Bayesian Ambient Noise Inversion for Geoacoustic Uncertainty Estimation: Final report

Jorge E. Quijano
School of Earth and Ocean Sciences, University of Victoria
3800 Finnerty Road
Victoria BC, Canada
phone: (250) 472-4685, email: jorgeq@uvic.ca

Stan E. Dosso
School of Earth and Ocean Sciences, University of Victoria
3800 Finnerty Road
Victoria BC, Canada
phone: (250) 472-4341, email: sdosso@uvic.ca

Jan Dettmer
School of Earth and Ocean Sciences, University of Victoria
3800 Finnerty Road
Victoria BC, Canada
phone: (250) 472-4026, email: jand@uvic.ca

Lisa M. Zurk
Electrical and Computer Engineering Department, Portland State University
1900 SW 4th Ave
Portland, OR 97207 USA
phone: (503) 725-5423, email: zurkl@cecs.pdx.edu

Martin Siderius
Electrical and Computer Engineering Department, Portland State University
1900 SW 4th Ave
Portland, OR 97207 USA
phone: (503) 725-3223, email: siderius@ece.pdx.edu

Grant Number: N000141110214

LONG-TERM GOALS

Estimation of seabed geoacoustic parameters in shallow water by acoustic 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.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE **Bayesian Ambient Noise Inversion for Geoacoustic Uncertainty Estimation: Final report**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Victoria,School of Earth and Ocean Sciences,3800 Finnerty Road,Victoria, BC Canada V8P5C2,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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, 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 and 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 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 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[3-4] (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.[5]

2) Implementing algorithms for numerical estimation of the posterior probability density (PPD) over the geoacoustic parameters of interest: 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.[4] 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 seabed power reflection coefficient R or the bottom loss ($BL = -10\log R$), 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).[2,6] 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 (e.g., aperture, sensor density) and experimental conditions (e.g., wind speed) in geoacoustic inversion by analysis of synthetic data obtained from the forward model.[5]

5) Applying the inversion framework to experimental data from previous publications.[6,8,9]

WORK COMPLETED

1) The ray-tracing representation of the ambient noise field developed by Harrison[2] has been adopted as the 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),[5] 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 simulated ambient-noise.[11]
3) The trans-D inversion was 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. Preliminary inversions using data from a drifting array from the Boundary 2003 experiment[8] were also carried out.
4) A sequential trans-D Monte Carlo algorithm[12] was applied to simulated data corresponding to a drifting vertical array. This 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 power reflection coefficient data,[13] computed as the array drifts along a range-dependent track.
5) Using simulated data, the impact of array aperture in geoacoustic resolution was studied. To resolve complicated seabed structure, large apertures are required. Since minimizing array aperture offers advantages in array design and deployment, signal processing techniques to extend short apertures (i.e., synthetic array apertures) were evaluated.

RESULTS

Trans-D approach to model selection: Initial results in this effort[5] 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. As a more general approach, the trans-D Bayesian inversion algorithm[11-13] was used to provide automated model selection over an unknown number of seabed layers 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 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 parametrization I_k, 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

$$\mathbf{m}_k = [c_1\ \rho_1\ \alpha_1\ z_1 \ldots c_{k+1}\ \rho_{k+1}\ \alpha_{k+1}\ SNR_1 \ldots SNR_F]^T, \qquad (2)$$

where c_i, ρ_i, α_i, and z_i are the sound speed, density, attenuation and interface depth of the i^{th} layer, respectively. The SNRs[5] 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,[4,14] which uses an extended Metropolis-Hasting (MH) criterion that allows trans-D jumps between parameterizations I_k, sampling probabilistically over models with different parametrizations (number of layers) and quantifying the uncertainty due to the lack of knowledge of the model parameterization.

Inversion results using a simulated environment consisting of depth-dependent variations in sound speed, density, and attenuation[11] were in good agreement with the true sediment profiles, as well as with similar inversions carried out with active source simulated data. The trans-D inversion was also applied to data obtained from a moored VLA during the MAPEX 2000 experiment,[11] providing improved estimates of parameter uncertainties compared to previous work under this effort[5] using the BIC approach to model selection.

