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INITIAL SHALLOW WATER BOTTOM LOSS MEASUREMENTS IN THE TIMOR SEA

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ABSTRACT

The acoustical features of the shallow water environment can have a harsh effect on the performance of sonar systems. By no means the least important of these features are low grazing angle values of bottom reflection loss, which can largely determine the level of transmission loss encountered. This paper presents the initial results of measurements of low grazing angle bottom loss conducted in the shallow waters of the Timor Sea to the north of Australia. The measurements were performed over the frequency band 0.5 - 4 kHz via a technique which exploited the interference field created by the interaction between direct path and bottom reflected sound.

1. INTRODUCTION

Bottom reflection loss is an important parameter in underwater acoustics which can have a significant effect on the propagation of sound, and hence the performance of sonar. This is particularly true in shallow water, where high levels of bottom interaction often occur. So that the acoustic characteristics of particular shallow water regions can be determined with confidence, it is important to establish techniques to measure bottom loss, and to relate the geo-acoustic characteristics of sediments to models of bottom loss. A significant amount of research has already been carried out in these areas (for example see references [1-6] for bottom loss measurements, and references [7-18] for bottom loss models and sediment geo-acoustics).

Referring to Etter [19]: "The standard method for measuring bottom loss is to use pings or explosive pulses and to compare the amplitude, intensity or energy density (integrated intensity) of the bottom pulse with that of the observed or computed pulse travelling via a direct path". In shallow water difficulties are experienced with this approach due to the presence of surface reflected and multipath sound, which hinders the discrimination of the direct path and bottom reflected pulses. In this paper, details are given of an alternative technique for measuring bottom loss which exploits the near-simultaneous arrival of direct path and bottom reflected pulses via measurement of the associated "Lloyd mirror" interference field. This technique was originally developed approximately 50 years ago at the Woods Hole Oceanographic Institution (see reference [20]), but since then, it does not appear to have been widely used, although references to bottom reflection interference patterns have appeared in the literature (for example see references [21, 22]). An outline is provided of an experimental trial in which shallow water bottom loss was determined from measurements of the bottom interference field. Rather than using a single hydrophone to perform the measurements (as done by the original developers of the technique), a VLA receiver was used to simultaneously sample the field to produce a "snapshot". There were a number of advantages associated with doing this which included greater accuracy of the sample spacing, and the ability to average consecutive snapshots. The paper proceeds with the presentation of some initial measurement results corresponding to the frequency 1970 Hz, and these are compared with modelled values of bottom loss. The model used for this comparison assumes that the bottom is a homogeneous lossy fluid with a plane interface, and uses geo-acoustic parameters determined from sediment samples taken at the measurement site. The paper finishes with a "summary and conclusions" section which includes details of the ongoing research being conducted by DSTO in this area.

2. EXPERIMENTAL TECHNIQUE

An experimental trial (titled "Shallow Water Active Sonar" SWAS 2/95) was conducted by the DSTO in September 1995 in the shallow waters of the Timor Sea to the north of Australia. A major objective of this trial was to conduct low grazing angle shallow water bottom loss measurements over the frequency band 0.5 - 4 kHz. Two trial sites (A and B) were selected which were located approximately 120 and 150 nautical miles west of Darwin, at the respective coordinates 128^{0}20' E 12^{0}20' S and 128^{0}45' E 12^{0}15' S. At site A the water depth was approximately 109 m, and the bottom type was broadly classified as clayey sand. At site B the water depth was approximately 100 m, and the bottom type was broadly classified as fine sand. At both sites the bottom was very flat with a slope less than 3-4 m over a range of 5 nautical miles from each site. Sound speed profiles measured during the trial had the characteristics that they were mildly downward refracting in the top half of the water column, and had nearly uniform values of 1538 m/s below 60 m.

