

FINAL REPORT

Quantitative Sediment Mapping: Surveys of Geoacoustic Properties Affecting Munitions Burial, Mobility and Detection

SERDP Project MR-2502

MARCH 2018

Charles W. Holland
Sheri Martinelli
The Pennsylvania State University, Applied Research Lab

Jan Dettmer
Stan E. Dosso
Eric Mandolesi
University of Victoria, School of Earth and Ocean Sciences

Distribution Statement A

This document has been cleared for public release



Page Intentionally Left Blank

This report was prepared under contract to the Department of Defense Strategic Environmental Research and Development Program (SERDP). The publication of this report does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official policy or position of the Department of Defense. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Department of Defense.

Page Intentionally Left Blank

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 01-03-2018		2. REPORT TYPE SERDP Final Report		3. DATES COVERED (From - To) 07/2015 - 05/2018	
4. TITLE AND SUBTITLE Quantitative Sediment Mapping: Surveys of Geoacoustic Properties Affecting Munitions Burial, Mobility and Detection				5a. CONTRACT NUMBER W912HQ-15-C-0063	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Charles W. Holland, Jan Dettmer, Stan E. Dosso, Eric Mandolesi, Sheri Martinelli				5d. PROJECT NUMBER MR-2502	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The Pennsylvania State University, Applied Research Lab, State College, PA University of Victoria, School of Earth and Ocean Sciences, Victoria, BC				8. PERFORMING ORGANIZATION REPORT NUMBER MR-2502	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) 4800 Mark Center Drive, Suite 17D03 Alexandria, VA				10. SPONSOR/MONITOR'S ACRONYM(S) SERDP	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) MR-2502	
12. DISTRIBUTION / AVAILABILITY STATEMENT DISTRIBUTION A. Approved for public release: distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The project objective was to measure sediment properties and their uncertainties that affect munitions mobility, burial, and detectability in underwater environments. Building on a prior work, significant advances were made including theoretical and computational aspects of sequential Bayesian inversion. Sequential algorithms quantify the information content of consecutive data sets by considering results from previous data sets along a survey track to inform the importance sampling at the current point. Therefore, efficient transition between data sets is of paramount importance. The most significant new theoretical advance is a novel particle filter that bridges between consecutive data sets via trans-dimensional parallel tempering. The success of this implementation is significant since it generalized the particle filter to a unified trans-dimensional algorithm. The anticipated benefits of this research are expected to go beyond the specific application in this project (water depths less than 35 m, the upper few meters of sediment) and could be used in many applications where quantitative seabed properties are needed. Depending on the frequencies and measurement geometry, the measurement and processing techniques could be exploited to obtain high-resolution geoacoustic properties in arbitrary water depths and to tens of hundreds of meters in the seabed.					
15. SUBJECT TERMS sediment geoacoustic properties, acoustic reflection, uncertainty quantification, Bayesian inference					
16. SECURITY CLASSIFICATION OF: U			17. LIMITATION OF ABSTRACT UNCLASS	18. NUMBER OF PAGES 54	19a. NAME OF RESPONSIBLE PERSON Dr Charles Holland
a. REPORT UNCLASS	b. ABSTRACT UNCLASS	c. THIS PAGE UNCLASS			19b. TELEPHONE NUMBER (include area code) 814 865-1724

Page Intentionally Left Blank

Table of Contents

Abstract	1
I. Objective.....	3
II. Background	3
A. The environmental issue	3
B. Summary of past research.....	4
C. Advances required for the munitions problem.....	5
III. Materials and Methods.....	6
A. Measurement quantity and forward model	6
B. Uncertainty Quantification: Bayesian Inference for Geoacoustic Remote-sensing Surveys	7
IV. Results and Discussion	8
A. Bayesian Inference	8
1. Progress	8
2. Test of Bayesian inference advances using synthetic data.....	11
3. Test of Bayesian inference advances using measured data	18
B. Prototype GeoSS high level design	27
1. Source	30
2. Receiver	33
3. Towing platform.....	37
4. Data acquisition system.....	37
5. Summary p-GeoSS design comments	38
V. Conclusions and Implications for Future Research/Implementation.....	38
VI. References.....	40
Appendix A. Supporting Data.....	44
Appendix B. List of Scientific/Technical Publications.....	44
Appendix C. Other supporting Material	44

List of Tables

Table 1. Comparison of computational domain from 2011 to 2016	18
Table 2. Comparison of performance gains from 2011 to 2016	18
Table 3. Comparison of computer costs	18

