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Automated geoacoustic inversion and uncertainty: Meso-scale seabed variability in shallow water environments

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LONG-TERM GOALS

Propagation and reverberation of acoustic fields in shallow water depend strongly on the spatial variability of seabed geoacoustic parameters, and lack of knowledge of seabed variability is often a limiting factor in acoustic modeling applications. However, direct sampling (e.g., coring) of vertical and lateral variability is expensive and laborious, and long-range inversion methods can fail to provide sufficient resolution. For proper quantitative examination of variability, parameter uncertainty must be quantified first which can be particularly challenging for large data sets, and in range-dependent and/or dispersive seabed environments. A long-term goal of this work is to substantially advance Bayesian inversion methodology to allow automated analysis of large and complex data sets. These advances will allow mesoscale spatial variability of seabed sediments to be quantified in two and three dimensions.

In addition, understanding acoustic dispersion in seabed sediments is of significant interest to the acoustical oceanography community. Obtaining meaningful inferences on low-frequency dispersion is a challenging inverse problem since estimates can strongly depend on the spatial structure (layering) of the sediment and multiple competing physical theories exist that can predict similar dispersion regimes. Further, direct sampling is currently not possible for low frequencies (hundreds of Hertz). Recent advances in Bayesian inversion (Dettmer et al. 2010, 2012a; Holland and Dettmer 2012) allow inferences on complex environments (arbitrary and unknown layering) and advanced physical theories (acoustics of dispersive media and spherical reflection coefficients). A long-term goal is to further understanding of such complex systems and develop a quantitative methodology for understanding and discrimination of physical dispersion theories.

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OBJECTIVES

The objective of this research proposal is to carry out geoacoustic inversions in 2D and 3D shallow-water environments. In particular, highly-informative data which reduce/eliminate oceanographic effects will be considered. The resulting geoacoustic models will represent benchmarks for meso-scale variability and uncertainty estimation, and also allow the study of compressional- and shear-wave dispersion and attenuation-frequency dependence. Bayesian hierarchical models and trans-dimensional (trans-D) inversions allow for increasingly automated data analysis in challenging shallow-water environments. The problems will initially be studied with existing data from a Mediterranean Sea test bed. Studies will then be extended to new data from upcoming shallow-water experiments, when available. Particular focus for new shallow-water data will be on rigorous variability and uncertainty estimation, attenuation-frequency dependence, sound-velocity dispersion, and shear-wave velocity structure of the seabed.

APPROACH

Quantifying parameter uncertainty in geoacoustic inversion is achieved here with probabilistic sampling methods (MacKay 2003). Probabilistic uncertainty estimation requires assigning a model which is defined here to include the physical theory describing signal-system interaction, an appropriate parametrization, and a statistical representation of residual errors (the difference between predictions and observations). This model specification constitutes prior information that fundamentally impacts uncertainty estimates. In particular, choosing a model parametrization that is consistent with the resolving power of the data and specifying a statistical description of residual errors are important inter-dependent components which are considered here.

Parametrization and discretization choices strongly influence how well predictions fit observations which can strongly impact uncertainty estimates. Hence, objective model selection is required to obtain meaningful uncertainty estimates. Here, trans-D inference is used to relax model specification from a single parametrization to groups of reasonable parametrizations. Such hierarchical Bayesian models require much less subjective input/choice and can be used for uncertainty estimation with advanced trans-D sampling algorithms (Dettmer et al. 2010).

A significant challenge in trans-D inversion is addressing dependence in residual errors that often arise due to intrinsically correlated noise and the limited ability of the model to capture the full extend of environment complexity for data with high information content. Bayesian inference requires that a statistical distribution form is assumed for residuals (e.g., Gaussian). However, the parameters of the distribution (variances and covariances) can be estimated as part of a hierarchical model (Dettmer et al. 2012b) which is particularly useful for trans-D algorithms. Hierarchical estimation of these parameters impacts uncertainties and can influence model selection when dependence is significant (Dettmer and Dosso 2012). In particular, covariance parameters can be estimated efficiently by modeling residual-error distributions as autoregressive processes.

Many trans-D algorithms are based on reversible jump Markov-chain Monte Carlo (rjMCMC) sampling (Green 1995), where jumps between sub-spaces are implemented using steps that create or delete structure (e.g., sediment layers). Designing efficient proposals for jump steps is extremely challenging, which results in rare acceptance (causing prohibitively-long convergence times). Population MCMC methods improve convergence rates for highly challenging non-linear problems with many posterior modes and strongly correlated parameters (Liu 2001), and have also been applied in rjMCMC resulting in much higher acceptance of jumps and improved chain mixing within dimensions (Jasra et al. 2007; Dettmer and Dosso 2012). Population rjMCMC is developed and applied for geoacoustic inverse problems in this project, providing the ability to carry out uncertainty estimation for highly complex geoacoustic inference problems.

