CHAPTER XVI.—RADIO AIDS TO NAVIGATION

D/F THEORY

Introductory

1. It is a remarkable fact that directional transmission and reception were realized in the earliest experimental work in connection with electro-magnetic radiation. The fact that the waves produced by Hertz in his classical research upon the radiation from an open oscillator could be reflected and refracted in a manner similar to light is regarded as a proof that light and hertzian waves are fundamentally of the same nature. Hertz used waves of the order of 0·5 metre in length, and was successful in producing beams of radiation by the use of parabolic reflectors, a technique which is in use to-day for certain radio-telephonic channels over comparatively short distances. The discovery (by Marconi) of the remarkable radiating properties possessed by the vertical earthed aerial wire caused a temporary suspension of research in the sphere of directional transmission and reception, although it was recognized that if transmitters and receivers could be given accurately directional properties, they would be of enormous value in marine and aerial navigation. The application of directional transmission as a means of telegraphic and telephonic communication over large distances leads to a considerable economy in capital and working costs. Certain forms of directional transmitter are also used purely for navigational purposes. They are collectively referred to as radio beacons, and will be briefly described in this chapter.

Direction finders

2. A direction-finder may be defined as a radio receiving station having an aerial system which possesses directional properties. By virtue of these it is possible to find the horizontal angle of incidence of an electro-magnetic wave arriving at the location of the receiver. A direction-finder thus gives a position line, which may in certain circumstances be made use of in obtaining a fix *i.e.* to ascertain the position of an aircraft. The words position line and fix are technical terms used in navigation, and are defined in A.P. 1234 Manual of Air Navigation, Vol. I. In general at least two position lines are necessary to obtain a fix; these may both be obtained by visual observation, one visually and one by radio, or both by radio. It may be here noted that the bearing obtained by radio is ordinarily subject to an ambiguity of 180°, as will be more fully explained later. The ambiguous bearing may be eliminated by suitably modifying the electrical properties of the receiver, and the latter is then said to operate as a sense-finder. Alternatively the ambiguity may be resolved by cross bearings from two or more stations.

The loop aerial

3. Consider a receiving aerial in the form of a rectangular conductive loop A B, C D, fig. 1, erected near to the surface of the earth in a vertical plane, its height being h metres and its width d metres. It is required to find the polar diagram of this loop for receiving purposes under the following conditions :—

(i) The transmitter is situated at a distance which is very much greater than either h or d and also compared with the wavelength of operation.

(ii) The wave front at the location of the receiver is a plane surface.

(iii) The electrical field strength of the wave is uniform over the whole region embraced by the loop, whatever its orientation.

(iv) The wave is normally polarized.

Under these conditions the electrical field vector at the receiver will be in the vertical plane and the magnetic field vector in the horizontal plane; these fields are of course, alternating quantities. The electric field strength will be denoted by $\gamma = \hat{\Gamma} \sin \omega t$ the unit being the volt per metre. The vertical polarization of the electric field ensures that no E.M.F. will be produced in the horizontal sides of the loop, which serve merely to form a conductive path for any current which may flow. It is therefore necessary to consider only the E.M.F. produced in the vertical sides. Two special cases will first be taken.

Resultant loop E.M.F.

4. (i) When the plane of the loop is perpendicular to the direction of propagation of the wave, the vertical sides of the loop are equi-distant from the transmitter and the E.M.F. produced in each side will be hy or $h\hat{\Gamma}\sin\omega t$, that is, they will be in phase with each other. At a given instant, *e.g.* when the E.M.F. has its peak value $h\hat{\Gamma}$ in the upward direction in the wire A B, there will be an equal peak E.M.F. $h\hat{\Gamma}$, also in the upward direction, in the wire C D. These two E.M.F.s are therefore acting in opposition to each other and the E.M.F. available to drive current round the loop is zero.

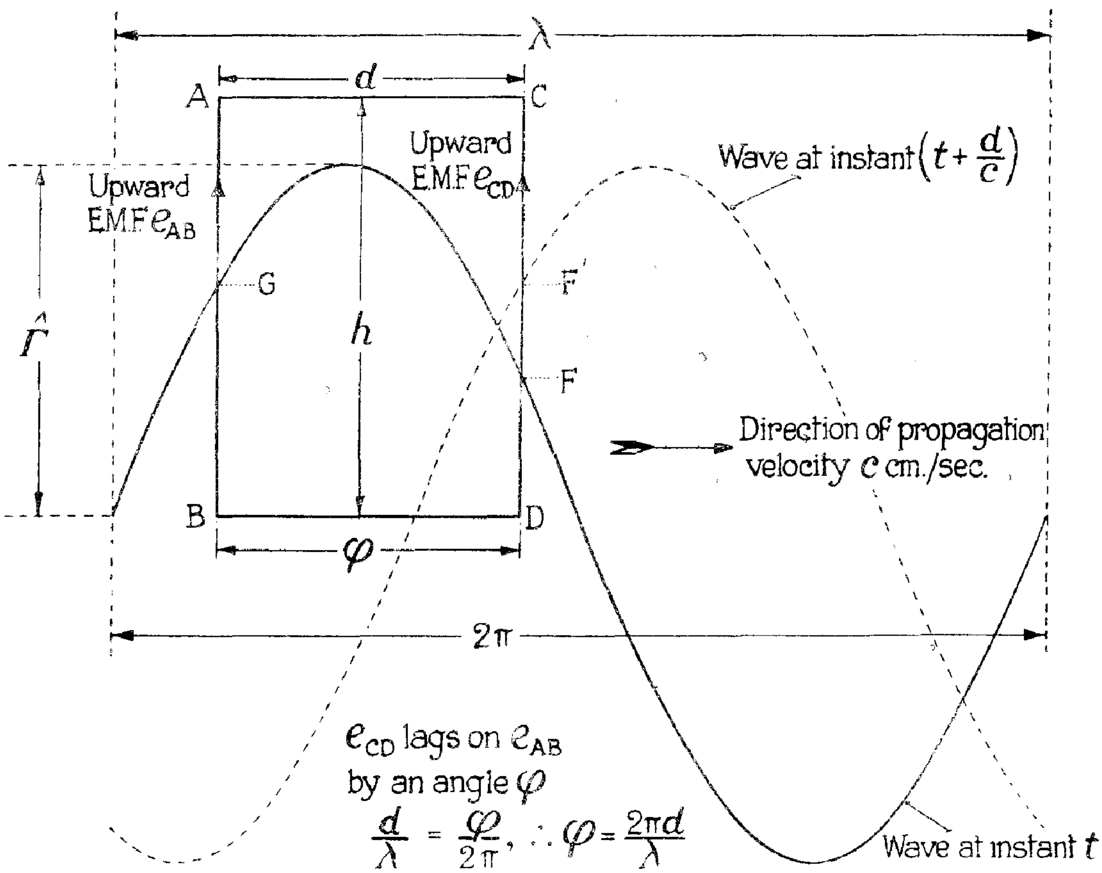


FIG. 1, CHAP. XVI.—Phase difference between E.M.F.s in opposite sides of loop aerial.

(ii) When the plane of the loop is parallel to the path of the wave, the peak value of the E.M.F. induced in each vertical side of the loop is again $h\hat{\Gamma}$, but the two E.M.F.s are no longer in phase, because at any given instant the two sides are not subject to the same portion of the electro-magnetic field. In the diagram, fig. 1, the strength of the electric field from point to point in space at a given instant, is shown by the solid-line sine curve. The instantaneous E.M.F. e_{AB} induced in the wire A B is proportional to G B, and that in the wire C D, *i.e.* e_{CD}, to F D. As the wave is travelling from left to right with a velocity $c = 3 \times 10^{10}$ centimetres per second, the field distribution a fraction of a second later will be as shown by the dotted-line sine curve. The E.M.F. e_{CD} induced in C D is now proportional to F′ D, and

F′ D = G B, *i.e.* e_{CD} at this instant is equal to e_{AB} at the previous instant. A moment's reflection will show that the instantaneous E.M.F. in C D will undergo exactly the same cycle of variation as that in A B, but these variations will be executed a fraction of a second later, *i.e.* the E.M.F. e_{CD} lags on the E.M.F. e_{AB} by some angle which may be denoted by φ. This angle is easily found from the diagram. If the wavelength λ and the width d of the loop are known, by simple proportion

$$\frac{\varphi}{2\pi} = \frac{d}{\lambda}$$

$$\text{and } \varphi = \frac{2\pi d}{\lambda} \text{ (radians).}$$

The total E.M.F. acting round the loop may now be deduced. The E.M.F.s in A B and C D are equal in peak value, but differ in phase by $\frac{2\pi d}{\lambda}$ radians. It is convenient to specify the phase of these E.M.F.s with reference to that which would be induced in a wire of equal length situated on the axis of the loop. If this E.M.F. is $e_0 = \mathscr{E} \sin \omega t$ where $\mathscr{E} = h\hat{\Gamma}$, the E.M.F. in A B will lead on e_0 by an angle $\frac{\pi d}{\lambda}$, while that in C D will lag by $\frac{\pi d}{\lambda}$. Hence

$$e_{AB} = \mathscr{E} \sin\left(\omega t + \frac{\pi d}{\lambda}\right)$$

$$e_{CD} = \mathscr{E} \sin\left(\omega t - \frac{\pi d}{\lambda}\right).$$

The total E.M.F. acting round the loop is $e_R = e_{AB} - e_{CD}$, or

$$e_R = \mathscr{E}\left\{\sin\left(\omega t + \frac{\pi d}{\lambda}\right) - \sin\left(\omega t - \frac{\pi d}{\lambda}\right)\right\}.$$

By means of the trigonometrical identities

$$\sin(P + Q) = \sin P \cos Q + \cos P \sin Q$$

$$\sin(P - Q) = \sin P \cos Q - \cos P \sin Q$$

this expression simplifies to

$$e_R = 2\mathscr{E} \sin \frac{\pi d}{\lambda}. \quad \cos \omega t,$$

i.e. the peak value of the resultant E.M.F. is $2\mathscr{E} \sin \frac{\pi d}{\lambda}$.

Vector diagram

5. The above trigonometrical manipulation is illustrated by a vector diagram in fig. 2. The vector $\mathscr{E} = h\hat{\Gamma}$ represents the peak value of the E.M.F. which would be induced in a vertical wire of height h situated at the centre of the loop. Then $\mathscr{E}_{AB}$ is the corresponding value of the E.M.F. induced in A B, leading on the vector $\mathscr{E}$ by an angle $\frac{\varphi}{2} = \frac{\pi d}{\lambda}$ radians, while the corresponding E.M.F. in C D is represented by the vector $\mathscr{E}_{CD}$ which lags on $\mathscr{E}$ by $\frac{\varphi}{2}$ radians. The

resultant E.M.F. $\mathscr{E}_R$ is found by taking the vector difference between $\mathscr{E}_{AB}$ and $\mathscr{E}_{CD}$. It is seen that $sin\frac{\varphi}{2} = \frac{\mathscr{E}_R}{2} \div \mathscr{E}_{AB} = \frac{\mathscr{E}_R}{2\mathscr{E}}$ because $\mathscr{E}_{AB}$ is numerically equal to $\mathscr{E}$ although they are not in phase, hence

$$\mathscr{E}_R = 2\mathscr{E}\ sin\frac{\varphi}{2}$$

$$= 2h\hat{\Gamma}\ sin\frac{\pi d}{\lambda}.$$

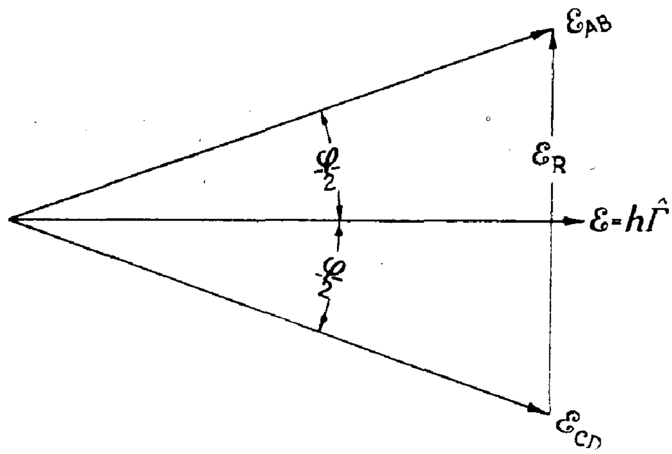


FIG. 2, CHAP. XVI.—Vector derivation of magnitude of resultant E.M.F. in loop aerial.

The instantaneous value of the resultant voltage is therefore

$$e_R = 2h\hat{\Gamma}\ sin\frac{\pi d}{\lambda}.\quad cos\ \omega t.$$

as already stated. The vectorial interpretation of the factor $cos\omega t$ is that $\mathscr{E}_R$ leads on $\hat{\Gamma}$ by 90°.

Horizontal polar diagram

6. Having investigated these two special cases, let us now consider the general case, where the loop is neither in the plane of propagation nor perpendicular to it. Let the loop be so oriented as to make an angle θ with the direction of propagation, as indicated by the sectional plan, fig. 3. Then in passing from the vertical side A B to the vertical side C D, the wave must travel not d metres but $d\ cos\ \theta$ metres. Hence the E.M.F. induced may be found by substituting $d\ cos\ \theta$

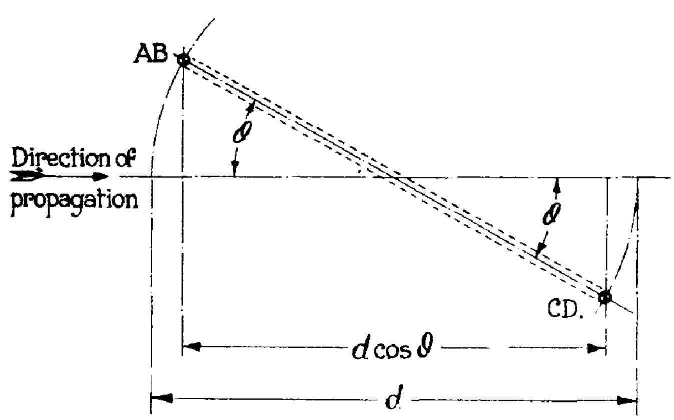


FIG. 3, CHAP. XVI.—Effective width of loop.

for d in the final equation of paragraph 5. If $e_{R\theta}$ is the resultant E.M.F. in the loop when it makes an angle θ with the direction of propagation

$$e_{R\theta} = 2h\hat{\Gamma} \sin \frac{\pi d \cos \theta}{\lambda} . \quad \cos \omega t.$$

Let us now examine the angle $\frac{\varphi}{2} = \frac{\pi d}{\lambda}$ for practical cases of loop reception. It is shown in Chapter V that when $\frac{\varphi}{2}$ is a very small angle its magnitude (in radians) and its sine are practically equal. Taking a numerical example, for the reception of waves of the order of 500 kc/s (600 metres) we are not likely to use a loop wider than about 10 metres, in fact, it is usually convenient to use a considerably smaller one. In this case $\frac{\pi d}{\lambda} = \frac{3\cdot 1416}{60} = \cdot 05236$ radians; the sine of $\cdot 05236$ radians differs from $\cdot 05236$ only in the fifth decimal place. For practical purposes, then, we may write

$$\mathcal{E}_{R\theta} = 2h\hat{\Gamma} \times \frac{\pi d \cos \theta}{\lambda}$$

or, as hd is the area A of the loop

$$\mathcal{E}_{R\theta} = \frac{2\pi A\hat{\Gamma} \cos \theta}{\lambda}.$$

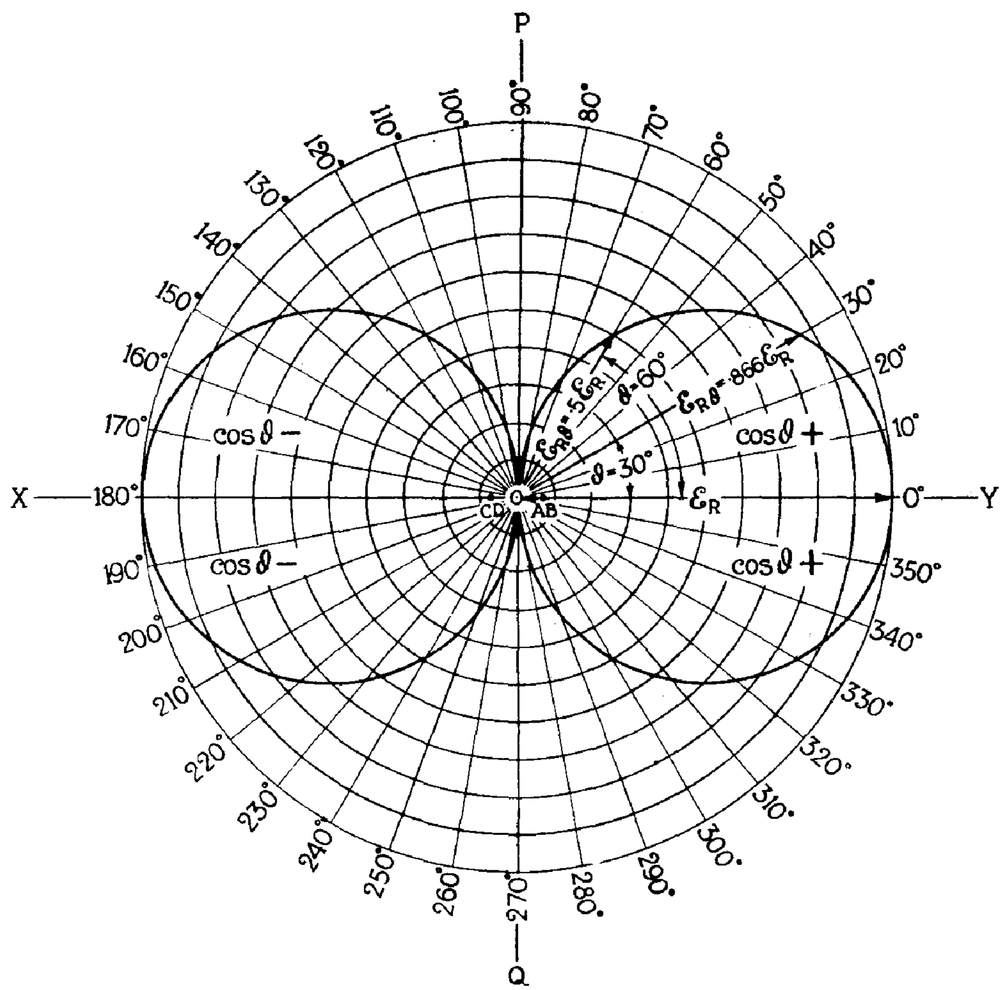


FIG. 4, CHAP. XVI.—Polar diagram of loop aerial (figure-of-eight diagram).

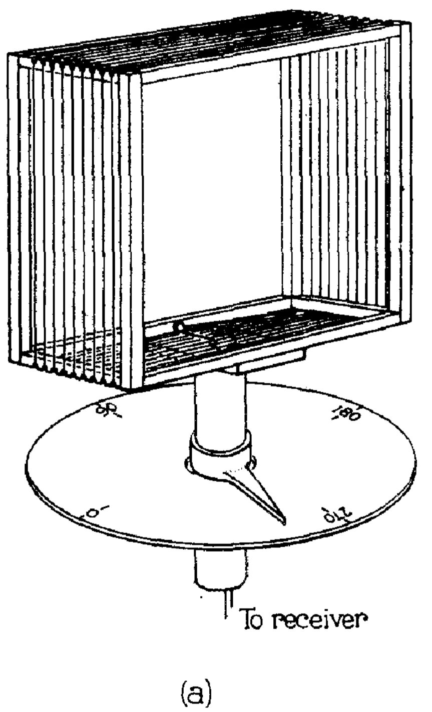
The horizontal polar diagram can now be plotted from this expression, and is shown in fig. 4, in which the vertical sides of the loop are denoted by A B and C D and the point O is the midpoint between them. Then O Y is the reference line from which angles must be measured, and may be drawn to represent $\mathscr{E}_R$ to any convenient scale. The angle θ is measured in an anti-clockwise direction from O Y. For example, if $\theta = 30°$, $\mathscr{E}_{R\theta} = \mathscr{E}_R \cos 30°$ or $0{\cdot}866\ \mathscr{E}_R$. Similarly if $\theta = 60°$, $\mathscr{E}_{R\theta} = 0{\cdot}5\ \mathscr{E}_R$ and if $\theta = 90°$, $\mathscr{E}_{R\theta} = 0$. In this quadrant, $\cos\theta$ is positive and the appropriate sign is inserted in the diagram. In the same way, the values of $\mathscr{E}_{R\theta}$ in the second and third quadrant may be drawn, but as $\cos\theta$ is negative between 90° and 270°, negative signs have been inserted in these quadrants, while between 270° and 360° $\cos\theta$ becomes positive once more. The polar diagram is seen to consist of two circles of diameter $\mathscr{E}_R$ and is often referred to as a figure-of-eight diagram. If the line P Q be supposed to represent the trace of a vertical plane perpendicular to X Y through the point O, the resultant E.M.F. set up by a transmitter situated to the left of P Q will act round the loop in a direction contrary to that set up by a transmitter situated on the opposite side, and this fact is of importance in the action of sense-finding devices.

Frame aerials

7. (i) The resultant E.M.F. acting in a single loop is very small compared with the E.M.F. in the vertical sides, but this may be partly overcome by using a number of turns of wire instead of a single loop. The resultant E.M.F. is then the sum of the E.M.F.s induced in the turns, and is therefore equal to the resultant E.M.F. of a single turn multiplied by the number of turns N, or

$$\mathscr{E}_R = \frac{2\pi N A \hat{F}}{\lambda}.$$

This form of aerial is usually referred to as a frame aerial. Two methods of construction are shown in figs. 5a and 5b. The first type, fig. 5a, is called a box frame, the turns being wound side by side, while the second, fig. 5b, is called a pancake frame, the turns being wound in a flat spiral. The pancake frame is often mounted, as shown, with one diagonal as the axis of rotation, but



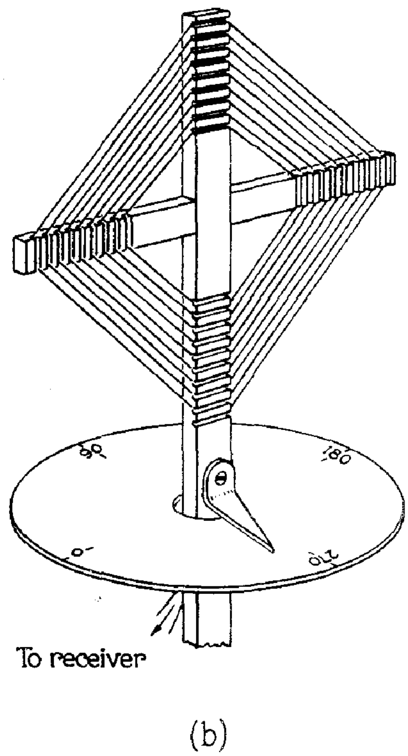


FIG. 5, CHAP. XVI.—Box and pancake types of frame aerial.

this does not reduce the resultant E.M.F., which can be shown to be proportional to the product of the area of the frame and the number of turns as in the former instance. In certain designs it is convenient to wind the frame in the form of a circle, because this shape lends itself to the design of a metal screen surrounding the coils. The purpose of such a screen will receive attention later.

(ii) When the operating frequency is below about 1,000 kc/s, the frame aerial is generally tuned by connecting a suitable condenser directly across the ends of the winding (*see* fig. 7). For higher frequencies, however, the aerial is usually coupled to the receiver by means of a special type of radio-frequency transformer. The secondary winding of the latter is tuned to the desired frequency by means of a variable condenser, the arrangement being analogous to the so-called aperiodic aerial in ordinary non-directional reception. The following table shows the order of the inductance and self-capacitance of different square, box frame aerials, each of which was designed to operate at frequencies below 1,500 kc/s.

h (metres).	No. of turns.	Spacing (cm).	L (μH)	C($\mu\mu F$)
1	8	·3	200	50
1·25	6	·6	150	60
2	4	·6	130	70
2·5	3	1·2	100	80

The given self-capacitance is only very approximate and is deduced from the fact that with no tuning capacitance the frequency of the frame aerial was found to be very nearly 1,600 kc/s in each case.

Effective height and pick-up factor of frame aerial

8. (i) The receptive property of a loop or frame aerial is often stated with reference to its effective height. This is the effective height of a vertical aerial in which a given field would induce an E.M.F. equal in magnitude to the resultant E.M.F. of the loop when oriented for maximum signal. Since the peak voltage induced in a vertical aerial of effective height h_e is $h_e\hat{\Gamma}$ volts, and the resultant E.M.F. in the frame aerial is $\frac{2\pi NA\hat{\Gamma}}{\lambda}$ volts, it follows that the effective height of the frame aerial is

$$h_e = \frac{2\pi NA}{\lambda} = \frac{\omega AN}{3 \times 10^8},$$

and is therefore dependent upon the frequency of the incoming wave. In all practical cases, the effective height is only a fraction of the actual height of the loop as defined in fig. 1. For example, in the case of a single turn 1 metre square, the effective height at a frequency of 300 kc/s is only ·00628 metres. If the frame aerial is tuned to the desired frequency by means of a variable condenser connected across its ends, the peak voltage at the condenser terminals will be $\chi\mathscr{E}_R$ where χ denotes the circuit magnification as usual. The radiation resistance of a frame aerial is negligible compared with the radio-frequency ohmic resistance of the conductor, and there is no added resistance due to an earth connection. Thus the magnification of the frame aerial is generally very much greater than that of an open receiving aerial, and this compensates to some extent for the comparatively poor " pick-up " of the frame.

Example

A frame aerial 1 metre square having 20 turns, is tuned to 300 kc/s by a capacitance of ·0003μF. If its resistance at this frequency is 8 ohms, find the P.D. V_c set up at the condenser terminals by an R.M.S. field of 1 millivolt per metre, when the loop is in the " maximum " position.

The effective height of a single turn 1 metre square is ·00628 metres, and of 20 turns is ·00628 × 20 = ·1257 metres.

The resultant loop E.M.F. $E_R = h_e\Gamma =$ ·1257 millivolts (R.M.S.)

$$\text{The circuit magnification} = \frac{1}{\omega CR} = \chi.$$

$$\frac{1}{\omega CR} = \frac{1}{2 \times 300{,}000 \times \cdot 0003 \times 10^{-6} \times 8}$$
$$= 220 \text{ (approximately).}$$
$$V_c = \chi E_R$$
$$= 220 \times \cdot 1257 \text{ millivolts}$$
$$= 26 \cdot 7 \text{ millivolts.}$$

(ii) In order to compare the receiving properties of different forms of direction finder, a quantity called the pick-up factor, p, is sometimes used. This is the ratio of the P.D., V, at the input terminals of the receiver proper, to the strength, Γ, of the electric field acting on the aerial system. Thus if a vertical aerial of effective height h_e and resistance R is tuned to a frequency $\frac{\omega}{2\pi}$ by the addition of an inductance L, and the P.D. across this coil is applied to the receiver,

$$V = \frac{\omega L}{R} h_e \Gamma$$

$$p = \frac{V}{\Gamma} = \frac{\omega L}{R} h_e.$$

Note that p is expressed in the same unit as h_e, i.e. in metres. The pick-up factor is in fact nothing more than the product of the circuit magnification and the effective height. The pick-up factor of a loop aerial tuned by a capacitance C across its terminals is equal to

$$\frac{2\pi AN}{\lambda} \times \frac{1}{\omega CR} \text{ or } \frac{AN}{3 \times 10^8\, CR},$$

C being expressed in farads, and R in ohms.

Maximum and minimum methods of obtaining bearing

9. A loop or frame aerial so mounted as to be capable of rotation about a vertical axis may be used to determine the position line upon which a distant transmitter is situated. As the loop is rotated, the signal strength will vary, reaching a maximum when the plane of the loop is coincident with the direction of propagation of the wave. Theoretically, the signal strength will fall to zero when the plane of the loop is perpendicular to the plane of propagation but for reasons discussed later, it is only rarely that an absolute zero is obtained. It would therefore appear that the bearing of the transmitter could be ascertained (with an ambiguity of 180°) by observation of the orientation giving either the maximum or minimum signal strength, as shown diagrammatically in fig. 6. The relative advantages and disadvantages of the two methods are as follows.

(i) Using the maximum method, if two operators are available, one may be engaged in finding the bearing while the other transcribes the W/T signal as received. This is an advantage in certain circumstances, *e.g.* in the case of an aeroplane transmitting an enemy report to a ground D/F station.

(ii) If the D/F receiver is located in a position where the interference level is high, it is difficult to observe the exact bearing upon which the minimum occurs.

(iii) With little or no interference the minimum is comparatively sharp, whereas the maximum is always very flat, *i.e.* the disadvantage of the minimum method, with a high interference level, applies to the maximum under all conditions.

