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HIGH-FREQUENCY ACOUSTIC SCATTERING

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ABSTRACT

Recent high-frequency acoustic ocean bottom scattering developments are described. A brief summary of experiments carried out in the frequency range from 5 to 180 kHz during the 1980's is presented. These experiments were performed to identify specific scattering mechanisms leading to bottom backscattering, bottom forward loss, and sound penetration into the ocean subbottom. The capability to accurately predict acoustic scattering is addressed through model and data comparisons. Pertinent unresolved issues are discussed.

INTRODUCTION

Underwater acousticians have been studying and measuring acoustic scattering from the ocean boundaries and from inhomogeneities in the water column for many years. There are at least two reasons for this. First, the effects and limitations of the very complex ocean environment on underwater acoustic devices must be determined for best system design and operation. Second, in order to model these effects so that accurate acoustic predictions can be made, it is necessary to understand the underlying physical principles governing the various forms of scattering. It is the intent of this paper to indicate some of the advances made during the past decade, the status, and the current technical/scientific issues in the area of high frequency acoustic scattering from the ocean bottom and subbottom. High-frequency signals are those with frequencies greater than 5 kHz.

Although the subject matter of this paper may not adhere directly to the theme of the Congress, the material should be of interest and challenging to many acousticians. This paper is concerned with scattering from the sea floor and subbottom. A brief review, the current status and outstanding issues are presented.

This paper does not address the extensive research carried out prior to 1980. For an excellent review of WWII underwater acoustics work the reader is referred to the "Red Books" [1,2]. Since then, excellent books (see, for example, [3]) have been published. In addition, an extensive literature exists primarily in the Journal of the Acoustical Society of America. The purpose of the present paper is to review past relevant work and present recent developments of ocean bottom scattering.

BOTTOM SCATTERING

The war-time work on bottom backscattering [2] indicated that the scattering strength increased with grazing angles between 10° and 30°. This dependence on grazing angle, $\varnothing_g$, was found to vary between $\sin\varnothing_g$ and $\sin^2\varnothing_g$. The frequency dependence of backscatter over a rock bottom showed no systematic variation from 10 to 80 kHz; but no data were available for other bottom types.

During the 50's, 60's and 70's efforts were directed towards extending the earlier work on the dependence of bottom backscattered sound on grazing angle, frequency and bottom properties. Figure 1 is an example of results from the work of McKinney and Anderson [4], and illustrates several important points. It is important to note, although it cannot be seen without the numerical data, that there is no systematic trend with mean grain size. However, the scattering strength does, in general, increase with increasing grazing angles between 10° and 30°, especially for sand bottoms. For the curves drawn, the angular dependence at low grazing angles varies from increasing, decreasing and remaining relatively constant with increasing angle. In the grazing angle region between 10° and 30° the dependence follows Lambert's law ($\sin^2\O_g$) for scattering from a rough surface. At angles greater than 30°, the rate of increase is less than Lambert's Law until specular reflection takes over as $\O_g$ approaches 90°. Clearly, a number of physical scattering mechanisms are at play here and additional concurrent environmental/geoacoustic measurements are needed to identify them. The lack of correlation of bottom backscattering strength with mean grain size suggests that a distribution of particle sizes should be measured. Bottom roughness as indicated by the grazing angle dependence between 10° and 30° is an important parameter, but one which was not measured. With the exception of mud bottoms the penetration of sound into the sediment was not expected to be important at these high frequencies, but such penetration could be a mechanism at grazing angles less than the critical angle (30°) for water-saturated sands.

The frequency dependence of bottom backscattering at a grazing angle of 10° is presented in Fig. 2 [4]. Because of the wide range of acoustic wavelength to scattering size ratios, the dependence is quite variable. For the sand locations, the bottom scattering strength increases with frequency at a maximum rate of $f^{1.6}$. Other areas display either little frequency dependence or a wildly fluctuating behavior. Even though the particle sizes of the sandy sites were much less than an acoustic wavelength, no fourth power of frequency dependence (Rayleigh scattering) was observed in the data. This suggested to McKinney and Anderson that the particles clump together to form scattering centers comparable to a wavelength and thereby account for the weak frequency dependence observed.