WORK COMPLETED

In the first year of this project, work has focused on advancing trans-D sampling algorithms to study complex geoacoustic inference problems, and in particular dispersive sediments (Holland and Dettmer 2012; Dettmer et al. 2012a). The new algorithms have been applied to successfully study acoustic dispersion and attenuation-frequency dependence at three experiment sites on the Malta Plateau. In addition, plane- and spherical-wave reflection-coefficient models were implemented on graphics processing units (GPU) using the compute unified device architecture. The GPU implementation resulted in an over 100-fold speed up for the plane-wave model and over 200-fold speed up for the spherical-wave model. Further, the rjMCMC algorithm was implemented for matched-field inversion (Dettmer and Dosso 2012). Our 170 core high performance compute cluster has been extensively used to support this research. The cluster is jointly funded by ONR and the Natural Sciences and Engineering Research Council (NSERC) of Canada. Several of the inversion algorithms for this project have been developed to take full advantage of the massively parallel architecture of the cluster. In addition, 3 low-cost GPUs were added to the compute abilities that, together with new GPU algorithms, result in a substantial increase of computational power.

RESULTS

Results presented in this section focus on some of the research carried out this year to develop a new approach to studying acoustic dispersion in seabed sediments and a new approach to matched-field inversion. A complete account is presented in Holland and Dettmer (2012), Dettmer et al. (2012a), and Dettmer and Dosso (2012).

Trans-D inversion is applied to data from *in-situ* sediments on the Malta Plateau (Site 2, see Fig. 1) to study dispersion and attenuation-frequency dependence. Reflection measurements were carried out during the SCARAB98 experiment in 153 m water depth. The reflection measurements were processed to yield reflection-coefficient data as a function of frequency and angle for the uppermost 4 m of sediment. Reflection-coefficient predictions were carried out using Buckingham's viscous grain shearing (VGS) theory (Buckingham 2007), which obeys causality and predicts velocity-dispersion and attenuation-frequency curves.

Figure 2 shows marginal profile distributions of four VGS parameters that were sampled as a function of depth. These marginal distributions are derived from the posterior density which constitutes the solution to the probabilistic inverse problem. This section shows several results that are obtained from the posterior by marginalizing in various ways. Several other parameters of VGS theory were fixed at measured *in-situ* values (obtained from a CTD cast) in the inversion. Figure 2 shows that porosity is the most sensitive parameter, while strain hardening is the least sensitive. The time constant τ governs transition between viscous and frictional losses. Viscous losses dominate for small τ values, resulting in attenuation-frequency dependence proportional to f^2 at low frequencies and proportional to $f^{1/2}$ at higher frequencies. For large values ($\tau \gtrsim \exp(-5)$) friction dominates and attenuation-frequency

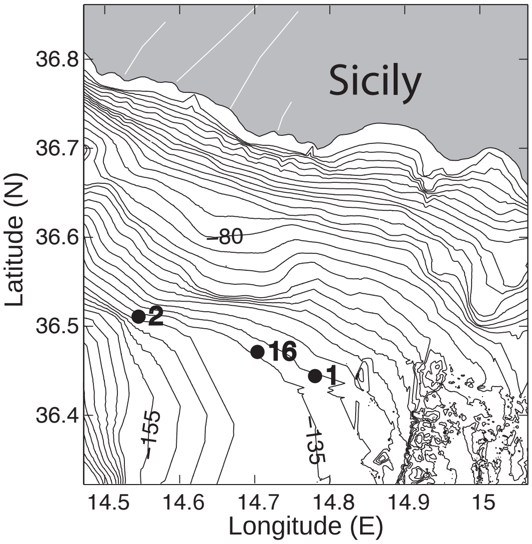

Figure 1: Site locations on the Malta Plateau for dispersion studies.

dependence is proportional to f^1: Dispersion curves are essentially independent of τ. Hence, Fig. 2 shows the significant result that the inversion is able to discriminate between two dispersion regimes. To 2.7-m depth friction losses dominate, while viscous losses dominate below that depth.