List of Figures

Figure 1. Schematic of the PT particle filter implementation for a progression from data set $t-1$ to t . All steps of the algorithm are trans-D. As new data are introduced, many particles exhibit poor fits and must migrate to higher-likelihood regions of the new posterior. To facilitate this migration, some particles are re-sampled onto a tempered distribution to move more freely around parameter space. Finally, all particles are re-sampled to the target distribution of $L^{1/1}$	11
Figure 2. Simulated seabed environment along a 7 km track. Broadband spherical reflection coefficients at multiple angles (from 28-68 °) are generated from this environment for each of 170 pings.	13
Figure 3. Histogram of algorithm timing, i.e. computation time per ping. Note that a small number of pings require a large fraction of the total computer time. This suggests that additional efficiency improvements are possible. The total computation time T is also shown.	13
Figure 4. Simulated data for pings 45 and 56 (black x) and predicted data (red lines) sets for a large random subset of models from the Bayesian inversion. The predicted data capture the interference pattern of the simulated reflection coefficients well and quickly adjust to the rapid change in reflection coefficient values caused by the fault between these ping locations.	14
Figure 5. Geoacoustic uncertainty estimates for pings 45 (top) and 46 (bottom). Depth is relative to the seafloor and the true model is given by the dashed lines. The top left panel for each ping shows the velocity estimate for the complete track and the position of this particular ping along the track (dashed). The bottom rows of panels for each ping illustrate the data fit for 3 representative frequency bands (out of 6). The top right panel for each ping shows the true (dashed) and estimated seabed complexity (histogram). These uncertainty estimates are available for all data sets along a survey track. The results for ping 45 are typical, those for ping 46 are among the worst along the track, i.e., are furthest from the true values.	16
Figure 6. Comparison of true and Inversion results in terms of posterior median models along the track consisting of 170 data sets. The velocity density and attenuation results (rows 1,3,5) are compared with the actual properties used in the simulation (in rows 2,4,6).	17
Figure 7. Location of 14 km seabed reflection track on the Malta Plateau in the Straits of Sicily.	19
Figure 8. Cartoon of source and receiver geometry for the seabed reflection experiment.	20
Figure 9. Data fits for two stacks: a) number 10 and b) number 3148.	22
Figure 10. Posterior mean geoacoustic results for the 14 km track	23
Figure 11. Geoacoustic uncertainties for the results in Figure 10 quantified as 95% credibility interval widths.	24
Figure 12. Comparison of estimated geoacoustic properties with core data estimates.	25
Figure 13. Comparison of layering structure (from the reflection data in the frequency-angle domain) with time domain normal incidence seismic profiling data along nearly the same track.	26
Figure 14. Comparison of layering structure (from the reflection data in the frequency-angle domain) with time domain normal incidence seismic profiling data nearly along the same track.	26

Figure 15. Simulation of experiment data, i.e., using the same experiment geometry, with estimated roughness values from laser line scanner data, Table 4, for various realizations (columns) and values of spectral cut-off, L (rows). The source plus receiver height above the boundary is 17 m.	28
Figure 16. The in-plane Fresnel zone radius for the experimental geometry employed in the reflection measurements. The source plus receiver height above the boundary is 17 m.	28
Figure 17. From left to right: photograph of Uniboomer source mounted on a catamaran, example of source pulse measured on axis at sea, and the resulting spectrum.....	32
Figure 18. Reflection coefficient, $ R_s $, for two layers 0.3 m and 0.7 m over a halfspace. The information content is in both the pattern (evolution of constant R_s over frequency-angle space) and in the amplitude oscillations from the peaks to troughs.	34
Figure 19. Seabed reflection angles (left panel), and phone-to-phone angle resolution (right panel) for a water depth of 10 m and evenly spaced hydrophones. Note that the difference in angles from phone to phone is about 4 times smaller at lower angles than at normal incidence. This provides a better sampling of the information content in the angular domain.	35
Figure 20. travel time differences between the direct and bottom reflected (solid line) and the bottom reflected and sea surface reflected (dash dot line) for a water depth of 10 m. The source depth is 0.3 m and results for two receiver depths are shown, 4 m (blue) and 6 m (red).	36
Figure 21. Tetrahedral hydro-phone (yellow) positions and roll sensor (green).	36
Figure 22. prototype GeoSS receiver array layout, with 48 tetrahedral elements. Each tetrahedral element (indicated by x) is comprised of 4 hydrophones. There are 36 elements spaced at 1 m, and a nested array at 0.25 m spacing at the front of the array.....	37

