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THE VARIATION OF SEABED SCATTERING STRENGTH WITH ANGLE AT HIGH FREQUENCIES

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INTRODUCTION

The variation of seabed back scattering strength with angle leads to a bias error in doppler sonar velocity sensors used in bottom track mode. In order to establish the magnitude of this bias error, experimental work was undertaken to measure the scattering strength variation at sample sites off the west coast of Scotland at frequencies of 200kHz and 550kHz. In the following paper, the experimental method is described, together with the analysis adopted to extract the scattering strength from the measured signals. It is shown that, for the sites investigated, the variations of the calculated signal strength of the return signal at the seabed are similar at both 200kHz and 550kHz. Sites off Troon, however, showed a marked increase of signal strength with angle, whereas sites in Upper Loch Fyne showed a more gentle increase, in particular at large angles of inclination. The effect of the worst case variation on the accuracy of doppler sonar sensors leads to an inaccuracy of approximately 1.5%, assuming a 10° beamwidth, and an angle of inclination of 60°.

EXPERIMENTAL AND ANALYTICAL METHOD

Four transducers, two facing fore and two aft, were held one metre below the ship's hull on a pole attached to the deck. One pair of transducers operated at 200kHz, the other at 550kHz. The angle of inclination of each pair of transducers was varied by means of a hand operated mechanism accessible from the top of the pole. At each site, the ship was anchored, and thirty seconds of data was collected at seven beam angles between 20° and 80° to the horizontal at 10° intervals. These angles could be set up with an accuracy better than 1°. The pulse length and pulse repetition rate were scaled at each site in accordance with the mean depth, in such a way that a constant mark to space ratio of 1:10 was maintained. It was thus ensured that the same amount of data was processed each time, and therefore any statistical fluctuation related to the number of independent samples was constant from site to site. The receiver gain was changed manually in 10 dB steps, as required, in order to increase return signal strength for small angles of inclination and correspondingly long ranges.

For each channel the sonar return signals were amplified and mixed with an offset carrier to yield a baseband signal centred on 2kHz or 4kHz for the 200kHz and 550kHz transducers respectively. These baseband signals were recorded on an analogue instrumentation tape recorder (IRIG wideband 2 FM at 7½ ips) and subsequently transcribed to disk storage on a minicomputer (VAX 11-730), by means of an A to D convertor sampling at 10kHz or 20kHz for the 200kHz and 550kHz signals respectively.

For each transmitted ping, an appropriate length of the sampled data following that ping was retrieved and analysis proceeded as follows; the envelope of the data is calculated, and the start and finish of the return pulse are located by establishing at what points the envelope crossed a threshold. The threshold level was chosen to be above the noise floor, and such that the mean of the calculated length of the return pulse when averaged over the data set, is equal to the length of the transmitted pulse, for reasons discussed subsequently. The satisfaction of this criterion, together with a check that the positions of the assumed return pulses do not vary radically from ping to ping, and are consistent with the measured depth, ensure that real bottom returns and not other artefacts are being measured. Having calculated the average signal strength over the return pulse for each individual ping, compensation is then made for the reduction in energy due to the spreading effect on return, and due to absorption by sea water.

The return signal strength amplitude at the seabed, s (Θ) is thus given by

$$s(\Theta) = a\,(\Theta).10^{((\beta 2r)/20)}\,r \qquad (1)$$

where

a is the amplitude of the return signal at the transducer, in relative units,
β is the absorption coefficient, in dBm^{-1}, and
r is the range to the seabed, compensating for spreading effects.

In practice, a quantity x is first output from the software. a(Θ) is related to x by

$$a(\Theta) = Kx \qquad (2)$$

K is calculated by taking into account the projector and hydrophone sensitivities of the transducers, which have been fully calibrated, the driving voltages, and a multiplicative factor, C, relating ADC values to the return voltage in volts and is equal to

$$K = 10^{-(S_p + S_h)/20}/(CV_i) \qquad (3)$$

where

S_p, S_h are projector and hydrophone sensitivities respectively,
V_i is the output voltage, and
C is a constant multiplicative factor.

Range is estimated from the position of the return pulse, identified by the thresholding technique.

