SHALLOW WATER BOTTOM SCATTERING STRENGTH AT LOW FREQUENCIES

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1. INTRODUCTION

Measurements of acoustic backscattering from the ocean bottom can be interpreted unambiguously if experiment geometries involving single propagation paths to the scattering region at the bottom are employed. In practice this condition has restricted most reliable measurements to deep water or to high frequencies, with the use of directional transducers, and with results limited to high grazing angles at the bottom.

Low frequency bottom backscattering measurements in shallow water are more complicated. The multipath propagation that is characteristic of shallow water channels precludes the ability to isolate paths contributing to the scatter return. Starting with the shallow water measurements of Urick [1], the technique conventionally used to characterize bottom scattering for these situations has been to extract a scattering strength from reverberation measurements by accounting for the two-way transmission from source to scattering area to receiver and by accounting for the size of the bottom region contributing to the reverberation at any instant.

This method of determining scattering strength does not probe the dependence on incident and scattered bottom grazing angles and, indeed, yields an integrated scattering strength that is dependent on the vertical angular distribution of propagated energy. Attempts to gain insight into the incident and scattering angle dependence of low frequency shallow water bottom scattering have typically used model-based manipulations of the scattering data (that is, the methods involve both a model of propagation and of the angular dependence of bottom scattering) [2, 3].

Most reported measurements of shallow water bottom reverberation at low frequencies have been made using explosive sources, which permits the frequency dependence of the bottom scattering strength to be determined. In fact, establishing the behavior with frequency of the scattering strength is the main feature of the reverberation extraction method. Until recently, however, there had been few measurements of low frequency shallow water bottom scattering and it is likely that this has delayed emergence of a coherent view of the variation with frequency of bottom scattering strength in shallow water regions.

In this paper measurements of shallow water bottom scattering from three areas are described. In addition to describing these measurements and the derived integrated bottom scattering strengths, an attempt is made below to consolidate the current understanding of the frequency dependence of shallow water bottom scattering. For the measurements reported here, vertical receiving arrays were used, which also has permitted the first direct determination in shallow water of the dependence of the low frequency scattering strength on scattering angle. The implications of these results are discussed in the context of proposed scattering models.

2. MEASUREMENTS

2.1 Measurement Technique

For the measurements at each site, separate transmission and reverberation data were acquired to permit extraction of bottom scattering strengths. The measurement procedures and instrumentation were as follows: Signals and reverberation in the band 25 Hz to 1 kHz from explosive sources (1.7 kg of Comp B explosive for the reverberation measurements) dropped from a test ship and detonated at mid-water depth were received on two collocated 25 element hydrophone line arrays, one vertical near the bottom and the other deployed horizontally on the bottom. Each array was configured as three nested subapertures with half wavelength element spacing at 100, 200 and 400 Hz. The arrays were electrically connected to two Seacal oceanographic data collection systems and the array elements used were dual sensitivity hydrophones, which could be reconfigured through the Seacal units to provide the necessary dynamic range interval to capture either transmission or reverberation data [4].

To accommodate slight bottom slopes the transmission runs were structured with distinct legs (typically 20 to 40 km in extent) such that the receiving arrays were oriented cross, up and downslope with respect to the tracks. Rates of explosive source expenditure for the transmission loss runs were designed to achieve spatial sampling of the propagation fields with about a 1 km interval. Reverberation runs were arranged to provide near monostatic geometries (minimum source-to-receiver separations of 1 km prevented test ship acoustic contamination of the reverberation data) and bistatic geometries with cross-slope source-to-receiver separations of 10 to 40 km in 10 km increments. Only the monostatic results are discussed in this paper. Statistical stability of derived scattering strength estimates was insured by employing at least 6 explosive sources for each geometry at each site.

