DOI: 10.61782/fa.2025.0916

TRANS-DIMENSIONAL BAYESIAN MATCHED-FIELD INVERSION FOR SEABED GEOACOUSTIC PROFILES

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ABSTRACT

This paper estimates depth-dependent profiles of seabed geoacoustic properties (sound speed, density, attenuation) by matching broadband complex acoustic fields, due to an impulsive sound source, recorded at a vertical array of hydrophones. Trans-dimensional Bayesian inversion is applied to sample probabilistically over the number of seabed layers and corresponding layer depths and geoacoustic parameters, as well as over the order and parameters of an autoregressive error model. The approach is based on reversible-jump Markov-chain Monte Carlo sampling, which provides objective, data-driven model selection and quantitative parameter/uncertainty estimation. Data were collected on the New England Mud Patch, off the northeast coast of the USA, where the sediment column is known to consist of an upper mud layer 10–11 m thick over a sand layer. Inversions are carried out for three frequency bands of 20–546 Hz, 20–1020 Hz, and 20–1504 Hz. Results in all cases indicate low sound speeds and densities with small uncertainties in the mud layer, increasing in a mud-sand transition layer and in the underlying sand. Results are similar for the three frequency bands with the exception of attenuation, which is estimated increasingly well for higher-frequency data. Inter-parameter relationships as a function of depth are also examined.

Keywords: *Geoacoustic inversion, trans-dimensional Bayesian inversion, New England Mud Patch.*

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1. INTRODUCTION

Knowledge of seabed geoacoustic parameters is required for acoustic propagation modelling and reverberation predictions, as well as for a variety of geotechnical, geophysical, and environmental applications. Geoacoustic inversion, whereby seabed model parameters are estimated from observed ocean acoustic data, represents an attractive alternative to direct sampling (e.g., coring) and has been an important field of research for several decades. In particular, geoacoustic inversion for fine-grained (muddy) sediments has been studied extensively in the Seabed Characterization Experiment (SBCEX), an international, multi-institutional, multi-year research program carried out on the New England Mud Patch (NEMP) test bed located off the northeast coast of the USA [1, 2]. Specific goals of the program include understanding the physical mechanisms that control acoustic propagation and assessing geoacoustic models, inversion methods, and uncertainty quantification for muddy seabeds. To this end, a variety of acoustic and non-acoustic data sets have been collected on the NEMP, including geoacoustic inversion surveys of various types [1, 2], high-resolution seismic-reflection surveys [3], core samples [4, 5], and *in-situ* probe measurements [4, 6].

This paper presents results of matched-field (MF) geoacoustic inversion on the NEMP. MF inversion consists of matching the spatial and frequency dependence of complex (frequency-domain) acoustic fields measured on an array of hydrophones. This paper considers acoustic fields recorded at the Shallow Water Acoustic Measurement Instrument (SWAMI) vertical line array (VLA). Inversion results for data sets with three different bandwidths are considered. A trans-dimensional (trans-D)

Bayesian formulation [7, 8] provides quantitative model selection and probabilistic inversion, yielding parameter estimates, uncertainties, and inter-relationships for generalized seabed- and error-model parameterizations.

2. DATA COLLECTION AND INVERSION

Data collection took place as part of the SBCEX 2017 on the NEMP and involved recording acoustic signals at the SWAMI VLA comprised of 14 hydrophones at 4.4 m spacing from 13.2–70.4 m depth. The signals were generated using a combustive sound source deployed at ∼10 m depth and 5.3 km range over a range-independent track with a mean water depth of 74.1 m and a sound-speed profile that varied from 1468 to 1469 m/s over the water column. A high-resolution seismic reflection survey carried out along the track [3] indicated a strong sub-bottom reflector identified as the interface between an upper mud layer and of an underlying sand layer. The composition of the mud and sand layers was determined from cores [4, 5] collected at thin-mud locations on the NEMP where coring penetrated to the sand layer. Cores also indicated a ∼1–2 m transition layer at the base of mud in which sand content increased with depth within the mud above the mud-sand interface.