The mean and standard deviation of the signal strength at the seabed for all return pulses at each site and angle are then calculated, and the variation of signal strength and range with angle is output graphically. In practice, the signal strength s(Θ)/K is shown on the figures. This is equivalent to the amplitude of the return signal strength at the seabed, in ADC units.

Various tests are undertaken as the data is processed in order to ensure that no spurious results are obtained. The range variation with angle of inclination should follow an inverse sine law, if the seabed is flat. The approximation of the data to this law is the first check of good data. The next is a range calculation check. The calculated range for each ping is compared with a weighted sum of previous good ranges, and if the value is significantly different from previcus good values, the ping is excluded from the data set.

A problem occurs in the case of a low signal to noise ratio. As the return signal strengths of each individual pulse fluctuates by approximately forty per cent from the mean (see Figs 1-2), the weakest returns are processed with difficulty, and, if spurious noise is stronger than the return in a particular case, the "bad range" criterion described above, will detect that the return has not been located, and will exclude the ping from the data set. Thus, the method is not applicable in cases of poor signal to noise ratio, as the processing method mitigates against weak returns, and will overestimate the average scattering strength. For this reason, runs are only included if the "bad range" flag is set in less than five per cent of cases.

A further effect of poor signal to noise ratio is that, within a given return, only the strongest parts of the return are detected, which will again lead to an overestimate of scattering strength. Another possibility is that a fluctuation in background noise above the threshold level will lead to an increase in the apparent length of the return. Both these effects lead to a larger than average fluctuation in the effective length of the signal return, and to a larger fluctuation in the range calculation. In cases where either effect is marked, results from the data set are not included.

In cases where the signal to noise ratio is high, the correct positioning of the threshold is important; if it is set too low, noise may be incorporated in the supposed return, leading to a longer than expected return pulse length; if the threshold is set too high, only the strong parts of the signal return will be detected, leading to a smaller than expected pulse length. The threshold is thus chosen so that the mean return pulse length is equal to the transmitted pulse length, and the standard deviation of the pulse length is small.

With the adoption of such tests and acceptance criteria, a high confidence can be placed on the scattering strength calculated by this method.

RESULTS

Results have been analysed at two different sites off Troon, and at two sites in Upper Loch Fyne, at both 200kHz and 550kHz. Sample graphical outputs are shown in Figs 1-2. The mean and standard deviation of return signal strength $s(\Theta)/K$, is plotted against angle.

The commensurate ranges calculated from the arrival times of the return pulses are given in Figs 3-4. AØ and BØ labels refer to the fore and aft transducers respectively.

In Figs 5 and 6 are plotted the seabed backscattering strengths in dB as a function of angle, for all sites. The scattering strengths are per unit area. At large angles of inclination, the whole footprint will contribute to the signal at any instant in time. At smaller inclination angles, however, the effective footprint size, ie the area at any instant contributing to the signal, is limited by the pulse length. The expressions for the two areas are as follows.

At large angles of inclination,

$$A = (\phi r)\,(\phi r/\sin\Theta) \qquad (4)$$

At small angles

$$A = (\phi r)\,(c\tau\,\sec\Theta/2) \qquad (5)$$

where

ϕ is the beam width
r is the range
τ is the pulse length
c is the velocity of sound, assumed to be $1500ms^{-1}$
Θ is the angle of inclination

This is clearly represented in Fig 7, reproduced from Urick (1954).

For each set of returns at one angle, the value of A is taken to be whichever is the smaller of the values given by equations (4) and (5).

Backscattering strength is defined as (Wong and Chesterman, 1968)

$$S_b(\Theta) = RL - I_0 + 20 \log (b(\Theta)) + 40 \log(r) + 2\beta r - 10 \log (A) \quad (6)$$

where

RL is the reverberation level, ie $RL = 20 \log (a(\Theta)) - 10 \log b(\Theta)$
I_0 is the initial signal intensity, ie
$I_0 = 20 \log (V_i) + S_p - 10 \log b(\Theta)$, and
$b(\Theta)$ is the directivity index.

Its relationship to the scattering strength, $s(\Theta)$, defined by equation (1) is

$$S_b(\Theta) = 20 \log (s(\Theta) - 10 \log (\phi c\tau/(2d)), \quad (7)$$

where d is the length of the footprint.

