Bayesian Ambient Noise Inversion for Geoacoustic Uncertainty Estimation

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LONG-TERM GOALS

Estimation of seabed geoacoustic parameters in shallow water by remote sensing remains a challenging task due to constraints on hardware, data collection and analysis, and cost of maritime surveys. This work focuses on the application of two techniques that might offer a solution to those constraints: the use of ambient noise to probe the seabed, and Bayesian inversion of these data to estimate geoacoustic parameters of interest together with their uncertainties. The long-term goal of this work is to establish general methods for processing and inverting ambient noise data and assessing the quality of the results by quantifying their uncertainties.

OBJECTIVES

This work has three main objectives: first, quantifying the ability to resolve seabed geoacoustic parameters using ambient noise measurements. Second, comparing those estimates to the ones obtained from active source inversion methods. Third, considering the effect of uncertainties on transmission loss and sonar performance prediction. A further objective related to this effort is increasing the understanding of the experimental conditions and equipment required for the collection of ambient noise data suitable for geoacoustic inversion.

APPROACH

Traditional investigation of seabed sediment properties has relied heavily on direct measurements such as core sampling/geo-probes, or indirect measurements with active systems. Direct methods have the evident problem of lack of spatial resolution due to time/cost constraints, while active methods can be limited due to deployment procedures and environmental concerns, often requiring the use of a vessel to tow the active device over a geographic area of interest. As an alternative to active systems, it is known that the wind-driven ambient noise field recorded at a vertical array carries information of the seabed layering structure[1], which is exploited in this research. The technical approach for this work consists of:

1) Defining an inversion method: the Bayesian framework has been selected in this study to carry out geoacoustic inversion from ambient noise data. The work by Dettmer and Dosso[2-3] (University of Victoria) and Holland (Pennsylvania State University) on Bayesian controlled-source reflection coefficient inversion is directly applicable to the proposed inversion of similar data as extracted from the ambient noise field[4].
2) Implementing algorithms for numerical estimation of the joint posterior probability density (PPD): Since analytical solutions for the PPD are generally not available for non-linear problems, Markov chain Monte Carlo (MCMC) methods are used to sample from this distribution[3]. In this work, Metropolis-Hastings sampling (MHS) is applied to determine marginal probability densities. Perturbations are applied in a principal-component parameter space, which is a rotated representation of the physical parameter space in which the axes align with the dominant correlation directions. This rotation provides a more efficient exploration of the parameter space, and is particularly effective when strong correlations between parameters are present.
3) Identifying a forward model: the input to the Bayesian inversion is the bottom loss (BL), which can be computed from the ratio of upward to downward energy fluxes obtained by beamforming ambient noise measured at a vertical linear array (VLA)[5,6]. The forward model consists of computing a representation of the ambient noise data covariance matrix, from which replicas of the BL can be calculated for different combinations of the geoacoustic parameters. This replica BL is adjusted to include the smearing effect introduced by the VLA's finite aperture. Software routines for the forward model have been validated by comparison with OASN, the ambient noise module from the wavenumber-integration model OASES[7] (OASN itself is too computationally expensive to use in the inversion algorithm).
4) Determining the impact of array design and experimental conditions (e.g., wind speed) in geoacoustic inversion, by analysis of synthetic data obtained from the forward model[4].
5) Applying the inversion framework to experimental data from previous publications[6,8,9], available through Martin Siderius from the NEAR-Lab.