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.1-(a) (similar panels for density and sediment attenuation were included in the simulation) 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] This simulated environment (used in previous work in the context of active-source surveys[12]) includes realistic features such as range-dependent smooth transitions in geoacoustic parameters, thin sediment layers, and abrupt variations introduced by a geologic fault and an erosional channel. Conventional beamforming was used to obtain the power reflection coefficient at 8 frequencies from 1000 Hz to 3000 Hz and grazing angles from 20^{o} - 90^{o}. These data were provided to the sequential Bayesian trans-D Monte Carlo algorithm for estimation of the PPD.[13] Figure 1-(a) (bottom) shows the estimated mean model of the sediment sound speed, corresponding to simulated data from a 224-element array (40 m aperture).

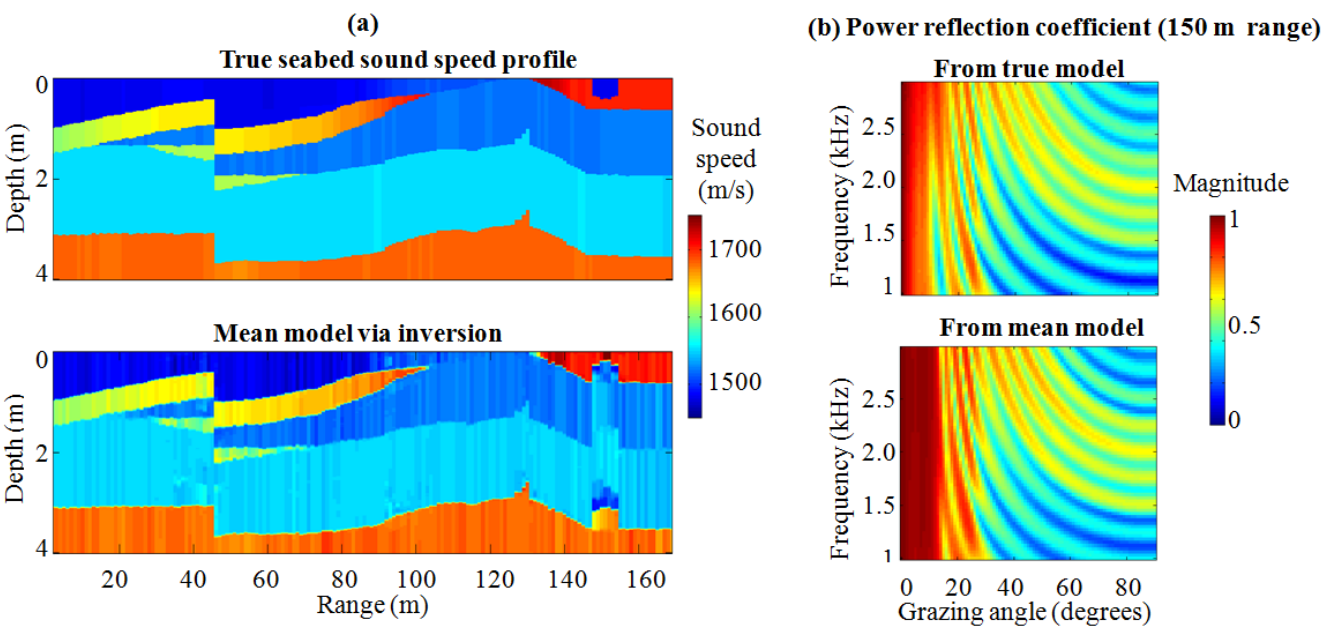

Figure 1 Geoacoustic inversion of ambient-noise sequential data: (a) True seabed sound speed profile input to OASES to generate simulated data vs mean model obtained via inversion. (b) Power reflection coefficient estimated by beamforming using the true parameters (top) from (a) and the most probable model obtained via inversion (bottom), at range 150 m.

The estimated geoacoustic parameters (sound speed, number/depth of sediment interfaces) closely resemble the true sediment profile even at ranges containing thin sediment layers which are challenging for an inversion algorithm. Similar agreement was obtained for the density and the attenuation.

