NATIONAL INSTITUTE OF OCEANOGRAPHY

WORMLEY, GODALMING, SURREY

Factors affecting the Detection of Pinger Transducers

by

M. L. SOMERS, B.A.

INTERNAL REPORT No. A 27

NOVEMBER 1966

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Introduction

The outstanding success of the Swallow float (pinger) method of measuring deep ocean currents has stimulated a succession of improvements to the original system described in Ref. 1. Fundamentally, each improvement has been aimed at increasing the amount of information obtained for a given expenditure of ship time, firstly by increasing the number of floats which can be tracked simultaneously and secondly by increasing the length of time for which each float can be tracked. In practice, both these aims imply an increase in the maximum range of detection and hence a reduction in the time required to search for a float and obtain a bearing.

In describing the situation as it now stands, this report has two objects - the first of which is to collect under a single cover the results of work done from time to time over a number of years by a number of people and to make a quantitative assessment of this work in the light of experience at sea - the second of which is to discern more easily the areas where future effort might best be made.

For the sake of completeness, the report opens with a very short account of the tracking system in operation. This serves the purpose only of clarifying the quantities affecting detection. The equation relating these quantities is then written down and the terms are examined separately.

The Tracking Method

This is as follows. Referring to Fig. 1, the ship S steams along a known track T towing astern two hydrophones F and A which are separated by a known distance d. When the angle between the ship's track, i.e. the line of the hydrophones, and the horizontal projection of the line joining the float P to the hydrophones is θ the pings are received on the forward hydrophone F a time t before they appear on the after one A where

$$t = \frac{d \cos \theta}{c}$$ and c is the velocity of sound in the sea.

A bearing is taken by steaming on a straight course until $t = 0$ when the float is abeam. If, when a measurement is started, the ping appears on the forward hydrophone first then the ship must alter course away from the float to bring it abeam, and this affords a means of removing the port or starboard ambiguity. Strictly speaking, $t = \frac{d}{c} \cos \theta \cos \phi$ where ϕ is the inclination to the horizontal of the line joining P to the hydrophones, so that after fixing the float the maximum value of t can be used as a rough indication of depth, bearing in mind the known range.

A block diagram of the receiver used to measure t is shown in Fig. 2. The hydrophones are hollow barium titanate spheres resonant at 82 kc/s, mounted with broadly tuned preamplifiers in short lengths of oil-filled plastic hose. They are towed by their respective electrical cables and form a compact streamlined unit with low towing noise. Each amplifier has an attenuator, a filter with three choices of bandwidth and a detector. The detected outputs are mixed, with provision for independent cut-out, and recorded on an 18" Mufax recorder. The Mufax is driven by an external oscillator with fine frequency control. The floats are coded by an individual repetition rate in the region of (nearly) one pulse per second. The Mufax drive oscillator is set to $\frac{1000}{T}$ where T is the pulse repetition period of the float in seconds. If the ship and float are at rest relative to each other the pulse as received on the forward and after hydrophones will appear on the Mufax record as twin vertical lines (see Fig. 3). Where there is relative motion, the lines will be inclined at an angle depending on the approach velocity and the geometry of the Mufax record. The apparent change in period is approximately $t_0 \, v/c$. where t_0 = true period, v = approach velocity and c = sound velocity in sea water. So that on an 18" record with $t_0 = 1$ sec the pulse moves to left or right by an amount $\frac{18v}{c}$ inches each sweep. There are 100 sweeps in an inch of record, so that the inclination of the lines to the vertical is $= \tan^{-1} \frac{1800v}{c} = \tan^{-1} .63v$ where v = knots, or just over 30° for 1 knot relative velocity. A more general situation occurs when the Mufax period is not precisely adjusted to that of the float and both drift slowly with time, when the whole pattern has a slowly changing bias slope. For the change in this bias slope to be less than the Doppler slope due to 1 knot relative velocity requires a relative frequency stability of about 1 part in 104 over any 5-minute interval. Fig. 4 is a reproduction of a record taken during actual operation.

The Quantities Affecting Detection

The output of the tracking receiver is a trace on a Mufax record and we wish to examine the signal to noise ratio when this trace is just detectable by the operator. This is a rather imprecise definition of signal to noise threshold since the performance of operators is variable. Also, if the period of observation can be extended at will, the chances of detection are considerably increased, whereas practical considerations usually limit the period to about 10 minutes or 6 inches of record for each setting.

The transmission equation governing the various parameters at maximum range is, in decibel notation, as follows, where the terms are explained below

$$S_0 - D_1 - 20 \log r_{max} - 10^{-3} a\, r_{max} - R - N - B + P = 0$$

S_0 = Omnidirectional source level re 1 μ Bar at 1 yard from source, corresponding to power output of pinger transducer.

D_1 = Directivity index of source transducer defined as 10 log $\frac{I_0}{I}$

where I_0 = omnidirectional source intensity

I = intensity in direction of ship.

r_{max} = Distance from float to receiver in yards, known hereafter as the range.

a = Attenuation coefficient in dB/10^3 yards at operating frequency.

R = Propagation loss due to refraction.

N = Effective spectrum level of noise at hydrophone re 1 μ Bar in a 1 H band. N includes such sources as sea state noise, towing noise, ship's noise, circuit noise, etc., and also includes any discrimination against directional sources of which the hydrophone is capable.

B = Noise bandwidth of receiver re 1 H

P = Processing gain in the Mufax, defined as the excess of noise over signal (at the input to the Mufax) at which the signal remains just discernible.

Quantitative Discussion of the Various Terms

These terms can conveniently be divided into four groups, as follows:

(a) The source, S_0 and D_1

(b) Transmission through the medium, $(20 \log r_{max} + 10^{-3} a\, r_{max} + R)$

(c) The receiver, N + B.