List of Acronyms

AIS: annealed importance sampling
BIC: Bayesian information criterion
CPU: central processing unit
CUDA: Compute Unified Device Architecture
GeoSS: Geoacoustic Sediment Survey system: the long-term goal or product of the project
GPU: graphics processing unit
PPD: posterior probability density
p-GeoSS: prototype Geoacoustic Sediment Survey system
PT: parallel tempering
rjMCMC: reversible jump Markov-chain Monte Carlo
SMC: sequential Monte Carlo
trans-D: trans-dimensional

Keywords: sediment geoacoustic properties, acoustic reflection, uncertainty quantification, Bayesian inference

Acknowledgements:

We gratefully acknowledge the funding support of the Strategic Environmental Research and Development Program (SERDP).

Abstract

Objective

The objective of this project is to measure sediment properties and their uncertainties that affect munitions mobility, burial, and detectability in marine, estuarine, lacustrine and riverine environments. The long-term goal is to develop a rigorous geoacoustic sediment survey (GeoSS) method which would be carried out before a detection survey. The short-term goal of this project is to extend/ modify our existing sediment measurement, processing, and inversion techniques to treat survey data in the shallow-water environments relevant to munitions detection.

Technical Approach

We have previously demonstrated the ability to accurately infer complex sediment structures that occur in marine environments using acoustic sediment reflection data. The vast majority of our results to date are at single locations on the mid- to outer-shelf (80–180 m water depth). For munitions applications, however, the data analysis/inversion procedures and system design must be modified to consider large sequential data sets collected in very shallow water (less than 35 m). Thus, two major extensions are required to apply our acoustic remote-sensing approach to sediment assessment for underwater munitions detection: (1) address the theoretical and computational demands of sequential Bayesian inversion for many data sets along a survey track, and (2) design a prototype geoacoustic sediment survey system for the shallow water depths of interest.

Results

We significantly improved several theoretical and computational aspects of sequential Bayesian inversion. Sequential algorithms, or particle filters, quantify the information content of consecutive data sets by considering results from previous data sets along a survey track to inform the importance sampling at the current point. Therefore, efficient transition between data sets is of paramount importance. The most significant new theoretical advance under this project is a novel particle filter that bridges between consecutive data sets via trans-dimensional parallel tempering. The success of this implementation is significant since it upgraded the particle filter to a unified trans-dimensional algorithm. In addition, the approach is intrinsically parallel which leads to efficient use of our new computer hardware; in particular, the new algorithm leads to full occupancy of high-performance graphics processing units (GPUs). Finally, a more informative prior for seabed complexity was introduced based on even numbered order statistics and a Poisson distribution. This prior prefers simple stratifications and avoids spurious layers that previously occurred due to data noise.

The new advanced sequential Monte Carlo algorithm was tested against simulated reflection data along a track. The advantage of using simulated data is that the seabed properties are completely known and thus performance of the algorithm can be quantified. The noise imposed on the simulated data as well as the source-receiver geometry were similar to measured data. The seabed environment was purposefully designed with challenging geologic features, including: change in geoacoustic properties within a layer along the track, change in the number of layers, an erosional channel, and two abrupt changes simulating a geological fault. These were designed to test the limits of the algorithm and in some cases exceed it. For example, we include a layer that pinches out gradually which has a thickness less than the reflection system is able to resolve

over a section of the track. In summary, the algorithm performed very well. The inversion was not able to resolve pinch-out near its apex, but the inversion was reasonably stable. The worst results were near the fault boundary where the inversion of several pings produced a poor representation of the true seabed. However, within three pings, the algorithm recovered to produce high-accuracy estimates of the seabed. Also, the reductions in runtime exceeded the Go/NoGo criteria by 50%, achieving 1500 data sets/week.

