'_R = \text{ a minimum, } \left[\tan\psi_3 - \left(1 - \frac{m}{2}\right)\tan\phi \right] k'' = 0 \qquad (95)$$

$$\text{or } \tan\psi_3 = \left(1 - \frac{m}{2}\right)\tan\phi \qquad (96)$$

$$\text{and } \psi_3 = \phi + \delta_3 = \tan^{-1}\left\{ \left(1 - \frac{m}{2}\right)\tan\phi \right\} \qquad (97)$$

$$\therefore \; \delta_3 = \left\{ \tan^{-1}\left(\left(1 - \frac{m}{2}\right)\tan\phi \right) \right\} - \phi \qquad (98)$$

B. <u>Bearing spread introduced due to blurring of the minimum.</u>

Let ψ_4 = the goniometer azimuth for which e'_R is 3 decibels or 1.4 times greater than its minimum value. This corresponds to the real part of equation (94) having the same magnitude as its imaginary part.

then $\delta_4 = \psi_4 - \psi_3$ = <u>one-half</u> the bearing spread or the change in ψ_3 necessary to increase e'_R 3 decibels over its minimum value.

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For e'_R to increase 3 decibels, $\left\{\tan \psi_4 - \left(1 - \frac{m}{2}\right) \tan \phi\right\} \equiv \frac{m}{2V \cos \phi}$ (99)

$$\text{or} \quad \tan \psi_4 = \left(1 - \frac{m}{2}\right) \tan \phi + \frac{m}{2V \cos \phi} \tag{100}$$

$$= \tan \psi_3 + \frac{m}{2V \cos \phi} = \tan \psi_3 + \frac{m}{2V} \sec \phi \tag{101}$$

$$\text{and} \quad \psi_4 = \tan^{-1} \left\{ \left(1 - \frac{m}{2}\right) \tan \phi + \frac{m}{2V} \sec \phi \right\} \tag{102}$$

$$\therefore \quad \delta_4 = \psi_4 - \psi_3 = \left[\tan^{-1} \left\{ 1 - \frac{m}{2} \left(1 - \frac{1}{V \sin \phi}\right) \right\} \tan \phi \right] - \psi_3 \tag{103}$$

Table 1

Rotatable Adcock System - Unbalance Voltage Analysis

(Refer to Appendix I and pair A-A' of Plate 3)

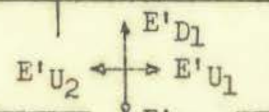
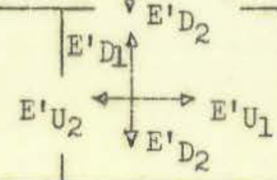
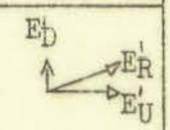
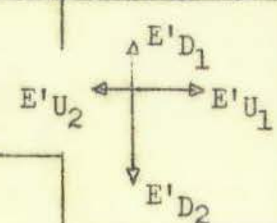
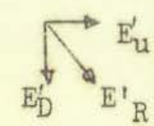
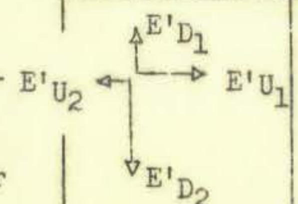
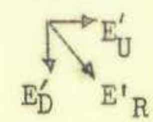
Behavior of minimum for various types of unbalance

Appendix I			Resultant Adcock Voltage $E_R = E_{R1}$		Bearing or Antenna Azimuth for Minimum		
Case							
No.	Type	Eq. No.	Directional Component	Non Directional Component	Azimuth or Position	Condition of Minimum	Bad Min. or Error Due to
1	Balanced	(54)	$E_{D_1} = 0$	$E_{U_1} = 0$	Correct	Null	None
2	Phase Unbalance	(61)	$E_{D_1} \neq 0$	$E_{U_1} = 0$	In Error	Null	Making $E_{D_1} = 0$
3	Amplitude Unbalance	(66)	$E_{D_1} = 0$	$E_{U_1} \neq 0$	Correct	Blurred	$E_{U_1} \neq 0$
4	Phase and amplitude unbalance	(61) and (66)	$E_{D_1} \neq 0$	$E_{U_1} \neq 0$	In Error	Blurred	Making $E_{D_1} = 0$ while $E_{U_1} \neq 0$

Table 2

Fixed Adcock - Unbalance Voltage Analysis
(Refer to Appendix II and Plate 3)

Behavior of minimum for various types of unbalance

Appendix II			Resultant Adcock Voltage E'_R		Goniometer Search Minimum			Vector Analysis	
No.	Case Type	Eq. No.	Directional Component E'_D	Non Directional Component E'_U	Azimuth or Position	Condition of Minimum	Bad Min. and Error Due To	E'_R Components	Summation for Best Minimum
1	Balanced	(27)	$E'_{D_1} = -E'_{D_2}$	$E'_{U_1} = -E'_{U_2}$	Correct	Null	None		E'_R
2	Phase unbalance	(72)	$E'_{D_1} \neq -E'_{D_2}$	$E'_{U_1} \neq -E'_{U_2}$	In error to correct for $E'_{D_1} \neq -E'_{D_2}$	Blurred	$E'_D \neq 0$ $E'_U \neq 0$		
3	Amplitude unbalance	(78)	$E'_{D_1} \neq -E'_{D_2}$	$E'_{U_1} \neq -E'_{U_2}$	In error to correct for $E'_{D_1} \neq -E'_{D_2}$	Blurred	$E'_D \neq 0$ $E'_U \neq 0$		
4	Phase and amplitude unbalance	(72) (78)	$E'_{D_1} \neq -E'_{D_2}$	$E'_{U_1} \neq -E'_{U_2}$	In error to correct for $E'_{D_1} \neq -E'_{D_2}$	Badly blurred	$E'_D \neq 0$ $E'_U \neq 0$		

Note: 1. The voltage analysis for the fixed Adcock system was based on the use of an inductive goniometer.
2. The behavior of the minimum in a resistance goniometer would be similar to the above.
3. If more than one antenna is unbalanced, their contribution to the error and blurring of the minimum will be superimposed on the values derived for a single unbalanced antenna.

Table 3

Fixed Adcock - Unbalanced Voltage Analysis

Evaluation of Bearing Error and Bearing Spread

Refer to Appendix II, Cases 4 and 5, and Plates 15 and 16.

Unbalance				
Phase β Degrees	Amplitude m %	Frequency kc	Maximum Bearing Error Introduced degrees	Maximum Bearing Spread* (Blurring of Minimum) Introduced degrees
0.5	-	300	0.73	± 0.16
0.1	-	300	0.15	± 0.03
0.5	-	1000	0.22	± 0.14
0.1	-	1000	0.04	± 0.03
-	5	300	0.73	± 4.20
-	1	300	0.18	± 0.83
-	5	1000	0.73	± 1.27
-	1	1000	0.18	± 0.25

* Based on the bearing change that is required to increase the goniometer voltage minimum 3 decibels or 1.4 times.

Note: 1. The above values of bearing error and bearing spread are based either on phase or amplitude impedance unbalance of a single antenna. The accumulate error and spread due to phase and amplitude unbalance in one or more antennas would add (by superposition) to the above values.

2. The above evaluation has been based on the use of an inductive goniometer. The values would not be materially altered for a resistance goniometer.

3. The near linearity of the increase of bearing error and spread with unbalance.

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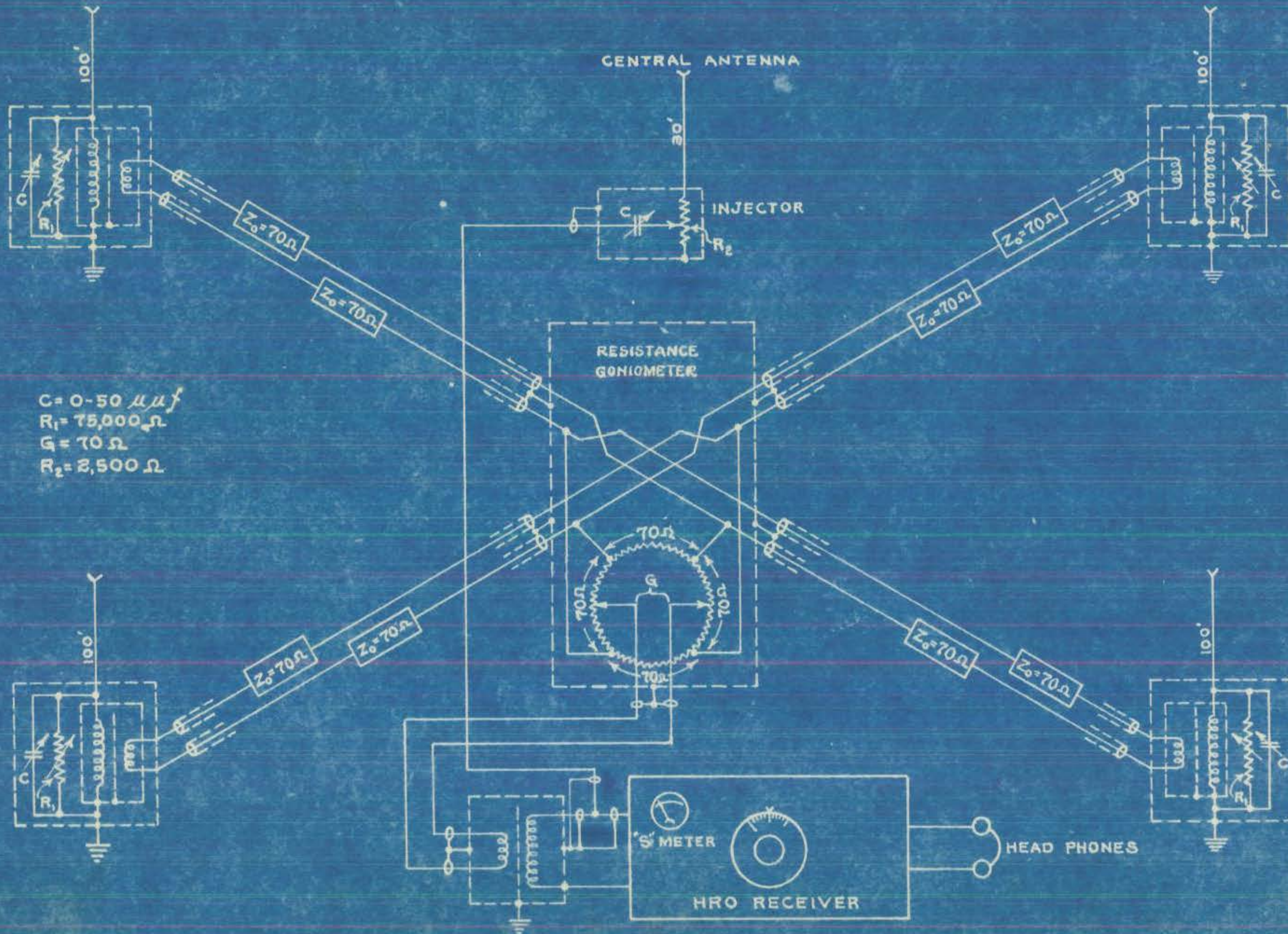

FIXED ADCOCK D.F. INSTALLATION AT N.R.L. 300 TO 1000 K.C.

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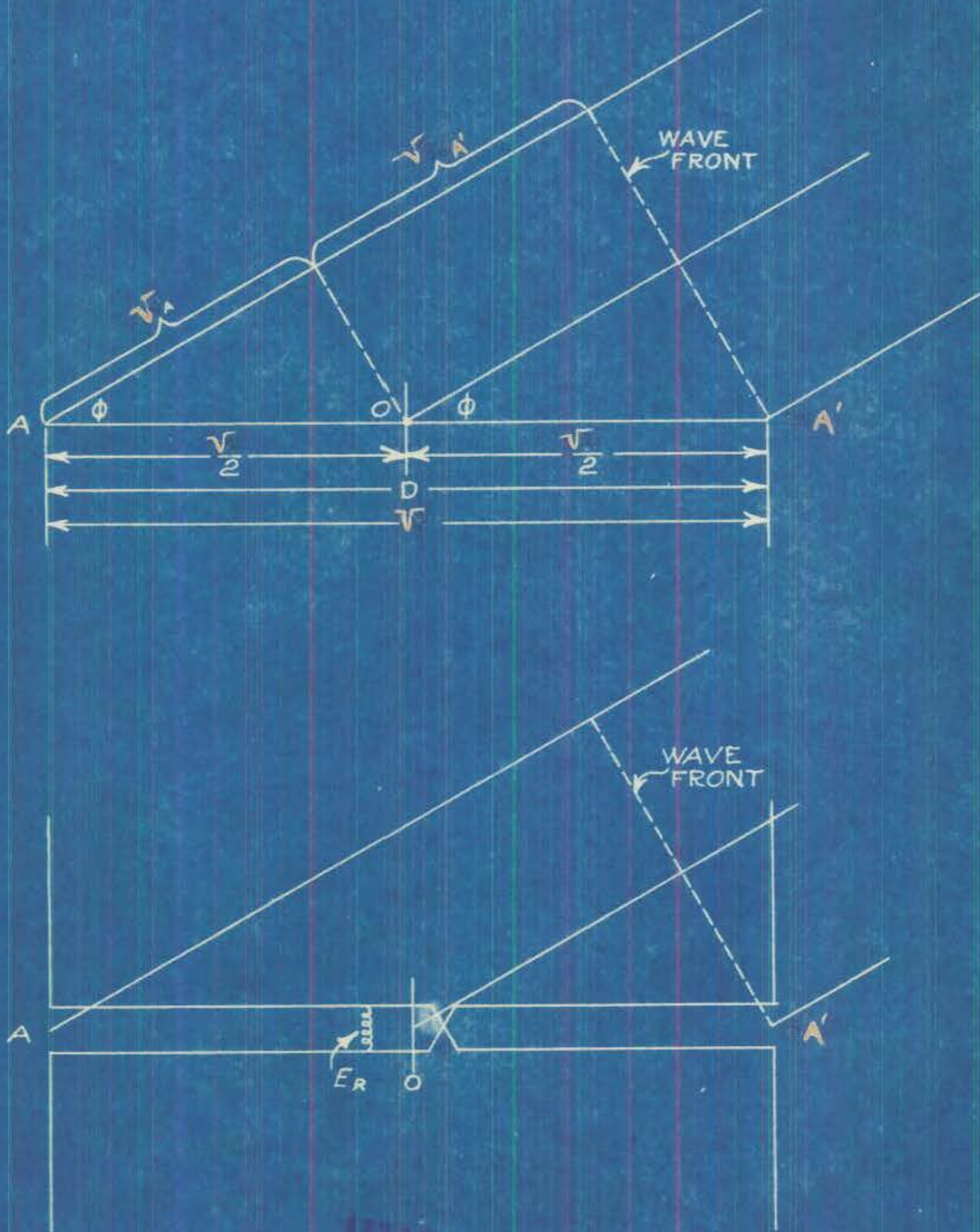
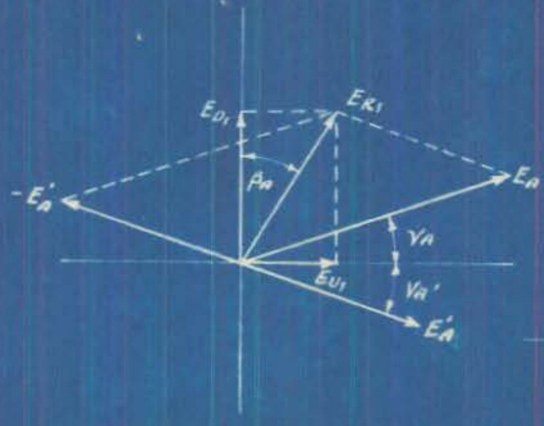
PLATE 1