Figure 3 shows the inversion results in terms of geoacoustic parameters which are derived from the VGS parameters. Note that VGS theory provides velocity and attenuation as a function of frequency, and results for 1400 Hz are shown. The inversion results agree very closely with estimates from independent cores taken at the experiment site. Figure 3 also shows profile marginals for shear velocity and attenuation. However, these parameters were not included in the reflection-coefficient predictions but are shown here to illustrate the values predicted by VGS theory. Posterior inferences can also be obtained for dispersion curves which are shown for selected depths in Fig. 4.

Inversions were also carried out for two other locations (Sites 1 and 16, see Fig. 1) and the results are shown in Figs. 5–8. Note the very close agreement between inversion and core estimates. In addition, Figs. 5 and 7 show velocity-marginal profiles extrapolated to 200 kHz (the frequency of velocity measurements on the core), which agree closely with the core estimates.

In addition to the work on reflection-coefficient inversions, a rigorous inversion approach was developed for matched-field inversion. In particular, the impact of correlated residual errors on trans-D inversion and on transmission-loss predictions was studied using the PROSIM’97 data set (Dettmer and Dosso 2012). Figure 9 shows inversion results for an inversion accounting for residual-error dependence using an autoregressive model, as well as results for an inversion that ignores residual-error dependence. Here, ignoring dependence leads to excessive model complexity which significantly impacts transmission-loss prediction uncertainty and bias (Fig. 10).

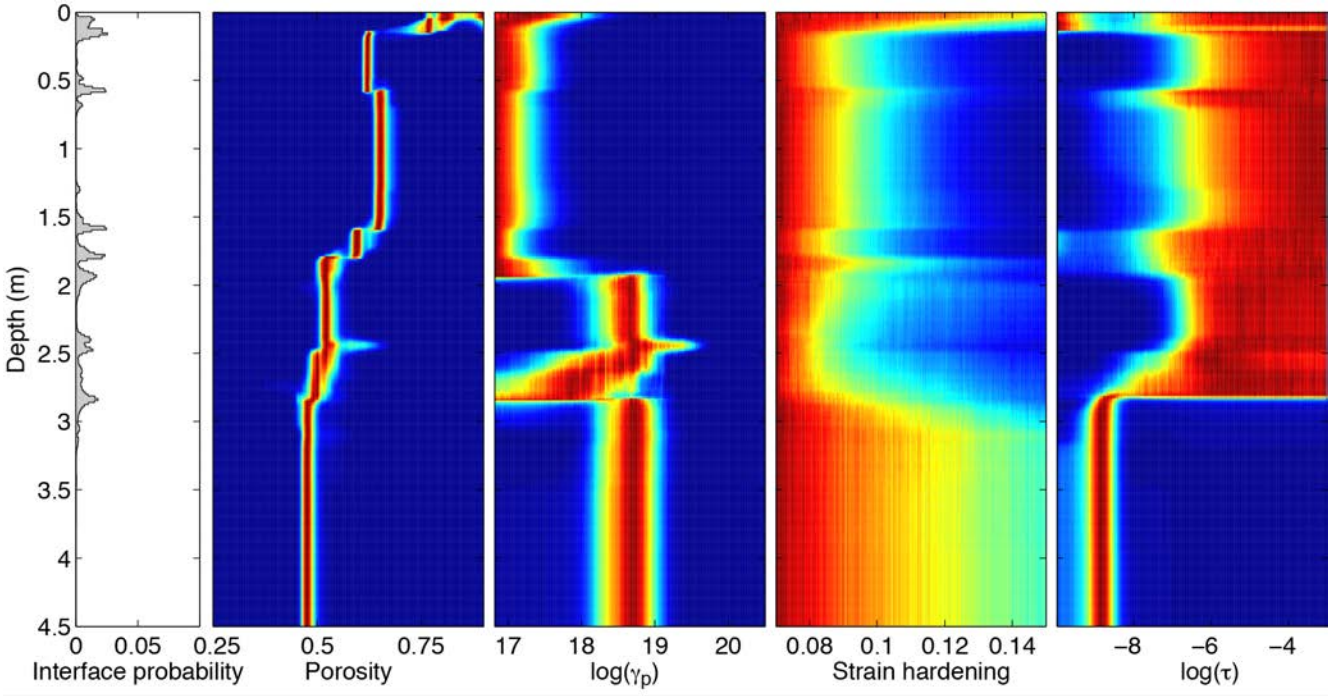

Figure 2: Site 2 marginal profile distributions of VGS parameters and interface probability.