From these experiments and others, a qualitative picture of bottom backscattering had emerged: (1) bottom reverberation is greater for hard bottoms (rock and coral) than for soft bottoms (mud and sandy silt); (2) Lambert's Law is reasonably valid for grazing angles between 10° and 30°; and (3) the frequency dependence of bottom reverberation is dependent on bottom type.

However, the large uncertainties in the bottom backscattering strength for various bottom types, the lack of knowledge about the exact frequency dependence and the general lack of backscattering measurements with concurrent roughness and sediment composition measurements indicated that a great deal more research was required.

During the 80's many concurrent environmental/acoustical experiments were conducted. Table 1 is a summary of these high-frequency environmental acoustic experiments. It must be emphasized that these experiments represent the first time that extensive environmental measurements were performed concurrently with the acoustics measurements. For interest, sea surface scattering experiments are also included.

The following figures show some results from these experiments. Figure 3 [5] shows the dependence of bottom backscattering strength on grazing angle at 90 kHz in shallow water off the coast of Jacksonville, FL. As can be seen, Lambert's Law is followed down to 5° with no azimuthal dependence exhibited. A comparison of bottom roughness vs bottom backscattering strength for a number of experiments conducted during the 80's is shown in Fig. 4. A dependence on RMS roughness was expected but is not observed in the data, leading researchers to investigate the roughness spectral characteristics and small-scale slope distributions. This work is presently underway.

An example of acoustic energy penetration into sediments is shown in Fig. 5 [5]. Here, backscattered energy is higher than model predictions based on scattering from the interface only. This suggests that the higher energy may be due to scattering from scatterers within the sediment. This interpretation is strengthened by the good agreement between data and modeling when the volume scattering parameter is increased from 0.002 to 0.01. This parameter is the ratio of the scattering cross-section to the attenuation coefficient.

Another example of acoustic penetration into the sediment is presented in Fig. 6 [6]. A projector mounted on a tower directed a narrow beam of energy at buried hydrophones at grazing angles significantly above and below the critical angle. The figure shows the difference between data measured by the buried hydrophones and model predictions is much greater below the critical angle (tower position 5). This suggests that energy is transmitted into the bottom at grazing angles less than the critical angle. The penetration appears to be frequency dependent.

In the important area of bottom forward scattering, including both specular and diffuse scattering, high-frequency acoustic measurements with appropriate geoacoustic measurements were lacking. In the past few years, however, acoustic forward reflection loss measurements have been made and used to verify a simple forward loss model [7]. Figure 7 shows the results of data/model comparisons for forward reflection losses vs grazing angle at three different bottom sites. The solid curves represent model runs using geoacoustical parameters. The dashed curves use the bulk, measured values. Neither the surficial geoacoustical parameters nor the bulk values provide a good match over all grazing angles. It is assumed that the parameter gradients play an important role in sound transmission into the sediment.

Although a wealth of literature exists on the theory of scattering dating back to Lord Rayleigh, very little theoretical work had been performed that was directly applicable to high- frequency acoustic scattering from the ocean bottom. The present bottom backscattering strength model [7] assumes the bottom material is a fluid, uses the composite roughness approximation, the Kirchhoff approximation, and a sediment volume scattering parameter. The forward loss model [7] is based on reflection, rather than scattering concepts, and includes a lossy Rayleigh coefficient. The status of these models is given in Table 2. Remaining gaps in our knowledge are also given in Table 2.