For the reverberation measurement sites reported here, the forward scattered boundary returns (i.e., fathometer echoes) at the receiver typically decayed below the reverberation in 1-3 sec (0.75-1.5 km), permitting reliable estimates of scattering strength to be made after the short dominance of the fathometer echoes. The downward refracting conditions and placement of the source below the thermocline at all the sites resulted in strong interaction of the sound with the bottom and weak interaction at the surface, and thereby insured, in each instance, that bottom reverberation and not surface reverberation was the dominant boundary scattered component. Also, although reverberation from fish was not measured, it is most likely that, at all the sites, strong downward refracting conditions caused the bottom reverberation to dominate any volume contribution.

2.2 Measurement Sites

The bottom scattering measurements, even though made at widely separated sites, share some common features, namely, all were made in shallow coastal areas with smooth (compared to an acoustic wavelength at 1 kHz), relatively flat (bottom slopes < 0.25° at all sites) sand bottoms and with downward refracting sound speed profiles in the water column. Having noted these similarities it should also be remarked that the areas differed considerably in their sub-bottom structures.

2.2.1 West Florida Shelf, Gulf of Mexico. Transmission and reverberation data were taken as part of Area Characterization Test I (ACT I) in September 1992 on the West Florida Shelf at 28°23'N, 85°18'W in water of depth 182 m (at the array site). The bottom sediment at the test site was sand-silt-clay, thus classified on the basis of grab sample grain size analysis [5]. The bottom sediment was laterally homogeneous and without stratification to depths of several meters. However, subsequent analysis of acoustic transmission records have shown the existence of a high acoustic impedance contrast layer at a depth of 8 m below the water sediment interface [4].

2.2.2 Southern New England Continental Shelf. Data were obtained at two locations during Area Characterization Test II (ACT II) conducted in September 1993. One site was approximately 10 km east of Hudson Canyon at 39°46'N, 72°13'W in water 100 m deep, and the second site was on the New Jersey Shelf, near the AMCOR 6010 borehole, at 39°03'N, 73°06'W in 73 m deep water. At both sites the bottom sediment is sand-silt-clay and at the New Jersey Shelf location extensive geological and geoacoustic surveying of that area [6, 7] has confirmed the presence of considerable near surface layering within the first 15 m below the sediment interface.

2.2.3 Balearic Islands, Mediterranean Sea. As part of the Balearic Islands Cruise under the aegis of SACLANTCEN in March 1993, transmission and reverberation data were obtained in 120 m deep water approximately 20 km west of Mallorca at 39°33'N, 2°11'E. The bottom at the site consists of a thin layer of fairly hard sand over a hard rock seabed 1-2 m below the water-sediment interface.

3. RESULTS

3.1 Integrated Scattering Strength Determination

The integrated scattering strength SS [dB] is given as

$$SS = 10\log(I_s/I_i), \tag{1}$$

where I_i is the incident intensity at the bottom (ideally assumed to be plane wave sound) and I_s is the intensity of sound scattered from a unit area of bottom, measured at a large distance from the scattering and referred back to unit distance from the scattering region on the bottom.

It can then be shown [1] that the integrated bottom scattering strength is determined from

$$SS = RL - ESL + 2TL - 10\log r - 10\log(\pi c), \tag{2}$$

where RL = reverberation power level in band [dB//μPa^2], ESL = energy source level in band [dB//μPa^2 sec @ 1 m], TL = one-way transmission loss [dB//m^2], r = range to reverberant bottom patch [m], c = sound speed at reverberant patch [m/sec].

3.2 Integrated Scattering Strength Estimates

Bottom scattering strength estimates for each site were computed using measured reverberation spectra, source energy spectra determined from separate source calibration tests, and transmission losses estimated from data obtained during the accompanying transmission loss runs and averaged for up and downslope propagation.

