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THE EFFECT OF A LAYER OF VARYING DENSITY ON HIGH-FREQUENCY ACOUSTIC REFLECTION, FORWARD PROPAGATION LOSS AND BACKSCATTERING STRENGTH

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The effect of a layer of varying density on high-frequency acoustic reflection, forward propagation loss and backscattering strength

A.P. Lyons and T.H. Orsi*

Executive Summary:

In the upper 30 cm of seabed sediment, marked variations of sediment density with depth have been observed. This thin layer of sediment has relatively little effect on low-frequency (less than about 5 kHz) acoustic transmissions but it may have considerable impact at frequencies greater than 10 kHz; at these frequencies, the acoustic impedance of the seabed becomes frequency dependent.

This report analyses the effect that a thin upper layer of seabed sediment with varying density has on the reflection, forward propagation loss and backscattering of high-frequency acoustic plane waves. It has been found that the inclusion of such a density profile results in estimates of the reflection coefficient and forward loss showing a marked frequency dependence. The most significant effect on total backscattering strength is for near normal incidence plane waves where the returns from the seabed are dominated by scattering at the interface between the water column and the seabed sediment.

The results presented in this report demonstrate that variations in the density of the first 30 cm of seabed sediment may have a significant effect at acoustic frequencies particularly relevant to minehunting operations where the detection of objects both on and buried in the seabed sediment is the aim. Furthermore, the effect of the density profile on the strength of acoustic returns suggests that care is required when using high-frequency acoustic transmissions for remotely measuring sediment properties, especially at near normal incidence.

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The effect of a layer of varying density on high-frequency acoustic reflection, forward propagation loss and backscattering strength

A.P. Lyons and T.H. Orsi

Abstract:

This report examines the impact that a thin layer of varying density would have on high-frequency reflection, forward loss and backscattering of acoustic plane waves from the seafloor. A functional form for density stratification was found by examination of several high-resolution density profiles obtained from x-ray computed tomography scans of seafloor cores. A solution based on these general profiles was used to estimate the reflection coefficient. The influence of the density profile on reflection loss and backscatter was then calculated using the estimated reflection coefficient. Parameter values used in simulations were obtained from the literature or from the CT scans of cores. It was found that inclusion of a density profile adds a strong frequency dependence to estimates of the reflection coefficient and forward loss. The largest effect on total scattering strength is near normal incidence where returns are dominated by interface scattering. The effect of the density profile on the strength of acoustic returns suggests that care should be taken when using high-frequency systems for measuring sediment properties, especially near normal incidence.

Keywords: High-frequency acoustics ∘ reflection coefficient ∘ forward loss ∘ seafloor scattering ∘ acoustic remote sensing

Contents

1 Introduction

Seafloor characterization by acoustic remote sensing techniques consists of many types of activities. One method measures the strength of returns from the seafloor for either vertical or oblique incidence of the acoustic waves on the bottom. The strength of this acoustic return is interpreted in terms of some characteristic(s) of the seafloor material. One assumption that is often made in the application of many high-frequency vertical and oblique measurement systems and in the modeling of the acoustic interaction with the seafloor is that the upper seafloor is homogeneous. When plane acoustic waves impinge on the abrupt change in density and sound speed that exists at the interface between the upper seafloor and the water column, the amplitude of the reflected wave is given by the well-known Rayleigh reflection coefficient. In this case (a plane interface between two homogeneous media) the reflection coefficient is independent of frequency. However, if there exists a thin region of high gradients in the properties of the top few centimeters or decimeters of the seafloor, then the behavior of acoustic reflection from the interface becomes more complicated and frequency dependent. While this near surface seafloor region would be relatively thin compared to low frequency wavelengths, it could be particularly important for wavelengths of the same order or smaller than the thickness of the high-gradient region. With many modern systems for probing the seafloor having frequencies greater than 10 kHz, this fine scale structure of the upper seafloor (subcentimeter) may have a large impact on the reflection and transmission of acoustic energy [1] and also on the strength of seafloor surface and volume scattering. A transition layer of non zero thickness has the potential to directly effect the classification of bottom/subbottom types, detection of buried objects, and propagation loss.

Evidence has been accumulating over the past several years implicating a lower density upper seafloor layer such as that described above as the cause of differences between high-frequency acoustic scattering or forward reflection loss data and model calculations. In several instances a lower value for density is used as input to the various models than was actually recovered from seafloor cores [2],[3],[4]. This reduced density value served to lower the modeled scattering strength or increase the modeled forward loss. Mourad and Jackson [3] conclude from theoretical calculations that if density gradients are weak enough then they can be ignored and that only surface values of geoacoustic parameters are necessary. What is meant by surface values is not explicitly defined in their analysis and would not completely address the issue of frequency dependence in any case as it is the overall shape not just the surface value that affects the acoustics. Another possible piece of evidence for the effect of density gradients on high-frequency acoustics can be found in Chotiros [5]. In this work, anomalies are found in comparisons of theoretical and experimental estimates of acoustic reflection. These anomalies include a reflection coefficient, calculated from the acoustic data which is consistently too low and also has a slight frequency dependence. While he attributes the discrepancy between theory and observation to the failure of viscoelastic wave theory, the same result, as will be shown in the following sections, can also be attributed to gradients in density.

The analyses of acoustic data sets discussed above, leads to a qualitative understanding of the importance of a low density layer on high-frequency acoustics but more quantitative studies on the influence of the very near surface density profile are lacking. This layer has not been studied due to lack of knowledge of the proper form for the density profile. This vital piece of information has been missing because of the paucity of geoacoustical data on relevant scales. Recent advances in techniques allow measurement of sediment density on scales less than 1 cm thus providing the much needed high-resolution description of the seafloor. One of these techniques is the use of x-ray computed tomography (CT) which can provide a three-dimensional description of the interior density distribution on scales much less than 1 cm^3 [6],[7]. Seafloor cores were taken as part of the Naval Research Laboratory's (NRL) Coastal Benthic Boundary Layer (CBBL) field program sponsored by the Office of Naval Research and very high-resolution analyses were performed. On each core, the analyses included X-ray CT scanning and high-resolution laboratory geotechnical analysis, the data were subsequently archived [8],[9],[10]. With this data set it is now possible to explore the dependence of the reflection coefficient, forward loss, and backscattering on the shape of the density profile and also to quantify the frequencies at which this upper density profile might be important.

2
Reflection from a fluid layer with continuously varying density

2.1 Geoacoustic modeling

2.1.1 General density profile

As attenuation at high-frequencies in sediments is generally high, properties in the region very close to the sediment-water interface will have a dominant effect on the acoustic wave interaction. In this near surface region of the seafloor, properties often display a tiered nature with depth. This tiering has been invoked to explain vertical variations in sedimentary structure [11],[12]. A recent study by Orsi [13] extends this type of analysis to density profiles obtained from X-ray computed tomography of seafloor cores obtained in a variety of shallow water areas. The tiers consist of a mixed layer, a transitional layer, and an historical layer. Of most importance to this study is the mixed layer which extends from the water-sediment interface to a few centimeters depth. This layer is continuously subjected to intense small-scale bioturbation which has the effect of lowering the porosity (hence density). Since the bioturbation is a function of depth (decreasing with depth), the very low bulk densities increase rapidly with depth in the layer. While the strong gradients are mostly a response to benthos, other mechanisms such as particle segregation and the initiation of self-weight consolidation may also influence the density structure as the mixed layer is very nearly fluid in most cases. Below the mixed layer, in the transitional and historical layers, density increases modestly in the upper decimeters of the seafloor due to decreasing bioturbation and consolidation (mechanical compaction.)

In order to facilitate the study of the effects of the density structure on acoustic interaction a general form for the profile must first be established. Robins [14],[15] and Ainslie [16] have described the seafloor density depth profile at a larger scale than studied in this report and have derived solutions for the reflection coefficient based on this description. The form of the large scale density structure used in these studies is given by the equation

$$\rho(z) = Be^{\alpha z}/(e^{\alpha z} + C)^2. \tag{1}$$

In this equation B and C arbitrary constants. This function behaves like $e^{\alpha z}$ for small z but $e^{-\alpha z}$ for large z. In addition to having a tractable solution, this profile has been shown to compare well with experimental data. This function, however, doesn't lend itself to the description of the shape of the very near surface density profiles as it increases too quickly with depth. A better representation of the shape of the profile for the upper few decimeters of the seafloor is based partially on a smoothed version of the tiered near-surface seafloor structure described above (Fig. 1). The general depth dependent density profile, $\rho(z)$, with which we propose to represent the upper seafloor is expressed as

$$\rho(z) = \begin{cases} \rho_w & z < 0 \\ \rho_s - \Delta\rho f_\rho^{-1} & z \geq 0 \end{cases}, \tag{2}$$

with

$$\Delta\rho = \rho_s - \rho_0. \tag{3}$$

ρ_s is the value that the density approaches at $z = \infty$, ρ_w is the density of the overlying water, and ρ_0 is the value of density just at the water-sediment interface. The density approaches ρ_s with depth according to the function

$$f_\rho(z) = 1 + az. \tag{4}$$

The parameter a in this equation, which will be refered to as the density profile parameter, is a measure of the thickness of the region of high density gradients in the combined mixed and transitional layers. The adequacy of this general form in representing measured high-resolution density profiles will be seen in the following section.