The MF data inverted here were computed by fast Fourier transforming the acoustic-pressure time series recorded at each VLA hydrophone to obtain complex acoustic fields as a function of depth and frequency. Three data sets are considered involving 18 frequencies from 20–546 Hz, 41 frequencies from 20–1020 Hz, and 54 frequencies from 20–1504 Hz (data are equally spaced in frequency in each case). Since there are 28 data at each frequency (real and imaginary parts of the acoustic field at each of 14 hydrophones), these three data sets involve 504, 984, at 1512 data, respectively. Predicted acoustic pressure fields required for the inversion were calculated using a normal-mode propagation model (ORCA) that assumes a linear increase in attenuation with frequency (represented here in units of decibels per meter per kilohertz) and wave speeds that are independent of frequency.

Bayesian inversion is based on estimating the posterior probability density of the geoacoustic model parameters based on data and prior information. The data information is formulated in terms of a likelihood function, which requires specifying the data error model. The trans-D inversion formulated here [8] applies the reversible-jump Markov chain Monte Carlo (rjMcMC) algorithm to sample probabilistically over the number of layers in the seabed model and the corresponding interface depths and geoacoustic properties of these layers, as well as over the order and parameters of an autoregressive (AR) error model [9], assuming a complex Gaussian-distributed error process. In particular, the trans-D error model samples probabilistically over zeroth- and first-order AR processes to represent data errors as either uncorrelated or serially correlated over depth along the VLA, respectively. The standard deviations and first-order AR coefficients at each frequency are included as unknown error-model parameters in the inversion.

The inversions applied bounded uniform priors for the geoacoustic parameters consisting of $[1440, 2400]$ m/s for sound speed c, $[1.3, 2.4]$ g/cm^3 for density ρ, and $[0.001, 1]$ dB/m/kHz for attenuation α (parameterized logarithmically). A uniform prior over $[1, 20]$ was applied for the number of layer interfaces with interface depths constrained to $[0, 150]$ m (although the mud-sand structure to ∼14 m depth is of primary interest). Source range and depth and VLA tilt are also included as unknown parameters with small prior bounds to account for uncertainties in nominal values.

3. RESULTS

The geoacoustic inversion results are shown in Fig. 1 in terms of marginal probability profiles for sound speed, density, and attenuation to 14 m depth for each of the three data sets (probability profiles are normalized independently at each depth for display purposes). Similar sound-speed and density profiles are obtained for each data set, consisting of essentially five layers with generally well determined parameters. The overall structure is consistent with results from coring, seismic reflection, and other geoacoustic inversions. In particular, the sediment model in Fig. 1 consists of a low-speed/low-density layer to about 10.7 m depth (the mud layer), underlain by higher-speed/density material (sand). The mud has relatively constant properties over most of its extent but with increased sound speed and density over the bottom 2 m, representing the transition layer over which sand content increases with depth. Attenuation is relatively low except for notably higher values in the transition layer. The results agree well with trans-D inversions of wide-angle reflection-coefficient (RC) data [10] and modal-dispersion data [11] recorded near the SWAMI site (although dispersion data do not constrain attenuation). Further, the interface at ∼10.7 m depth agrees well with the mud-base seismic reflector depth also shown in the figure.

