FOG SIGNALS BY ROTATING NAUTOPHONE (PENDULUM VIBRATOR)

by

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Some time ago the Polish Maritime Office, in charge of Lighthouses and Beacons, installed signals which, during fog, enable vessels to obtain the acoustic bearing from a transmitter. The transmitters are placed, one at the entrance to the port of Gdynia and the other at Hel, on the "Swedish Hill".

The acoustic apparatus consists of fog sirens with a trumpet erected on a vertical pivot so that it can move around this axis and thus direct the beam of sound of maximum amplitude successively towards the different points of the horizon.

During the continuous sound emission, the trumpet sweeps a known sector of the horizon with a rotatory movement at uniform speed, starting from a certain bearing, in a definite direction, until it reaches a second bearing whence it starts immediately the return movement to the initial bearing which is the position of silence.

Thus a vessel lying within range of the sound signal emitted by the siren and in the sector swept by the sound, will hear during the period of emission two sound maxima, more or less separated according to the position the vessel occupies within the sector swept by the sound.

To fix in terms of time the two sound maxima observed, a sort of W/T pendulum swings in synchronism with the azimuthal movement of the siren and a series of W/T dots, transmitted in unison with the movement of the trumpet of the siren, allows the relative position of the axis to be fixed with reference to its initial position at the beginning of the movement.

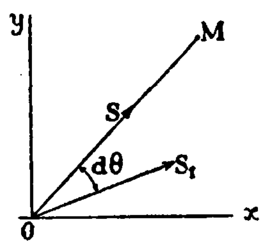


FIG. 1

It is seen on figure (1) that the vessel M does not hear the maximum of sound when the trumpet S coincides with the direction OM but only at some later instant, when the trumpet S occupies the position S_1 so that :

$$d\theta = \omega\, dt \qquad\qquad dt = \frac{OM}{V}$$

dt being the time necessary for the sound to travel from O to M.

ω is the angular speed of the axis of the siren.

V is the speed of the sound in the air, i.e. an average of 335 metres/second under normal atmospheric conditions.

In practice the sound requires 1.1 seconds to travel 370 metres or two cable-lengths. The beat of the W/T position-finding pendulum is tuned to this figure of 1.1 sec., and in this manner the distances in cable-lengths which separate the observer from the point of sound-emission are easily obtained by simply counting the dots of the W/T signal, on condition that the two kinds of signal, sound signal and radio signal, are properly synchronised or else that their initial phase difference has the requisite value.

Therefore let the value 1.1 sec., the interval between each beat of the radio signal be selected as the unit of time, and let ω be the value of the corresponding angular increase for the rotation of the axis of the trumpet.

Let OA (Fig. 2) be the initial position of this axis at the commencement of the sound emission; then, for instance, the rotation follows the direction indicated by the arrow in uninterrupted motion up to the extremity OB of the given sector which is

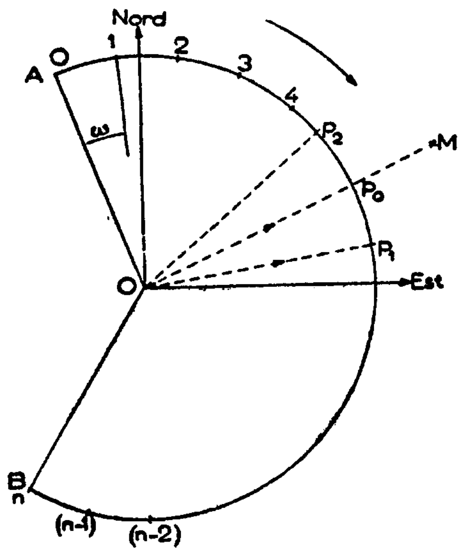


FIG. 2

reached at the instant of the beat n (point n) of the radio-electric pendulum. At this moment the trumpet, still in uninterrupted motion, oscillates in the opposite direction from the arrow to return with the same regular movement to A at the instant of beat $2n$ of the radio-electric pendulum. Figure 2 indicates, in azimuth, the various positions of the axis of the siren corresponding to the dots 1, 2, 3, 4, ... $(n - 1)$, n of the radio signal.

Let po be the point for which the axis of the siren passes in the azimuthal direction of the observing vessel M. The latter hears the maximum of the sonic signal (1st maximum since the origin of the sound emission) when the trumpet of the siren is at the point p_1.

Putting $OM = D$ we have $p_1 - po = \dfrac{D \text{ cable-lengths}}{2}$ (1)

During the return sweep from OB towards OA, in the direction opposite from the arrow, the observer M will hear the second maximum of sound at the point p_2 of the radio-signal, point p_2 being, on the figure, symmetrical with respect to p_1 with reference to po.

According to figure 2 we have :-

$$p_2 = n + (n - po) + \frac{D \text{ cable-lengths}}{2} \qquad (2)$$

$$p_2 = 2n - po + \frac{D \text{ cable-lengths}}{2}$$

$$p_1 = \qquad po + \frac{D \text{ cable-lengths}}{2}$$

$$p_1 + p_2 = 2n + D \text{ cable-lengths}$$

whence D cable-lengths $= p_1 + p_2 - 2n$ (3)

$$p_2 - p_1 = 2\ (n - po)$$

Now, $po = \dfrac{\alpha + R}{\omega}$ (fig. 3), whence

$$R = n\omega - \alpha - \frac{1}{2}\ \omega\ (p_2 - p_1) \qquad (4)$$

Formula (3) gives the distance as a function of the sum of points p_1 and p_2, first and second maxima of the radio signal beat; formula (4) gives the bearing as a function of the difference of these same pendulum beats between the first and second maximum of sound from the siren.