On the whole, then, the minimum method is preferable, but in the presence of a high noise level the bearing is usually taken by swinging the loop through a small arc on either side of the minimum, observing the bearings upon which the signal is just audible. The bearing (or its reciprocal) is assumed to be the mean of these. The rotating loop is, as a rule, fitted with a

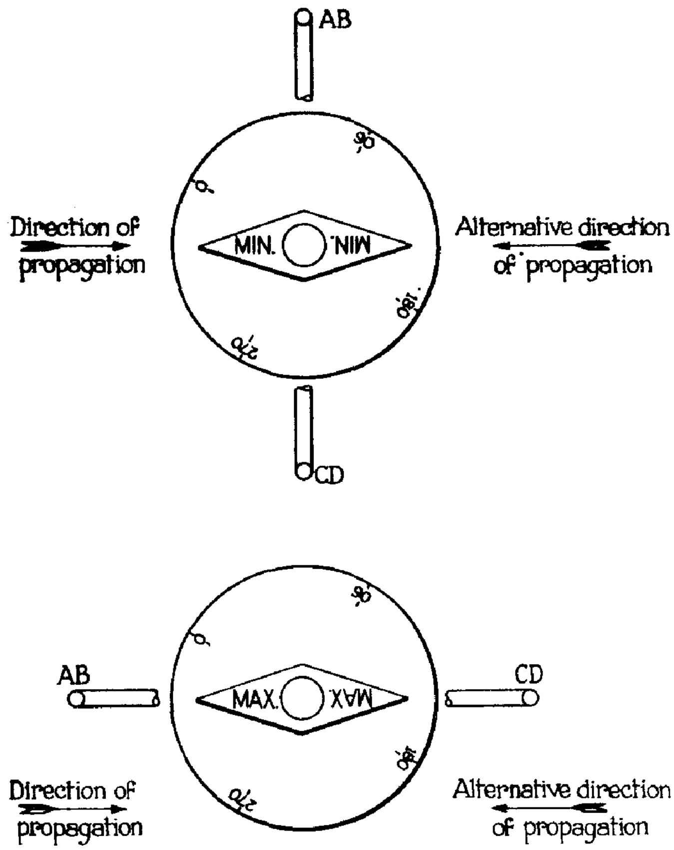


FIG. 6, CHAP. XVI.—"Maximum" and "minimum" methods of obtaining a bearing.

single pointer as in fig. 5, although it may appear that time would be saved by fitting a double pointer showing the bearing and its reciprocal at a glance. In operation however it is most desirable to turn the loop through more than 180°, observing both the minima. Owing to certain phenomena described below, these may not be exactly 180° apart.

Local errors

10. Before proceeding further with the practical application of the foregoing theory, it is necessary to deal with the phenomena which give rise to inaccurate bearings. Certain of these, which are due to the fact that the simplifying assumptions made in paragraph 3 are rarely applicable in their entirety, must be considered at a later stage, but immediate attention will be devoted to the errors which are due to the electrical properties of the direction-finding receiver itself. These errors may be attributed to

(i) direct pick-up,
(ii) vertical or antenna effect.
(iii) displacement currents.

Direct pick-up in quadrature

11. The direct pick-up effect, as its name implies, is the result of the E.M.F. induced by the incoming electro-magnetic wave in any portion of the electrical wiring preceding the detector valve, or even in the post-detector stages if any electrical coupling exists between this portion of the receiver and the R.F. circuits. Referring to fig. 7, let A B, C D be a loop aerial with its plane in the direction of propagation of the signal, which is incident in the direction A C. The loop is tuned to the desired frequency by means of a variable condenser C_1 which is located inside the screening box containing the receiver proper. The loop is assumed to be connected to this condenser by a short length of twin flexible cable, which is screened from direct pick-up, but in order to reach the lower terminal of the condenser an additional conductor E F of length l metres is necessary; this is in series with A B, and for simplicity, suppose this wire to be placed vertically under the axis of rotation of the loop. If the dimensions of the loop are,

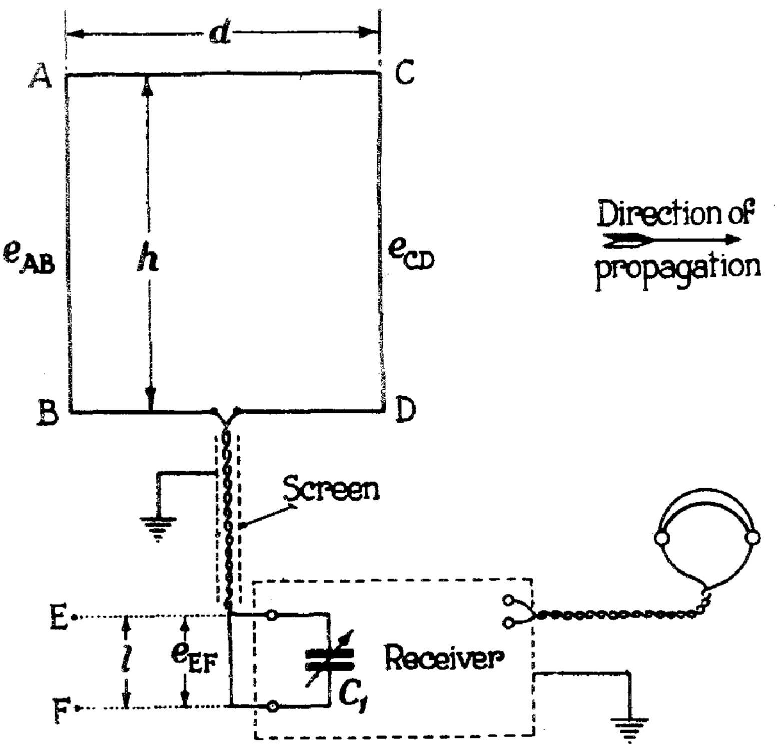


FIG. 7, CHAP. XVI.—Loop aerial with direct pick-up.

height h metres, width d metres as before, and the incoming wave has an electric field strength of peak value $\hat{\Gamma}$ volts per metre, the E.M.F. e_{AB}, set up in the side A B (fig. 7) will be

$$e_{AB} = h\,\hat{\Gamma} \sin\left(\omega t + \frac{\pi d}{\lambda}\right)$$

and in the side C D

$$e_{CD} = h\,\hat{\Gamma} \sin\left(\omega t - \frac{\pi d}{\lambda}\right).$$

As the conductor E F is also subject to the influence of the electric field, an E.M.F. e_{EF} will be set up in it. Since E F is in line with the axis of the loop, and the phase angles $\pm \frac{\pi d}{\lambda}$ are stated with reference to a conductor situated on this axis,

$$e_{EF} = l\,\hat{\Gamma} \sin \omega t$$

The resultant E.M.F. acting round the loop, in the absence of the conductor E F, has already been shown to be

$$e_R = 2h\,\hat{\Gamma}\sin\frac{\pi d}{\lambda}\cos\omega t.$$

Owing to the presence of the conductor E F, however, the total resultant E.M.F., e'_R, is $e_R + e_{EF}$ or

$$e'_R = 2h\,\hat{\Gamma}\sin\frac{\pi d}{\lambda}\cos\omega t + l\,\hat{\Gamma}\sin\omega t$$

$$= \frac{2\pi A\,\hat{\Gamma}}{\lambda}\cos\omega t + l\,\hat{\Gamma}\sin\omega t$$

$$= \mathscr{E}_R\cos\omega t + \mathscr{E}_{EF}\sin\omega t.$$

This resultant E.M.F. therefore consists of two components which are 90° out of phase with each other.

Effect of direct pick-up on polar diagram

12. The polar diagram of reception is plotted in fig. 8 for a particular ratio of $\frac{\mathscr{E}_R}{\mathscr{E}_{EF}}$. The figure-of-eight diagram shown in heavy line is the polar diagram of the loop alone, and the lighter circle is that of the wire E F alone. Consider a wave incident in the direction P O. The peak

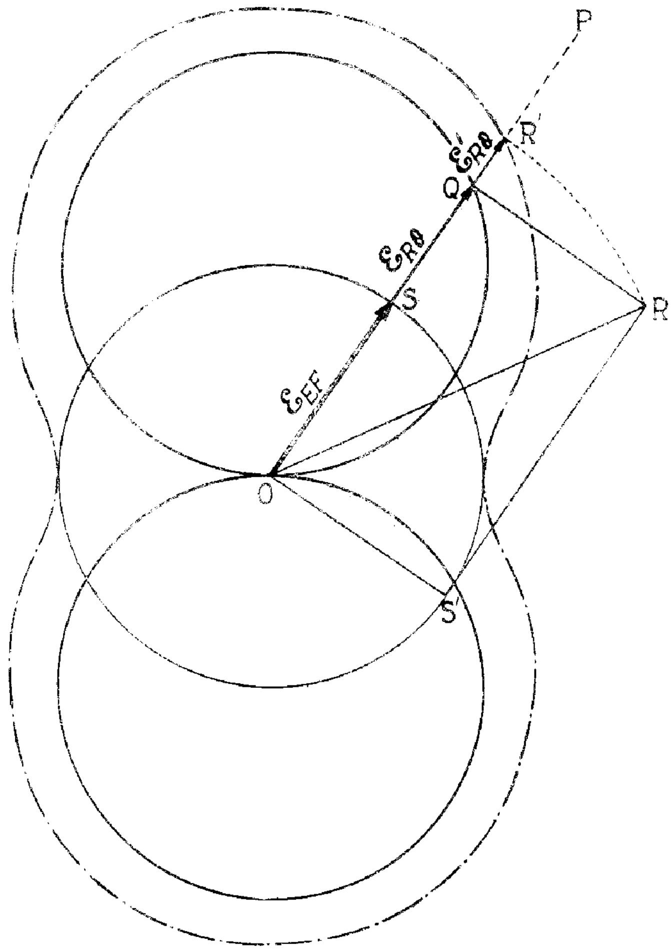


FIG. 8, CHAP. XVI.—Polar diagram showing effect of direct pick-up in quadrature with resultant loop E.M.F.

value $\mathscr{E}_{R\theta}$ of the resultant E.M.F. in the loop will be O Q, and the peak value of the direct pick-up E.M.F. $\mathscr{E}_{EF}$ will be O S; since $\mathscr{E}_{R}$ and $\mathscr{E}_{EF}$ are in quadrature, the peak value of the resultant E.M.F. $\mathscr{E}'_{R\theta}$, due to a wave travelling along P O, will be $\sqrt{OQ^2 + OS^2}$. Graphically, $\mathscr{E}'_{R\theta}$ may be derived by drawing O S′, perpendicular to O S, and completing the parallelogram O Q R S′. Then O R is the amplitude of $\mathscr{E}'_{R\theta}$, but its direction is along O Q and is easily transferred thereto, giving the point R′. The complete polar diagram is obtained by repeating this construction at 10° intervals and is shown in chain-dotted line. It is seen that the effects of any direct pick-up which sets up an E.M.F. exactly in quadrature with the loop E.M.F. are as follows :—

(i) No orientation of the loop gives complete extinction of the signal; the strength of signals varies between a maximum and a minimum as the loop is rotated in azimuth.

(ii) The minima are not sharp and are generally spoken of as " blurred minima."

(iii) The minima are in their true positions with respect to the bearing of the transmitter, and are 180° apart, in accordance with the simple theory.

13. It is of interest to calculate the length l of unbalanced conductor which will cause the amplitude of the direct pick-up E.M.F. to be equal to that of the loop. Consider the loop previously taken as an example, (paragraph 8). It was there found that in a field having a strength of 1 millivolt per metre, the resultant loop E.M.F. was ·1257 millivolt. The direct pick-up E.M.F. will be equal to this if $l = \cdot 1257$ metre or approximately 5 inches. Even such a short length of unscreened and unbalanced conductor will thus give an appreciable signal when the loop is in the " minimum " position. The ratio of maximum to minimum signal is $\frac{\sqrt{[\mathscr{E}^2_{R} + \mathscr{E}^2_{EF}]}}{\mathscr{E}_{EF}}$. In the above instance, therefore, the maximum signal is $\sqrt{2}$ times the minimum, corresponding to a change of only 3 db. In fig. 8, $\mathscr{E}_{R} = 2\mathscr{E}_{EF}$ and the ratio of maximum to minimum is 2·24 to 1, corresponding to a change of about 7 db.

Direct pick-up in phase

14. The direct pick-up E.M.F. is rarely in exact quadrature with the loop E.M.F. as in the case just examined. For illustrative purposes, let us suppose the receiver in fig. 7 to be removed in the direction A C to a distance of $\frac{\lambda}{4}$ from the centre of the loop, and connected as before by a twin screened cable, with the exception of the unbalanced conductor E F, which is again vertical. The incident wave will now give rise to resultant E.M.F.s $\mathscr{E}_{EF}$ and $\mathscr{E}_{R}$ as before, but the field at E F will lag by 90° on the field at the axis of the loop and therefore $\mathscr{E}_{EF}$ and $\mathscr{E}_{R}$ will be either in phase or 180° out of phase with each other. If, in the vertical sides of the loop, the E.M.F. $\mathscr{E}_{AB}$ leads on $\mathscr{E}_{CD}$, i.e. if A B is the side nearest the transmitter, $\mathscr{E}_{R}$ and $\mathscr{E}_{EF}$ will be in anti-phase and vice versa. The total resultant E.M.F. $\mathscr{E}'_{R}$ is therefore equal to the sum of $\mathscr{E}_{R}$ and $\mathscr{E}_{EF}$ when the wave is incident in the direction C A, and to the difference between $\mathscr{E}_{R}$ and $\mathscr{E}_{EF}$ when the wave is incident in the direction A C. Referring to fig. 9, the polar diagram of the loop is shown by the figure-of-eight diagram, and that of the vertical aerial by a circle having the centre O. The polar diagram of the combination is found by algebraic addition of the two constituent diagrams, and is shown in chain-dotted line. If the wave is incident in the direction P O, the loop E.M.F. $\mathscr{E}_{R}$ is proportional to O Q, the direct pick-up E.M.F. $\mathscr{E}'_{R}$ to O R, and the total resultant E.M.F. $\mathscr{E}'_{R}$ to O Q + O R = O S. If incident in the direction P′O, however, $\mathscr{E}_{R}$ is proportional to O Q′= −O Q, $\mathscr{E}_{EF}$ to O R′=O R and $\mathscr{E}'_{R}$ to O Q′+O R=O R−O Q= −O S′. The negative sign of the latter must be interpreted as signifying contrariety of direction with respect to the direct pick-up E.M.F.

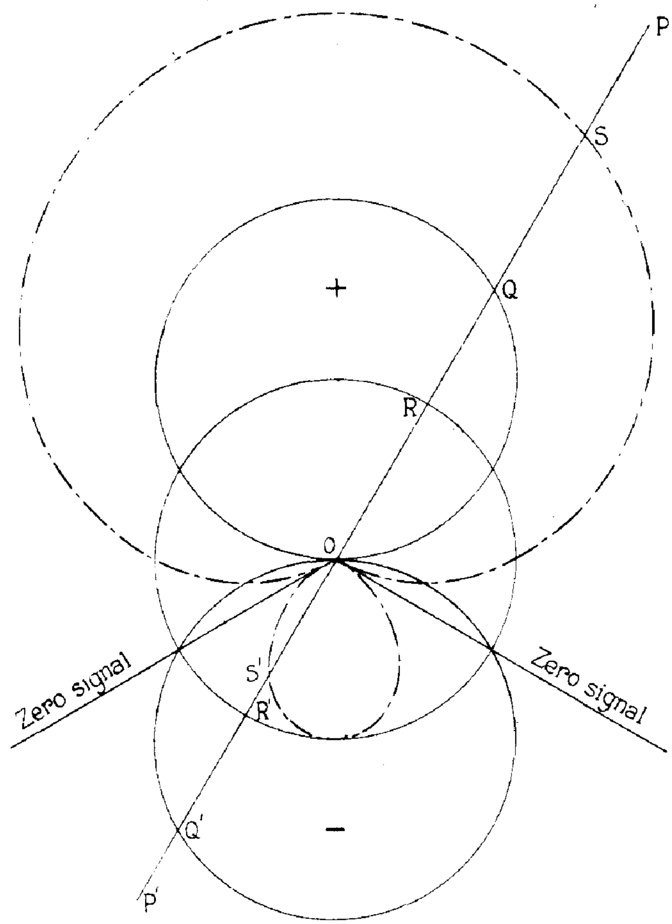


Fig. 9, Chap. XVI.—Polar diagram showing effect of direct pick-up in phase with resultant loop E.M.F.

Effect of "in-phase" direct pick-up

15. This resultant diagram differs from that of fig. 8 in three respects. First, the positive and negative portions of the diagram are not symmetrical, a signal in the direction P O giving a louder response than one in the direction P′O; second, the minima are less than 180° apart; third, an absolute zero, even sharper than that of a figure-of-eight diagram, is theoretically obtainable. The zeros are symmetrically disposed with respect to the two maxima and the direction of the true maxima can be found by bisecting the angle between them. Finally let us consider again the loop aerial and vertical conductor, when the latter is situated at a distance of less than $\frac{\lambda}{4}$ from the axis of the loop. Then the direct pick-up E.M.F. $\mathscr{E}_{EP}$ will be less than 90° out of phase with $\mathscr{E}_R$, and the polar diagram will be a combination of the chain-dotted diagrams of figs. 8 and 9, becoming somewhat as shown by the chain-dotted outline in fig. 10. The effects of direct pick-up which is neither in phase nor in quadrature with the loop E.M.F. are :—

(i) Unequal maxima.

(ii) Minima blurred.

(iii) Minima not exactly 180° apart.

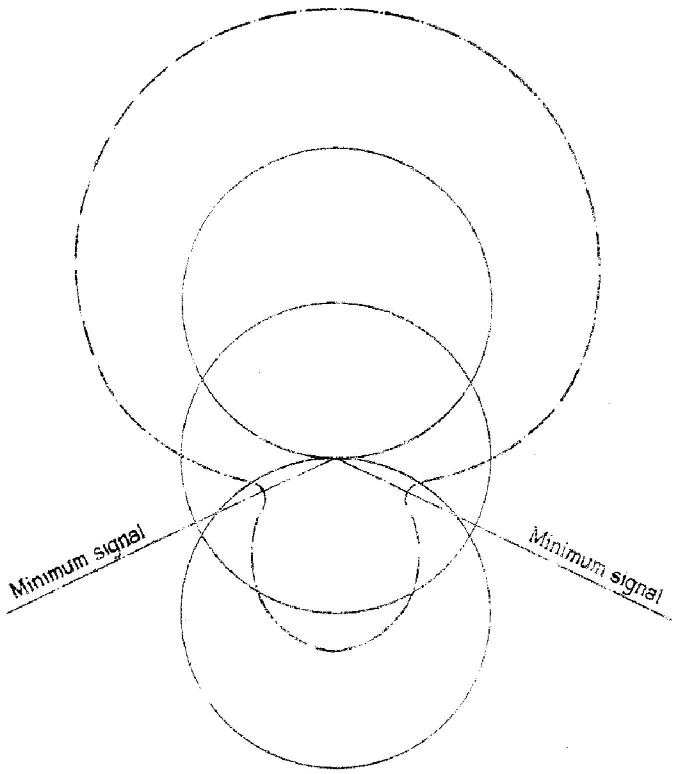


FIG. 10, CHAP. XVI.—Polar diagram showing general result of direct pick-up.

Elimination of direct pick-up

16. In the above discussion, the direct pick-up is assumed to occur in what is to all intents and purposes, a small vertical aerial directly coupled to the loop. Similar effects will however occur if the receiver is supplied with any E.M.F. due to the signal, other than the loop E.M.F. $\mathscr{E}_B$. To avoid any direct pick-up it is absolutely necessary to arrange all portions of the wiring symmetrically with respect to earth, and all connecting leads must be well screened by low-impedance conducting sheaths earthed at each end.

Vertical effect

17. " Vertical " or " antenna " effect is said to be present in a loop or frame aerial when unequal E.M.F.s exist in the vertical sides, due to imperfect electrical symmetry. The effect is therefore practically the same as direct pick-up, and both "in-phase" and "in quadrature" vertical effect may be found. As a rule, any accidental " vertical " is out of phase with the loop E.M.F. by an angle less than 90°. Vertical effect is often said to be due to the capacitance of the loop with respect to earth, but the significance of this statement is only appreciated after a careful examination of the conditions in which the resultant E.M.F. is obtained. In deriving an expression for the loop E.M.F. $\mathscr{E}_B$ in paragraph 4 it was assumed that the effective height h_e of each of the vertical sides A B, C D, of the loop is equal to the true height h. This is equivalent to assuming that the current is of the same amplitude at all points in the loop, and therefore that the wires have no capacitance with respect to each other or to the ground. This is of course incorrect, but provided that the two sides A B, C D, are perfectly symmetrical with respect to each other, and the ground, their effective heights will be the same and the induced E.M.F.s will have the same peak values, *i.e.* $\mathscr{E}_{AB} = \mathscr{E}_{CD}$. Let us now dispense with this assumption and

suppose the effective heights to be h_{AB} and h_{CD} respectively. If now a wave is incident along the plane of the loop in the direction A to C (cf. fig. 1) we have

$$e_{AB} = h_{AB}\,\hat{\Gamma}\,\sin\left(\omega t + \frac{\pi d}{\lambda}\right)$$

$$e_{CD} = h_{CD}\,\hat{\Gamma}\,\sin\left(\omega t - \frac{\pi d}{\lambda}\right),$$

or

$$e_{AB} = h_{AB}\,\hat{\Gamma}\left(\sin\omega t\cos\frac{\pi d}{\lambda} + \cos\omega t\sin\frac{\pi d}{\lambda}\right)$$

$$e_{CD} = h_{CD}\,\hat{\Gamma}\left(\sin\omega t\cos\frac{\pi d}{\lambda} - \cos\omega t\sin\frac{\pi d}{\lambda}\right).$$

Also

$$e_R = e_{AB} - e_{CD},$$

whence

$$e_R = (h_{AB} + h_{CD})\,\hat{\Gamma}\sin\frac{\pi d}{\lambda}\cos\omega t + (h_{AB} - h_{CD})\,\hat{\Gamma}\cos\frac{\pi d}{\lambda}\sin\omega t.$$

As already shown, the angle $\frac{\pi d}{\lambda}$ is always much smaller than unity. $Sin\,\frac{\pi d}{\lambda}$ may be replaced by $\frac{\pi d}{\lambda}$, and $\cos\frac{\pi d}{\lambda}$ by unity with negligible error, so that

$$e_R = \hat{\Gamma}\left\{(h_{AB} + h_{CD})\frac{\pi d}{\lambda}\cos\omega t + (h_{AB} - h_{CD})\sin\omega t\right\}.$$

This E.M.F. is equal to that given by a loop having sides of equal effective height $h_e = \frac{h_{AB} + h_{CD}}{2}$, with a length $(h_{AB} - h_{CD})$ of vertical unbalanced conductor situated on its axis. The above expression is therefore analogous to the final equation of paragraph 11. The polar diagram of a frame aerial with this form of vertical is similar to fig. 8 illustrating direct pick-up in quadrature.

Elimination of " vertical "

18. Having shown that " vertical " is due to lack of symmetry between the two sides of the loop, the steps necessary to reduce it to a minimum are easily seen. However carefully the loop itself and the connections thereto are arranged, one such asymmetry normally exists at the point

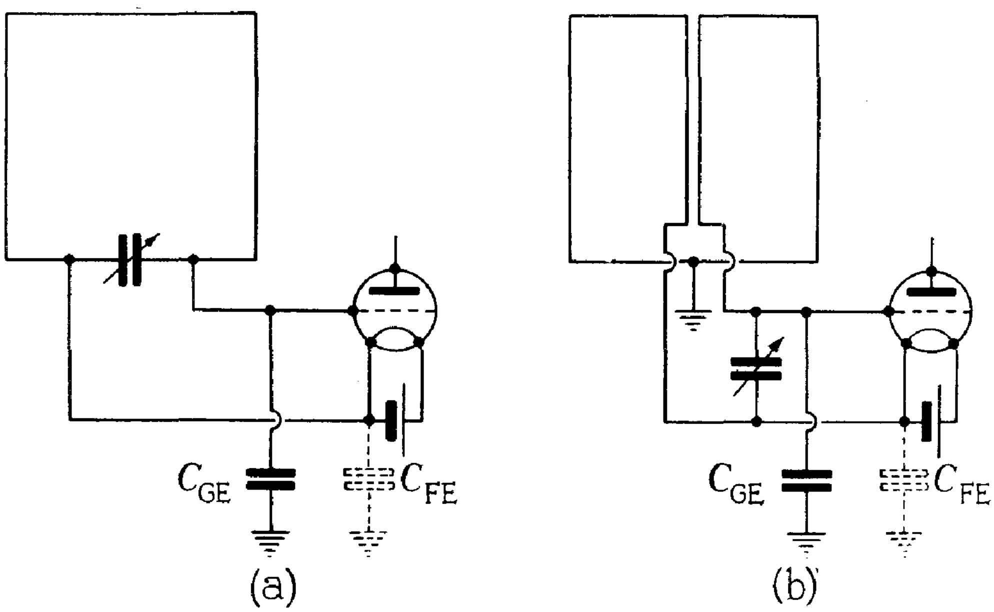


FIG. 11, CHAP. XVI.—Reduction of vertical effect due to unbalanced receiver.

where the resultant E.M.F.—or condenser P.D. in the case of a tuned loop—is applied to the first valve of the receiver. Referring to fig. 11a the filament of the valve is always at or near earth potential; even if insulated from earth, the capacitance C_{FE} between the L.T. battery and earth is invariably very much larger than the capacitance between the grid and earth. A possible remedy for this form of assymmetry is to connect a variable condenser C_{GE} between grid and earth, adjusting its value while taking a bearing, until the minima are 180° apart. In certain instances, and particularly on very high frequencies of the order of 10 Mc/s and above, it is necessary to achieve a high degree of symmetry and the early stages of the receiver may be arranged in push-pull to this end.

Screened loop

19. The effect of assymmetry caused by slightly unequal dimensions of nominally identical portions of a loop aerial can be reduced by winding the loop in two equal sections which are connected as in fig. 11*b*, the centre point of the loop being earthed. The capacitive balance just mentioned is still necessary for the purpose of balancing the amplifier input. The most effective method of reducing " vertical " in the frame or loop aerial itself is to ensure that the capacitance to earth of every element of wire in one side is exactly equal to that of the corresponding element in the other side of the loop. In this way the effective heights of both sides are equalized and vertical is practically eliminated. In practice this is often accomplished by enclosing each half of

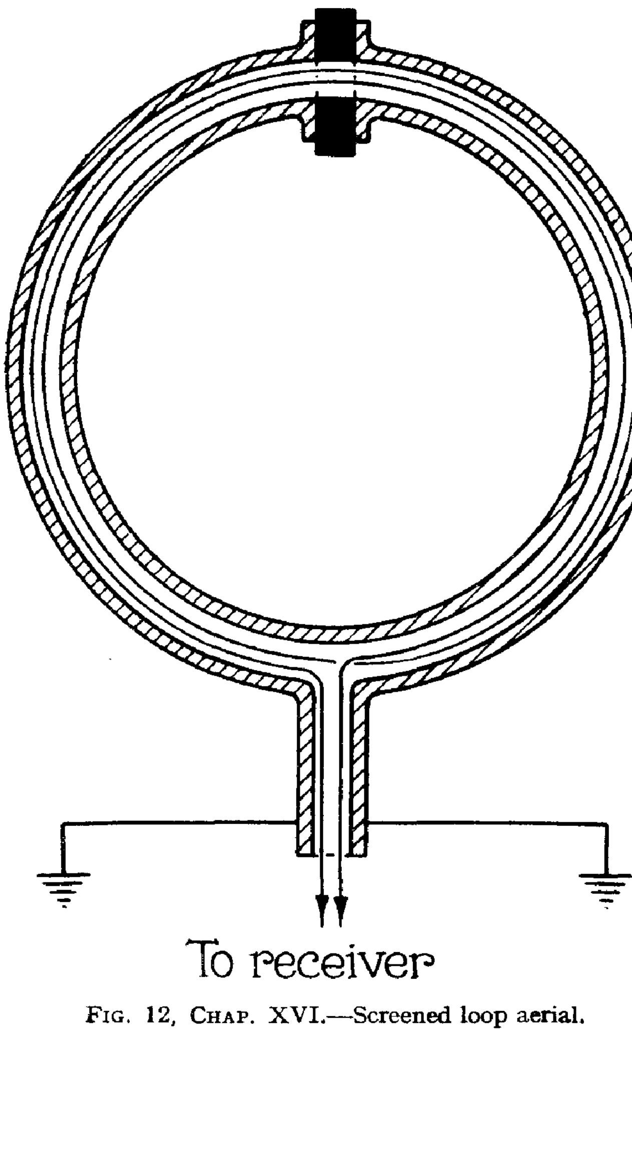


FIG. 12, CHAP. XVI.—Screened loop aerial.

the loop in a metal tube, the arrangement being referred to as a screened loop. This nomenclature is perhaps unfortunate since it is apt to give the impression that the loop is screened from the electro-magnetic wave, in which event no E.M.F. would be induced in it. Actually, the metal tube has negligible screening effect, because it does not form a closed path in which current can circulate. The most common method of construction is to use as a " screen " a metal tube bent into a circle, which is however broken at the centre point by the insertion of a tubular insulator of porcelain or of some phenolic compound (fig. 12), the tube itself being earthed at a point diametrically opposite to that at which the insulator is inserted.