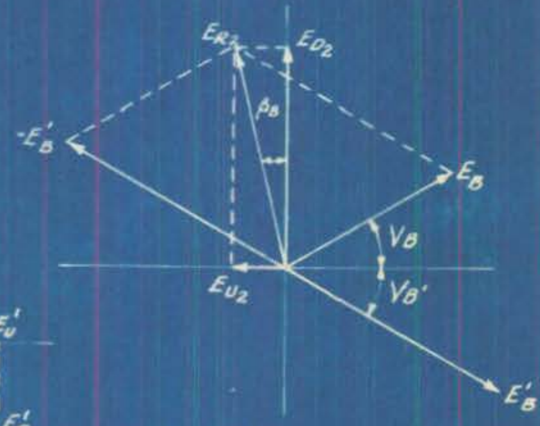
DIRECTIONAL CHARACTERISTIC OF A DIRECTIVE ADCOCK ANTENNA





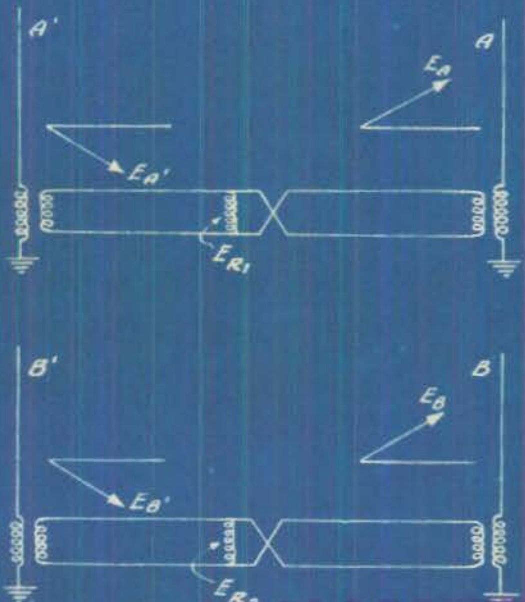
SUMMATION OF PAIR A-A' IN FIXED COIL OF GONIOMETER.

SUMMATION OF PAIRS A-A' AND B-B' IN PICK-UP COIL OF GONIOMETER.



SUMMATION OF PAIR B-B' IN FIXED COIL OF GONIOMETER.

GONIOMETER ACTS TO "BUCK" VOLTAGES IN PAIR A-A' AGAINST THE VOLTAGES IN PAIR B-B' YIELDING A RESULTANT E_R



E_A, E_A', E_B and E_B' = Induced antenna voltage.

V_A, V_A', V_B and V_B' = Phases of induced antenna voltages.

$-E_A'$, $-E_B'$ = Reversed induced antenna voltage.

E_{R_1} = Resultant of E_A and $-E_A'$.

E_{R_2} = Resultant of E_B and $-E'_B$.

E_{D_1} = Desired component of E_{R_1}.

E_{D_2} = Desired component of E_{R_2}.

E_{U_1} = Undesired component of E_{R_1}.

E_{U_2} = Undesired component of E_{R_2}.

β_A = Angle between E_{R_1} and E_{D_1}.

β_B = Angle between E_{R_2} and E_{D_2}.

E_R' = Resultant in goniometer pick-up coil.

E_D' = Desired component in goniometer pick-up coil.

E_U' = Undesired component in goniometer pick-up coil.

β_R = Angle between E_R' and E_D'.

E'_{R_1} = Proportion of E_{R_1} appearing in pick-up coil.

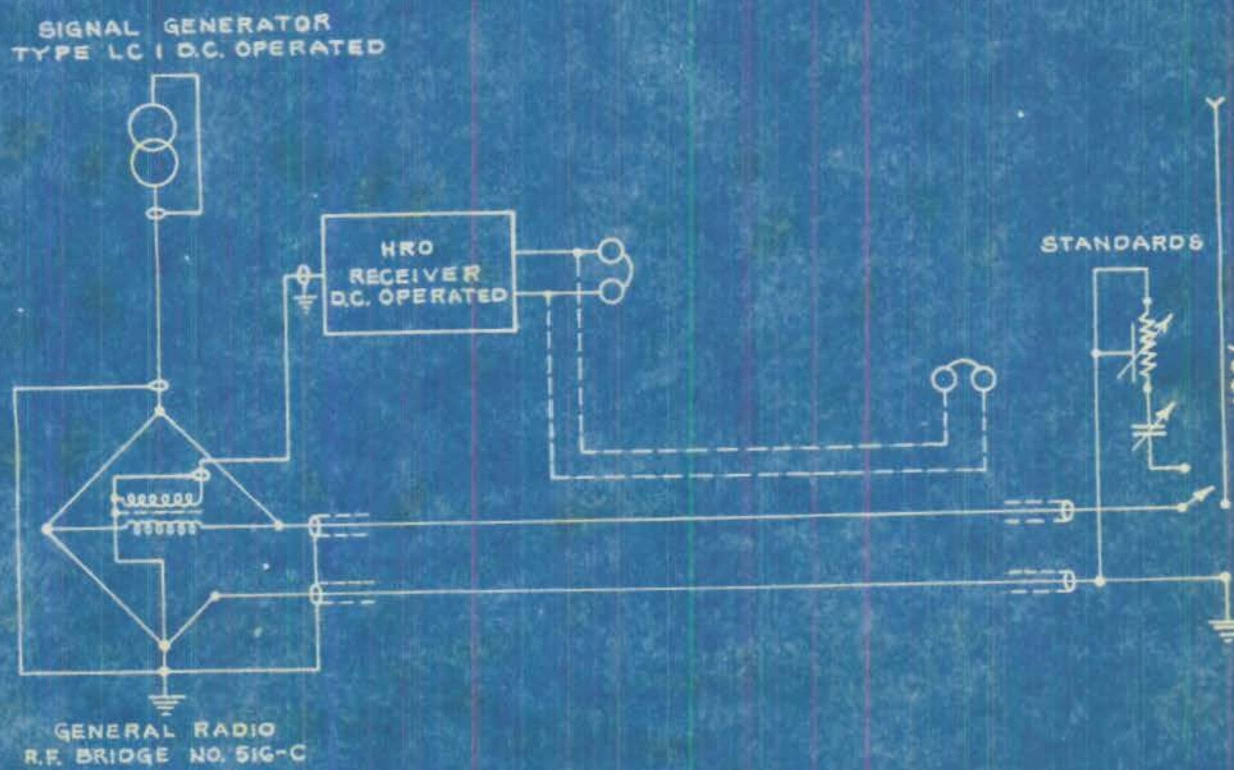
E'_{R_2} = Proportion of E_{R_2} appearing in pick-up coil.

VOLTAGE UNBALANCE ANALYSIS OF A FIXED ADCOCK COLLECTOR SYSTEM

PLATE 3

ANTENNA IMPEDANCE MEASURING METHOD

FIG. A



ANTENNA BALANCING METHOD

FIG. B

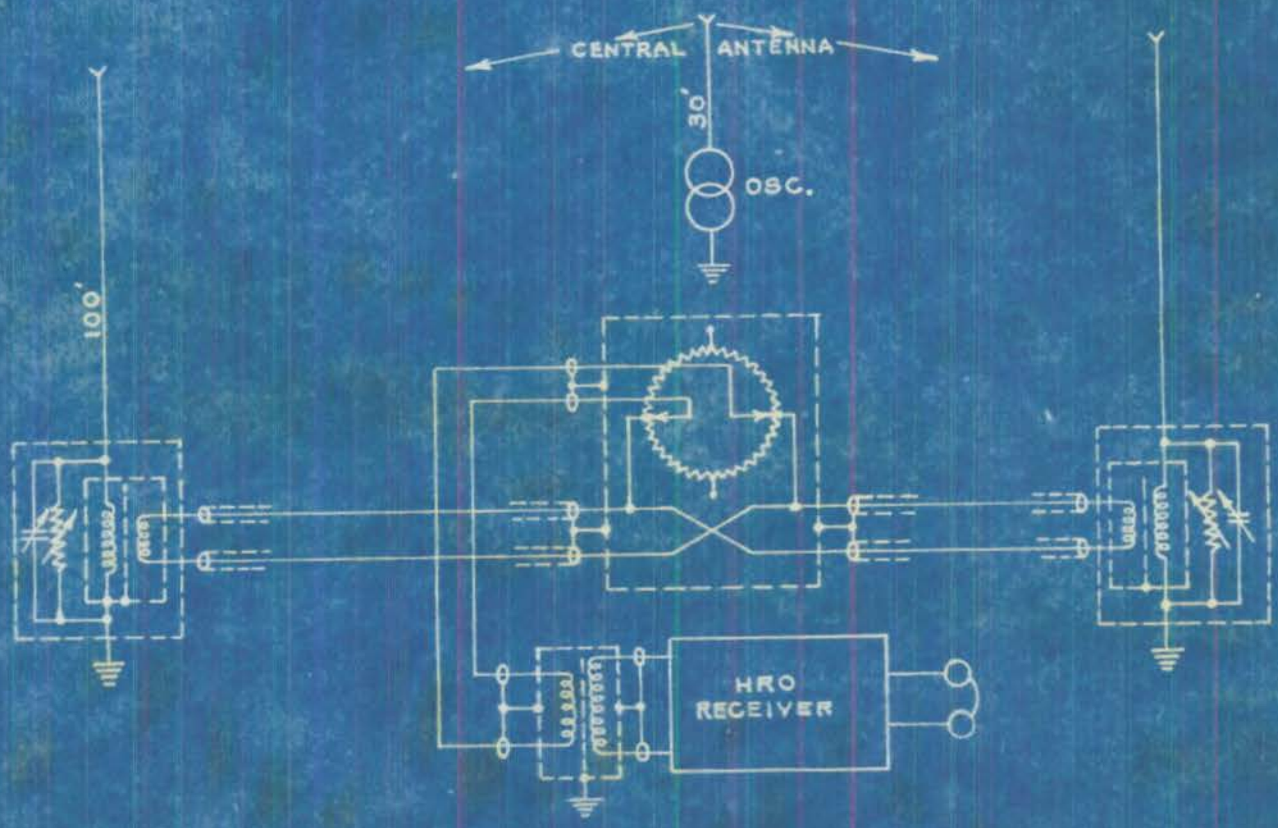
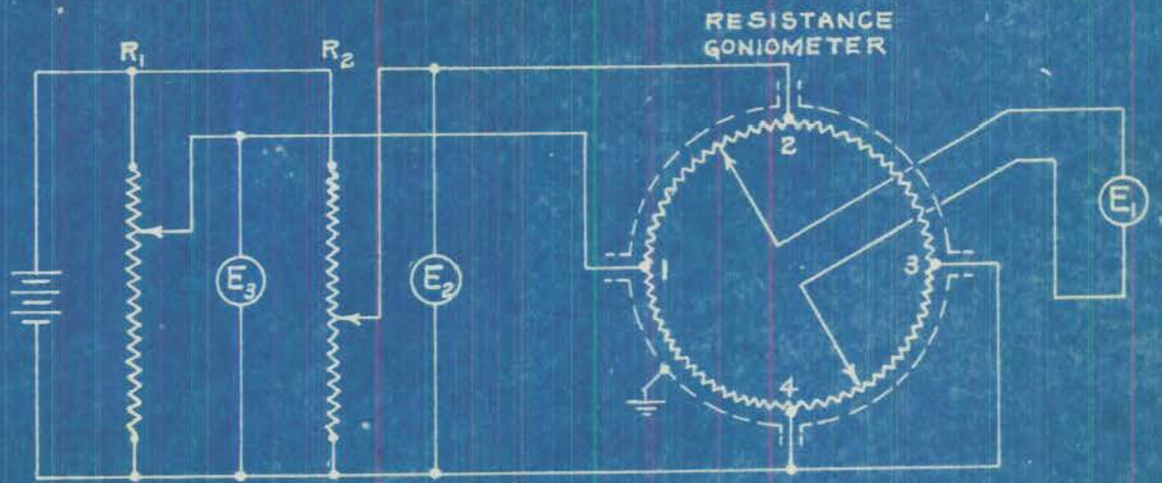
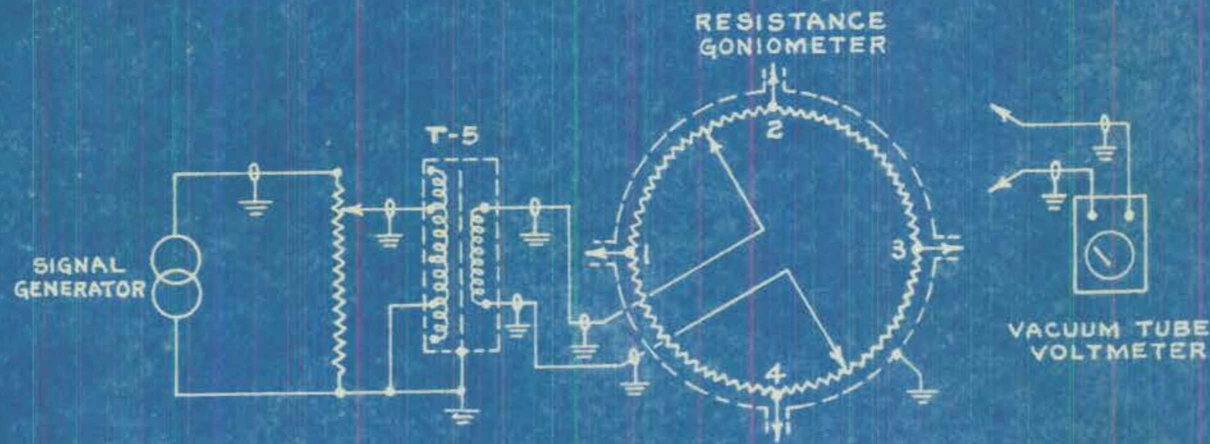