The new advanced sequential Monte Carlo algorithm was also applied to a measured data set. The importance of the application to measured data is that despite the care taken to make the simulation challenging, the physics used to generate the simulated data are the same as used in the inversion. That the physics/assumptions made in the inversion process are adequate for field surveys can only be tested with measured data. We have made numerous such tests to date using single site data, but this is the first time we have used sequential data along a long (14 km) survey track. In summary, only 13% of the track could not be inverted due to physics limitations. The results showed an unprecedented degree of geoacoustic detail and quantified spatial variability along the track in both vertical and horizontal directions. We mapped a low-velocity, low-density sediment wedge (in which a munition would likely bury) 1 m thick near the beginning of the track thinning out to about 0.1 m at the end of the track. Underneath the wedge we mapped a more competent layer which likely would have resisted burial. We were also able to map a high velocity, high density sub-bottom erosional layer as it changed depth across the area. Our quantitative mapping results were compared with two kinds of independent data: cores and seismic imaging. We had core measurements of velocity (at 400 kHz) and density at the start and end of the track, which showed generally close agreement. The greatest differences were in velocity where the core data are known to be biased by multiple scattering (due to the high frequencies used and the presence of shell material in the core of order or larger than the wavelength). The quantitative mapping results were also compared with independent seismic data for layer positions. The layer structure from the inversion (inferred from the frequency domain reflection coefficient) compared well with the time domain seismic data.

A fundamental aspect of our approach is the requirement of considerable care in the design and execution of the measurements. The information content for quantitative sediment properties in wide-angle reflection data is extremely high; however, exploiting this information content requires achieving small measurement uncertainties in angle and amplitude. To achieve these small uncertainties for support of munitions detection/classification requires a system adapted to very shallow water depths (less than 35 m). We developed a high-level system design for a prototype geoacoustic sediment system for the SERDP munitions mission, that features a surface-towed 0.2-10 kHz source and a 35 m towed receiver array with some of the array populated by tetrahedral elements.

Benefits

Fundamental physics and empirical observations indicate that the nature of the sediment structure plays an important role in the ability to detect/classify proud or buried munitions. Thus, foreknowledge of the sediment structure can substantively improve munitions detection and classification. The anticipated benefits of this research are aimed at providing that foreknowledge.

Our success in obtaining accurate sequential inversions of geoacoustic properties in a complex sedimentary environment along a survey track sets the stage for testing the inversion with data sets collected in water depths less than 35 m. The development of high-level specifications for a prototype geoacoustic sediment system is a key step for construction and testing of such a system. The successful development testing and validation of a robust sequential inversion algorithm opens the door to analyzing survey data from that system.

In addition to SERDP-specific benefits, the progress made in sequential Bayesian inversion and experiment design can be used in other applications including scientific and applied problems, e.g., geohazard surveys.

I. Objective

The objective is to measure sediment properties and their uncertainties that affect munitions mobility, burial, and detectability in marine, estuarine, lacustrine and riverine environments. The long-term goal is to develop a rigorous geoacoustic sediment survey (GeoSS) method which would be carried out before a detection survey. The short-term goal of this project is to extend/modify our existing sediment measurement, processing, and inversion techniques to address the water depths and survey needs of the munitions detection/classification problem.

II. Background

A. The environmental issue

The SERDP Statement of Need is to develop technologies to detect, classify, and remediate military munitions found at underwater sites. Underwater acoustic methods (sonars) are one of the primary approaches for detecting and classifying such munitions. One of the significant challenges is that munitions lie on or are buried in sediments which have generally unknown acoustic properties. These properties are strongly spatially dependent (in three dimensions), are frequency dependent, and in some cases time dependent. The complexity and variability of the sedimentary environment is expected to degrade the capability to detect, classify and remediate munitions in underwater environments.

Our assertion is that detection and classification success is significantly enhanced when the sediment structure and relevant properties are measured, i.e., known in advance. The long-term goal is to develop a system to measure those properties at each SERDP designated site before conducting the detection/ classifications surveys. Specifically, foreknowledge of the sediment properties will enable:

- 1) *Better informed mission planning.* Mission planning is enhanced, for example, by determining which areas are prone to impact burial or burial by sediment mobility, or have a low likelihood of burial by any mechanism. Knowledge of burial mechanisms will inform decisions regarding what kinds of detection systems should be employed. For example, in areas with low likelihood of burial, higher frequency systems might be preferable, while in areas where there is a reasonable burial probability, lower frequency systems would be employed (likely in addition to high frequency systems).

- 2) *Better sonar performance prediction.* In each survey area designated for munitions detection, it is important to estimate how well sonar systems can be expected to function. Foreknowledge of sediment properties is crucial to predicting that performance. For example, the sediment properties control depth of acoustic penetration (e.g., can buried munitions be detected with a given system?) and also control sonar survey coverage rates for buried munitions. These and other performance metrics are important for planning and conducting sonar surveys.
- 3) *Determination of optimal detection/classification sonar parameters.* Some sonars have variable parameters, e.g., frequency, bandwidth, pulse type. Foreknowledge of sediment parameters can inform decisions about those settings. Frequency and bandwidth are parameters that can have a substantial effect on detection and classification. Given the variety of possible sediment structures, it is expected that the sonar setting suite will need to be varied as a function of sedimentary environment.
- 4) *Sonar performance modeling.* The development of a munitions detection and classification sonar will require performance modeling. Performance modeling is typically done both with synthetic and at-sea data, but the latter generally provides the greatest value. Such modeling cannot be performed without knowledge of the sediment properties.
- 5) *Better informed remediation decisions.* Knowledge of sediment properties in a given region is expected to be a very useful for informing remediation decisions.