WORK COMPLETED

1) The ray-tracing representation of the ambient noise field developed by Harrison[5] has been adopted as a forward model to compute the angle- and frequency-dependent seabed BL. This approach considers wind-driven surface dipoles as the driving mechanism for the ambient noise. The strength of this field relative to other unwanted noise mechanisms defines a signal-to-noise ratio (SNR)[4], which is included in this work as an unknown frequency-dependent parameter.
2) Trans-dimensional (trans-D) Bayesian inversion with parallel tempering[10] was used for geoacoustic parameter estimation from BL data derived from ambient-noise[11]. To gain insight into the algorithm's performance, the trans-D method was first applied to simulated data computed for a realistic seabed consisting of smooth variations in sound speed and density as a function of depth.
3) The trans-D inversion was also applied to data from the MAPEX 2000 experiment[11] and the results were compared to previous work that utilized the Bayesian information criterion (BIC) for fixed-dimensional inversion.
4) A sequential trans-D Monte Carlo algorithm[11] was applied to simulated data corresponding to a drifting vertical array. This sequential approach provides estimates of geoacoustic parameters, true-depth layering structure of the seabed, and parameter uncertainties. The inversion was applied to incoherent estimates of seabed BL data,[13] computed as the array drifts along a range-dependent track.

RESULTS

Trans-D approach to model selection: Previous results[4] illustrated the application of Bayesian inversion to BL data using the BIC for model selection. The impact of wind strength in the estimation of seabed geoacoustic parameters was quantified, and results from geoacoustic inversion were compared to direct (core) measurements. An important factor to consider in geoacoustic inversion is the selection of a model to represent the sediment, which can substantially impact the estimation of parameters and uncertainties. As a more general approach, the trans-D Bayesian inversion algorithm[11,13] was used to provide automated model selection and to quantify the uncertainty due to model selection. With the trans-D method, models from a set of *K* candidates are included in the estimation of the joint PPD, defined as

$$P(\mathbf{m}_k, I_k \mid \mathbf{d}) = \frac{L(\mathbf{d} \mid \mathbf{m}_k, I_k) P(\mathbf{m}_k \mid I_k) P(I_k)}{P(\mathbf{d})}, \qquad (1)$$

where $L(\mathbf{d} \mid \mathbf{m}_k, I_k)$ is the likelihood function, while $P(I_k)$ is the prior distribution for the parametrization, assumed here as a discrete uniform distribution. $P(\mathbf{m}_k \mid I_k)$ is the prior distribution for the geoacoustic parameters $\mathbf{m}_k$ for a layered seabed with *k* interfaces. The vector $\mathbf{m}_k$ is defined as

$$\mathbf{m}_k = [c_1\ \rho_1\ \alpha_1\ h_1 \ldots c_{k+1}\ \rho_{k+1}\ \alpha_{k+1}\ SNR_1 \ldots SNR_F]^T, \qquad (2)$$

where c_i, ρ_i, α_i, and h_i are the sound speed, density, attenuation and thickness of the i^{th} layer, respectively. The SNRs[4] account for the unknown strength of the wind-driven ambient-noise data (i.e. the useful signal) versus other unwanted sources of noise at F frequencies. The PPD is sampled by a reversible-jump Markov chain Monte Carlo (rjMCMC) algorithm[3], which uses an extended Metropolis-Hasting (MH) criterion that allows trans-D jumps between parameterizations I_k, quantifying the uncertainty due to the lack of knowledge of the model parameterization.

Trans-D inversion applied to fixed-array simulated data: a seabed of 4 m depth was constructed[11] using measurements of sound speed and density from cores extracted in the Malta Plateau. Properties from these cores were partitioned into 120 layers of varying thickness to provide true sediment profiles with fine structure below the resolving power of BL data. The model OASES[7] was used to compute the simulated ambient-noise field at the array, and the BL data for inversion was calculated at eight frequencies from 300-1400 Hz. Figure 1(a) shows the marginal PPD profiles for geoacoustic parameters along with the true sediment profiles (dashed lines). At most depths, the support of the marginal PPDs concentrates around the true parameters, indicating good agreement. The marginal PPDs obtained by this passive method have similar characteristics as those obtained from trans-D inversion of active source data[3] [Fig.1(b)]. In particular, the depths of interfaces of high acoustic contrast are consistent between both (passive and active) techniques.