(d) The recorder, P.

(a) S_0 and D_1 were measured for a number of transducers in the N.I.O. acoustic tank using a Type "D" pinger unit and a calibrated hydrophone. The nickel scroll transducers were drawn from stores and treated exactly as production units. Though the Type "D" pinger is a precision timed instrument unit, it has the same output amplifier as the Type "B" units used in deep current measurements. In all, eight scrolls were measured. Typical polar plots are shown in Figs. 5a and 5b where the scale is linear and one division = $10^3\,\mu$ Bar at one yard. There is a considerable variation in pattern from scroll to scroll, but it is clear that the radiation is strongest at an angle of about 45° to the scroll axis. The output in the plane of the scroll is up to 3dB less than the maximum, and in general there is a broad minimum along the axis. Some 20-30% of scrolls, however, actually show a maximum along the axis and it is suggested that this anomalous behaviour is due to a variation of stiffness along the depth of the scroll so that the mode of vibration is roughly as shown in Fig. 6. The variation of pattern in the plane of the scroll is probably due to a similar variation of stiffness and consolidation round the scroll circumference. This departure from axial symmetry can be as much as 6dB maximum to minimum, while the variation from scroll to scroll can be as much even with the inferior specimens discarded. Consequently little precision can be attached to a discussion of source level, but approximate figures are quite instructive.

Let the pressure distribution about the scroll at one yard be given by $p(\theta, \phi)$ where θ = the latitude and ϕ = longitude relative to the axis of the scroll, and let $W(\theta, \phi)$ be the total acoustic output in watts of an <u>isotropic</u> source whose uniform pressure amplitude p_0 happens to be equal to $p(\theta, \phi)$; $W(\theta, \phi)$ and $p(\theta, \phi)$ are connected by the relation

$$10 \log_{10} W(\theta, \phi) = 20 \log_{10} p(\theta, \phi) - 71 .$$

The power put out per unit solid angle in the direction (θ, ϕ) is $W(\theta, \phi)/4\pi$, so that the total power output from the scroll is $W_0 = 1/4\pi \iint_{\Omega} W(\theta, \phi)\, d\Omega$ where Ω represents solid angle, and $d\Omega = \cos\theta\, d\theta\, d\phi$. Where measured polar plots are available for several planes containing the axis it is convenient to assume axial symmetry and carry out the integration in ϕ using the average of all measurements as the polar plot in θ. Accordingly

$$W_0 = \frac{1}{2} \int_{-\pi/2}^{\pi/2} W(\theta) \cos\theta \; d\theta$$

and it is convenient and sufficiently accurate to replace this integral by a sum of about 10 terms, which gives for the scroll depicted in Fig. 5a a total acoustic output of 5.25 watts during the pulse, so that $S_0 = + 78.5$dB. While this is a representative figure, scrolls were encountered which were ± 3 dB different.

At extreme ranges (say five miles) the ray reaching the hydrophones is radiated at about 20° above the horizontal and the mean level in this direction for the scroll of Fig. 5a is +80 dB giving a directivity gain D_1 of -1.5 dB. This is not a very meaningful remark as at an unfavourable azimuth angle D could easily be +1.5 dB. Similarly D_1 would be positive for the anomalous scrolls with marked axial peaks, and more strongly negative for those scrolls with marked axial nulls.

As a broad average figure it is fair, provided the spread is borne in mind, to take +80 dB re 1μ Bar at one yard for $S_0 - D_1$.

(b) In its passage from scroll to hydrophone the acoustic energy suffers attenuation, absorption, scattering and refraction. The terms 20 log r and

$10^{-3}ar$ take account of attenuation and absorption where a has a value of very nearly 1 dB/10^3 yards at 10 kc/s, and Fig. 7 shows a graph of these quantities combined as a function of range. Sound is scattered out of the beam by biological material, air bubbles and to a lesser extent other sources such as internal waves. Horton ("Fundamentals of Sonar" U.S. Naval Institute) gives a set of curves for working propagation loss, indicating that at 10 kc/s the scattering loss is approximately the same as the attenuation loss, namely 1 dB/10^3 yards. This effect is added to spreading and attenuation in curve b Fig. 7.

The main effect of refraction is to limit the range of direct ray coverage, but in all normal situations the limit is greater than ten miles which is considerably greater than the maximum range of detection at present.

(c) The receiving circuits have a single-tuned band pass response with a choice of three bandwidths, the smallest of which is 200 cycles/sec designed to accommodate the 5 msec pulse length of the pinger. The ratio of noise bandwidth to 3 dB bandwidth of a single-tuned stage is 1.57 so that here the noise bandwidth is 315 c/s, so that B = +25 dB.

In assessing the spectrum level of the noise, several difficulties are encountered. The hydrophones are towed near the surface at some distance from the ship. With a source and hydrophone near the surface destructive interference occurs between the source and its image in the surface, so that the noise at the hydrophone due to the ship is reduced both by spherical spreading and interference. Unfortunately, the interference effect is not very useful since the pinger signal at extreme ranges arrives at about the same inclination to the horizontal as the ship's noise. Moreover, with a wavelength of only six inches, the hydrophone depth is critical but quite unknown. The situation is further complicated by the nature of the sea surface, so that it seems safest to take the measured spectrum level of ship's noise modified only by spherical spreading. For R.R.S. "Discovery" steaming at six knots the spectrum level at 10 kc/s at 100 yards is -48 dB re 1 μ Bar in a 1 c/s band.

The generation of near-field towing noise has been discussed by Skudrzyk and Haddle (Ch. 14 Underwater Acoustics - Alber. Plenum, N.Y., 1961). They give a formula and curves for the equivalent spectrum level of a towed hydrophone of about the right diameter, and from this information the figure obtained for towing noise spectrum level is -55 dB at five knots.

