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AN OVERVIEW OF OUTSTANDING PROBLEMS IN OCEAN BOUNDARY SCATTERING AT HIGH FREQUENCIES

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INTRODUCTION

Many ocean measurements of both surface and bottom backscatter have been made at high frequencies (10 kHz to 100 kHz). These measurements have resulted in widely used but poorly documented models that are primarily empirical in nature. Moreover, these empirical models need improvement both in theoretical grounding and in the use of more appropriate physical input parameters. For example, empirical models for surface backscattering currently use wind speed as the only input parameter despite the fact that field data show a more complex picture in which for a given wind speed at a given location, the scattering strength measured may vary by 10 dB. Further, field data show that a more rapid decrease in scattering strength at shallow grazing angles occurs for fetch-limited conditions than in the open ocean.

Until very recently, a similar problem existed for bottom backscatter where for a given bottom type (sand, mud, gravel) large variations exist for both scattering strength and small grazing angle dependence [1,2,3]. Recent work [4,5,6] has resulted in a new model identifying several physical parameters as model inputs, thus reducing the uncertainty though not eliminating it.

Unfortunately, the development of boundary scattering models currently in use has not been closely tied to theoretical work that could illuminate analysis of the field data and reduce the need to rely upon expensive experimental measurements. Several boundary scattering theories [7-11] have been developed that include many different approximations, but their significance and range of validity are often not well understood. Moreover, these theoretical models are seldom used in solving applied problems in high frequency ocean acoustics. This is in contrast to the analogous situation in centimeter-wavelength radar where theoretical models receive considerable attention, particularly in remote sensing applications.

To improve the environmental acoustic models used in the evaluation and development of underwater systems, additional work involving coordinated field and theoretical studies is needed on boundary backscatter, especially for shallow water. In addition, to fully understand an underwater system's performance under many conditions, other parameters that have received relatively less attention should be investigated. These include, in an approximate order of practical significance, surface loss, bottom loss, surface bistatic backscatter, bottom bistatic backscatter, and surface forward out-of-plane scattering. Spatial coherence and time spreading should also be modeled because there are important system applications for these quantities; however, this is beyond the scope of this discussion.

THEORY

Theory, obviously, has a great deal to offer in a practical sense if it can be verified by experiment. It is extremely difficult and expensive to measure boundary bistatic scattering under a wide variety of conditions. A good verified theory would not only reduce the measurements required to develop empirical models, but provide a sound basis for remote sensing.

A present need is to determine what theory and set of approximations, if any, fits the experiments and to determine where the various approximations are reasonably accurate. Two simplifying approximations commonly used in modeling interface scattering are the Kirchhoff and the Rayleigh-Rice approximations. The Kirchhoff approximation is applicable to surfaces whose local radius of curvature, R, is large compared to the acoustic wavelength, λ. The surface may have undulations that are large compared to a wavelength, but these undulations must be smooth in the sense

$$R \gg \frac{\lambda}{2\pi \sin^3\theta}$$

where θ is the grazing angle. The Rayleigh-Rice approximation is applicable if the wavelength is much greater than the rms relief [7].

The ocean surface and bottom typically violate both these conditions for centimeter wavelengths. In response to this dilemma, the composite roughness approximation has been developed and has been applied to realistic surfaces [7,11]. This approximation assumes that the rough surface height function can be expressed as the sum of large-scale and small-scale components separately satisfying one or the other of the two conditions.

This approach has met with success in modeling the surface and bottom, but problems remain. First, owing to the grazing angle dependence of the Kirchhoff criterion, the composite roughness model might not be applicable at grazing angles below 10 or 20°. Second, the division of the surface into large-scale and small-scale parts is not always clear-cut. Surface and bottom roughness spectra typically increase monotonically as wavelength increases and do not separate naturally into two parts. This leads to an ambiguity in model predictions, which becomes a serious problem near vertical incidence and in the forward direction. Finally, the conditions for applying the composite roughness model and its underlying assumptions are not well understood. Conditions such as "much greater than" (as in the formula given above) are too indefinite to delineate regions of applicability in a practical way.

For the sea surface, McDaniel and Gorman [11,12] showed by comparing their composite roughness model with available data that surface roughness alone could not explain measured low grazing angle backscattering strengths. They also showed that reasonable near-surface bubble densities could explain the discrepancy.

