Geoacoustic Inversion of Broadband Data from the Florida Straits

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Abstract. Acoustic propagation experiments have been carried out in the Florida Straits with a multi-frequency broadband source that transmitted M-sequence pulses over a range of 10 km to a sparse-filled vertical line array. The sound source was cycled in octaves from 100 Hz to 3200 Hz, transmitting each octave for one hour. This paper presents results of matched field inversions of the acoustic field data to estimate geoacoustic model parameters for the experimental site. The inversion is very sensitive to the sediment sound speed at the sea floor. The estimated value of 1560 m/s is consistent with fine-grain calcareous sand material that is considered to represent ground truth for the site.

INTRODUCTION

Experiments with broadband sound sources were carried out in the South Florida Straits to study variability and coherence in sound propagation on the continental shelf. Previous work by DeFerrari [1] has concentrated on analysis of the effects of the oceanographic conditions in the strait that give rise to spatial and temporal inhomogeneities of the sound speed in the water column. The sound propagation is bottom limited in the shallow water environment, but there is relatively sparse information about the geoacoustic parameters. This paper describes results of matched field inversion of the acoustic field data from the experiment to estimate a geoacoustic profile for the region.

The experiment is described in the next section. This is followed in the next section by a discussion of the features of sound propagation that affect the design of the inversion method. The results of the inversion are presented and summarized in the final section.

FLORIDA STRAITS EXPERIMENT

The experimental geometry is shown in Fig. 1. A sound source moored on the sea floor transmitted M-sequence signals to a sparse-filled vertical line array at a range of 10 km. The average water depth over the distance between the source and receivers was 145 m. The sequence of events was a 6-hour transmission series that consisted of M-sequence signals at 100 Hz for the first hour, then 200 Hz for the next hour, then 400 Hz, increasing each hour in octave steps to 3,200 Hz for the 6^{th} hour. This series of signals was repeated throughout the experiment. At each frequency, the M-sequence repetition rate was ~2.55 s, and the spectral band width at each frequency was one quarter of the value of the carrier frequency. The received signals were coherently averaged for one minute, and processed to generate complex envelopes [2]. The vertical line array consisted of 32 sensors that were non-uniformly spaced from 39 m to 140 m. The system was bottom moored and stretched nearly vertical by a subsurface float. Data from seven hydrophones were used in the inversions (Fig 2).

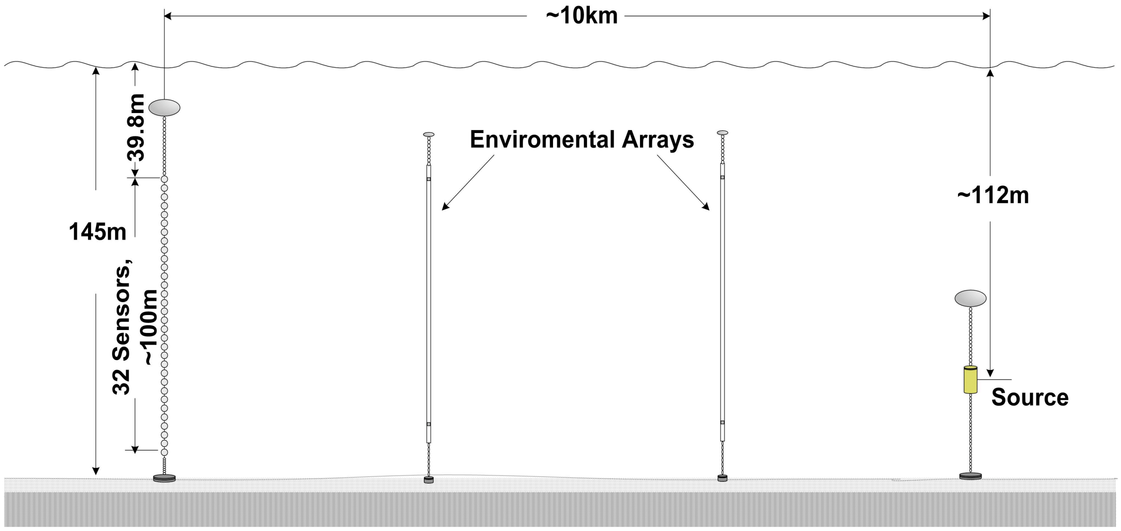


FIGURE 1. Experimental geometry for the South Florida Strait site.