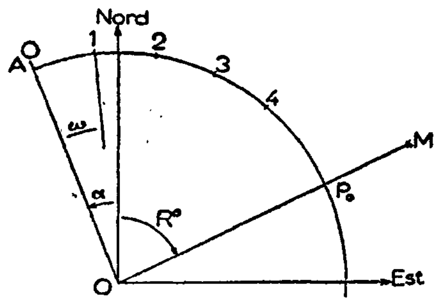


FIG. 3

Formula (3) shows that all the points of the circle of radius D are such that the sum of $p_1 + p_2$ is a *constant*.

Formula (4) shows that, for all the points of an identical bearing R, the difference $p_2 - p_1$ remains *constant*.

This formula may be written:

$$R + \alpha = \omega \left[n - \frac{1}{2} (p_2 - p_1) \right] \qquad (5)$$

In this form it is seen that, in the plane of the horizon, the sector swept by the W/T siren may be characterised by the series of bearings, equally spaced angularly round the point O, for which the difference $p_2 - p_1$ has the consecutive values 0, 1, 2, 3, 4,..... $2n$.

The locus of difference $p_2 - p_1 = O$, where $p_2 = p_1$, is obviously the limit OB of the sector where the change of direction of motion occurs; that of difference $2n$ is the limit OA, at once origin and extremity of the oscillatory movement of the siren. (Fig. 4).

The angular difference common to the various bearings for which the difference $p_2 - p_1$ increases, or decreases, by one unit, is precisely $\frac{\omega}{2}$, ω being the angle traversed by the siren in the unit selected for the measure of time, i.e. in 1.1 sec., the common interval of the W/T pendulum beats.

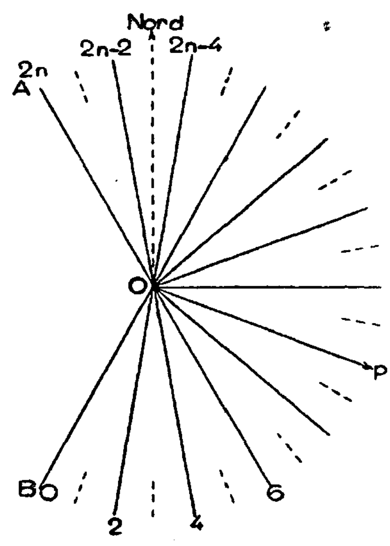


FIG. 4

The mechanism so constituted is therefore represented, within the plane of horizon of the station O, under the fictitious form of the rose in Figure 4.

According to the local requirements, one may select either the amplitude of the active sector AOB, the azimuth OA origin of the oscillatory movement of the siren, or the number of beats $2n$, the speed ω being determined therefrom. Again, one might as an alternative direct in the horizon one of the bearings of the rose, that which corresponds, for instance, to a certain difference p, towards a characteristic point : for instance, the geographical North or East, etc.

Devices of this nature (aerial rotating vibrator synchronised with W/T pendulum) have been installed and function at the entrances to the Polish ports, Hel and Gdynia ;