2.1.2 Comparison with core data

During 1993-94, the sediment cores used in this study were obtained from Eckernförde Bay, Germany, in the vicinity of Panama City, Florida, and in the western Florida Keys (Marquesas Keys). The cores were taken as part of the Naval Research Laboratory's Coastal Benthic Boundary Layer field program sponsored by the Office of Naval Research. One of the primary goals of the CBBL was to relate high-frequency acoustic scattering and propagation to sediment structure [17]. The sediment cores used in this study were obtained either by subsampling box cores or by divers. Box coring provides one of the most reliable means, short of *in situ* study, of obtaining the high-quality seafloor samples needed in geotechnical studies [18]. Several types of analyses were performed on each core, including X-ray computed tomography (CT) scanning and high-resolution laboratory geotechnical analysis, and the data subsequently archived [8],[9],[10].

The primary core data analyzed and presented in this report consists of CT scan data. Sequential CT scans of these cores were taken as the sample was moved along

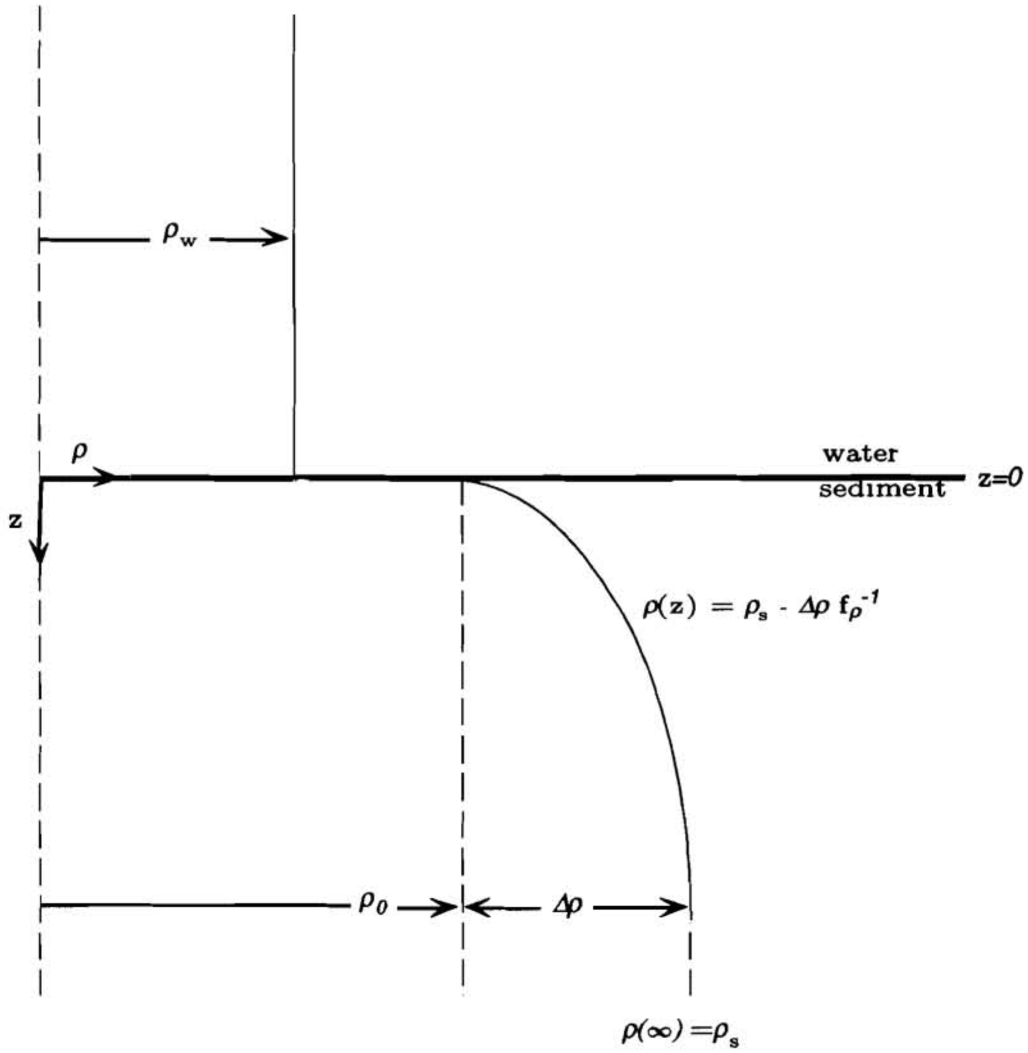

Figure 1 *Seabed layering model for density with $f = 1 + az$.*

its principal axis, resulting in a three dimensional data base of CT numbers for the entire scanned portion of the core. All the cores mentioned in this study were scanned using a 2 mm thickness for the scanned section along with a 2 mm downcore translate distance. With this scheme, a continuous profile of CT number was created with no overlap of the CT images. CT numbers can be, and in this analysis are, related to the bulk density of the scanned material. Each CT value represents the bulk density of a very small volume element (voxel) of the sediment. Cores were subsampled and measurements of bulk density were made to provide normal, high-resolution physical sample density profiles and to serve as part of the calibration for interpretation of CT data as density. Details of the calibration scheme can be found in Orsi [13]. Average CT density for each scan was determined using 10,000 measurements from a 100 × 100 voxel region of interest (ROI) selected from the geometric center of the CT image. Vertical profiles of density can then be created with these average densities.

Examples of density profiles from cores taken in the Eckernförde Bay, Panama City, and the Florida Keys are shown in Fig. 2. Cores from Eckernförde Bay, Panama City and the Marquesas Keys are designated with BS, PC, and KW respectively in the core names. Also in the core names, BC signifies a box core and DC signifies a diver core. In these examples, the region of the profiles with strong gradients in density is of the order of 1-5 cm. It is in this region that density data has been lacking in the past as it is often disturbed by the coring/sampling process or is omitted entirely in a coarse sampling scheme. Along with the density profiles, Gauss-Newton least-squares curve fits of the general profile function to the data are also shown in Fig. 2. The values of ρ_s are restricted to physically realistic values in the fitting procedure. The functional form, as can be seen in Fig. 2, provides a reasonable description of the density data.

The values given in Table 1 summarize the available CT scanned CBBL core data in terms of the layering model parameters for cores from each of the three experimental sites. Although there is the potential when analyzing cores for the sediment-water interface to be disturbed by the sampling process, the cores presented here were taken either by divers or as box core subsamples so that disturbance of the interface was minimal. In the following sections these parameter values will be used in calculations of the reflection coefficient.

2.2 Calculation of the reflection coefficient

The problem of calculating the coefficient of reflection of an acoustic wave impinging on the seabed is a complex one, involving a large number of geoacoustic parameters. These include sound speed, density, and attenuation, all of which might vary with depth in the sediment. In order to isolate the effect of the density profile on the

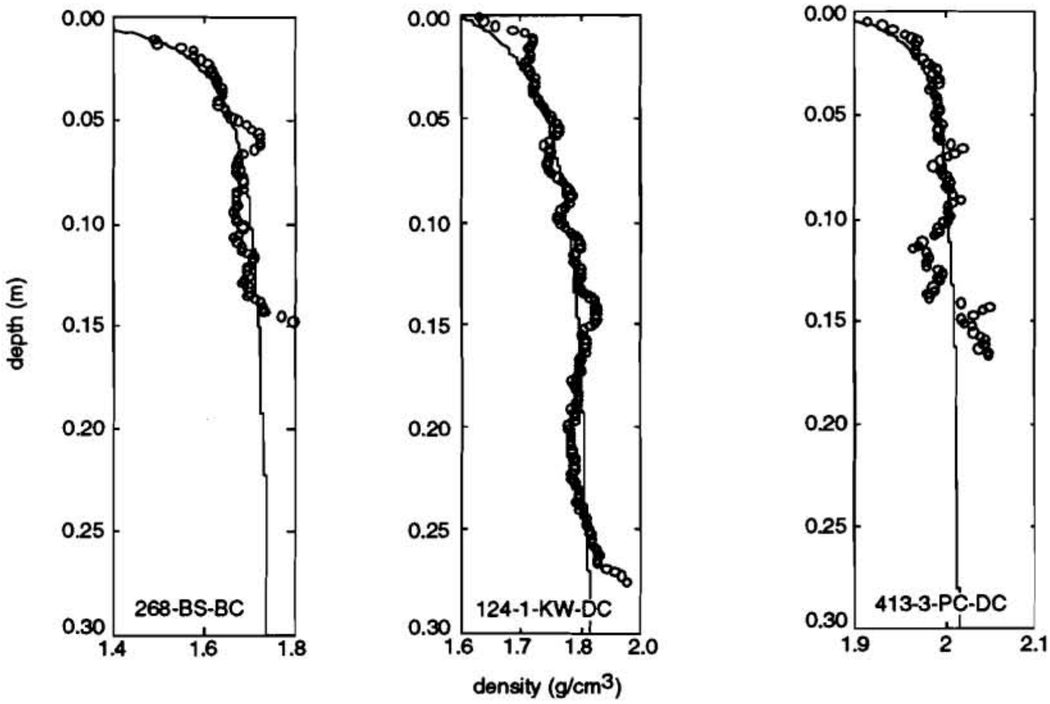

Figure 2 *Density profiles from three CBBL sites plotted with the function* $\rho(z) = \rho_s - \Delta\rho f(z)^{-1}$.