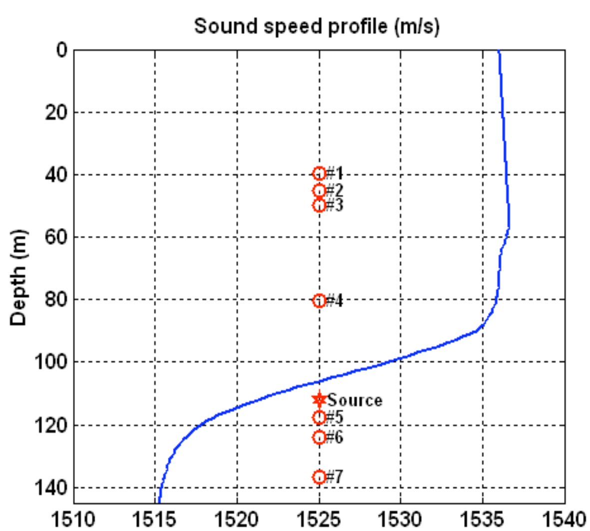


FIGURE 2. Sound speed profile, and locations of source and receivers in the water column.

The sound speed profile in the water was measured throughout the 28-day experiment at 10-element environmental sensor arrays at two locations along the propagation path. Temperature measurements at the two stations generally were correlated for periods of up to three hours, indicating very little range dependence. The measured profile in Fig. 2 shows the sound speed for the time period of the acoustic data that were used in this work. The conditions were uniform in the upper part of the water to a depth of about 80 m. Below this depth, there was a strong thermocline that generated a waveguide in the bottom portion of the channel. The sound source was located at 112 m in the deep waveguide, and the receiver depths relative to the waveguide are shown in Fig. 2.

GEOACOUSTIC INVERSION

Acoustic Propagation

The signal field at all frequencies from a source in the deep waveguide consists of two components that can be described in terms of ray theory (Fig. 3). Steep angle rays propagate by Surface-Reflected/Bottom-Reflected (SRBR) paths that span the entire water column. These paths are received at all sensors in the array, and arrival times span about 300–400 ms. Shallow angle rays less than 7.6° are trapped in the deep waveguide, and arrive as a strongly focused group of refracted/bottom-reflected (RBR) rays. Arrival times of rays in this group are within 10–20 ms, and the intensity of the group is 10–15 dB higher than that of the SRBR components. This signal is observed only on the deeper hydrophones of the vertical array that are within the deep waveguide. In both cases of SRBR and RBR paths, the propagation is bottom limited with 8–10 bottom interactions along the travel path.