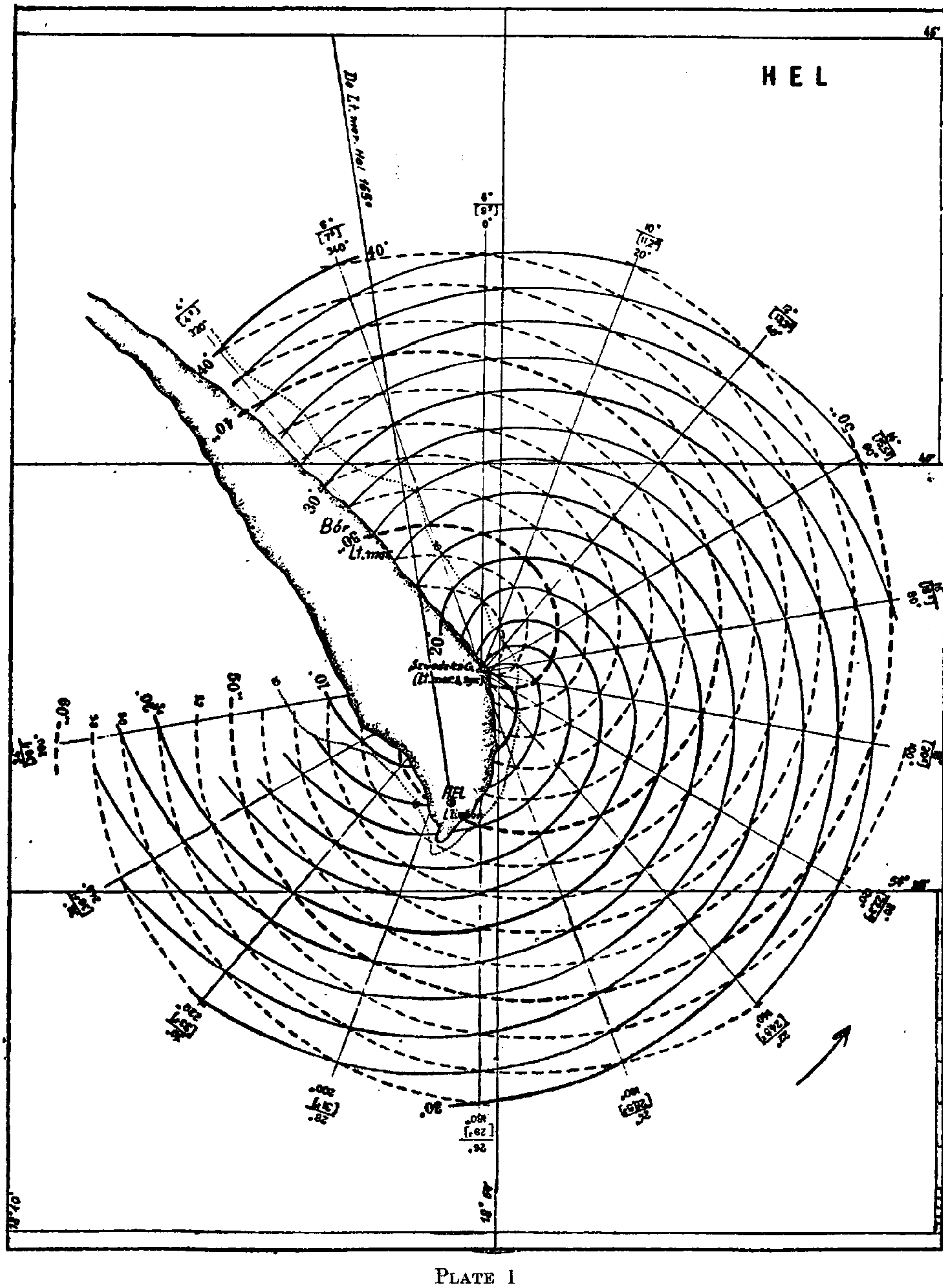
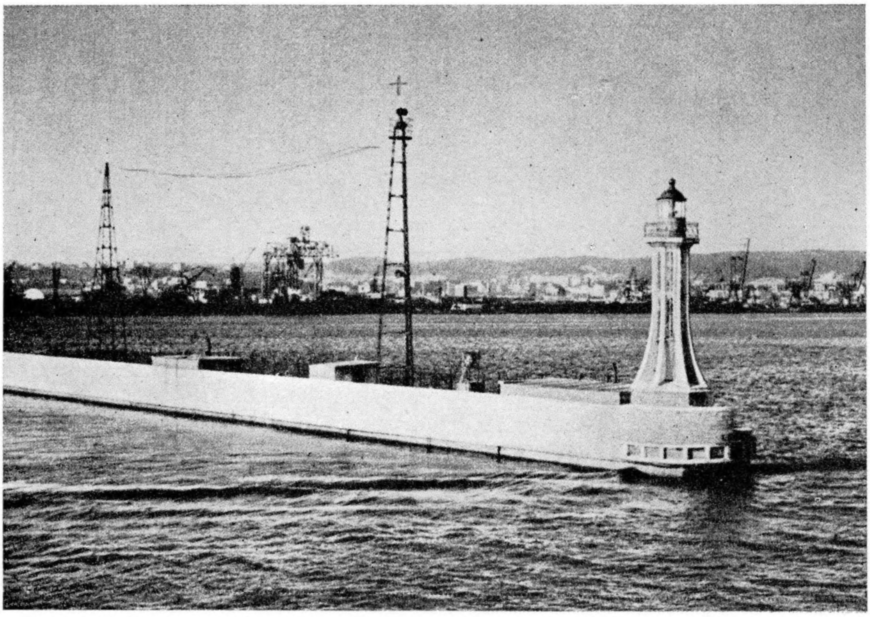


PLATE 1



\+ *Vibrateur aérien oscillant de l'Entrée du Port de Gdynia*
Rotating Nautophone at Port of Gdynia entrance

a detailed description of them will be found in the Lists of Wireless Fog Signals published by the Hydrographic Offices.

Plate (1) shows the rose in the vicinity of Hel harbour. Having regard to the preceding, it is self-explanatory. The height of the note emitted is 700 vibrations, the siren's angular speed of rotation is 20° in 1.1 sec.; theoretically the sector swept is 360°, point of departure 280° from the W/T signal; the movement is first anti-clockwise through South, East, North up to 280°, then clockwise from this bearing through North, East, South and West of the beacon to the initial position. This sweep is made during the emission of the long sound of the siren — duration 40 seconds or 36 dots of the W/T pendulum. The apparatus is so placed that the navigator situated true East from the siren hears 17 dots (= 19 seconds) between the two consecutive maxima of sound p_1 and p_2.

This difference varies by one dot each time that one deviates by 10° from this azimuth, increasing towards the South, decreasing towards the North.

Let us substitute these data in formula (4) :

$$2n = 36 \qquad \omega = -20^\circ$$
$$n = 18 \qquad \alpha = +80^\circ \qquad R^\circ = -360^\circ - 80^\circ + 10^\circ (p_2 - p_1)$$

whence $R^\circ = 10^\circ (p_2 - p_1 - 8)$

and according to (3) D cable-lengths $= p_1 + p_2 - 36$.

Appendix to Notice to Mariners N° XXI/1937 published 1st November 1937 by the Polish Hydrographic Office gives very practical diagrams for the graphical determination on the chart of the ship's position relative to the W/T Beacon in conjunction with the pendulum-siren for the ports of Gdynia and Hel.