The third contribution to ambient noise is due to sea-state noise, which at sea state 4 is -49 dB and these three sources combined give a resultant level of -45 dB re 1 μ Bar in a 1 c/s band.

(d) It is well known that a continuous signal can be extracted from any level of noise provided that the characteristics of the signal are known and the appropriate averaging process is carried out for long enough. In pinger tracking the signal is a continuous line of small curvature on a facsimile record and experiments were carried out to determine the minimum signal to noise ratio at the input to the marking amplifier at which the signal was just detectable. An artificial signal and wide band noise from a noise generator were injected into a pinger receiver, the Mufax bias was adjusted for normal operation and the signal reduced in steps to the limit of detectability. Fig. 8 shows a record obtained with a signal to noise ratio of -4.5 dB. Fig. 9 shows a record obtained at sea, from which it can be seen that the noise encountered at sea is not strictly stationary Gaussian noise. An interesting feature of this correlation effect is that the human eye can only assess a limited length of record, so that there is a limit to the minimum signal to noise ratio and a figure of -4 dB is used for working calculations (see Tucker, D.G., J. Brit. I.R.E., Vol. 17, pp. 319-329, June 1957).

Maximum Detection Range

$$S_0 - D_1 = 80 \pm 6 \text{ dB}$$

$$N + B = -20 \pm 3 \text{ dB}$$

$$P = 4$$

$$104 = 20 \log r + 10^{-3} a\, r + \text{scattering loss}$$

From Fig. 7 the range for a total transmission loss of 104 dB is 11,300 ±25% yards. In view of the variation encountered in $S_0 - D_1$ and the uncertainty of the noise prediction this result shows encouraging agreement with practice and enables a certain amount of confidence to be attached to the discussion of possible improvements. It is, however, worth noting that at this range the transmission loss is increasing very rapidly, so that the possible error of ±9 dB results in a ratio of only 1.8 : 1 in maximum ranges.

Discussion

Before discussing lines of enquiry which might be profitable it should be pointed out how small the improvements are likely to be. Firstly, it is unreasonable to expect to be able to increase the term $S_0 - D_1$ by as much as 20 dB, as will be explained below. Secondly, one might consider using a directional hydrophone but complete elimination of ship's noise would lead only to a 3 dB improvement in noise level at sea state 4. Directivity can not be employed to reduce sea noise since the bearing of the float is unknown; and bandwidth reduction carries its own problems. In all, a 40 dB improvement seems highly optimistic although it would lead to less than 3 to 1 maximum range improvement. In the light of these remarks it is possible to discuss the terms of the transmission equation separately.

(a) $S_0 - D_1$. The power output of a nickel scroll has already been worked out at about 5 watts. By measuring the voltage and current it has been possible to work out the efficiency and to some extent the contributions of various lossy terms. Fig. 10 is an oscillographic recording of scroll voltage and current taken simultaneously with zero levels and scales indicated. A point by point numerical analysis over one cycle was carried out using 22 points and this gave the following quantities:

Total power input to scroll 75 watts.

D.C. power input to scroll 15 watts, to maintain magnetic bias.

Power drawn from the supply 250 watts.

Magnetic bias = 420 Amp-turns/metre.

Peak magnetic field = 1330 A-t/m.

Minimum " " = -240 A-t/m.

r.m.s. current = 4.4 Amps.

AC + DC copper loss ≃ 5 watts.

Electro-acoustic efficiency η = 6.5%.

These figures are more meaningful when studied in conjunction with the hysteresis loop shown in Fig. 11a, where the bias and AC operating regions are shown. The magnetostrictive strain s is given very closely by $s = c(B - \mu_0 H)^2$ to very high fields, where c is a constant characteristic of the material, but for all practical purposes this may be written $s = cB^2$ (for nickel with $B_{sat} = 0.6$ W/m^2 the error involved is about 10% at 16,000 A-t/m). The first thing to notice is that the scroll is being driven between nearly saturation and zero or in this case reversed flux, in fact the peak to peak driving stress is very near its absolute limit, which implies that the power output also is. The reversed flux has two effects: first it reduces the peak to peak driving stress at the fundamental frequency and dissipates energy in harmonics and secondly, a remark which applied to any flux below the "knee" of the hysteresis loop, it greatly increases the area of the hysteresis loop and hence the hysteresis loss. From the figures given above this loss is (with eddy currents) about 50 watts so it is well worth reducing. In fact by restricting the flux density to be greater than B_{rem} the output will fall by only 3 dB while the hysteresis loss will be nearly an order of magnitude less. Advantage could also be gained, since the scroll is mechanically tuned with a Q of about 5, by shaping the input current to give a sinusoidal driving stress. However, these measures are unlikely to increase the power output to more than 10 watts or the efficiency to more than 15 - 20%. One approach would be to use more nickel, that is, have an array of scrolls which would also serve to improve the load impedance presented by the water due to the larger area. The penalties would be extra weight and more copper losses but 3 or 4 scrolls might give 30 to 50 watts output at 10 to 20% efficiency, and a directivity gain of 10 dB.

An alternative approach is indicated in Fig. 11b which is a hysteresis diagram for a Permendur scroll. The constant c is rather less for Permendur than for nickel commonly being about half the value, however, the range of flux density available without going past the "knee" is about four times as great for twice the number of ampere turns. The peak to peak strain amplitude is given approximately by $s_{ac} = 2\ C\ B_{mean}\ \Delta B$, and restricting operation to similar portions of the hysteresis loop it can be seen that it is possible to generate five times the strain in Permendur, again for twice the number of ampere turns. In this case the permeability is of the order of 200 compared with 50 for nickel. It is not surprising that an experiment in which a Permendur scroll was substituted direct for a nickel one gave a negative result, since these remarks illustrate the different drive requirements of the two cases.