Inversion of fixed-array experimental data: Trans-D inversion was also applied to data obtained from a moored VLA during the MAPEX 2000 experiment[11]. Previous work[4] using the BIC approach to model selection yielded a 3-layer sediment profile in good agreement with core samples of sound speed and density from the region, shown in Fig. 2(a). These results were also in agreement with inversions using an active-source technique[2] based on a single hydrophone and towed source. Figure 2(b) shows the improved marginal PPDs obtained from the trans-D approach, with more reasonable (slightly larger) uncertainties. The underestimation of the parameter uncertainties using the BIC can be explained as a result of applying a point estimate for parametrization selection. With the trans-D approach, the parametrization is treated as a random variable with its own distribution determined by the information content of the data. This impacts geoacoustic parameter estimation by increasing the corresponding uncertainties and therefore providing more realistic estimates.

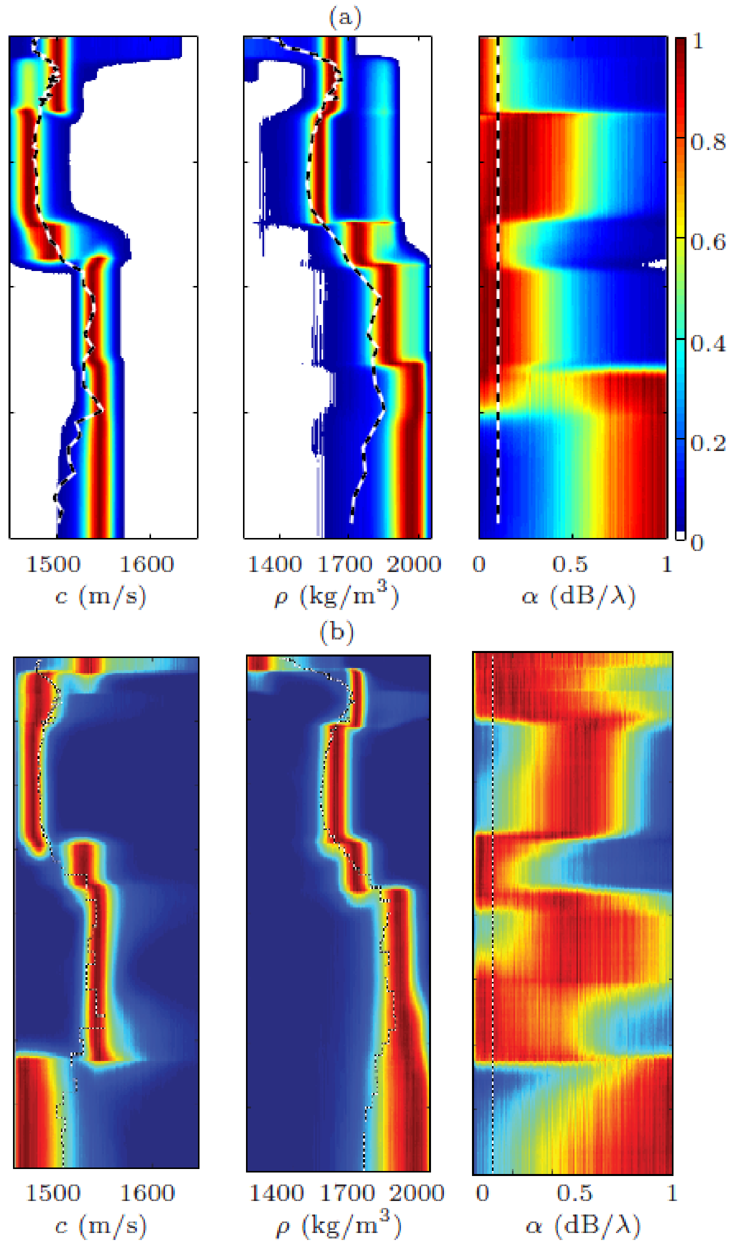

Figure 1: Marginal probability profiles from trans-D geoacoustic inversion applied to: (a) Simulated passive (ambient noise) data (Quijano et al.[11]); (b) Simulated active-source data (Dettmer et al.[3]). True profiles indicated by dashed lines.