SUMMARY

Tables 3 and 4 summarize some of the current issues or shortfalls for several acoustic parameters. It can be seen that there are issues remaining in both the modeling and measurement areas. Bottom reverberation intensity is the one area where we feel we have a capability to perform accurate acoustic predictions, particularly in sandy environments. The value of performing simultaneous environmental acoustic measurements has been successful in providing accurate data for model development and verification. The models are needed for the prediction of high-frequency acoustic system performance. In addition, specific measurements needed prior to the 1980's included scattering experiments at low grazing angles from well-known seafloors were accomplished for a variety of bottom types. However, we still have not identified all scattering mechanisms. Much needs to be done.

ACKNOWLEDGEMENTS

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TABLE 1.
SUMMARY OF EXPERIMENT

EXPERIMENT	TYPE OF MEASUREMENT	FREQUENCY RANGE (kHz)	GRAZING ANGLES (deg)	BOTTOM TYPE
North Sea, English Channel APL/UW, are (TTCP) Oct 81	Bottom back & forward scatter, backscatter variability, survey track	20-85	5-90	Sandy silt Gravel
San Diego, NOSC Tower ARL/UT, NORDA Apr-May 82	Sea surface and bottom backscatter	30-95	2-45	Fine sand Coarse sand
North Atlantic, Long Island NUSC/NL, NORDA May 82	Surface and bottom back and forward scatter	2-80	2-30	Fine sand
Quinault Range, Washington APL/UW, NORDA Apr 83	Surface and bottom back and forward scatter	16-85	5-90	Fine sand
Charleston, SC ARL/UT, NORDA Jun 83	Bottom backscatter fixed/mobile platform	30-95 4-75	1-10	Fine sand w/shells
Arafura Sea May 84 APL/UW, NORDA, RANL (TTCP)	Bottom back and forward scatter	15-45	3-90	Clayey sand with shells
Panama City, FL NORDA Aug 84	Bottom backscatter	20-180	3-45	Medium-fine sand no shells
Kings Bay, Jacksonville ARL/UT, NUSC/NL, NORDA, APL/JHU, UK Aug 85	Surface and bottom backscatter, coherence, scattering within sediment	5-180	3-90	Rippled sand with shells
North Sea Tower NUSC/NL, NORDA. FWG Nov-Dec 85	Sea surface scatter high sea state, bubbles	3-18	15-90	—
Whidbey Island, Puget Sound APL/UW Jan-Feb 86	Sea surface scatter high sea state, bubbles	15-50	Lon	
Panama City, FL ARL/UT, NORDA, NCSC Sept 86	Bottom backscatter and sediment penetration	5-80	3-90	Sand Sand Ridge Mud

TABLE 2
HIGH-FREQUENCY ACOUSTICS
BOTTOM SCATTERING MODEL STATUS AND GAPS

MODEL	1989 STATUS	REMAINING CRITICAL GAPS
Bottom reverberation	• Model uses theory and data sets from 3 laboratories • Model accuracy greatly improved • Theory includes roughness and scattering from within sediment	• Include gradients and layering of sediments • Bistatic scattering strength • Spatial variability
Bottom forward loss	• Model based on simple theory and small HF data set • Model accuracy improved • Consistent with backscatter model	• More data needed • Include gradients and layering of sediments • Spatial coherence

TABLE 3
SUMMARY
HIGH-FREQUENCY ACOUSTICS BOTTOM REVERBERATION

CHARACTERISTICS		APPLICABLE MODEL	MODEL STATUS	REMAINING ISSUES
Mean Intensity	Bottom	Composite-roughness	Fair agreement with data	Model inputs: roughness spectra physical properties of bottom. Role of penetration and rescattering
Spatial Coherence	Bottom	No model	No data comparisons	Model, measurements
Intensity Fluctuations	Bottom	"Spectral estimation" Model	Fair agreement with data at low grazing angles	Effect of large-scale surface No stationarity of surface Penetration
Arrival Angle Fluctuations	Bottom	No models	No data for comparison	Model, measurements