Figure 1 shows the deployment of equipment for undertaking the bottom loss measurements. The source was deployed from the anchored CSIRO Fisheries Research Vessel "Southern Surveyor", and consisted of a vertical line array (VLA) of 4 Sparton Barrel Stave elements (Model 03BA1100) which were driven in-phase and could have the separation distance fixed at half wavelength for 1, 2 and 4 kHz (assuming 1500 m/s speed of sound). The source level varied between 170-190 dB re μPa @ 1m depending upon the frequency and element spacing. The receiver was deployed from the drifting RAN vessel "HMAS Balikpapan", and consisted of a VLA of 25 hydrophones, spaced to provide three 13 element nests with half wavelength spacing for 1, 2 and 4 kHz. Data recording was only possible on one hydrophone nest at a time, and the data sampling rate was 10 kHz. Sensors located on both the source and receiver enabled the depth and tilt of the equipment to be continuously monitored.

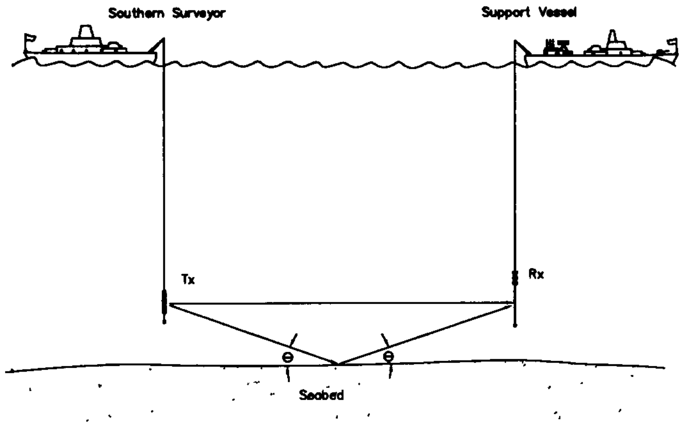

Figure 1: *Deployment of equipment for the measurement of bottom loss.*

The measurements were made using 0.2 s duration sinusoid pulses at the frequencies 500, 1175, 1500, 1970, 2500, 3000 and 4000 Hz. The procedure was to allow the ships to drift apart while the pulses were projected at the rate 1 pulse every 5 s. For each pulse, the data gathered by the VLA receiver was initially comprised of direct path sound, followed shortly after by a combination of direct path and bottom reflected sound, before the arrival of surface reflected and multipath sound. The data corresponding to the combined direct path and bottom reflected sound formed a Lloyd mirror interference pattern, which was effectively sampled by the VLA receiver as a "snapshot". The source and receiver were deployed to a depth of approximately 30 m (VLA midpoint) above the seabed during the measurements. This was done to ensure that the greatest integration times could be achieved for the snapshot before the arrival of the surface reflected and multipath sound. This also ensured that the measurements were conducted as far away as possible from sound speed gradient effects associated with the sea surface (e.g. ducts). Drift distances approximately ranged from 100 - 600 m so that measurements could be made at grazing angles within the range 5 - 30 degrees. The drift distance was determined via a hand-held laser ranger which was operated from the deck of HMAS Balikpapan, and unfortunately, the approximate nature of these measurements may have lead to significant source-receiver range (and therefore grazing angle) errors.

Ray theory can be used to show that for low grazing angles, specular reflection and iso-velocity conditions, the acoustic intensity created by direct path and bottom reflected sound satisfies the following proportionality:

$$I \propto \left[1+|R|^2+2|R|\cos\left(\frac{2ksz}{d}+\phi\right)\right] \quad (1)$$

where $|R|\exp(i\phi)$ is the complex seabed pressure reflection coefficient for plane waves, k is the wavenumber, s is the vertical distance of the source above the seabed, d is the horizontal separation range between the source and receiver, and z is the vertical distance of the receiver above the seabed. From equation (1) it follows that the ratio of minimum to maximum intensity received when z is varied is:

$$\frac{I_{\min}}{I_{\max}}=\left(\frac{1-|R|}{1+|R|}\right)^2, \tag{2}$$

and the vertical distance between the intensity minima (or maxima) is $\Delta z = d\lambda/(2s)$, where λ is the acoustic wavelength in water. The effect of the phase ϕ of the reflection coefficient on the intensity pattern is to determine its vertical translation. For example, if $\phi=\pi$ then there will be an intensity minimum at the seabed $z=0$, and the first intensity maximum will be a distance $\Delta z = d\lambda/(4s)$ above the seabed. Therefore, the phase of the reflection coefficient can be determined from a measurement of the vertical translation distance of the interference pattern. The accuracy of equation (1) is compromised when the bottom grazing angle is not "small", the point of bottom reflection or the receiver are not located in the far-field of the source, and non-specular reflection takes place. When undertaking the measurements, consideration was given to these points, and the errors associated with using equation (1) (together with the angular errors associated with the finite length of the VLA receiver) were not considered to be excessive for most of the measurements.