These diagrams give to the scale of 1:100 000, which is sufficient for graphical construction on the chart, the geometrical loci of the points on the horizontal plane for which the observer hears the maximum of sound of the siren in exact coincidence with the consecutive dots of the W/T signal both on the forward and backward travel of the siren.

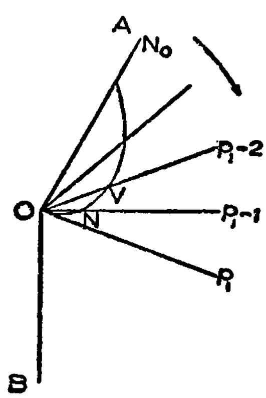


FIG. 5

Take, for instance, the instant of the dot p_1 of the W/T signal,the point O, origin, is obviously a point of maximum at that instant. On the azimuth corresponding to the instant of the dot $(p_1 - 1)$ of the W/T signal (Fig. 5), the point of the locus p_1 will be in N so that $ON = 2$ cable-lengths, since, according to the selected conventions, the sound will have travelled the distance ON while the siren has rotated from azimuth $(p_1 - 1)$ to azimuth p_1. On the azimuth $(p_1 - 2)$ the point of the locus will be in V so that $OV = 4$ cable-lengths, etc. The curve ONV...... No of the loci where the maximum of sound occurs for beat N° p_1 of the W/T pendulum is therefore a curve tangent to Op_1 in O; the equation of which, in polar co-ordinates, is written :

$$\rho = \omega (p_1 - p)$$

i.e. an Archimedes spiral.

The locus of the points where the maximum occurs for the beat $(p_1 + 1)$ of the W/T signal is identical in shape, and its spiral may be deduced from the preceding by simply turning it through the angle ω round the point O, etc.

The geometrical locus of the points of the second maximum p_2 is obtained by the same method of deduction, starting this time from OB as origin and returning towards OA ; this is the symmetrical of the preceding loci with reference to the bisector of the sector BOA ; but the numbering of the dots differs :

$$p_2 = n + p_1$$

is the relation between the dots for which the intercepts are equal on the limits OA and OB of the sector. (Fig. 6).

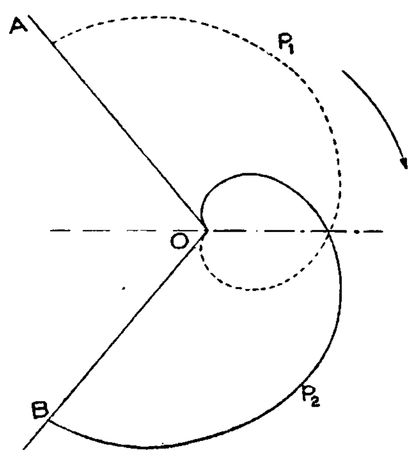


Fig. 6

The whole is based on the assumption that the commencement of the emission of the characteristic dots of the W/T signal is synchronized exactly with the commencement of the sound emission of the rotating siren.

This is the case with regard to the synchronized signals of Hel : the commencement of the sound emitted by the siren coincides exactly with the end of the dash of the W/T signal which is the origin of the series of 50 dots of the pendular W/T signal, spaced at intervals of 1.1 sec. (Fig. 7).

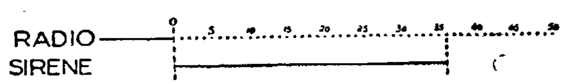


Fig. 7

The active sector of the pendulum-siren of Hel is shown on Figure 8. Its movement starts from OA in the direction of the arrow ; it occupies, at the instants of the different dots of the W/T signal, the azimuths represented by the radii 1, 2, 3...... p...... of the figure.

At the instant of the dot n of the radio signal the siren is directed along OB, extremity of the active sector ; whence it starts to return in the opposite direction from the arrow.

This figure (8) also shows the spiral locus of the points for which the maximum is heard at dot 3 of the signal : this locus starts from 3 on OA and reaches O, being tangent at this point to the radius 3. In the same manner the locus of the dot p is the spiral which starts from the graduation p on OA to reach O, tangent to the radius p. This locus does not go farther.

The locus of the dot n is the spiral which starts from the graduation n on OA and arrives at O, tangent to OB, without going farther, etc.

At the end of the first sweep, the locus of the dot $(n + 3)$ arrives at the point marked $n + 3$ on OB. On the return sweep the locus of the points for which the second maximum coincides with the beat $n + 3$ of the pendulum is the spiral shown by the dotted line on figure 8, symmetrical to the spiral arc of dot 3 referred to the bisector of the angle AOB. In the same way the return spiral arc $n + n = 2n$ is the symmetrical of the spiral arc of the dot n, and terminates at O where it is tangent to OA.