At high frequencies, the surface roughness is almost always so large that reflection is not, strictly speaking, a correct description of surface bounce. Instead, acoustic energy is scattered, mostly in a narrow range of angles around the specular direction. Because existing ray trace simulations only allow for the use of a reflection loss, when and if a reflection loss can be used as a good approximation should be investigated.

At APL-UW, work on this problem [13] supports the use of an energy reflection loss model for systems with beam patterns greater than about 20° when energy is a sufficient quantity. For low wind speeds the APL-UW analysis predicts 0 dB reflection loss, which is consistent with heuristic conservation-of-energy arguments. At higher wind speeds, the effective reflection loss is given entirely by the bubble absorption, which increases rapidly with wind speed.

BOTTOM SCATTERING

Although bottom scattering would seem to be the most difficult process to model because of the large variety and complexity of bottom types, it is in some respects simpler to model than surface scattering. At high frequencies, acoustic attenuation prevents penetration to depths much greater than 1 m, eliminating the need to consider geological layering. There has been progress in obtaining data on the bulk acoustic properties of sediments [14] and also in understanding the effect of hydrodynamic and biological processes on the surface layers of the bottom [15,16]. However, there are relatively little data on roughness properties. Figure 1 shows roughness spectra measured by Igarashi and Allman [17] and Crisp et al. [4]. These spectra from four different sites show similar power-law behavior. Compared with sea surface spectra, these fall off more slowly with frequency, having greater high-frequency content and less low-frequency content. The rms relief of a 1 m track is typically only about 1 cm. This simplifies application of theoretical models in some respects, but the elevated high frequency content causes problems as it implies small radii of curvature.

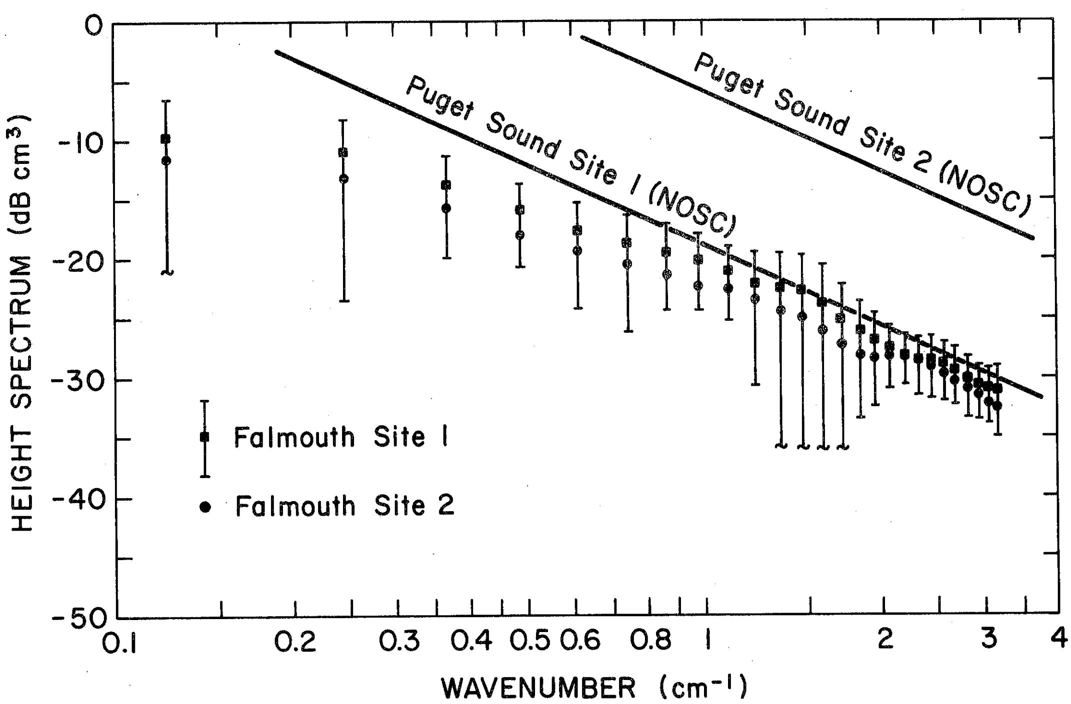

Figure 1. Bottom roughness spectra.

A semi-empirical bottom backscattering model has been developed, employing three underlying physical models [6]. As Figure 2 indicates, roughness scattering is treated by the composite roughness model except near vertical incidence where the Kirchhoff approximation provides more accurate results. Sediment volume scattering is handled by a simple model adapted from that of Ivakin and Lysanov [18]. The final model has four parameters: the ratio of densities for the bottom and water, the ratio of sound velocities for the bottom and water, the ratio of sediment volume scattering cross-section to sediment absorption coefficient, and the rms relief of a 1 m track. The last parameter fixes the strength of a model roughness spectrum having power-law behavior as in Figure 1.