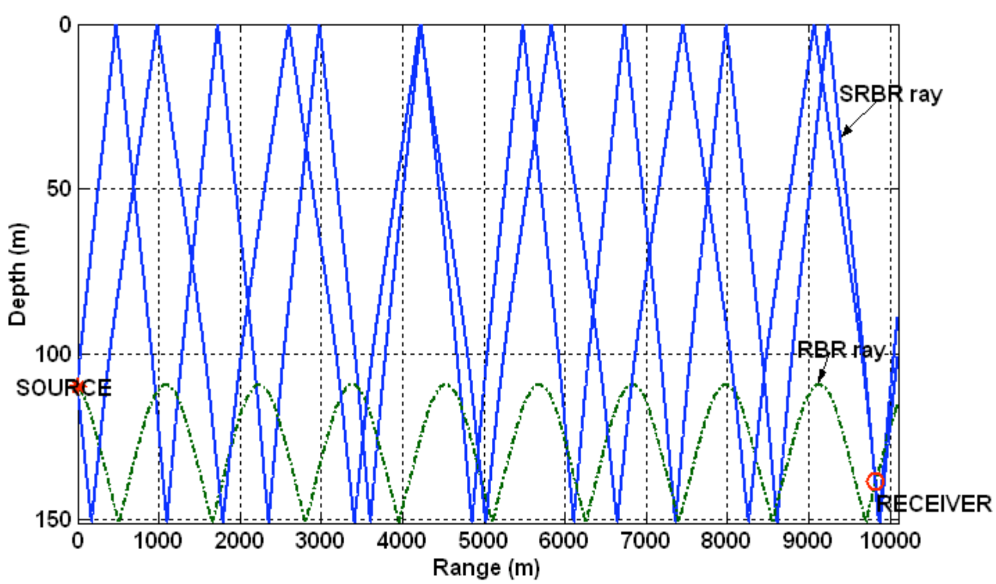
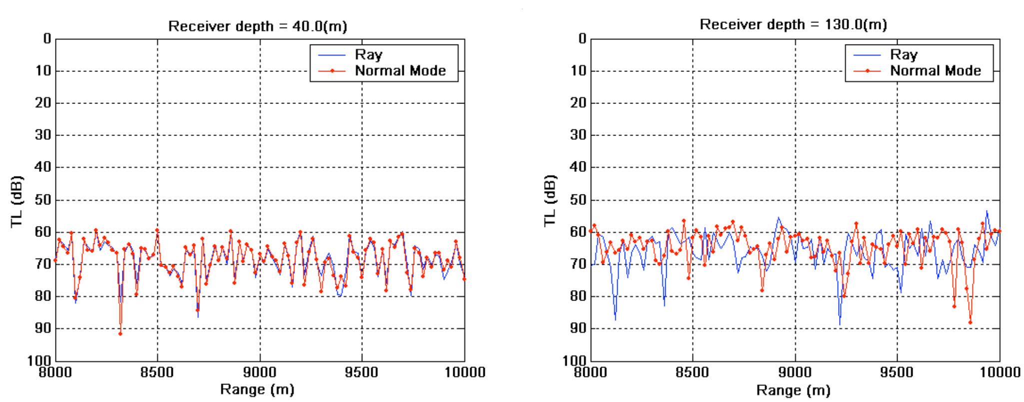


FIGURE 3. Illustration of RBR and SRBR rays from the source at 112 m.

Strategies for Inversion

The overall objective of this work is to invert geoacoustic parameters for a simple gradient layer model of the sound speed profile in the sediment, using data separately from each of the six frequency bands that were transmitted in the experiment. The very long range geometry presents significant challenges for implementing matched field inversion. Conventional matched field processing, which makes use of spatial phase coherence across the array, is the method of choice for the lower frequency signals. However, at higher frequencies, (> 800 Hz) it is more effective to exploit the temporal coherence of the signal, and base the inversion on modeling the signal waveform at single sensors.

Normal mode propagation models are most appropriate for calculating acoustic fields for matched field inversions at the lower frequencies, but at higher frequencies it is more efficient to use ray theory for calculating the waveform [3,4]. However, it is first necessary to benchmark the ray model. We show in Fig. 4 a comparison between transmission loss calculated by ray theory [5] and normal modes [6] for the Florida Straits sound speed profile and a half space geoacoustic model with sediment sound speed of 1700 m/s. The left and right panels show the results for receivers at 40 m and 130 m, respectively, for the source depth of 112 m in the waveguide. The comparison demonstrates that ray theory can model the field accurately for the shallow receiver where the propagation is by SRBR rays. However, the ray model does not perform as well in modeling the RBR waveguide propagation. This result suggests that the inversions at higher frequencies should be restricted to data from the shallow hydrophones above the deep waveguide.



(a) (b)

FIGURE 4. Comparison between TL calculated by normal mode and ray theory at different receiver depth (a) Receiver depth at 40 m; (b) Receiver depth at 130 m

Fast Gibbs Sampling

In this paper we describe the application of conventional matched field inversion to spectral components of the transmitted signal. The spatial coherence across the array was first examined for each spectral component in the band to select five frequencies that were suitable for matched field processing. The spatial coherence was not uniformly high across the band, and, generally, poor coherence was associated with low signal strength at several of the sensors.

We assumed that the environment was range independent, and used the normal mode model ORCA [6] to calculate the replica fields for a simple gradient layer geoacoustic model as shown in Fig. 5. This model is similar to the model used in previous work by DeFerrari and Monjo [1] to predict channel pulse response. However, the shear wave effect was not considered here. The complete model consisted of five geoacoustic parameters, including the water depth, and the density, attenuation, sound speed gradient and sound speed at the top of the sediment layer. Both the density and attenuation were assumed to be constant with depth. The inversion also estimated three geometrical parameters of the experiment – the source depth, depth of the topmost receiver in the vertical array, and the range.