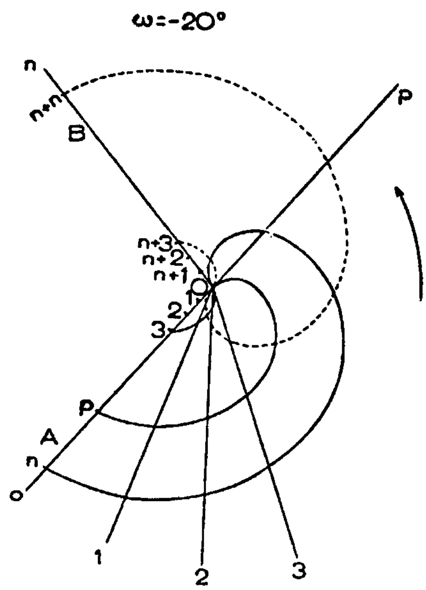


FIG. 8

It is seen that with this arrangement, given the coincidence of the commencement of the siren rotation and of the beats of the W/T pendulum, the original bearing OA is regularly divided into double cable-lengths from the origin O through the successive loci of dots 1, 2, 3...... n...... etc.; while the limiting bearing OB is regularly divided into double cable lengths, from O, through the successive loci of dots n, $n + 1$, $n + 2$...... $2n$...... etc.

In the 40 seconds' (= 36 dots) duration of emission of the long dash of the siren, the sound travels about 7 nautical miles, which corresponds very nearly to the range of the sonic signal. The Hel signal has a 42 seconds' silent period after this long dash, part of which is occupied by the emission of the remainder of the 50 dots of the W/T signal, allowing a "fix" for a supplementary range of about 2.7 nautical miles — in all a range of about 10 nautical miles.

In addition, the Hel siren repeats a complete oscillation after this 42 seconds' silence; during this second travel the W/T pendulum is mute, but the bearing derived from the first and second maxima may be re-taken by means of a stop-watch. In this case, if S_1 and S_2 are the instants in seconds of the first and second maxima the bearing is obtained by the formula :

$$R^{o} = 9^{o} (S_2 - S_1 - 9)$$

Considering now the port of Gdynia, the height of the note emitted by the oscillating siren is 500 vibrations, its angular speed of rotation in 1.1 sec. is 40°, the swept sector is 240°, departure 10° from the W/T signal clockwise through East and South to 250°, then anti-clockwise from this bearing through South and East to 10°, which is the initial position. This sweep is made during the emission of sound of the siren which lasts 13.32 seconds (= 12 dots of the W/T pendulum).

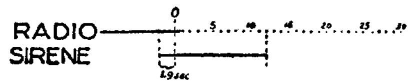


FIG. 9

For the W/T pendulum aerial rotating nautophone of Gdynia, however, the synchronism is not effected in the same way: the emission of the long dash of the oscillating siren begins *before* the zero (fictitious) of the series of dots of the W/T signal, as shown on figure 9.

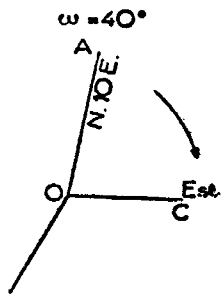


FIG. 10

This advance is about 2.1 sec. (= 2 dots). During this phase-lag, the trumpet, which starts from *OA* through (approx.) N.10.E. in the direction of the arrow (Fig. 10), has already travelled about 80° and is consequently pointed towards the East when the fictive beat N° *O* of the W/T pendulum is produced.

On the figure (3 *bis*) the "phase-lag" is represented by Φ^o, or φ equivalent dots:

$$\Phi^o = \varphi \times \omega$$

we obtain:

$$p_1 - po = \frac{D \text{ cable-lengths}}{2}$$

$$p_2 = 2\,(n - \varphi) - po + \frac{D \text{ cable-lengths}}{2}$$

$$p_1 = \qquad po + \frac{D \text{ cable-lengths}}{2}$$

$$p_1 + p_2 = 2\,(n - \varphi) + D \text{ cable-lengths}$$

$$\text{whence } D \text{ cable-lengths} = p_1 + p_2 - 2\,(n - \varphi) \qquad (3\ bis)$$

$$p_2 - p_1 = 2\,(n - \varphi - p_o)$$

$$\text{or} \quad po = \frac{\alpha + R}{\omega} - \varphi \qquad \text{whence}$$

$$R^o = n\,\omega - \alpha - \frac{1}{2}\,\omega\,(p_2 - p_1) \qquad (4)$$

It is seen that in the phase-lag only the formula giving the distance is affected; that which gives the bearing is independent of the phase-lag, since here the direction-finding dots intervene by subtraction and not by addition.

In the case of Gdynia, and for the summer period from 1st April to 1st December, we have :–

$2n = 12$ $\quad \omega = +40^\circ$

$n = 6$ $\quad \alpha = -10^\circ$ $\quad R^\circ = 250^\circ - 20^\circ (p_2 - p_1)$

whence $R^\circ = 20^\circ \left[12.5 - (p_2 - p_1) \right]$

for $R = 90^\circ$ $\quad p_2 - p_1 = 8$

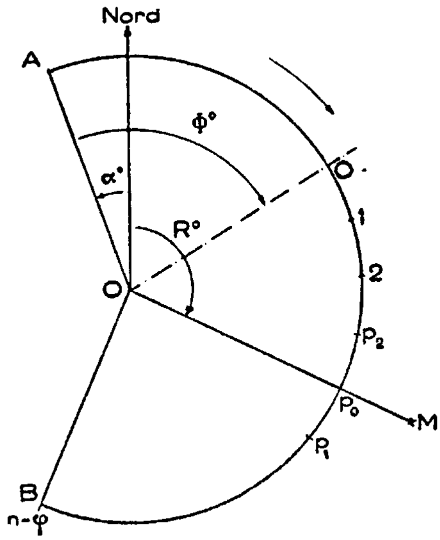


FIG. 3 bis

The apparatus is therefore so arranged that the navigator situated true East from the vibrator hears exactly 8 dots of the W/T pendulum between the two consecutive maxima of sound p_1 and p_2; and this difference varies by one dot each time that one deviates by 20° from this azimuth, decreasing towards the South, increasing towards the North.