Shielded R.F. transformer

20. In certain instances, the loop itself is aperiodic and is coupled to the receiver by means of a radio-frequency transformer in which the two windings are separated by an earthed electrostatic screen. The latter is so designed that although it is of metallic material, it does not form a closed circuit in which currents can circulate, and therefore does not screen the circuits from each other electro-magnetically. For low frequencies, e.g. below about 1,000 kc/s, a simple layer of copper foil may be employed, the overlapping edges being separated from each other by empire cloth. For higher frequencies a more elaborate construction is necessary. In one form, the primary winding is wound upon an ebonite former and a thin celluloid sleeve slipped over it. A close winding of silk-covered copper wire is put on this sleeve. All the turns are then bared for about one-eighth of an inch, a common earthing wire soldered to each, and the whole doped together with celluloid solution, the winding being then cut through at a point diametrically opposite to that at which the earthing wire is soldered. Finally another thin sheet of celluloid is doped down on the screen to serve as a foundation for the secondary winding.

Displacement effect

21. The error called displacement effect is always present in the box type of frame aerial. Suppose we have a frame consisting of four vertical conductors, A B, C D, A′ B′, C′ D′, suitably interconnected, as shown in perspective in fig. 13a. When the wave is incident in the direction shown, i.e. perpendicular to the plane of the loops, the E.M.F.s e_{AB} and e_{CD} neutralize each other, as do $e_{A'B'}$ and $e_{C'D'}$ likewise. The wires A B and A′ B′ also form a loop, however, the circuit being completed by the distributed capacitance between them. Similarly with the wires C D and C′ D′. Referring to fig. 13b, it will be seen that these small " phantom " loops are so disposed that maximum resultant E.M.F. is induced when the plane of the frame aerial is perpendicular to the direction of propagation, *i.e.* when according to the foregoing theory, the resultant E.M.F. is zero. The displacement E.M.F. gives rise to errors resembling out-of-phase " vertical ". Unlike the latter, however, the displacement E.M.F. changes sign when the frame is rotated through 180°.

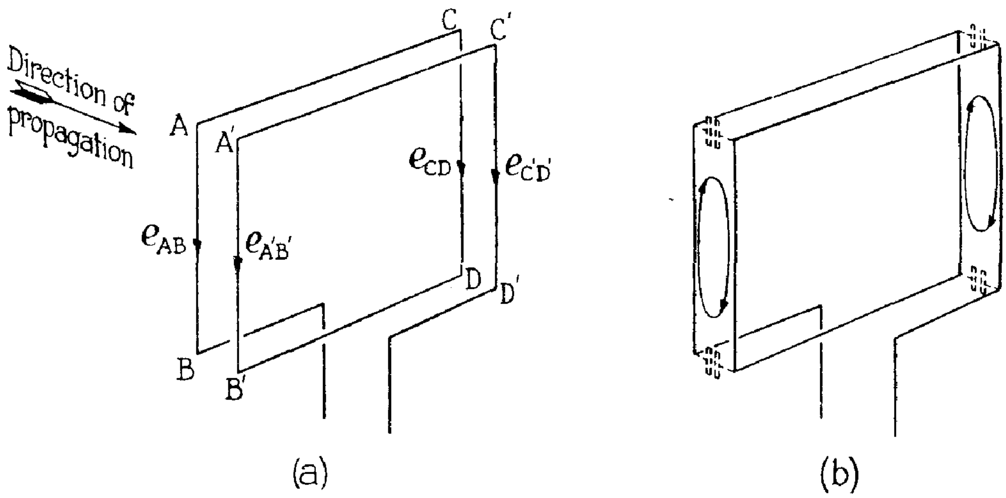


FIG. 13, CHAP. XVI.—Displacement effect in box-type frame aerial.

Properties of box and pancake frames

22. (i) At first sight the absence of displacement effect would appear to make the pancake frame preferable to the box type. This is not necessarily so, because the former is inherently subject to appreciable vertical error. Referring to fig. 5 it will be seen that owing to the method of winding, the length of wire comprising one half-turn is necessarily longer than that of the corresponding half-turn on the other side of the frame. As a result, the effective heights of the two sides are not equal and the reasoning of paragraph 17 applies. This is what is meant by the statement that the effective capacitance of a pancake frame is greater than that of a box frame.

(ii) When it is necessary to use a frame consisting of a large number of turns it is usual to construct it by winding a number of pancake coils which are mounted side by side, and connected in series, thus forming a combination of the box and pancake types. The capacitance of such a frame is less than that of a pancake frame, while the product (number of turns × effective area) is greater. Since, for optimum resultant E.M.F. in the "maximum" position, this product must be as large as possible, the combined type gives a larger ratio of maximum to minimum signal than a pancake frame. The vertical and displacement errors are however less than those of a box frame having the same number of turns.

Coastal refraction

23. It is usually assumed that electro-magnetic waves arrive at the receiving station by the shortest path between the transmitter and receiver. This is not invariably the case. As stated in a previous chapter the velocity of the wave in or over a material medium is slightly less than in free, unbounded space. When a wave passes either over or through the boundary between two material media therefore, the direction of propagation may deviate through a small angle. One of the most important instances which arises in practical direction-finding is when the wave crosses the coast-line at an acute angle. As the velocity over sea is usually from 2 to 5 per cent. greater than over land, the direction of propagation may change by as much as 10°, while errors of from 3° to 4° are common. Where it is necessary to erect a ground D/F station near the coast, the arcs over which bearings are unreliable are usually noted during calibration and bearings lying in these arcs are treated with suspicion. The exact procedure to be adopted in such cases is a matter of signals organization. When possible however, such sites are avoided. Coastal refraction errors are of greater magnitude on high frequencies than on low and are generally very small on frequencies below 150 kc/s.

Sense-finding

24. The rotating loop or frame aerial gives a position line upon which the transmitter lies but it is often desirable to find the actual bearing of the transmitter, i.e. the direction in azimuth from which the wave reaches the receiving aerial. This is achieved by deliberately introducing a certain degree of in-phase vertical effect. Let us suppose that the relative magnitudes of the resultant loop E.M.F. and the vertical E.M.F. are such that the respective polar diagrams are those shown by heavy and light lines respectively in fig. 14, the relative direction of the E.M.F's being indicated by the conventional signs. Then the total polar diagram is found by adding the polar radii of the two diagrams, giving the curve shown by a chain-dotted line, which is called a cardioid or heart-shape. It will be seen that this polar diagram has only one minimum and one maximum. Both maximum and minimum are less sharp than are obtained with the figure-of-eight diagram, and the minimum is displaced by 90° from that of the figure-of-eight diagram. If then a rotatable receiving aerial system is so arranged that its polar diagram is heart-shaped, it can be used to determine the direction from which the wave is received i.e. it becomes a sense-finder.

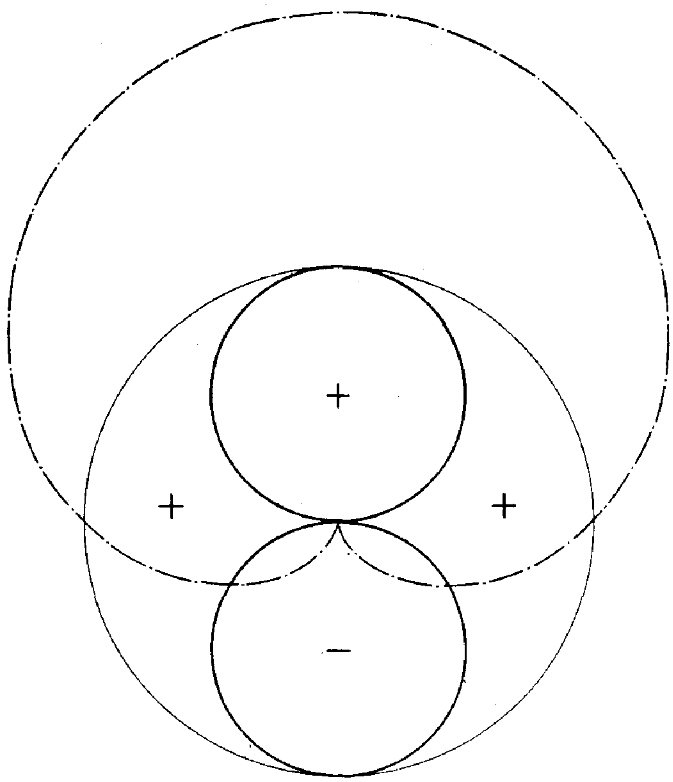


FIG. 14, CHAP. XVI.—Development of cardioid diagram.

Introduction of required " vertical "

25. The necessary vertical E.M.F. may be introduced in any one of several ways, provided always that the correct phasing is maintained. The arrangement shown in fig. 15a is most usually adopted on account of its simplicity. Here both the loop and the vertical aerial are inductively coupled to a tuned circuit, the P.D. across the condenser C being applied to the first valve of the receiver. A vector treatment will show whether the vertical and loop E.M.F.s cause in-phase P.D.s across the condenser. The relative phase of the condenser P.D. due to the

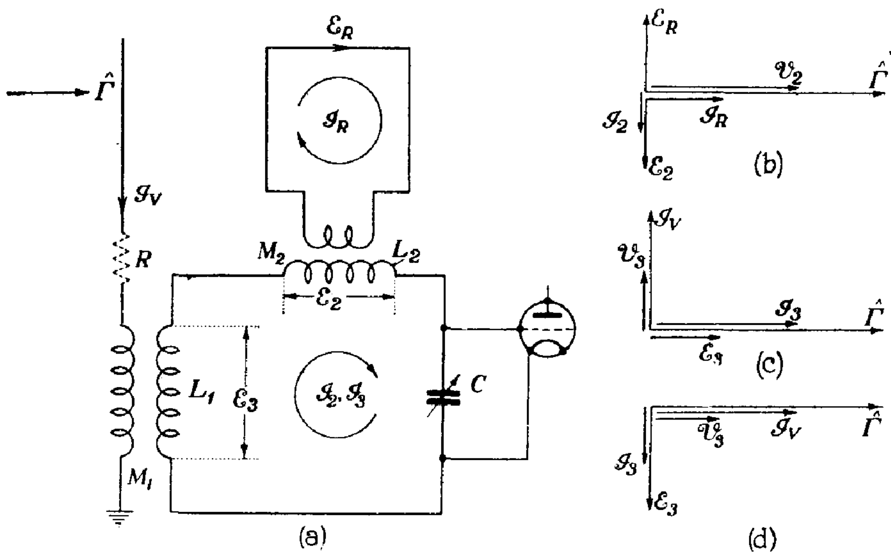


FIG. 15, CHAP. XVI.—Basic circuit for sense-finding and conditions for correct phasing.

loop E.M.F. is shown in fig. 15b. The vector $\hat{\Gamma}$, which may be regarded as the datum, represents the electric field of the wave, and the resultant loop E.M.F. $\mathscr{E}_R$ is perpendicular to this (cf. paragraphs 4 and 5). Since the loop offers a positive (i.e. inductive) reactance, the loop current $\mathscr{I}_R$ will lag on $\mathscr{E}_R$ by 90°. The current $\mathscr{I}_R$ causes an induced E.M.F. $\mathscr{E}_2$, lagging on $\mathscr{I}_R$ by 90°, in the inductance L_2. If the circuit L_1, L_2, C is tuned to the incoming frequency, the resulting current $\mathscr{I}_2$ is in phase with $\mathscr{E}_2$. The corresponding condenser P.D. $\mathscr{V}_2$ leads on $\mathscr{I}_2$ by 90° and is in phase with the original field.

Use of phasing resistance

26. (i) Now consider the vertical wire, the vector diagram being given in fig. 15c. The reactance of a short open aerial is predominantly capacitive, and the current $\mathscr{I}_V$ will lead on $\hat{\Gamma}$ by practically 90°. This current will induce in the inductance L_1 an E.M.F. $\mathscr{E}_3$, lagging on $\mathscr{I}_V$ by 90°, and a current $\mathscr{I}_3$ will flow in the tuned circuit, in phase with $\mathscr{E}_3$. The P.D. $\mathscr{V}_3$ set up between the condenser plates by this current will lead on $\mathscr{I}_3$ by 90° and will be in quadrature with $\mathscr{V}_2$. Hence this method of connection will not give in-phase E.M.F.s at the condenser terminals.

(ii) Now suppose that a resistance R is inserted in series with the vertical aerial, its value being very much larger than the capacitive reactance of the vertical wire. The conditions for the loop E.M.F. will not be affected, but the current $\mathscr{I}_V$ will now be practically in phase with $\hat{\Gamma}$, (fig. 15d). It follows that $\mathscr{V}_3$ will now be in phase with $\mathscr{V}_2$ and therefore the loop and vertical E.M.F.s combine in the correct manner to give a cardioid diagram of reception in azimuth.

(iii) Theoretically, the correct phasing could be achieved by tuning a very short vertical aerial to exact resonance with the incoming signal instead of by adding the resistance R. In these circumstances, however, a slight degree of mis-tuning is sufficient to swing the apparent sense through 90° in either direction, depending upon whether the aerial reactance becomes inductive or capacitive, and the method is therefore unreliable. With resistance phasing, if the circuit L_1, L_2, C is out of resonance, the voltages $\mathscr{V}_2$ and $\mathscr{V}_3$ are affected in the same manner and the sense-finding property is not impaired.

Value of phasing resistance

27. As a rule, the effective height of the vertical aerial is considerably greater than that of the frame aerial. To obtain a perfect cardioid diagram, the P.D.s $\mathscr{V}_2$ and $\mathscr{V}_3$ should be equal and the value of the resistance is chosen with this end in view. Referring again to fig. 15, if the inductance of the loop and the primary winding of the coupling M_2 is L, and the effective height of the vertical aerial is h_e, we have the following approximate relations :—

$$\mathscr{E}_R = \frac{2\pi AN\hat{\Gamma}}{\lambda} = \frac{\omega NA\hat{\Gamma}}{3 \times 10^8}$$

$$\mathscr{I}_R = \frac{\mathscr{E}_R}{\omega L}, \ \mathscr{E}_2 = \omega M_2 \mathscr{I}_R = \frac{M_2}{L} \times \frac{\omega NA\hat{\Gamma}}{3 \times 10^8}$$

$$\mathscr{E}_V = h_e\hat{\Gamma}$$

$$\mathscr{I}_V = \frac{\mathscr{E}_V}{R}, \ \mathscr{E}_3 = \omega M_1 \mathscr{I}_V = \frac{\omega M_1 h_e \hat{\Gamma}}{R},$$

and a perfect cardioid will be obtained if $\mathscr{E}_2 = \mathscr{E}_3$,
that is if

$$\frac{\omega M_2 NA\hat{\Gamma}}{3 \times 10^8 L} = \frac{\omega M_1 h_e \hat{\Gamma}}{R}$$

or

$$R = \frac{3 \times 10^8 \, h_e L M_1}{NAM_2}.$$

Thus, if the values of M_1, M_2, L and h_e are truly independent of frequency, the resistance required to give a perfect cardioid is constant, and can easily be found by calculation.

Example

In fig. 15, the vertical aerial has an effective height of 1 metre, the frame aerial has 20 turns of area 1 square metre, the total inductance being $200\mu H$, whilst $M_1 = M_2$. Find the resistance required to give a perfect cardioid.

$$R = \frac{3 \times 10^8 \times 1 \times 200 \times 10^{-6}}{20 \times 1}$$
$$= 3{,}000 \text{ ohms.}$$

Departure from perfect cardioid

28. In practice, the quantities M_1, M_2, L and h_e are not absolutely independent of frequency and it is not possible to obtain a perfect cardioid over a very wide frequency range with a single value of resistance. For a determination of sense, however, the perfect cardioid is not necessary, all that is required being an appreciable difference in the signal strength between the true bearing and its reciprocal. Fig. 16 shows the kind of polar diagram obtained when the vertical P.D. $\mathscr{V}_3$ is considerably less than that required to give a true cardioid; the resemblance between this figure and fig. 9 should be noted. It will be observed that under these conditions, and in the absence of all other forms of pick-up, the polar diagram has two absolute zeros and two maxima,

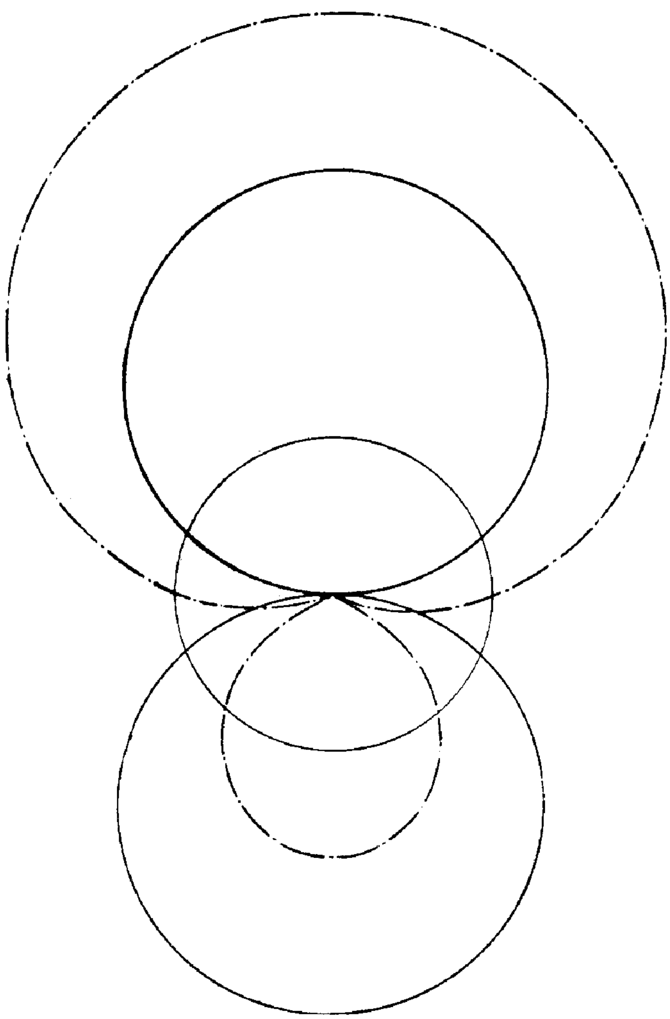


FIG. 16, CHAP. XVI.—Effect of reduction of vertical component.

one of which is greater than the other. A diagram of this kind is to be avoided if possible. If equality of the P.D.s $\mathscr{V}_2$ and $\mathscr{V}_3$ is not practicable it is preferable that the vertical P.D. should slightly exceed the loop P.D., giving rise to a diagram similar to that shown in chain-dotted line in fig. 17. This has only one maximum and one minimum and is less likely to lead to confusion. This requirement is sometimes met by providing a range of values of resistance.

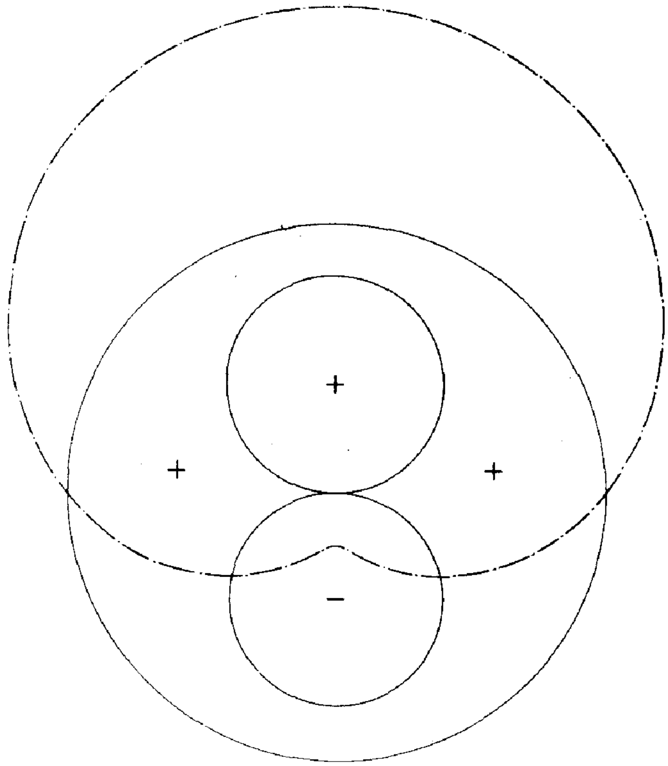


FIG. 17, CHAP. XVI.—Effect of increase of vertical component.

Adjustment of sense-finder

29. (i) In certain circumstances it may be possible to employ a continuously variable phasing resistance. The best adjustment for any particular frequency is then easily found in the following way. A double-pole two-way switch is fitted in the loop circuit, so that the connections of the loop to the coupling coil of the receiver may be reversed at will. With the vertical aerial disconnected and earthed, the loop is orientated to give maximum signal from a distant transmitter operating on the desired frequency. The vertical aerial is then connected in circuit, and the reversing switch is operated repeatedly while the phasing resistance is adjusted. The best value is obviously that which gives the greatest change of signal strength when the loop connections are reversed. In certain cases it is practicable and desirable to fit a separate pointer to the rotating loop in order to indicate the sense. Although for any given circuit it is possible to set this pointer from purely theoretical considerations, this procedure is seldom, if ever, adopted. The practice is to adjust it during the course of a test of the kind just described, i.e. by determining the sense of a transmitter in a known position. Observing however that if the D/F properties of the loop are accurate, the sense pointer must be at right angles to the pointer giving the D/F bearing it is possible to dispense with a sense pointer altogether. During the test the operator notes the actual bearing and the bearing shown by the D/F pointer ; the former is either 90° more or 90° less than the latter, and may be recorded as " for sense add 90° to bearing shown " or " for sense subtract 90° from bearing shown ". Provided that no connection is altered, this indication will then hold good on future occasions. It is therefore particularly necessary that the reversing

switch should be left in the position of calibration. Where a sense pointer is necessary, it is usually shorter than the D/F pointer and carries no definite indication of the exact bearing, in order to avoid any temptation to ascertain the latter by the sense-finding property alone. The bearing reported should always be one of the two obtained in the D/F position.

(ii) Although in the above discussion reference is made to the use of a vertical aerial, it must be understood that any form of aerial which has an approximately circular horizontal polar diagram, e.g. an L or T aerial, may be employed. Thus in an aeroplane, either the fixed aerial or the trailing aerial may be used for this purpose, the former being generally preferable.

AIRCRAFT D/F

Loop aerials

30. The installation and operation of D/F apparatus in aircraft presents a number of problems which are not met with in a ground D/F station. Many of these difficulties are of course common to all forms of aircraft W/T equipment, e.g. space and weight considerations and engine noise. The design of a rotating loop aerial for use in modern high-speed aeroplanes presents more difficulty than is apparent at first sight. A loop 18 inches in diameter, in a screening tube about 1¼ inches in diameter, may increase the drag by about 2 per cent, and will reduce the maximum speed in approximately the same degree. A reduction in the size of the loop will reduce the drag but will also reduce the pick-up factor of the loop. A possible solution is to use a comparatively

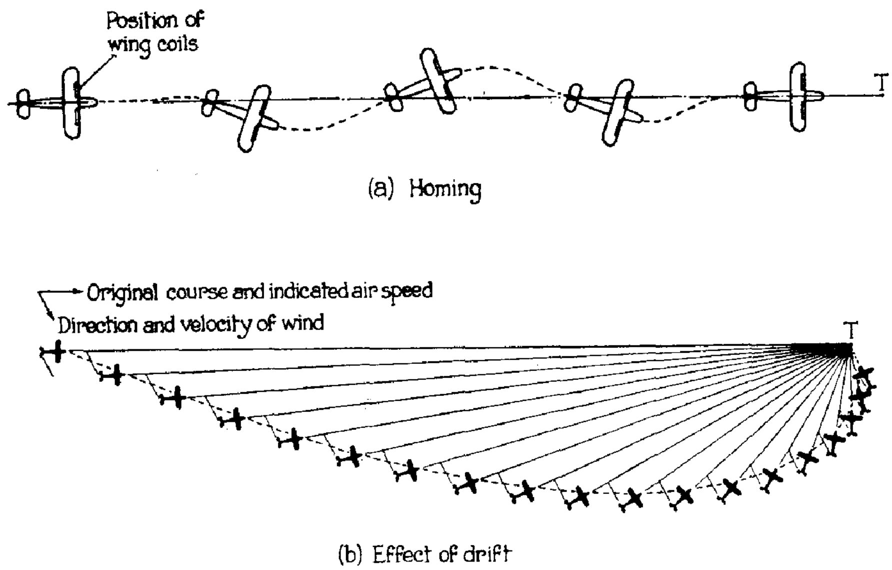


FIG. 18, CHAP. XVI.—Operation of wing coil D/F.

small loop, e.g. of about 12 inches diameter, mounted in a screened, streamlined casing above the structure. The simplest form of aeroplane D/F apparatus is that in which so-called wing coils are employed, but these are not suitable for use in all-metal aeroplanes. The wing coil is simply a frame aerial consisting of one or more turns of wire, the horizontal members being laid along and doped to the wing perpendicularly to the fore-and-aft line and the vertical members accommodated inside one of the struts on either side of the fuselage. Such a wing coil, when tuned by a variable condenser and connected to a suitable amplifier, will give minimum signals from a given transmitter when the aeroplane is heading directly towards or away from the transmitter. Since the 180° ambiguity is generally resolvable by geographic considerations, an installation of this kind may be used for homing. The method of operation is indicated in fig. 18a. When flying directly towards the transmitter station no signals are received, since the wing coil is perpendicular to the direction of propagation of the wave. The reception of signals is an indication that the machine is off its course; by swinging alternately to port and starboard, matching the strength of signals in each direction, the mid-point can be estimated and the course set as desired. If, however, a strong cross wind is blowing, homing by D/F bearings as above is subject to a certain limitation, owing to the drift to leeward of the machine. The effect of flying the D/F bearing without allowance for drift is shown in fig. 18b. In the original position, the course and speed of the aeroplane, and the direction and velocity of the wind, are as shown in the vector diagram. This course corresponds with the D/F bearing. After flying for a short distance on this course, the aeroplane will drift into the second position. If the pilot now corrects his course to the new D/F bearing, the aeroplane will, in a short time, reach the third position and so on. The actual course flown will therefore be as shown by the dotted line, and the aeroplane will reach the vicinity of the transmitter flying directly into the wind. The effect of drift must therefore be counteracted by setting a course slightly into the wind with reference to the D/F bearing after the latter has been ascertained.

Quadrantal correction

31. The wing coil system is not adapted for taking cross bearings in order to obtain a fix for which purpose a rotating loop is much more convenient. When used in an aeroplane, however, the rotating coil is subject to a type of error which is of no importance with the wing coil system. This error is caused by the induction of radio-frequency currents in the metal-work of the aeroplane itself. The existence of such currents connotes the production of both radiation and induction electro-magnetic fields, to which the D/F loop is subjected in addition to the radiation field of the distant transmitter. It must be realized that the fields due to the aeroplane itself are very complex owing to the different sizes, shapes and dispositions of the current-carrying members, but in general they may be resolved into two components which differ in direction in space and are in quadrature with respect to each other, as in fig. 19 in which the axis of the loop is located at the point P. The wave is incident in the direction T P, the positive direction of its electric field vector being upward out of the paper. For the purpose of illustration it is convenient to show the magnetic vector $\mathcal{H}$ which is positive in the direction shown, perpendicular to the direction of propagation. The instantaneous magnetic field of the incoming wave is of course sinusoidal and may be considered to be $\mathcal{H} \sin \omega t$ at the point P. The fields due to the aeroplane itself will then be (i) $\mathcal{H}_R \sin \omega t$, the radiation field, which is in phase with the wave field, and (ii) $\mathcal{H}_I \cos \omega t$, the induction field, which is in quadrature therewith. The direction in

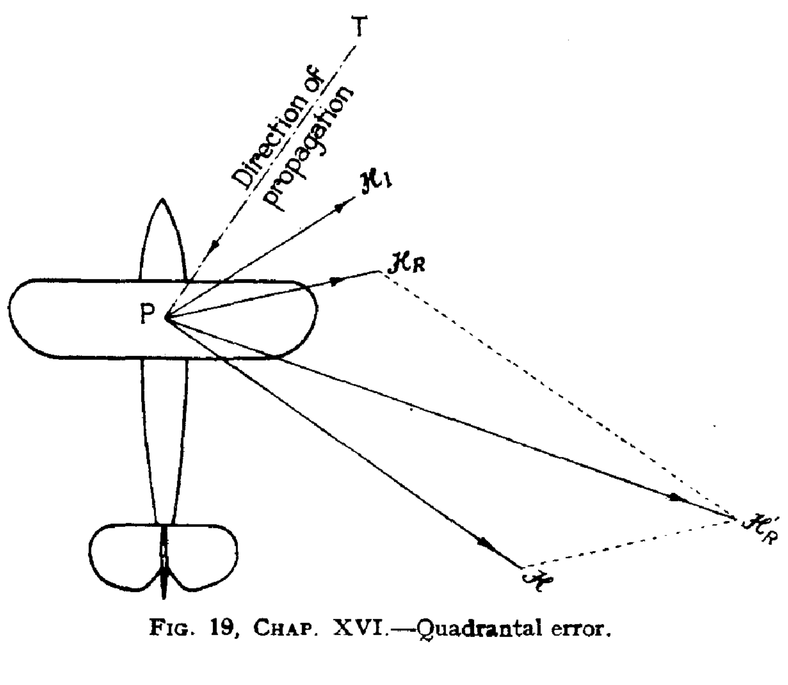


FIG. 19, CHAP. XVI.—Quadrantal error.