As an example of the resolution limitation of the data, Fig. 1-(a) exhibits a mismatch in the inversion results at ranges 148-154 m corresponding to the erosional channel. To explain this mismatch, Fig.1-(b) shows the power reflection coefficient estimated by beamforming using the true geoacoustic parameters (top) and the most likely model obtained via inversion (bottom). The structure of the interference pattern in both cases is very similar for the angular range used for inversion (20^o - 90^o), causing the inversion algorithm to have slow convergence to the true solution while searching over the parameter space. Given more iterations, the estimated profile should eventually converge to the theoretical environment. Figure 1 shows the best results in a series of simulations in which the length of the array was varied from 40 m to 6 m to observe the impact of array aperture into the estimated sediment profiles. As the aperture decreased, features in the power reflection coefficient are lost due to beamforming smearing, resulting in low geoacoustic resolution. For field experiments, increasing geoacoustic resolution by augmenting the array aperture would make array deployment more difficult and decrease array stability while drifting. Therefore, other options such as synthetically extending the array were analyzed.

Extension of the array aperture by signal processing: Given an N-element array with inter-element spacing Δz, the seabed power reflection coefficient at grazing angle θ can be approximated as $R(\theta) = B(-\theta)/B(\theta)$, where $B(\theta)$ is the output of the conventional beamformer:

$$B(\theta) = \mathbf{w}^H(\theta)\begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1N} \\ C_{21} & C_{22} & \cdots & C_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ C_{N1} & C_{N2} & \cdots & C_{NN} \end{bmatrix}\mathbf{w}(\theta) \equiv \mathbf{w}^H(\theta)\,\mathbf{C}\,\mathbf{w}(\theta). \qquad (3)$$

In (3), $\mathbf{w}(\theta)$ is the array steering vector, while C_{ba} is the spatial coherence between two sensors separated a distance $(a-b)\Delta z$, with $1 \le b \le a \le N$. Under mild requirements[15], the matrix $\mathbf{C}$ for ambient noise at a vertical array can be modelled as Toeplitz and only the first row must be known to uniquely determine the matrix. Increasing the array aperture by signal processing techniques (as opposed to by physically adding sensors to the array) requires extension of the coherence function, which can be achieved by zero padding[15] or by extrapolation. For example, to obtain a synthetic 6-element array from a 3-element array it is required to approximate the true spatial coherence as:

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \end{bmatrix} \approx \begin{cases} \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \end{bmatrix} & \text{zero-padding,} \\ \begin{bmatrix} C_{11} & C_{12} & C_{13} & \hat{C}_{14} & \hat{C}_{15} & \hat{C}_{16} \end{bmatrix} & \text{extrapolation.} \end{cases} \qquad (4)$$

The zero-padding method has been shown to enhance features of the estimated power reflection coefficient.[15] However, the power reflection coefficient obtained by a zero-padded covariance matrix differs from the corresponding quantity that would be obtained by using an actual array of similar aperture. In inversion, this represents a potential problem, since the forward model used while navigating the parameter space must accurately represent the data to obtain unbiased estimation of the geoacoustic parameters of interest. To avoid this issue, for inversion problems extrapolation of the coherence function should be considered.

The spatial coherence due to surface-generated ambient noise can be written as[15]

$$C(z) \approx 2\pi \int_{0}^{1/\lambda} [1 - R(k)]^{-1} \left[e^{ikz} + R(k)e^{-ikz}\right] dk, \qquad (5)$$

where λ is the wavelength, $R(k)$ is the seabed power reflection coefficient, and $k = 2\pi \sin\theta / \lambda$ is the vertical spatial wavenumber. It has also been shown[15] that the Fourier transform of the spatial coherence is

$$F\{C(z)\} \approx \begin{cases} [1 - R(k)]^{-1} R(k) & -1/\lambda \le k < 0, \\ [1 - R(k)]^{-1} & 0 \le k \le -1/\lambda. \end{cases} \qquad (6)$$

Therefore, $C(z)$ is band-limited and methods such as the iterative Papoulis-Gerchberg algorithm[16] or its non-iterative versions[17] can be used for extrapolation. Figure 2(a) shows an example of the estimation of the bottom loss for a two-layer environment consisting of a 0.75 m sediment layer (sound speed=1550 m/s, density=1.5 g/cm^3, attenuation=0.2 dB/λ) on top of a halfspace (1600 m/s, 2.0 g/cm^3, 0.15 dB/λ).