In this manner, on the diagram which shows the geometrical loci of the dots of the W/T signal, the scale of equi-distances 0, 1, 2, 3, etc. the origin *O* of which coincides with the point *O*, is placed on the radius *OC* (Fig. 11) and not on the radius *OA* as for the Hel W/T siren.

As a result of this arrangement, the spiral of the dot 4 ends at *O* tangentially to *OB*. The spiral of the dot 8 on the return of the siren, ends at *O* where it terminates tangentially to *OC*.

Also the return spiral from dot 10 ends at *O* tangentially to *OA* (Fig. 11).

The return spirals of dots 12, 13, etc. end respectively along *OA* at the same divisions as the forward spirals of dots 0, 1, 2, etc.

The return spirals of dots 8, 9, 10, etc. intersect the straight line *OC* respectively at the forward intersections of dots 0, 1, 2, etc.

In 13.32 seconds, which is the duration of 12 dots of the period of emission of the Gdynia W/T-siren, the sound travels about 2.4 miles. The siren then remains in the position of silence for 8.96 sec. equal to 1.8 miles of sound travel. The respective sums of these two durations correspond exactly to 20 dots of the W/T signal. Immediately after those 20 dots, the Gdynia siren executes a second double oscillation similar to the first during which the previously-observed values p_1 and p_2 may be checked, deducting the figure 20, however, from the new numbers recorded, d_1 and d_2, provided always that d_2 does not exceed 30, limiting total number of dots of the W/T signal.

The same procedure is still applicable beyond this figure, using a stop-watch to "fix" the maxima of sound in place of a fix by W/T signals, noting, however, that the number of dots is equivalent to 9/10ths of the corresponding interval of time measured in seconds.

In this case the formula giving the bearing is as follows :

$$R^\circ = 18^\circ \left[13.8 - (S_2 - S_1) \right]$$

For the Gdynia vibrator (summer period) the distance is given by the following formula :

$$D \text{ cable-lengths} = p_1 + p_2 - 2\ (n - \varphi) \qquad (3\ bis)$$

On the bearing East of the siren we obtain $p_2 = p_1 + 8$
On this bearing the distances are given in cable lengths by the formula :

$$D \text{ cable-lengths} = 2p_1 + 8 - 2n + 2\varphi$$

The 3 seconds phase-lag before the emission of the 1st dot of the W/T signal was selected so as to give on the azimuth *OC* (true East from the siren) the following property : the distance of the vessel from the siren is given on this azimuth, in *double cables,* by the number of W/T signal dots heard before the first maximum of sound.

Now $D/2 = p_1 + 4 - N + \varphi$

therefore $4 - n + \varphi = 0$ $n = 6$ has been selected

whence $\varphi = +2$ (where $\Phi = +80^\circ$)

(3 *bis*) thus becomes : D cables $= p_1 + p_2 - 8$.

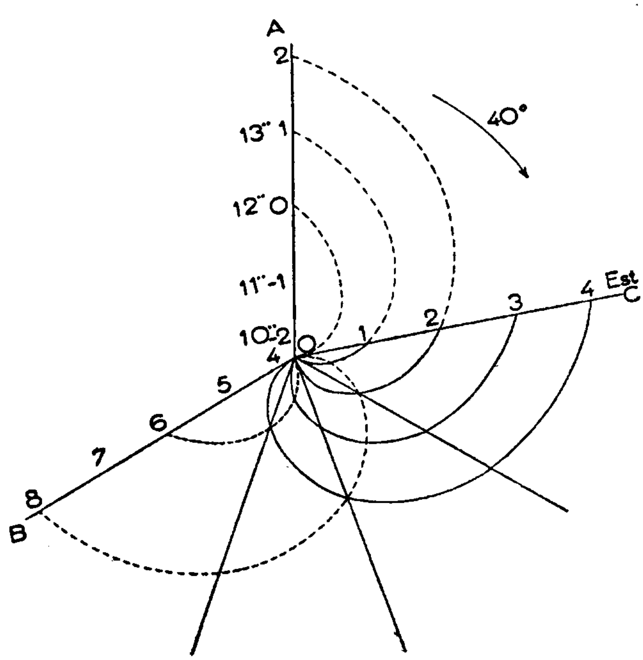


FIG. 11

The diagrams given for Hel in Appendix to Polish Notice to Mariners N° XXI-1937 and for Gdynia in Notice to Mariners N° IV-51/1938 are reproduced on the accompanying plates. On these diagrams the geometrical loci of the points for which the first maximum of sound coincides with the consecutive beats of the W/T signal (dots p_1°) are shown by full lines ; the geometrical loci of points for which the second maximum of sound coincides with the consecutive beats of the W/T signal (dots $p_2^{\circ\circ}$) are shown by dotted lines.

The time interval between the two observed maxima p_2^{oo} and p_1^{o}, measured in W/T signal dots, or in seconds of time, gives the bearing from the rotating vibrator.