0	0	120	-8	240	+7
10	+6	130	-9	250	+5
20	+9	140	-10	260	+3
30	+10	150	-10	270	0
40	+10	160	-9	280	-3
50	+9	170	-6	290	-5
60	+7	180	0	300	-7
70	+5	190	+4	310	-9
80	+2	200	+8	320	-10
90	0	210	+10	330	-10
100	-3	220	+10	340	-9
110	-5	230	+9	350	-7

R.A.F. FORM 2026

QUADRANTAL CORRECTION CARD

AIRCRAFT TYPE:- ....

AIRCRAFT No:- ....

D.F. LOOP TYPE:- ....

D.F. LOOP SERIAL No:- ....

CHECKED:- ....

DATE:- ....

TRANSMITTER	FREQUENCY

INITIALS:- ....

RANK:- ....

QUADRANTAL CORRECTION CARD

FIG. 20

CHAP. XVI

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space of these fields depends upon the disposition of the current-carrying members of the aeroplane. Since the fields $\mathcal{H}\ sin\ \omega t$ and $\mathcal{H}_R\ sin\ \omega t$ are in phase, they may be added, giving a resultant field $\mathcal{H}'_R\ sin\ \omega t$, so that finally we have two fields in quadrature, their magnitudes being $\mathcal{H}'_R$ and $\mathcal{H}_I$.

32. The effects of these fields may be considered separately. Supposing $\mathcal{H}_I$ to be zero, let the loop be rotated into the position giving minimum signal. This will obviously occur when the loop does not link with the field $\mathcal{H}'_R$, and the apparent bearing is then nearer to the fore-and-aft line than the correct bearing. If the aeroplane were perfectly symmetrical (*a*) on either side of the for-and-aft line and (*b*) on either side of a transverse line through the point P, the error would be zero when the correct bearing was either 0°, 90°, 180° or 270°, and the maximum error would be found on bearings of 45°, 135°, 225° and 315°. On the other hand, if the field $\mathcal{H}'_R$ were entirely absent, maximum flux, linkage between the loop and the induction field $\mathcal{H}_I$ would occur when the plane of the loop was in the fore-and-aft line. Considering both fields together and dispensing with the assumption of a perfectly symmetrical aeroplane, it will be seen that as the fields $\mathcal{H}'_R$ and $\mathcal{H}_I$ are always in phase quadrature, and differ in magnitude and direction, they cannot be combined to give a resultant field having a constant direction in space. In general, their combination gives rise to a field which rotates in space at the frequency of the incoming wave and also varies in magnitude according to the bearing of the transmitter. As a result, the resultant field will affect the loop to some extent, in whatever direction it may be placed. The effect of the metalwork is therefore two-fold. In the first place it gives rise to erroneous bearings, maximum error usually occurring approximately in the middle of each quadrant. This is termed the quadrantal error. Its magnitude depends upon the construction of the aeroplane, and upon the position of the D/F loop; it is usually of the order of 6° to 12°. In the second place the presence of the induction field causes blurred minima, particularly when the bearing of the transmitter is in the neighbourhood of 90° or 270°.

Calibration

33. (i) The present practice is to allow for quadrantal error by calibrating the direction-finder. In brief, this process consists of taking D/F bearings of a transmitter of which the actual bearing is known, and so determining the correction to be applied. Since it is necessary to turn the aeroplane so that D/F bearings of the transmitter are obtained on a number of different relative bearings, the operation is sometimes termed " swinging for quadrantal correction " by analogy with the process of swinging an aeroplane in order to determine and correct the compass deviation. At the present time, however, no attempt is made to correct the loop by electrical means, although as mentioned later it is possible in certain cases to apply the correction mechanically. The term " relative bearing " used above and subsequently, denotes the bearing of a transmitter with reference to the head of the aeroplane, measured in degrees in a clockwise direction.

(ii) While it is possible to perform the operation of calibration in several ways, the following procedure is suggested as being as rapid as any, and requiring a minimum of calculation. It is applicable both to large and small aeroplanes. The preliminary step is to select a suitable transmitter, e.g. in the United Kingdom, one of the B.B.C. broadcasting stations, or any other which is known to maintain continuous transmission during the calibrating period. In certain circumstances, particularly overseas, it may be necessary to arrange for a suitable transmission in advance. The selected transmitter should, of course, give sufficient field strength at the aerodrome, but should not be too near the latter. Ideally, it should be from 50 to 100 miles away.

34. Calibration should be performed on a site as far away as possible from all buildings; the former practice of using the compass base for D/F calibration is only permissible if its site error (*see* paragraphs 40, 73, *et seq.*) is negligible. There is little to be gained by using it in any case. The D/F calibration when executed in the manner following depends upon either the pilot's or observer's compass in the aeroplane itself. It is, therefore, essential that the compass shall be

swung immediately prior to the D/F calibration. The occasions upon which the compass is swung are clearly defined in K.R. and A.C.I., and it is desirable to perform a D/F calibration as soon as possible after every occasion of such swinging. In any event it is important to ensure that all the removable equipment which is ordered to be in the aeroplane on the occasion of swinging for compass adjustment shall be in position during the D/F calibration. It must also be noted that the first fitting of a D/F loop may in certain circumstances entail compass swinging under these regulations.

35. In the actual calibration, it is preferable to refer only to magnetic and compass bearings, the magnetic bearing being the compass bearing corrected for compass deviation from Form 316 or Form 316a, depending upon which compass is employed. The *magnetic bearing* of the transmitter will be ascertained prior to the commencement of operations. If time permits, it is desirable to calibrate at intervals of approximately 10°, otherwise 15° or 20° intervals may be taken. The following pro forma should be prepared beforehand.

(1) Line	(2) Compass heading (proposed)	(3) Compass heading (actually used)	(4) Relative bearing of transmitter by D/F
1	0°		
2	10°		
3	20°		
4	30°		
5	40°		
6	50°		
7	60°		
8	70°		
etc.	etc.		

The figures in column 2 are intended merely as an aid to memory as to the proposed number of points, but it is not necessary to waste time in accurately placing the aeroplane on these bearings. For example, if the aeroplane is taxied on to the aerodrome, heading 42° (compass), column (3) of line 5 should be completed by inserting 42°, crossing out 40° in column (2). The relative bearing of the transmitter is ascertained and inserted in column (4). The aeroplane may then be so handled that the compass heading is 49°, columns (3) and (4) of line 6 being completed accordingly and the entry 50° in column (2) crossed out. Before taking the W/T observation on each heading the tail should be raised in order to bring the aeroplane into the normal flying position. In certain types of aeroplane, the error introduced by ignoring this instruction may be negligible but in the absence of definite orders to the contrary the tail should always be lifted.

36. When the data have been obtained for the required number of points, the following pro forma should be completed.

Magnetic bearing of transmitter ......*320°*.

(1) Line.	(2) Head by Compass.	(3) Magnetic Head	(4) Relative bearing of transmitter	(5) Relative bearing by D/F.	(6) Quadrantal correction
1	*0°*	*0°*	*320°*	*330°*	*−10*
2	*21°*	*22°*	*298°*	*306°*	*−8*
3	*39°*	*45°*	*275°*	*276°*	*−1*
4	*60°*	*64°*	*256°*	*252°*	*+4*
5	*81°*	*82°*	*238°*	*229°*	*+9*
6	*90°*	*90°*	*230°*	*220°*	*+10*
etc.	etc.	etc.	etc.	etc.	etc.

Column (2) is identical with column (3) of the previous pro forma, while column (3) is column (2) corrected for compass deviation from Form 316 or 316a, depending upon which compass is used.

(1) Line	(2) Compass heading	(3) Magnetic heading	(4) Relative bearing of Transmitter	(5) Relative bearing by D/F	(6) Quadrantal correction
1	0	0	320	330	-10
2	21	22	298	306	-8
3	39	45	275	276	-1
4	60	64	256	252	+4
5	81	82	238	229	+9
6	90	90	230	220	+10
7	100	98	222	212	+10
8	120	117	203	196	+7
9	140	136	184	183	+1
10	160	157	163	169	-6
11	180	180	140	150	-10
12	200	202	118	127	-9
13	220	224	96	98	-2
14	240	244	76	72	+4
15	260	262	58	49	+9
16	270	270	50	40	+10
17	280	279	41	31	+10
18	300	296	24	16	+8
19	320	315	5	3	+2
20	340	337	343	350	-7

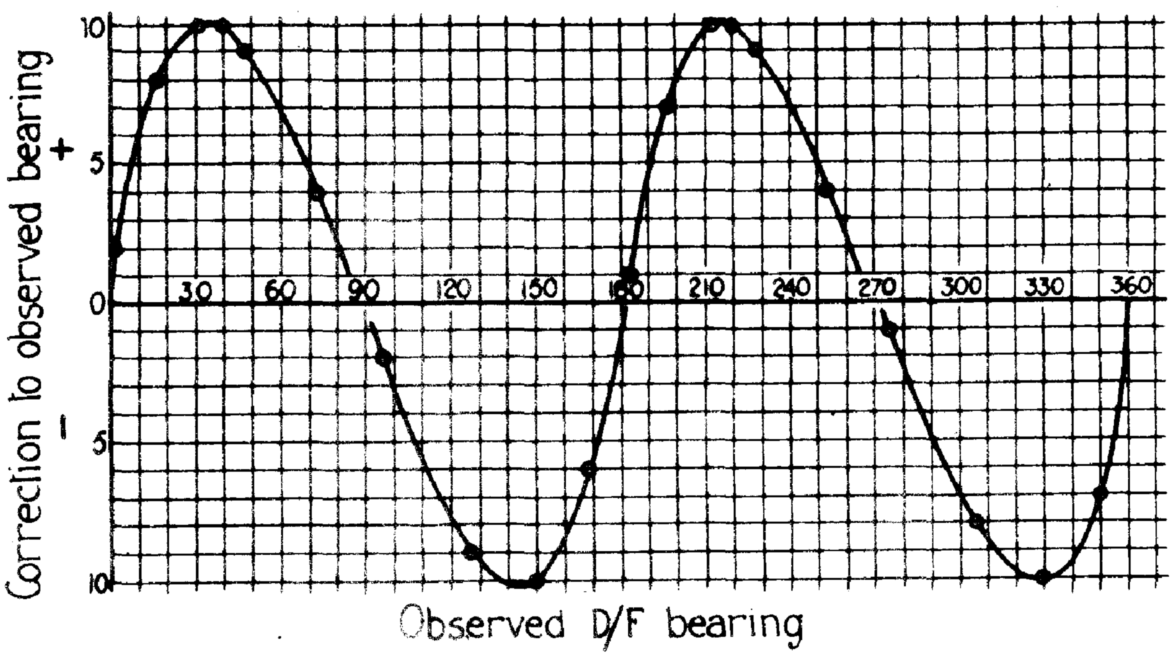

FIG. 21
CHAP. XVI

PRO FORMA AND CORRECTION CURVE

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Column (4) is obtained by subtracting the figure in column (3) from the magnetic bearing of the transmitter (adding 360° if necessary). Column (5) is identical with column (4) of previous pro forma. Column (6) gives the correction which must be applied to the W/T. bearing, Column (5), to obtain the relative bearing of the transmitter, column (4).

Quadrantal correction card

37. For purposes of easy reference, it is necessary to transfer the results of column (6) to the Quadrantal Correction Card, Form 2026. The latter is of the same shape and size as the Compass Deviation Card, Form 316a, and is intended to fit into a similar holder. An enlarged specimen copy is shown in fig. 20. It will be observed that the printed figures, 0 to 350, show observed W/T bearings, and the quadrantal correction is to be inserted in the corresponding blank space. Since it is not expedient directly to obtain the relative bearings so printed, it is necessary to plot a curve showing the quadrantal correction for the whole 360°, with " D/F bearing " from Column 5 as abcissa and " quadrantal correction " from Column 6 as ordinate. A curve should be drawn through the points so obtained and the correction for 10°, 20° etc. taken from the curve and entered on Form 2026. Until further experience has been obtained, it is difficult to say to what extent it is permissible to smooth out this curve, but any point widely diverging from the general trend should be verified. In certain circumstances the graph may reveal the necessity for a constant, or nearly constant, correction on all bearings, in addition to the quadrantal correction. This correction may be applied by shifting the pointer with reference to the plane of the loop, if such provision is made. A typical completed pro forma, and the correction graph are shown in fig. 21 ; the corrections taken from the latter are those entered on the Quadrantal Correction Card in fig. 20.

Calibration on fixed base

38. In certain circumstances it may be convenient or desirable to calibrate on a fixed base similar to that used for swinging a compass. It is necessary to choose a suitable site, out of the path of aeroplanes taking off or landing, and remote from all buildings, railway lines etc., in accordance with paragraphs 73 *et. seq.* A peg is driven into the ground at the centre of the site and a circle of 35 or 40 feet radius marked out. The direction of true north is then obtained by means of a theodolite or by observation of the sun's passage across the meridian at local noon. The circle is divided into arcs of 20°, pegs are driven in and strings stretched across opposite ones. These should all intersect at the centre of the circle, corresponding radial lines are then marked out on the ground by digging narrow trenches which may be filled in with white-wash. The accuracy of the calibration will depend chiefly upon the care with which the base is marked out. To perform it, the aeroplane is placed over or parallel to each line in succession and a pro forma is filled in as before, except that all bearings are either relative or true. The calibration is therefore independent of the aircraft compass. The pro forma is as follows :—

True bearing of transmitter ......330°

(1) Line	(2) True heading	(3) Relative bearing of transmitter	(4) Relative bearing by D/F	(5) Quadrantal correction
1	0°	330	340	−10
2	20°	310	318	−8
3	40°	290	292	−2
4	60°	270	270	0
etc.	etc.	etc.	etc.	

Column (3) is the true bearing of the transmitter minus the true heading, column (2). The remainder of the work is as before.

Precautions

39. A quadrantal correction calibration made on the ground as above does not necessarily hold good when the aeroplane is in flight, but may be expected to do so under the following conditions :—

(i) The rotating loop is fitted *above* the structure of the aeroplane. If this is not so the ground calibration is not valid in the air and an air calibration becomes necessary. This requires steady flying and therefore good weather conditions, but otherwise presents little difficulty although of course some experience of calibration is required.

(ii) The site chosen for calibration is reasonably clear of metallic masses which have appreciable pick-up on the frequency involved. It is difficult to dogmatize in this respect, but the conditions stated in paragraphs 65 *et. seq.* are generally applicable.

(iii) The site error of the source used for calibration is known.

With reference to (ii) and (iii) a possible method of ascertaining whether any error is present is to make a preliminary investigation with a special portable direction-finder consisting of a small screened loop mounted on a wooden structure so that it has negligible quadrantal error.

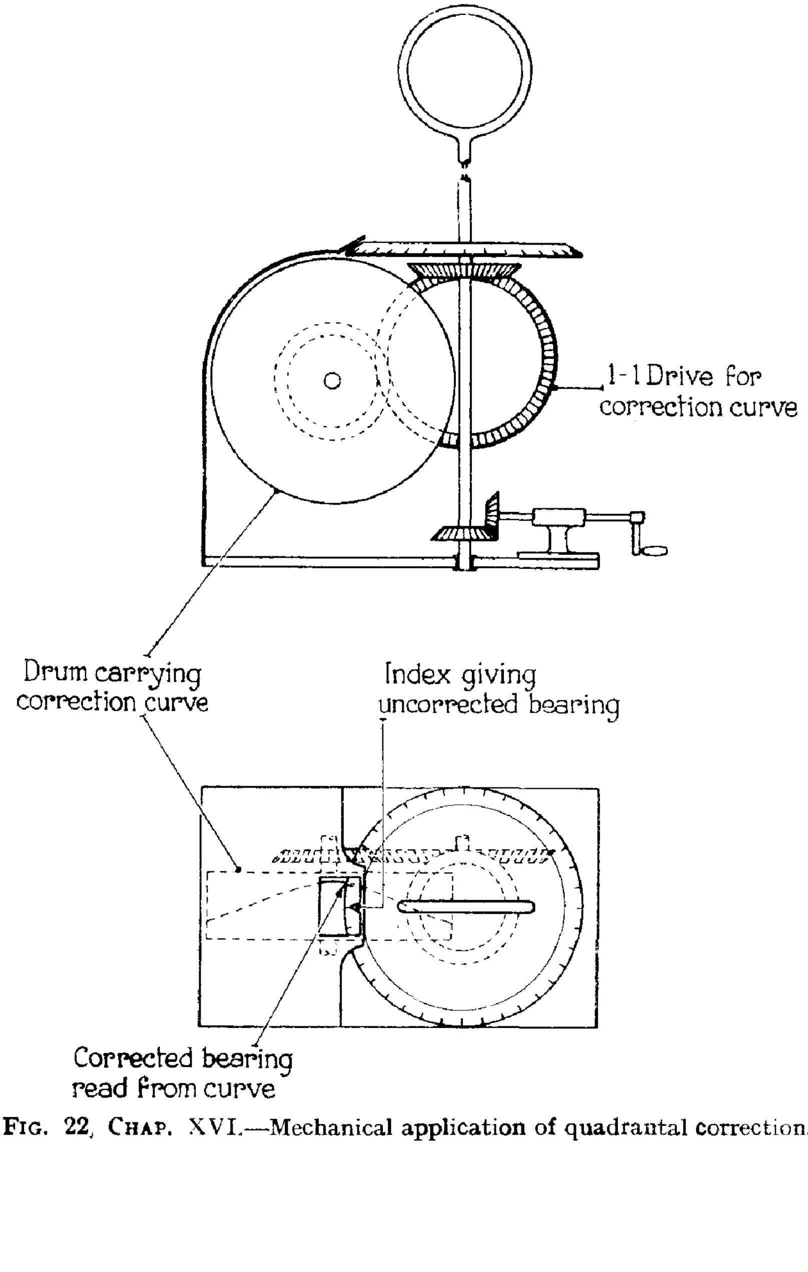


FIG. 22, CHAP. XVI.—Mechanical application of quadrantal correction.

Mechanical correctors

40. In certain installations, the quadrantal correction may be applied automatically. This may be achieved by incorporating a special cam in the drive between the shaft of the rotating loop and the bearing pointer. As initially supplied the cam is circular and the pointer gives the uncorrected reading. After calibration, the periphery of the cam is machined to shape in such a manner that on any given bearing, the pointer lags or leads on the loop to an extent governed by the required correction. Should this method be adopted, special instructions will be promulgated with regard to the operation of cutting the cam. In another form of automatic corrector, the bearing scale rotates with the shaft of the loop and the uncorrected bearing is read from a fixed lubber line engraved on a stationary bracket. A drum is geared to the shaft in such a manner that it makes one complete turn for each revolution of the loop. The axis of the drum is perpendicular to the shaft of the loop and its curved surface rotates in proximity to the periphery of the bearing scale. A line drawn on the curved surface may therefore be used as a lubber line for observation purposes, and this line may be so drawn as to show the corrected bearing. Both the methods described embody the same mechanical principles, and the latter is illustrated in fig. 23 since the mechanical details are less complicated than in the former type.

41. Where it is intended to operate the loop as a sense-finder, the occasion of calibrating for quadrantal error provides a suitable opportunity of adjusting the phasing resistance in order to obtain the best practicable cardioid, provided that the " vertical " is to be provided by a fixed aerial above the airframe. Obviously this is not possible if a trailing aerial is to be used for sense indication. It must always be remembered, also, that if provision is made for the use of either of two aerials, one above and one below the structure, the sign of the 90° correction to the D/F pointer (*see* paragraph 29) will change from positive to negative or vice versa on changing from one aerial to the other. Since their effective heights may be very different, a change-over from one to the other will also generally necessitate a re-adjustment of the phasing resistance.

Conversion angle

42. Radio waves travel over the earth's surface along arcs of great circles, but on charts and maps used for navigation, great circles are not represented as straight lines. Provided that both the transmitter and the aeroplane are in the area shown on a flying map, the difference between a straight line, and the arc of the great circle upon which they are situated, is negligible. Charts used for long distance flying are drawn on Mercator's projection, in which all meridians of longitude are parallel lines, instead of being convergent towards the geographical poles. On obtaining the bearing of a transmitter by means of a loop aerial, the navigator desires to draw, through the W/T station, a straight line upon which the aeroplane is situated, i.e. the position line referred to in paragraph 2. It must first be noted that the bearing from the W/T station is the reciprocal of the bearing of the latter from the aeroplane, but before drawing the position line upon the chart a correction must be applied to allow for the difference between great circle and Mercatorial bearings. This correction, which is called the conversion angle, is negligible in latitudes below 60° unless the distance between transmitter and aeroplane is more than 100 miles, but should always be applied in other cases. In order to preserve a record of the observation and to facilitate the work of obtaining the mercatorial bearing of the transmitter from the observed D/F bearing, Form 2058 has been introduced. This form will be issued in pads for insertion in a suitable cover, the inner side of which is finished in a washable white material. This is intended for recording in pencil the names, frequencies, and geographical positions of such W/T stations as are likely to be available for D/F purposes during a particular flight. It is suitably ruled and engraved with the appropriate legends for this purpose.

43. A specimen copy of Form 2058 is shown in fig. 23. The W/T operator is only concerned with the insertion of the name of the transmitting station, its frequency, and the following details of the bearing, viz. (i) the observed bearing (ii) the time at which it was taken (iii) the classification, as laid down in the signals organization. The time of observation is of primary importance

and must never be omitted. The remainder of the form (including the portion for quadrantal correction) is for the use of the navigator, but will be briefly summarized by an example, in order that W/T personnel may appreciate the significance of their work.

Example

During a flight from Reykjavik to Plymouth, a D/F bearing of 335° is obtained at 1035 hours from Aberdeen W/T station transmitting on 315 kc/s, when the true course is 140° and the position by dead reckoning is Lat. 60° 32′ N., Long. 15° 40′ W. The position of the W/T station, namely, 57° 8′ N., Long. 2° 4′ W., has previously been inserted in the cover for Form 2058.

The operator, after inserting the name and frequency of the transmitting station, enters the observed bearing, the time at which it was taken, and the classification of the bearing. He then passes the form to the navigator, who completes the work as follows :—

Time 1035 hours	Observed bearing	335°
G.M.T.	Quadrantal correction	− 8°
	Corrected bearing	327°

The operator then passes the form to the navigator, who completes the work as follows :—

Latitude of W/T station	57° 8′ N.
D.R. latitude at 1035	60° 32′ N.
Sum latitudes	117° 40′ (≑ 118°)
Longitude of W/T station	2° 4′ W.
D.R. longitude	15° 40′ W.
D. Long.	13° 36′
True Course	140°
True bearing of W/T station	467°

The latter is the sum of the true course and the corrected relative bearing; when this sum exceeds 360°, the latter figure is subtracted, giving

True bearing .. .. 107°

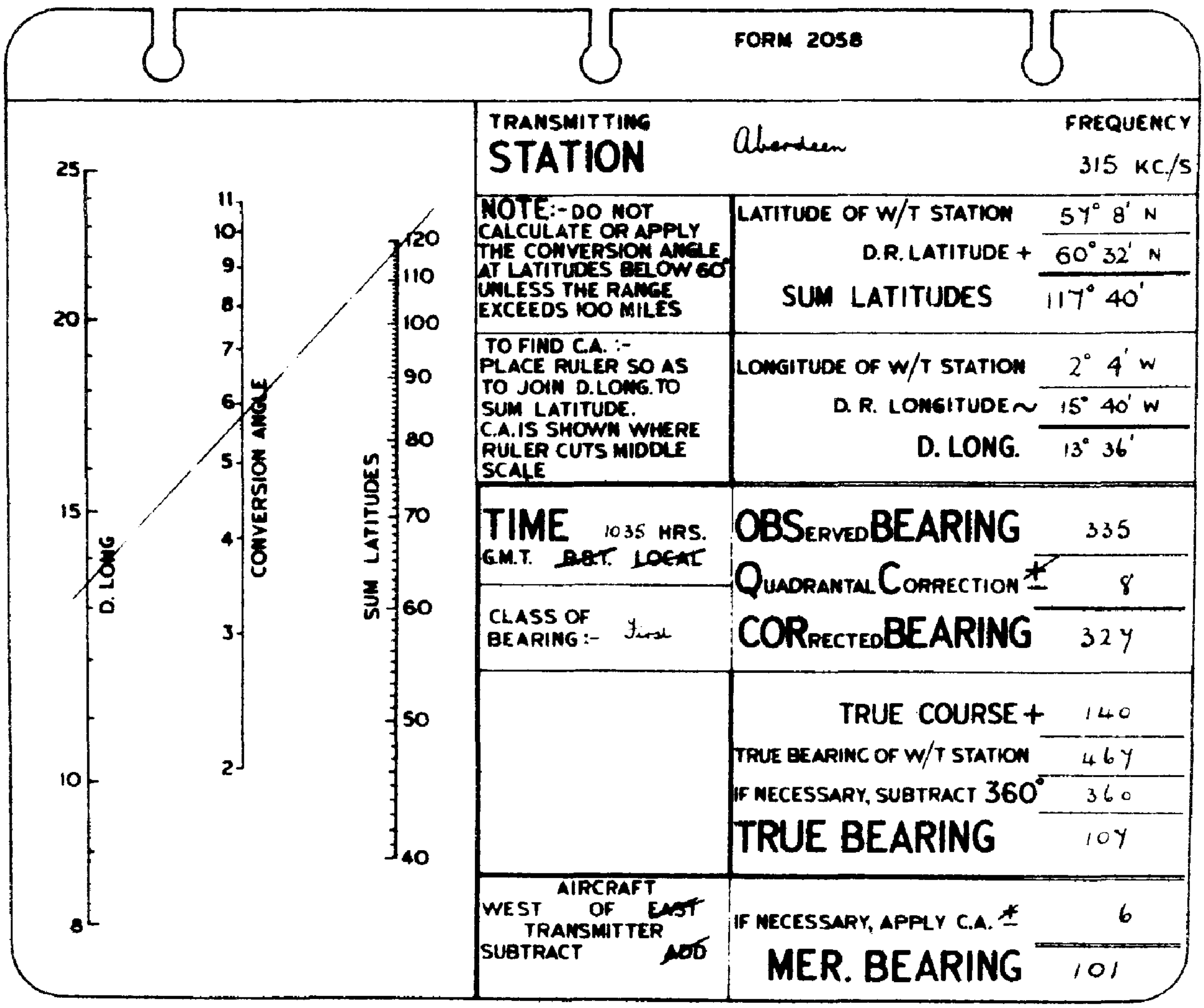
To obtain the mercatorial bearing, the conversion angle must be applied. The necessary calculations have been made and the results exhibited in the form of a nomogram which is printed on the left-hand side of Form 2058, together with instructions for its use. A straight line drawn on the nomogram, through the points " D. Long., 13° 36′ " and " sum latitudes, 118° " gives the conversion angle, from the middle scale, as $\pm 6°$ approximately. Since the aeroplane is west of the transmitter the negative sign is taken. Hence the final entry is

Mercatorial bearing .. .. .. 101°

The reciprocal of 101° being 281°, the latter is the bearing on which the position line must be drawn from the transmitter.

