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INTERPRETATION OF LLOYD MIRROR IN SIDE-SCAN SONAR

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SYNOPSIS

In the introduction, reference is made to the Towed Geological Sonar (based on the National Institute of Oceanography design [1]) and to the Transit Sonar. Experience has showed that, from time to time, these sideways-looking equipments produce records indicating Lloyd Mirror effect, caused by reflection from the sea surface.

A theoretical study (Haslett, unpublished) showed the conditions under which these interference fringes would be expected and the limitations of the method.

Details are given of the practical interpretation of records, taken at Burnham-on-Crouch, Firth of Forth, St. Raphael and Plymouth, to illustrate the information which can be obtained of the depth, the shape of the sea bed and its slope, as well as the inaccuracies and ambiguities which may occur.

The authors give their views on the present situation in regard to this method.

1. Introduction

The development of side-scan sonar for civil uses has led to the design of several instruments which have appeared over the past few years. The usefulness of side-scan sonar in various fields has been amply demonstrated, but the techniques of its application, and of the interpretation of results, require some guidance. In the course of the development of the equipments, the opportunity has been taken to make some observations of the Lloyd Mirror effect.

2. The equipments

Two designs of side-scan sonar [2] were used and the results, naturally, depend upon their operating characteristics. The Geological Sonar uses a freeflooding towed-body (Fig.1) containing a magnetostrictive transducer, driven by an 8 kw pulse transmitter. The fan-shaped beam (narrow in the horizontal plane) is directed at right angles to the ship's track and successive echoes are recorded on an extensively modified Muirhead helical recorder (Fig.2). The second design, the Transit Sonar, with which most of the observations have been made, comprises an open transducer (Fig.3) rigidly mounted over the side of the vessel and driven by a 180 W pulse transmitter. The echoes are displayed on a small and robust dry-paper recorder (Fig.4), which also contains all the electronics. Characteristics which are common to both these equipments are the transducer frequency which is 48 kHz, and the horizontal angle of the fan-shaped beam, which is about 1.8 degrees. (The vertical beam angles are somewhat different but this does not greatly affect the results, so far as the present work is concerned.)

3. The Lloyd Mirror effect

Lloyd's original optical experiment employed a monochromatic beam of light, a mirror and a screen. The seagoing acoustic equivalent to this arrangement consists of a fan-shaped beam of coherent pulsed sound, the underside of the water surface acting as a mirror, and the seabed itself which replaces the optical screen. The seabed P (Fig.5) is 'illuminated' by the transducer along two paths, one direct OP and the other after reflection from the water surface OSP. Where the path difference (Δ Fig.6) amounts to an odd number of half-wavelengths, reinforcement occurs; where it is an even number of half-wavelengths, there is cancellation. (N.B. There is a phase change of 180^o at S.) Thus, as each pulse travels over the seabed, the train of echoes reaching the transducer along the two paths alternately reinforce and cancel. It has been found from other experiments that interference occurs equally, either on transmission or reflection, and hence the results as recorded are the sum of two identical additive processes. Repeated transmissions give rise to a series of interference fringes formed on the seabed, and recorded on the instrument. As observed in reference (5), multiple reflections via longer alternative paths have not been recorded. The loci of constant path-differences comprise a family of hyperbolae with the foci at the real transducer in the water and at the image transducer above the surface[3].

The situation may be simplified as seen in Fig.6. In practice, the depth (h) of the sound source 0 is very small compared with the range R. OTO' may be taken as a triangle which is similar to the triangle PQO, where
- 0 = real transducer,
- 0' = image transducer,
- R = slant range of nth fringe,
- λ = wavelength of sound in water,
- n = fringe order number,
- D = depth of water at nth fringe,
- h = depth of transducer below the surface,
- Δ = path difference.

Geometrical consideration of the triangles OQP and O'QP leads to the equation for depth,[4] using the destructive fringes:

$$D = \frac{Rn\lambda}{2h} + \frac{(n\lambda)^2}{4h}$$

The maximum path difference is $2h = n\lambda$ (the distance between the real and image transducers) so that the maximum value of the second numerator is $4h^2$ and the last term reduces to a maximum of 'h' and a minimum of zero. However, due to limitations imposed by the pulse length, the maximum value of 'h' is never realised and the fringe order number does not generally exceed 20. As $\lambda = 0.1$ft at 48 kHz and 'h' is large compared with 1ft, the last term can be neglected for practical purposes, as it will not exceed 1/h.

For these observations, therefore, it is convenient to put

$$D = \frac{R n \lambda}{2h}$$

and thus economise in the computations.

4. Choice of fringe number 'n'

In solving the equation for depth D, the problem lies in arriving at the correct value of 'n,' the fringe order number. The zero-order fringe clearly has its locus in the water surface and lies at infinite range when in open water. Even when dry land is within range, the zero fringe cannot be identified with certainty due to difficulties associated with the shore line.

