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TRANS-DIMENSIONAL BAYESIAN INVERSION FOR SEABED AND WATER-COLUMN MODELS

Stan E. Dosso
School of Earth and Ocean Sciences
University of Victoria
Victoria, British Columbia, Canada
sdosso@uvic.ca

Julien Bonnel
Applied Ocean Physics and Engineering Dept
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts, USA
jbonnel@whoi.edu

ABSTRACT

Geoacoustic inversion requires specification of the depth-dependent parameterization for the seabed model parameters. In cases where the water-column sound-speed profile (SSP) is of special interest or not sufficiently well-known, the SSP can also be parameterized and included in the inversion. For quantitative inversions, these parameterizations (seabed and water column) must be consistent with the resolving power (information content) of the acoustic data to be inverted. Trans-dimensional (trans-D) Bayesian inversion represents an automated approach to quantitative model selection, based on sampling probabilistically over various choices of parameterization. Here trans-D inversion is applied separately to seabed and water-column models. The trans-D seabed model is formulated as an unknown number of uniform layers, while the SSP is formulated as an unknown number of depth/sound-speed nodes. The Bayesian formulation allows different levels of prior information to be applied to the seabed and water column to represent different problems of interest; for example, either the seabed or the water column (or both) could be the primary goal of inversion. The joint trans-D inversion approach is illustrated here for the inversion of modal-dispersion data, considering data collected on the New England Mud Patch.

Keywords: *geoacoustic inversion, trans-dimensional inversion, water-column tomography, modal-dispersion data*

1. INTRODUCTION

Knowledge of geoacoustic properties of the seabed is required for modelling ocean acoustic propagation in a particular shallow-water environment [1]. Geoacoustic inversion is a common approach to estimating a model of the seabed by fitting observed ocean acoustic data. A Bayesian approach to geoacoustic inversion provides full uncertainty analysis in terms of the posterior probability density (PPD), representing the state of information of the seabed model given the observed data and independent prior information. To account for the fact that the seabed model parameterization (e.g., number of sediment layers) is itself generally not known, trans-dimensional (trans-D) Bayesian inversion has been applied, which samples probabilistically over the model parameterization as well as the corresponding model parameters [2–4].

Geoacoustic inversion generally requires knowledge of the water-column sound-speed profile (SSP), which can be measured with CTD (conductivity, temperature, depth) casts or thermistor chains at the acoustic experiment site. However, in some cases (e.g., rapid, mobile experimental configurations) this may not feasible. Further, spatial and/or temporal variations in water-column properties due to dynamic oceanographic conditions can result in undersampling the environment, even in cases where CTD or other measurements are made. Hence, this paper considers an approach to geoacoustic inversion that accounts for lack of knowledge of the water column by carrying out joint trans-D Bayesian inversion for both the water SSP and the seabed geoacoustic model. The approach is validated here by application to modal-dispersion data collected on the New England Much Patch (NEMP) [5].

2. DATA AND INVERSION ALGORITHM

The acoustic measurements considered here were carried in May, 2021, based on recording the acoustic signal from

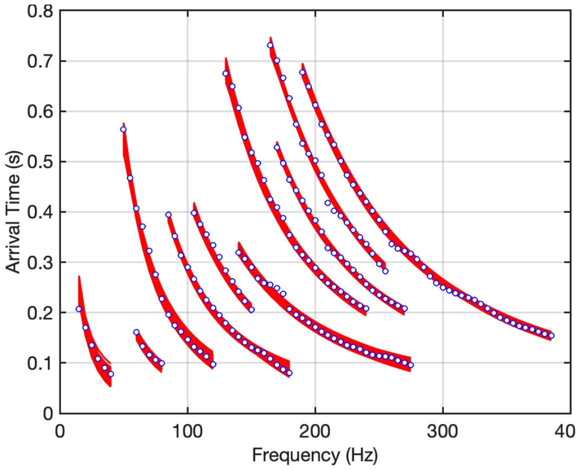

Figure 1. Observed modal-dispersion data from warping analysis (open circles) and predicted data from the Bayesian inversion (red distributions).