The Robinson system

44. (i) Owing to the high noise level which prevails in an aeroplane, it is more difficult to obtain a reliable bearing by the minimum method than in a ground D/F station. In the Robinson system, an attempt is made to secure the advantages of both maximum and minimum methods. In this system two frame aerials are employed; these are rigidly fixed at right angles to each other in such a manner that the combination can be rotated in azimuth. The frame aerials are connected to the receiver proper as shown in fig. 24. The smaller aerial L_1 is called the main coil and the larger one, L_2, the auxiliary coil. The relative proportions of these coils will be discussed later. Two change-over switches, S_1, S_2, are included. When thrown over to the left, the switch S_1 connects the auxiliary coil in series with the main coil, but when thrown over to the right, the auxiliary coil is removed from the circuit and a small coil L_3 is substituted. This coil is designed to have negligible pick-up, so that when it is in circuit, the signal is received only on the main coil. The inductance of L_3 is equal to that of the auxiliary coil. The aerial circuit is tuned to the desired frequency by a variable condenser C. This adjustment holds good for



STATION	FREQUENCY	LATITUDE	LONGITUDE	REMARKS
Aberdeen	315 kc/s	57° 8' N	2° 4' W	

Inside of cover

PRO FORMA FOR D/F CALCULATIONS

FIG. 23
CHAP. XVI

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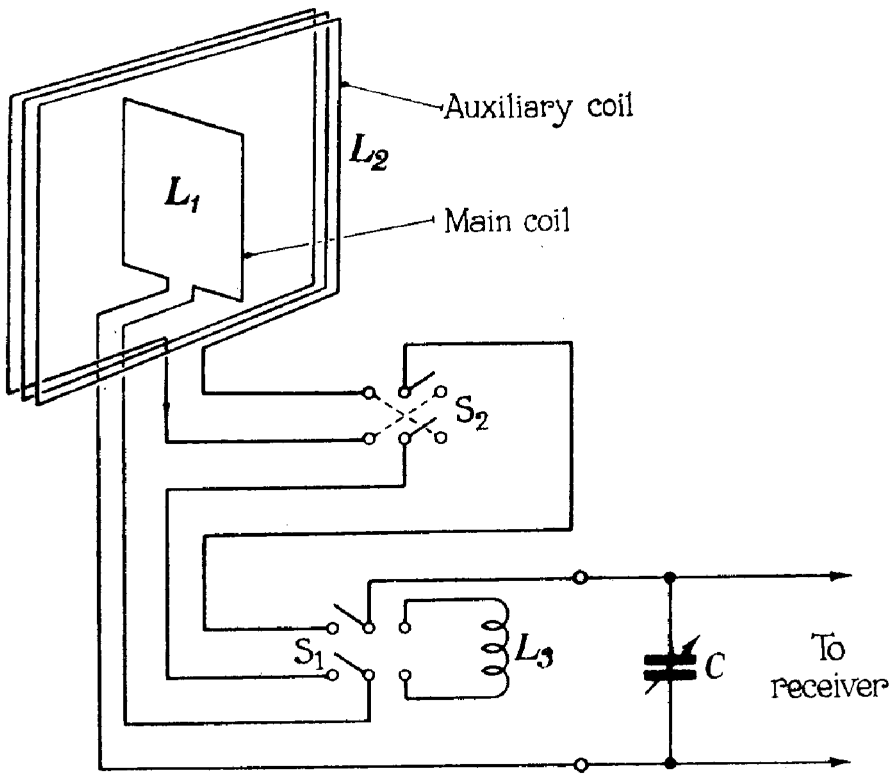


FIG. 24, CHAP. XVI.—Principle of Robinson system.

either position of the switch S_1, provided that the inductance of L_3 is correctly adjusted. The switch S_2 is called the reversing switch. Its function is to reverse the direction of winding of the auxiliary with respect to that of the main coil, when both are in circuit.

(ii) The method of obtaining a bearing is as follows. The switch S_1 is thrown over to the right so that only the main coil is operative, and the coils rotated until the signal appears to be of maximum strength. Owing to the wide arc of maximum signal this bearing may be several degrees in error. If this is so, an E.M.F. is also set up in the auxiliary coil, although as this is not in circuit it has no effect upon the signal strength. If the switch S_1 is now thrown over to the left, both the main and auxiliary coils are in circuit. The resultant E.M.F. of the auxiliary coil is now algebraically added to that of the main coil and the signal strength will be either increased or decreased, according to whether the respective voltages are in phase or in opposition. It follows therefore that the signal strength will vary between two levels when the switch S_2 is thrown from left to right and vice versa. When the main coil is truly aligned in the direction of the transmitter, however, no resultant E.M.F. is developed in the auxiliary coil and the operation of the change-over switch S_2 has no effect whatever upon the signal strength. The operator therefore swings the coils through a small arc while reversing the switch S_2 as necessary until a position is found in which the signal strength is unaffected by the reversal. The bearing of the transmitter, with an ambiguity of 180°, is then given by the orientation of the main coil.

45. In order to obtain a high degree of accuracy, it is necessary that when the auxiliary coil is only very slightly off the zero-signal bearing, the resultant E.M.F. induced in it shall be sufficient to cause a perceptible difference in signal strength when its reversal is performed. It is difficult to say what constitutes a perceptible change, but for the present purpose we may

assumė that 3 db. will be sufficient. Let us suppose the main coil to be θ degrees off the correct bearing. The resultant E.M.F.s in the two coils will then be

$$e_a = (A_a N_a K \sin\theta) \cos\omega t$$
$$e_m = (A_m N_m K \cos\theta) \cos\omega t$$

where e_a and e_m are the resultant E.M.F.s, A_a, A_m the areas, N_a, N_m the numbers of turns in the auxiliary and main coils respectively, and K is a constant. The amplitude of the total resultant E.M.F. is therefore

$$e_1 = (A_m N_m \cos\theta + A_a N_a \sin\theta) K$$
$$\text{or } e_2 = (A_m N_m \cos\theta - A_a N_a \sin\theta) K$$

depending upon the position of the reversing switch The output of the receiver due to the above voltage will depend upon the nature of the rectification process. For C.W. reception with a strong heterodyne, (which is the normal method in modern practice in order to secure the maximum signalling range), the rectification is approximately linear. The change of signal strength on reversal will then be proportional to the ratio $\frac{e_1}{e_2}$, that is to

$$\frac{A_m N_m \cos\theta + A_a N_a \sin\theta}{A_m N_m \cos\theta - A_a N_a \sin\theta}$$

For a change of 3 db. $\quad \frac{e_1}{e_2} = \sqrt{2}$, and therefore

$$A_m N_m \cos\theta + A_a N_a \sin\theta = \sqrt{2}\,(A_m N_m \cos\theta - A_a N_a \sin\theta)$$
$$(1 + \sqrt{2})\, A_a N_a \sin\theta = (\sqrt{2} - 1)\, A_m N_m \cos\theta$$
$$\frac{A_a N_a}{A_m N_m} = \frac{\cdot 414}{2 \cdot 414} \cot\theta$$
$$= \cdot 172 \cot\theta.$$

From the final equation it is easily found that to obtain the required change of signal strength with a bearing error of 1°, the area-turns of the auxiliary coil must be 9·8 times that of the main coil, for 2°, 4·9, and so on.

46. Let us consider the conditions which prevailed at the time this system was in general use, namely the reception of spark or I.C.W. signals with little or no regenerative amplification. The detection process then approximates to square-law rectification and a change of 3 db. would be obtained if the ratio $\left(\frac{e_1}{e_2}\right)^2$ were equal to $\sqrt{2}$., i.e. if $\frac{e_1}{e_2} = \sqrt[4]{2}. = 1.19.$

Repeating the above calculation it then appears that $\frac{A_a N_a}{A_m N_m} = \frac{\cdot 19}{2 \cdot 1} \cot\theta = \cdot 087 \cot\theta.$ For a discrimination within 1°, the ratio of auxiliary to main area-turns is then only 5, while a ratio of 2·5 gives a discrimination within 2°. In practice, ratios of from 2·5 to 6 were used for reception under the latter conditions. The system has fallen out of use owing to the large ratio required under modern conditions of reception. As the ratio is increased the system approaches more nearly to a simple frame aerial operated upon the minimum method, the so-called "main coil" merely contributing a small "displacement" component. Another disadvantage attending an increase in the size of the auxiliary coil is the difficulty of preserving a suitable ratio of inductance to minimum capacitance, in order to cover the desired frequency range. Finally, the adoption of all-metal construction precludes the use of wing coils, for which the system was originally designed.

The radio compass

47. The radio compass is intended chiefly for use in homing, and is a modification of the Robinson system. A simple form is illustrated in fig. 25a. The loop aerial is usually fitted in a suitable streamlined housing, in such a manner as to give minimum signal when the machine is flying towards the transmitter. The loop is wound in two equal sections, the electrical centre being connected to the common filament connections of the valves T_1, T_2, to the grids of which the outer ends of the two loops are also connected ; a mean grid bias is established by the grid

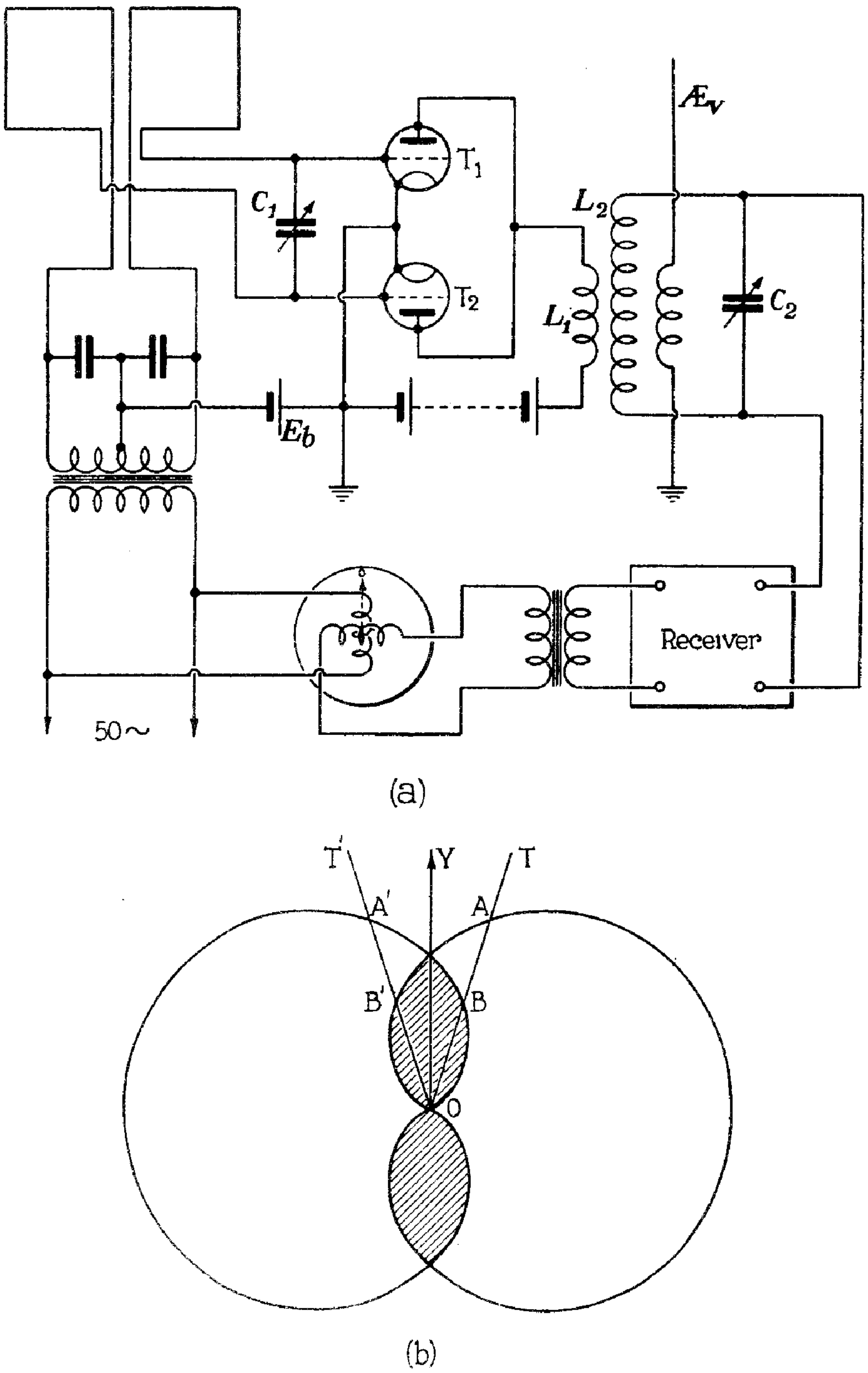


FIG. 25, CHAP. XVI.—Principle of radio compass (fixed loop type).

battery E_b, this voltage being just sufficient to reduce both anode currents to zero. In addition to the steady bias, a 50-cycle alternating voltage is applied to the grids so that they are made alternately more or less negative, and each valve will pass anode current only under the latter condition. As the anodes of the two valves are in parallel, only the one having the less negative bias is operative at any given instant, and this valve supplies a radio frequency current to the coil L_1; consequently this current suffers an abrupt reversal in phase one hundred times per second, i.e. at each half-cycle of the alternating bias frequency, and the induced E.M.F. in the tuned secondary circuit L_2 C_2 will suffer a like reversal. This circuit is also coupled to a vertical aerial $Æ_v$ which supplies an E.M.F. to the circuit L_2 C_2, in phase or in anti-phase with that due to the loop aerial, according to which of the two valves is passing anode current. It will be observed that the algebraic sum of the loop and vertical E.M.F.s will give rise to a cardioid diagram, which however changes its orientation abruptly every half-cycle of the biasing frequency, (fig. 25b). The rectified current from the W/T receiver is supplied to the moving coil of a small dynamometer instrument, the fixed coil of which is synchronously energized at the bias frequency. Referring to fig. 25b, suppose the transmitter to be in the direction T, then the current in the moving coil of the dynamometer will be proportional to O A − O B, and the pointer will be deflected accordingly, while if the transmitter is in the direction T′ the current will be proportional to O B′ − O A′, and will be in the reverse direction. If however the transmitter is situated at Y, the current in the moving coil will be zero and the pointer undeflected. When flying approximately toward the transmitter, the application of right rudder causes the pointer to deflect to the right and vice versa, while if flying away from the transmitter, right rudder gives left deflection of the pointer. In practice therefore the 180° ambiguity is easily resolved.

48. A radio compass operating upon an entirely different principle is shown diagrammatically in fig. 26. This type consists of a small screened loop which is mounted in a suitable streamlined housing above the structure of the aeroplane, and is rotated at a constant speed of 300 r.p.m. by a small electric motor. The loop is connected by slip rings to the input circuit of an amplifier. If

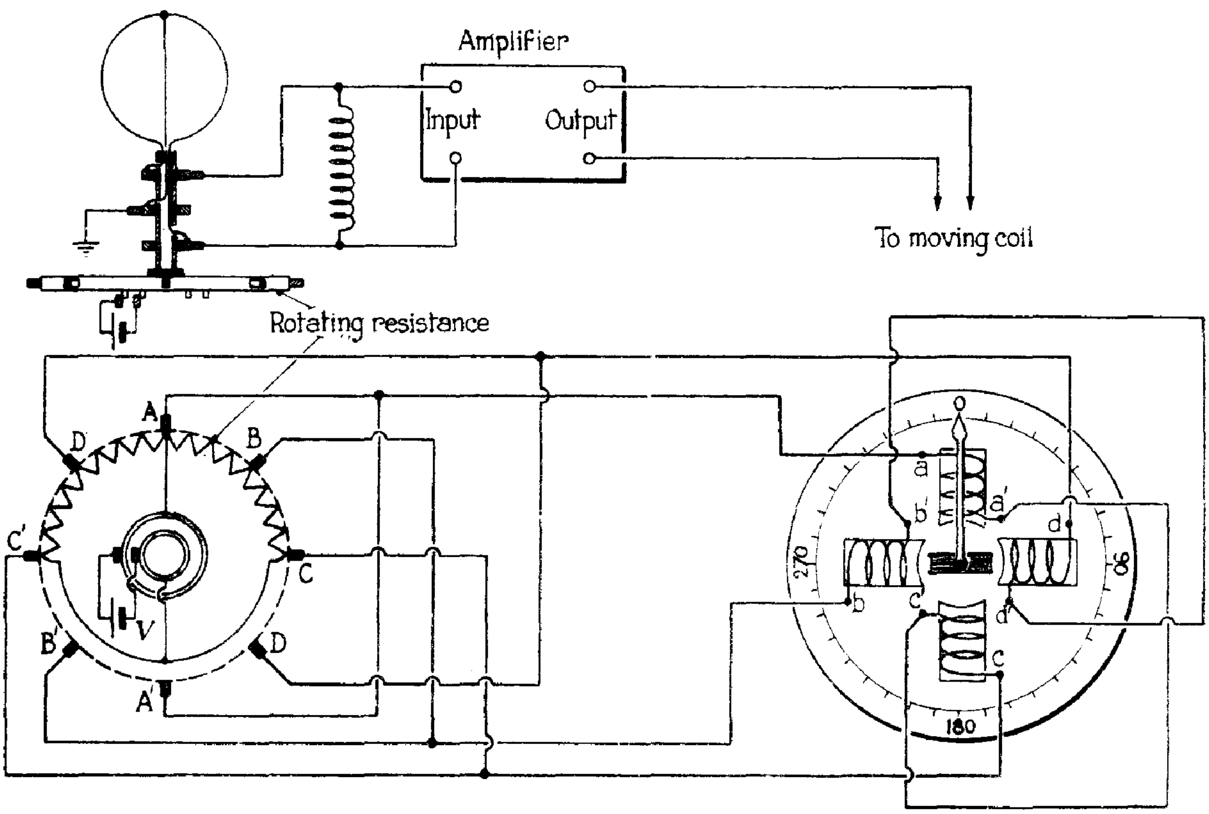


FIG. 26, CHAP. XVI.—Radio compass (revolving loop type).

a continuous wave of constant amplitude is received, the input to, and therefore the output of, the amplifier will vary according to the relative position of the loop with reference to the direction of the transmitter. To all intents and purposes, the output of the amplifier is an alternating current having a frequency of 10 cycles per second. This output current is caused to give an indication of the bearing of the transmitter in the following manner. The rotating spindle of the loop also carries on its lower extremity a semi-circular resistance, wound upon a circular former which rotates with the loop. This resistance is supplied with direct current from a source of constant E.M.F., and eight brushes are arranged at equal intervals round the former, opposite brushes being directly inter-connected, as shown in the diagram. The pairs A A′, C C′ form the terminals of one pair of supply leads and the pairs B B′, D D′ the terminals of another pair of supply leads for the bearing indicator. The latter is a particular form of dynamometer instrument.

49. Referring to the diagram it is seen that when the resistance is in the position shown, the brush A is V volts positive with respect to the brushes C, C′, and a current will flow in the fixed coils a a′ c c′ of the indicator from a to c′. The brushes B and D′ are at the same potential and no current flows in the fixed coils b b′ d d′ of the indicator. One-eighth of a revolution later, however, brush B is at a potential of V volts above that of the brushes D D′, while the brushes A and C are at equal potential. After one-quarter of a revolution, the brush C is at a potential of V volts above that of the brushes A A′, while the brushes B and D are at equal potential. Tracing a complete revolution of the resistance in this way it will be seen that the arrangement is in effect a two-phase generator. The fixed coils a a′ c c′ and b b′ d d′ of the indicator each carry an alternating current at a frequency of 10 cycles per second (two cycles per revolution), but the respective currents are in quadrature with each other. These currents therefore set up a rotating field in the air gap in which the moving coil of the dynamometer is situated. This field rotates in space 10 times per second.

50. The moving coil carries the output current of the amplifier, and during the reception of a wave of constant amplitude, from a fixed direction with reference to the aeroplane, the current in the moving coil will reach a maximum when the loop is pointing toward or away from the transmitter. At this moment, then, the total flux in the air gap will have its greatest possible value. The coil tends to turn to the position in which it is threaded by the greatest possible flux, and therefore takes up a position depending upon the direction of the distant transmitter. The coil is fitted with a pointer which indicates the direction of the transmitter upon a fixed scale graduated in degrees with reference to the fore-and-aft line, subject to an 180° ambiguity. The bearing indicator is lined up with the two-phase current generator by shifting the latter upon its spindle until correct bearings are obtained from a known transmitter. It is, however, necessary to apply a quadrantal correction, after calibrating, in the same manner as with the simple rotating loop. This correction is usually applied by means of a cam incorporated in the driving mechanism of the loop.

51. In the present stage of development all visual-indicating radio compasses suffer from the great disadvantage that they cannot completely discriminate between the wanted signal and that from a station on the same or an adjacent frequency, but on a different bearing. When such interference is present the instrument may either integrate the total field and give an erroneous bearing, or may oscillate violently and indicate no bearing whatever. It must be appreciated that such interference may be present even if it gives little or no audible indication on an aural receiver, e.g. it may be within the limits of the dead space, or sufficiently different in frequency to give a heterodyne beat above the audible limit. These instruments function best on a wave of constant amplitude such as the unmodulated carrier of an R/T transmitter, but are very erratic when the transmitter is deeply modulated or key-controlled. The indications are also unreliable unless the aeroplane is in perfectly steady flight.

GROUND STATION D/F

Bellini-Tosi system

52. It has already been shown that in all practical cases, i.e. when the width d of a loop aerial is small compared with the wave-length, the resultant loop E.M.F. is very much smaller than that set up in a vertical wire having a height equal to the actual height h of the loop. In order to obtain appreciable pick-up, we may increase the area of the loop, or the number of turns, or both, but practical limitations arise as follows. (i) An increase either in area or in the number of turns increases the inductance of the loop and therefore affects the frequency coverage. (ii) An increase in the number of turns increases the vertical and displacement effects, according to the manner of winding. (iii) An increase in the area necessitates a corresponding increase in the inertia of the frame, and it becomes too unwieldy for the rapid swinging necessary to obtain a bearing by the minimum method. Again, if an attempt is made to increase the effective operational range of a small frame aerial by additional radio-frequency amplification, a limit is imposed by the increased noise level. The Bellini-Tosi system was originally developed in order to overcome the above limitations.

53. The Bellini-Tosi direction-finder employs a system of fixed loop aerials in conjunction with a device known as a radio-goniometer. The principle of this instrument is shown in fig. 27; it consists of two small frame coils mounted rigidly at right angles to each other. These are called the fixed coils. A smaller coil, called the search coil, is mounted upon a spindle passing through the axis of symmetry of the fixed coils. The ends of this winding are connected to the receiver proper, while the ends of the fixed coils are connected to the loop aerials as described below. The whole assembly is completely screened by enclosure in a copper-lined box or compartment. A bearing plate is provided, and the spindle of the search coil carries a pointer which shows the angle at which the search coil is set with reference to one of the two fixed coils. The term " goniometer " means " angle-measurer." As the fixed coils are perpendicular to each other, the mutual inductance between them is zero, while the mutual inductance between either of the fixed coils and the search coil is variable, according to the angle at which the latter is set.

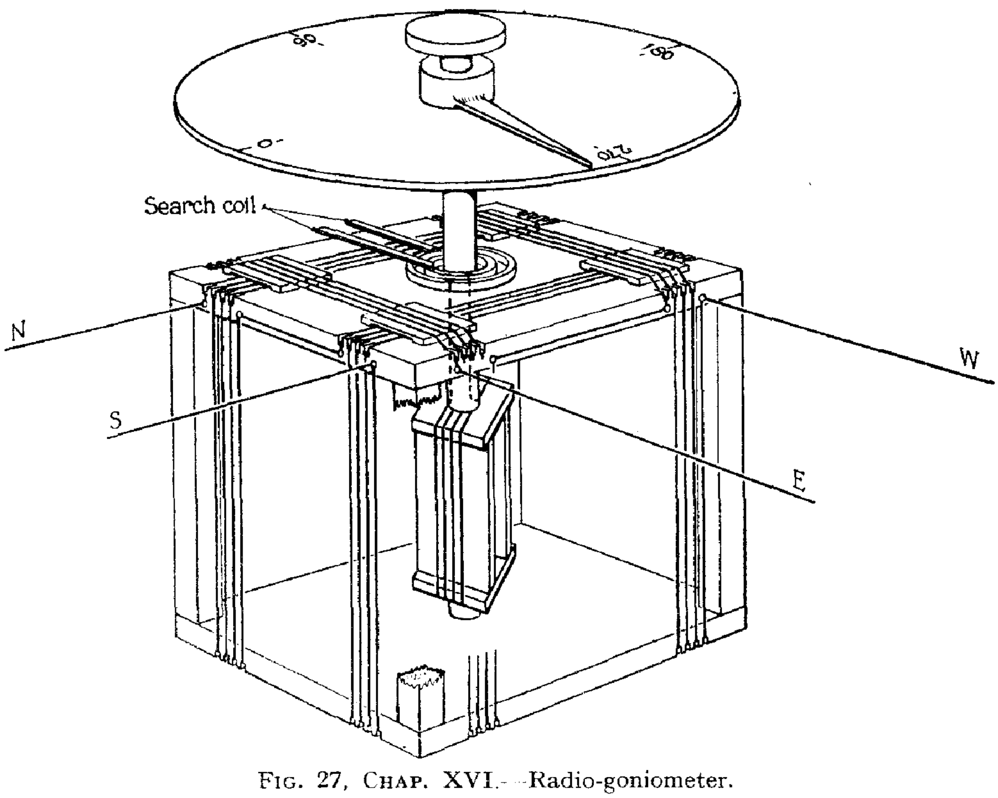


FIG. 27, CHAP. XVI.—Radio-goniometer.

54. The aerials of the Bellini-Tosi direction-finder consist of two vertical loops of wire. As a rule one is erected with its plane in the North and South (true) meridian, and the other perpendicular thereto, about a common axis. They may be of any shape and size, but are often triangular in order that they may be supported by a single tall mast together with four shorter ones. For theoretical purposes we may suppose them to be of equal size and rectangular in shape, the connections to the radio-goniometer being shown diagrammatically in fig. 28. The aerial N S is connected to one fixed coil N'S' and the aerial E W to the other fixed coil E'W'.

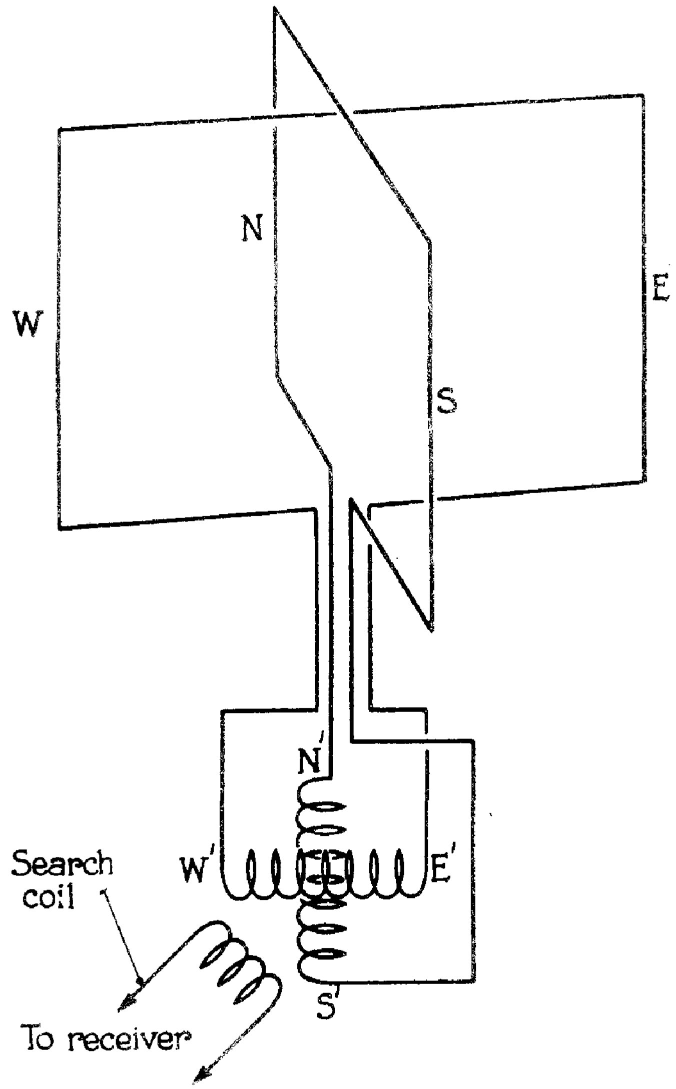


FIG. 28, CHAP. XVI.—Bellini-Tosi D/F.

As already stated the search coil is connected to the W/T receiver, suitable tuned, coupled circuits being generally employed. The loop aerials and radio-goniometer are shown in sectional plan in fig. 29. Suppose an electro-magnetic wave to arrive at the aerial system from a transmitter situated due north (fig. 29a); a resultant E.M.F. will then be set up in the loop N S. A corresponding current will flow in the loop itself and in the fixed coil N'S' connected to it, setting up an alternating flux in and around the coil. The directions of the current and flux at a particular instant are indicated in the conventional manner in the diagram. No E.M.F. will however be set up in the loop E W, and the fixed coil E' W' establishes no flux. If the search coil is rotated, therefore, the signal strength will be a maximum when it is in the position shown, for the flux-linkage is then maximum. On the other hand, if the axis of the search coil is perpendicular to the flux, the induced E.M.F. will be zero.