TABLE 4
HIGH-FREQUENCY ACOUSTICS BOTTOM FORWARD SCATTER

CHARACTERISTICS		APPLICABLE MODEL	MODEL STATUS	REMAINING ISSUES
Intensity	Bottom	Kirchhoff-Fresnel	Fair agreement	Bottom properties
Time Spread	Bottom	K-F	Fair agreement	
Coherence	Bottom	K-F	No data for comparisons	Beam pattern effects difficult to incorporate in K-F unless symmetric and specular point
Intensity Fluctuations	Bottom	No models	No data for comparisons	Model, measurements
Arrival Angle Fluctuations	Bottom	No models	No data for comparisons	Model, measurements

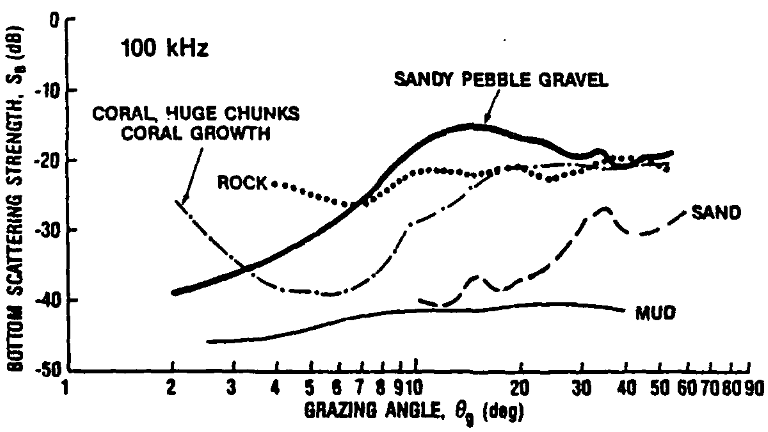

Figure 1. Bottom backscattering strength vs. grazing angle, from McKinney and Anderson [Ref. 3].

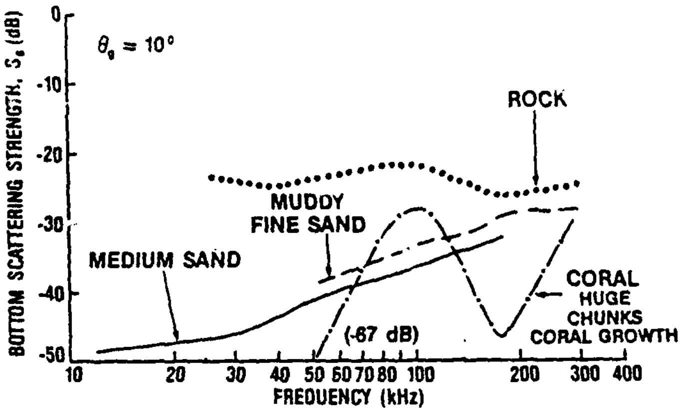

Figure 2. Bottom backscattering strength vs. frequency, from McKinney and Anderson [Ref. 3].

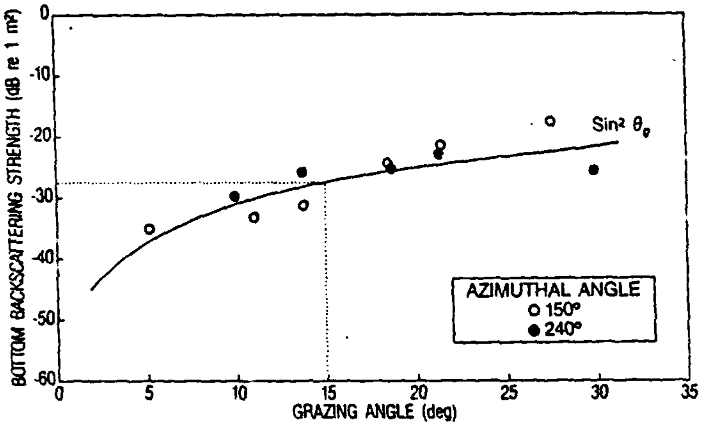

Figure 3. High frequency acoustics, azimuthal dependence of bottom backscatter at 90 kHz (Jacksonville).