The following trends will be noted from Figs 5 and 6. The results from the sites off Troon show a marked increase in scattering strength with angle, which is quite linear in the range 30°-70° and spans approximately 10dB over the whole range. The increase in scattering strength for Loch Fyne is less steep, and increases less markedly at higher angles of inclination. The increase is on average 3dB over the range from 40°-80°. (Data for smaller angles of inclination is not available for Troon).

It is interesting to compare these results with those reported in the literature. Wong and Chesterman (1968) made measurements at 48kHz over a variety of seabed types but at smaller angles of inclination. Urick (1954) considered frequencies of 55kHz and 60kHz, and found increases of scattering strength with angle of the order of 30dB over the range 20°-80°. Madhavan and Vijayakumar (1981) carried out experiments at 19.1kHz and 9.5kHz and report a gradual increase of scattering strength with angle. McKinney and Anderson (1964) undertook a more comprehensive survey at 16 locations, over a frequency range of 12.5kHz to 290kHz, and these results are the most relevant to the present survey.

Their results in general show an increase in scattering strength with angle, at 100kHz, which varies from 15dB for a rock seabed, to approximately 5dB for sand over a range 20°-80°. With a mud or gravel seabed, the increase was less than 1dB over the 20°-80° range. The curves for very fine muddy sand and silt show a tendency to level off at higher angles. Our results thus agree well with the results of McKinney and Anderson, and suggest that the seabed in Loch Fyne is likely to be of fine mud or silt, and the seabed off Troon would appear to have characteristics similar to rock.

EFFECT ON THE ACCURACY OF DOPPLER SONAR SIGNALS

As has been discussed in a previous paper (Boulton, 1984), a variation in scattering strength with angle leads to a bias error in estimation of the doppler shift in a backscattered signal received by a ship moving relative to the seabed. This is due to the fact that, as the beamwidth is finite, one side of the beam intersects the seabed at a steeper angle than the other side, and receives a smaller doppler shift. If the beam elements giving rise to a smaller doppler shift also lead to stronger return signals, due to the variation in scattering strength with angle, then the frequency spectrum will be skewed towards the lower frequencies. Our trials have demonstrated that the degree of variation at the frequencies of interest is not constant from site to site, so it would not be possible to compensate completely for the skewing effect in the general case. The worst case variation over an assumed 10° beamwidth is of the order of a factor of 1.25 dB. This will lead to a shift in beam centroid of less than 0.5°.

The doppler shift, Δf, is given by

$\Delta f = 2f\ v\ \cos\Theta / c$,

where

v is the ship's velocity
f is the transmitted frequency
c is the velocity of sound
Θ is the angle of inclination (8)

The relative error in doppler shift, and hence in the velocity estimate, is given by

$e = \cos\Theta / \cos(\Theta + \delta\Theta)$ (9)

where

$\delta\Theta$ is the shift in the beam centroid.

Hence, for a shift of 0.5° and an angle of inclination of 60°, the relative error, e, is equal to 1.5%.

It is to be noted that, if the increase in scattering strength is most marked at large angles of inclination, around 80°, any pitch and roll, even if measured and compensated for, will increase calibration error as the sonar beam shifts to a more vertical position.

CONCLUSIONS

Experimental work has been undertaken to measure the seabed backscattering strength with angle of inclination at sample sites off the west coast of Scotland, at frequencies of 200kHz and 550kHz. The results are in agreement with those reported by other authors, and show an increase in scattering strength with angle of inclination. The rate of increase is significantly greater at sites off Troon than at sites in Upper Loch Fyne.

Our particular interest in scattering strength variations is with respect to its effect on the accuracy of doppler sonar systems operating in bottom track mode. The worst case variations leads to an inaccuracy of approximately 1.5%, assuming a 10° beamwidth, and a 60° angle of inclination.