55. Fig. 29b shows the conditions which arise when the transmitter is situated to the north-east. The wave now reaches the sides N and E of the two loops simultaneously, and after a very short interval, the sides S and W. The direction of current in each loop circuit at a given instant is again indicated conventionally. As the two circuits are assumed to be electrically similar,

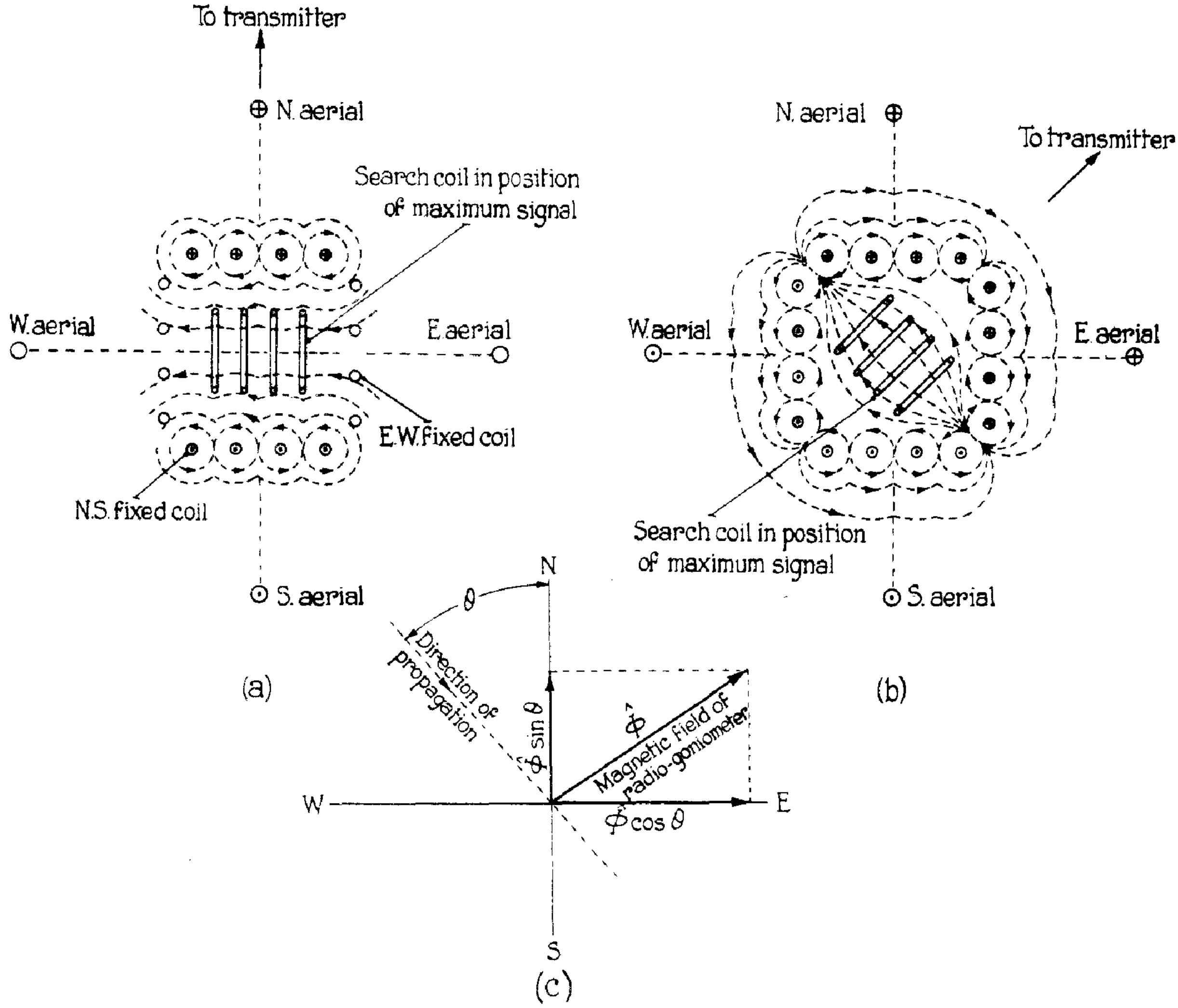


FIG. 29, CHAP. XVI.—Action of radio-goniometer.

the currents in the coils N′ S′, E′ W′ are equal and give rise to equal magnetic fluxes. These fluxes combine in such a manner that the resultant flux is in a diagonal direction. In the diagram, the search coil is in the position of maximum flux-linkage. In both the cases illustrated, then, a pointer mounted on the spindle of the search coil, parallel to the turns of the winding, would indicate the direction of the transmitter by the maximum method. It will also be noted that provided the connections between loops and fixed coils are correctly made, and a bearing plate rigidly attached to the fixed coils, the radio-goniometer itself may be placed in any convenient position without affecting the accuracy.

56. Having dealt with the principle physically, let us suppose a vertically polarized electric field $\gamma = \hat{\Gamma} \sin \omega t$ to be incident upon the aerial system at an angle θ, reckoned from true north. From paragraph 6, the resultant E.M.F. in the loop N S is

$$e_{NS} = \frac{2\pi A \hat{\Gamma}}{\lambda} \cos \theta \cos \omega t$$

and in the loop E W

$$e_{EW} = \frac{2\pi A \hat{\Gamma}}{\lambda} \sin \theta \cos \omega t.$$

Let each loop and search coil have a total impedance Z ; the currents will then be

$$i_{NS} = \frac{e_{NS}}{Z}$$

$$i_{EW} = \frac{e_{EW}}{Z}.$$

For simplicity, we may assume that the resistance of each circuit is negligible compared to its inductive reactance. We then have

$$i_{NS} = \frac{2\pi A \hat{\Gamma}}{\lambda \omega L} \cos \theta \cos \left(\omega t - \frac{\pi}{2} \right)$$

since

$$\lambda = \frac{c}{f} = \frac{2\pi c}{\omega}$$

$$i_{NS} = \frac{A \hat{\Gamma}}{cL} \cos \theta \cos \left(\omega t - \frac{\pi}{2} \right)$$

and similarly

$$i_{EW} = \frac{A \hat{\Gamma}}{cL} \sin \theta \cos \left(\omega t - \frac{\pi}{2} \right).$$

The magnitude of the current in each fixed coil is therefore independent of frequency. Each current will set up a flux proportional to the current and to the number of turns on the fixed coil. These fluxes may be written

$$\varphi_{NS} = \hat{\Phi} \cos \theta \cos \left(\omega t - \frac{\pi}{2} \right)$$

$$\varphi_{EW} = \hat{\Phi} \sin \theta \cos \left(\omega t - \frac{\pi}{2} \right)$$

and are shown vectorially in fig. 29c. The magnitude of the resultant flux is

$$\sqrt{[\hat{\Phi}^2 \cos^2 \theta + \hat{\Phi}^2 \sin^2 \theta]} = \hat{\Phi},$$

and is therefore independent of the direction of incidence of the wave. The direction of this flux is such that it makes an angle θ with a plane perpendicular to the turns of the fixed coil N'S', and maximum E.M.F. will be induced in the search coil when it links with the greatest flux. On the other hand, when the search coil is so orientated that it links with no flux at all, no E.M.F. will be induced in it, and therefore, as the coil is rotated, the signals in the telephone receivers are found to indicate two maxima and two minima, spaced alternately 90° apart, just as is found with the rotating frame aerial. To a near approximation, the polar diagram of the arrangement is a figure-of-eight pattern, and in practice, the bearing is always obtained by observation of the two minima.

57. The earliest form of the Bellini-Tosi system made use of two vertical loops each of which was separately tuned to the desired signal, and the search coil was small compared to the fixed coils, in order that it should rotate in a very uniform portion of the field. This arrangement

was very difficult to maintain in working order and was superseded by the aperiodic loop system which is substantially that described in the preceeding paragraph. In this form of apparatus the radio-goniometer is so constructed that the coupling between the search and fixed coils is as tight as possible. The search coil then forms part of an intermediate or link circuit between the fixed coils and the tuned circuit forming the input to the receiver proper. The coupling at the latter point is usually by means of a shielded radio-frequency transformer (*see* paragraph 20) in order to prevent electro-static coupling between the receiver and the aerials and so eliminate any vertical error due to the receiver itself. The link circuit is usually aperiodic but in some installations it is tuned. The tightly-coupled search coil gives rise to an error due to the fact that the field in which it rotates is far from uniform. The error is a maximum (of the order of 2°) at about 22·5°, 67·5°, 112·5° and so on ; as there are eight points of maximum error in the 360° it is called octantal error. It is practically eliminated by suitable design of the search coil, one method being to place a second winding on the search coil in series with the first, the two windings making an angle of approximately 45°

58. Apart from errors due to the development of a faulty connection or the like, the most likely errors to be found in the Bellini-Tosi aperiodic aerial system are :

(i) mutual inductance between aerials,

(ii) vertical error.

The presence of mutual inductance between the aerials may be detected by disconnecting one aerial from the radio-goniometer and energizing it by coupling to a perfectly-screened oscillator. If the aerials are truly perpendicular to each other, the oscillator radiation will not be detectable in the receiver, which is still coupled to the unenergized aerial by the radio-goniometer. Once the aerials are correctly set up, it is most important that their position should be maintained, and it is necessary to pull the wires very taut during erection in order to prevent swaying. Each aerial is tested independently for vertical error by disconnecting the other from the radio-goniometer and then observing whether the two minima of a distant transmitter are 180° apart, as well as reasonably sharp. The two sides of each aerial must be perfectly symmetrical with respect to earth. The lower, approximately horizontal portions are generally to be first suspected, in the event of vertical error due to aerial asymmetry, because these have the greatest capacitance to earth. Instrumental vertical is eliminated by the employment of shielded transformers for coupling purposes, and by earthing the midpoint of each fixed coil of the radio-goniometer (cf. paragraph 19).

Comparison between rotating loop and Bellini-Tosi systems

59. It must be understood that since the fixed aerials and radio-goniometer of the Bellini-Tosi system are the electrical equivalent of a rotating frame aerial, there is no question of one system giving more accurate bearings than the other. Provided it can be mounted in a suitable position, therefore, the rotating coil has the advantage of simplicity. An electrical defect, such as a badly soldered connection, may result in weak signals, or even to no signals at all, but will rarely give rise to an erroneous bearing. In the Bellini-Tosi system, the two aerial circuits must be perfectly balanced, and the sudden occurrence of a fault in one circuit may cause an error of 90° in the apparent bearing. The Bellini-Tosi type of D/F aerial has, in recent years, been largely supplanted by spaced open aerials, in order to reduce errors due to abnormally polarized waves.

POLARIZATION ERROR

60. Hitherto, it has been assumed that the electro-magnetic wave is incident upon the D/F aerial with normal polarization. If the wave travels for an appreciable distance over the surface of the earth before reaching the receiving aerial, this must be the case (Chapter XIV). The incident wave may however be abnormally polarized (i) when it is transmitted from an aeroplane which is so near to the receiving aerial that an appreciable amount of energy is incident at an

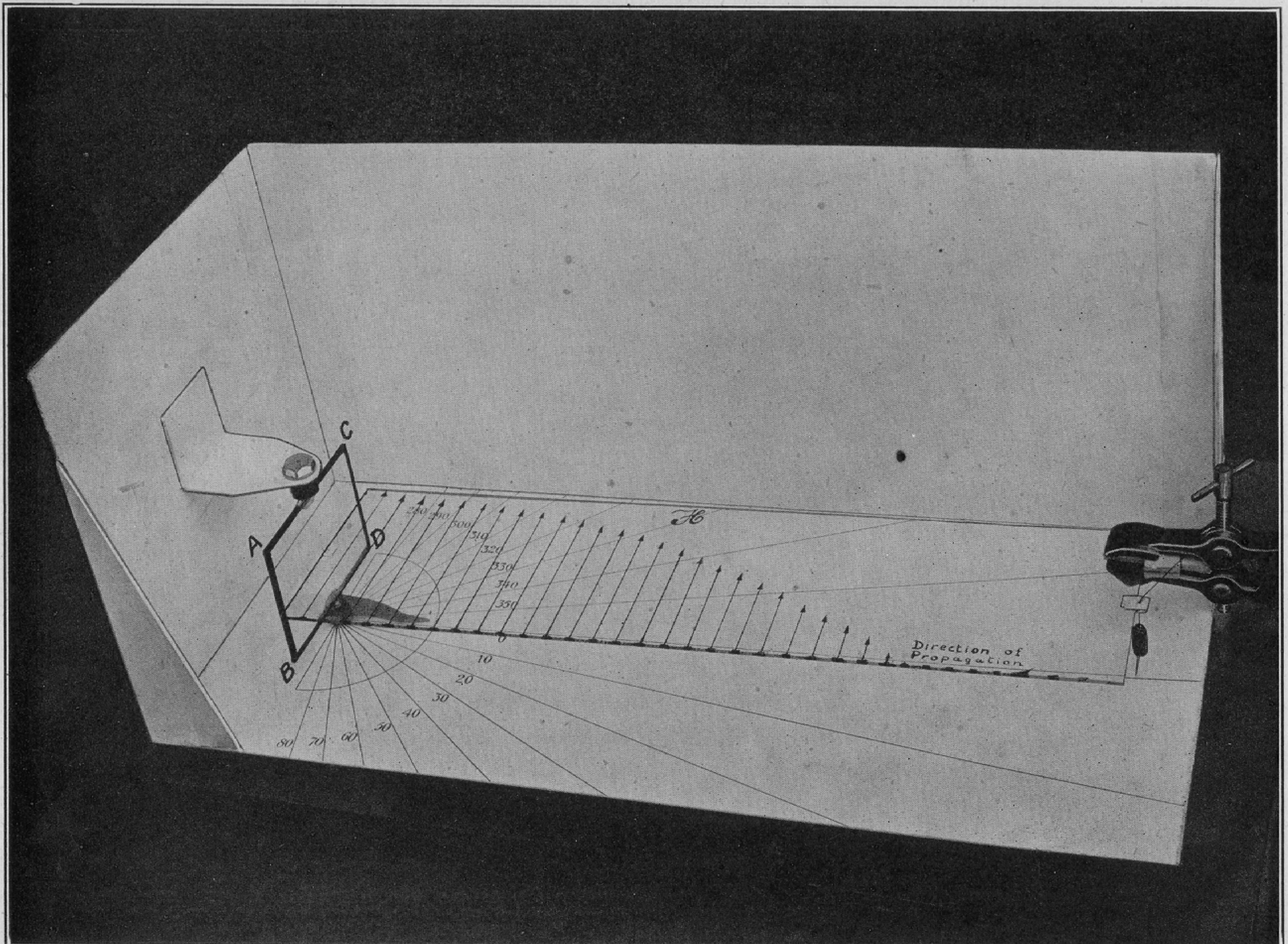


FIG. 30, CHAP. XVI.—Minimum when wave is normally polarized.

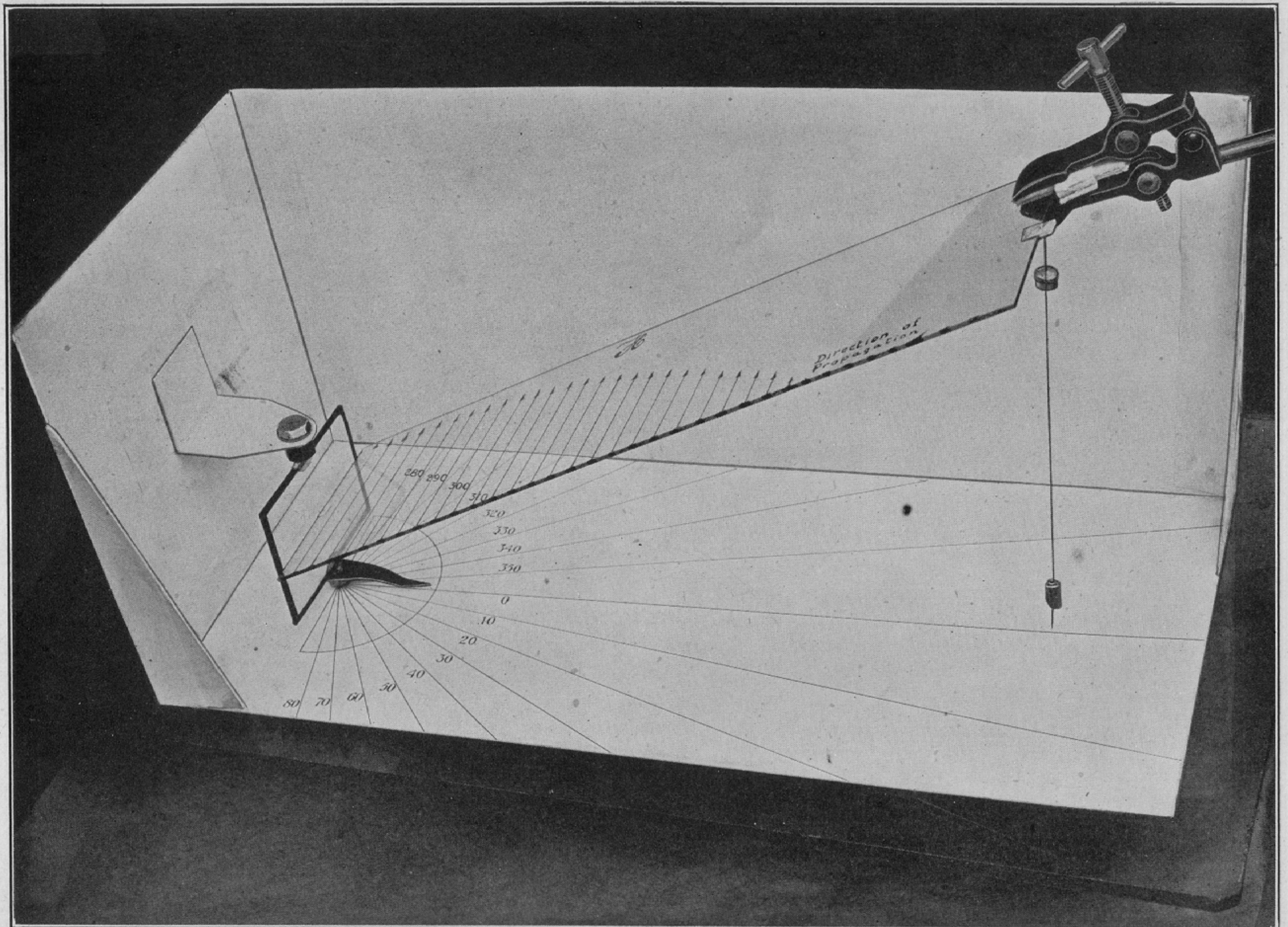


FIG. 31, CHAP. XVI.—Minimum with normally polarized down-coming wave.

angle to the horizontal or (ii) when it reaches the receiver by reflection from the ionosphere. The effects are the same in either case and are as follow :—

(*a*) The minima may be blurred.

(*b*) The minima may be sharp, but successive bearings of a stationary transmitter are not in agreement. The apparent bearing may vary during the time it is being obtained.

(*c*) It may be impossible to observe any minima.

In the following discussion, abnormally polarized waves are discussed with reference to a rotating loop aerial on the ground, but the deductions are equally applicable to rotating loop aerials in aircraft and to fixed loop aerials used in conjunction with a radio-goniometer.

61. The action of waves which are incident upon the loop aerial at an angle to the horizontal —which may for brevity be called " downcoming waves "—is more easily understood if we consider the wave to induce an E.M.F. by virtue of the velocity of its magnetic field, and may be illustrated in a conventional manner by the model shown in succeeding figures. In this model, the loop aerial has vertical sides A B, C D, and horizontal sides A C, B D ; it is capable of rotation about a vertical axis and is mounted over a bearing plate. For simplicity the transmitter is supposed to be situated due north (0°) of the loop. A pointer is fitted indicating the apparent bearing of the transmitter (or its reciprocal) when the loop is in the position giving the minimum signal.

62. In the first diagram, fig. 30, the wave is arriving in parallelism with the ground, and is normally polarized. The magnetic flux of the wave will induce an E.M.F. in each of the vertical wires A B, C D, but not in the horizontal wires A C, B D, because these are parallel to the flux. For simplicity we may confine our attention to the peak value of the flux ; if the loop is turned so that the pointer indicates, e.g. 60°, the peak value of the flux will reach the wire C D before it reaches the wire A B, and similarly for all other instantaneous values, i.e. a sinusoidal E.M.F. will be induced in each wire, but that in A B will lag behind C D. The resultant E.M.F. acting round the loop is the vector difference of these. If, however, the loop is orientated as shown in the figure, the peak value of magnetic flux links with both vertical wires simultaneously, and this is true of all other instantaneous values, hence the induced E.M.F. in A B is in phase with that in C D and the resultant E.M.F. is zero. The plane of the loop is perpendicular to the direction of the transmitter and the pointer correctly indicates the direction of the transmitter, with an ambiguity of 180°. Now consider the conditions which arise in the reception of a downcoming wave which is normally polarized, and illustrated by the model in fig. 31. The magnetic field again links only with the vertical sides of the loop, and the induced E.M.F. in A B will be in phase with that in C D when the plane of the loop is perpendicular to the bearing of the transmitter. The pointer, then, gives the correct bearing of a downcoming wave, provided it is normally polarized.

63. Since normal polarization is generally attributed to the fact that the wave is travelling over the surface of a conductive earth, there is no reason why downcoming waves should be normally polarized, whereas there are many phenomena which may cause the polarization to be abnormal, even if the wave leaves the transmitter with normal polarization. Suppose the wave to reach the loop aerial in a downward direction, and to be polarized at an angle of 90°, so that the magnetic field is in the vertical plane and the electric field horizontal. Let the loop be turned so that its plane is perpendicular to the direction, in azimuth, of the transmitter, so that the pointer gives the correct bearing. The magnetic field does not link with the vertical wires A B, C D, but links with the horizontal wires A C, B D, and although no E.M.F. is induced in the vertical wires, there is a resultant E.M.F. acting round the loop in this position. Suppose we now rotate the loop until a minimum signal is obtained ; this will occur when the loop is in the position shown in fig. 32, for in these conditions the magnetic flux does not link with any of the four wires constituting the loop. The pointer indicates the apparent bearing as 270° or 90°, i.e. there is an error of 90° in the bearing given by the minimum method.

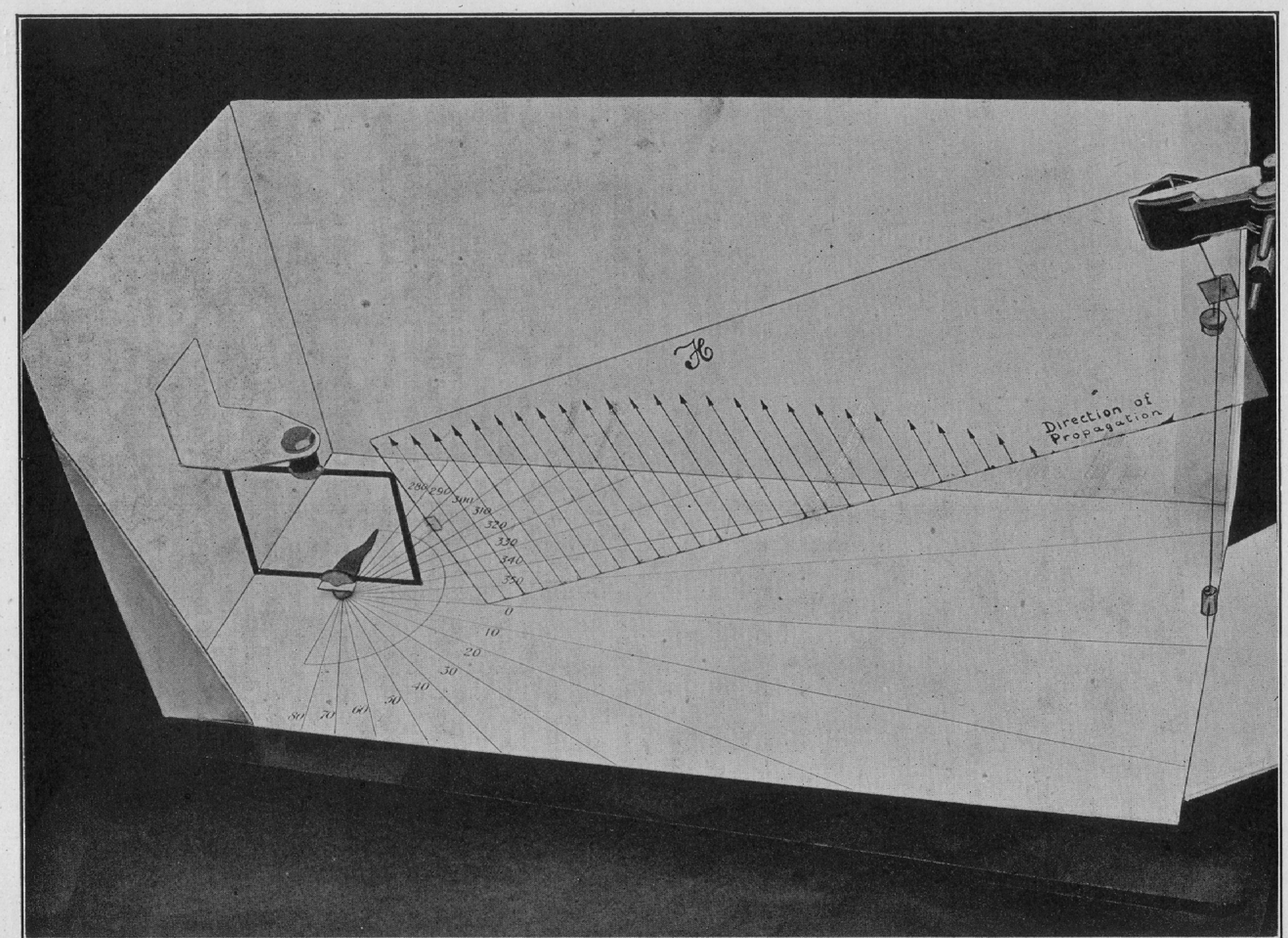


FIG. 32, CHAP. XVI.—Minimum with horizontally polarized wave.

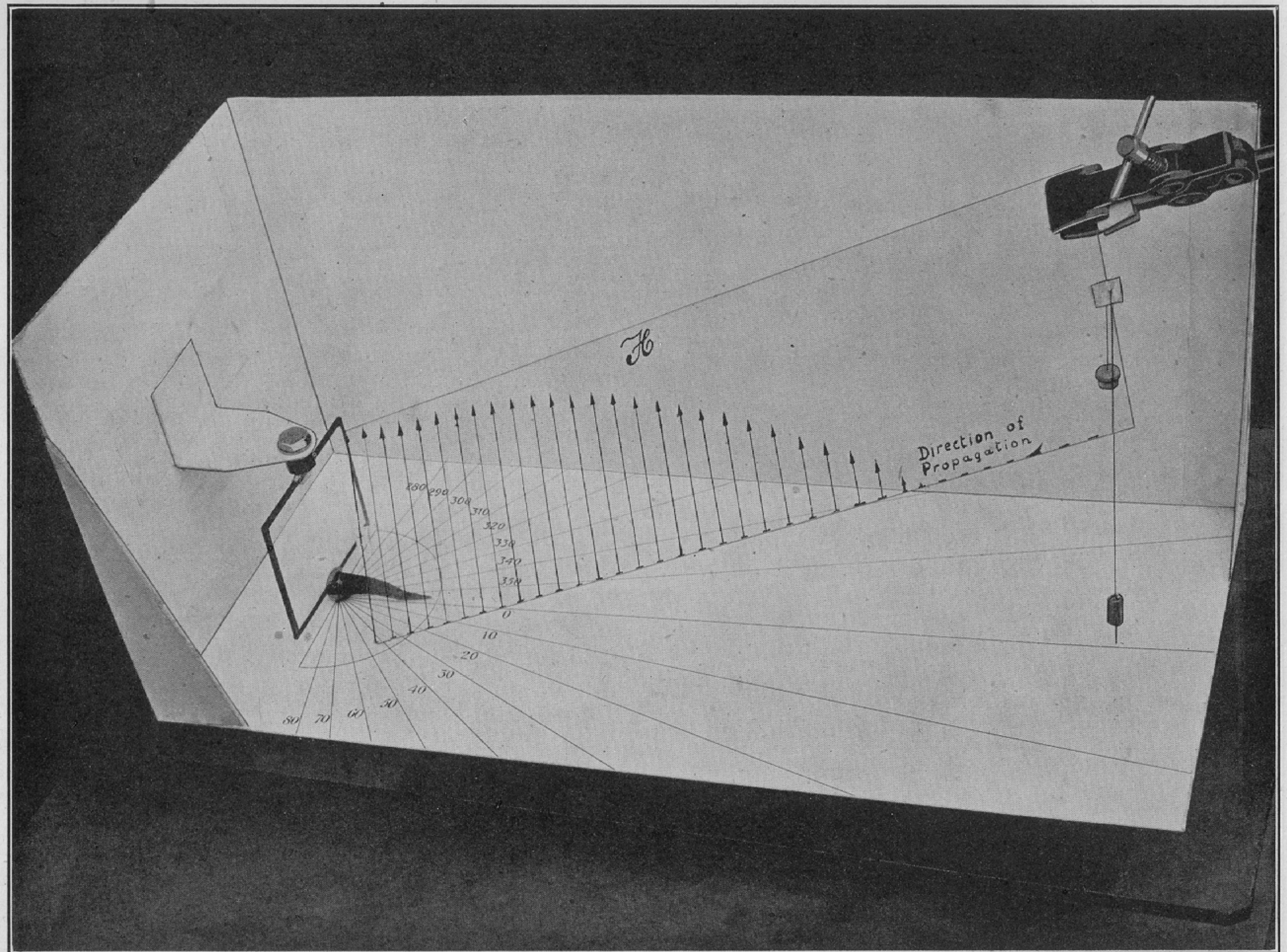


FIG. 33, CHAP. XVI.—Down-coming, abnormally polarized wave.