Scattering strength estimates obtained for reverberant patch ranges of 10 km for each of the four measurement locations are shown in Figures 1-4. Each of the estimated bottom scattering strengths has a frequency regime where the strength is as low as - 60 dB, however the frequency dependencies of the scattering strengths are quite different for the different sites. Integrated bottom scattering strength for the Gulf of Mexico site is monotonically increasing with about an f^2 dependence from its lowest value at 40 Hz. The strengths for the two continental shelf locations near Hudson Canyon show broad minima at about 150 Hz, but neither estimate is a strong function of frequency. The bottom scattering strength for the Balearic Islands site has a very strong frequency dependence, exhibiting a pronounced minimum of about - 60 dB at 500 Hz and rising sharply to about - 40 dB at 100 Hz and 1 kHz.

One of the more noteworthy features of the integrated scattering strength estimates for the sites and acoustic conditions described above is that, beyond ranges of order 6-8 km, the estimates were found to be independent of the range of the scattering patch. This is illustrated in Figure 5, which shows scattering strength estimates in the octave bands 50-100, 100-200, 200-400 and 400-800 Hz plotted as a function of the reverberant patch range. While this behavior has been observed in other shallow water bottom scattering work [2], it is not consistent with a simple view of shallow water propagation and scattering from a bottom with enhanced contributions at increasing bottom grazing angles. Indeed, by straightforward reasoning it is expected that integrated scattering strength should decrease with range as a result of the progressive stripping away of high angle paths to the bottom, thereby producing smaller effective grazing angles at the longer ranges. However, a more detailed description that accounts for path cycle distance as a function of bottom grazing angle will predict the observed independence of integrated scattering strength with range.

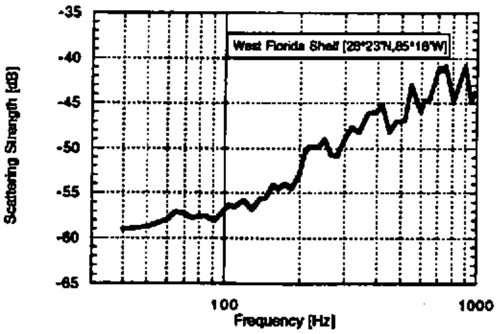

Figure 1. Integrated bottom scattering strength from the West Florida Shelf, Gulf of Mexico.

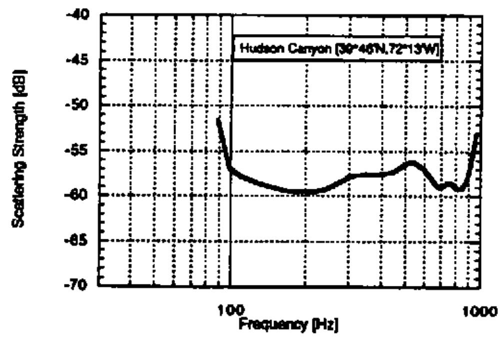

Figure 2. Integrated bottom scattering strength from the New England Continental Shelf near Hudson Canyon

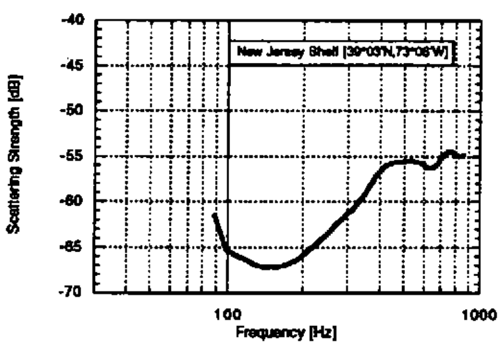

Figure 3. Integrated bottom scattering strength from the New Jersey Continental Shelf.

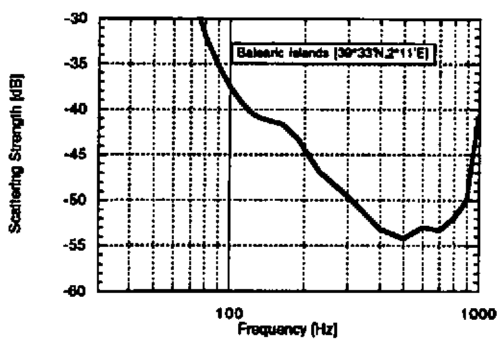

Figure 4. Integrated bottom scattering strength from the Ballearic Islands.