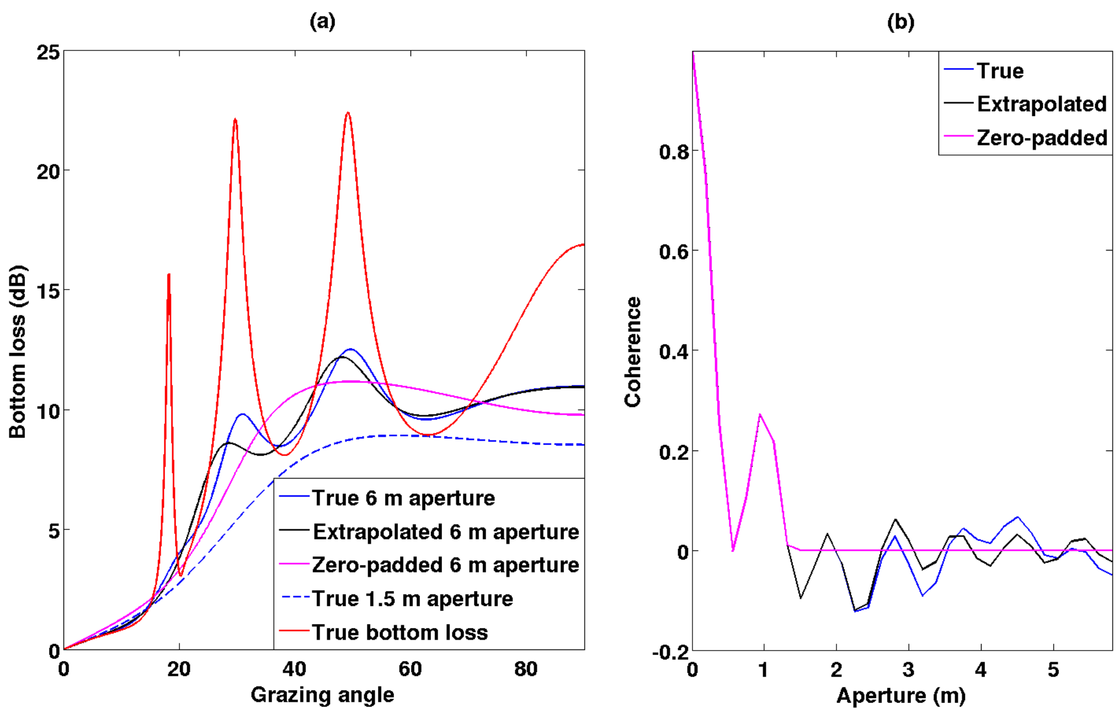

Figure 2 Comparison of array-extension techniques for a 1.5-m aperture array used to approximate a 6-m array in a 2-layer environment: (a) Bottom loss obtained from the analytical solution and from beamforming using true apertures of 1.5 m and 6 m, as well as 6 m synthetic apertures using the zero-padding[15] and extrapolation[16] approaches. (b) Spatial coherence (4) for a true 6-m aperture, a zero-padded 6-m aperture, and an extrapolated 6-m aperture.

Figure 2-(a) shows an example in which the actual array is only 1.5 m aperture. The true bottom loss is shown as a reference, with sharp peaks at 18°, 30°, and 49°. In this case, the zero-padding technique fails to reveal the *BL* peaks at 30° and 49° when used to synthesize a 6-m aperture, while the extrapolation technique shows those peaks. For inversion purposes, the most important characteristic of the extrapolation technique is that the results from the extrapolated 6-m aperture are in reasonable agreement with the results from a true 6-m aperture. Figure 2(b) compares the true coherence function over 6 m, to the extrapolated coherence function and the zero-padded coherence. The extrapolated coherence resembles the true coherence, following the same oscillatory pattern. The difference between the extrapolated and the true coherence is due to the slow convergence of the Papoulis-Gerchberg algorithm,[16] which in Figure 2(b) was truncated at 1000 iterations (~2 minutes computational time).