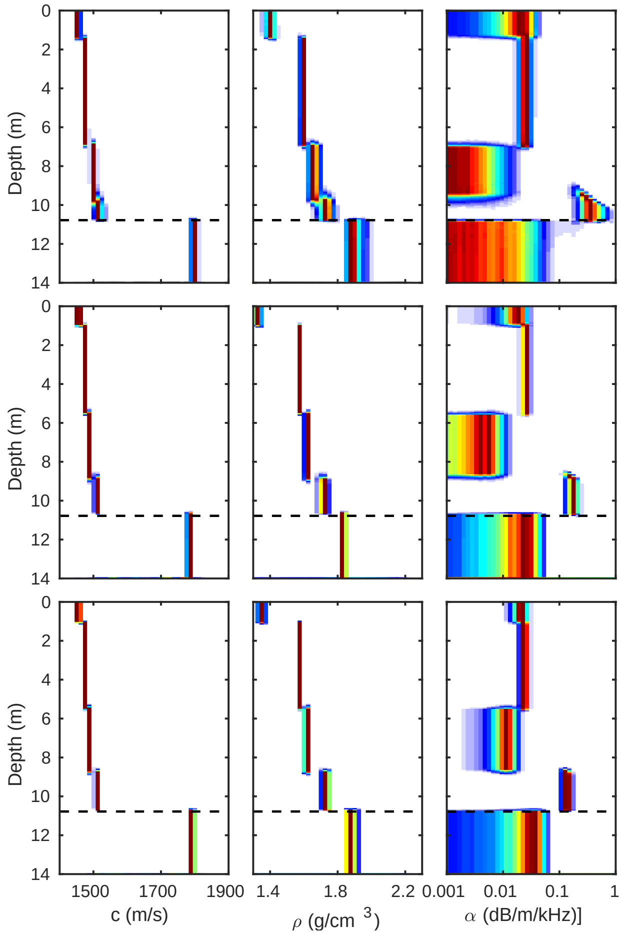

Figure 1. Marginal probability profiles for seabed sound speed c, density ρ, and attenuation α from MF inversions with bandwidths of 20–546 Hz, 20–1020 Hz, and 20–1504 Hz (panel rows top to bottom, respectively). Dashed lines indicate the mud-base seismic reflector depth.

While the sound-speed and density profiles are similar for all three data sets, Fig.1 shows that parameter uncertainties generally decrease with increasing frequency content. The largest differences between the three inversion results are for attenuation, with a substantial decrease in uncertainties with increasing frequency content. For the highest-frequency inversion, the attenuation profile is reasonably-well estimated at all depths, although the uncertainty increases significantly in the sand layer below $\sim$10.7 m depth. Further, there is general agreement between this attenuation profile and that estimated near the SWAMI site via trans-D inversion of RC data at 410–1242 Hz [10].

To more fully understand the geoacoustic inverse problem, it is also of interest to consider relationships between parameters in terms of joint marginal probability densities and correlation coefficients, as shown in Fig. 2 for five depths corresponding to the five sediment layers in Fig. 1 (results are shown for the 20–1504 Hz inversion, with similar results for other frequency bands). Space constraints preclude a full discussion here but as general observations, Fig. 2 shows significant correlations between c and ρ that alternate between positive and negative as a function of depth, and generally weak correlations between c and α and between ρ and α at all depths.

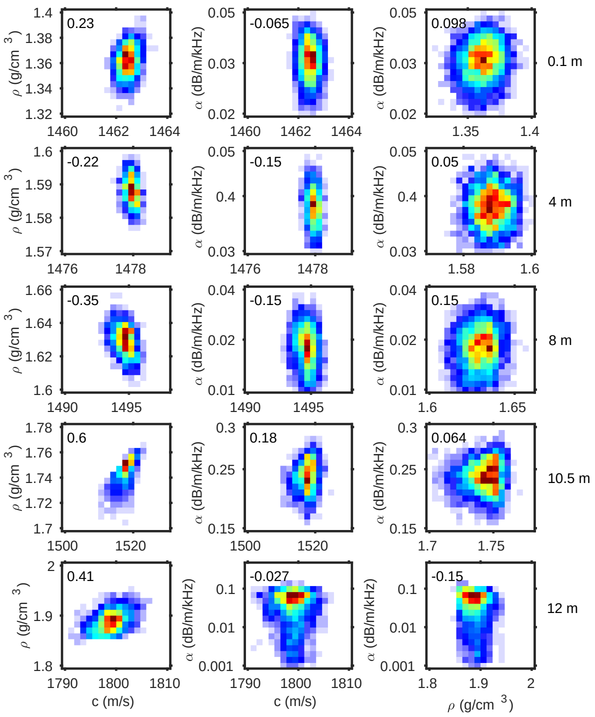

Figure 2. Joint marginal probability densities at five depths at indicated on right. Correlation coefficient values are given in the top left of each panel.

4. SUMMARY

This paper presented results of MF geoacoustic inversion at the NEMP, considering three data sets with increasing bandwidths. Trans-D Bayesian inversion was applied to estimate marginal probability profiles representing parameter uncertainties over depth. Results indicate an upper mud layer, including a mud-sand transition layer at its base, over sand, in agreement with other inversions, cores, and high-resolution seismics. Results are consistent between the three inversions, with a significant reduction in attenuation uncertainties for the widest bandwidth. Inter-parameter relationships are illustrated as joint marginal densities and correlation coefficients at various depths.

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