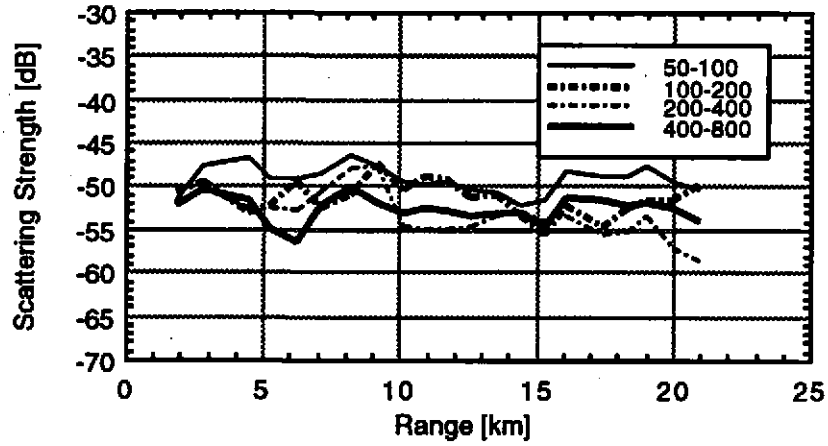

Figure 5. Range dependence of integrated bottom scattering strength estimates for the octave bands 50-100, 100-200, 200-400, 400-800 Hz from the New Jersey Continental Shelf site.

During the ACT I measurements in the Gulf of Mexico, a computer controlled signal repeater was suspended near the bottom from another test ship. This asset permitted determination of bottom scattering strength using a calibrated echo. Direct comparison of the signal repeater return and of the reverberation return from the same range yielded an estimate of scattering strength after correction for the area contributing to the reverberation. The values obtained by this second method agreed closely with those obtained by the technique described earlier and provided a calibration check with the results obtained using the independent transmission loss estimates [4].

3.3 Scattering Strength Comparisons

The number of published determinations of low frequency shallow water bottom scattering strength is quite limited, but yet large enough to make a comparison of all reported data of considerable interest. Figure 6 presents a summary of reported results for shallow water sand bottom scattering strengths. The data are shown over a frequency range from about 40 Hz to 10 kHz (greatly exceeding the low frequency regime) in order to fully examine the frequency dependence of bottom scattering strength In addition to the results reported in this paper from the West Florida Shelf, Balearic Islands and the New England Continental Shelf, the data shown in Figure 6 include an extensive set of measurements obtained by Thiele and Tielburger [2], in different seasons, from various locations in the North Sea. Also shown in Figure 6 are scattering strength determinations reported by Zhou *et al* [3] from the Yellow Sea and the measurement by Urick [1], mentioned earlier, from the Gulf of Mexico at a location about 100 miles southeast of the ACT I West Florida Shelf site.

A significant characteristic of the composite results in Figure 6 is the strong frequency dependence at low frequencies, with a general decrease in strength below about 2 kHz to a minimum in the mid-hundreds of hertz, and a typical pronounced rise in strength at low frequencies. Also significant is the generally weak frequency dependence of scattering strengths above about 2 kHz, as has been previously observed [8, 9]. It has been suggested that the fractal (i.e., self similarity) character of the shallow seabed roughness could account for the lack of frequency dependence of Bragg (i.e., resonant) backscatter down to frequencies of 2-3 kHz [10]. At lower frequencies, but not so low that there would be significant bottom penetration by the sound, a reduced roughness spectrum at the longer wavenumbers would result in lower scattering strengths. Thiele and Tielburger propose that, at still lower frequencies, sound penetrates into the bottom and an increase in scattering strength as the frequency is lowered is attributable to scattering from structure within the volume of the sediment [2].