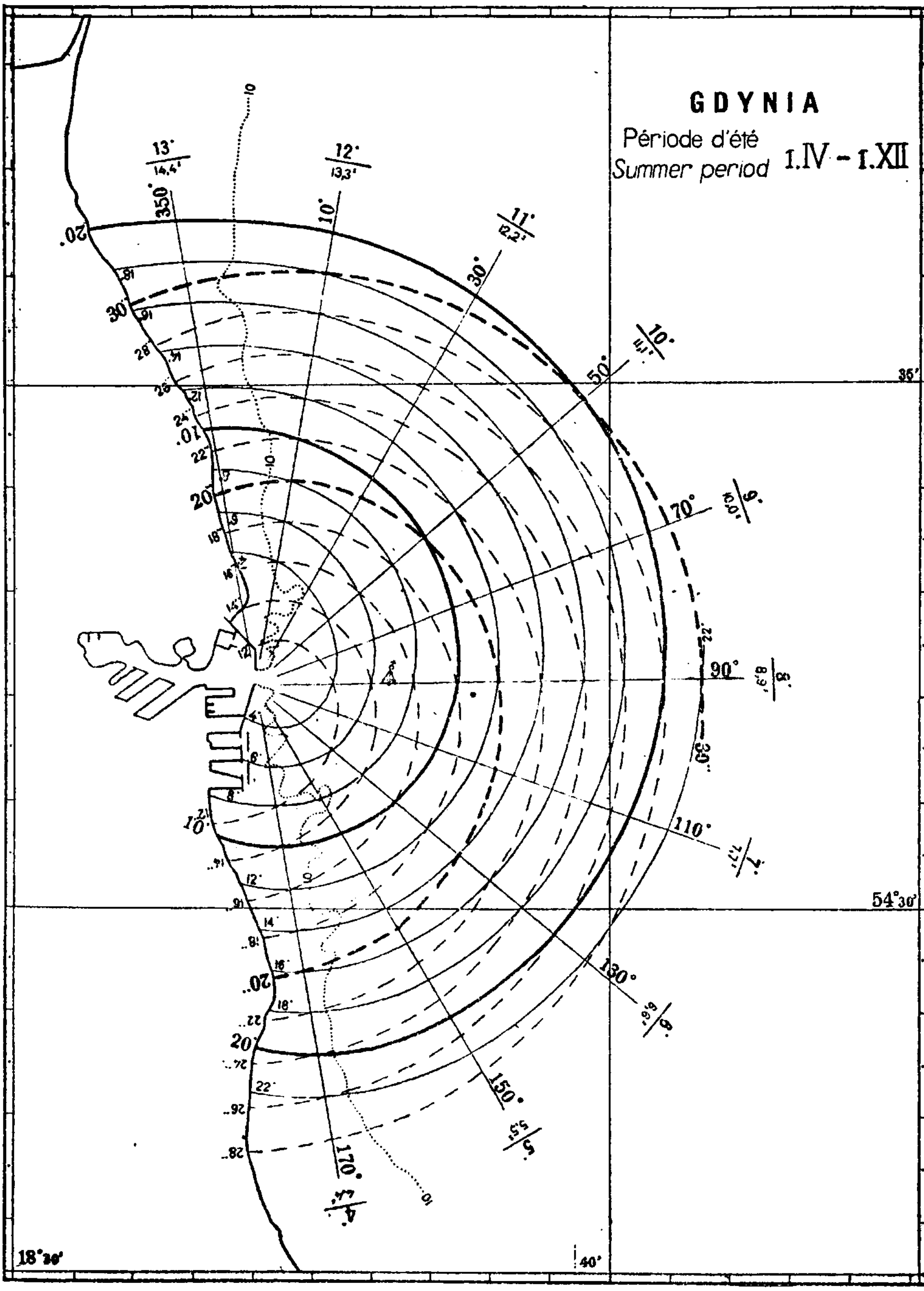


PLATE 2

The intersection of two spirals, geometrical loci of the observed dots of maximum p_2^{oo} and p_1^{o} determines the position of the observing vessel.

The accuracy of this intersection depends upon its distance from the siren. The tangent to the Archimedes spiral makes with the radius vector $\rho = K\alpha$ an angle β so that $\tan \beta = \alpha = \frac{1}{K} \rho$. This angle having at its origin the value zero, increases with ρ, although remaining always less than $\frac{\pi}{2}$ (Fig. 12).

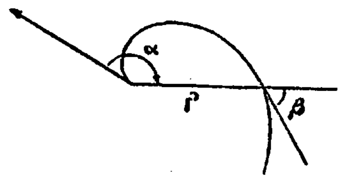


FIG. 12

Owing to the symmetrical shape of the backwards and forwards spirals with relation to any chosen radius, it is necessary that the angle β should not exceed the critical value of 75° if we wish to obtain a good intersection of the two loci at an angle say of about 30°. Tan 75° = 3.73 gives the critical value of the angle α in radians, that is, $\alpha = 215°$ (approx.).

In the present case the critical value of the distance to the rotating vibrator will be $\varphi_i = K\alpha_i$ or $K = \frac{2 \text{ cable-lengths}}{\omega}$.

For Hel $\omega = 20°$, consequently $\varphi_i = 2.14$ miles.

For Gdynia $\omega = 40°$, consequently $\varphi_i = 1.07$ miles.

An error of 0.5 second in the observation of time between two sound maxima corresponds to an error of $\pm$ 5° on the azimuth. On the other hand the accuracy of the calculated distance is about $\pm$ 5 %.