To identify a fringe number, therefore, some independent aid is necessary, or an empirical approach can be adopted. For example, if the vessel turns slowly through a circle and no change is observed in the range of interference fringes, the seabed is obviously flat and an echo-sounder measurement can be used to identify a fringe number. The observations forming the subject of this paper, however, have generally not allowed the use of an echo sounder; nor indeed, has a flat seabed appeared on these occasions. Therefore, the choice of values for 'n' has been made by inference or by "best fit" selection.

5. Some practical results

Turning now to some examples of Lloyd Mirror interference, the first illustration (Fig.7) shows two very similar recordings taken of the same area on two separate occasions. The upper record is a normal side-scan display of an area just South of Calshot Point on the Solent. The vessel's track is represented by the transmission line at the top of each record and the range displayed below this line is 900 feet. The length of the record represents approximately 2000 feet. From this we conclude that the area has no particular features, except that the sandy bottom appears to shoal steadily towards the shore line (at the foot). The lower record contains well formed Lloyd Mirror fringes which follow the shape of the area almost like contours on a map. At the left-hand end of both records, there is shown a patch of rather complex features of sand which, though well depicted in the normal side-scan mode, have broken up the interference fringes so that they can no longer be followed.

The next illustration (Fig.8) shows an echo-sounder profile taken across the River Crouch in Essex, and the side-scan fringes along the profile, which is indicated by the line near the top. The bottom is composed of mud, and as on many other occasions in this locality, the Lloyd Mirror effect is seen to be very strong. The echo-sounder profile is slightly distorted at the right-hand side, where the vessel had to turn when approaching the river bank. The limits of the profile are shown by the vertical lines on the extreme left and right ends of the echo-sounder record.

In Figure 9, the actual echo-sounder profile has been re-plotted at the positions where fringes appear on the side-scan record, and is compared with the profile calculated from the interference pattern. The central portion shows the closest agreement, the difference in depth being only 6 inches, or about 1½%. At the left-hand end, the two graphs diverge by amounts that cannot be explained by the neglect of the last term in the equation for depth. The considerable divergence (2 to 3ft) at the right-hand end may be explained by a reduction in the vessel's speed as it approached the river bank obliquely: however, divergence at both ends may well be due to a non-linear horizontal scale to the echo-sounder profile, due to variations in vessel's speed. A more rigorous control of the experiment was not possible at the time. It is highly probable that the correct fringe numbers have been used. For example, the depth at fringe 5 has been plotted for 'n' = 4. This illustrates the large (and unacceptable) change which occurs at small values of 'n'.

Another approximate comparison between a known situation and the profile derived from the interference pattern appears in Figures 10 and 11. Figure 10 shows part of an extensive pattern observed in the Firth of Forth. Most of the area is seen to be of smooth sand, and the interference pattern clearly reveals the shape of a steep slope in the lower part of the record. The position of the vessel is known approximately by reference to buoys near the track, and a profile has been selected from this record, midway between the vertical lines which correspond to the buoy positions.

In Figure 11, the Lloyd Mirror profile is compared with that taken from the Admiralty Chart. The relatively small scale of the chart and the sparse soundings render this profile rather approximate. A condition of "best fit" has been selected, consistent with known factors, but once again a rigorous comparison is not possible due to lack of exact data.

An adjacent section of the side-scan record is reproduced in Figure 12[5]. This shows a conventional record with the interference effect superimposed upon it. The dark areas at the top are due to exposed patches of clay, and the lighter areas result from sand. The lower portion corresponds to a shallow area. The interference fringes reveal the present of a steep slope and there are signs of sand ripples adjacent to the clay. Crombie pier is clearly depicted, and, due to the vertical pile construction, echoes are received from a length of the pier beyond the display range, but recorded one cycle later than targets within range. The dredged approach to the pier is also seen. In this example, the nature of the interference suggests the shape of the seabed, but the fringes show some discontinuities and the extraction of depth values from the fringes becomes more difficult.

Figure 13 shows a portion of record taken near St. Raphael. Strong interference has occurred over part of the seabed, and none over the remainder. Enquiries at a local geological institute revealed that the seabed is predominantly mud, but that a dense form of weed grows above a certain depth, and each annual growth decays to form a dense mat. At the time of taking this record, there were confused waves up to about one foot in height. This condition has destroyed low intensity interference over the mud area, but the reflections from the area of matted weed have interfered strongly. A depth plot of this area reveals a mean gradient of about 11 degrees which has probably contributed to the result.