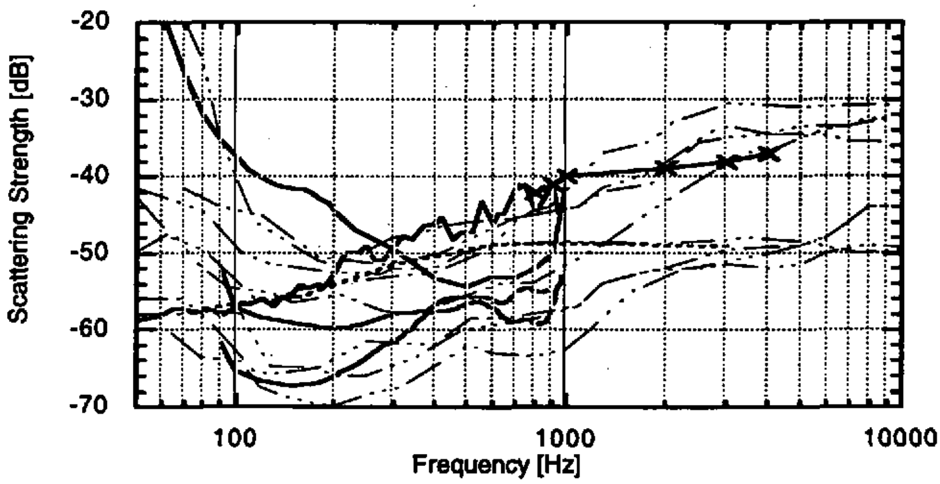

Figure 6. Comparison of shallow water sand bottom scattering strength determinations. The solid curves are the data from this paper (shown in Figures 1-4); the dashed curve is from Urick's measurements in the Gulf of Mexico [1]; the broken curves are from the North Sea data of Thiele and Tielburger [2]; the solid curve marked with x's is Zhou's measurement from the Yellow Sea [3].

Our data support the above conjectures. At each of the measurement sites there was a fast bottom (that is, the sediment compressional speed exceeded the speed of sound in the water at the bottom) with a smooth interface for the frequency band in which data were taken. Significant penetration of sound into the bottom was expected only below mid-hundreds of hertz, frequencies below which scattering contributions from the sub-bottom could become important. On the West Florida Shelf there was no observable structure in the bottom down to 8 m and the scattering strength for this site was decreasing to 40 Hz, the lowest frequency measured. Near Mallorca, where there was a thin sediment layer overlying a hard substrate, the scattering strengths exhibited a pronounced minimum at 500 Hz, consistent with the 1-2 m depth of the rock basement below the water-sediment interface. On the New Jersey Shelf, the multiple layers within the first 15 m of the bottom afford the possibility for scattering from the rough interfaces separating layers; the relatively flat dependence of the scattering strength with frequency is consistent with the multiscale sub-bottom structure (i.e., several layers and multiple roughness scales at each layer).

3.4 Scattering Angle Dependence

Using the West Florida Shelf data from ACT I, it has been possible to obtain estimates of the scattering angle dependence of the bottom scattering strength by comparing reverberation levels with signal repeater returns (cf Section 3.2) in beams formed using the vertical receiving array. For an unshaded beam formed at an off broadside look direction θ_0, the corresponding look angle at the bottom is θ given by Snell's law, $c \cos\theta_0 = c_0 \cos\theta$, where c_0 = sound speed at the vertical array midpoint and c is the sound speed at the bottom. Then the bottom scattering strength SS(θ) for a scattering angle θ can be estimated as

$$SS(\theta) = RL + G - EE - 10\log r - 10\log(\pi c) - 10\log\Theta, \qquad (3)$$

where EE = signal repeater return energy in band[dB//μPa^2 sec], G = signal repeater gain [dB], Θ = receiving array broadside beamwidth [rad], and where the other quantities are defined as in Equation (2).