In operating over an appreciable portion of the hysteresis loop a non-linear impedance is presented to the output amplifier which in the present arrangement is operated in the half-wave class B mode (but roughly tuned). With a linear resistive load and full use of the supply voltage the output stage should have an efficiency of 60 - 70%, depending on the transistor bottoming voltage. The experimental arrangement has an efficiency of 30% because the load is neither linear nor resistive and the output transistor was not bottoming. With full use of the supply voltage and careful adjustment of the drive to the output amplifier, it might be possible to achieve about 50%, particularly with Permendur scrolls which have a more constant permeability. This would lead to an overall efficiency of 5 or 10% instead of the present 2%. In conclusion, it can be said of all magnetostrictive scrolls that to obtain more than a few dB increase in acoustic output would incur a heavy curtailment of battery life. The output stage efficiency could be increased by applying a square wave base drive to the output transistors so that they operate either bottomed or cut off. This would involve heavy overdrive on the base to ensure bottoming during the high peak currents drawn when the scroll approaches saturation and would thus make the output stages very vulnerable to fault conditions. If this risk is acceptable the output stage efficiency could be increased to 85 - 90%, but it would not increase the efficiency of the scrolls.

An alternative form of transducer which comes near to competing with the scrolls in cheapness and simplicity is the open ferro-electric ceramic tube, operated in the half wave organ pipe mode, in which the water column resonates at a frequency where the tube is half a wavelength long. The author has obtained an acoustic output of several tenths of a watt at an overall efficiency of more than 50%. It is not at present known what the main limitations on power output are, but the main practical problems to be overcome are insulation of the silvered ceramic surfaces and the mechanical fragility of the tubes. It is, however, worth enquiring further into this form of transducer due to its combination of cheapness and efficiency. An alternative form of transducer is known as the barrel stave arrangement which is constructed in the form of a ring with alternate segments of ceramic and heavy metal. The heavy metal segments serve the purpose of reducing the operating frequency for given dimensions. These transducers would undoubtedly have much lower losses than scrolls, but are an order of magnitude more expensive and are very fragile. They suffer the same wiring and insulation problems as the ceramic tubes.

(b) In considering the transmission loss it is clear that this can only be reduced by a lower frequency of operation and present thinking inclines to a value of 7 kc/s as a compromise between transmission anomaly and transducer convenience. This frequency also opens up the possibility of using as a receiver the powerful transducer being built at N.I.O. for the G.L.O.R.I.A. project. Some 30 dB improvement in threshold noise seems to be available.

(c) The only possibility of reducing the spectrum level of noise at the hydrophone lies in making the hydrophone directional, which has the disadvantages of making the search pattern more complicated and the hydrophone more cumbersome. It is, however, a possibility. Bandwidth reduction is limited by Doppler shift of the pulse frequency. At 6 knots relative velocity the Doppler shift in 10 kc/s is 20 c/s, so that unless a search in Doppler is carried out there is but limited scope for increasing the pulse length and reducing the receiver bandwidth from its present 200 c/s. The only other line to be pursued is the prospect of transmitting a long coded pulse and using correlation techniques in the receiver, which might improve the signal to noise ratio by 20 dB with suitable system constants. The gain would be made by putting 100 times as much energy into the water during the long pulse and this might again raise problems of battery life.

Conclusion

There seems to be little prospect of significantly raising the output of the nickel scroll transducers in use at present, unless they can be used in an array. On the other hand, the efficiency of operation could be much improved if a lower source level were tolerable. Permendur scrolls offer in principle the prospect of 10 - 15 dB greater output at equal or better efficiency, if the power amplifier is carefully designed. Open ceramic tubes are a promising line of enquiry particularly in the direction of increased efficiency.

In conclusion, it should be emphasised that the improvement of more than 20 dB necessary to double the range is not likely to come about as the result of a simple and cheap modification to the system.

Reference

(1) Swallow, J.C. and Worthington, L.V. 1961 An observation of a deep counter-current in the western North Atlantic. Deep-Sea Research, **8**, 1-19. (No. 356 in N.I.O. Collected Reprints).