Table 1 *Density profile parameters for cores from three CBBL sites.*

Core Name	$\rho_s(g/cm^3)$	$\Delta\rho(g/cm^3)$	a $(1/m)$
227-BS-BC	1.21	0.03	97.0
250-BS-BC	2.05	1.05	13.8
260-BS-BC	1.57	0.46	61.6
264-BS-BC	1.22	0.10	88.5
268-BS-BC	1.75	0.51	100.4
89-1-KW-DC	1.83	0.22	12.2
89-2-KW-DC	1.83	0.21	8.9
124-1-KW-DC	1.84	0.19	19.3
124-2-KW-DC	1.78	0.07	42.5
413-2-PC-DC	2.03	0.23	224.4
413-3-PC-DC	2.02	0.13	62.6
490-PC-DC	1.99	0.14	207.4

reflection coefficient, seafloor sound speed will be assigned a constant value, and attenuation will be considered depth independent. These assumptions, which greatly simplify the derivation of the reflection coefficient, are reasonable, as some of the few high-resolution analyses of seafloor ground truth cores have shown that in the seafloor, unlike the water column, relative vertical gradients in attenuation and sound speed are often weaker than the observed variations in porosity (or density) in the upper seafloor [19],[20],[4]. Jackson and Briggs [2] also suggest that it is the low density upper layer that is the controlling factor for the differences between modelled and experimental scattering strength results, not sound speed. In the following derivation, the sound speed will be used in the form of the index of refraction and as the medium is considered lossy, absorption is added by making the index of refraction complex in the sediment.

$$n = (c_w/c_s)(1 + i\epsilon). \tag{5}$$

The parameter ϵ is the loss tangent [21]. We follow Hamilton [22] in assuming a linear dependence of attenuation on frequency (ϵ=constant). We also assume a fluid sediment rather than an elastic, or visco-elastic solid in the upper decimeters, that is, we are only considering pressure waves in this analysis.

Brekhovskikh [23] gives an approximate method for obtaining the reflection coefficient, $\mathcal{R}$, for a medium with an arbitrary law for change in parameters (section 25.5). In this derivation the usual procedure of writing the equation for the field and attempting to solve it is not followed. Instead, the problem is in finding the ratio of the complex amplitudes of the reflected and incident wave (reflection coefficient.)

This is accomplished by solving a nonlinear first order differential equation known as the Riccati equation for the reflection coefficient. Following Brekhovskikh this differential equation is given as:

$$\mathcal{R}' = -2i\beta\mathcal{R} + \gamma(1 - \mathcal{R}^2). \tag{6}$$

with γ defined as:

$$\gamma(z) = q'/2q. \tag{7}$$

The primes indicate differentiation with respect to z. In Eq. (7) q is defined as

$$q(z) = \beta/\rho, \tag{8}$$

with

$$\begin{aligned} \beta(z) &= (k^2 - k_0^2 cos^2\theta)^{1/2} \\ &= k_0(n^2 - \cos^2\theta)^{1/2}. \end{aligned} \tag{9}$$

The vertical wave number in the sediment, β, is a function of the grazing angle, θ, and the acoustic wave number in water, $k_0 = \omega/c_w$. The boundary condition needed to solve Eq. (6) is taken as the vanishing of the reflection coefficient at infinity

$$\mathcal{R} \to 0 \text{ for } z \to \infty .$$

With this condition an approximation to the reflection coefficient is:

$$\mathcal{R}(0) = -\int_0^\infty \gamma(z) exp(2i\phi)dz, \tag{10}$$

with

$$\phi = \int_0^z \beta dz. \tag{11}$$

If the sediment properties just at the interface ($z = 0$) are significantly different to those of water, *i.e.* a step change at the interface, then this method must be modified. In the more general case where $\rho_0 \neq \rho_w$ a solution can be found by dividing the medium into two components; the first being from $z = 0$ to $z = 0^+$ (0^+ is just below the water-sediment interface) and the second from $z = 0^+$ to ∞. If the thickness of the first component is vanishingly thin then the reflection coefficient is the result given by Brekhovskikh and Lysanov [24]

$$\mathcal{R} = \frac{\mathcal{R}_1 + \mathcal{R}_2}{1 + \mathcal{R}_1\mathcal{R}_2}. \tag{12}$$

In Eq. (12) $\mathcal{R}_1$ represents the reflection coefficient when the density profile is set to a constant that is equal to the surface value and is given by

$$\mathcal{R}_1 = \frac{q(0) - q(0^+)}{q(0) + q(0^+)}. \tag{13}$$

This is simply the reflection coefficient calculated using the sound speed and density values found at the surface $z = 0^+$ ($i.e.$ k_0, ρ_0.)

In order to obtain an expression for $\mathcal{R}_2$, we start by using Eqs. (2)-(4) with Eqs. (8) and (9), and then differentiate the result to get

$$q' = -\frac{a}{\rho f^2}(n^2 - cos^2\theta)^{1/2}. \tag{14}$$

The previous expression, when used in Eq. (7), yields

$$\gamma = -\frac{a\Delta\rho}{2f^2\rho}. \tag{15}$$

Using again the definition given in Eq. (9) in Eq. (11) and assuming a constant sediment sound speed yields for ϕ the simple expression

$$\begin{aligned} \phi &= k_0 \int_0^z (n^2 - cos^2\theta)^{1/2} \\ &= k_0 sin\theta. \end{aligned} \tag{16}$$

With Eqs. (15) and (16), the reflection coefficient, $\mathcal{R}_2$, can now be calculated using Eq. (10). The solution derived in this section is valid at both extremes of wavelength. For relatively low frequencies the acoustic wave feels only the impedance mismatch caused by sediment bulk properties (ρ_s, c_s), while at very high frequencies it feels only the impedance mismatch caused by the surface properties (ρ_0, c_s).

3
Results

3.1 Reflection

In this section numerical results of reflection are presented using the complex reflection coefficient described in the preceding section. In order to highlight the effects of the density profile on the reflection coefficient, calculations were made with the parameter values: $\rho_w = 1.0$, $\rho_0 = 1.0$, $\rho_s = 1.75$, $\epsilon = 0.018$, $a = 50.0$, and the ratio of sediment to water sound speed set to unity. These reflection coefficient results are presented in the form of bottom loss,

$$-20log_{10}|\mathcal{R}(\theta)|, \tag{17}$$

The graphs in Fig. 3 display the calculated reflection coefficient versus grazing angle (at 20 kHz), versus frequency (at normal incidence), and versus the profile parameter, a, (also at normal incidence and at 20 kHz). While some of the parameter values used in this calculation are not entirely realistic, it is readily apparent that the inclusion of the density profile reduces the estimated reflection coefficient with respect to that made with the sediment density (ρ_s) only. The reflection coefficient is seen to decrease as a function of increasing frequency (or equivalently decreasing values of a). Chotiros [5] has discussed discrepancies between echo sounder measurements of reflection coefficient and estimates of reflection coefficient computed from sediment sound speed and density. Chotiros finds that the reflection coefficient calculated from the acoustic data is consistently too low (when compared with estimates made using ground truth core data). He concludes that this is due to the failure of viscoelastic wave theory. As shown in Fig. 3, the same result can be attributed to gradients in density. The slight frequency dependence that is evident in his 8-20 kHz data can also be explained as resulting from the near surface density profile.

Ignoring the density profile in inverse model predictions can result in errors in the estimation of seafloor physical properties made with acoustic remote sensing data. This fact is increasingly relevant as many remote sensing systems such as NRL's Acoustic Sediment Classification System (ASCS) [25] are moving to higher frequencies in order to improve resolution. If it is assumed that the sound speed in the surface sediments is equal to the value in water, then the density value, ρ_{est}, that

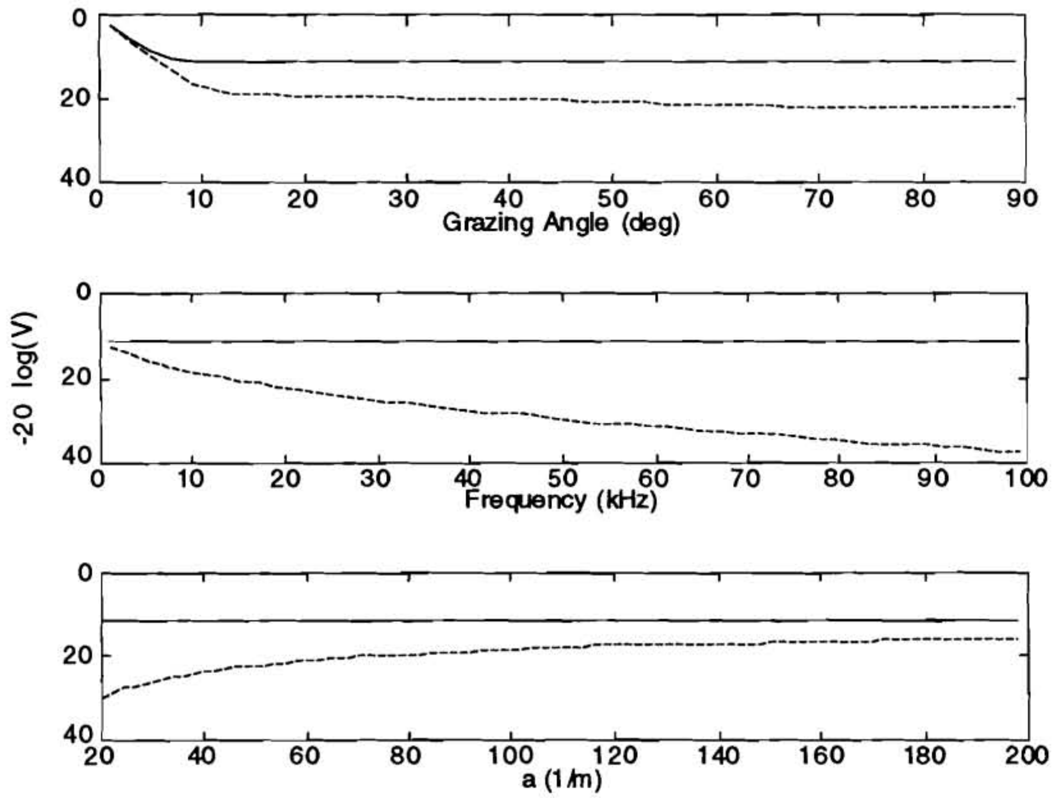

Figure 3 *Reflection coefficient calculated without density gradient effects (solid line) and with (dotted line) as a function of grazing angle (top), frequency (middle), and layer thickness parameter (bottom).*