Figure 7 shows bottom scattering strength from the West Florida Shelf as a function of scattering angle at the bottom, determined as above, for the three frequency bands 50-100, 100-200 and 200-400 Hz. Note that these scattering strength data, although the scattering angle dependence is resolved, are still integrated over incident grazing angle. Also illustrated in Figure 7, for comparison, are curves of sinθ fitted to the scattering data in each band at θ = 10°. A comparison indicates that the measured strengths depend on grazing angle at least to a first power in sine of the scattering angle; the scattering angle dependence appears to be too weak to be explained by a Bragg scattering (rough surface) description [11] of the bottom interaction. If it is assumed that the incident grazing angle dependence of the scattering strength depends linearly on sine of the angle (as both Lambert's [12] and Lommel-Seeliger [9] laws specify), then the West Florida Shelf scattering strength data are consistent with a Lambert's law picture of bottom scattering.

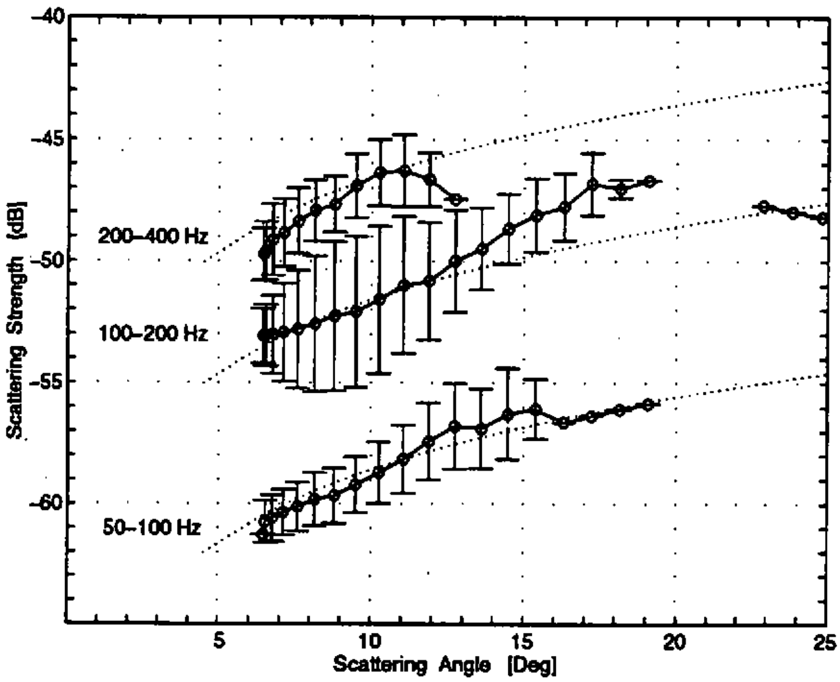

Figure 7. Scattering angle dependence of bottom scattering strength from the West Florida Shelf site. The dotted curves are proportional to sine of the scattering angle and are fitted to the data at θ = 10°.

4. CONCLUSIONS

This paper has reported the results of low frequency bottom scattering strength measurements performed at three shallow water sites, all having sand bottoms but otherwise exhibiting markedly different sub-bottom structures. These data have been compared with other reported integrated bottom scattering strength determinations from sandy shallow water sites. In general, integrated scattering strengths for sand bottoms are found to decrease below 1-2 kHz and often to exhibit a minimum in the range of a few hundred hertz. While the spread over all the data compiled at any frequency is of order 20 dB, in the decade 100 Hz-1 kHz the bottom scattering strengths are typically significantly lower than those predicted by the (frequency independent) Mackenzie values [12], which generally should apply only above about 1 kHz. It has been suggested that the frequency dependence of the scattering strengths can be explained as being caused by the competition of scattering mechanisms, that is, volume scattering within the bottom sediment at low frequency giving way to rough bottom interface scattering at the high frequencies. A direct determination of the scattering angle dependence of the scattering strength from one site is consistent with a Lambert's law description of the bottom scattering.

4.1 Acknowledgements
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