FIGURE 1

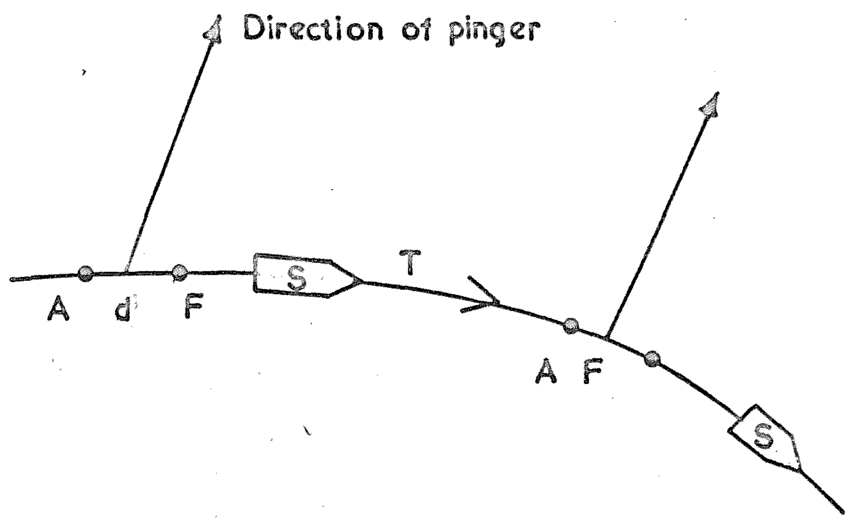


FIGURE 2

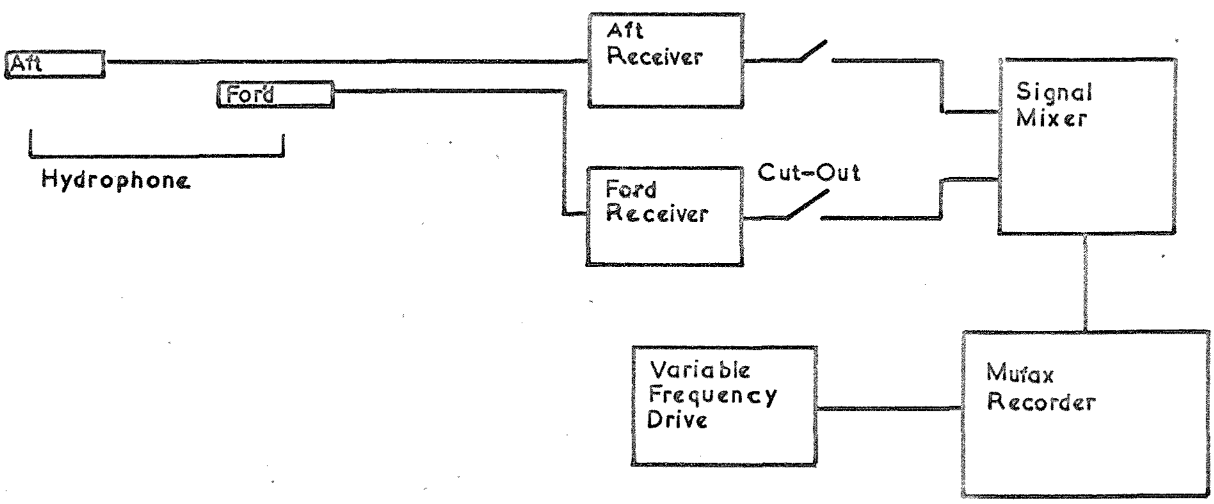
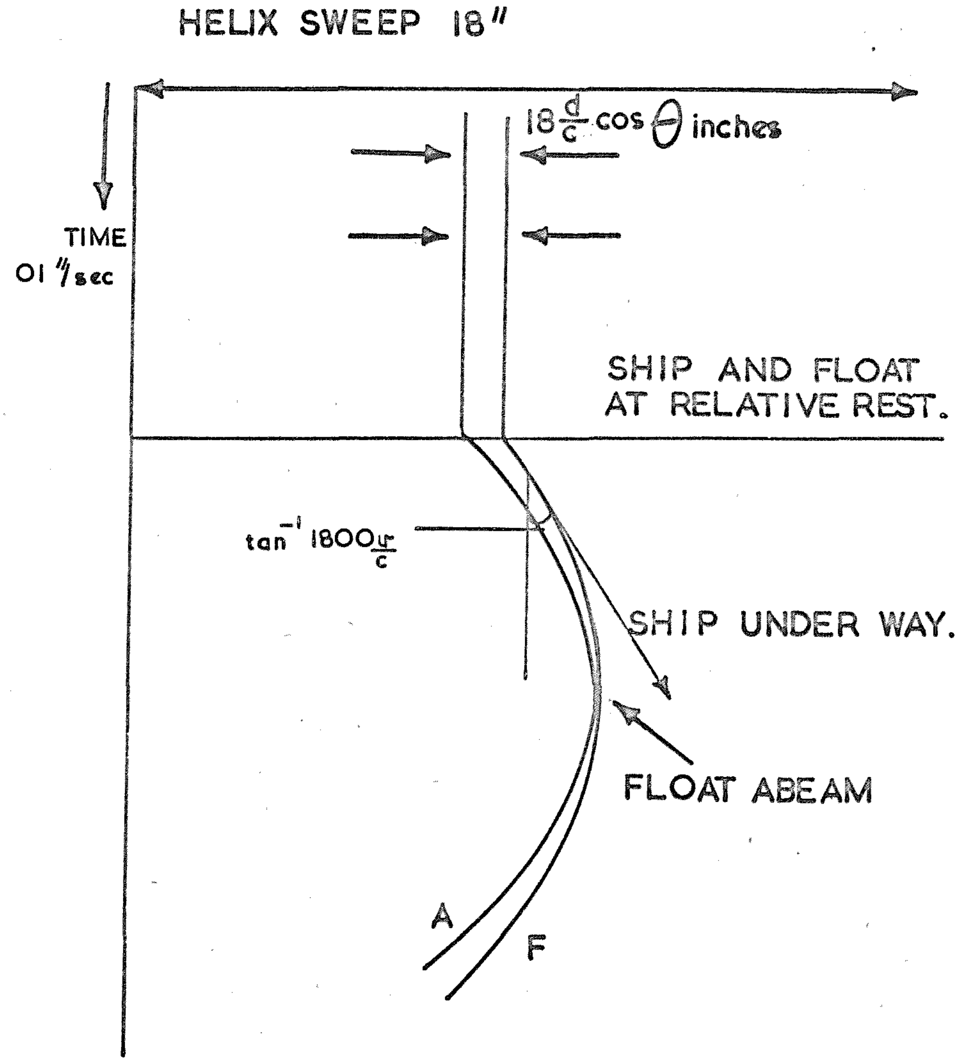


FIGURE 3



HELIX SWEEP 18"
$18\frac{d}{c}\cos\theta$ inches
TIME
O1 "/sec
SHIP AND FLOAT
AT RELATIVE REST.
$\tan^{-1} 1800\frac{v}{c}$
SHIP UNDER WAY.
FLOAT ABEAM
A
F

FIGURE 4

Reproduction of Mufax record.