In summary, foreknowledge of sediment properties provides important advantages for detecting, classifying and remediating munitions in the underwater environment.

B. Summary of past research

Our assertion is that many key sediment properties can be inferred *in situ* from acoustic remote sensing in a rapid, cost-effective approach which scales effectively to relevant survey sizes (in contrast to some direct sampling methods such as coring). Over the past decade, we have developed sophisticated measurement and Bayesian inference techniques to probabilistically estimate sediment geoacoustic properties ([1]- [20]). Important aspects of the approach are:

1. High depth resolution (typically <0.1 m) in the upper ~ 1 m of sediments.
2. Rigorous parameter uncertainty estimation via Bayesian inference.
3. No requirement for *a priori* knowledge of sediment properties or layering structure (e.g., no need for “site calibration” as required by some methods).
4. Low uncertainties, e.g., typically porosity at $\pm 3\%$, p-wave velocity at $\pm 0.5\%$ in the top 1 m.
5. Ability to extrapolate the geoacoustic properties in frequency (useful for sonars operating across a wide frequency band and/or that are in a different band than GeoSS measurements).

Our method provides depth-dependent geoacoustic properties of the sediment column. There is strong evidence that sediment depth-dependence is valuable information for munitions detection and classification; e.g., modern mine burial models explicitly treat the depth dependence (e.g., [21] - [23]). Many existing seabed classification methods yield only surficial sediment-type estimates integrated over some depth interval related to instrument type. Such depth integration can cause misleading results since sediments are typically complex layered media with strong depth variability, particularly in the uppermost sediment column. For example, high frequency sonars which average over the upper few centimeters may detect surficial mud but not a sandy or rocky layer 10 cm below the water-sediment interface. Alternatively, lower frequency sediment-characterization systems that average over the upper few meters can yield strongly-biased predictions of burial depth and sediment mobility and sonar performance when layering below that scale is present. Further, some existing sediment-characterization approaches employ co-located source-receiver (monostatic) configurations. While monostatic measurements are simple from engineering and analysis viewpoints, fundamental physics dictate that these systems cannot separately resolve density and velocity, and generally cannot separate attenuation from other effects. The method proposed here exploits multiple sediment incidence angles and multiple frequencies to resolve sediment sound velocity, density, and attenuation profiles, including both discrete layering and smooth gradients.

Many methods developed in the seismic/geophysics community provide only velocity profiles and rely on empirical relationships for density (which would give erroneous results). However, for the prediction of munitions burial (via impact or sediment transport), the density/porosity profile (not the velocity profile) is a key parameter [22]. While it may seem surprising that our acoustic method is highly sensitive to density, this is due to the processing of the reflection coefficient in the frequency domain rather than the common approach of peak picking in the time domain (as used in the seismic community and extensively in the underwater acoustics community).

C. Advances required for the munitions problem

While our previous research has demonstrated the ability to accurately infer complex sediment structures that occur in marine environments using acoustic survey data, the vast majority of our results to date are at single locations on the mid- to outer-shelf (80–180 m water depth). For munitions applications, however, the data analysis/inversion procedures and system design must be modified to consider large sequential data sets collected in very shallow water (0–35 m).

Thus, two major extensions are required to apply our acoustic remote-sensing approach to sediment assessment for underwater munitions detection: (1) address the theoretical and computational demands of sequential Bayesian inversion for many data sets along a survey track, and (2) design a prototype geoacoustic sediment survey (p-GeoSS) system for the shallow water depths of interest. These two research areas comprise the technical components of this project.

The result of this work will be the first major step in extending our remote-sensing methodology to shallow-water area surveys, and will provide the foundation for subsequent efforts to build and field a system to collect and analyze practical data for munitions applications.

III. Materials and Methods

We first describe the measurement quantity and forward model that forms the foundation of our sediment remote sensing methodology. We then describe the inversion or uncertainty quantification method.