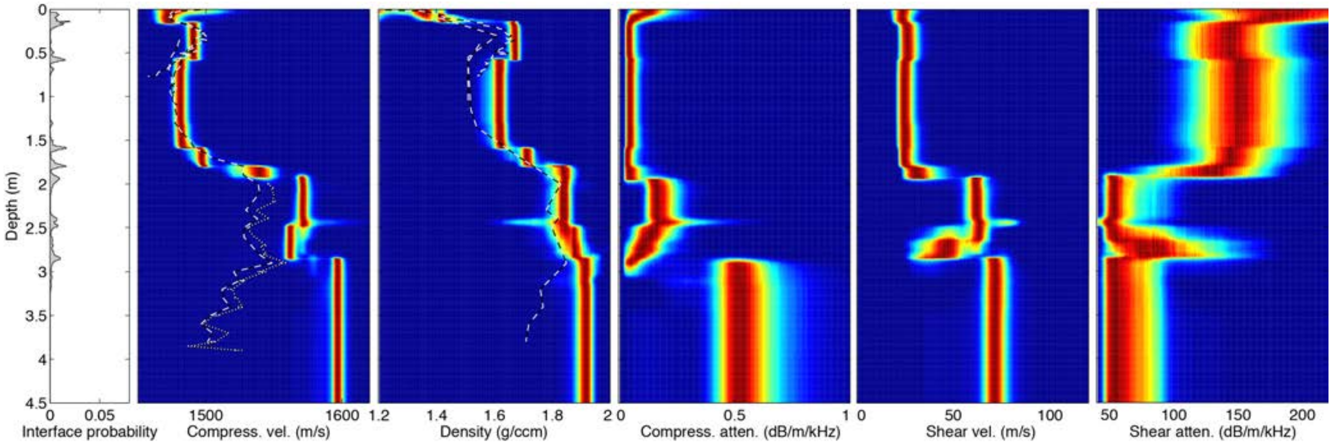

Figure 3: Marginal profile distributions for geoacoustic parameters, derived from the VGS parameters in Fig. 2. Estimates from independent core samples are shown as dashed lines.