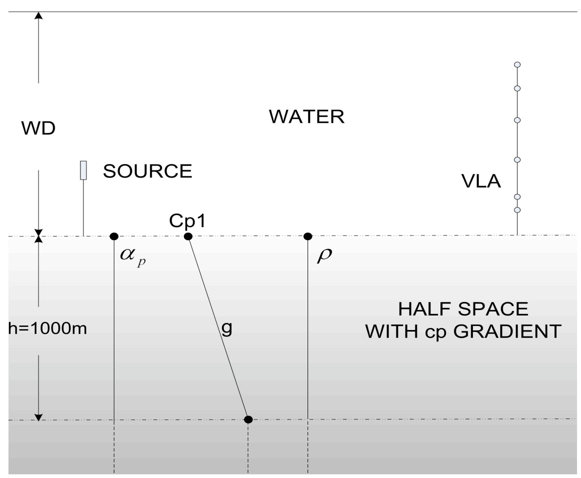


FIGURE 5. Geoacoustic model used for the South Florida Strait environment.

The model parameters were estimated using the Fast Gibbs Sampling method [7,8]. This approach provides an unbiased, asymptotically converging sample of the *a posteriori* probability distribution that represents the complete solution to the inverse problem in the Bayesian formulation. The method uses the same selection criterion as in conventional optimization by simulated annealing, except that all samples are drawn at T = 1. The samples were generated by evaluating a multi-frequency cost function that was based on the single frequency, normalized Bartlett processor.

Inversion Results

The marginal densities that were derived from the Gibbs *a posteriori* probability distribution are shown in Fig. 6 for the eight model parameters. The distributions indicate that all parameters except the sound speed gradient have been well estimated. The estimates for the geometrical parameters are generally consistent with ground truth measurements from the experiment. The range and water depth estimates are strongly correlated, but the inversion prefers deeper depths and shorter ranges than expected from the experimental deployment. Range errors of up to 250 m are not uncommon in localizing the source and array, but the water depth errors are more difficult to interpret. If the impedance contrast at the sea floor is weak, the low frequency 200-Hz signal may be sensing a deeper interface within about a wavelength of the sea floor.

Sediment sound speed is very well estimated, and the maximum *a posteriori* (MAP) value is consistent with expected values for calcareous sand that is thought to be the sea bed material in the region. Density is not well estimated, but the MAP value is also consistent with calcareous sand. These estimates represent at best an average over the multiple bottom interactions along the propagation paths.

Overall correlations between the measured signal and signal envelopes calculated using the MAP estimates are about 80 % over the array. The estimated parameters support SRBR and RBR modes that model the dominant first arrival components of the signal very well. However, a group of weaker arrivals that are delayed by about 300 ms are not predicted by the gradient sound speed geoacoustic model. These later arrivals in the 200-Hz signal are likely due to interactions with the subbottom structure. This interaction is described by the sediment sound speed gradient in the working geoacoustic model. However, the inversion indicated that there is little information about the gradient parameter in the data. At higher frequencies, the inversion sensitivity to the details of the deeper structure is likely to remain low.

