An experimental investigation of the contribution of sediment volume scattering to acoustic backscatter measured in the shallow waters of the Florida Strait

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Abstract

Experiments were conducted in the Florida Strait region of the United States in July 1995 for the purpose of investigating the contribution of sediment volume scattering to measured backscatter levels at frequencies between 3.5 and 30 kHz. Each of five sites were analyzed for bottom backscattering level in both the radial and azimuthal directions. A relatively new volume scattering model was employed and the results compared with predictions made using a composite rough interface scattering model. Environmental parameters were established by a cross well tomographic measurement and used as input values for the modeling. Comparison of model predictions with the measured data showed that for grazing angles from the critical angle to approximately 60° volume scattering dominated, while for angles greater than approximately 60° surface roughness scattering consistently dominated. In geographic areas where the interface sound speed ratio exceeded one, roughness scattering controlled the backscattered level for grazing angles less than the critical angle.

Inversion of the measured backscatter data was performed using a genetic optimization algorithm developed around the volume scattering model. Inversion results were found to agree well with measured data and measured environmental parameters which describe the scattering volume. A second similar inversion was made to determine spectral properties of a two dimensional transform of the compressional velocity tomograms. This inversion was based upon a power law representation of the spectral structure.

1. Introduction

Ocean bottom scattering can have a beneficial or detrimental effect, depending on the objectives of the acoustic study. For many sonars, sea bottom scattering has a detrimental and limiting effect; for others, the scattered noise may be used as a tool for examining the physical properties of the scatterers. In either case, a thorough knowledge of the effect of the sea bottom on acoustic propagation is needed.

A great deal of seafloor acoustic reverberation data has been taken in the past, much of which has been processed for bottom scattering strength. In general, the results have been characterized by the empirical value $10\log(\mu)$ taken from Lambert's rule [1]. Lambert's rule works well for the water - sediment interface, but neglects the contribution from the sub-bottom volume and sub-bottom interfaces. It also does little to relate the measured backscatter to the physical properties of the scatterers. This limitation is profound when the interface roughness is very small or as the impedance ratio between the water and sediment approaches unity. Under these conditions the volume and/or sub water - sediment interface horizons become significant or even dominant scattering mechanisms and cannot be neglected.[2] The desirability of a physically based model of the complete scattering phenomenon has become a topic of recent interest to many and is the reason for this study.

Two models, one developed for rough interface scattering and the other for volume scattering were chosen for their physics based approach to scattering and are utilized in the data analysis. Jackson's composite roughness model [3] and Yamamoto's volume scattering model [4] combine to help yield insight into the physics of the scattering mechanisms. The composite roughness model describes the rough interface via the Kirchhoff approximation for angles near the Snell's law direction and via perturbation theory for all other directions. Interpolation combines the pair. Although Jackson's model provides a formulation for volume scattering, it is disregarded in this work because of its empirical nature. Yamamoto's volume scattering model also follows perturbation theory and represents the scattering kernel with a power law formulation when describing the fluctuations of compressional velocity within the volume. The general form of the volume scattering model is

$$VBS = 10\log(\sigma_v) \tag{1}$$

$$\sigma_v = k_o^4 \Gamma^2 \beta \Lambda^2 B\left(\Lambda^2 k_1^2 + \Lambda^2 k_2^2 + k_3^2\right)^{-\frac{(\beta+2)}{2}} \tag{2}$$

where VBS is volume backscatter, σ_v is the differential backscattering cross section per unit volume, k is the wavenumber incident (subscript o) and axial (subscripts 1, 2, 3), Γ is a magnification factor due to the relationship of density and compressional velocity fluctuations in the sediment, β is the spectral exponent factor, B the spectral intensity factor and Λ the aspect ratio describing the anisotropy of the inhomogeneities in the sediment. A provision for dipped layering may be included in the definitions of the axial components of wavenumber and is outlined by Yamamoto [5]. Propagation effects are accounted for as direct path spreading loss, attenuation and transmissivity.

$$\sigma_a = \sigma_v \left(\frac{\sin\theta_s}{4\alpha}\right) T_{12}^2 T_{21}^2 \left(\frac{\cos^2\theta_s}{\cos^2\theta_w}\frac{\sin^2\theta_w}{\sin^2\theta_s}\right) \tag{3}$$

This result is expressed as an equivalent interface scattering strength and may be combined directly with the result from the composite roughness model. θ_w and θ_s are the incident and refracted grazing angles at the water sediment interface, $T_{12}^2 T_{21}^2$ is the transmissivity across the interface and $\left(\frac{\cos^2\theta_s}{\cos^2\theta_w}\frac{\sin^2\theta_w}{\sin^2\theta_s}\right)$ accounts for the spreading of incident wave energy at the interface. Total bottom backscatter is computed as

$$BBS = 10\log(\sigma_r + \sigma_a) \tag{4}$$

σ_r is rough interface scattering.