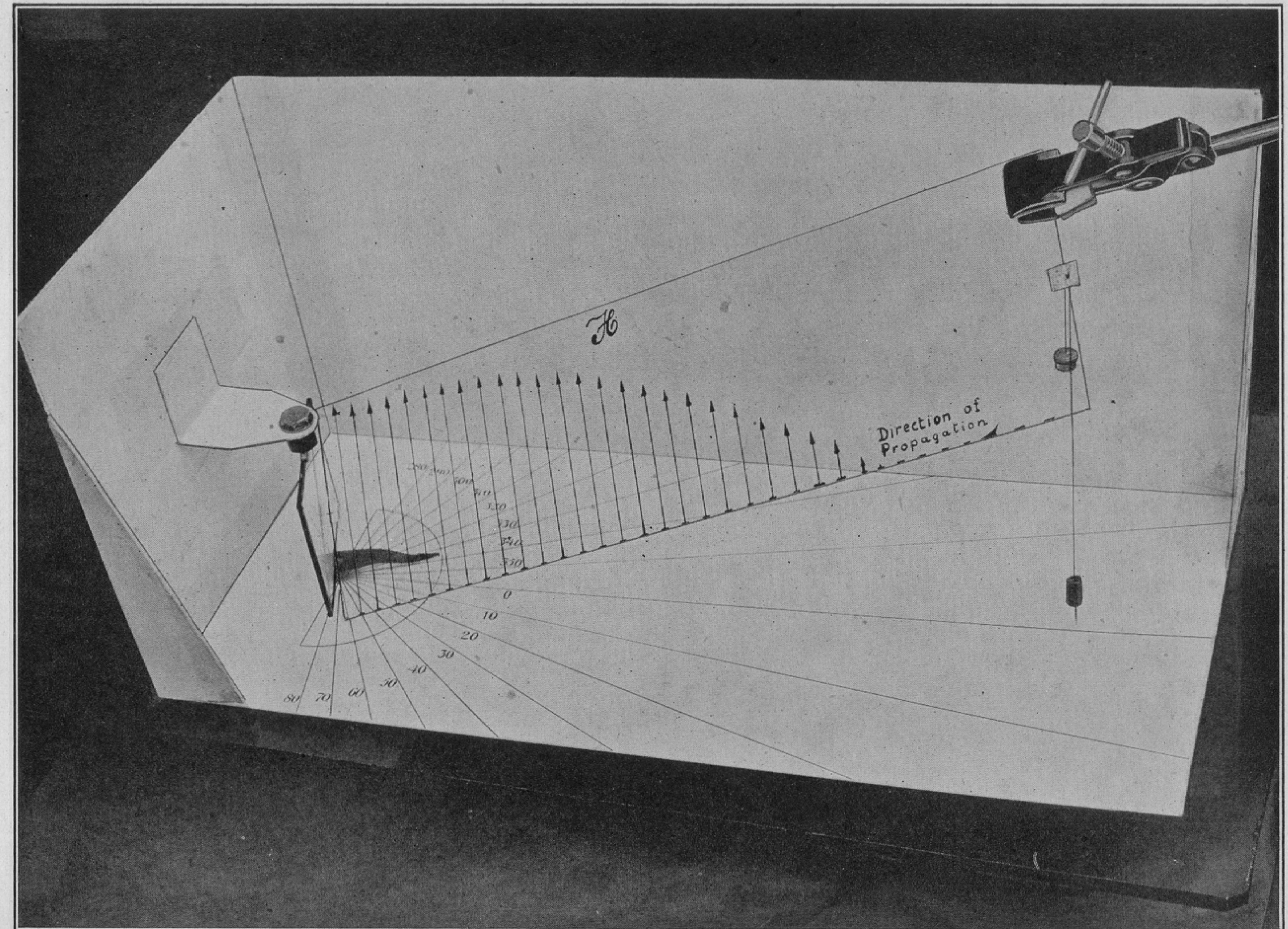


FIG. 34, CHAP. XVI.—Minimum with normally polarized, down-coming wave.

64. The most general case is illustrated in figs. 33 and 34. Here a downcoming wave is polarized at an angle of about 50°, and at the moment illustrated in fig. 33, the vertical wire C D is linking with the peak value of the magnetic flux ; the wire A B is however linking with a flux of smaller magnitude. In addition, both the upper and lower horizontal sides now link with the flux ; the E.M.F.s in these sides are not in phase with each other, for any given instantaneous value of flux links with the upper before linking with the lower wire. When the plane of the loop is perpendicular to the bearing of the transmitter, therefore, there is a resultant E.M.F. acting round the loop and minimum signal is not obtained in this position. If however the loop is rotated a position will be found (fig. 34), in which the peak magnetic flux links with all four sides simultaneously ; the two E.M.F.s in the vertical sides A B and C D are then equal in amplitude and in phase, giving zero resultant, and the E.M.F.s in the horizontal sides A C and B D are also equal in amplitude and in phase, thus also giving zero resultant, consequently the minimum signal is obtained with the loop in this position. In fig. 34 the apparent bearing of the transmitter, as found by the minimum method, is about 335° i.e. the bearing is 25° in error.

65. The foregoing photographs therefore demonstrate that if a loop aerial is rotatable about a vertical axis, it will give minimum signal when the plane of the loop is perpendicular to the position line upon which the transmitter lies, only if the wave is polarized with its magnetic field in the horizontal plane ; if the wave is polarized in any other plane, and this polarization and the angle of incidence remain constant, the loop will give sharp minima, but they will be displaced to any extent up to 90°. Since however in the case of downcoming signals there is no agency tending to maintain constant polarization, we find that plane polarized waves of this kind give minima which move round on the bearing plate, apparently indicating that the bearing of the transmitter is changing from instant to instant. Actually, of course, what is changing is the angle of polarization and possibly the angle of incidence also. It has also been tacitly assumed that the downcoming wave reaches the loop by only a single path. This is unlikely to be the case and therefore the bearing giving minimum signal for one path and angle of polarization, will give an appreciable signal owing to the energy arriving by some other path. Instead of sharp though displaced minima, we shall obtain blurred and moving minima. This is in fact the most frequent indication that abnormally polarized signals are being received. If the wave is circularly or elliptically polarized, no orientation of the loop will give a minimum signal on a constant bearing. Again, interference between waves travelling along different paths may cause fading, which may be mistaken for a minimum and give rise to an erroneous bearing.

Adcock aerial systems

66. The effect of abnormally polarized waves upon the horizontal members of a loop aerial may be eliminated by the virtual removal of these members ; this modification was first proposed by Lieutenant F. Adcock, R.E., in 1919, but its practical development occupied many years. The Adcock aerial system may be adapted for use either as the equivalent of a rotating loop, or in conjunction with a radio-goniometer. The latter form of installation is referred to as the Bellini-Tosi-Adcock direction-finder.

U type

67. The simplest form of Adcock aerial is that called the U type. This consists of two vertical aerials, fig. 35a, the lower ends of which are connected by a horizontal wire to the inductance *L*. The latter serves to couple the aerial to the receiver in the usual manner. If such an aerial were erected over perfectly conductive ground, with its horizontal member at or very near ground level, a horizontally polarized wave would have no effect whatever upon the system, but it would be acted upon by vertically polarized waves like an ordinary loop. Under certain conditions, e.g. over sea water or soil of very high conductivity, the polarization error of such an aerial may be less than that of the loop, but under ordinary conditions its performance is little better. An improvement is effected by enclosing the lower horizontal member in a screening tube earthed at the outer ends ; this type is referred to as a "screened U" (fig. 35b).

H type

68. In the elevated or H type, the vertical aerials are in the form of dipoles, the lower ends of which are clear of the ground. The horizontal leads connecting opposite members are situated at the midpoint of the dipoles and are therefore at a height above ground at least equal to one-half the total height of the aerials (fig. 35c). This system is entirely free from polarization error if it is sufficiently remote from the earth's surface, but the proximity of the ground introduces a certain degree of asymmetry, which in turn gives rise to polarization error. The reason for this is easily seen from the fact that the capacitance to earth of the lower half of each dipole is greater than that of the upper half. Unfortunately however it is not possible to compensate for this simply by shortening the lower members, for the effect of a given degree of asymmetry

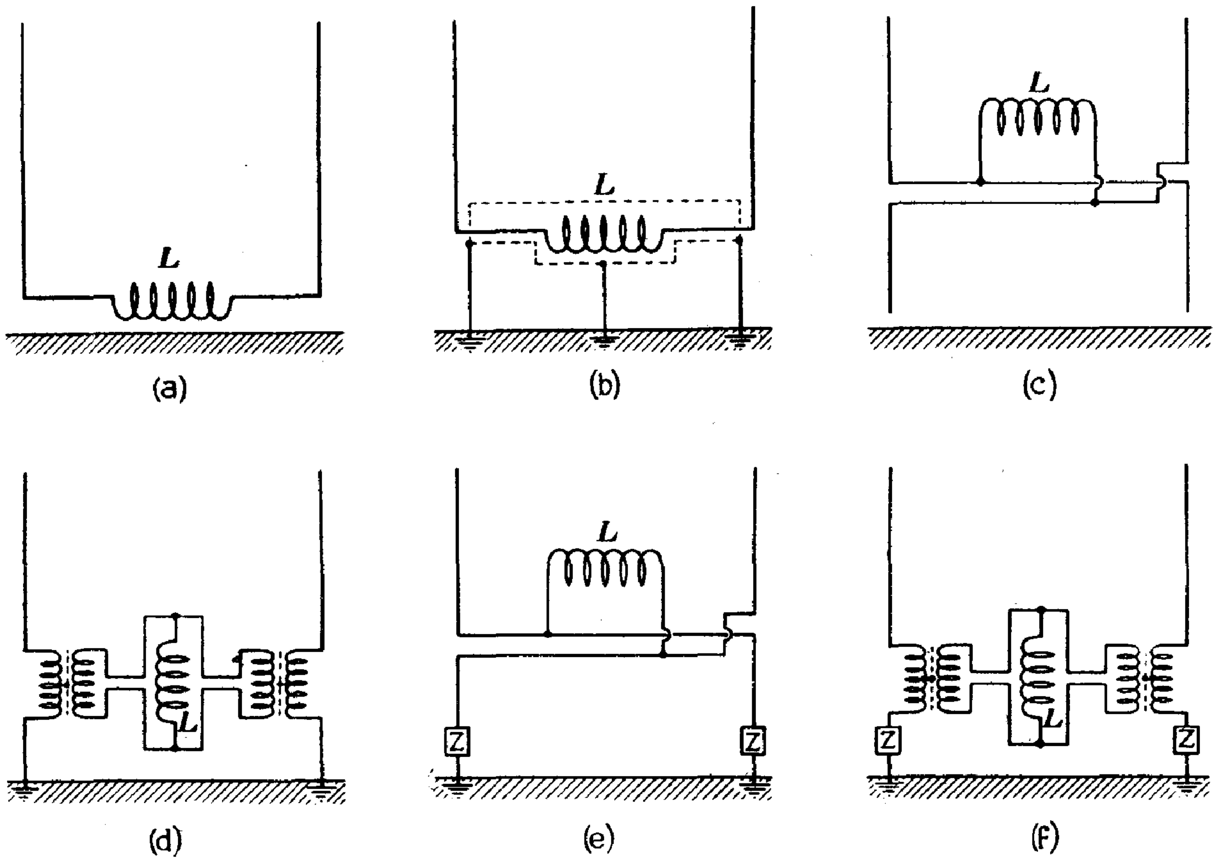


FIG. 35, CHAP. XVI.—Types of Adcock aerial.

varies with the angle of incidence of the downcoming, abnormally polarized wave. An advantage of the H type is that the polarization error is practically independent of the electrical nature of the ground.

Coupled type

69. The coupled type, shown in fig. 35d, is distinguished by the fact that there is no direct connection between the two spaced aerials forming the directional pair. This form may be made to give a very good performance on medium frequencies and is superior to those previously mentioned on high frequencies. The chief factor which allows the abnormally polarized wave to affect the receiver is the capacitance coupling between the windings of the coupling transformers and the latter are usually of the shielded type (paragraph 20). The coupled aerial is obviously ill-adapted for use as a rotating system, but there is no difficulty in using two pairs of aerials in conjunction with a radio-goniometer.

Balanced type

70. The balanced type, fig. 35e, is practically the same as the H system, except that the lower members of the aerials are shorter than the upper members, and are connected to earth through suitable impedances, which are denoted by Z in the diagram. The polarization error can be reduced to a very small magnitude by adjustment of these, but for complete elimination it would be necessary to design the system for operation on a single frequency.

Balanced coupled type

71. Fig. 35f shows a combination of the " balanced " and " coupled " systems known as the balanced-coupled system. It apears that this arrangement may be made almost free from polarization error. The performance depends to a great extent upon the correct design of the coupling transformers, and also upon the arrangement of the feeders. In this respect it is to be noted that although it would appear desirable to use buried, screened feeders, it may be found preferable to use overhead quadruple wires. This form of line is illustrated in fig. 36. Each diagonally opposite pair of wires is linked together at the ends to form one of a pair of twin transmission lines, the arrangement being practically non-radiative and therefore having negligible pick-up properties.

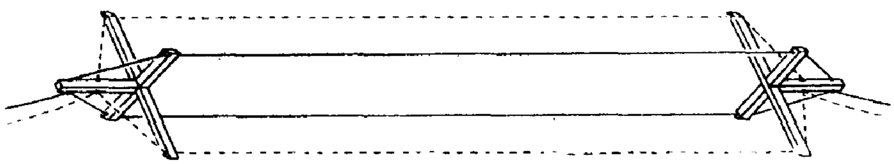


FIG. 36; CHAP. XVI.—Twin feeder for Adcock aerials.

72. In the design of an Adcock aerial the following points must be taken into consideration. First, in a rotating aerial system, it is not possible to increase the pick-up factor by increasing the number of vertical sides as in a frame aerial ; increased sensitivity can only be obtained by an increase in the area embraced by the aerial system. Second, as each aerial is an open oscillator and its height is only a fraction of a wavelength, its effective height is of the order of only one-half the actual height. Third, each pair of aerials, considered as a single unit, offers a large capacitive reactance, whereas each turn of a closed loop offers a comparatively small inductive reactance. In certain cases, the aerial capacitance is increased by using multiple wire vertical aerials instead of single wires. This also reduces the R.F. resistance and so increases the pick-up factor. The Adcock aerial system is usually coupled to a closed oscillatory circuit which is so adjusted that the P.D. across the condenser terminals is a maximum. The pick-up factor is then the ratio of the condenser P.D. to the field strength. It is found that to obtain a high pick-up factor the area embraced by the aerials should be as large as possible, subject to the limitation imposed by the necessity for keeping the fundamental frequency above the highest operating frequency. In the Bellini-Tosi-Adcock direction-finder a further limitation is imposed by the fact that if the spacing, d, between the two aerials of a pair is an appreciable fraction of a wavelength, the approximation $\sin\frac{\pi d}{\lambda} = \frac{\pi d}{\lambda}$ does not hold. The result is that an octantal error is introduced. This error is negligible if the ratio $\frac{d}{\lambda}$ is less than $0 \cdot 1$, and of the order of $1°$ if $\frac{d}{\lambda} = 0 \cdot 2$.

Selection of site for ground D/F station

73. The site for a ground D/F station should, if possible, be a flat open piece of land about half a mile in diameter, of uniform soil surface, and not near the sea. It need not be absolutely bare, rough grassland and hedges do not matter, but the site should be free from trees, buildings, streams and other objects specifically dealt with later. A site fulfilling these conditions will be practically perfect, but as a rule it will be necessary to accept one which falls short of this ideal.

The whole area under consideration may be hilly, woody, industrialized or near the sea; it is also desirable to locate the D/F station conveniently near to the remainder of the station buildings. The under-mentioned factors will contribute to the site errors.

(i) Trees and woods.
(ii) Cables and wires laid along or under the ground.
(iii) Overhead cables and wires.
(iv) Mountains, hills and cliffs.
(v) Buildings.
(vi) Roads and railways.
(vii) Rivers and streams.
(viii) Aerials and vertical conductors such as metallic poles and pylons.
(ix) Wire fences.
(x) Coastal refraction.

The following discussion on the effect of these positions on the performance of the direction finder covers the frequency range 100 to 15,000 kc/s.

74. *Trees and woods.* Large masses of trees within half a mile will probably produce considerable errors, which amount to 5 or 6 degrees. This type of error depends upon the frequency, but the rate of variation with frequency is uncertain. It must be realized that errors of such magnitude do not occur on every wooded site. It might, for example, happen that a degree of symmetry in the position of the trees around the site would render the error negligible. An error may be produced by a single tree, and a direction finder located within several yards of a tall tree may be expected to experience an error of several degrees on short waves. For example, an error exceeding nine degrees has been observed at a distance of ten yards from a tree 60 feet high; a distance of 30 yards from a single tree, however, may be considered great enough to reduce all errors to zero.

75. *Cables and wires.* It appears safe to conclude that cables and wires may be led into a D/F operating room along the ground, provided they are earthed at the point where they enter and at points less than $\frac{\lambda}{2}$ apart for a distance of 200 yards or more. In the case of screened cable, earthing implies connection of the metallic sheath to earth and in the case of an unscreened pair of wires a radio-frequency earth for each wire by means of suitable condensers. Wires should not be run on overhead poles within about 200 yards of the site, in the case of medium frequencies. For frequencies of the order of 15,000 kc/s. it may be necessary to bring the wires down 400 yards away or even more.

76. *Overhead cables and wires.* A certain amount of experimental work on long waves with small loops shows that a distance of 200 yards, from telegraph wires 10 yards high, is sufficient to reduce all errors to a negligible quantity. Overhead wires carried by tall pylons may be expected to have greater influence than telegraph wires but it is unlikely that errors will be experienced at distances greater than 400 yards. The distortion produced by the pylons themselves must also be taken into account. These constitute radiating vertical aerials. In general it may be assumed that a D/F receiver erected within 50 yards of overhead telegraph lines or within 100 yards of a high power line will be subject to very grave site error which might be as much as 10°, while at a distance of 200 yards from a high power line the error might amount to 2° or 3°. At 400 yards from high power lines the site error would probably be negligible under all circumstances.

77. *Mountains, hills and cliffs.* A site in a mountainous country is liable to a large error (exceeding 10°) as a result of reflection and bending of the waves. The same applies to hills but to a lesser degree; in hilly country it is preferable to choose a site on high rather than low ground, but a sloping hillside site should be avoided. Any sudden change of slope is liable to give errors

up to 10° on short waves, for instance, in the vicinity of a cliff, complete immunity will not be obtained unless the site is at least 10λ from the edge of the cliff. On medium frequencies a distance of 200 yards will probably ensure that the error is less than 3°. The effect produced by mountain ranges may persist into low-lying flat country situated well away from the mountains.

78. *Buildings.* A metal building is liable to cause more disturbance than one made of stone, brick or other non-conductive material, but as most large buildings contain metal work in the form of gas pipes, electric light wires, water systems, etc., it is probably desirable to consider all buildings on the same footing. If the building as a whole, or any part of it, resonates to the frequency in use, the disturbing effect may be large at a distance of many wavelengths from the building. Thus a large modern type of building may be expected to give errors of several degrees on a direction finder erected within 100 yards but would probably have negligible effect at a distance of 200 yards, except for the above-mentioned resonant effect which however would probably be negligible at distances of 500 yards or over.

79. *Roads and railways.* Ordinary stone metalled roads are not likely to give rise to site error at any frequency, but this is not the case with a modern type of concrete road which probably contains steel in the foundation. However, it is considered that roads and railways are unlikely to produce errors exceeding 5° and if over 100 yards from the site will produce no appreciable error. Electric railways may cause considerable interference with reception at greater distances than this.

80. *Rivers, streams and canals.* A small stream or brook is electrically of similar nature to the reinforced concrete road mentioned above but its conductivity is of course much smaller, and it will probably have negligible effect if it is more than 30 yards from the direction finder. A large river will produce a greater effect and it is considered undesirable to site a station within about 500 yards.

81. *Aerials and vertical conductors.* An aerial or vertical conductor may effect a direction-finder in two ways, which may be distinguished by the terms " re-radiation error " and " screening error " respectively. The first is most likely to be caused by resonating conductors at distances from the receiver large compared with the spacing of the aerial and represents a genuine re-radiated wave. The second occurs chiefly when untuned aerials or resonating vertical conductors are situated at distances comparatively near to the direction-finder. This is in the nature of a screening effect, which, acting unequally on each of the aerials, causes an unbalancing of the aerial system similar to that caused by inequality of their effective heights. To avoid these effects no vertical conductor of height comparable with that of the D/F aerial should be allowed within a distance of three times the aerial spacing, and no tuned aerial or vertical conductors in the D/F waveband should exist within six wavelengths of the D/F receiver. Lamp standards, lightning conductors and pylons all come within this category.

82. *Wire fences.* Experiments performed with a small fence in the neighbourhood of a short-wave Adcock direction-finder indicates that an insulated length of wire fence in resonance with the operating wave might produce an appreciable polarization error. The fence when well earthed had no effect. The effect of a long length of wire fencing has not been studied but the experiment makes it probable that the disturbing effect will be considerably less than would be expected and it is anticipated that a fence more than 30 yards away would have no detectable effect. As a matter of precaution however it is advisable to earth all wires on the fence at several points less than $\frac{\lambda}{2}$ apart in the vicinity of the receiver, or preferably to break all wires into sections less than $\frac{\lambda}{2}$ in length by suitable insulators.

83. *Coastal errors.* Serious errors, i.e., of the order of 5° to 10°, may exist on sites close to the sea unless the wave crosses the coast line at an angle greater than 30°. These errors are greatest for soil of low conductivity and on high frequencies, decreasing as the distance from the coast is increased. Coastal errors are unlikely to be appreciable at distances exceeding 10 miles from the

coast and may be neglected for waves making angles greater than 30° with the coast. There is no method of correcting for coastal error, and it is usual, on charts showing coastal direction-finding stations, to indicate the arc within which accurate bearings cannot be guaranteed.

Radio beacons

84. The simplest form of radio beacon is a transmitting station having an aerial system designed to give substantially uniform radiation in all directions in azimuth. The station will emit a characteristic signal, e.g. its W/T call sign, either continuously or in accordance with a prearranged time schedule, and may therefore be used by aircraft fitted with direction-finding apparatus to obtain a position line, or if sense-finding devices are installed, the bearing of the transmitter with reference to the aircraft. Other forms of beacon, such as the equi-signal and rotating loop types, are designed for the use of aircraft not fitted with D/F apparatus. Equi-signal beacons are primarily intended for homing, and are largely used in America, but not to any extent in this country. One factor which makes their adoption difficult in Europe is the absence of any frequency allocation for this purpose. In the United States the frequency band of 210–410 kc/s. is allotted solely for the air navigation and weather broadcast service.

The loop or frame aerial transmitter

85. In Chapter VII reference is made to the radiating properties of a loop aerial and these may now be discussed in greater detail. In fig. 37 A B and C D represent the two vertical sides of a rectangular loop in elevation (fig. 37a) and in sectional plan (fig. 37b). As in the receiving case, the dimensions *h* and *d* are supposed to be small, compared with the wavelength. The lower horizontal wire is assumed to be very near the ground level. If the loop is supplied with a radio-frequency current of constant amplitude in such a manner that the magnitude of the current is the same at all points, all four sides of the loop will give rise to electro-magnetic radiation, the vertical sides setting up a vertically polarized wave and the horizontal sides a horizontally polarized wave. The solid polar diagram of the loop transmitter is therefore rather complex. For simplicity, it is convenient to consider the vertically and horizontally polarized portions of the radiation field separately, and also to postulate a perfectly conductive earth. If the radiation is received at ground level by means of a vertical aerial, the latter will be affected only by the vertically polarized portion of the field.

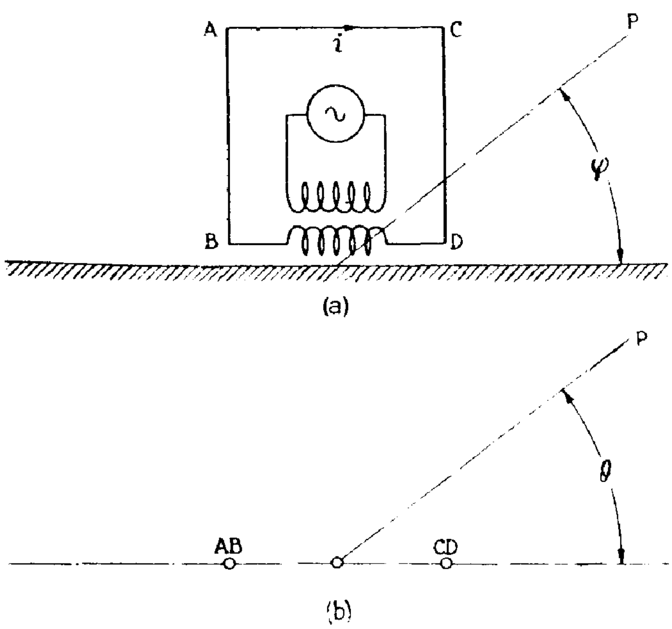


FIG. 37, CHAP. XVI.—Loop aerial transmitter.

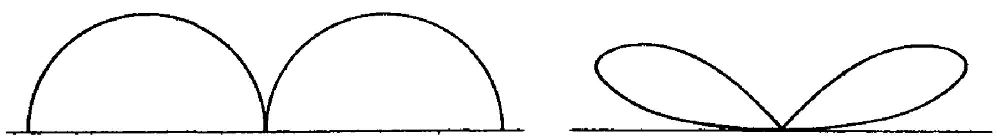
86. By methods explained in Chapter XIV it is easily seen that the horizontal polar diagram of this portion is a figure-of-eight pattern. The amplitude of the vertical field strength at any point P, making an angle θ with the line passing through the vertical sides (fig. 37b), is.

$$\hat{\Gamma}_V = \frac{240\pi h}{\lambda r} \mathcal{I} \sin \frac{\pi d \cos \theta}{\lambda}$$

$$= \frac{240\pi^2 A \mathcal{I} \cos \theta}{\lambda^2 r},$$

by making the substitutions $sin \frac{\pi d}{\lambda} \doteqdot \frac{\pi d}{\lambda}$, $A = hd$ as in previous paragraphs. The effect of the ground is here taken into account. In free space the field strength would be only one-half of that given. If the point P is situated above ground level, at an angle φ as in fig. 37a, the vertical field strength is obtained by multiplying the above expression by a Current Distribution Factor. For the present case (uniform current distribution in the aerial) the C.D. Factor is $\cos \varphi$, hence the polar diagram in the plane containing the vertical sides is as shown in fig. 38a. The effect of the finite conductivity and permittivity of the ground is to modify this diagram somewhat as shown in fig. 38b.

87. It is of interest to calculate the R.M.S. current required to obtain a given field strength at any distance from the transmitter, assuming a perfect earth. Let the area of the loop be



(a) (b)

FIG. 38, CHAP. XVI.—Vertical polar diagrams of loop transmitter.

10 square metres, the wavelength 1,000 metres ($f = 300$ kc/s). If the field strength on the ground, at a distance of 100 miles, is to be 50 microvolts per metre, (R.M.S.).

$$\Gamma = \frac{149\pi^2 A I}{\lambda^2 r}$$

where r is in miles, hence

$$I = \frac{\lambda^2 r \Gamma}{149\pi^2 A}$$

$$= \frac{(10^3)^2 \times 100 \times 50}{149\ \pi^2 \times 10 \times 1{,}000}$$

$$= 334 \text{ amperes.}$$

It is difficult to provide such a large oscillatory current as this, but if a frame aerial of four turns is employed, the required current is only 84 amperes which is still large but not impracticable. In discussing the application of a loop transmitter to direction finding, we may first consider the vertically polarized field to be the only one radiated. The horizontally polarized field must be discussed later when the possible errors are considered.

The rotating beacon

88. A rotating beacon consists of a loop transmitter, its exact location being notified to those concerned. The loop is usually rotated at a speed of one revolution per minute, this rate being maintained with a high degree of accuracy by means of a special timing mechanism. The figure-of-eight pattern of vertically polarized radiation therefore rotates in space at the same rate.

A special signal, called the north indicating signal, is emitted when the minimum of the diagram is exactly upon the meridian through the transmitter. The method of obtaining a bearing is as follows. The only apparatus required is an ordinary, (i.e. non-directional) W/T receiver, and a stop watch. An operator, listening to the signal, starts the stop watch exactly on receipt of the north indicating signal, and stops it when the figure-of-eight minimum is observed. The number of seconds indicated by the watch, when multiplied by six, gives the true bearing in degrees from north. To avoid the difficulty of correct observation of the north marking signal, when the observer is due north or south of the beacon, an east marking signal is also transmitted. This may be used in exactly the same manner as the north marking signal, but 90° must be subtracted from the calculated bearing.

89. The advantages of this method of direction-finding are :—

(i) It can be used by any aircraft fitted with a W/T receiver.

(ii) Any number of aircraft can obtain bearings simultaneously.

The disadvantages being

(iii) At least 30 seconds are required for each bearing. In this connection it should be noted that it is generally possible to make two observations during each rotation of the loop, giving the bearing and its reciprocal.