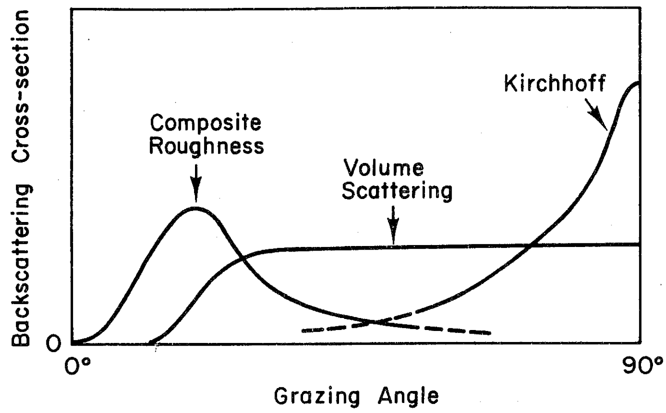

Figure 2. Underlying physical models.

Figure 3 shows a typical comparison of model and data. Such comparisons are often compromised by a lack of physical data from which to estimate the four parameters. Fits of the model to acoustic data usually provide physically reasonable values for these parameters. Since scattering strength near vertical incidence is governed in this model by roughness and acoustic impedance, vertical incidence data go a long way toward determining the model parameters. Similarly, the volume scattering parameter can be determined by fitting to the data at middle angles, near 30°, where volume scattering is dominant, at least in soft sediments. Figure 3 illustrates one such fit. It has been established that, in most cases, backscattering strengths at high and low grazing angles are caused by small scale roughness and are dominated by volume scattering within the sea bed for intermediate grazing angles [5,6,19]. Both theory [5] and recent experiments [4,20] show a rapid decrease in scattering strength at shallow grazing angles. Measurements also show bottom scattering strength to be frequency independent, for the most part [3,4], with some exceptions [1,20].

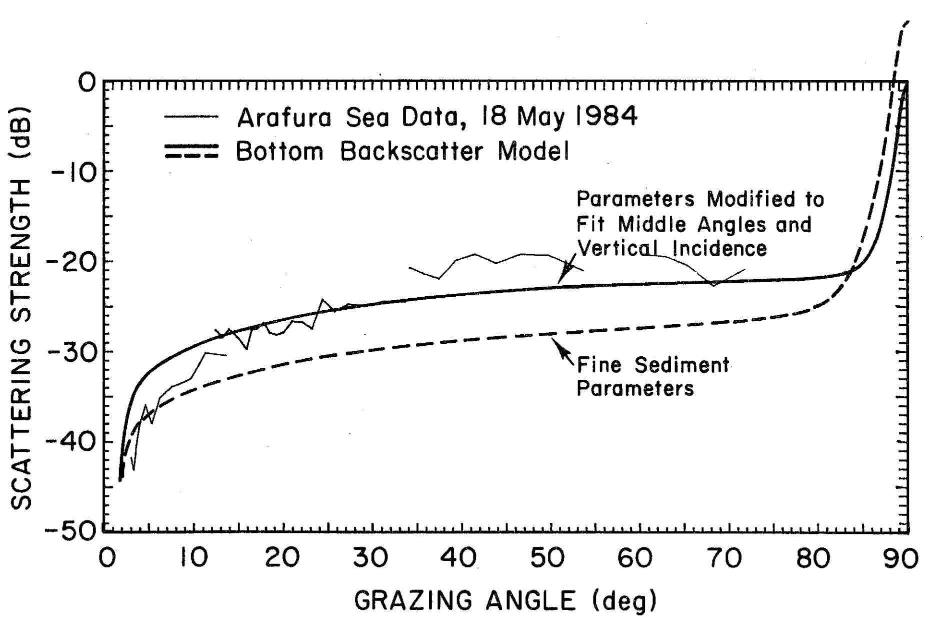

Figure 3. Arafura Sea bottom backscatter strength compared to model predictions.

Unpublished measurements of forward bounce made by APL-UW show replicas of short pulse transmissions (1 ms) indicating that a reflection loss model [21] may be adequate, thus greatly simplifying the modeling task. Scattering could be needed in modeling a hard, rough bottom, but this condition might be rare enough to be of little practical interest.