This volume scattering model was the motivation for much of the work done in the Florida Strait. Beyond its' direct or forward application, the volume scattering model is inverted to find the sediment properties from the collected backscatter data. To do this one of the first applications of genetic algorithm optimization techniques to underwater acoustics is implemented. This type of inversion was chosen for its' robust nature and computational efficiency and provided a useful and unique tool for sediment classification.

Collocated acoustic backscatter and sediment property data were taken on the Florida continental shelf at site 1 of 5 experimental sites and is emphasized in this short paper. The measurements were made using newly developed instrumentation and techniques; a sparse volumetric array to measure seafloor scatter generated by a central omnidirectional sound source and cross well acoustic tomography for determining the sediment character. The sparse array expedited data collection where information in both grazing angle and azimuthal angle was desired. The technique of high frequency marine cross well acoustic tomography provided an advantage over traditional coring methods for sediment measurement by providing largely undisturbed measurement. Sediment coring tends to disturb the sediment structure and lacks two or three dimensional information which is necessary to describe the scattering mechanism sufficiently. Two or three dimensional information is also required for implementation of the volume scattering model and inversion comparison.

2. Experiment

The Florida Strait experiment included five acoustic backscatter sites and one cross well tomographic experiment at site 1. The concentration of this paper will be upon the 38 foot deep site 1. For both types of experiment, center frequencies of

7.5kHz and 15kHz were used. Cross well tomography was used to measure the sediment properties to be used as input parameters to scattering models and for inversion comparison. During burial of equipment for cross well tomography divers noticed strong layering as wells were driven into the seafloor. This is confirmed by the cross well tomography result. Based upon these and samples taken during the diving operation it is proposed that the site has sediment structure consisting of sand and shell fragments intermixed with layers of mud and silty clay.

2.1 Equipment

Traditional approaches to measuring acoustic backscatter from the seafloor use either a single fathometer device which yields a reflection result (near grazing angle = 90^{o}), a line array which has ambiguity about its axis when beamformed, or a seafloor mounted tower with a directional source and receiver. The last of these three approaches is the most accurate and repeatable but in its' most common configuration it requires that the directional source receiver pair be steered to all angles of interest and this can make data collection a time consuming endeavor. In an effort to reduce experimental duration and still provide a system which could examine all points on the bottom within the region about the measurement device, an array of receivers were chosen which would be recorded simultaneously and later beamformed. Recognition that the use of a broadband source signal with a sparse array can yield a high resolution result for a minimal number of hydrophones further defined the array [6]. The orientation of the sensors was therefore very important and after much simulation and evaluation were arranged in a manner to give excellent broadband beamformed response throughout all grazing and azimuthal angles for the frequencies of interest. The design is similar to a vertically extended Mill's cross as seen below (figure 1a).

An omnidirectional sound source located at the geometric center of the array was activated repeatedly using Hanning weighted linear frequency modulated signals and the reverberation recorded at each hydrophone for some period of time. Averaging of repeated traces removed much of the incoherent noise. With this source and receiver array pair the seafloor backscattered response was quickly and accurately imaged.