During the processing of the VLA receiver data, time gates were applied for each pulse so that only direct path and bottom reflected sound was used to calculate the intensity pattern snapshot. The relatively slowly varying characteristics of the intensity pattern with drift-time/range enabled groups of (typically 4) intensity snapshots to be averaged to provide a more stable representation of the interference pattern. Each of the averaged interference pattern snapshots corresponded to a particular drift-time/range, and a knowledge of the depth of the source and receiver VLA mid-points enabled the corresponding grazing angle to be approximately determined. Equations (1) and (2) were used to provide an estimate of $|R|$ from the interference pattern snapshot as follows: Firstly, the calculated hydrophone intensities were fitted in a least-squares sense to the general form of equation (1), namely $I=a+b\cos(pz+q)$. From this expression, the ratio of minimum to maximum intensity is given by $(a-b)/(a+b)$. Equating this to the right-hand side of equation (2) and solving for $|R|$ yields:

$$|R|=\frac{\sqrt{a+b}-\sqrt{a-b}}{\sqrt{a+b}+\sqrt{a-b}}. \tag{3}$$

Finally, allowance was made for the beampattern of the VLA source by multiplying the right-hand side of equation (3) by the ratio of the beampattern pressure amplitudes for the direct path and bottom bounce rays. In hindsight, the use of a single omni-directional source would have been sufficient for the measurements, and would have overcome the need to make an allowance for the beampattern of the source in equation (3). Having calculated $|R|$, the bottom loss σ in dB was determined from the equation $\sigma=-20\log_{10}|R|$.

One can see from equation (3) that the estimate of $|R|$ is independent of common scaling of the parameters a and b. An advantage which follows from this is that the measurements require only a relative calibration of the VLA receiver hydrophones. During the measurements, this was achieved in-situ by using the direct path component of pulses received at close range. The parameters p and q from the least-squares fit had the potential to provide the horizontal separation range d between the source and receiver (knowing k, s, z), and the phase of the reflection coefficient ϕ. This has not yet been achieved, but will be considered as part of our ongoing research.

3. RESULTS OF MEASUREMENTS

Some initial results have been obtained from measurements at the frequency 1970 Hz at site A. Figure 2 shows the sampled interference patterns corresponding to the grazing angles 8, 9, 10 and 11 degrees. The asterisks in the plots represent the hydrophone samples in the snapshot of the interference pattern, and were vertically located 0.75 m apart - corresponding to the 1 kHz VLA receiver nest. Generally, when conducting the measurements, the selection of the VLA receiver nest was altered to ensure proper sampling of the interference pattern waveform as it expanded in the vertical direction while the drift range increased. The solid curves in the plots represent the least-squares fit to the snapshot data of the function $I = a + b\cos(pz + q)$. Note that in the axis labels for the plots in figure 2, *SPL* signifies the received sound pressure level for the interference pattern in dB re 1 μ Pa, and *Z* represents the vertical distance in metres from the centre of the VLA receiver.