a rupture-induced underwater sound source (RUISS) [6] at 40 m depth at a TOSSIT receiver [7] located about about 7.2 km away along a range-independent propagation track with a water depth of ∼74 m. Warping time-frequency analysis [8] was applied to the recorded (deconvolved) waveform to extract dispersion measurements (arrival time as a function of frequency) for 10 of the first 11 modes (mode 7 was poorly detected), as shown in Fig. 1 (open circles). CTD casts were taken before and after the acoustic experiment to measure the SSP. The water column was stable at the scale of this experiment, and the average SSP is shown by the solid line in Fig. 2(b). In addition, high-resolution seismic-reflection survey of the NEMP carried out in 2015 [9] provided two-way travel-times to seabed reflectors that can be interpreted in terms of sub-bottom depth, given a model of seabed sound speeds. This knowledge about the seabed is not used by the trans-D inversion, but rather is used to evaluate the quality of the inversion results.

The Bayesian inversion algorithm is based on separate trans-D partition models for the water-column SSP and the seabed geoacoustic model. The SSP is a piecewise-continuous function parameterized in terms of an unknown number of depth/sound speed nodes, with a 1/(sound speed)^2 linear dependence between nodes, and node depths and sound speeds as unknown parameters (except for the depth of the sea surface node). The

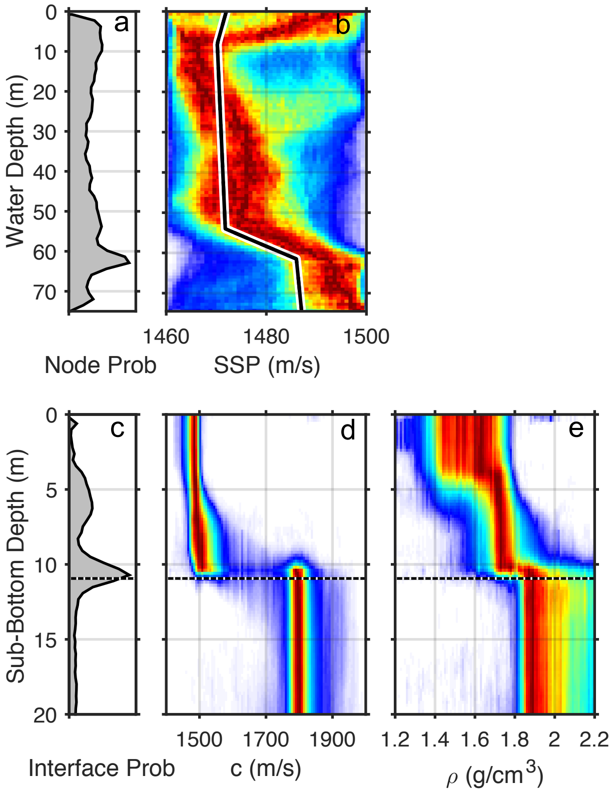

Figure 2. Marginal probability profiles from joint trans-D Bayesian inversion for (a) water-column node depths, (b) water-column sound speed, (c) seabed interface sub-bottom depths, (d) seabed sound speed, (e) seabed density. The solid line in (b) indicates the SSP measured at the NEMP (averaged over two CTD casts), and the dotted lines in (c)–(e) indicate the sub-bottom depth of the seismic reflector interpreted as the base of an upper mud layer above a layer of sand.

seabed is represented as an unknown number of uniform layers, with unknown interface sub-bottom depth, sound speed, and density for each layer, plus an underlying semi-infinite basement with unknown sound speed and density. The seafloor depth, source-receiver range, and source transmission time are also unknowns. A trans-D autoregressive (AR) error model [10] is applied that allows error correlations with frequency along a mode, with unknown AR coefficients and standard deviations for each mode.

The trans-D PPD for all of the above parameters is sampled using the birth/death reversible-jump Markov-chain Monte Carlo (rjMcMC) method [2–4].