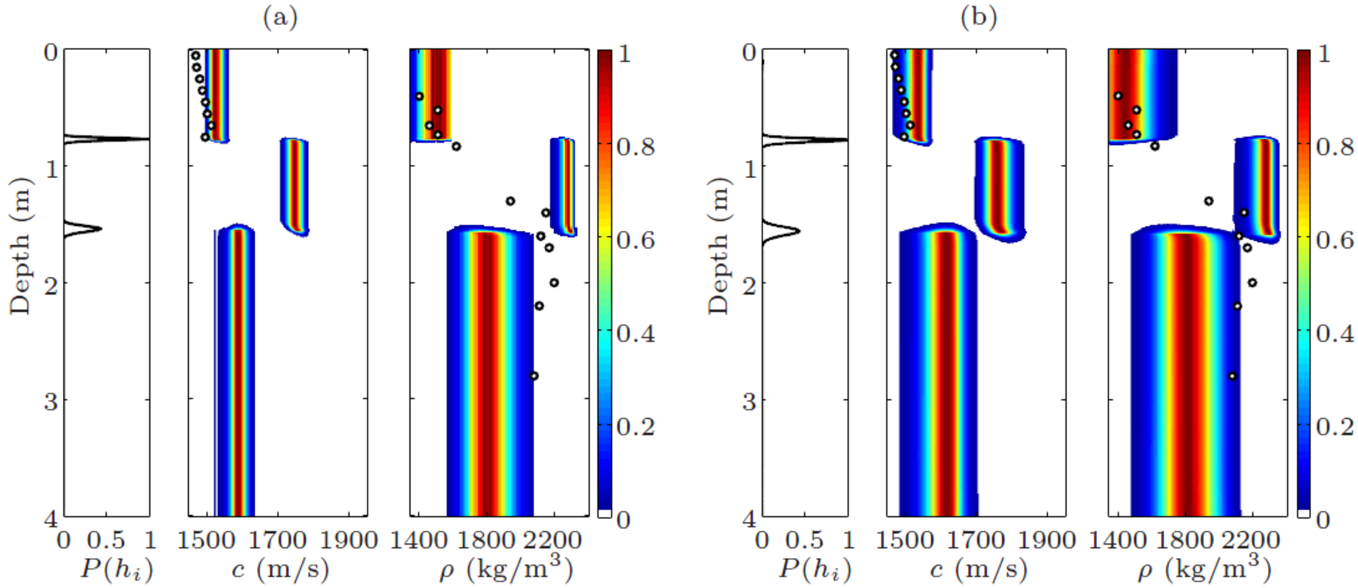

Figure 2 Marginal probability profiles from inversion of ambient noise data, using: (a) BIC approach (Quijano et al[4].) and (b) trans-D approach (Quijano et al.[11]). The dots are experimental measurements of sound speed and density from core samples taken ~400 m from the array.

Inversion of drifting-array simulated data: For a drifting array, the PPD evolves with time as the array moves over sediments in which the number of layers, the depth of interfaces, or the geoacoustic parameters change as a function of range. Sequential datasets can then be obtained by discretizing continuous-time recordings of ambient noise. For this application, a particle filter[12] is used to update the estimated geoacoustic parameters from one array position to the next as new data become available. To generate simulated sequential data, the environment shown in Fig. 3(a) was input to OASES[7] for computation of the range-dependent ambient-noise field at a 32-element VLA with 0.18 m inter-element spacing[13]. Conventional beamforming was used to estimate the BL at 8 frequencies from 550 Hz to 1400 Hz. The BL data at 20 uniformly-spaced grazing angles from 14^{o} - 90^{o} was provided to the sequential Bayesian trans-D Monte Carlo algorithm for estimation of the PPD (details of the algorithm found in Ref. 12). Figure 3(b) shows the estimated mean value of the sediment sound speed, density, and attenuation. Note that the estimated geoacoustic parameters and the depth (and number) of acoustic interfaces closely resemble the true profiles.