would be estimated from an experimentally determined reflection coefficient, $\mathcal{R}_{exp}$ is given by

$$\rho_{est} = \frac{1 + \mathcal{R}_{exp}}{1 - \mathcal{R}_{exp}}. \tag{18}$$

The expected density as a function of frequency is given in the middle graph of Fig. 4. Parameter values used to calculate the reflection coefficient are as before. As can be seen in this figure, the reduced reflection coefficient due to the density profile causes the value of the estimated density to be lowered, with the estimate becoming worse as frequency is increased.

Related to the reflection coefficient, the transmission coefficient is of importance in the remote sensing of features beneath the seafloor interface as well as to scattering from the seafloor volume. The quantity which describes transmission through the interface into the seafloor and then back into the water is given by the simple relation

$$\mathcal{T}^2(\theta) = 1 - \mathcal{R}^2(\theta). \tag{19}$$

In this equation, it is assumed that the reflection coefficient is the same whether looking at the interface from the water column or from the seafloor. The bottom graph in Fig. 4 shows calculations of the two-way transmission loss made using the same parameters as were used previously. For this set of parameters, the transmission loss approaches zero as frequency increases demonstrating that at higher frequencies, the interface is transparent. The density profile causes the interfacial region to act as a high pass filter to incoming acoustic waves and thus may have a strong effect on broad band pulse propagation. The frequency dependence of transmission into the seafloor has particular relevance for broadband remote sensing systems that are becoming popular for seabed classification [26],[27].

3.2 Forward loss

The reflection coefficient of a lossy fluid half-space as put forward by Mackenzie [28], has been shown to be an accurate estimator of forward loss [29],[3]. As in the high-frequency forward loss model of Mourad and Jackson [3], losses due to interface roughness scattering are neglected in the model of forward loss used here, Eq. (17). This assumption is validated somewhat by available data on bottom roughness spectra which show the seafloor to be relatively smooth [30].

Figs. 5, 6, and 7 contain contours of forward loss calculated using parameter values from three of the CBBL cores found in Table 1. The top panel in each figure displays contours of forward loss and the bottom panel shows the difference between forward loss estimates made including the full density profile and estimates made only with the sediment density, ρ_s. The three cores used in the following examples of forward

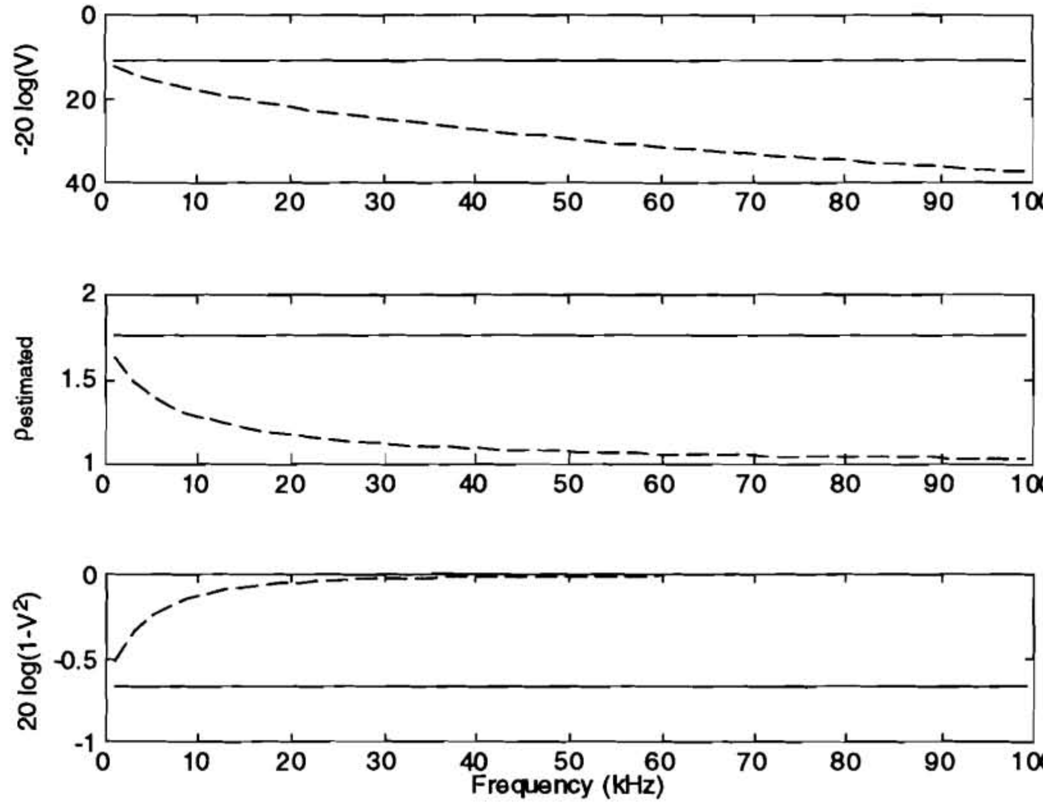

Figure 4 *Top: reflection coefficient as function of frequency without including density gradient effects (solid line) and including gradient effects (dashed line); middle: estimated density as a function of frequency; bottom: two-way transmission loss as a function of frequency.*

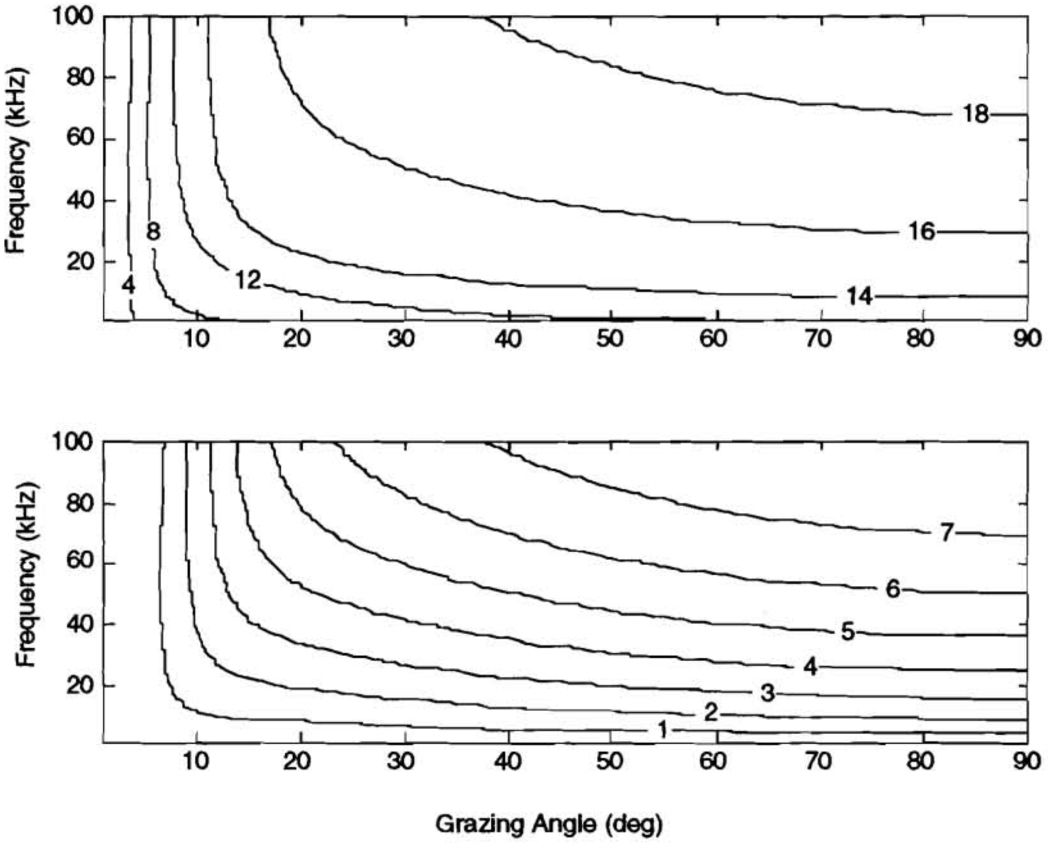

Figure 5 *Top: contours of forward reflection loss for Eckernförde Bay core 268-BS-BC; bottom: contours of the difference between loss estimates calculated with and without density gradients.*