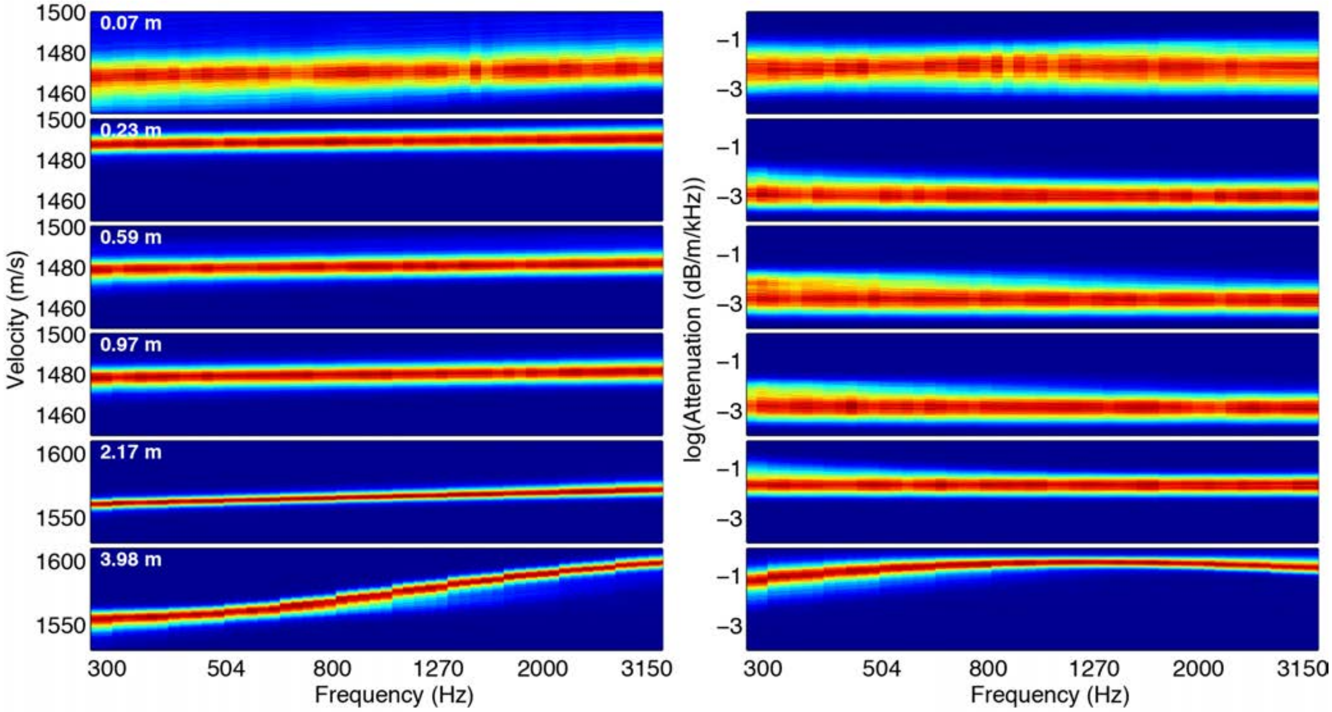

Figure 4: Velocity-dispersion and attenuation-frequency curves for select depths (Site 2).

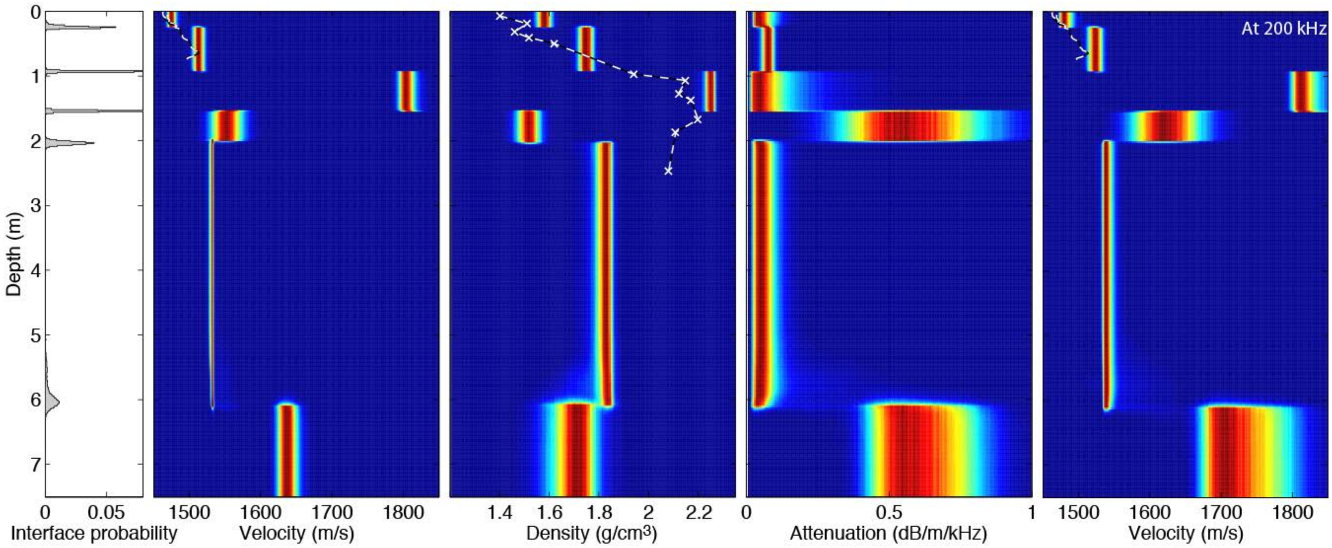

Figure 5: Marginal profile distributions for geoacoustic parameters, derived from VGS parameters (Site 1). Estimates from independent core samples are shown as dashed lines.