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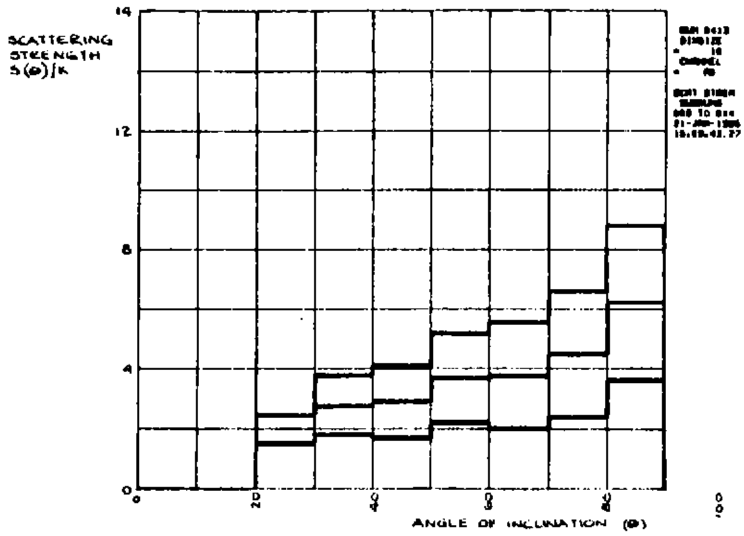