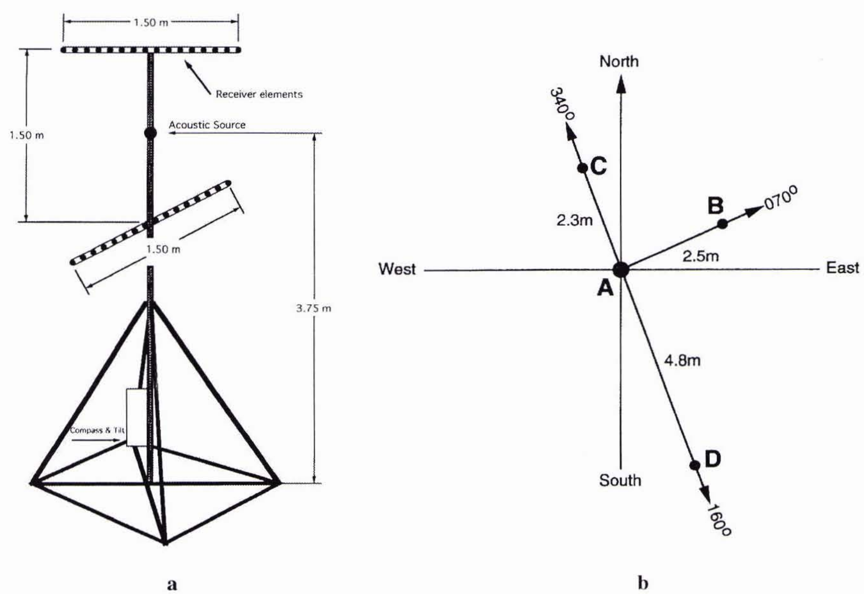


Figure 1a and 1b: a - A schematic diagram of the sparse volumetric acoustic array; b - A diagram of the cross well tomographic plan on the seafloor, wells are located at positions A, B, C and D.

2.1.1 Three dimensional broadband array design

The standard approach to array design for signals which contain more than one octave of bandwidth has been to nest several sub-arrays each cut for a different octave. Data from each is band passed for its corresponding octave and beamformed conventionally. This method requires a significant number of sensor elements. An alternative is to process the data over the entire frequency band using only the array cut for the lowest octave. Using this method, with sufficient bandwidth, the many grating lobes which occur for frequencies greater than the frequency for which the array was cut (spatially aliased frequencies) tend to smear one another out leaving the beam along the maximum response axis intact or even narrowed. Integration over the full bandwidth reveals a comparable directivity index while sharply reducing the number of sensors. During processing the backscattered data were examined every 2.5^0 in azimuth and every 2^0 of grazing angle.

The physical design of the 3-D broadband array, called the acoustic backscatter antenna (ABA), consisted of two 16 channel linear arrays of hydrophones spaced 0.10m and placed horizontally in orthogonal directions. A preamplifier providing 50 times gain accompanied each hydrophone. Vertical separation between the linear arrays was equivalent to a single segment's aperture of 1.5m. Onboard compass and tilt sensors provided the array's relationship to with the earth; angles if inclination or declination were accounted for as a step of data processing. The array is illustrated in figure 1a with the acoustic source located at the geometric center of the receive array.

2.2 Acquisition of backscattering data

Source signals were Hanning windowed linear frequency modulated (LFM) upsweeps of bandwidths 15 and 30 kHz centered at 7.5 and 15 kHz respectfully. These signals were chosen for their fairly low sidelobe level upon correlation and good correlation gain, i.e. high signal to noise. The signal also provided sufficient bandwidth for the broadband beamforming techniques employed in the processor.

Data acquisition took place via a cable connection to the research vessel. Traces were amplified one hundred times and high pass filtered using a -3dB cutoff at 1kHz. This ensured maximum amplitude would be recorded without clipping the A/D converter and that 60Hz electronic noise would be suppressed without harming the data integrity. Data then passed through a 200kHz throughput, 12 bit, 16 channel A/D converter and was recorded to the hard disk of a 486/66 personal computer. Experiment backup was made on Exabyte 8mm magnetic tape. The control software recorded three channels at a time at 66666 Hz for 0.2 s per shot. 200 signals were recorded per station . This yielded 85.33 Mb per experimental location and the duration of an experiment was just under 20 minutes. Data were later averaged, correlated with the source function and beamformed.

2.3 Cross well tomography experiment

The tomography measurement was collocated with the scattering experiment at site 1. Four wells were bored into the seafloor approximately 2m in depth. The orientation of these well is shown in figure 1b. Into the well