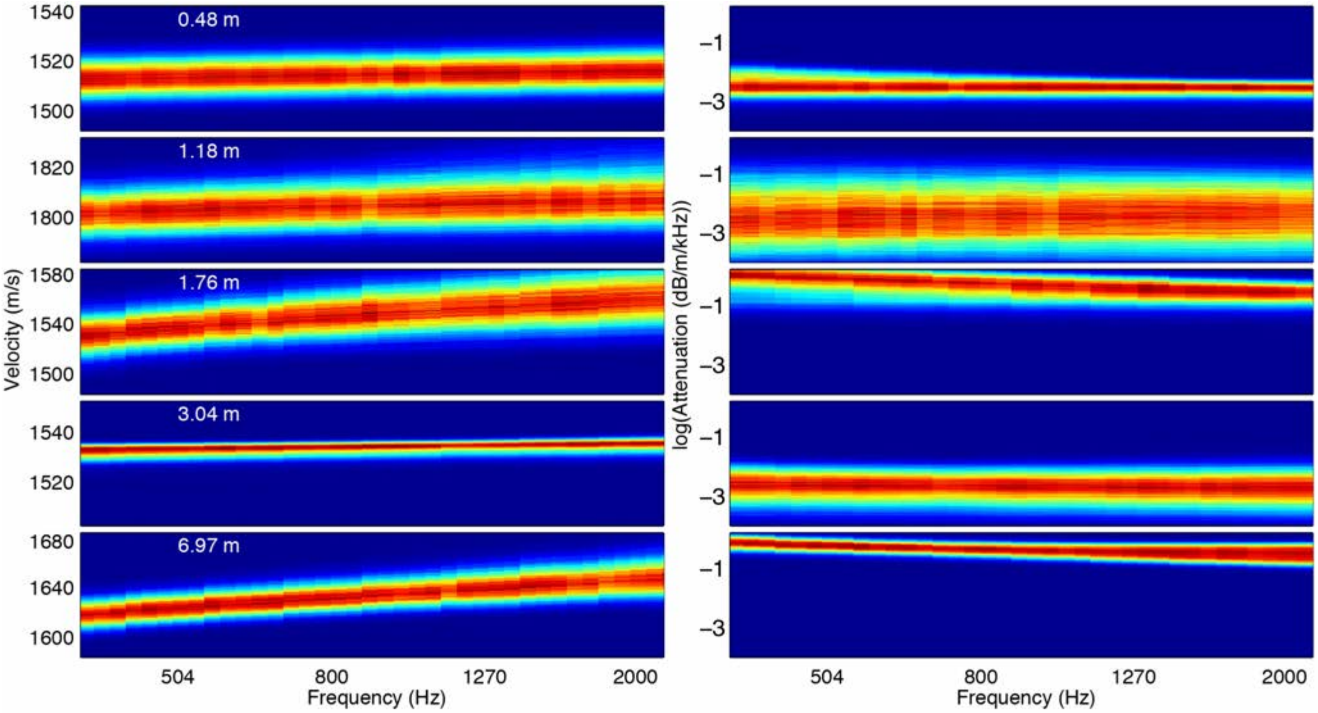

Figure 6: Velocity-dispersion and attenuation-frequency curves for select depths (Site 1).

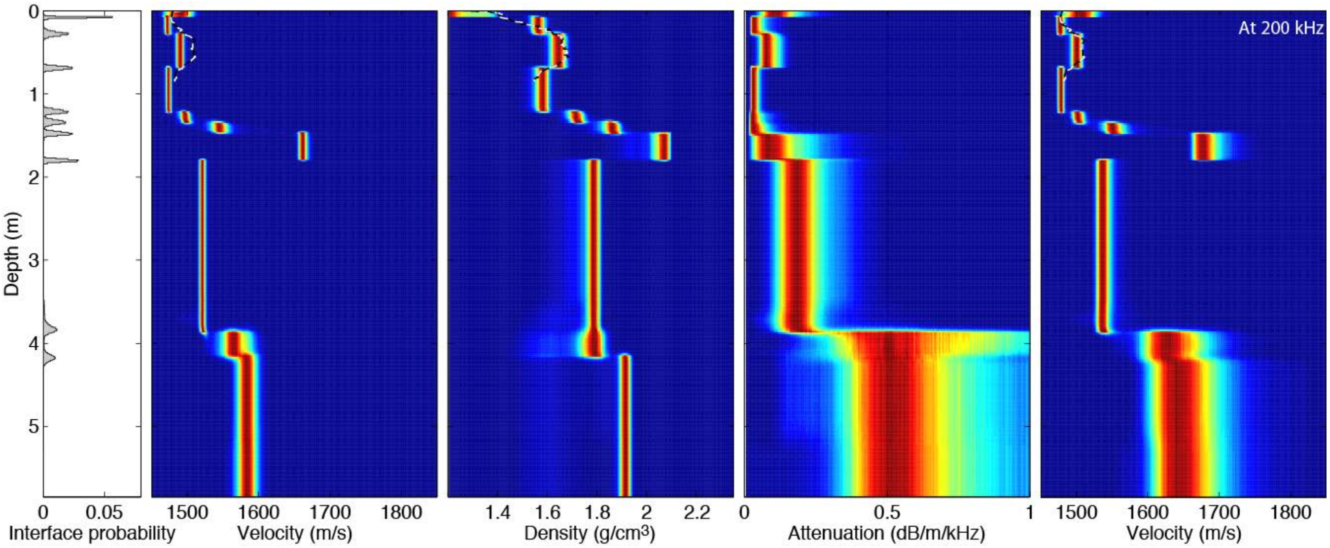

Figure 7: Marginal profile distributions for geoacoustic parameters, derived from VGS parameters (Site 16). Estimates from independent core samples are shown as dashed lines.