PLATE 4

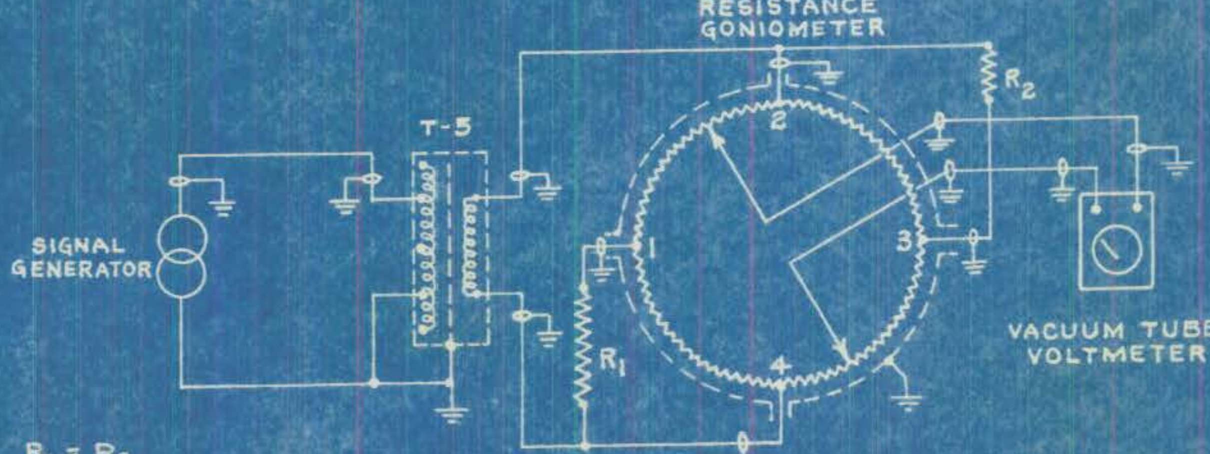
GONIOMETER CALIBRATION METHODS



METHOD A



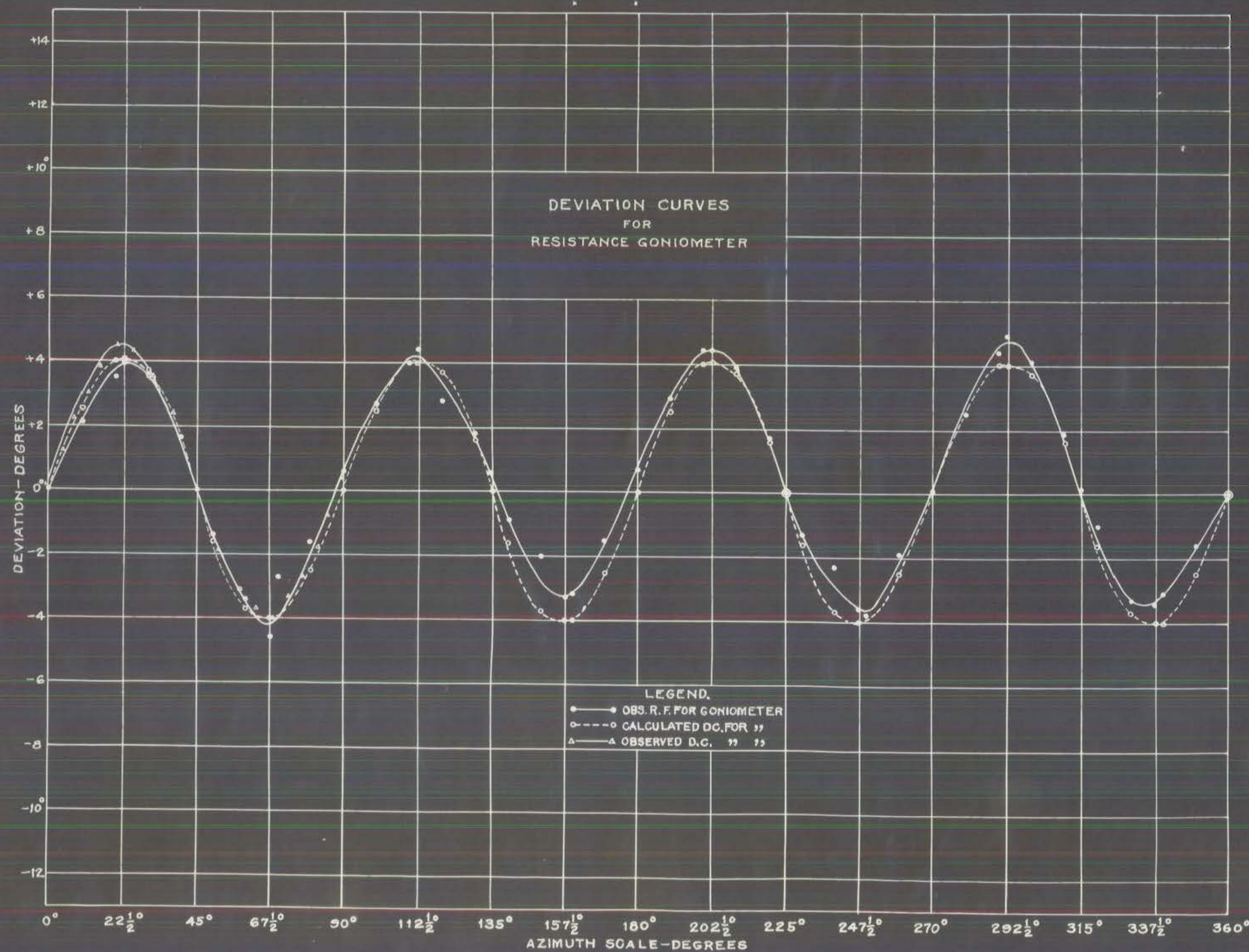
METHOD B



$R_1 = R_2$

METHOD C

UNCLASSIFIED



DEVIATION CURVES
FOR
RESISTANCE GONIOMETER
LEGEND.
OBS. R. F. FOR GONIOMETER
CALCULATED D.C. FOR ,,
OBSERVED D.C. ,, ,,
DEVIATION - DEGREES
AZIMUTH SCALE - DEGREES
+14
+12
+10°
+8
+6
+4
+2
0°
-2
-4
-6
-8
-10°
-12
0°
22½°
45°
67½°
90°
112½°
135°
157½°
180°
202½°
225°
247½°
270°
292½°
315°
337½°
360°

PLATE 6

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IF SHEET IS READ THIS WAY (HORIZONTALLY) THIS MUST BE TOP. IF SHEET IS READ THE OTHER WAY (VERTICALLY) THIS MUST BE LEFT-HAND SIDE