(iv) Since in practice it is desirable to take the mean of a number of observations, the process is rather slow.

(v) The loop transmitter is subject to vertical effect, which may cause the two minima to be less than 180° apart.

(vi) The bearing may be in error owing to the reception of abnormally polarized waves.

90. The general design of a rotating beacon transmitter is shown in fig. 39. The whole of the transmitter is fitted inside the loop itself, in order to avoid the necessity for feeding a large radio-frequency current by means of brushes and slip rings. Instead, only the comparatively small anode and filament currents are so carried. The oscillatory circuit is a parallel-feed Hartley. The components, and particularly the frame tuning condenser, must be carefully positioned within the frame in order to reduce the vertical effect to a minimum. The remainder of the vertical component is attributable to unequal currents in the vertical members of the loop, *i.e.* to an unequal distribution of capacitance. It is reduced to a negligible quantity by careful design, particular care being necessary to ensure exact verticality during rotation, which is more difficult than would appear superficially.

91. Let us now briefly consider the horizontally polarized radiation from the loop, assuming the lower horizontal member to be at ground level and the ground to be a perfect conductor. The polar diagrams are then exactly the same as those of a horizontal hertzian doublet of length d, situated at a height h above the ground. The exact diagrams are easily calculated by methods explained in Chapter XIV, but for the present purpose it is sufficient to say that to all intents and purposes the radiation is directed upwards, approximately in the form of an obtuse, elliptical cone. A receiver situated at ground level is therefore unaffected by the direct radiation from the horizontal members, but will be affected by the wave reflected at the ionosphere if its electric field vector has a component parallel to any portion of the receiving aerial. Since the polarization of the wave may be rotated in passing through the ionosphere it is obvious that interference may occur between the direct vertically polarized wave and the reflected wave, so that false minima (or fading which may be mistaken for minima) are likely to be observed. It can be proved that if the ionsophere has exactly the same effect on radiation from all directions, the signals received on a vertical aerial from a loop transmitter will be of the same strength and subject to the same polarization error as would be observed if the signal were transmitted by the vertical aerial with the same radiated power and frequency, and received on the loop aerial. This proposition may have an important application in the siting of a beacon transmitter, *e.g.* the suitability of a suggested site may be tested by locating a portable D/F receiver on the site and observing the systematic errors in bearing of a number of known transmitters. The practical utility of this expedient is still under investigation.

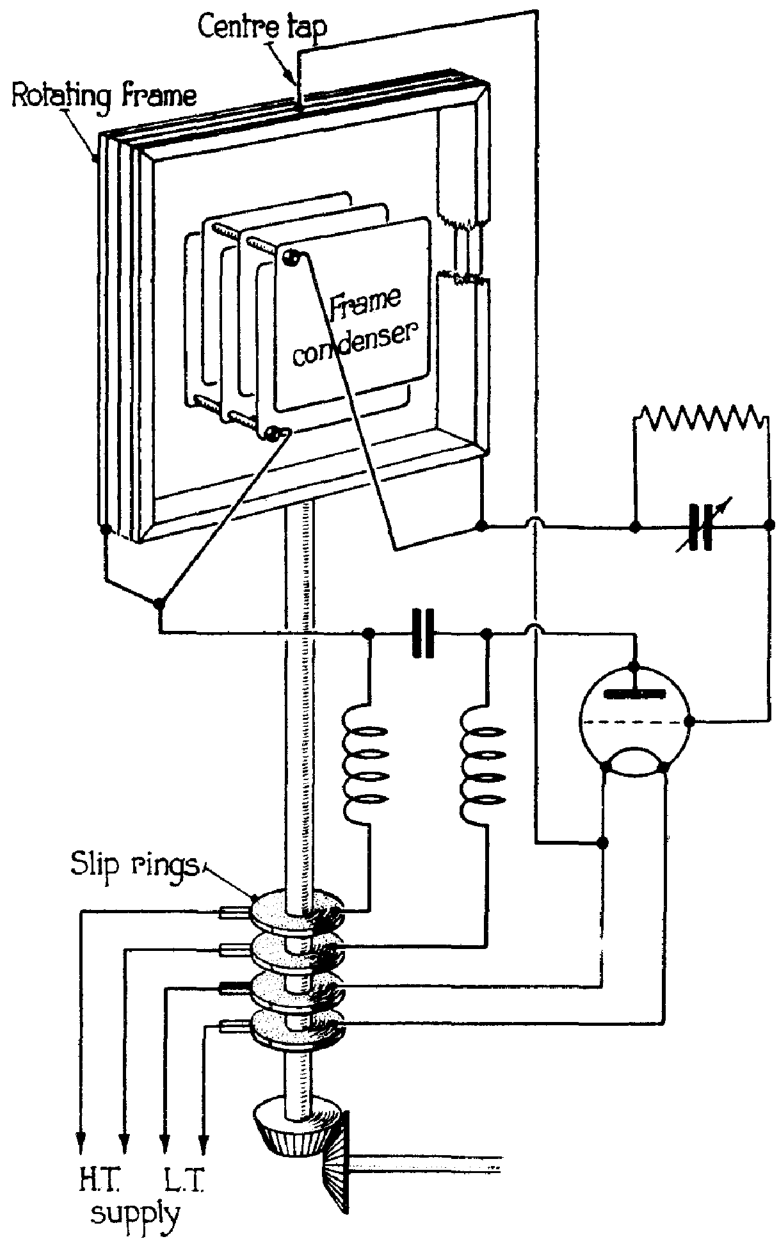


FIG. 39, CHAP. XVI.—Rotating beacon transmitter.

Course or equi-signal beacons

92. This form of beacon employs two directional aerials placed at right angles to each other. The directional aerials may take the form of large loops, say, 100 metres wide and 20 metres high, or, alternatively, an " Adcock " form may be employed. In this case the aerials consist of four vertical aerials supported by towers, 40 metres or so in height, which are placed at the corners of a square of, e.g., 100 metres side and fed from a suitable transmitter by concentric feeder lines. Each pair of diagonally opposite verticals forms one directional aerial system ; the two aerials of each pair carry currents in anti-phase so that they function in exactly the same manner as the two sides of a loop aerial, giving a figure-of-eight polar diagram. The " Adcock " arrangement reduces the polarization error to a considerable degree. The principle of operation is shown in fig. 40. The radiation from the two aerials is of equal intensity along

the lines O B, O C, O X, O Y, but elsewhere one of the waves is stronger than the other. Assuming that means are provided by which the two radiations may be distinguished, an aircraft can follow a course along the lines of equal intensity O B, O C, O X, O Y. In the aural-reception equi-signal beacon two opposite letters of the morse code are transmitted by the respective aerials, e.g. " a " by the E W aerial and " n " by the N S aerial. These symbols are interlocked so that the " elements " of one letter fall in the " spaces " of the other. When the aircraft is flying along a line of equal signal intensity, both letters are received and merge into a continuous sound, but if the aircraft is off the desired course to one side " n " is louder than " a ", and vice versa.

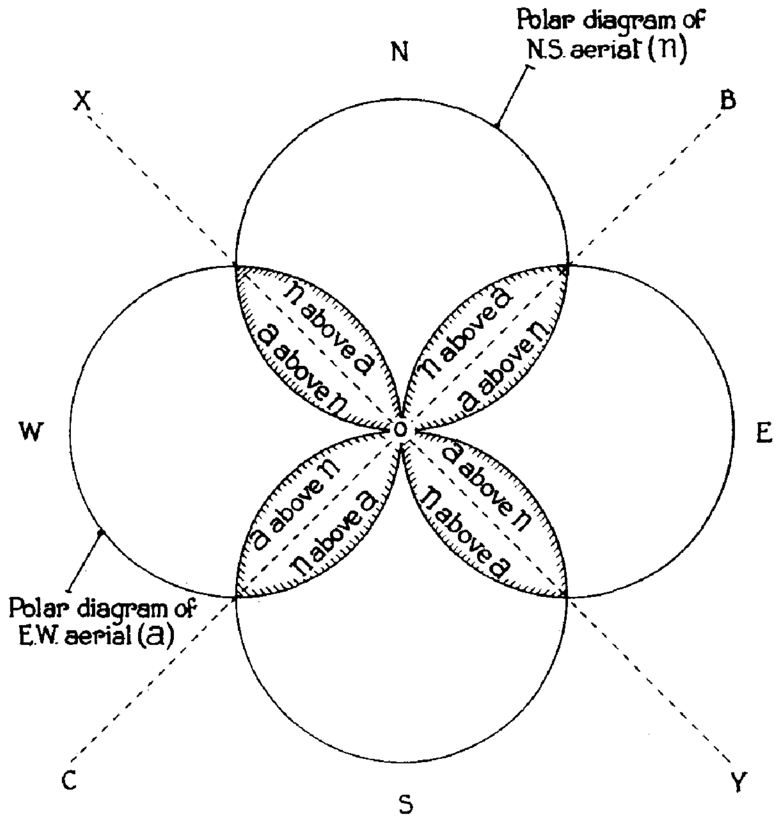


FIG. 40, CHAP. XVI.—Courses laid down by aural-type beacon.

93. Although the aerial systems are fixed in position, the double figure-of-eight radiation pattern can be rotated in azimuth in order that the routes may be marked along any convenient lines of bearing. In the aural-type beacon this is accomplished by coupling the aerial systems to the transmitter by means of a radio-goniometer, consisting of two primary and two secondary windings. The primaries are crossed at right angles, as are also the secondaries, and the angle between the two sets of coils can be varied by relative rotation, so that each primary, in conjunction with its secondary winding and associated aerial system, is in effect equivalent to a loop aerial which is capable of rotation. The coupling between the primary windings and the transmitter proper is by means of a link circuit, the keying being performed by switching from one primary to the other.

94. In the foregoing, it was assumed that the desired routes were perpendicular to each other although this may not be desirable. It is, however, possible to effect a considerable change from the 90° relationship by control of the relative phasing and magnitude of current in the two verticals comprising each aerial of an Adcock-type system, or by the use of additional vertical radiators in the case of the loop-aerial system. Only a few examples need be given to illustrate the possibilities, loop aerials being dealt with as the underlying

theory is simpler than in the case of Adcock aerials. In fig. 41a it is desired to lay down one route in the direction 330°–150° and a second in the direction 210°–30°. As these lines are symmetrical about the N S and E W bearings, the loops will have their respective maxima in the latter directions. Let O a b c represent one of the loops of the figure-of-eight pattern produced by the E W loop, the position line 330°–150° intersecting it at a. Bisect O a. The bisector intersects the line N O at P. With P as centre describe a circle of radius O P, this circle will represent one-half of the figure-of-eight pattern which must be produced by the N S aerial to mark the desired route. This pattern can be produced by reducing the loop current in the N S aerial as compared with that in the E W aerial. In fig. 41b the desired routes are not symmetrically placed with reference to the N S, E W axes. The radiation patterns are produced by the introduction of " in-phase vertical " in the E W aerial, and swung into the required directions by means of the coupling radiogoniometer.

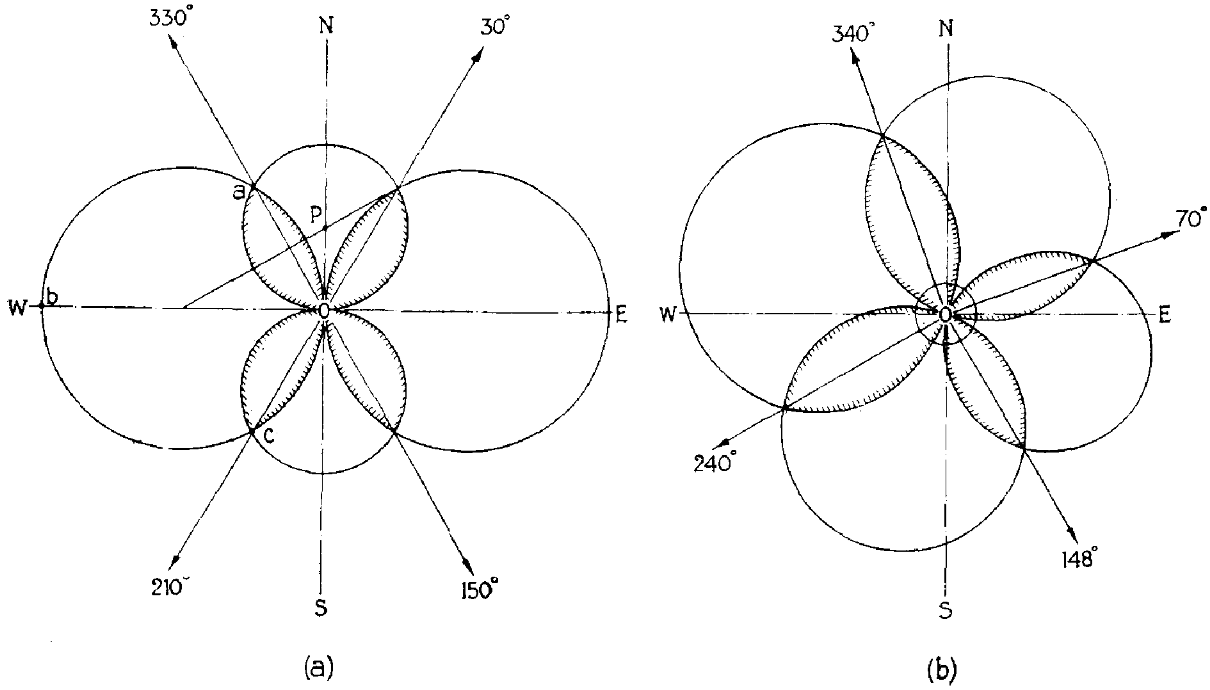


FIG. 41, CHAP. XVI.—Control of courses laid down by equi-signal beacon.

95. In certain instances, the aural-type beacon transmits interlocked " dots " to port and " dashes " to starboard of the marked route, instead of the letters " a " and " n," the dashes being about five times the duration of the dots. It is then possible to design a receiver which is capable of giving simultaneous aural and visual indications. The visual indicator is fed from the secondary of an iron-core transformer, the primary being connected in parallel with the telephones. The secondary winding supplies a voltage to the grid and filament of a triode rectifier. In the anode circuit the rectified current flows through the moving coil of a special form of centre zero instrument. The peculiar feature of this instrument is that it is most sensitive in the region of zero deflection : it is very heavily damped and therefore sluggish in response to a variation of current. The pointer is deflected to the left during the reception of dots and to the right during the reception of dashes, this effect being achieved solely by virtue of the unequal sensitivity and variation of damping at various points on the scale.

96. In the visual type beacon the two radiations are continuously modulated at different audio-frequency rates, e.g. 65 and 86·7 cycles per second. The receiver passes its rectified output to the coil of a small frequency meter of the tuned reed type, carrying only two reeds. When

flying along the equi-signal path both reeds vibrate with equal amplitude. Alternatively, the movement of each reed is caused to induce a small alternating E.M.F. in a suitably placed coil, the resulting current being passed through a metal rectifier and supplied to one winding of a differentially wound, centre-zero moving-coil microammeter. When the amplitude of vibration of both reeds is the same, i.e. when the aircraft is on the desired course, both windings carry equal current and the pointer is not deflected. Off course, the pointer is deflected to port or starboard according to which reed has the greater amplitude, the dial being so marked as to indicate the necessary alteration in course.

97. The routes laid down by the visual type beacon depend upon the depth of modulation and upon the relative phasing of the carrier currents in the two directional aerials. In the aural type these are never simultaneously energized and the question of relative phase does not arise. Suppose the carrier currents in a visual type beacon to be exactly in phase ; the sideband energy radiated by each aerial possesses the usual figure-of-eight characteristic, but the carrier energies combine to give a large figure-of-eight rotated through 45°, and as a result only two routes are marked instead of four. If however the carrier currents are 90° out of phase, and the depth of modulation is the same on each carrier, the resulting routes are four in number and are symmetrically disposed. An increase in the depth of modulation of one radiation with respect to the other has the same effect as an increase of aerial current in the aural type beacon. By variation of the relative phasing and depth of modulation, the four routes can be laid down in any direction likely to be required.

Blind approach systems

98. The operation of effecting a landing on an aerodrome under conditions of low or zero visibility may be conveniently divided into three stages :—

(i) The aircraft must be brought to a point within a few miles of the landing ground.

(ii) It must then be guided towards the latter on a safe approach track, and finally across the aerodrome itself in a direction suitable for landing, with due regard to the wind.

(iii) Suitable indications must be given to the aeroplane regarding its distance from the aerodrome during approach, and its height above ground.

Under the first heading, ordinary navigational methods, assisted when necessary by directional wireless, will meet the case. The operations (ii) and (iii) are accomplished by different methods in the several systems of blind landing aids which have been proposed. In the development of any such system, it is essential to take into consideration the available frequency allocations ; in Europe, no medium-frequency allocation is possible owing to the demands of the broadcasting services, and the 30–35 Mc/s band is the only one available. The blind approach system developed by the C. Lorenz Company in Germany, which operates entirely on frequencies in this region, has therefore been extensively adopted in Europe for commercial purposes and may be taken as a typical example.

99. The principle of the method is as follows. Referring to fig. 42 an approach path is laid down by an equi-signal beacon which indicates both aurally and visually if the aeroplane is to port or to starboard of the correct line of approach. The equi-signal zone subtends an angle of about 4°, and gives an aural range of about 20 miles, at an altitude of 1,500 feet. Situated upon the line of approach near the actual landing ground are two marker beacons, the inner beacon being about 300 yards outside the aerodrome and the outer beacon some 3,000 yards. The aeroplane is fitted with suitable apparatus for the reception of signals from both main and marker beacons. The bearing upon which the approach track is laid must be known to the pilot ; when flying in the equi-signal zone of the main beacon, the pilot receives a steady signal in the telephone receivers, and the pointer of the visual indicator remains steady at zero. When the aeroplane is to the left of the approach path, a succession of dots is received, while if to the right the received signal consists of a series of dashes. Corresponding indications are also given on the visual indicator.

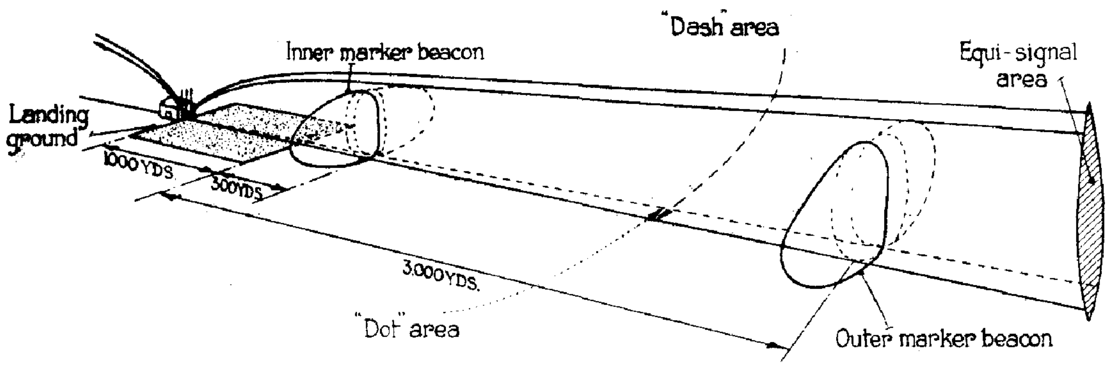


FIG. 42, CHAP. XVI.—Lorenz blind approach system.

100. The main beacon signals are of the M.C.W. type, the standard modulation frequency being 1,150 cycles per second. On passing over the outer marker beacon, the pilot will hear, superimposed upon the steady note of the main beacon, a deep note of 700 cycles per second, while a very sharp indication of the exact position of the outer beacon is given by the flashing of a neon lamp. Similarly, when the inner marker beacon is approached, a high-pitched note (1,700 cycles per second) is heard and its exact location indicated by another neon lamp. The pilot is now aware that there are no obstacles to his flight in the final section of the landing path. Although not immediately apparent from the foregoing it must be emphasized that the master instrument in the whole manoeuvre is the directional gyro. The actual procedure is to pick up the main beacon at a range of about 20 miles and an altitude of say 2,000 feet. When the equi-signal zone is located, the aeroplane is turned quickly to the known bearing of the approach track, and held steady on this course by the directional gyro. The centre of the approach track may now be maintained with considerable accuracy by observation or either the visual or aural equi-signal indications—a combination of both methods being most effective. Height may be lowered to about 1,000 feet after crossing the outer marker and to below 200 feet after crossing the inner marker, the final stage being of course to touch down on the aerodrome.

101. No mention has been made of the method of navigation in the vertical plane. It has been proposed to employ a locus of constant field strength (i.e. the lower edge of a vertical polar diagram in the equi-signal zone) as a glide path, but although this idea is practicable under certain conditions it is not so generally. Two difficulties arise, namely (i) the shape of the vertical polar diagram does not correspond exactly with the natural glide path of any existing aeroplane. This might be overcome by automatic correction of the intensity of the received signal, (ii) even if the shape of the vertical polar diagram could be correctly adjusted for a given set of conditions, day to day or even hour to hour adjustment might be necessary, because the polar diagram depends to a great extent upon the state of the ground. The present practice therefore is to employ a sensitive Kollsman altimeter for vertical navigation, the barometric pressure at the aerodrome level being given to the pilot by R/T immediately before the landing.

Lorenz system—equipment

102. The manner in which the required equi-signal zone is achieved is illustrated in fig. 43. The aerial system of the main beacon consists of a vertical dipole, which is energized by the main transmitter, and if used alone, the horizontal polar diagram would approximate to a circle. Two reflector dipoles are placed one on each side of the main energized dipole, and are alternately keyed in the manner shown in fig. 43a. When the switch K_1 is closed, the reflector R_1 is resonant with the energized dipole S, but the switch K_2 is broken and the reflector R_2 is completely out of resonance. Under these conditions the polar diagram is that shown by the horizontally shaded area, in fig. 43b. When the switch K_1 is open, K_2 is closed and only the reflector R_2 is operative, the polar diagram being then as shown by the vertically shaded area. The equi-signal zone of the alternately energized aerial-reflector system will therefore be somewhat

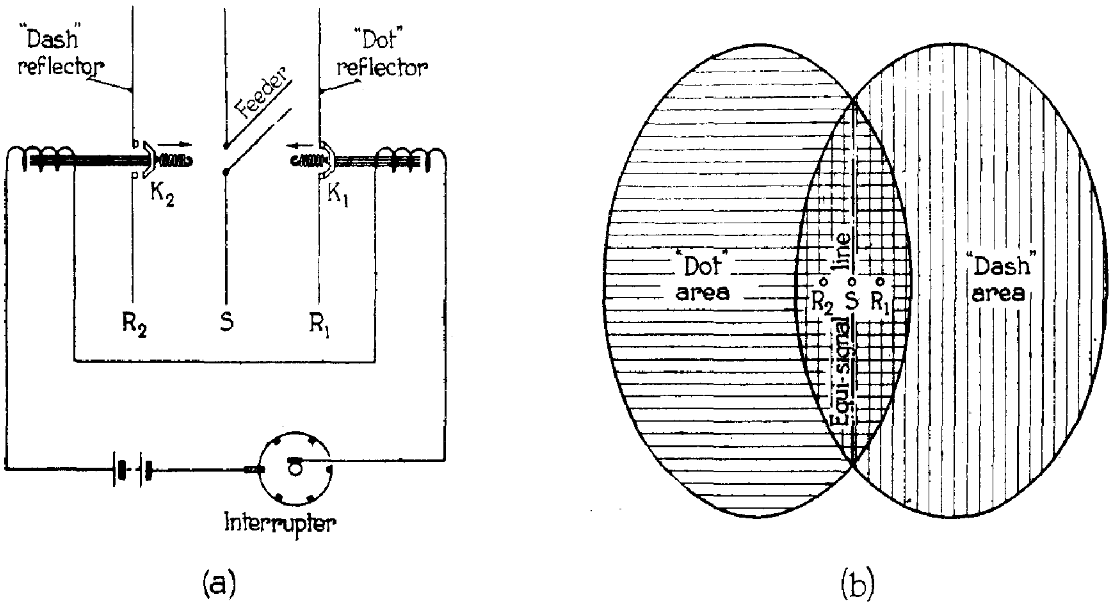


FIG. 43, CHAP. XVI.—Method of keying main beacon aerial and resultant horizontal polar diagram.

as shown by the overlapping areas. The energized dipole is fed from a crystal-controlled M.C.W. transmitter having a power input of 500 watts, the frequency being in the vicinity of 33 Mc/s, while the marker beacons are supplied by 5-watt transmitters and operate on a higher frequency, e.g. 38 Mc/s. As already stated the radiation from the marker beacons is modulated at 700 cycles per second (outer) and 1,700 cycles per second (inner). The radiating systems of

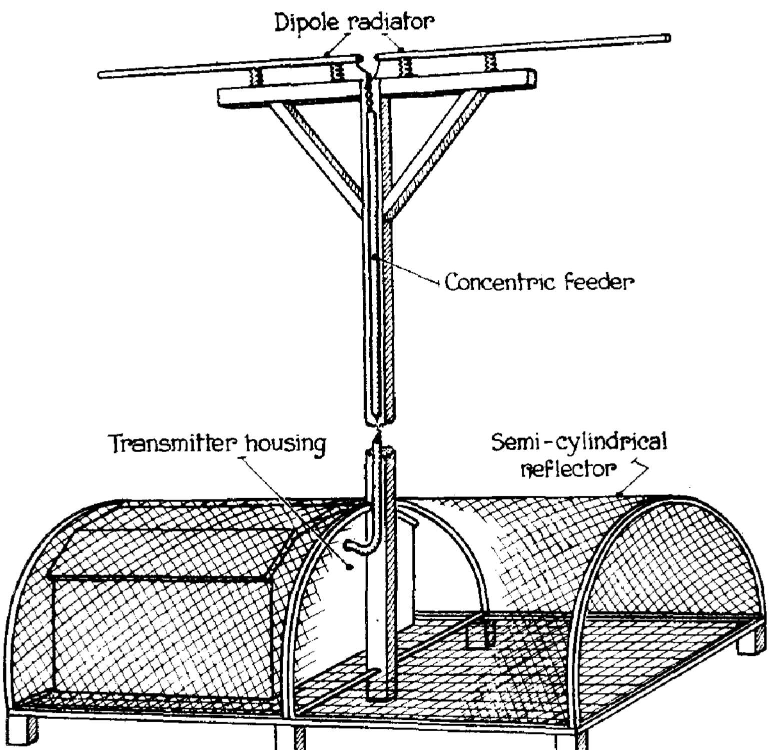


FIG. 44, CHAP. XVI.—Marker beacon.

both marker beacons are of similar design, and the main features are shown in fig. 44. The aerial itself is a horizontal dipole ; the transmitter is situated immediately underneath it, and is enclosed in a screen of expanded metal which is semi-cylindrical in shape. The highest point in the screen is approximately one half-wavelength below the dipole, and the screen, operating as a reflector, gives the peculiarly shaped polar diagrams shown in fig. 45, which are desirable for the function of the marker beacons.

103. The receiving apparatus for the main beacon consists of a simple amplifier having one R.F. stage, with automatic gain control, a detector and one A.F. stage, while a tuned circuit

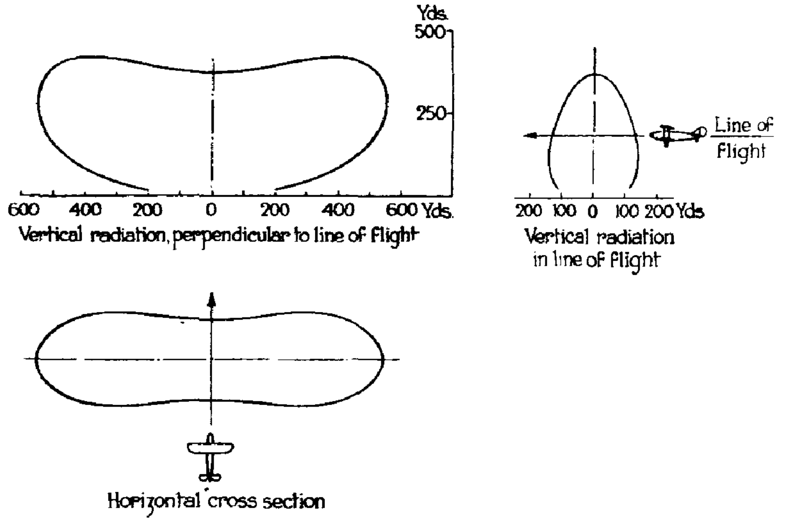


FIG. 45, CHAP XVI.—Polar diagrams of marker beacon.

with a simple detector serves as a receiver for the marker beacon signals, the rectified current from these being fed into the A.F. stage of the main receiver. The output of the latter, during passage through the field of a marker beacon, contains both main and marker modulation frequencies. The output is connected through to suitable filter circuits which supply the appropriate frequencies to the various indicating instruments. The receiving aerial equipment consists of a vertical dipole about ·9 metres in height for the reception of the equi-signal beacon, and a horizontal dipole about 1 metre in length for the marker beacons, the latter aerial being generally mounted beneath the fuselage.

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