Previous work with sequential data by Siderius et al.[1] shows that coherent processing of ambient noise (i.e. the “passive fathometer”) can produce images of the seabed layering structure, as a function of range and travel time. The inversion method proposed here has potential advantages, by estimating full sets of range-dependent geoacoustic parameters and their uncertainties. For example, Fig. 4(a) shows the interface-depth probability distribution versus range, from which the number of layers and their *true depth* can be obtained. In addition, at each array position the sequential inversion algorithm provides marginal probability profiles for sound speeds, densities and attenuations. An example of the sound speed and density profiles corresponding to range=29 (length units) are shown in Fig. 4(b). Good agreement between the true parameters (dashed lines) and the estimated profiles is evident, particularly for the case of sound speed, which is known to be a sensitive parameter (compared to density) in matching the BL data used as input to the inversion. Current work focuses on the application of the sequential Bayesian inversion to experimental data from the Boundary 2003 experiment.

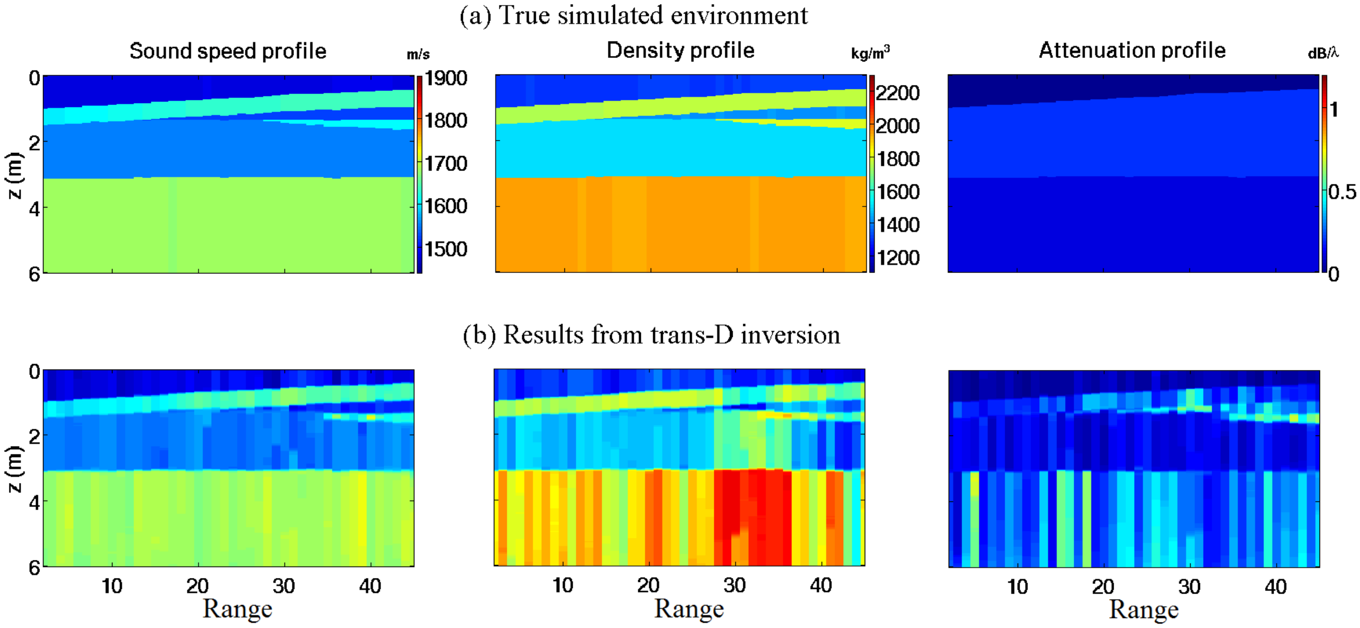

Figure 3 Geoacoustic inversion of ambient-noise sequential data: (a) True seabed environment input to OASES to generate simulated data. (b) Mean sediment sound speed, density, and attenuation from the estimated PPD via inversion.