A 1982 experiment [4] in the North Sea (undertaken by the Admiralty Underwater Weapons Establishment and APL-UW) measured bottom backscattering strength for a set of fixed grazing angles along a 40 mile track and showed a great deal of spatial variability (Figure 4). Grab samples taken along the track did not indicate any significant difference in the bottom characteristics. In 1984 an experiment was conducted by APL-UW and several other laboratories in the Arafura Sea in which the data were processed at sea to identify sites for detailed bottom characterization so that the bottom properties relevant to acoustic variability could be identified. The Arafura Sea data showed surprisingly little spatial variability and a rather high level of sediment volume scattering. Additional work is needed to determine the cause of variability and sediment volume scattering to improve our confidence in the model and to determine if spatial variability is so common that it must routinely be included in bottom models used for system development and performance prediction.

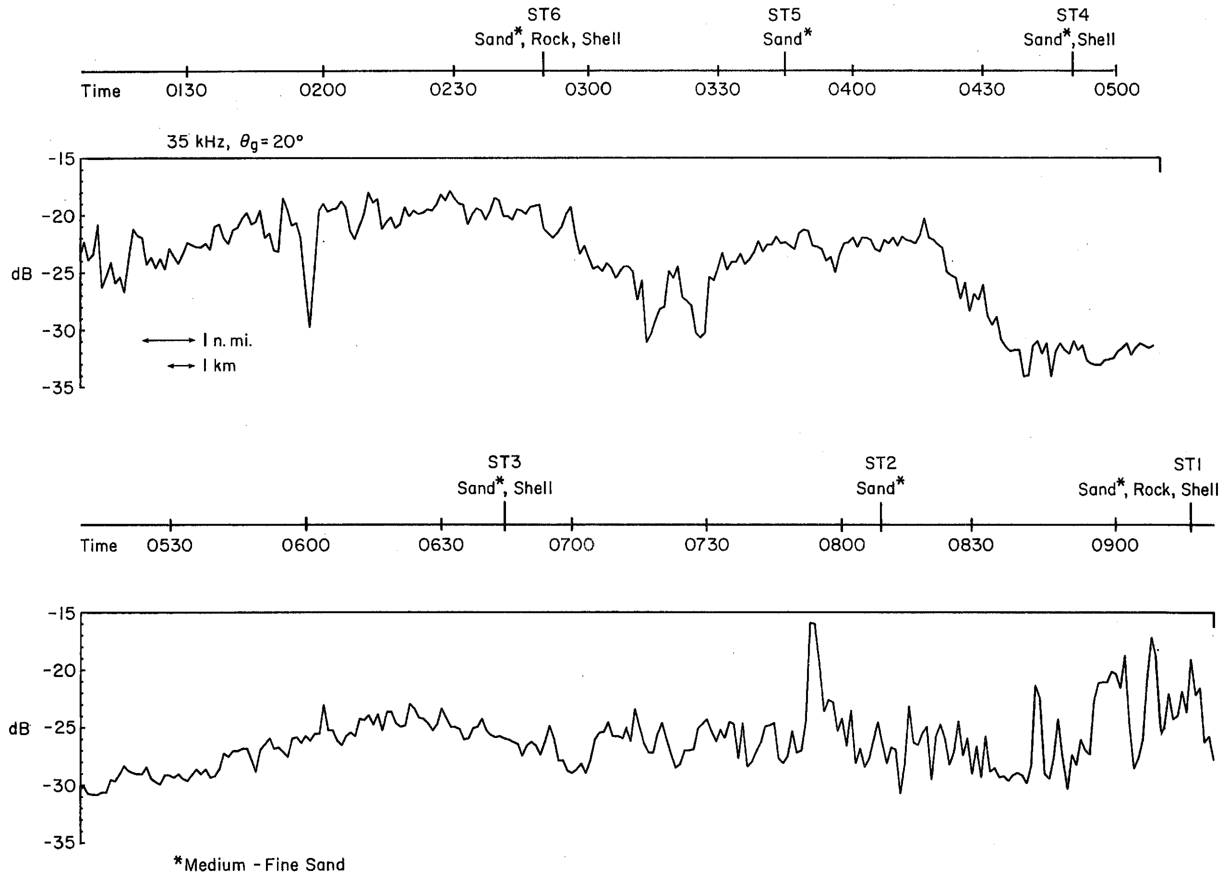

Figure 4. North Sea survey track, 1981.