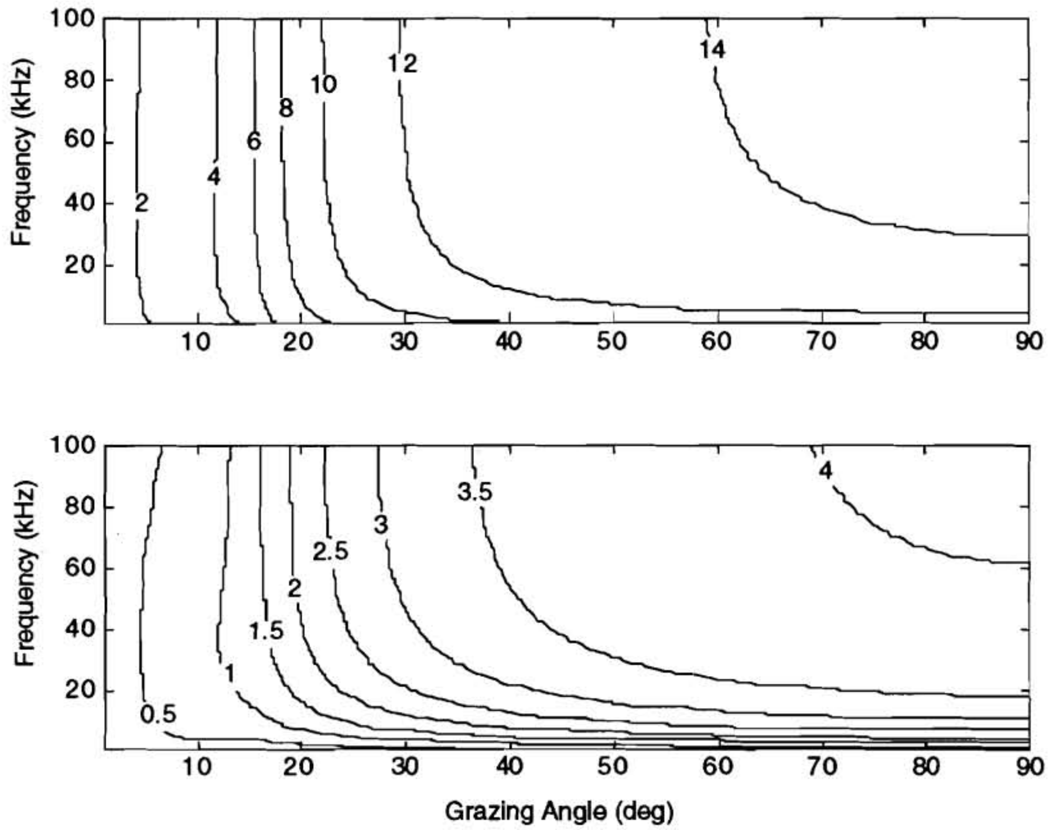

Figure 6 *Top: contours of forward reflection loss for Marquesas Keys core 89-1-KW-DC; bottom: contours of the difference between loss estimates calculated with and without density gradients.*

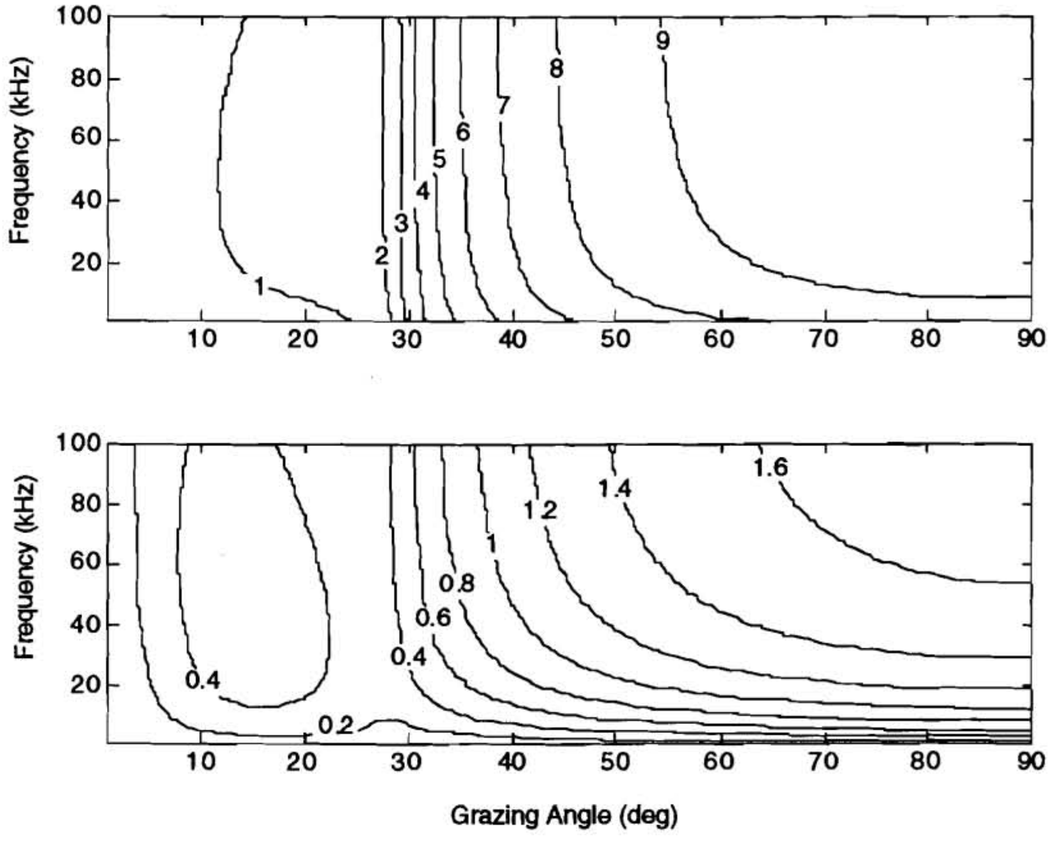

Figure 7 *Top: contours of forward reflection loss for Panama City core 413-2-PC-DC; bottom: contours of the difference between loss estimates calculated with and without density gradients.*

loss are each chosen from one of the three CBBL sites discussed in the previous section. Sediment sound speed values of 1500, 1555, and 1725 m/s and loss tangent values of 0.018, 0.009 and 0.016 were used for the Eckernförde Bay core, the Marquesas Keys core, and the Panama City core respectively. The greatest differences in the forward loss can be seen in the estimates of loss for high frequencies and large grazing angles with the largest overall difference values found for Eckernförde Bay core estimates and with the smallest differences seen in the Panama City estimates. The dominant control on the magnitude of the difference can be attributed to the $\Delta\rho$ values for each core. For a seafloor with a density profile that has a large difference between values found at the surface, ρ_0, and those found at depth, ρ_s, (e.g. core 268-BS-BC) and at sufficiently high frequency, the seafloor density 'looks' to the acoustic wave to be closer to that of water than to ρ_s and so has larger forward loss. The frequency dependence of forward loss displayed in the figures is in part determined by the profile parameter, a. This is due to the frequency dependent surface impendance caused by the profile shape and is very similar to the the effect on bottom loss produced by a thin low density surface layer [31]. At high frequency and with large values of $\Delta\rho$ and a, the method proposed by Mourad and Jackson for dealing with the lower density upper seafloor (*i.e.* using the surficial values) should be sufficient. However, this technique might not be valid when using broadband systems or if the seafloor density profile is described by smaller values of a.

3.3 Backscatter

In this section, scattering strength predictions are made using parameter values obtained from the CBBL study sites and from the seafloor scattering literature. The primary goal is to learn something of the effect of density gradients on backscattering strength. We are interested in the effects of the density profile on contributions from the seafloor interface as well as the sediment volume over the whole angular range for backscatter. The model used in this study, therefore, is a combination of a perturbation approximation surface scattering model, a Kirchhoff approximation surface scattering model, and a perturbation approximation volume scattering model. The models and the assumptions used in their derivation are discussed in Moe and Jackson [32], Mourad and Jackson [3], and Lyons *et al.* [33]. Therefore, we will give only a brief descriptions of these models in this section.

Bottom backscattering strength is defined as the dB equivalent of the total bottom backscattering cross section per unit area of seafloor per unit solid angle, $\sigma(\theta)$, and θ is the grazing angle. The cross section is assumed to be the sum of the contributions from the surface roughness and the volume heterogeneities of a fluid seafloor:

$$\sigma(\theta) = \sigma_s(\theta) + \sigma_v(\theta). \tag{20}$$

The surface-roughness cross section $\sigma_s(\theta)$ is treated in the perturbation approximation except for grazing angles near $\theta = 90°$, where the Kirchhoff approximation is used. The Kirchhoff solution is valid near normal incidence [34] even when the Rayleigh parameter ($k_0\sqrt{<h^2>}\sin\theta$, where h is the surface height deviation from the mean) is greater than unity. For small values of the Rayleigh parameter, perturbation theory yields satisfactory results for backscattering. The seafloor volume scattering portion of cross section is treated using perturbation theory. With the typical values of density and sound speed variance found for the upper seafloor [35], this solution should be valid over a wide wave number range. Inherent in the approach of summing the roughness and volume cross sections to obtain total cross section, is the assumption that there are no correlations between the parts of the scattered field resulting from the interface roughness and volume heterogeneity.