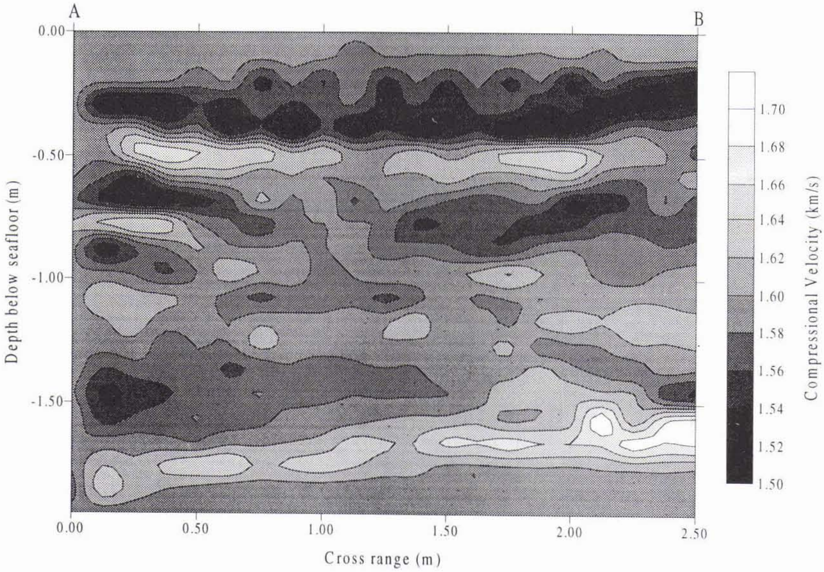


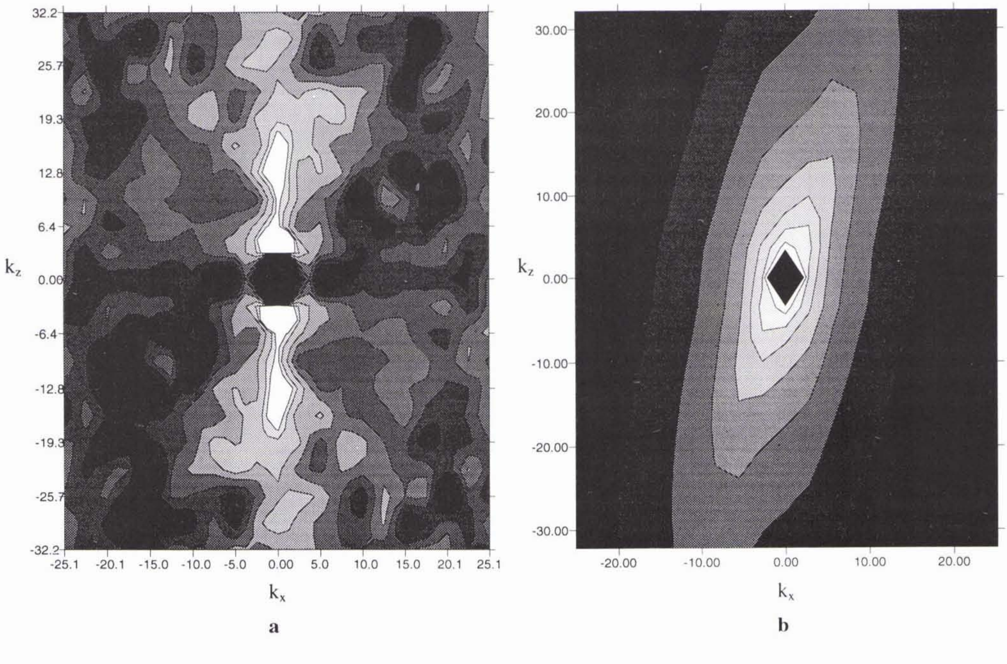
Figure 2: Compressional velocity cross well tomogram of section A-B at site 1 Florida Strait continental shelf acoustic experiments 1995.

'A' an array of 16 acoustic sources spaced 0.10m was deployed and into wells 'B,C & D' arrays of 16 receivers were deployed also separated at 0.10m. Multiple source shots were transmitted for each source channel which were averaged and recorded after being received. A shipboard display of the incoming traces successively averaged was observed until it was determined that a sufficient signal to noise ratio was achieved and the first arrival of the signal could be determined. These data were archived and later used in the tomographic inversion which determined the compressional velocity structure of the sections between well 'A' and the others. Information on the tomographic inversion may be found in the paper by Bregman *et al.* [7]. The compressional velocity cross well tomogram cross section A-B is shown in figure 2.

3. Data analysis and modeling

3.1 Cross well tomograms

To determine the properties needed for input to the acoustic models the tomograms were analyzed using one and two dimensional Fourier analysis. Using a virtual sediment core taken as a one dimensional section in depth and analyzing the power spectral density of the compressional velocity fluctuations along that section the power law behavior expected from equation 2 was revealed. A first order polynomial fit to the spectrum provided the spectral exponent and spectral intensity facters, β and B respectfully. One dimensional data such as this or from sediment cores cannot provide information needed such as the aspect ratio or dipped structure. From a two dimensional power spectrum of the tomographic section the aspect ratio of the horizontal to vertical inhomogeneities and any dipped structure can be determined. A useful tool for finding all four of these parameters from the two dimensional power spectrum was an inversion of the volume scattering model to fit the spectral data. A genetic algorithm similar to the one used in the inversion of the measured backscatter data was applied. An example of the two dimensional power spectra of the compressional velocity cross section is shown in figure 3a and the result of the inversion in figure 3b.