In shallow water, acoustic energy is scattered and reflected off the surface and bistatically backscattered off the bottom. The backscatter strength for the arithmetic or geometric mean of the incident and scattered angles is often used in simulations, but without any physical basis. A model of bistatic backscattering from the sea bed is therefore needed, especially for an understanding of shallow water acoustics.

Another practical need is to find a set of simple measurements that can be taken by survey ships to characterize areas of interest. Work is currently underway to develop a technique for estimating scattering model parameters for the bottom from vertical incidence measurements. This work is, however, in its infancy and considerable additional work is needed.

SURFACE SCATTERING

At low wind speeds, less than 10 kn, surface roughness is the dominant physical mechanism for surface scattering. Above 10 kn bubbles are formed at the surface and mixed into a near-surface layer, the characteristics of which are determined by at least the wind conditions and the wave field, especially the large-scale waves. The bubble scattering and absorption are dominated by the resonant bubbles. The effects caused by the bubbles are highly frequency dependent because the number of small bubbles, which have longer lifetimes, is much greater than the larger ones. In a recent APL-UW experiment, the results of which are shown in Figure 5, vertical incidence measurements at a wind speed of 15 kn showed a strong frequency dependence where very little scattering was observed from below the surface at 20 kHz, but high scattering strength from a bubble layer was observed at 50 kHz as depicted by the shaded area in the figure. Scattering from both wave peaks and troughs produced the feature at about 8 dB below the maximum return for both frequencies. For comparison, the vertical incidence return for a calm surface is given by the light line in Figure 5.

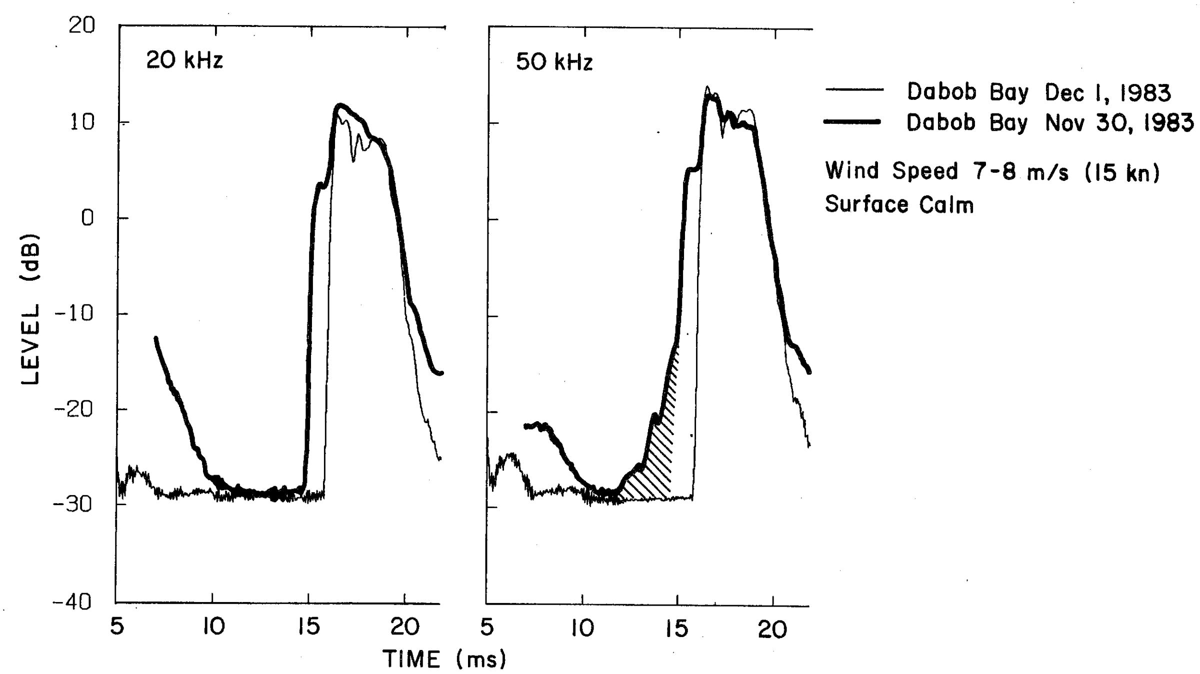

Figure 5. Surface vertical incidence return.

One important set of problems, therefore, is to develop models of the sea surface and the bubble layer as a function of both the sea surface environment and the dynamics of the surface layer. A practical model is needed that has readily measurable parameters as inputs. The existing acoustic backscattering and forward loss models need to be improved and extended especially to include both the effects of bubbles and the azimuthal spread of energy in the forward direction.