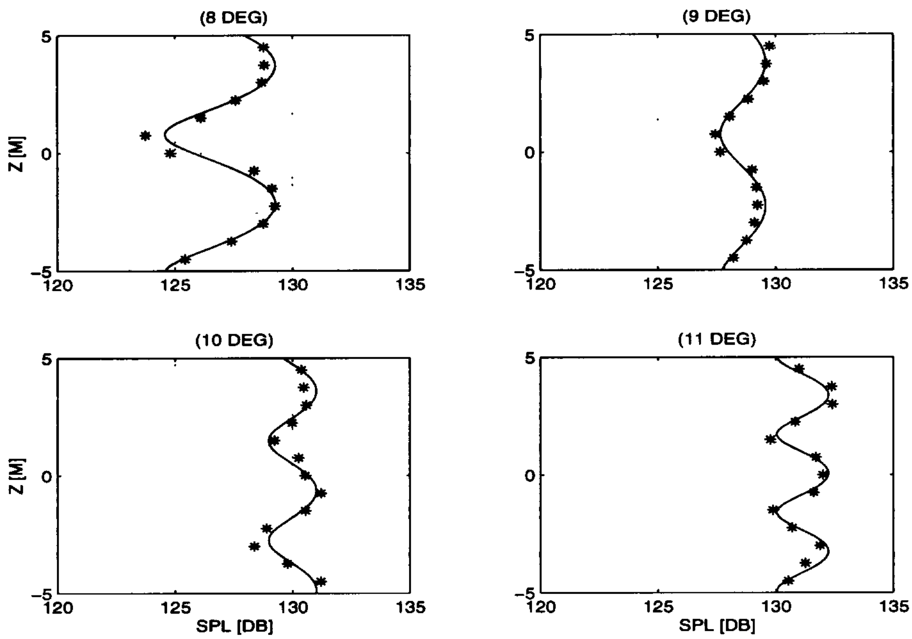

Figure 2: Interference pattern snapshots measured at the frequency 1970 Hz at site A when the bottom grazing angles were approximately 8, 9, 10 and 11 degrees.

Application of the analysis described in section 2 to the data presented in figure 2 yielded $|R|$ = 0.30, 0.12, 0.14 and 0.16 at the bottom grazing angles 8, 9, 10 and 11 degrees respectively.

4. GEO-ACOUSTIC MODELLING

Samples of the bottom sediment have been gathered at the experimental trial sites, and the analysis of these samples [23, 24] has indicated that at site A (and the frequency 1970 Hz), the sediment had the following average characteristics: porosity n=0.71, grain density ρ_s=2650 kg/ m^3, sediment/water velocity ratio for compressional waves v_{sw}=0.97, compressional wave attenuation α=0.1 dB/m. The geo-acoustic model that was initially used to determine R from these parameters assumed that the sediment was a homogeneous lossy fluid with a plane interface [1, 25]. The corresponding equation for R was:

$$R = \frac{\rho_{sw}\sin(\theta) - \sqrt{\beta^2 - \cos^2(\theta)}}{\rho_{sw}\sin(\theta) + \sqrt{\beta^2 - \cos^2(\theta)}} \quad \text{where} \quad \beta = \frac{1}{v_{sw}} + i\frac{\lambda\alpha'}{2\pi}, \tag{4}$$

the bottom grazing angle was θ, the saturated sediment/water density ratio was $\rho_{sw} = n + (1-n)\rho_s / \rho_w$, the density of seawater was ρ_w=1024 kg/ m^3, the acoustic wavelength in water was λ=1538/1970=0.78 m, $i = \sqrt{-1}$, and the sediment compressional wave attenuation in neper/m was (see reference [19], pp. 66-67) $\alpha' = \alpha / (20\log_{10} e)$.

In figure 3, the asterisks represent the measured $|R|$ versus θ data given in section 3, and the solid curve represents the modelled values as determined by equations (4) for the above parameter values. A significant feature of the model's predictions is the presence of an angle of intromission at approximately 13 degrees, where all of the acoustic energy is transmitted into the sediment. The relatively low value of the sediment compressional wave attenuation (i.e. α=0.1 dB/m) did not significantly affect the values of $|R|$ obtained from equations (4), which were essentially the same as those for a zero-loss fluid. An indication of the effect of higher attenuation is given by the dashed curve in figure 3, which represents values of $|R|$ obtained from equations (4) when α was increased to 1.5 dB/m.