Figures 3a and b: a- Power spectral density of compressional velocity cross well tomogram A-B from site 1. b- Result of inversion using the volume scattering model to fit the power spectral density computed directly from the cross well tomogram A-B. Axis are wavenumber (1/m).

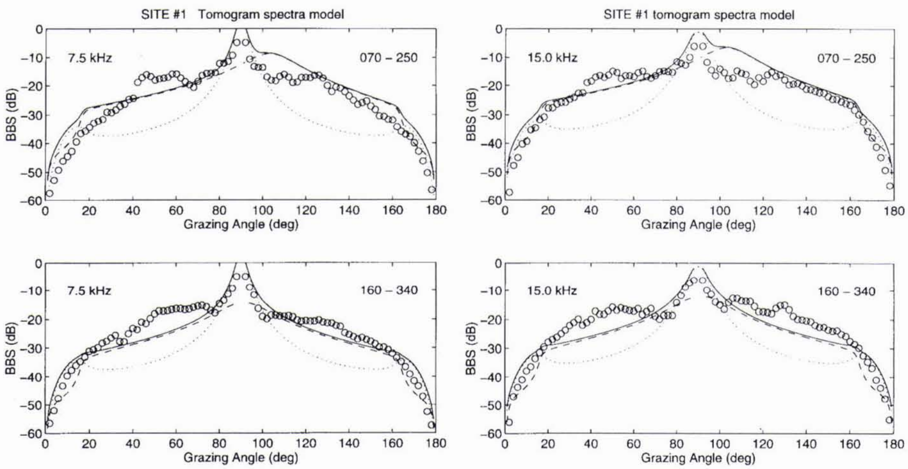
Note the off axis nature of the elliptical shape in figure 3b. This indicated the existence of a preferential dipped structure at the site. Aspect ratio is determined as the ratio of the major ($k_z/\cos\delta$) axis to minor ($k_x/\sin\delta$) axis of the ellipse, where δ is the dip angle from the k_z axis. Table 1 lists the sediment parameters computed from both one and two dimensional techniques and inversion along with several estimates made for use with the scattering models where data was not available. No interface properties were measured at the site, therefore these were estimated based upon diver observations and sediment samples referenced to previous work by Jackson and Briggs [8].

	Volume Values						Sediment			Surface Values	
LINE	Spectral B	Model β	Aspect Ratio Λ	Dip from Λ δ	Vertical B	Cores β	Sound Speed C_p/C_w	Attenuation α_a (dB/m/kHz)	Density Ratio ρ	Spectral Strength $\omega 2$	Spect. Exp. γ
A-B	4.98e-5	0.312	4.556	-14.1^0	1.16e-5	0.500	1.039	0.15	1.79	0.0042	3.25
A-C	1.27e-5	0.214	4.442	1.36^0	1.04e-5	0.341	1.047	0.15	1.81	0.0042	3.25
A-D	2.29e-5	0.778	6.77	-1.39^0	4.68e-5	0.744	1.043	0.15	1.76	0.0042	3.35

Table 1: Sediment parameters computed from one and two dimensional spectral techniques and inversion. Underlined values are estimated values for modeling purposes only.

3.2 Backscatter

The beamformed acoustic scattering data were evaluated azimuthally and found to have only minor azimuthal variation at these sites. Emphasis was placed on the azimuthal data whose radials coincided with the directions of the measured cross well tomograms. From figure 1b it is seen that these lie along 70^0-250^0 and 160^0-340^0 magnetic. Along these azimuths the measured and inverted sediment properties from table 1 were input into the composite roughness and volume scattering models.



a b

Figure 4a - b: Acoustic backscatter data and modeling results for the composite roughness model estimate (dotted line), the volume scattering model (dashed line) and their combination (solid line). a- 7.5 kHz 070°-250° and 7.5 kHz 160° -340° b- 15.0 kHz 070°-250° and 15.0 kHz 160°-340°