Figure 3-(a) shows a similar example with a true 6-m aperture array (dashed curve), in which the *BL* peaks at 30° and 49° can be observed. The zero-padding technique was used to double the length of the array, and the result shows sharper peaks approaching the true bottom loss. However, the *BL* is underestimated at grazing angles around 90°, and in general the results from this extrapolation do not agree with the results from a true 12-m aperture. The extrapolation technique using the Papoulis-Gerchberg algorithm is also demonstrated, showing also an improvement in the height of the *BL* while being in good agreement with the true 12-m aperture over most grazing angles.

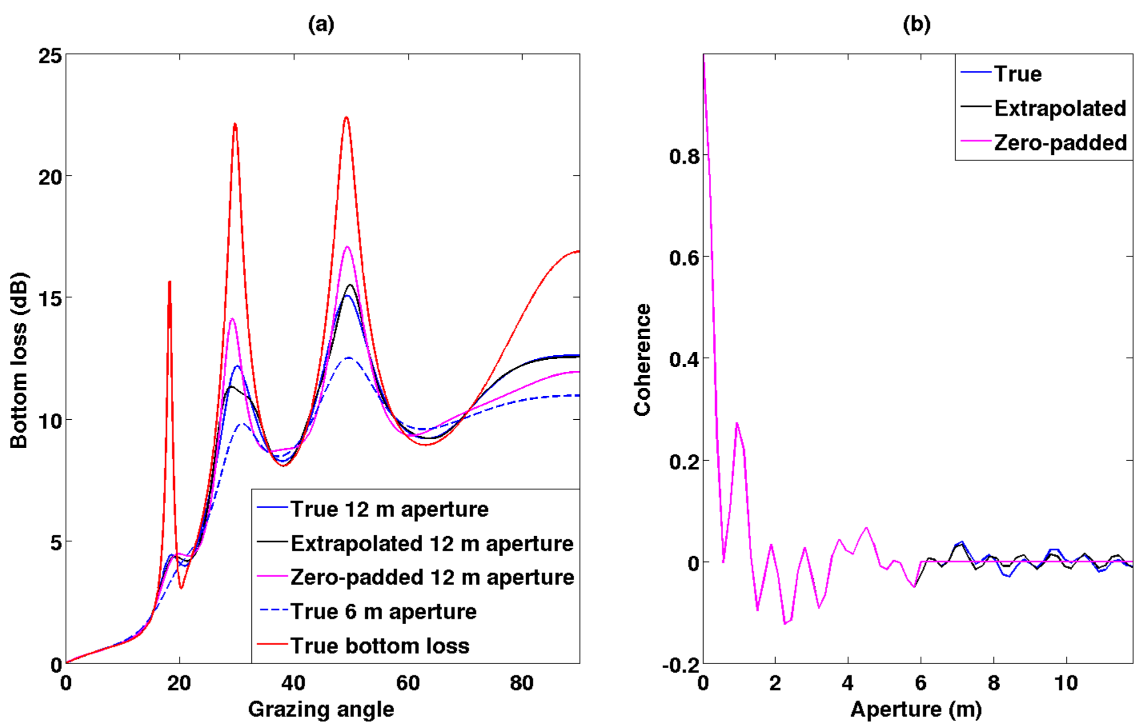

Figure 3 Comparison of array-extension techniques, similar to Fig.2, with a 6-m aperture array used to approximate a 12-m aperture array. As in Fig.2, the results from the extrapolated 12-m aperture are in good agreement with the results that would be obtained with a true 12-m aperture.

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 are 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[5,11,13] using experimental and simulated ambient noise data show great potential to overcome limitations of current methods of geoacoustic inversion. The smearing introduced by beamforming is one of the main factors limiting the resolution of ambient noise remote sensing methods. Since increasing the array length is an impractical solution to these problems, zero-padding and extrapolation techniques may be helpful.

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).*

REFERENCES

[1] M. J., Buckingham, and Jones, S. A. S., ‘‘A new shallow-ocean technique for determining the critical angle of the seabed from the vertical directionality of the ambient noise in the water column,’’ J. Acoust. Soc. Am. 81, 938–946 (1987).