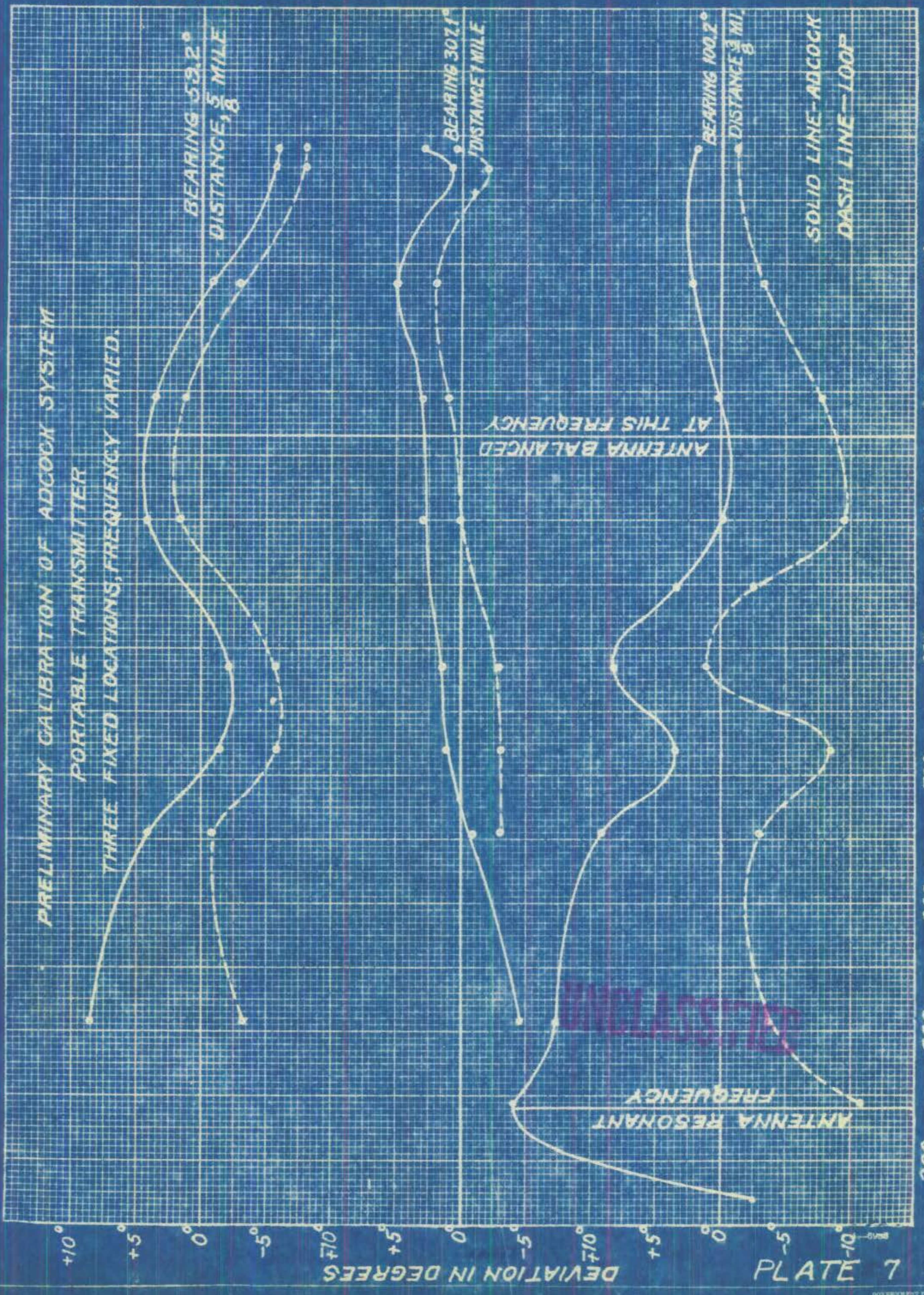


PLATE 7

N. R. L. 34

ADCOCK SYSTEM
TRANSMISSION EFFICIENCY
PICK-UP FACTOR
MEASURING CIRCUIT

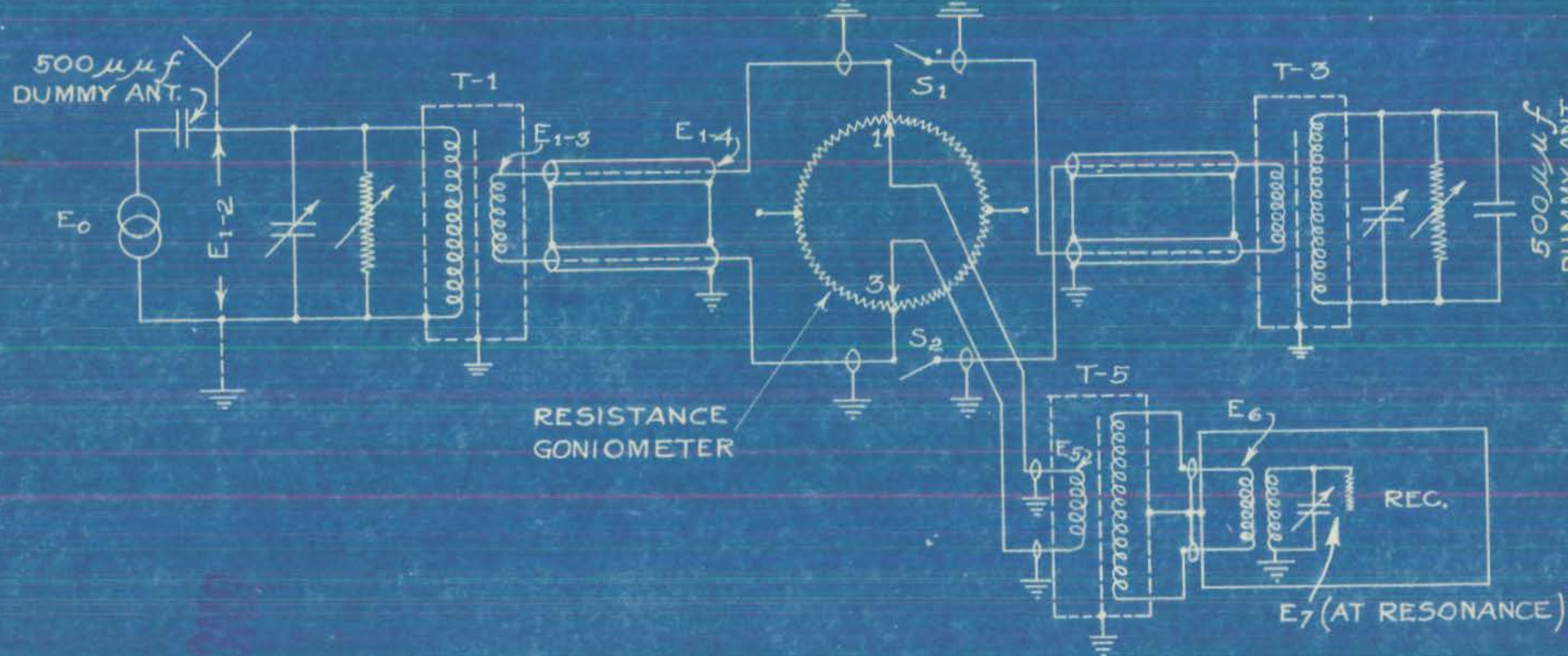


PLATE 8

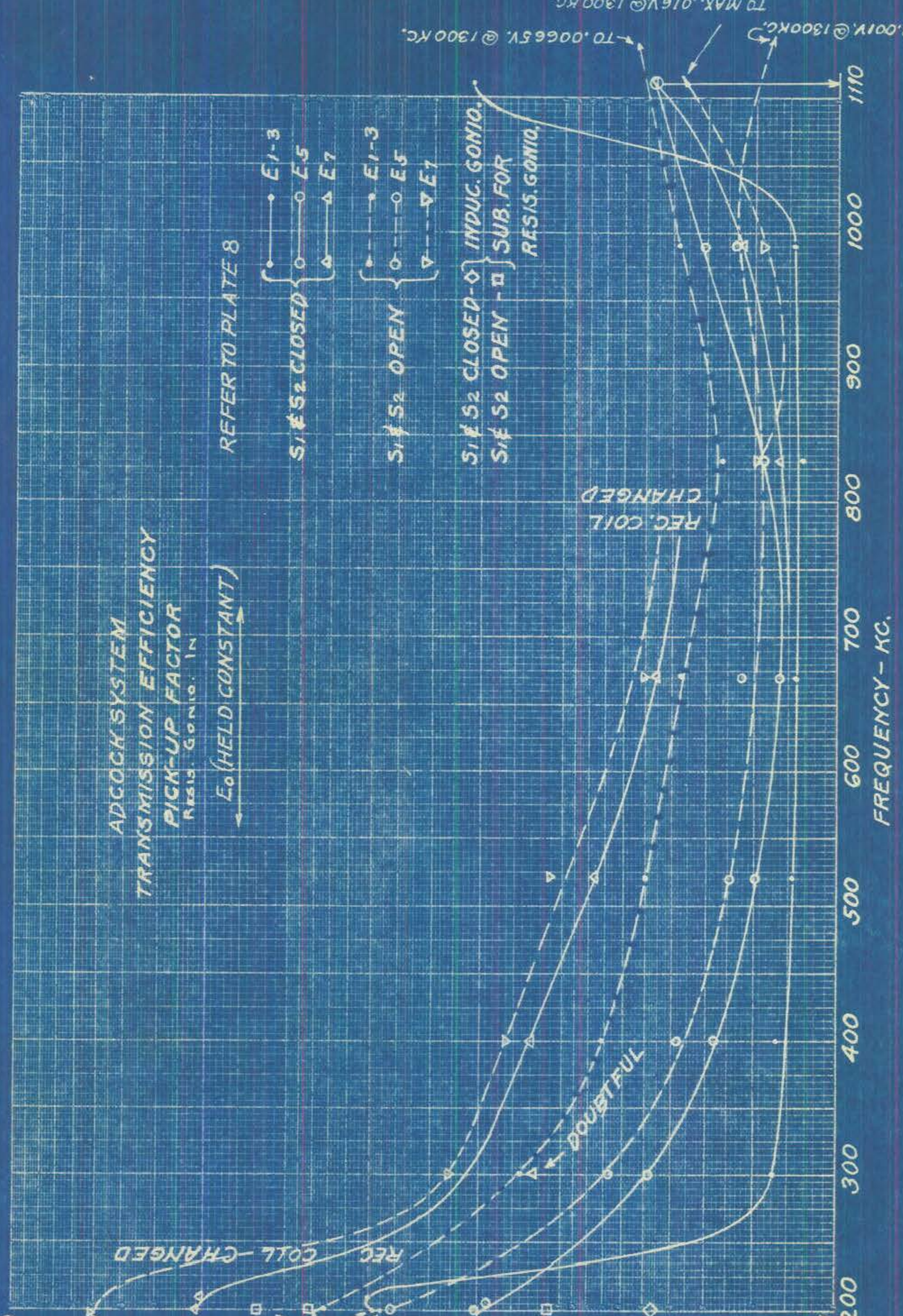

ADCOCK SYSTEM
TRANSMISSION EFFICIENCY
PICK-UP FACTOR
RESIS. GONIO. IN
E0 (HELD CONSTANT)
REFER TO PLATE 8
S1 & S2 CLOSED
E1-3
E5
E7
S1 & S2 OPEN
E1-3
E5
E7
S1 & S2 CLOSED - ◇ INDUC. GONIO.
S1 & S2 OPEN - □ SUB. FOR RESIS. GONIO.
REC. COIL CHANGED
REC. COIL - CHANGED
DOUBTFUL
TO .00665V. @ 1300 KC.
TO MAX. .016V @ 1300 KC.
TO .001V. @ 1300 KC.
1.0
0.1
.01
.001
R.F. VOLTS
200
300
400
500
600
700
800
900
1000
1110
FREQUENCY - KC.

PLATE 9A

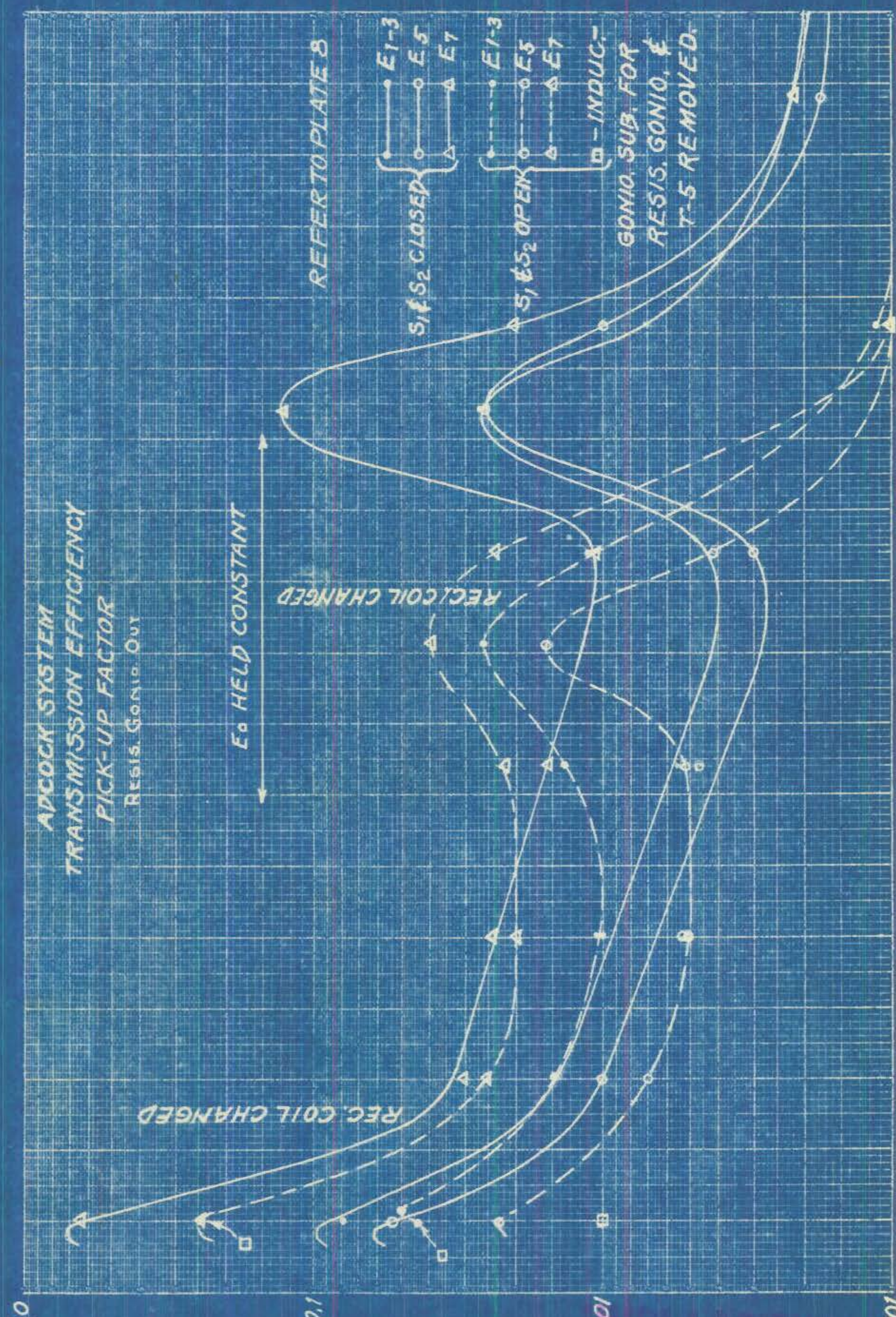
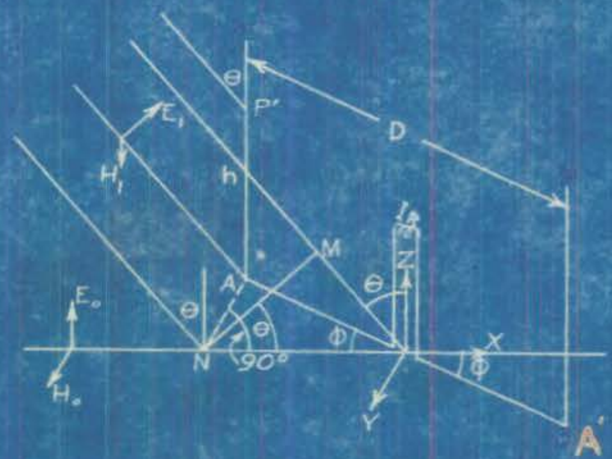

ADCOCK SYSTEM
TRANSMISSION EFFICIENCY
PICK-UP FACTOR
RESIS. GONIO. OUT
E0 HELD CONSTANT
REC. COIL CHANGED
REC. COIL CHANGED
REFER TO PLATE 8
S1 & S2 CLOSED
E1-3
E5
E7
S1 & S2 OPEN
E1-3
E5
E7
- INDUC.-
GONIO. SUB. FOR
RESIS. GONIO. &
T-5 REMOVED.
1.0
0.1
.01
.001
R.F VOLTS
200
300
400
500
600
700
800
900
1000
FREQUENCY - KC.

PLATE 9B

RESPONSE ANALYSIS OF THE ROTATING ADCOCK

FIG. A



WHERE

E_G is proportional to E_o the direct wave intensity.

E_A is proportional to E_1 the sky wave intensity.

D = distance between the antennae in meters.

λ = wave length of wave in meters.

$\omega = 2\pi f$ = angular velocity of wave.

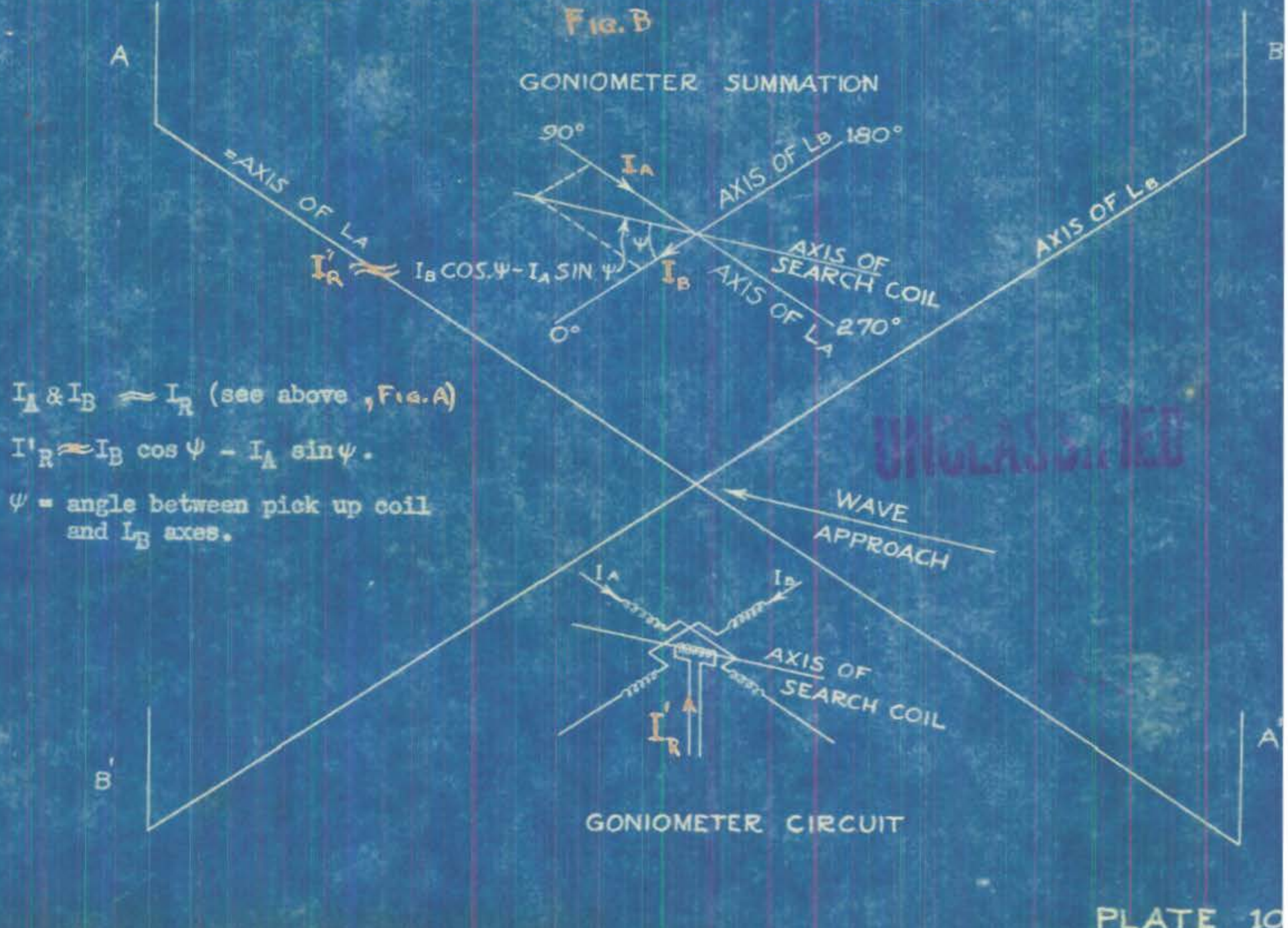
θ = vertical angle of incidence between antenna plane and sky wave [illegible]

ϕ = horizontal angle of incidence between antenna plane and sky wave [illegible]

I_R = resultant current in pick up coil due to one pair of antennas.