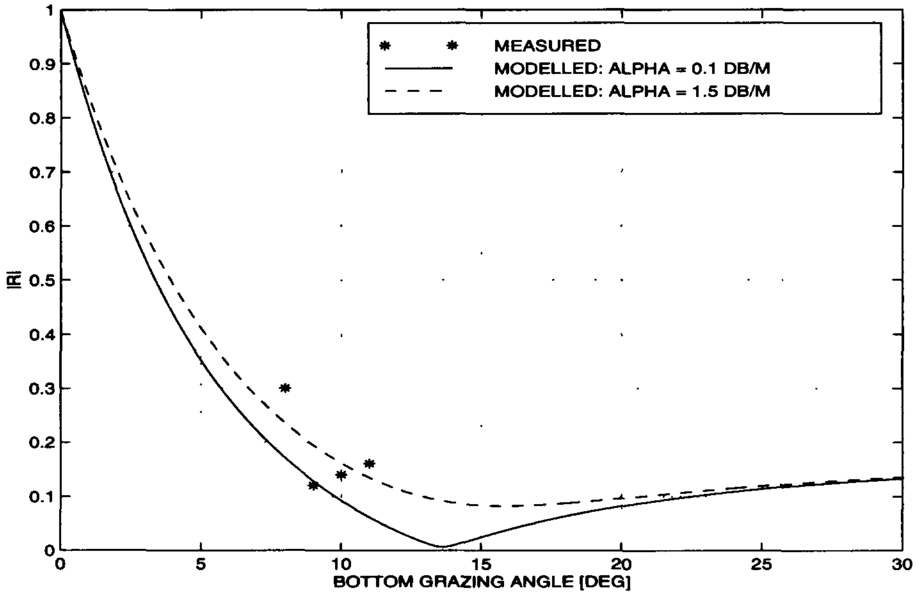

Figure 3: Measured values of $|R|$ versus θ at site A at the frequency 1970 Hz, and modelled values when α = 0.1 and 1.5 dB/m.

5. SUMMARY AND CONCLUSIONS

In this paper, a description has been provided of an experimental technique which was used to measure low grazing angle forward reflection loss in shallow water. The technique involved "snapshot" sampling, via a VLA receiver, of the Lloyd mirror interference pattern created by the interaction between direct path and bottom reflected sound. The magnitude of the bottom reflection coefficient (and hence the bottom loss) was obtained from the ratio of the minimum to maximum intensity in the interference pattern. Advantages associated with this technique were: (1) A direct and coherent measurement of the bottom reflection coefficient versus grazing angle was obtained. (2) Only a relative calibration of the VLA receiver hydrophones was required, and this was achieved using the direct path component of pulses measured at close range. (3) The VLA receiver enabled the interference pattern to be simultaneously and accurately sampled at known depth increments. (4) The stability and slowly varying (with range) nature of the interference pattern allowed multiple pulse averages to be computed as the source and receiver drifted apart. (5) Conducting the measurements close to the sea bottom reduced the impact on the measurements of sound speed gradient effects associated with the sea surface (e.g. ducts). Regarding potential sources of error in the measurements, it was noted that inaccuracies related to the use of equation (1) and the finite length of the VLA receiver were not considered to be excessive for most of the measurements. However, these issues will be further considered during the ongoing process of data analysis. Similarly, the approximate means by which the source-receiver range was determined (inter-ship distance via laser ranger) may have lead to significant grazing angle errors, and these will need to be accounted for. A better method for determining the source-receiver range would have been via measurement of the direct path propagation time with the aid of GPS synchronisation. Unfortunately the equipment required to do this was not available during the experimental trial.

Some initial results were presented which corresponded to data gathered at the frequency 1970 Hz at site A, where the water depth was 109 m, and the bottom sediment was broadly classified as clayey sand. These results were compared to the predictions of a simple geo-acoustic model, in which the sediment was assumed to be a homogeneous lossy fluid with a plane interface. The comparison provided some validation of the model; however, the addition of more data points will be required to provide greater confidence in this area. A significant feature of the model predictions was the presence of an angle of intromission, at which all of the acoustic energy would be transmitted into the sediment. The addition of more measured data may confirm the presence of this feature. It was noted that the relatively low value of the compressional wave attenuation for the sediment (at the frequency 1970 Hz) did not play a significant role in determining the values of the modelled bottom loss.

Continuing research will involve the analysis of data from both the trial sites, at the full range of frequencies and grazing angles considered. This should provide a greater level of confidence in the experimental technique, and more data for validating the lossy fluid bottom loss model. An attempt will also be made to obtain phase information from the experimental data, and the applicability of more complex bottom loss models will be investigated. It is hoped that this will yield greater insight into the physical mechanisms of bottom acoustical reflection, which in turn will contribute to an improved ability to predict the performance of sonar in shallow water.

6. ACKNOWLEDGEMENTS

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