[2] C. H. Harrison and D. G. Simons, “Geoacoustic inversion of ambient noise: A simple method”, J. Acoust. Soc. Am. 112, 1377–1389 (2002).

[3] J. Dettmer, C. W. Holland, and S. E. Dosso, “Analyzing lateral seabed variability with Bayesian inference of seabed reflection data”, J. Acoust. Soc. Am. 126, 56–69 (2009).

[4] J. Dettmer, S. E. Dosso, and C. Holland, “Trans-dimensional geoacoustic inversion”, J. Acoust. Soc. Am. 128, 3393–3405 (2010).

[5] J. E. Quijano, S. E. Dosso, J. Dettmer, L. M. Zurk, M. Siderius, and C. H. Harrison, “Bayesian geoacoustic inversion using wind-driven ambient noise”, J. Acoust. Soc. Am. 131, 2658-2667 (2012).

[6] M. Siderius and C. H. Harrison, “High-frequency geoacoustic inversion of ambient noise data using short arrays”, AIP Conference Proc. 728, 22-31 (2004).

[7] H. Schmidt, OASES version 3.1 User guide and reference manual.

[8] M. Siderius, H. Song, P. Gerstoft, W. S. Hodgkiss, P. Hursky, and C. H. Harrison, “Adaptive passive fathometer processing”, J. Acoust. Soc. Am. 127, 2193–2200 (2010).

[9] M. Siderius, C. H. Harrison, and M. B. Porter, "A passive fathometer technique for imaging seabed layering using ambient noise", J. Acoust. Soc. Am. 120, 1315–1323 (2006).

[10] S. E. Dosso, C. W. Holland, and M. Sambridge, "Parallel tempering strongly nonlinear geoacoustic inversion", J. Acoust. Soc. Am. 132, 3030-3040 (2012).

[11] J. E. Quijano, S. E. Dosso, J. Dettmer, L. M. Zurk, and M. Siderius, "Trans-dimensional geoacoustic inversion of wind-driven ambient noise", J. Acoust. Soc. Am., Express Letters 133, EL47-EL53 (2013).

[12] J. Dettmer, S. E. Dosso, and C.Holland, "Sequential trans-dimensional Monte Carlo for range-dependent geoacoustic inversion", J. Acoust. Soc. Am. 129, 1794–1806 (2011).

[13] J. E. Quijano,S. E. Dosso, J. Dettmer, "A Bayesian framework for geoacoustic inversion of wind-driven ambient noise in shallow water", Proceedings of the Annual Conference of the Canadian Acoustical Association, 80-81 (2012).

[14] P. J. Green, "Reversible jump Markov chain Monte Carlo computation and Bayesian model determination," Biometrika 82, 711–732 (1995).

[15] M. Siderius, L. Muzi, C. H. Harrison, and P. L. Nielsen, "Synthetic array processing of ocean ambient noise for higher resolution seabed bottom loss estimation", J. Acoust. Soc. Am., Express Letters 133, EL149-EL155 (2013).

[16] A. Papoulis, "A new algorithm in spectral analysis and band-limited extrapolation", IEEE Transactions on Circuits and Systems 22, 735–742 (1975).

[17] A. K. Jain and S. Ranganath, "Extrapolation algorithms for discrete signals with application in spectral estimation", IEEE Transactions in Acoustics, Speech, and Signal Processing 29, 830-845 (1981) .

PUBLICATIONS

J. E. Quijano, S. E. Dosso, J. Dettmer, L. M. Zurk, and M. Siderius, "Trans-dimensional geoacoustic inversion of wind-driven ambient noise", J. Acoust. Soc. Am., Express Letters 133, EL47-EL53 (2013).

J. E. Quijano, S. E. Dosso, J. Dettmer, L. M. Zurk, M. Siderius, and C. H. Harrison, "Bayesian geoacoustic inversion using wind-driven ambient noise", J. Acoust. Soc. Am. 131, 2658-2667 (2012).

J. E. Quijano, S. E. Dosso, J. Dettmer, "A Bayesian framework for geoacoustic inversion of wind-driven ambient noise in shallow water", Proceedings of the Annual Conference of the Canadian Acoustical Association, 80-81 (2012).