Statistical properties of the seafloor interface and volume are required in the scattering model. The seafloor roughness is assumed to exhibit power-law spectra with isotropic statistics. This type of roughness spectrum has been measured for several sites [36],[37] and is used in several seafloor scattering models [38],[3],[39]. The two-dimensional roughness spectrum is then given by

$$W(\mathbf{K}) = \Gamma K^{-\xi} \tag{21}$$

where $\mathbf{K}$ is a two-dimensional wave-vector with magnitude equal to the wave number K, Γ with units of cm^4 is the spectral strength, and ξ is the spectral exponent. For the seafloor volume inhomogeneities, an exponential correlation function is assumed. While this type of function has been used by many authors [40],[41] based on its ease of mathematical use, there is some physical basis for its use as it has been found to successfully fit values calculated from seafloor ground truth cores [33],[7]. Lyons *et al.* [33] used an anisotropic form of the correlation function, but for the sake of simplicity we will use the isotropic form which is given by the expression:

$$B(\mathbf{r}) = e^{-|\mathbf{r}|/d}. \tag{22}$$

In this equation, d is defined as the correlation length or the value at which the correlation function equals $1/e$ or the distance within which the random medium has some correlation [42], $|\mathbf{r}|$ is the separation distance between volume elements.

Moe and Jackson [32] have demonstrated that the effect of gradients may be added to the perturbation roughness scattering solution relatively easily through the use of the flat surface reflection coefficient, $\mathcal{R}$. They derived the transition matrix relating the incident pressure field to the scattered field in a fluid above a rough surface, to first order, using the Rayleigh-Rice perturbation theory, which resulted in a general expression for the scattering strength. Following their formulation and using the assumed roughness spectrum (Eq. (21)) evaluated at the Bragg wave number, $2k_0\cos\theta$, we have for the surface scattering cross section in our notation:

$$\sigma_s(\theta) = \left(\frac{\beta k_0^{4-\gamma}}{2^{\gamma+2}}\cos^{-\gamma}\right)|1+\mathcal{R}|^4\left|1-\frac{\rho_w}{\rho_0}n^2+\left(1-\frac{\rho_w}{\rho_0}\right)\left[\cos^2(\theta) + \frac{\rho_0}{\rho_w}\sin^2(\theta)\left(\frac{1-\mathcal{R}}{1+\mathcal{R}}\right)^2\right]\right|^2. \tag{23}$$

In the absence of gradients this expression agrees with previous results found with the perturbation approximation [3].

The effect of density gradients are also added in a straightforward manner to the Kirchhoff approximation scattering solution by way of the flat surface reflection coefficient. For this study the analytical solution given by equation (19) of Mourad and Jackson [3] to the integral obtained in the Kirchhoff approximation is used. In their approximation the integral is evaluated for the special case of $\theta = 90°$ so that the backscattering cross section is given by the pressure release result multiplied by the Rayleigh reflection coefficient for vertical incidence $\mathcal{R}(90°)$.

The composite roughness and Kirchhoff cross-sections are combined via the interpolation scheme presented in Mourad and Jackson [3]. With this interpolation, the total interface backscattering cross section, $\sigma_s(\theta)$, is dominated by the Kirchhoff cross section for seafloor grazing angles from 90° down to the angle for which the Kirchhoff cross-section has fallen 15 dB below its peak value at 90°. For lower grazing angles, $\sigma_s(\theta)$ is predominately determined by the perturbation cross section term.

For the volume scattering cross section per unit volume, the model of Lyons *et al.* [33] is implemented in our analysis. In this model, the assumptions (a) that the scattering volume is in the far field and (b) that variations in the magnitude of density and compressibility fluctuations are sufficiently small are applied so that the Born approximation holds. It is also assumed that the size of the scattering volume is greater than the correlation distance in the random medium. Using the specified form for the correlation function of the inhomogeneous medium (Eq. (22)), yields for backscattering cross section per unit volume, the expression

$$\mu = \frac{k^4 d^3 \eta^2}{2\pi}[1 + 4k^2 d^2]^{-2}. \tag{24}$$

In this equation, η^2 represents the variance of density and compressibility.

As in Jackson *et al.* [38], the scattering cross section per unit volume, Eq. (24), is used in a seafloor volume scattering model similar to that of Stockhausen [43]. The Stockhausen model includes transmission loss, refraction and attenuation in a statistically homogenous sediment with a flat interface. The resulting volume scattering strength can be written as

$$\sigma_v(\theta) = \frac{\mu T^4(\theta)\sin^2\theta}{2\alpha \sin\theta_2}. \tag{25}$$

The term α in this equation is the attenuation coefficient and is given by

$$\alpha = \mathrm{Im}(n) + 4\pi\mu, \tag{26}$$

where μ is the volume scattering cross section. Eq. (26) includes attenuation by isotropic scattering and absorption and is valid in the single scattering regime.

The dimensionless result of dividing the backscattering cross-section, μ, by α is, in essence, a surface scattering parameterization of the volume scattering cross section of Eq. (24), which, because of high absorption, is valid at high frequencies. As the low density region of the seafloor is assumed to be thin, the effect of the density gradient on volume scattering enters in Eq. (25) as a modification of the transmission coefficient which was given by Eq. (19).

In order to demonstrate the effect of the density profile on seafloor backscattering, simulations were made with the seafloor parameters that were given for two sites presented in Mourad and Jackson [3] and with parameters obtained from the same three CBBL cores used previously for estimating forward loss. The specific parameter values used in scattering strength calculations are given in Table 2. With the exception of the correlation length, d, and the profile parameter, a, the Quinault Range and Arafura Sea locations have been thoroughly characterized in terms of the roughness and volume geoacoustic parameters necessary for model calculations [3],[35]. The Quinault site has scattering contributions from both the volume and interface while the Arafura site is completely dominated by volume scattering. The CBBL sites have been characterized by geoacoustic information obtained from the cores studied in this paper and additionally from a recent paper by Jackson *et al.* [4] which dealt with seafloor scattering at the same sites. The volume variance parameter values listed in Table 2 include only the variance due to density fluctuations as these have been shown to dominate in several studies [35],[44].

Figure 8 presents results of calculations of scattering strength at 35 kHz versus grazing angle made for the Quinault Range site. A correlation length value of $d = 0.04$ m was used for this simulation and was set by adjusting the overall value of scattering strength to the acoustic data presented in [3]. Based on the values found in Table 1, an average value of $a = 50$ was arbitrarily chosen for the profile parameter. The density profile has a complicated effect on total scattering strength, which depends on the relative levels of interface and volume scattering at a given grazing angle (Fig. 8). The inclusion of the profile affects predominantly interface scattering, the greatest influence being at steep angles ($> 65°$) where roughness scattering dominates the returns. A maximum of about 4 dB difference between scattering strength estimates made without and with the profile can be seen near normal incidence. A small difference of about 1 dB is seen at shallow angles ($< 25°$) due to higher volume scattering as a result of increased transmission into the sediment. For most of the range of grazing angles ($20° - 60°$), however, there is almost no effect due to the density profile. Again this is because returns are dominated by volume scattering (on which the density profile has less importance) in this angular region. Although a direct comparison cannot be made with the model curves presented in [3], inclusion of the density profile achieves the desired result of decreased interface scattering near normal incidence and increased volume scattering at shallower grazing angles, evident in their model/data comparisons. For the 20 kHz Arafura Sea scattering strength estimates, only the steepest grazing angles are