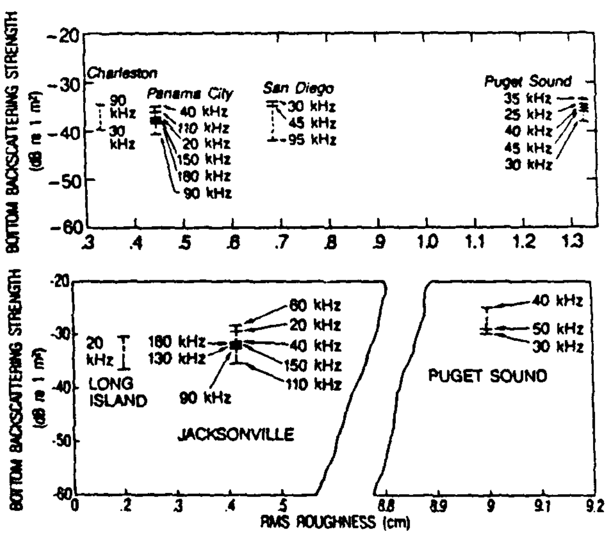

Figure 4. High frequency acoustics, comparison of bottom roughness vs. scattering strength.

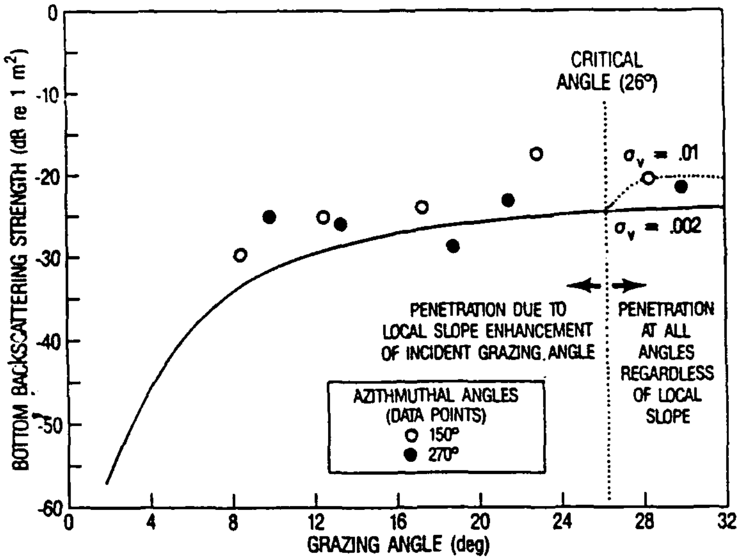

Figure 5. High frequency acoustics, model and data comparison for Jacksonville measurements — 20 kHz.

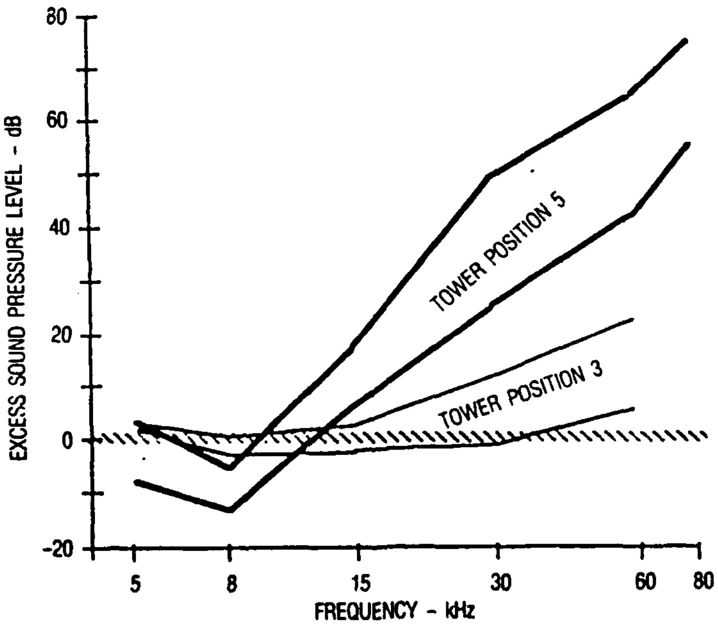

Figure 6. Measured minus predicted acoustic pressure levels in the sediment: mean values ± one standard deviation at tower positions 3 and 5.