IMPACT/APPLICATIONS

In shallow water regions the performance of Navy sonar systems is strongly influenced by acoustic interaction with the seabed and, therefore, knowledge of geoacoustic parameters and their corresponding uncertainties is required to predict and optimize sonar performance. Bayesian inversion methods offer an elegant and powerful framework not only for parameter extraction but also for uncertainty estimation, thereby quantifying the geoacoustic information content of the data. The proposed inversion methodology has been highly effective when applied to active surveys, and current results[4,11,13] using experimental and simulated ambient noise data show great potential to overcome limitations of current methods of geoacoustic inversion.

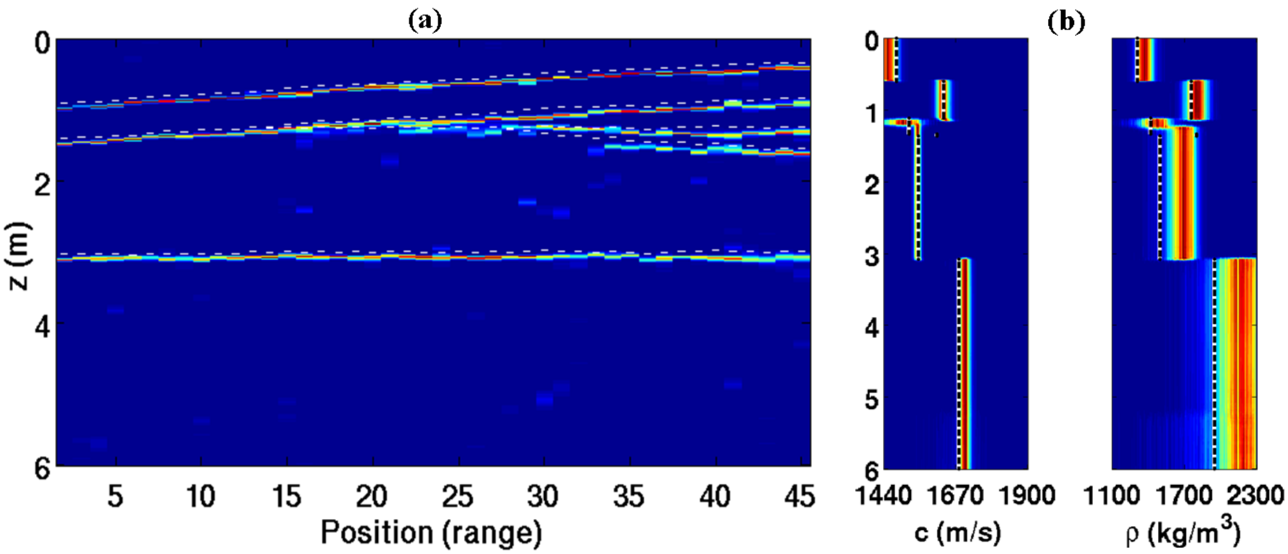

Figure 4 Geoacoustic inversion of ambient-noise sequential data: (a) Interface-depth probability distributions versus range. True interfaces are shown as dashed lines which are offset slightly for display purposes; (b) Marginal probability profiles at range=29 (length units), with true parameters shown as dashed lines.

RELATED PROJECTS

1) *Automated geoacoustic inversion and uncertainty: Meso-scale seabed variability in shallow water environments (Award Number: N00014-09-1-0394)*. This project develops a Bayesian methodology for advanced and automated geoacoustic inversion. A range of active source data are inverted to quantify geoacoustic uncertainty. This project applies and further develops these methods for ambient-noise data.

2) *Ocean Ambient Noise Studies for Shallow and Deep Water Environments, 2012-2014 (Award Number: N00014-12-1-0017).*

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PUBLICATIONS

J. E. Quijano, S. E. Dosso, J. Dettmer, L. M. Zurk, and M. Siderius, "Trans-dimensional geoacoustic inversion of wind-driven ambient noise", submitted to J. Acoust. Soc. Am., Electronic Letters, (2012).

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