FIGURE 1

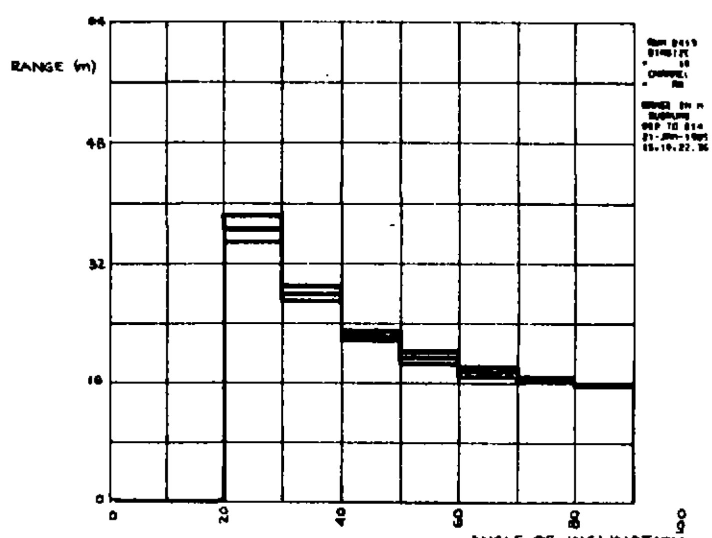

FIGURE 2

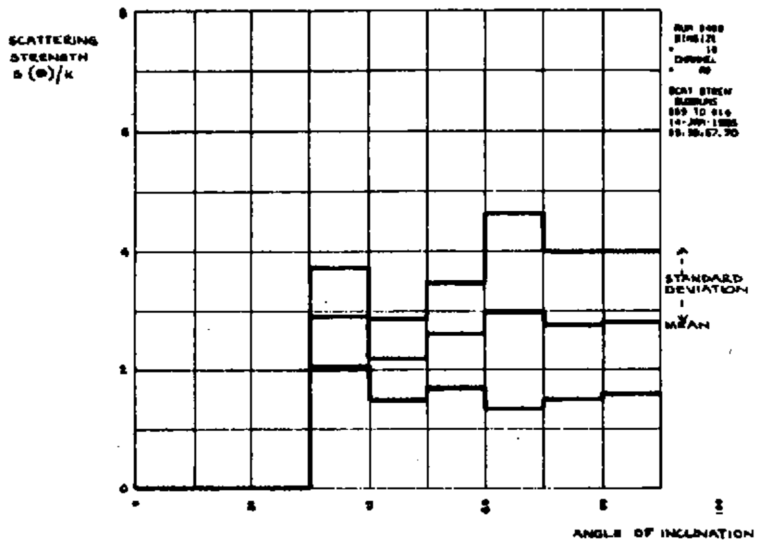

FIGURE 3

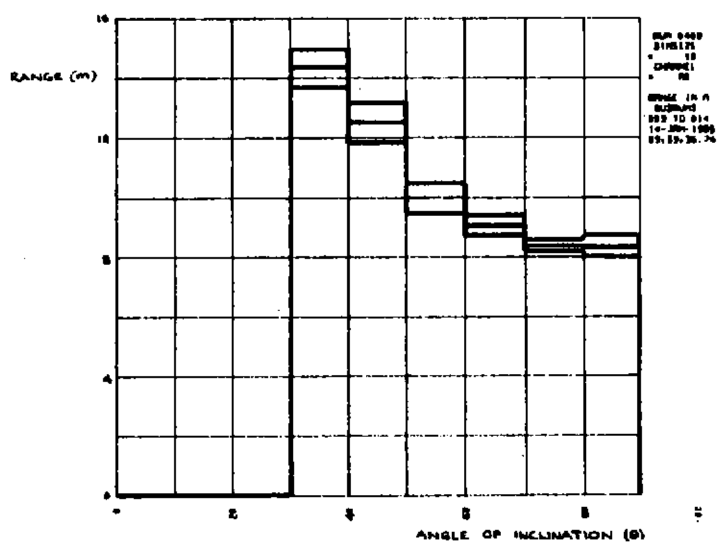

FIGURE 4

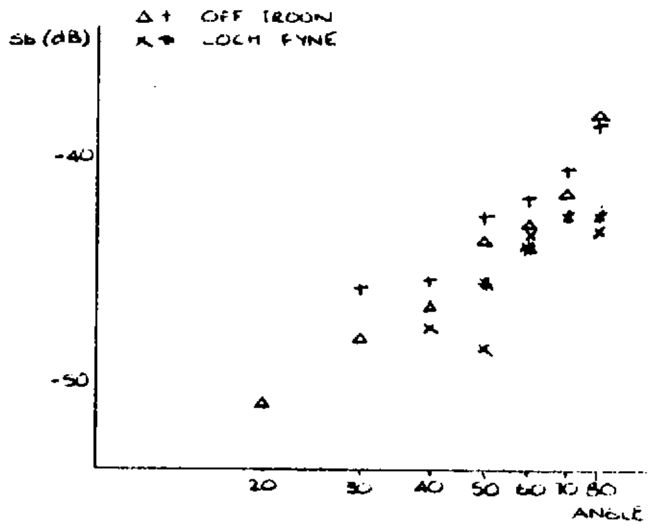

FIGURE 5
SCATTERING STRENGTH v ANGLE OF INCINATION AT 550 KHz

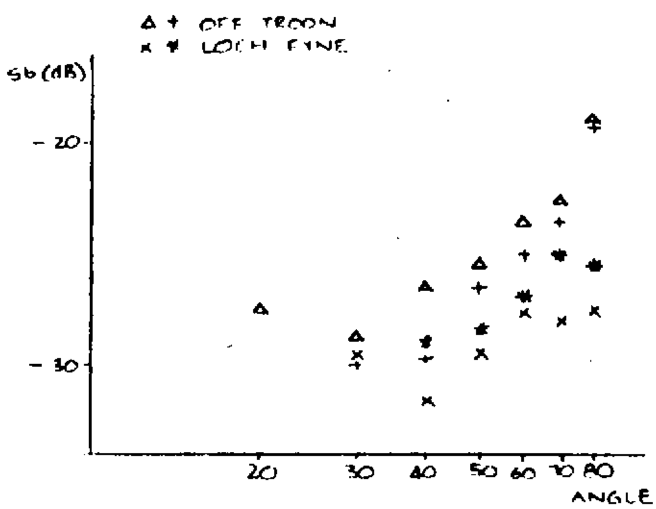

FIGURE 6 SCATTERING STRENGTH v ANGLE OF INCLINATION
AT 200 KHz

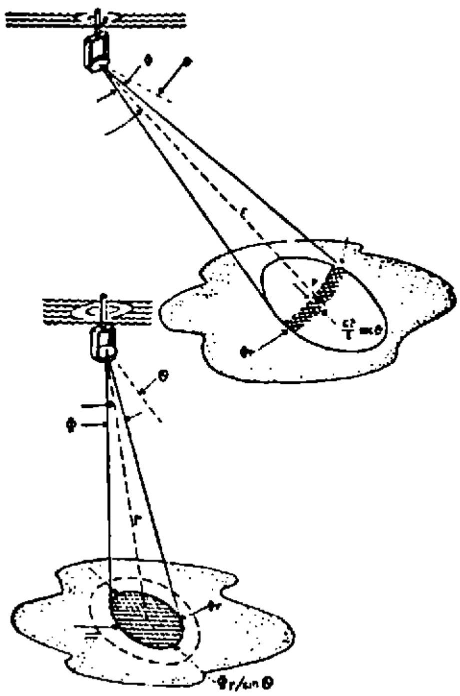

FIG. 7 Geometry of scattering with a searchlight transducer beam.