FIGURE 5a 5b

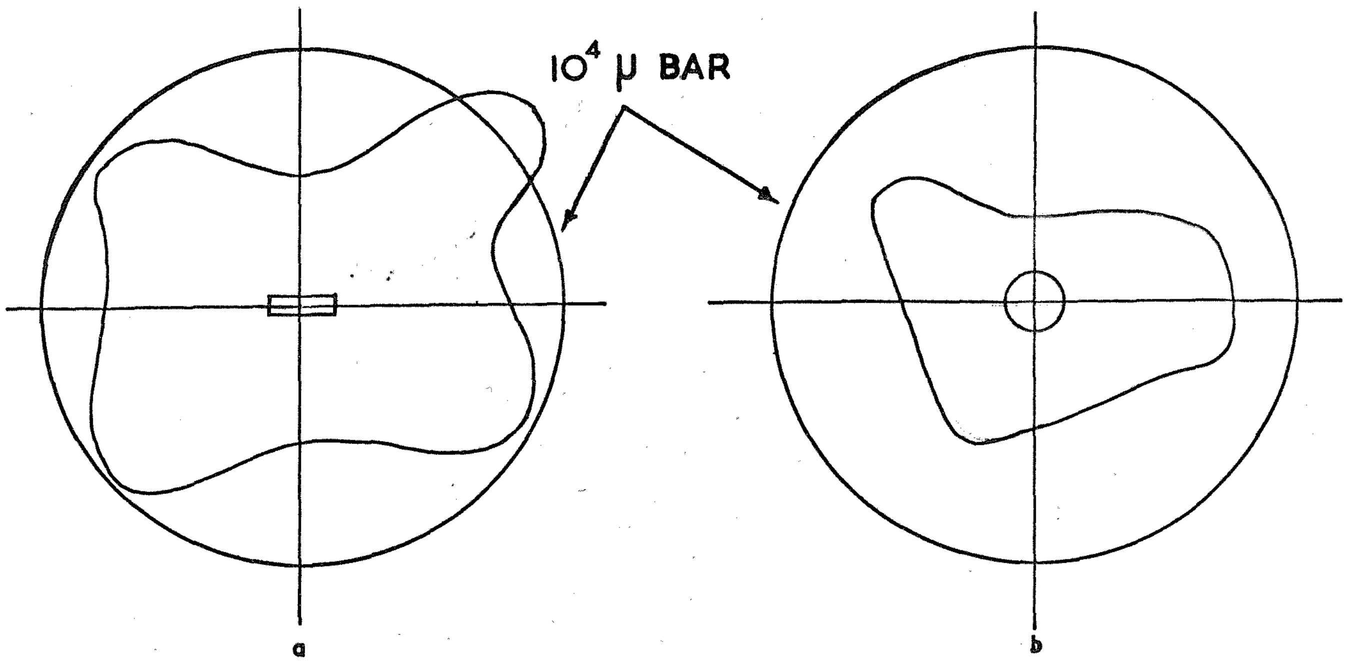
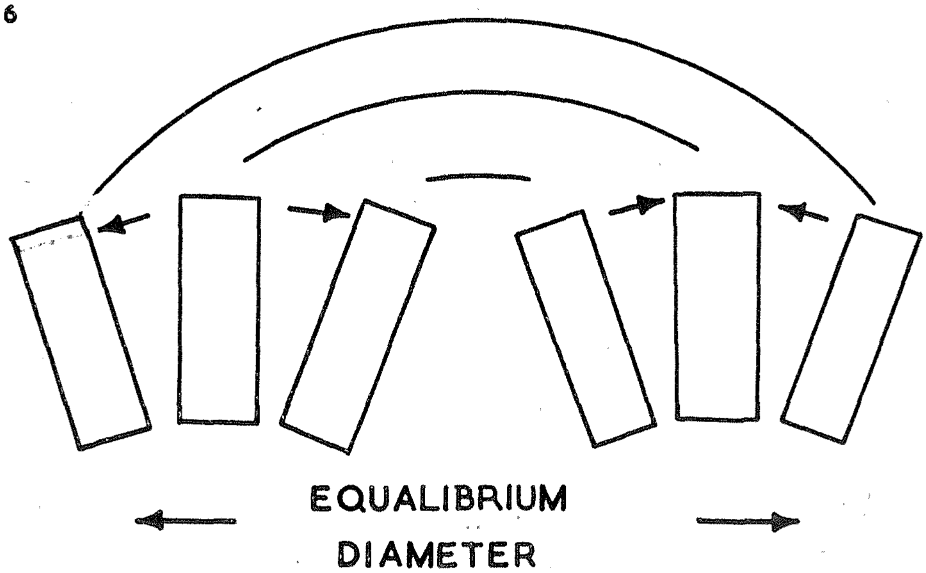