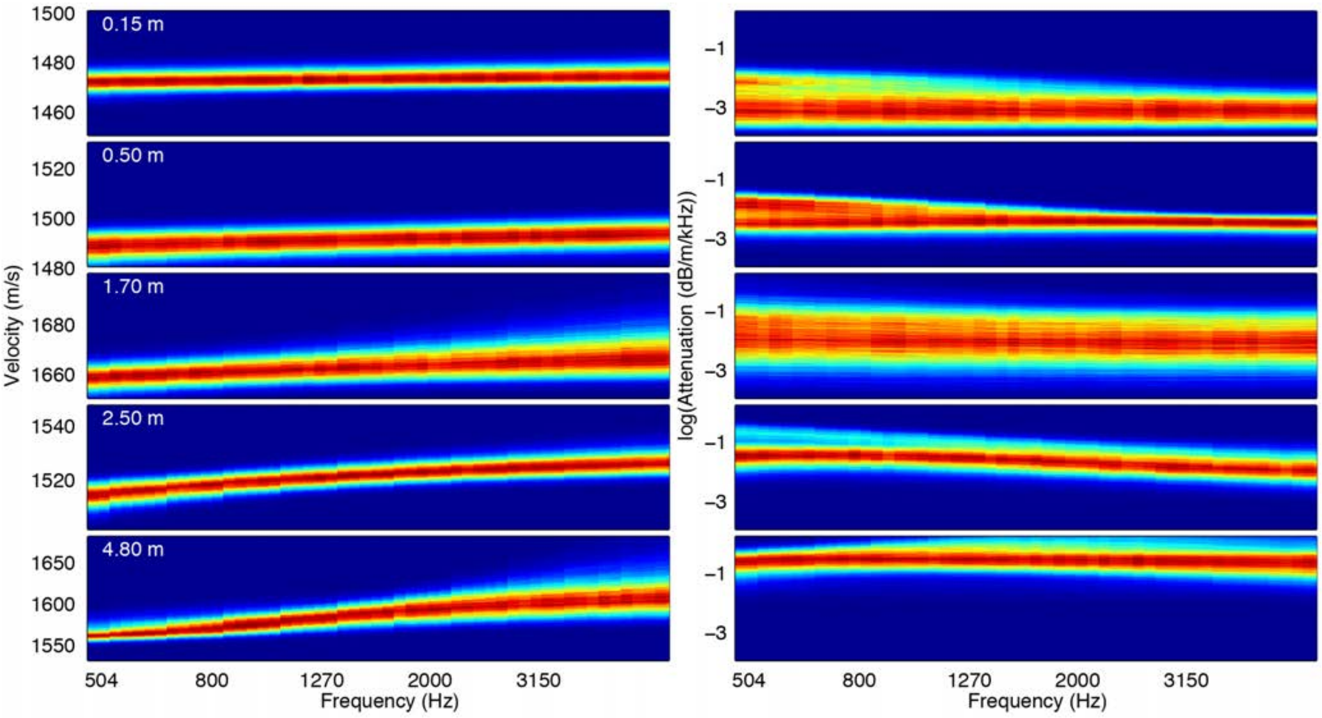

Figure 8: Velocity-dispersion and attenuation-frequency curves for select depths (Site 16).

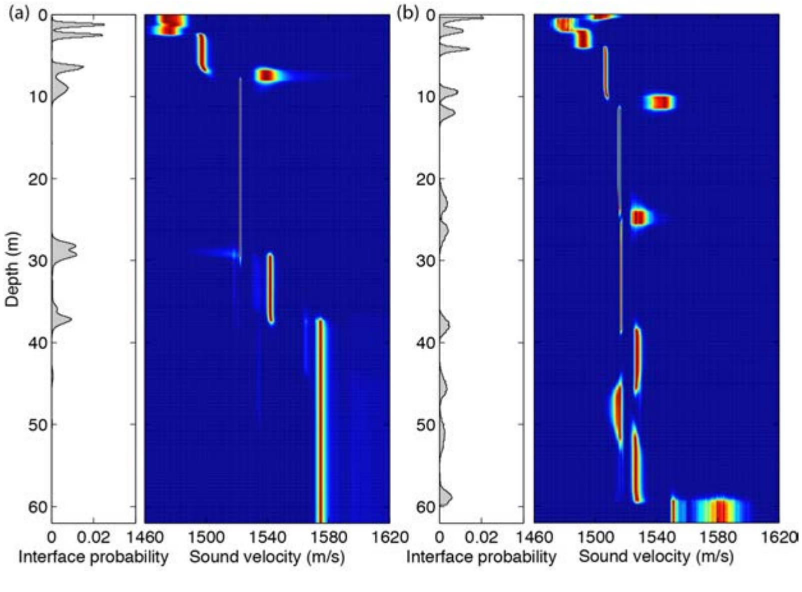

Figure 9: Comparison of trans-D MFI inversion results (a) accounting for correlated errors and (b) ignoring correlated errors.