In Figure 14, a steep gradient, rising to the shore-line of Plymouth Sound, has compressed the fringe spacing to the limit of legibility (and they may not be discernible in the illustration). The accompanying profile is reproduced to equal horizontal and vertical scales. In the absence of a charted comparison, the truth of the profile cannot be sustained other than to observe that it is consistent with a visual appreciation of the area. (The fringe numbers may be in error by $\pm$ 1.) It is interesting to note, however, that 27 fringes are recorded, whereas in less extreme conditions the number is usually under 20. Some comments on this point appear later.

6. General remarks on results

Six examples of the interference effect have been reproduced in this paper, each showing its points of interest. Some deductions may be made.

First, it is important to comment on the smoothness, or otherwise, of the water surface and its specular properties with respect to a sound wavelength of 3 cm. The interference records shown in Figures 7, 10, 12 and 14 were made under conditions of perfect calm where the water surface was truly a mirror. On the other hand, the remaining records in Figures 8 and 13 were made in disturbed conditions with confused waves up to about 1 foot in height. Other examples exist where interference has occurred under a rough water surface. Conversely, interference has frequently failed to form under a perfectly smooth surface. Further investigations will be necessary to determine the relationship between interference formation and water roughness, but it is already clear that where seabed reflectivity is high, some water roughness can be tolerated. Figure 13 is a good example of this.

7. Factors affecting clarity of fringes

It will be noted that interference is not produced at ranges near to the transducer. This is partly due to the very close spacing of fringes at short range, but the limiting factor is the pulse length of the system.

Near the horizontal, the overlap between the pulses received via the two paths is almost complete whilst as the angle of inclination is increased, the number of overlapping waves within the pulse declines.

On both the side-scan equipments, a pulse length of 1 millisecond has been found to be about optimum for normal operations, and this would correspond to 48 waves. However, in practice, the Lloyd Mirror patterns fade out after about 20 fringes. This suggests that the clarity declines appreciably when the overlap is reduced to about half the pulse length. It also depends on the type of seabed.

To investigate this limit the following measurements were made on good quality recordings:

Table 1

Depth D	Slant range of nearest fringe R	D/R
63	274	0.23
32	117	0.27
75	280	0.27
27	126	0.21
54	235	0.23
36	113	0.27
45	210	0.21
41	207	0.20
30	133	0.23
32	126	0.26
		Mean 0.24

The value of D/R is nearly constant, and $\sin^{-1}$ D/R gives the angle of incidence OPQ of the nearest fringe ($14\frac{1}{2}$ degrees). From Figure 6, this angle is, for practical purposes, approximately equal to the angle O′OT at the source subtended by the path difference (Δ). The transducer depths were all between 3.5 and 4.0 feet, so h 3.75, and D/R = 0.24 (mean value) may be inserted.

Hence:- $\Delta_{max} = 2h \frac{D}{R}_{min} = 7.5 \times 0.24 = 1.8$ ft, indicating an effective pulse-length of 0.4 millisecond centred on the pulse peak.

Similar measurements were made on records published under reference (6) and give the following values:-

Table 2

Depth D	Slant range of nearest fringe R	D/R
30	440	0.07
33	400	0.08
21	380	0.06
21	315	0.07
40	440	0.09
21	355	0.06
40	440	0.09
30	430	0.07
		Mean 0.07

Again the value of D/R is nearly constant. In this case h = 15 and the mean value of D/R = 0.07.

Hence:- $\Delta_{max} = 2h \frac{D}{R}_{min} = 30 \times 0.07 = 2.1$ ft, thus agreeing closely with the previous value.

In the example seen in Figure 14, a few more fringes appear. In this case h = 4, D = 64 and R = 177; hence 2h D/R = 2.9 feet corresponding to a pulse length of about 0.6 millisecond.

8. Main effects of motion of vessel

One of the attractions of the Lloyd Mirror method is that it is self-stabilising in the sense that the transducer image always lies vertically above the real transducer (except in the presence of a long sea swell). Since most of the equipment designs provide for the transducer to be mounted or suspended from the side of the vessel, which may suffer rolling motion, the transducer depth (h) varies and, thereby, the fringe pattern is disturbed. This effect can generally be recognised from the regular periodic shift in the pattern. Provided that the roll period is not too short in relation to the speed of paper advance in the recorder, this effect can be smoothed. This penalty could be largely removed by changing the method of transducer mounting and control.

9. Present state of the art

In collecting these results, there was little opportunity to establish sufficiently accurate navigation, or a truly precise basis for comparison, but depth measurements, both here and in other observations suggest that an accuracy better than $\pm$ 2ft should be possible on a slowly undulating seabed before needing to make any modifications to improve fringe resolution, (for example by a multiplicative system [7]). When interference is formed on complex rock formations, quantitative measurements are not possible due to discontinuities in the fringes.

The overall accuracy would not satisfy the hydrographic requirements of today, but the interference method might well be useful for general topographical survey. Image interference, using the sea surface, is rather unpredictable but the observations, described here, might lead to an acceptable method of reconnaissance survey.

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10. References

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