RESPONSE ANALYSIS OF THE FIXED ADCOCK

FIG. B



I_A & $I_B \approx I_R$ (see above, FIG. A)

$I'_R \approx I_B \cos\psi - I_A \sin\psi$.

ψ = angle between pick up coil and L_B axes.

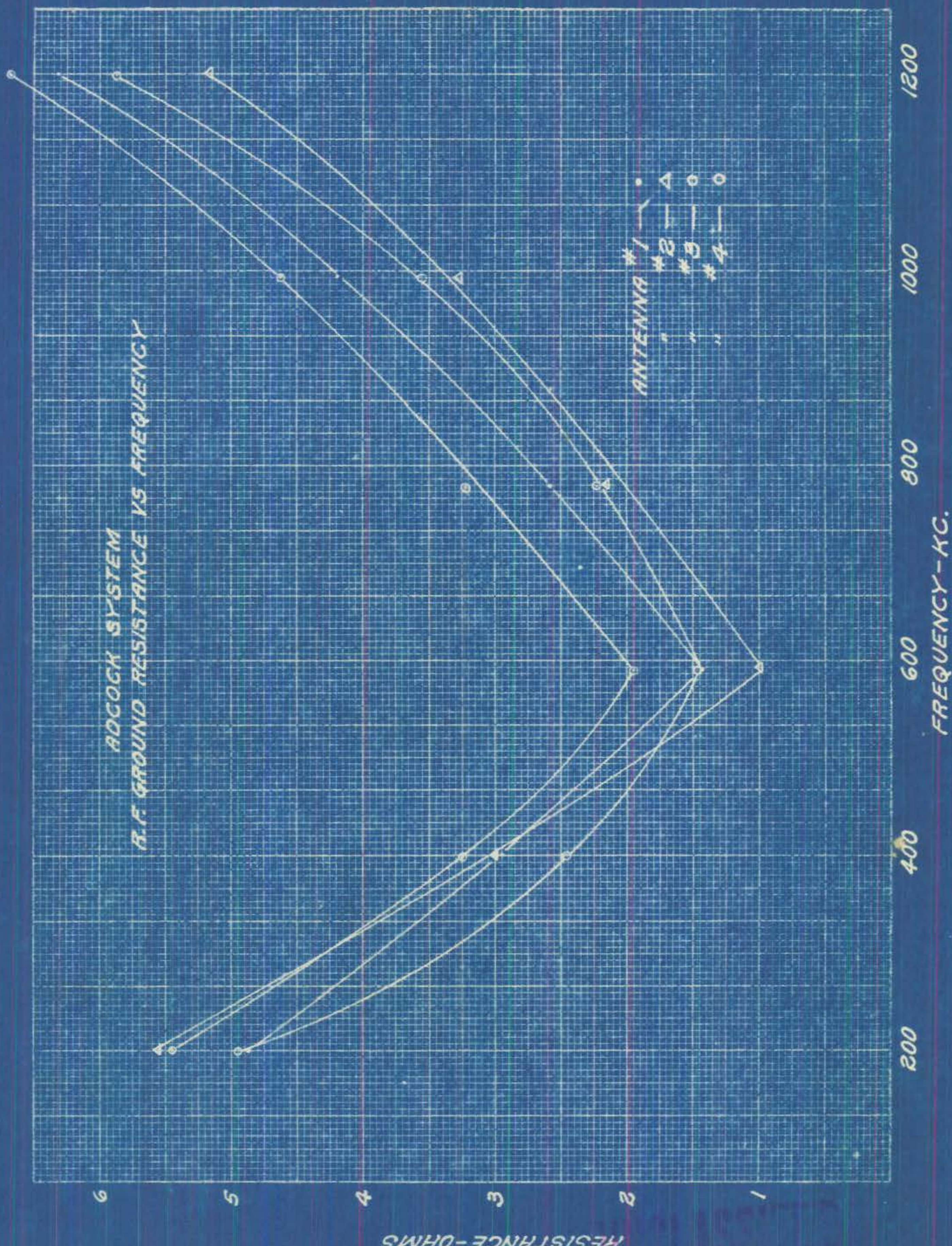

ADCOCK SYSTEM
R.F. GROUND RESISTANCE VS FREQUENCY
ANTENNA #1
#2
#3
#4
FREQUENCY-KC.
200
400
600
800
1000
1200
RESISTANCE-OHMS
1
2
3
4
5
6

PLATE 11

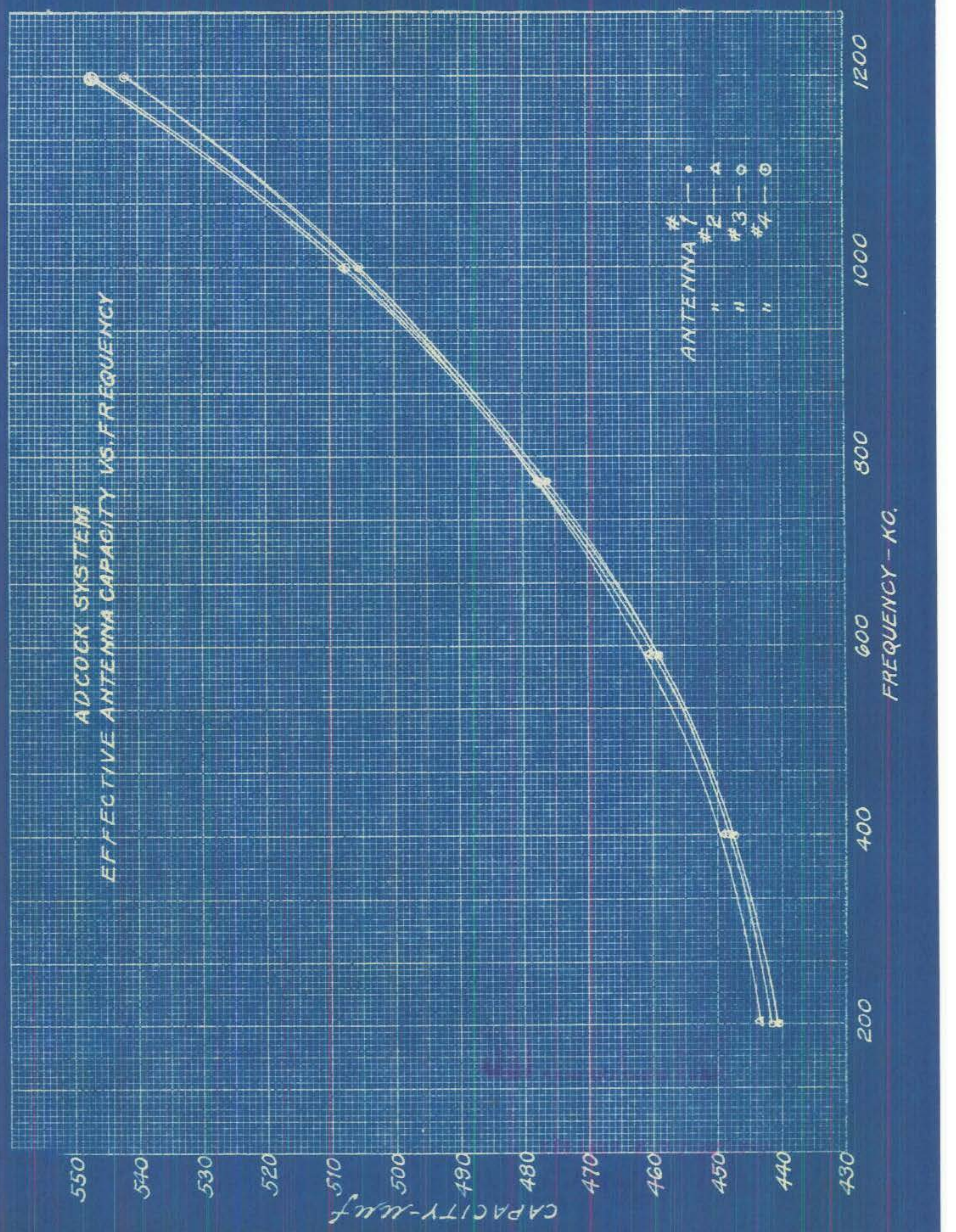

ADCOCK SYSTEM
EFFECTIVE ANTENNA CAPACITY VS. FREQUENCY
ANTENNA #1 — •
" #2 — Δ
" #3 — o
" #4 — ⊙
200
400
600
800
1000
1200
FREQUENCY - KC.
550
540
530
520
510
500
490
480
470
460
450
440
430
CAPACITY-μμf

PLATE 12

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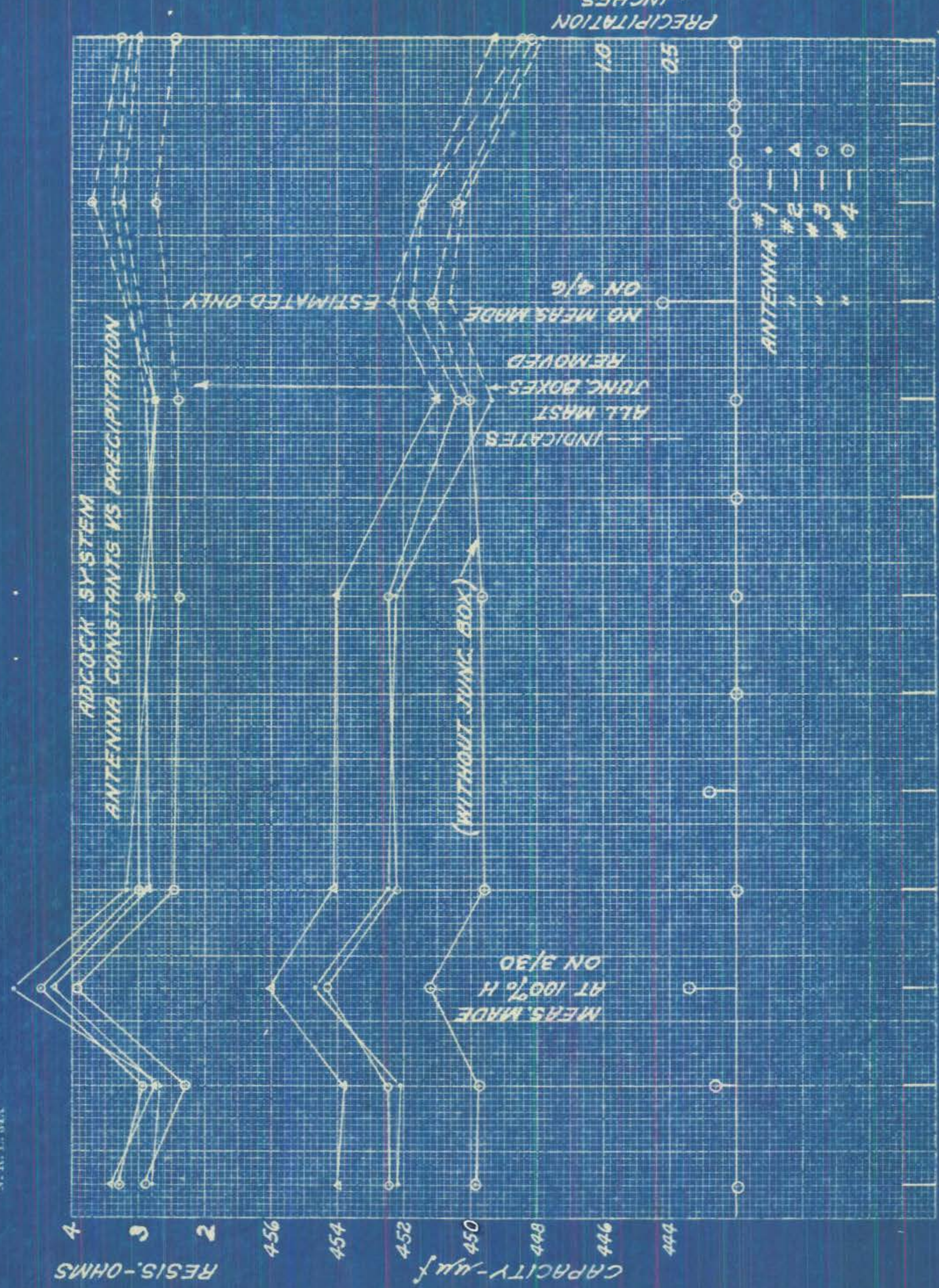
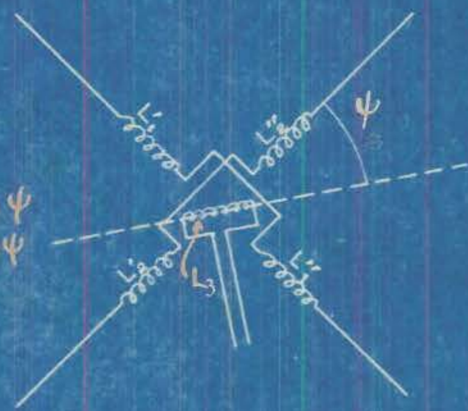