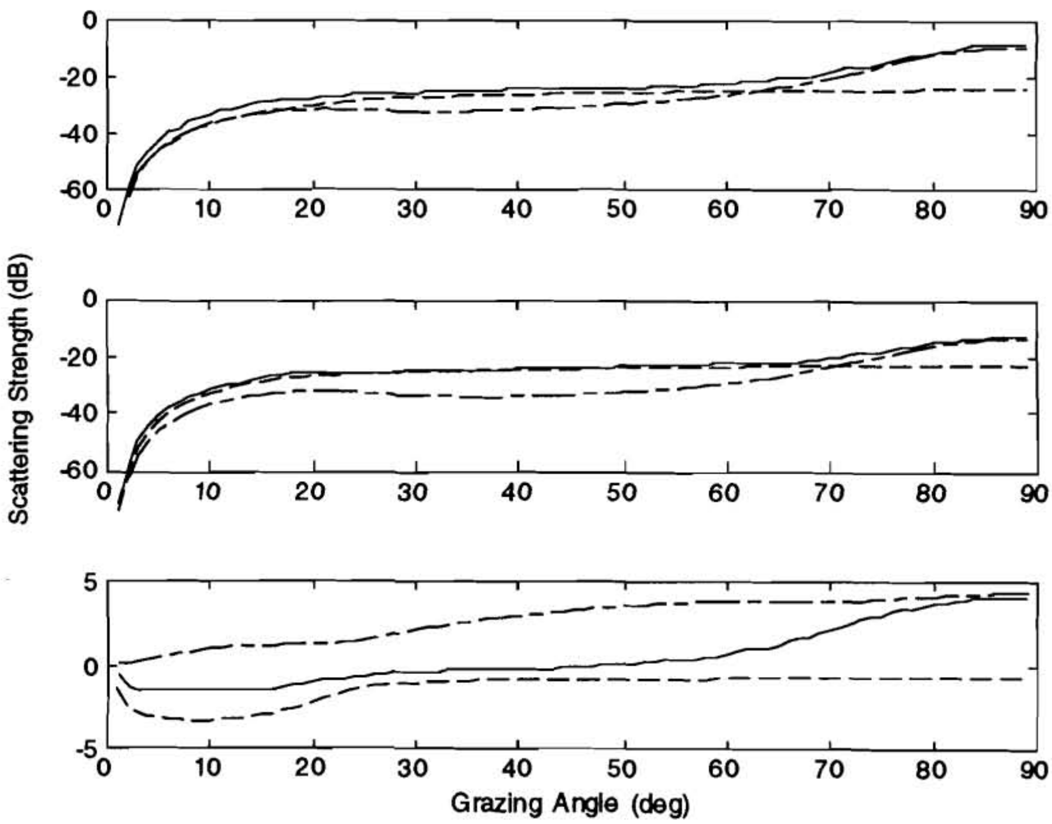

Figure 8 *Estimates of the effect of density gradients on backscattering strength based on Quinault parameters taken from references [3] and [35]; top: estimates of total (solid line), interface (long dash - short dash line) and volume scattering (dashed line) without density gradients; middle: estimates with density gradients; bottom: differences between estimates calculated without and with density gradients.*

Table 2 *Parameter values used in calculations of seafloor scattering.*

Location[a]	ρ_0/ρ_w	c_s/c_w	ϵ	ξ	Γ	η^2	d	a	ρ_s
Quinault Range	1.34	1.08	0.026	3.67	0.004	0.0009	0.04	50	1.93
Arafura Sea	1.15	0.99	0.013	3.18	0.002	0.0025	0.04	50	1.49
Eckernförde Bay	1.20	1.01	0.018	3.42	0.002	0.0012	0.02	100	1.75
Marquesas Keys	1.56	1.03	0.009	3.29	0.012	0.0010	0.04	12	1.83
Panama City	1.75	1.13	0.016	3.12	0.008	0.0003	0.01	224	2.03

[a]Quinault and Arafura Sea data from [3],[35]; others from CBBL cores and [4].

appreciably affected by the density profile as volume scattering dominates most of the angular range (Fig. 9). Again, the reduction of near normal incidence scattering seen in the model results of Mourad and Jackson, is evident in our calculations.

Figs. 10, 11, and 12 contain contours of total scattering strength calculated for the three CBBL sites. The top panel in each figure presents contours of scattering strength and the bottom panel gives the difference between scattering strength estimates made using the sediment density, ρ_s only and estimates made including the full density profile. As for forward loss, the largest overall differences can be seen in the estimates of loss for the Eckernförde Bay core, while the smallest differences are seen in the Panama City estimates. As noted for the examples discussed above, the greatest impact on total scattering strength for estimates made with the CBBL cores is near normal incidence. As with forward loss, the major control on the magnitude of the scattering strength difference estimates is the value of $\Delta\rho$ and the dominant control on the frequency dependence of the difference is the the profile parameter. As shown before [2],[3],[4], our results indicate that bulk values of density are not enough to describe the upper seafloor for the purposes of modeling high-frequency acoustic scattering. We reiterate that when using broad-band systems or when the seafloor density profile parameter is small, the validity of using surficial values for estimating scattering strength at high-frequencies becomes questionable, especially near normal incidence.

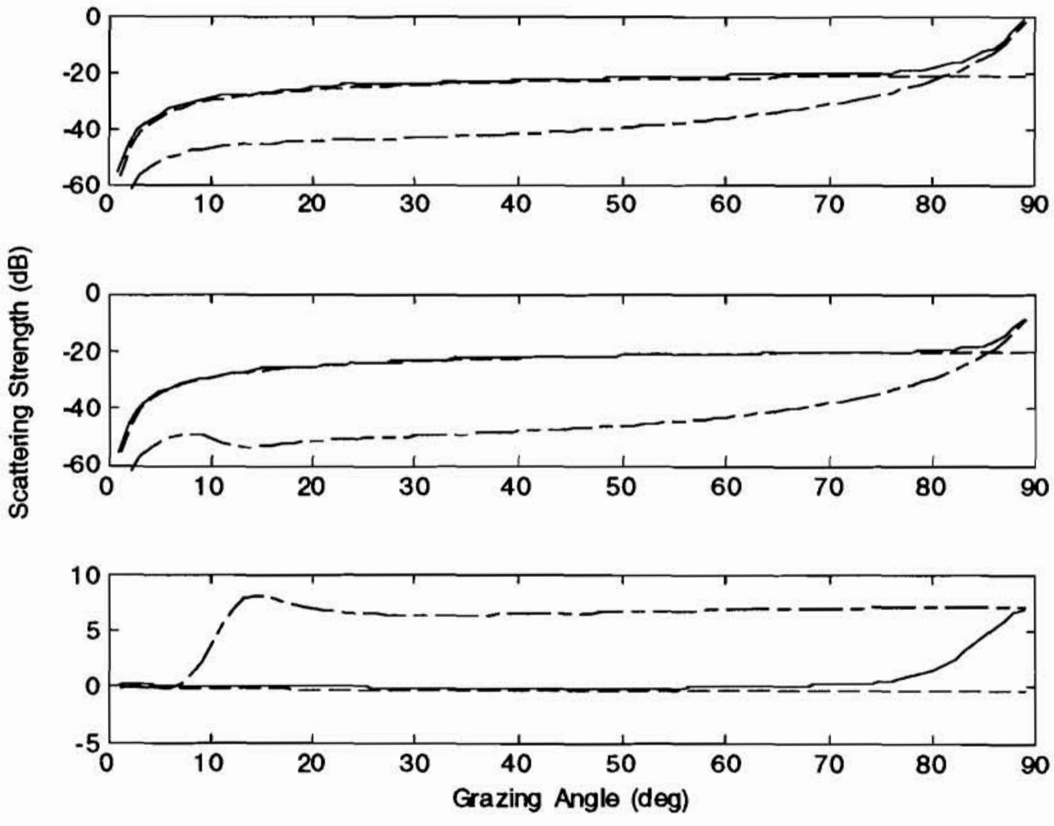

Figure 9 *Estimates of the effect of density gradients on backscattering strength based on Arafura Sea parameters taken from references [3] and [35]; top: estimates of total (solid line), interface (long dash - short dash line) and volume scattering (dashed line) without density gradients; middle: estimates with density gradients; bottom: differences between estimates calculated without and with density gradients.*

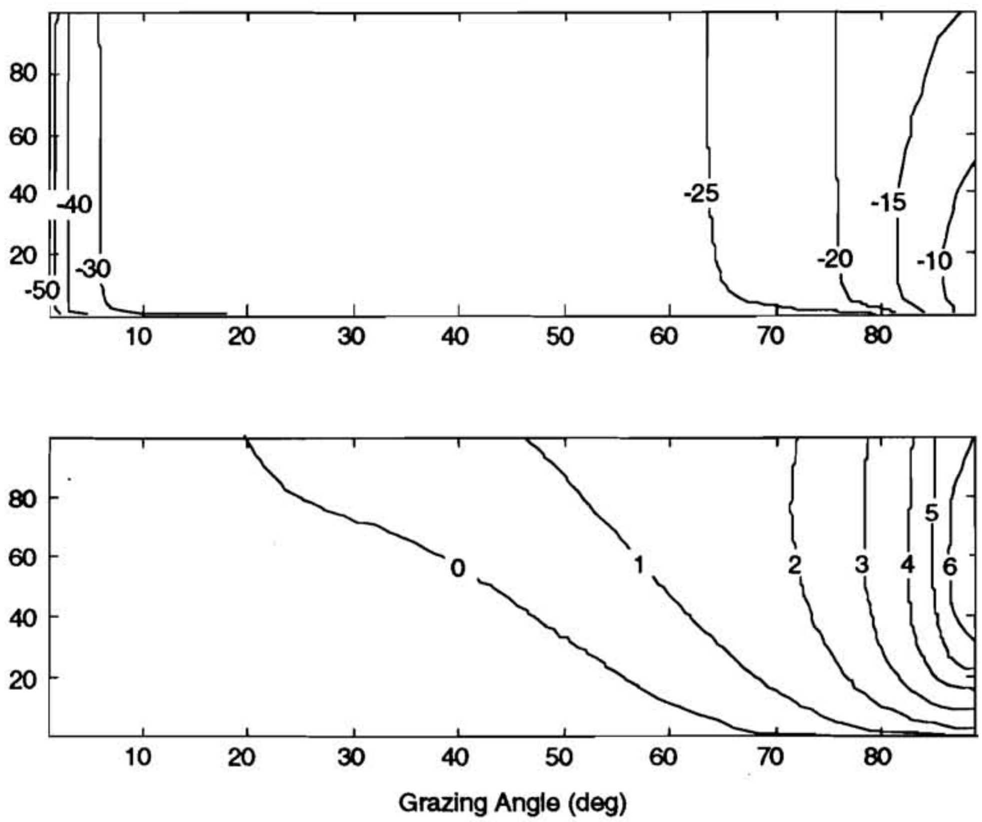

Figure 10 *Top: contours of total scattering strength (dB) for Eckernförde Bay core 268-BS-BC; bottom: contours of the difference between scattering strength estimates calculated without and with density gradients.*