FIGURE 6



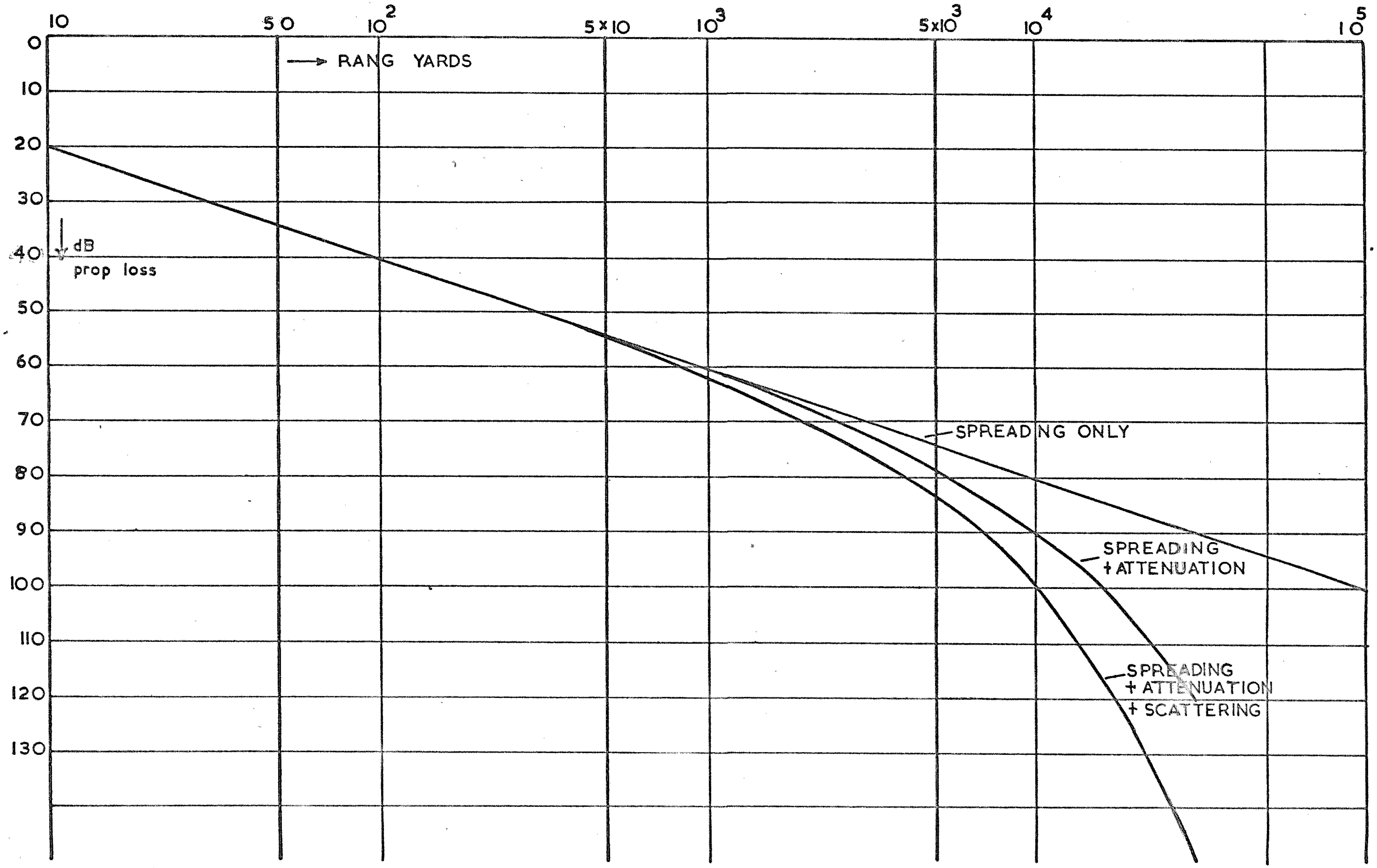

10
50
10²
5×10
10³
5×10³
10⁴
10⁵
RANG YARDS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
dB
prop loss
SPREADING ONLY
SPREADING
+ ATTENUATION
SPREADING
+ ATTENUATION
+ SCATTERING