PLATE 13

ANALYSIS OF INDUCTIVE GONIOMETER

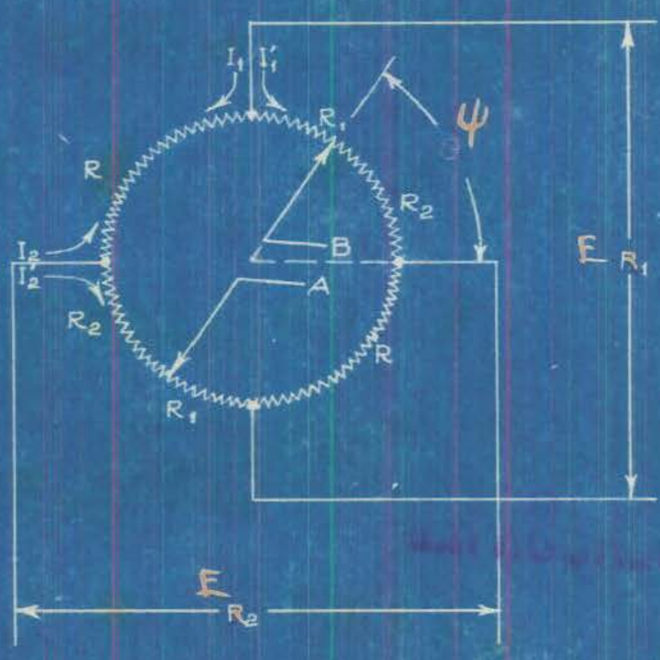
FIG. A

$L_1 = L_1' + L_1''$
$L_2 = L_2' + L_2''$
$M_{1\text{-}3} \approx L_1 \sin\psi$
$M_{2\text{-}3} \approx L_2 \cos\psi$



ANALYSIS OF RESISTANCE GONIOMETER

FIG. B



U. S. NAVAL RESEARCH LABORATORY
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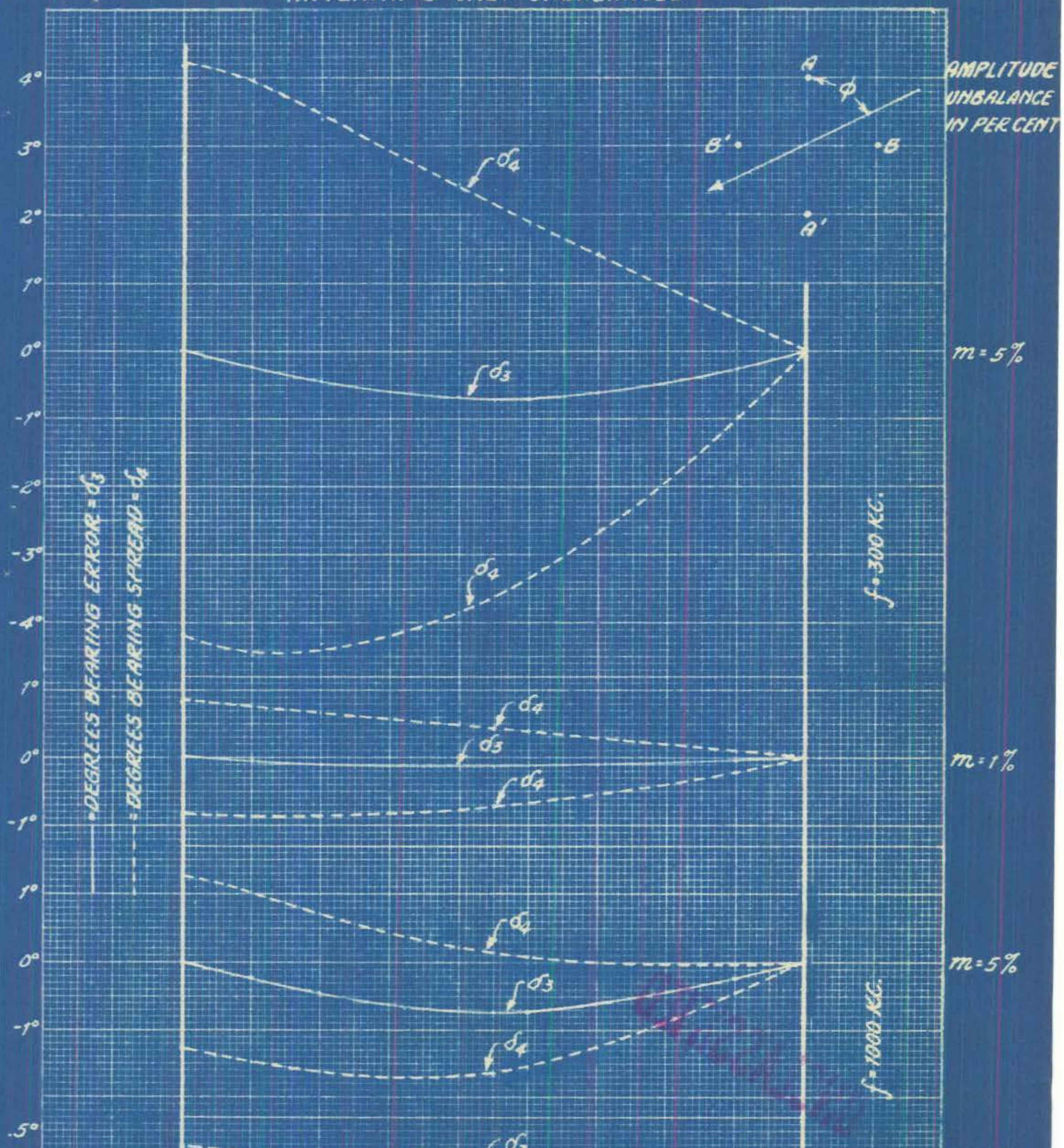
FIXED ADCOCK SYSTEM

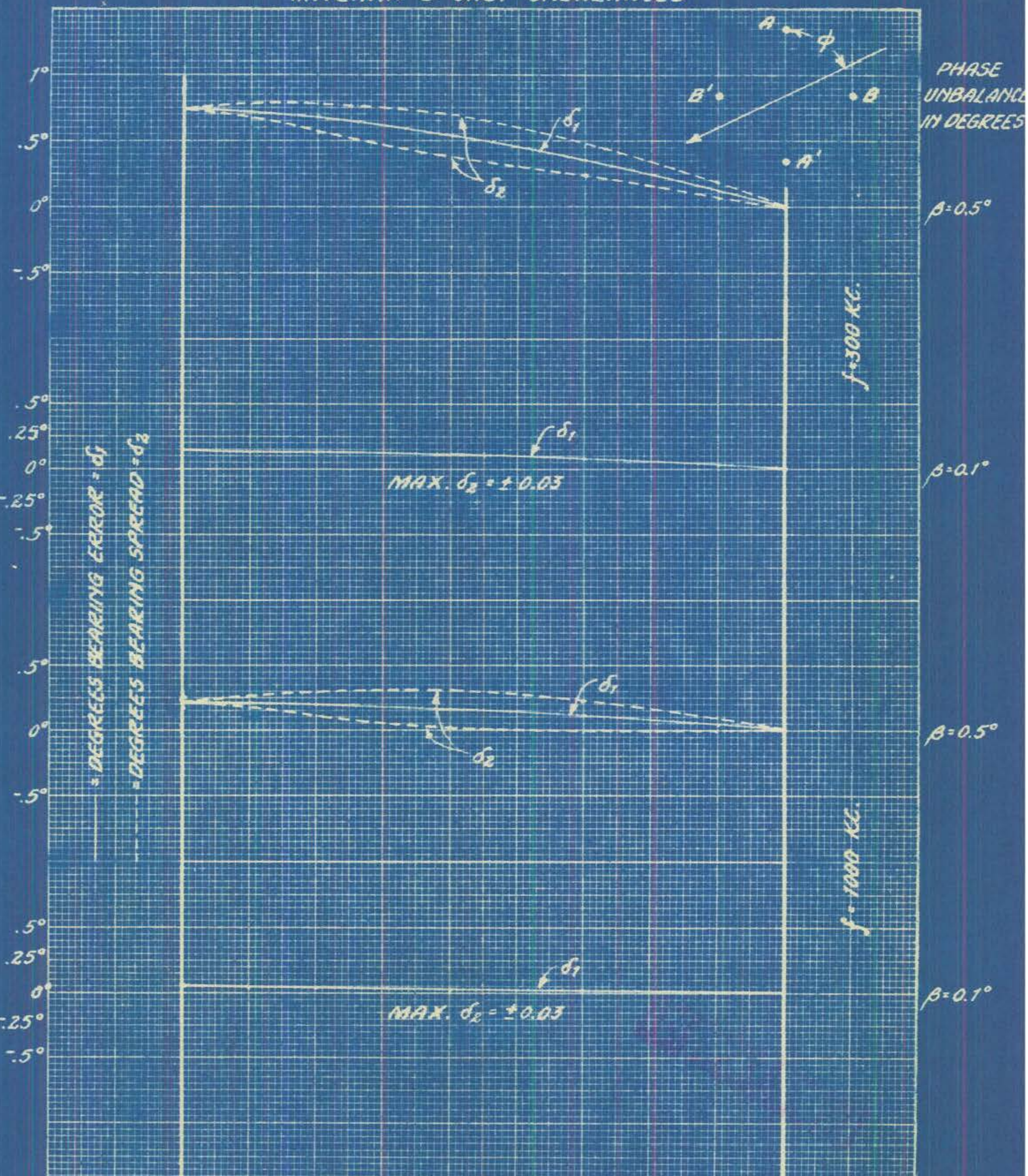
BEHAVIOR OF BEARING MINIMUM IN AN AMPLITUDE UNBALANCED SYSTEM
ANTENNA B' ONLY UNBALANCED



(REFER TO APPENDIX II, CASE 5, EQUATIONS 98 AND 103)

FIXED ADCOCK SYSTEM

BEHAVIOR OF BEARING MINIMUM IN A PHASE UNBALANCED SYSTEM
ANTENNA B' ONLY UNBALANCED



(REFER TO APPENDIX II, CASE 4, EQUATIONS 86 AND 89)