3. RESULTS

Good agreement between the predicted data distributions from the joint trans-D inversion and the observed modal-dispersion data is shown in Fig. 1. The inversion results are shown in Fig. 2 in terms of marginal probability profiles for water-column and seabed properties. The SSP marginal profile is in reasonably good agreement with the measured SSP, except over the uppermost 5 m where the inversion results are highly uncertain. In particular, an increase in sound speed from about 50–60 m due to a warm-water intrusion at depth is recovered in the SSP model. The seabed geoacoustic results indicate a low-speed layer to about 11 m sub-bottom depth, consistent with the upper mud layer known to exist at the NEMP. The sub-bottom depth of this layer in the inversion results corresponds closely to that of a seismic reflector interpreted to represent the transition from mud to a sand layer [9]. The seabed profiles agree well with other geoacosutic inversion results (computed with known SSPs) at the NEMP, e.g., [5, 11, 12].

4. SUMMARY

This paper described and illustrated joint estimation of water-column sound-speed profile and seabed geoacoustic profiles, and their uncertainties, based on trans-dimensional Bayesian inversion of modal-dispersion data collected at the New England Mud Patch with a rapidly-deployable source/receiver system. The SSP is modelled as a piecewise continuous function based on an unknown number of depth/sound-speed nodes; the seabed is modelled as an unknown number of uniform layers, underlain by an unknown basement. Water-column inversion results are in generally good agreement with the SSP measured at the experiment site, and the seabed model agrees well with a seismic-reflection survey and with other geoacoustic inversion results at the NEMP computed with a known SSP.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] N. R. Chapman and E. C. Shang, "Review of geoacoustic inversion in underwater acoustics," *J. Theor. Comput. Acoust.*, vol. 29, pp. 1–66, September 2021.

[2] P. J. Green, "Reversible jump Markov chain Monte Carlo computation and Bayesian model," *Biometrika*, vol. 82, pp. 711–732, December 1995.

[3] J. Dettmer, S. E. Dosso, and C. Holland, "Trans-dimensional geoacoustic inversion," *J. Acoust. Soc. Am.*, vol. 128, pp. 3393–3405, December 2010.

[4] S. E. Dosso, J. Dettmer, G. Steininger, and C. W. Holland, "Efficient trans-dimensional Bayesian inversion for geoacoustic profile estimation," *Inverse Problems*, vol. 30, pp. 1–29, October 2014.

[5] J. Bonnel, A. R. McNeese, P. S. Silson, and S. E. Dosso, "Geoacoustic inversion using simple hand-deployable acoustic systems," *IEEE J. Oceanic Eng.*, pp. 1–12, 2023.

[6] A. R. McNeese, K. M. Lee, J. D. Sagers, M. J. Lee, and P. S. Wilson, "Experimental observations of a rupture induced underwater sound source," *J. Acoust. Soc. Am.*, vol. 148, pp. EL370–EL374, October 2020.

[7] D. Zitterbart, A. Bocconcelli, M. Ochs, and J. Bonnel, "TOSSIT: A low-cost, hand deployable, ropeless and acoustically silent mooring for underwater passive acoustic monitoring," *HardwareX*, vol. 11, April 2022.

[8] J. Bonnel, A. Thode, D. Wright, and N. R. Chapman, "Nonlinear time-warping made simple: A step-by-step tutorial on underwater acoustic modal separation with a single hydrophone," *J. Acoust. Soc. Am.*, vol. 147, pp. 1897–1926, March 2020.

[9] J. Goff, J. D. Chaytor, A. H. Reed, G. Gawarkiewicz, P. S. Wilson, and D. P. Knobles, "Stratigraphic analysis of a sediment pond within the New England Mud Patch: New constraints from high-resolution chirp acoustic reflection data," *Marine Geology*, vol. 412, pp. 81–94, June 2019.

[10] G. Steininger, J. Dettmer, S. E. Dosso, and C. W. Holland, "Trans-dimensional joint inversion of seabed scattering and reflection data," *J. Acoust. Soc. Am.*, vol. 133, pp. 1347–1357, March 2013.

[11] J. Belcourt, C. Holland, S. E. Dosso, J. Dettmer, and J. A. Goff, "Depth-dependent geoacoustic inferences with dispersion at the New England Mud Patch via reflection coefficient inversion," *IEEE J. Oceanic Eng.*, vol. 45, pp. 69–91, January 2020.

[12] S. E. Dosso and J. Bonnel, "Hybrid seabed parameterization to investigate geoacoustic gradients at the New England Mud Patch," *IEEE J. Oceanic Eng.*, pp. 620–634, July 2023.