FIGURE 7

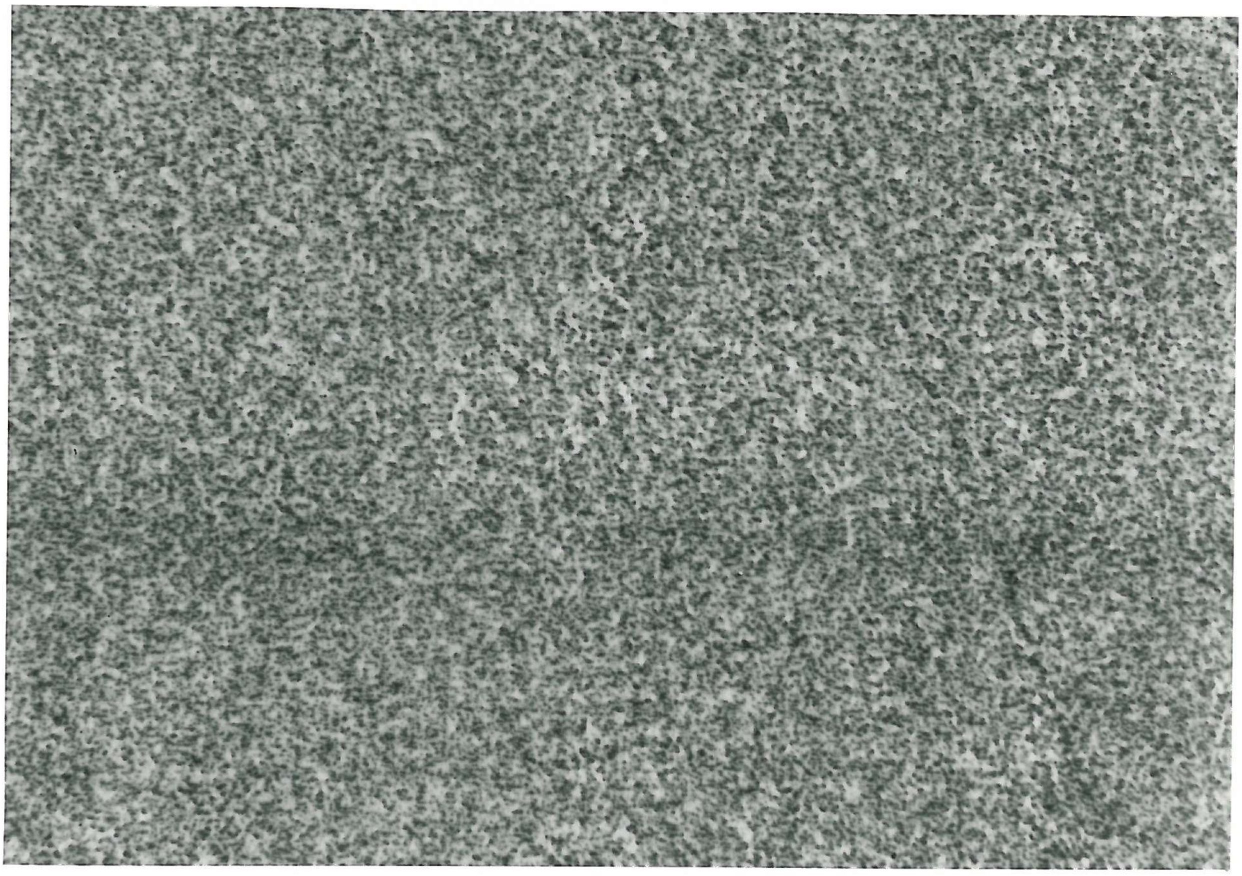


FIGURE 8

Photograph of -4.5 dB S/N Mufax record

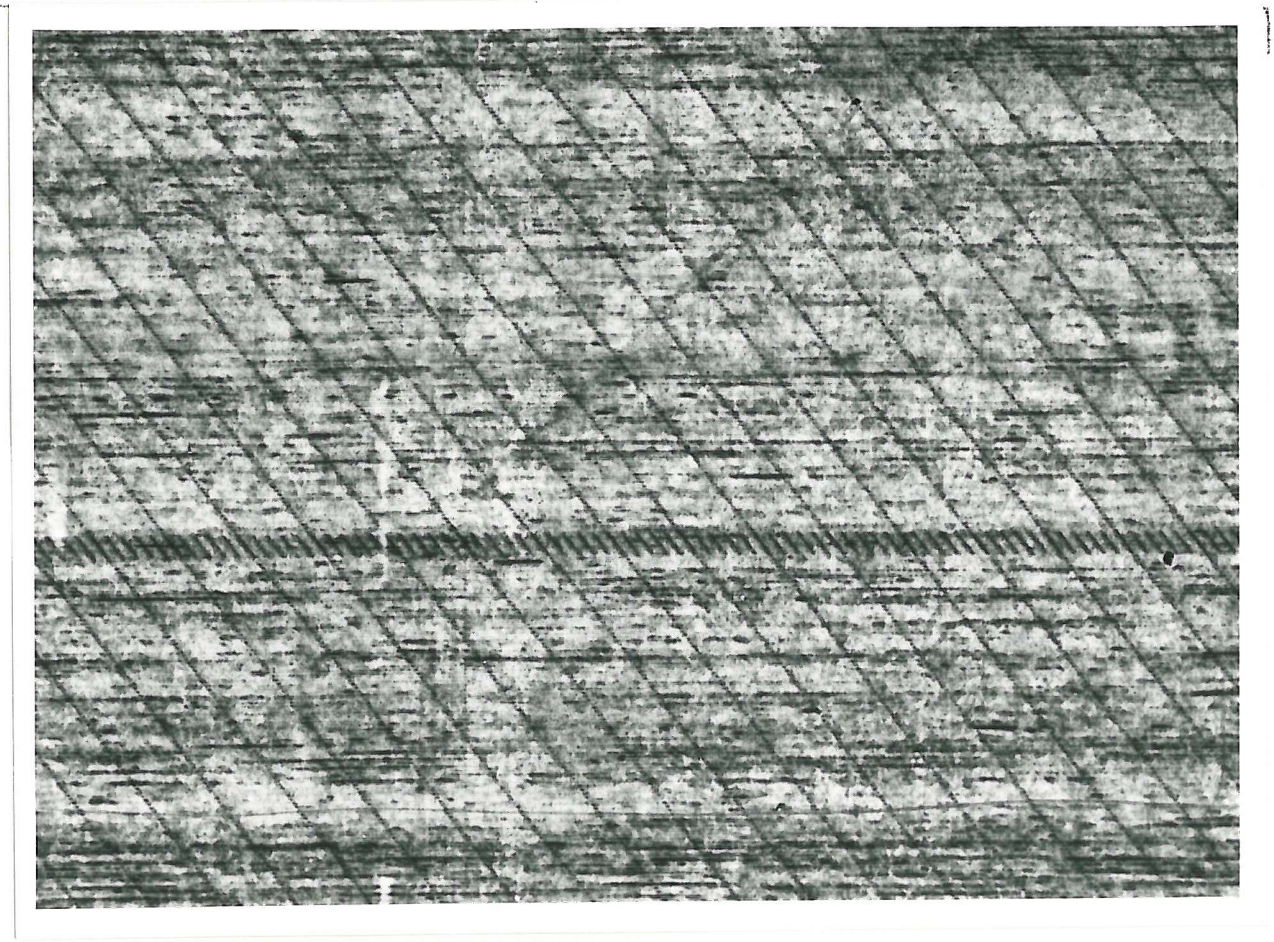


FIGURE 2

Low signal obtained at sea

FIGURE 10

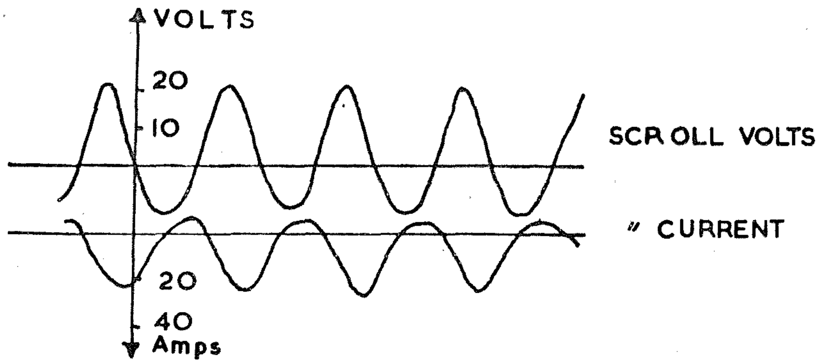


FIGURE 11