Plate 3 shows the diagram of the Gdynia rotating nautophone for the winter period from 1st December to 1st April. During this period the phase-lag is such that with an East magnetic azimuth of the radio-station, the difference in seconds between the two maxima equals 8 seconds (instead of 8 dots). Under these conditions the formula giving the distance in terms of "radio-points" is the following :-

$$D = p_1 + p_2 - 6$$

In view of the high velocities of rotation of these trumpets, and realising also how delicate a matter it is to procure good synchronisation and the possibility of errors exceeding several degrees for tenths of a second, it is recommended in the sailing directions that the measurements and the determinations of the dots p_1 and p_2 be repeated several times before definitely fixing the position of the ship by this kind of signal. This is the more necessary in that atmospheric conditions in fog sometimes show unforeseen anomalies and lateral refractions capable of falsifying to an unknown degree the indications based on mean theoretical conditions.

In this connection, the Hel and Gdynia W/T stations provide another kind of signal, through which the navigator may obtain a check to a certain extent. The W/T signal of each of these stations includes also the emission of a series of 25 equi-distant pendulum dots generally distributed over 15.6 seconds, i.e. dots 0.625 second apart, an interval which corresponds, in average temperature and salinity conditions, to the propagation in sea water of a submarine sound signal over 1/2 nautical mile.

With suitable synchronisation, there may also be obtained a confirmation of the distance in miles by simply counting the beats of the W/T pendulum preceding the reception on board of the submarine sound signal while the ship's radio compass might,

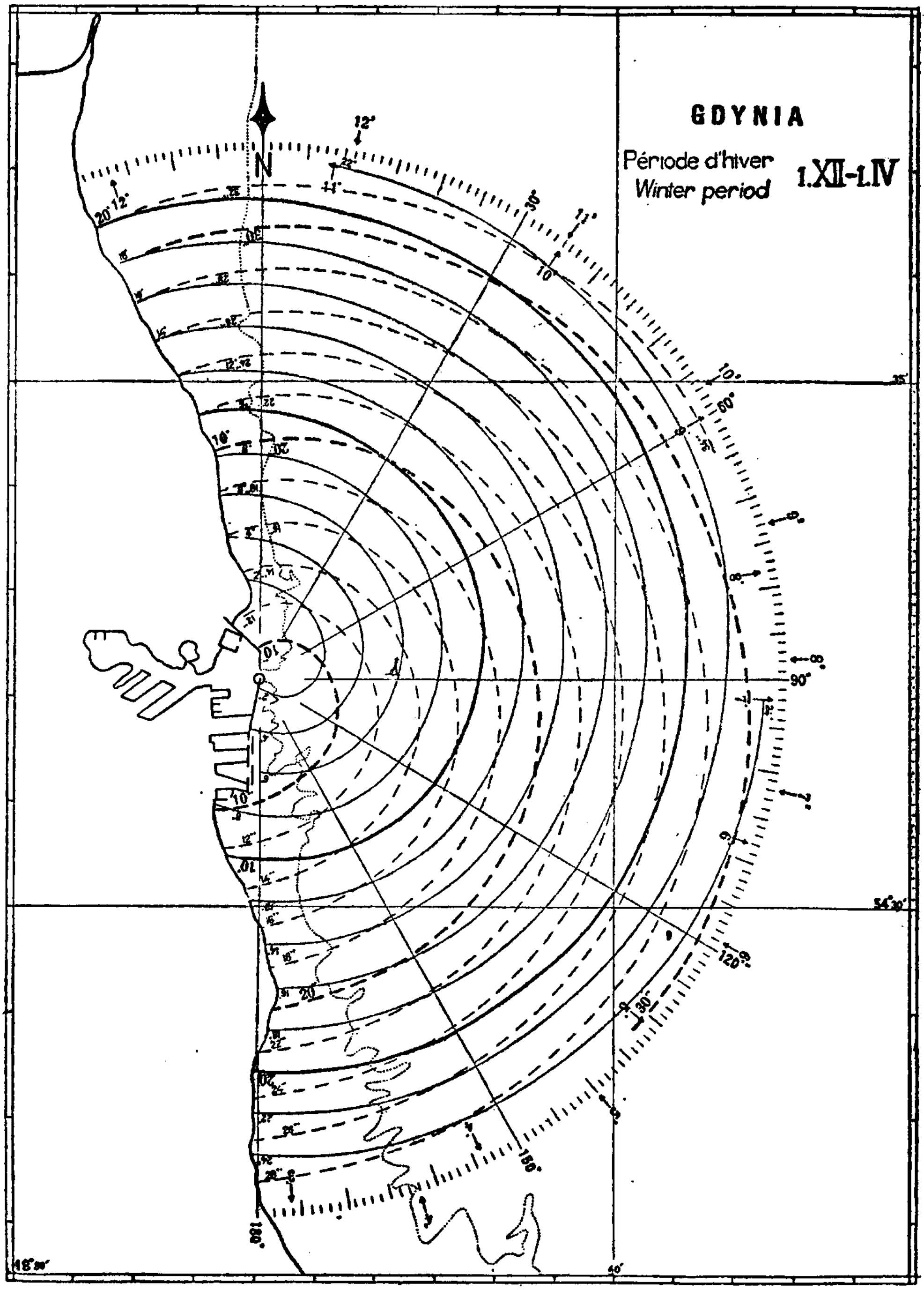


PLATE 3

if need be, supply a check on the W/T-pendulum bearing.

8th December 1937. H. B.