PLATE 16

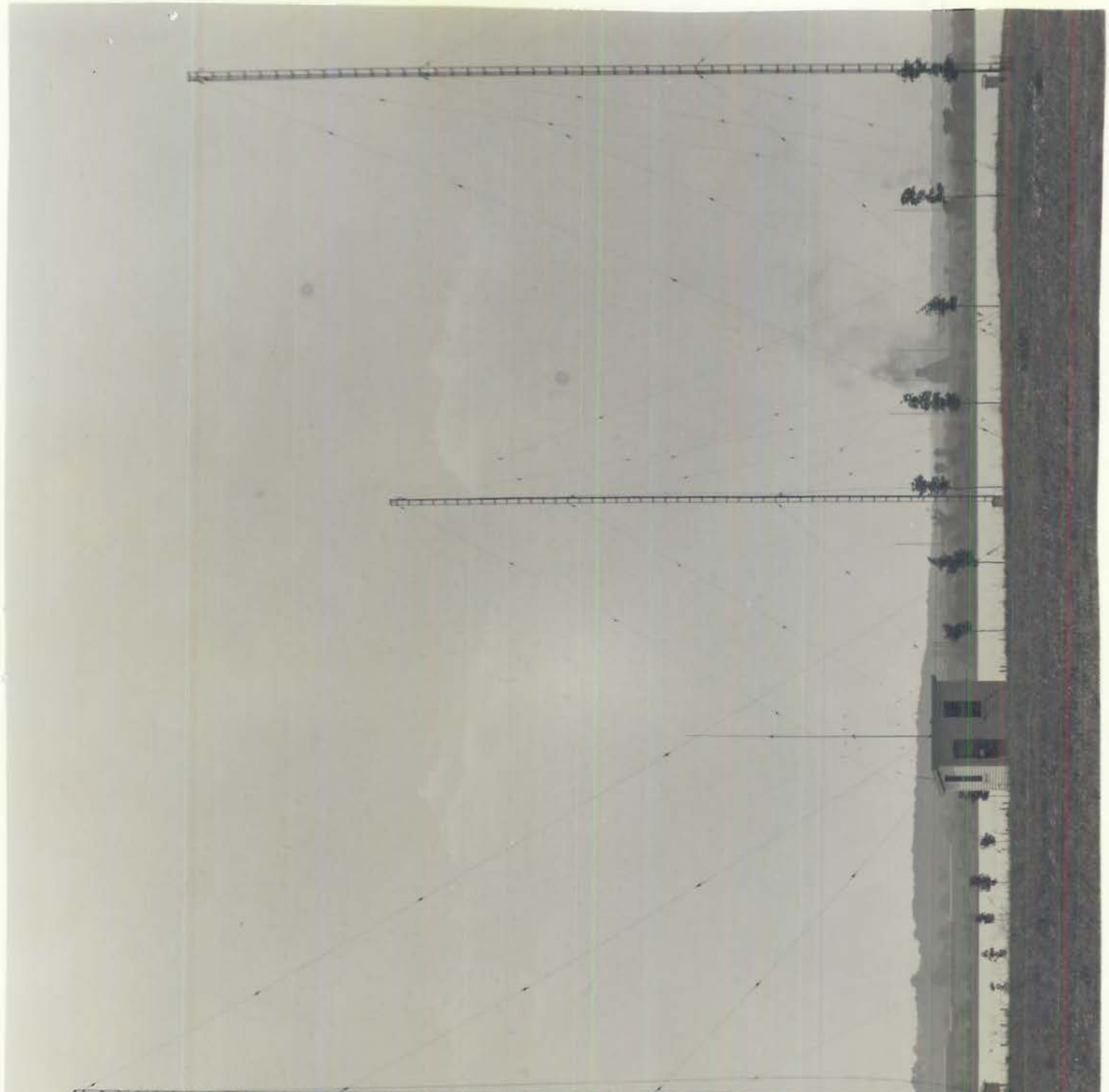


Plate 17

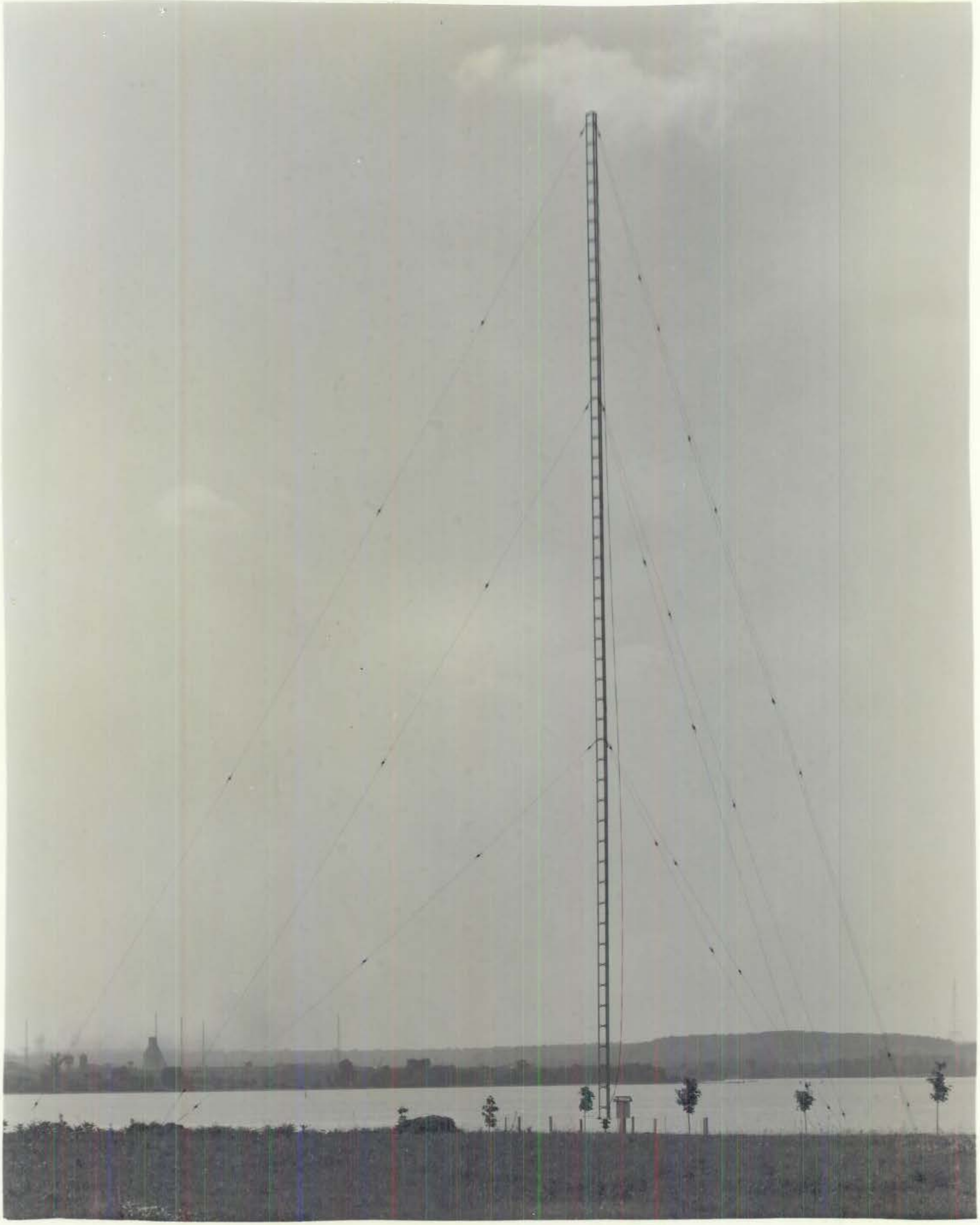
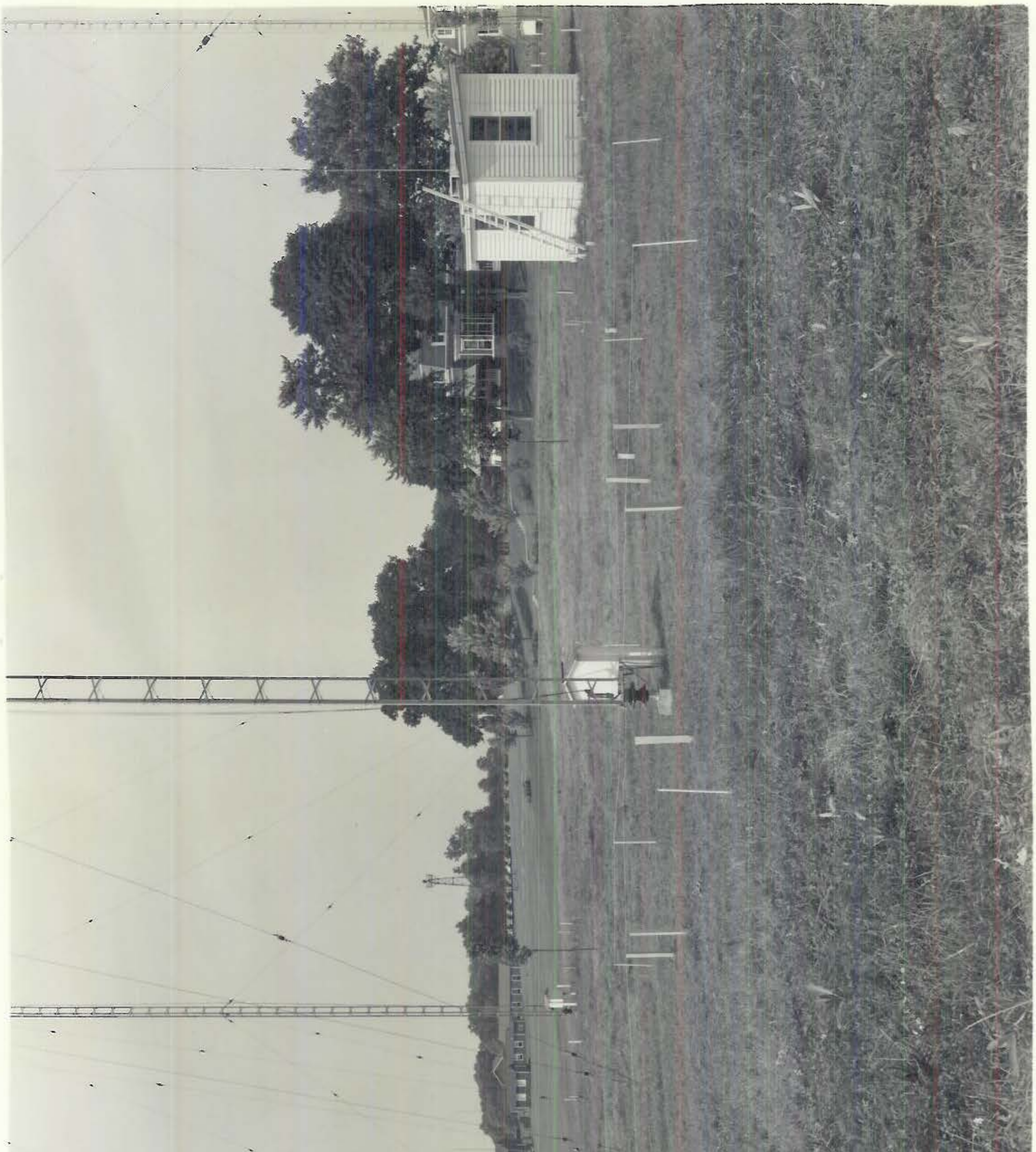