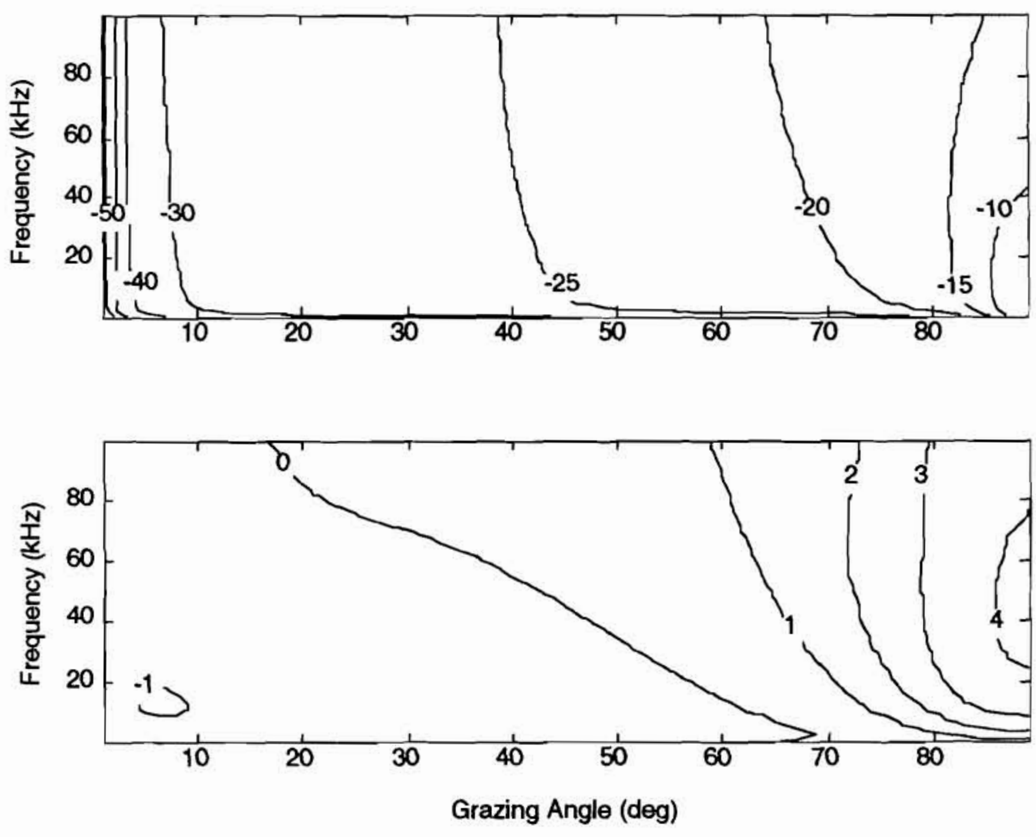

Figure 11 *Top: contours of total scattering strength (dB) for Marquesas Keys core 8IIfig10C; bottom: contours of the difference between scattering strength estimates calculated without and with density gradients.*

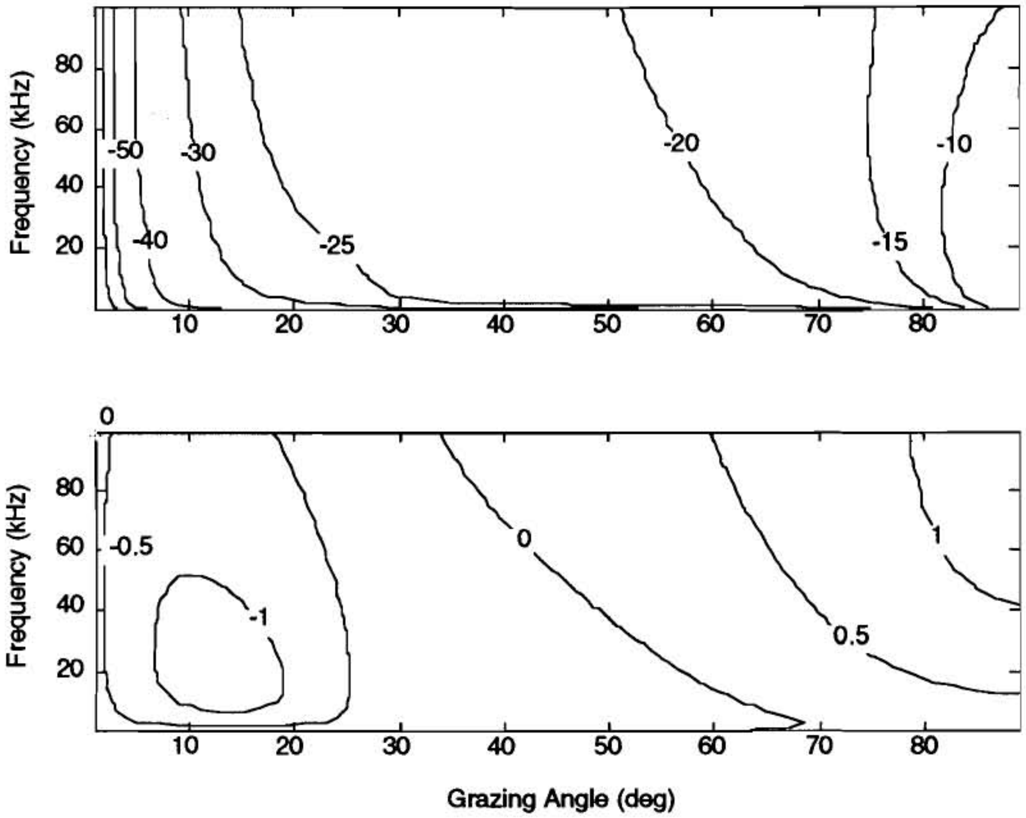

Figure 12 *Top: contours of total scattering strength (dB) for Panama City core 413-2-PC-DC; bottom: contours of the difference between scattering strength estimates calculated without and with density gradients.*

4
Summary

A functional form for the vertical density structure of near surface sediments was found by examination of several high-resolution density profiles obtained from x-ray computed tomography scans of seafloor cores, taken recently as part of the CBBL field program. It was possible to make estimates of the reflection coefficient based on these general density profiles in order to examine their impact on seafloor reflection, forward loss, and scattering. The inclusion of the density profile reduced the estimated reflection coefficient with respect to that calculated using only the sediment density, thus a reflection coefficient calculated from acoustic data would indicate a seafloor bulk density that is too low. The underestimate is exacerbated at higher frequencies with the density estimate tending toward the surficial values of density. As a result of including the near surface density profile, the reflection coefficient was seen to decrease as a function of increasing frequency or decreasing values of the profile parameter. This fact implies that the density profile causes the interfacial region to act as a high pass filter to incoming acoustic waves which would have a strong effect on broad band pulse propagation.

The influence of the density profile on reflection loss and backscatter was also calculated using the estimated reflection coefficient. The density profile was found to have a significant impact on forward loss and scattering. The major control on this impact was attributed to the difference between the value of density found at depth and the value found at the surface, $\Delta\rho$. The profile parameter, a, added additional frequency dependence. The largest effect on forward loss and total scattering strength was found to be near normal incidence. The effect of the inclusion of the density profile on total scattering was found to depend on the relative levels of interface and volume scattering at a given grazing angle with interface scattering being predominantly affected. As roughness scattering will usually dominate acoustic returns near normal incidence, the density profile had the greatest impact at these angles with a decrease seen in the total scattering strength. An increase in volume scattering could be seen in softer sediments at grazing angles where there was an appreciable component of volume scatter.

Although lacking a direct comparison between acoustic data and predictions made using high-resolution co-located ground truth cores, our results indicate that bulk values of density are not enough to describe upper seafloor for the purposes of modeling high-frequency acoustic scattering. When surficial values of density are low compared to average sediment density and when the profile parameter is large enough, the method of using the surficial values for dealing with a lower density upper seafloor should be sufficient at high frequency. However, this technique might not be valid when using broadband systems or if the seafloor density profile is described by smaller values of the profile parameter. The effect of the density profile on the strength of acoustic returns suggests that care should be taken when using high-frequency systems for measuring sediment properties, especially near normal incidence.

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Title

The effect of a layer of varying density on high-frequency acoustic reflection, forward propagation loss and backscattering strength

Abstract

This report examines the impact that a thin layer of varying density would have on high-frequency reflection, forward loss and backscattering of acoustic plane waves from the seafloor. A functional form for density stratification was found by examination of several high-resolution density profiles obtained from x-ray computed tomography scans of seafloor cores. A solution based on these general profiles was used to estimate the reflection coefficient. The influence of the density profile on reflection loss and backscatter was then calculated using the estimated reflection coefficient. Parameter values used in simulations were obtained from the literature or from the CT scans of cores. It was found that inclusion of a density profile adds a strong frequency dependence to estimates of the reflection coefficient and forward loss. The largest effect on total scattering strength is near normal incidence where returns are dominated by interface scattering. The effect of the density profile on the strength of acoustic returns suggests that care should be taken when using high-frequency systems for measuring sediment properties, especially near normal incidence

Keywords

High-frequency acoustics – reflection coefficient – forward loss – seafloor scattering – acoustic remote sensing

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