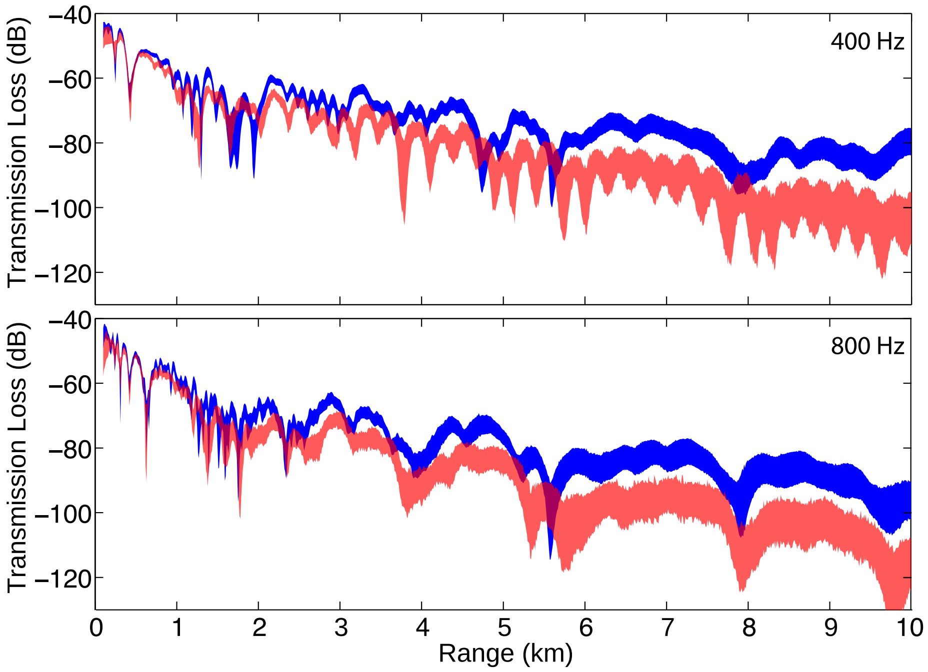

Figure** 10: **Transmission-loss prediction uncertainty at 400 and 800 Hz for inversions ignoring (red) and accounting for (blue) residual-error dependence.

IMPACT/APPLICATIONS

The ability to obtain *in-situ* seabed parameter estimates remotely (i.e., without direct sampling) has important geoscience implications (e.g., understanding sediment processes) and in some cases can be the only feasible way of obtaining such inferences (e.g., low-frequency dispersion). Further, variability estimates for seabed parameters are important for understanding the physics of acoustic-seabed interaction. Since variability can only be estimated if uncertainties are understood, uncertainty estimation is crucial. Important applications also include improved Navy databases (for ASW and MCM), as well as many commercial applications (pipeline or cable laying). A particular strength of this work is rigorous geoacoustic uncertainty estimation. These geoacoustic uncertainty models impact reliability and quality of transmission loss prediction.

RELATED PROJECTS

- Broadband Clutter JRP project (NURC, ARL-PSU, DRDC-A, NRL)
- Dosso's NSERC Discovery Grant "Geoacoustic Inversion" (2009-2014) at the University of Victoria: Dosso and Dettmer work closely together on advancing Bayesian inference applications.
- "Bayesian ambient noise inversion for geoacoustic uncertainty estimation" (2011–2012, Jorge Quijano ONR Postdoctoral Fellowship N000141110214) (Quijano et al. 2012ab): Quijano uses and further develops several algorithms that originated from Dettmer's work.
- "Bayesian inversion of seabed scattering data" (2011–2013, Gavin Steininger ONR PhD

Fellowship N00014110213): Steininger uses and furthers several algorithms that originated from Dettmer's work. Dettmer is on Steininger PhD supervisory committee.

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PUBLICATIONS

J. Dettmer, C. W. Holland, and S. E. Dosso. Trans-dimensional uncertainty estimation for dispersive seabed sediments. *Geophysics*, 2012 [submitted, refereed].

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