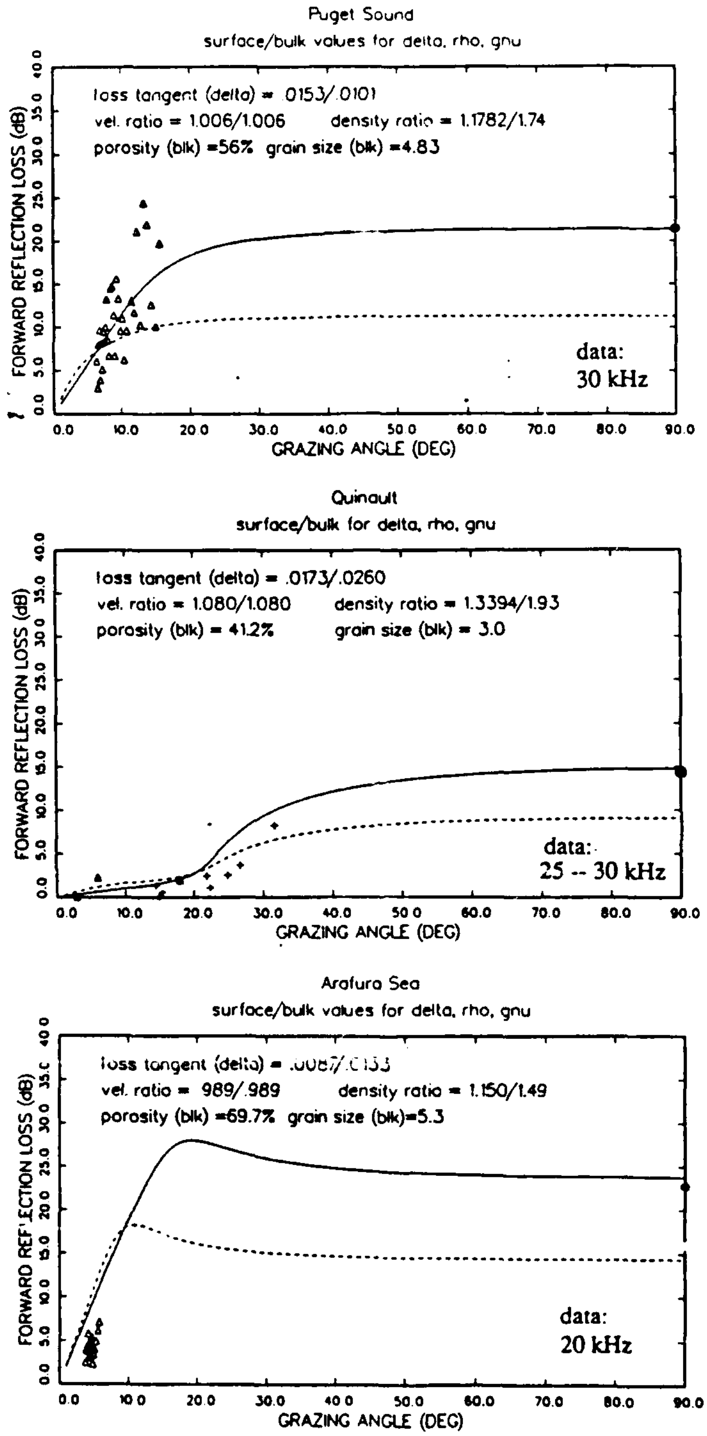

Figure 7. Comparison of forward loss model with data from three different sites. The dashed curves use measured model inputs and the solid curves use inputs from grain size parameterization.