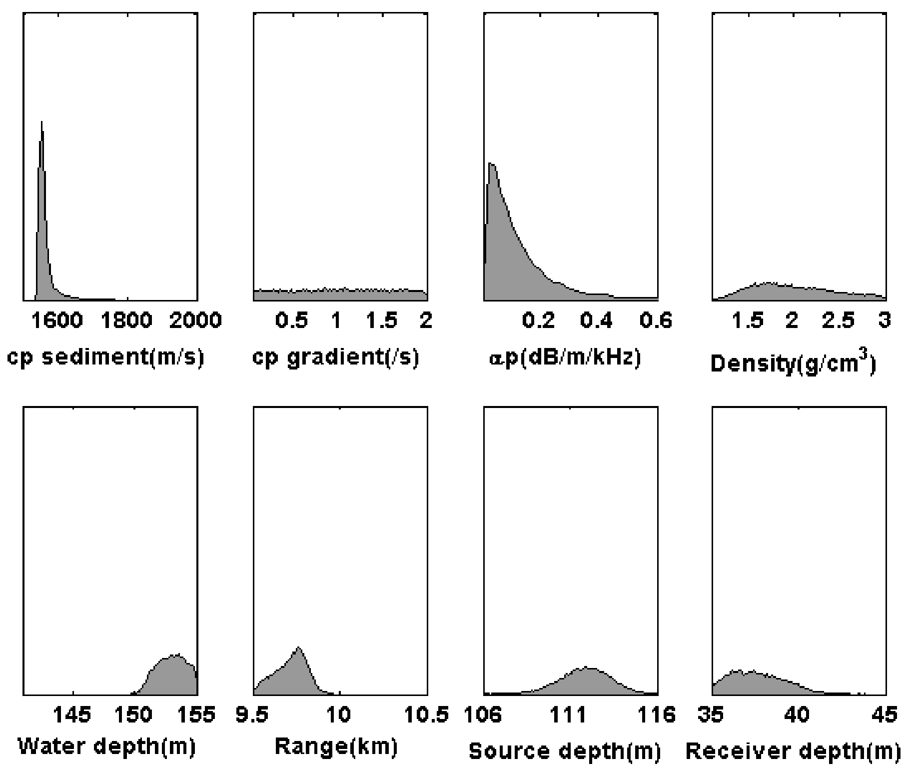


FIGURE 6. Marginal densities generated from the Gibbs sampling inversion for the geoacoustic and geometric model parameters.

SUMMARY

Strategies for inversion of low and high frequency signals that were transmitted in the experiment in the South Florida Straits are discussed in this paper. The inversion strategy for the low frequency data is based on conventional matched field processing, whereas the inversions at high frequencies are based on waveform matching of the received signals. The inversion results for the 200-Hz data provide a baseline geoacoustic model for comparing with the results from inversions at higher frequencies. The inverted geoacoustic profile is sensitive to the sediment parameters at the sea floor, and the estimates for sound speed and density are consistent with expected values for calcareous sediment material.

ACKNOWLEDGMENTS

This work was supported by the Ocean Acoustics Team at the Office of Naval Research. Discussions with Harry DeFerrari and Neil Williams about the experiment were greatly appreciated.

REFERENCES

1. H. A. DeFerrari, N. J. Williams and H. B. Nguyen., "Variability, coherence and predictability of shallow water acoustic propagation in the Straits of Florida," *Impact of Littoral Environmental Variablility on Acoustic Predictions and Sonar Performance*, edited by Nicholas G. Pace and Finn B. Jensen, Dordrecht/Boston/London: KLUWER ACADEMIC PUBLISHERS, 2002, pp.245-254.
2. Hien B. Nguyen, Harry A. DeFerrari, and Neil J. Williams, "Ocean Acoustic Sensor Installation at the South Florida Ocean Measurement Center," *IEEE J. Oceanic Eng.,* vol. 27, NO.2, 2002, pp.235-244.
3. Evan. K. Westwood, "Broadband Matched Field Source Localization", *J. Acoust. Soc. Am*, **91**, 2777-2789, (1992).
4. N. R. Chapman, J. Desert, A. Agarwal, Y. Stephan and X. Demoulin, "Estimation of Seabed Models by Inversion of Broadband Acoustic Data", *Acta Acustica*, 88, 756-759, (2002).
5. M. B. Porter and H. Bucker, "Gaussian Beam Tracing for Computing Ocean Acoustic Fields", *J. Acoust. Soc. Am*, **82**, 1349-1359, (2002).
6. Evan K. Westwood, C. T. Tindle and N. R. Chapman, "A Normal Mode Model for Acousto-elastic Ocean Environments," *J. Acoust. Soc. Am*, **100**, 3631-3645, (1996).
7. Stan E. Dosso, "Quantifying Uncertainty in Geoacoustic Inversion. I. A fast Gibbs sampler approach," *J. Acoust. Soc. Am*, **111**, 129-142, (2002).
8. Stan E. Dosso, and Peter L. Nielsen, "Quantifying Uncertainty in Geoacoustic Inversion. II. Application to Broadband, Shallow-water Data," *J. Acoust. Soc. Am*, **111**. 143-159, (2002).