Plate 18



UNCLASSIFIED Plate 19

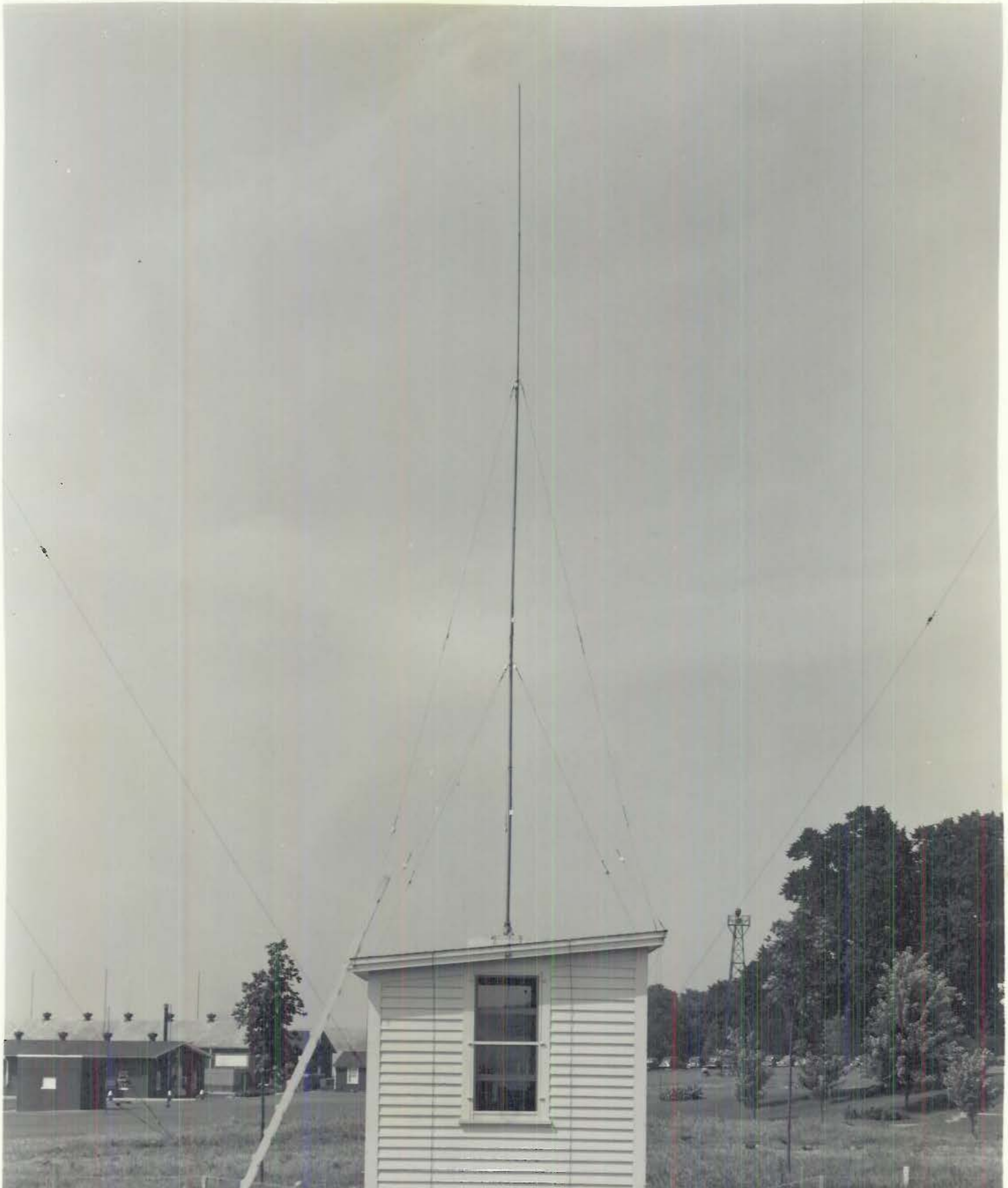


Plate 20

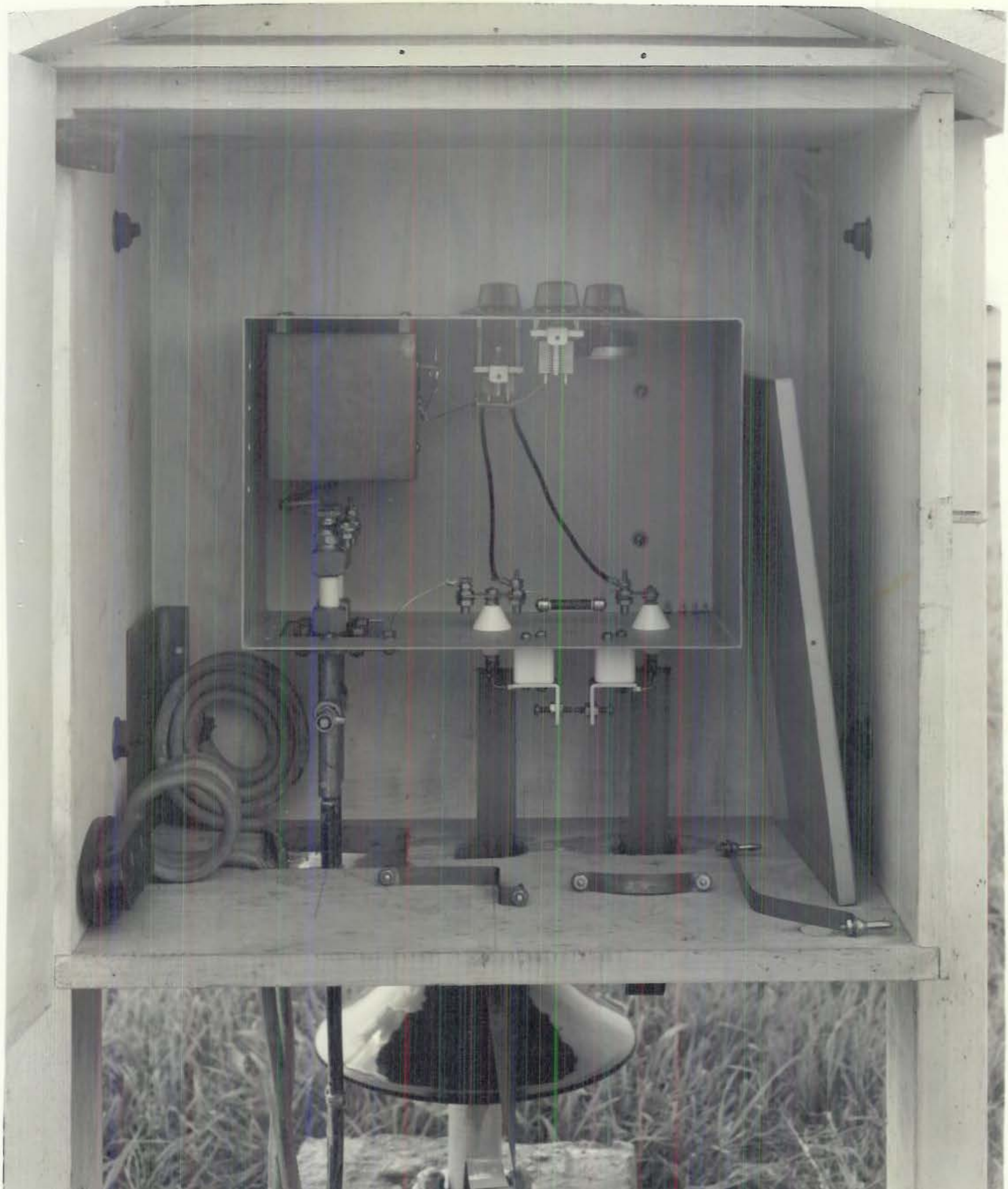


Plate 21

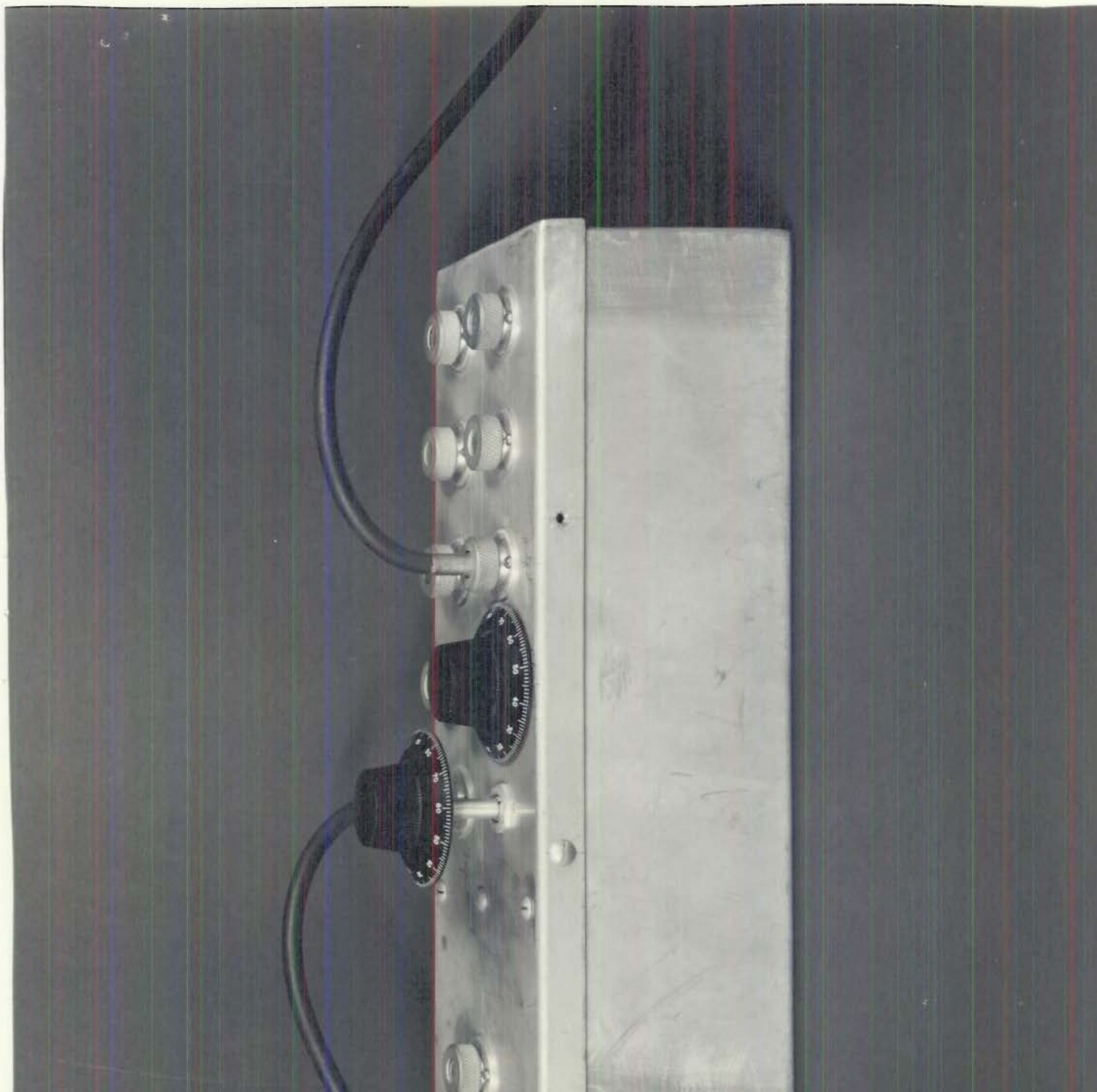


Plate 22

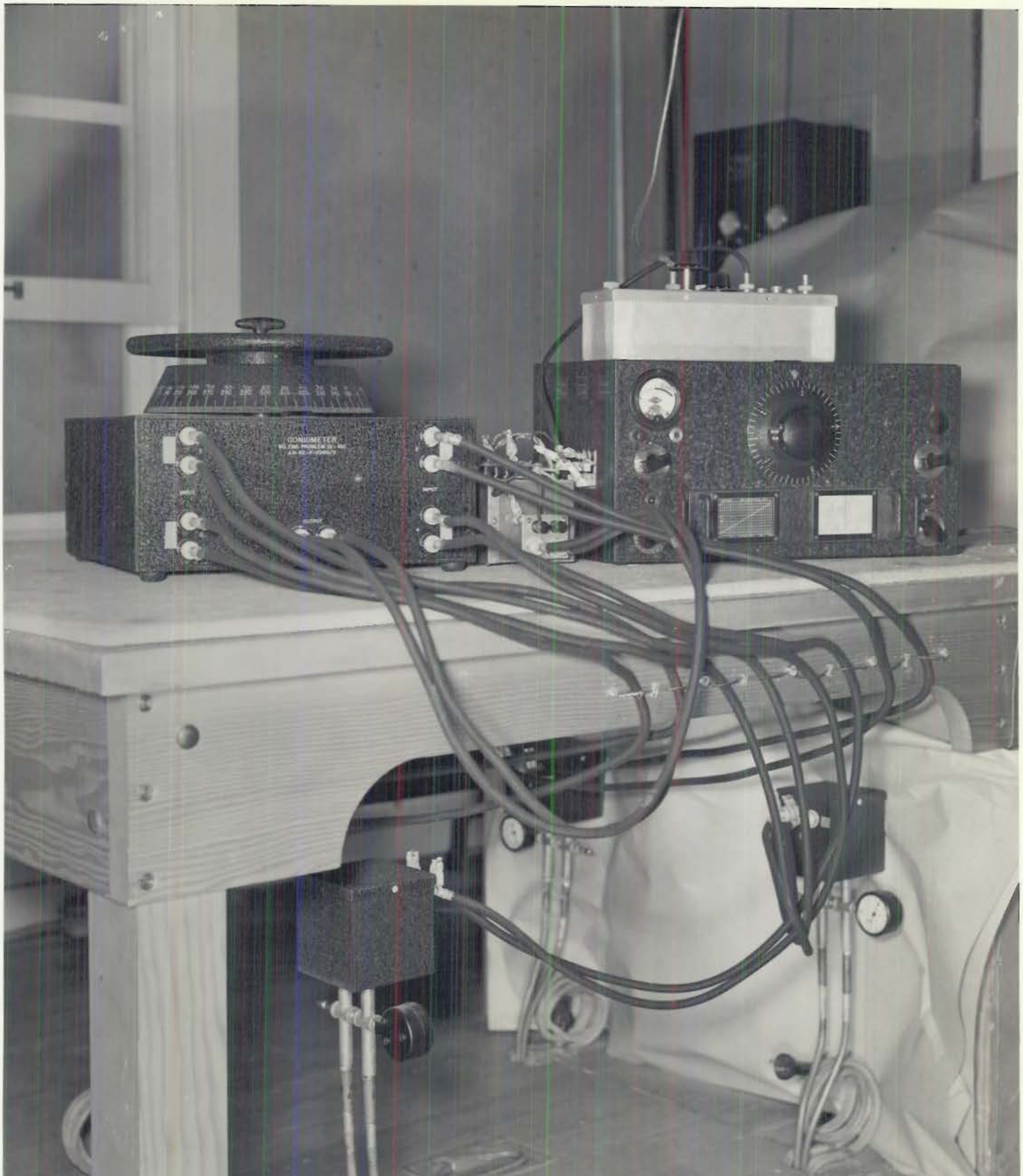


Plate 23

Plate 24

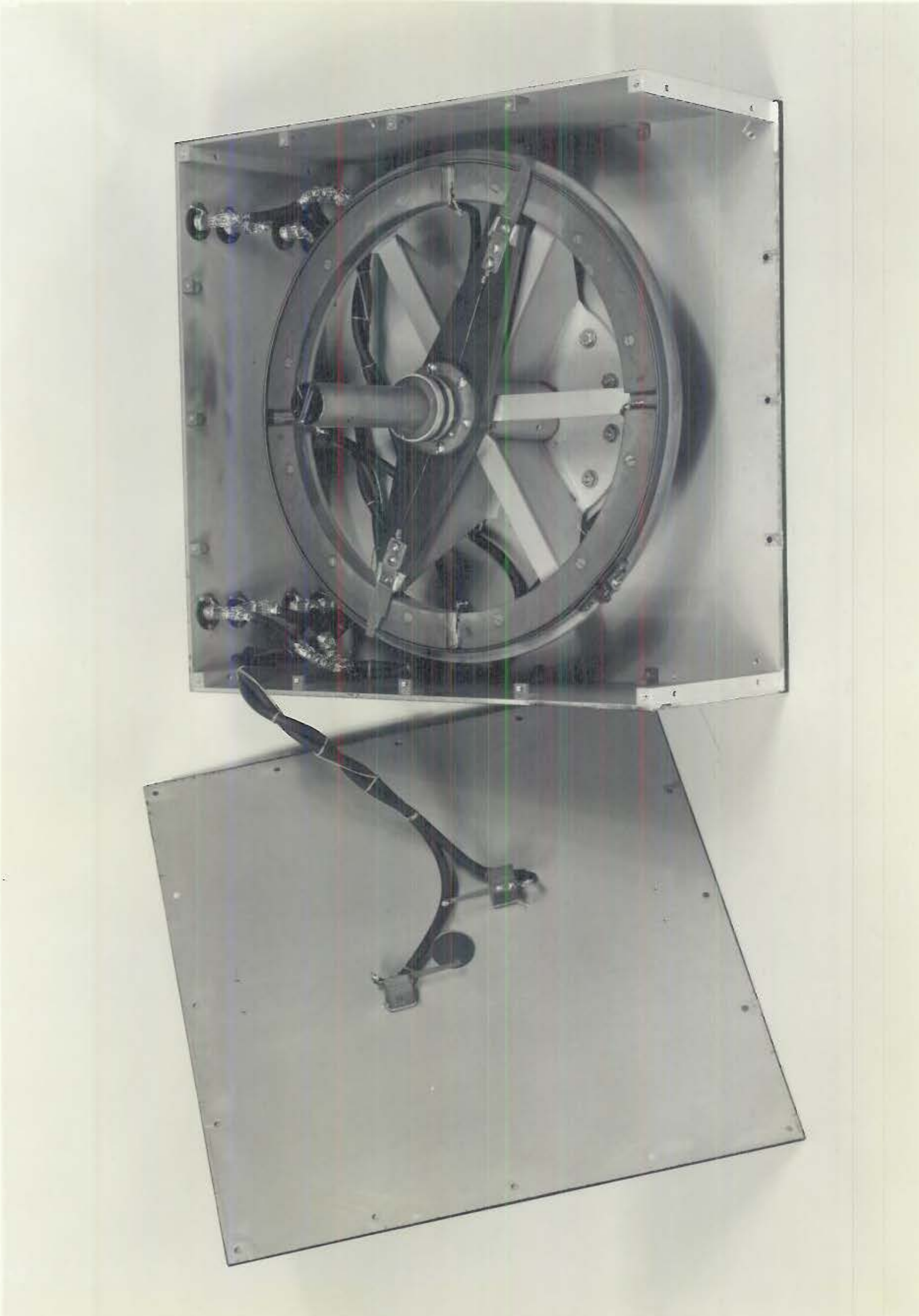
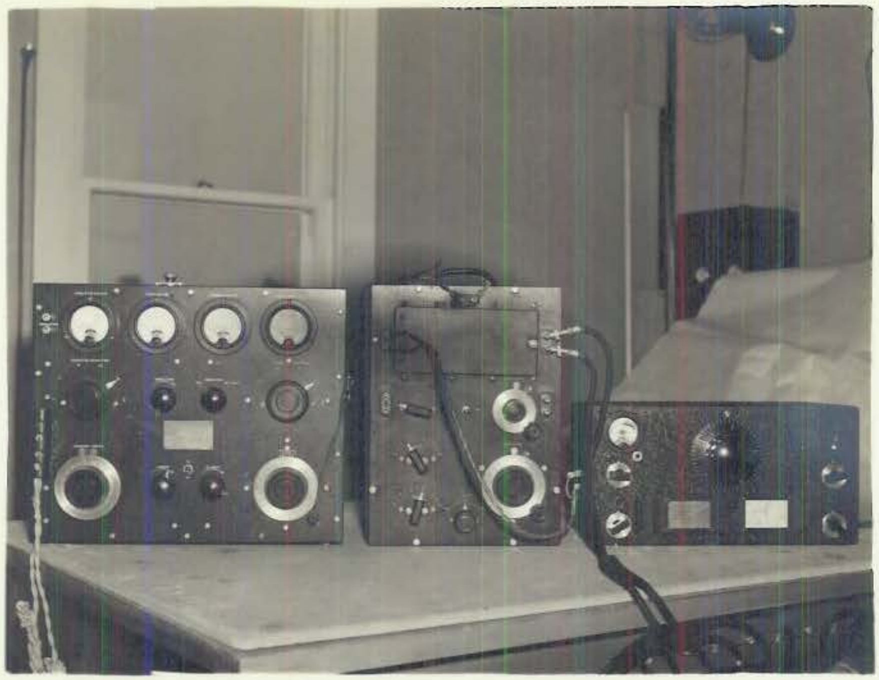


Plate 25



A

B