For high wind speeds, bubble effects can be expected to dominate as the scattering mechanisms for backscatter and as the absorption mechanisms for forward loss. Measurements at the Quinault Range [22] in 1983 in the 10-20 kn range show forward losses up to 15 dB in the 20-30 kHz range at a grazing angle of 7°. The measurements showed even higher losses as the frequency increased. As discussed earlier in the theory section, surface roughness dominates for low wind speeds. Under these conditions a surface loss of 0 dB is required when modeling reverberation in order to match various data sets with simulations as shown in Figure 6. This figure shows the match of data to the 0 dB loss model and the variation caused by changing the loss model. However, since the energy is spread in time and space for a signal that bounces off a rough surface, it is difficult to develop a comprehensive practical model for this surface interaction, and additional progress is needed. The intermediate wind speed range is the most difficult range to model because it is a region where, for small changes in air-sea parameters, large changes occur in the acoustic effects [13], and where both the bubble layer and surface roughness are significant.

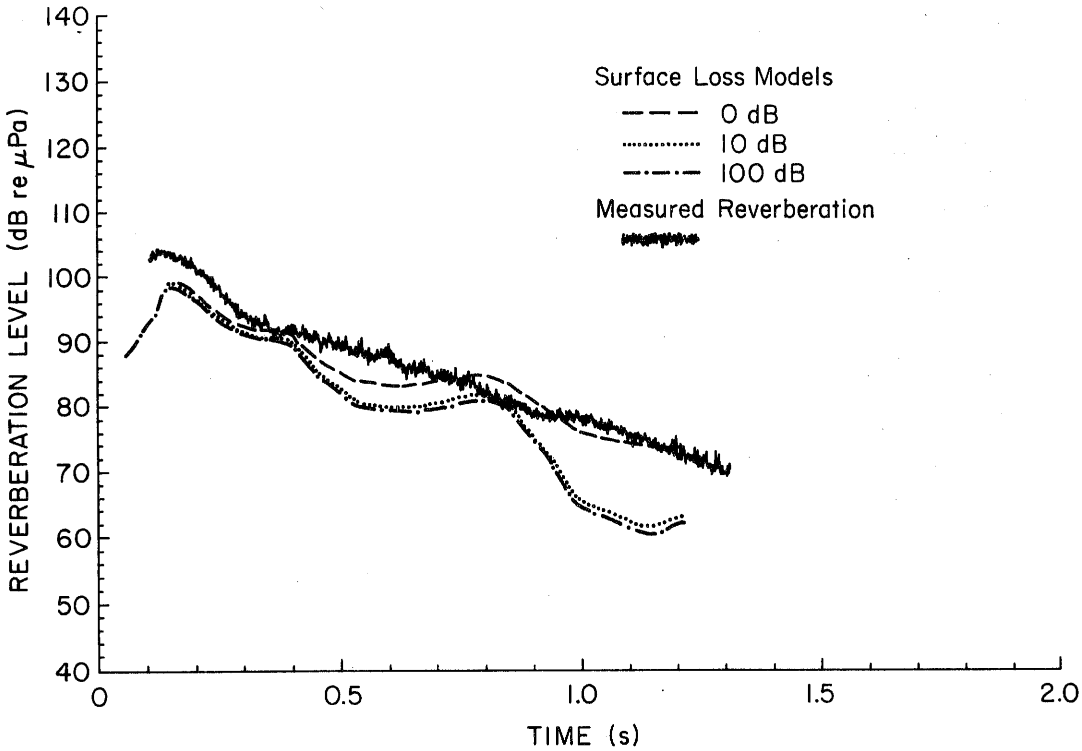

Figure 6. Measured reverberation level compared to simulated reverberations using 0 dB, 10 dB, and 100 dB surface loss models.

Surface bistatic backscatter, like that for the bottom, is modeled in simulations using the arithmetic or geometric mean of the scattering angles. A data set [23] taken in 1977 showed slightly lower bistatic scattering strengths than either mean, but was not at all conclusive because of its limited nature. Additional measurements and model development are required.

Many other effects are of practical significance such as various types of spatial and temporal coherence, but the list of problems discussed earlier is more basic and seems logical to attack first. In general, the environmental acoustics community is well behind the needs of system developers, a situation not likely to change for many years.

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PROC. INST. ACOUSTICS VOL 7 PT 3 1985

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 $7\frac{1}{2}$ 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