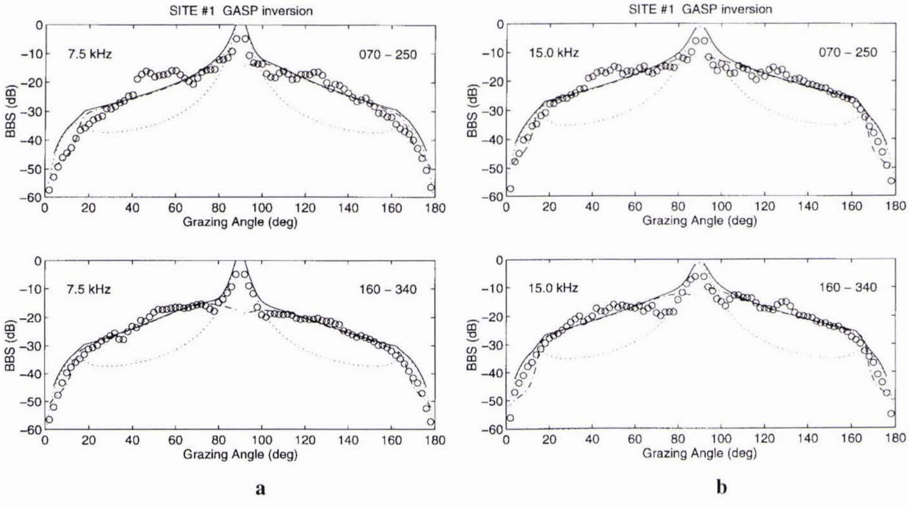
Figures 4a and 4b show the measured data verses grazing angle at 7.5 kHz and 15.0 kHz along with the forward model predictions based on the values from table 1. Note the effect of the dipped structure in the 070^0-250^0 result as the peak is offset to roughly 14^0. The volume scattering model shows a particularly good fit for this bearing. The choice of the interface scattering parameters is constant throughout these examples due to the lack of measured data but facilitates some indication, under the assumption of a similar sediment, of the roughness scattering effect. It shows that at very high grazing angles and angles beyond the critical angle, in this case approximately 16^0 grazing, rough interface scattering dominates. Through the mid angle sections volume scattering largely controlled scattering behavior.

Inversion of the volume scattering model was made for data at each of the azimuthal directions 70°, 160°, 250° and 340°. This inversion predicted seven parameters: a dip azimuth, dip grazing angle, spectral exponent, spectral intensity, aspect ratio, attenuation and sound speed ratio at the water-sediment interface. Table 2 shows the results for 7.5 kHz and 15.0 kHz.

Freq. (Hz)	Heading (deg.)	Dip Azimuth (deg.)	Dip Angle (deg.)	Spectral Exponent	Spectral Intensity	Aspect Ratio	Atten. (dB/m/ kHz)	Sound Speed (km/s)
7.5	070	12	-5.03	0.222	5.02e-5	6.53	0.35	1.061
7.5	160	263	19.8	0.379	4.53e-5	5.44	0.35	1.045
7.5	250	276	18.9	0.695	5.77e-5	2.85	0.29	1.040
7.5	340	193	3.4	0.746	5.94e-5	3.11	0.24	1.037
15.0	070	24	-15.7	0.318	4.58E-5	5.85	0.37	1.045
15.0	160	121	-12.6	0.382	8.15E-5	1.95	0.39	1.055
15.0	250	213	14.2	0.760	1.0E-4	1.97	0.20	1.041
15.0	340	2	2.54	0.633	5.07E-5	2.60	0.185	1.037

Table 2: Inversion results for experiments conducted in the Florida Strait at site 1.

The best fit results for site 1 are shown in figure 5 using the previous estimates for inputs into the composite roughness model. It can be seen that at both frequencies there is excellent model data agreement. The model to data error was less than 0.17 for all cases when measured as a ratio of the sum of the errors to the sum of the data, better than 83% agreement.



Figures 5a - b: Results of the volume scattering model inversion and composite roughness model estimates. The dash-dot, dotted and solid lines indicate the inversion, roughness model estimate and combined inversion and roughness model estimate results respectively. a- 7.5 kHz 070°-250° and 7.5 kHz 160°-340° b- 15.0 kHz 070°-250° and 15.0 kHz 160°-340°

The inversion is limited in describing the scattering due to the exception of the rough interface scattering model. In the future it is hoped that this will be included and the data reevaluated. The estimate made for this data evaluation of the rough interface backscatter level combined with the inversion result shows very good agreement to the data. A collocated interface and volume physical property measurement is needed and should be pursued. The volume/rough interface inverse model at that point could be evaluated and should prove a very useful tool for estimating the physical properties of the sediment via a single remote measurement.

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