A. Measurement quantity and forward model

Our measurement methodology employs an acoustic source and receivers towed above the seabed. In the data processing, we form a frequency-domain seabed reflection coefficient for each source ping by scaling the magnitude of the band-filtered received pressure by the Green's function along the specular path (source to seabed to receiver) and normalizing by the source amplitude (defined at 1 m from the source), see Ref [2] for details. This quantity we refer to as the spherical reflection coefficient which is a function of source-receiver geometry and frequency. Typically our total measurement bandwidth is several kilohertz which is analyzed in sub-bands of bandwidth less than about 100 Hz.

In order to model the measurement, the proximity of the acoustic source (which emits spherical waves) to a planar boundary necessitates either the source be expanded into plane waves, or the seafloor and all sub-bottom layers be expanded in spherical basis functions. The former is more convenient. Then, the reflected acoustic pressure field p_r from the seabed due to a unit amplitude point source can be written via plane wave expansion about the source (e.g., [24]) as

$$p_r(\theta_o, f, z_t) = ik \int_0^{\frac{\pi}{2} - i\infty} J_0(kr \cos \theta) R_p(\theta, f) e^{-ikz_t \sin \theta} \cos \theta d\theta, \quad (1)$$

where θ is grazing angle in the vertical plane; θ_o is the specular angle for a given source/receiver range (horizontal offset) r ; R_p is the plane wave pressure reflection coefficient; z_t is the sum of the source and receiver heights; J_0 is the Bessel function of order 0, k is the wavenumber, and f is frequency. We refer to this as the Sommerfeld integral, although it is typically written in terms of the horizontal wavenumber, whereas here the integral is written in terms of the grazing angle θ .

The modeled spherical wave reflection coefficient, R_s , is then defined exactly as in the data processing, by scaling the pressure by the Green's function along the specular path (of length D) and accounting for the source beampattern S

$$R_s(\theta_o, f, z_t) = \frac{ikD}{e^{ikD}} \frac{1}{S(\theta_o, f)} \int_0^{\frac{\pi}{2} - i\infty} S(\theta, f) J_0(kr \cos \theta) R_p(\theta, f) e^{-ikz_t \sin \theta} \cos \theta d\theta. \quad (2)$$

In the geoacoustic inversion method, this forward model is typically evaluated on the order of 10^6 times for a single source transmission. Given that the integrand is highly oscillatory and therefore must be finely discretized, the uncertainty quantification is computationally demanding.

B. Uncertainty Quantification: Bayesian Inference for Geoacoustic Remote-sensing Surveys

In Bayesian inversion, the solution to the inverse problem is given probabilistically by the posterior probability density (PPD) of model parameters [28]. Bayesian inversion considers prior information (independent information about the parameters expressed as a probability) and updates the prior with data information (expressed in terms of a likelihood function) to obtain the PPD. Bayes' theorem is given by

$$P(\mathbf{m}|\mathbf{d},H) = P(\mathbf{d}|\mathbf{m},H) P(\mathbf{m}|H)/P(\mathbf{d}|H),$$

where $\mathbf{d}$ are data, $\mathbf{m}$ is a set of unknown model parameters, and $P(\mathbf{m}|\mathbf{d},H)$ is the PPD. The choice of model is given by H and includes the physical theory and a statistical representation of the data error distribution $P(\mathbf{d}|\mathbf{m},H)$ (e.g., multivariate Gaussian) both of which are parameterized by $\mathbf{m}$. The model H describes the system of interest (e.g., bottom-interacting acoustic propagation). For the observed (fixed) data, $P(\mathbf{d}|\mathbf{m},H)$ can be interpreted as the likelihood function $L(\mathbf{m})$ (a function of $\mathbf{m}$). The likelihood quantifies the probability of obtaining the measured data $\mathbf{d}$ given a particular $\mathbf{m}$. Prior information about parameters is expressed by $P(\mathbf{m}|H)$. Note that for nonlinear problems (such as geoacoustic inversion), estimation of the PPD must be carried out numerically such as by Markov chain Monte Carlo (MCMC) or sequential Monte Carlo (SMC) methods. The probability $P(\mathbf{d}|H)$ provides a data-based, objective criterion for model selection. For observed data, $P(\mathbf{d}|H)$ can be interpreted as the likelihood of a model H and is referred to as the Bayesian evidence. Evidence (or approximations to it) provides an objective model selection criterion within a group of models that naturally satisfies parsimony (favors simple models that are consistent with the resolving power of the data).

While sediments can often be considered laterally invariant on meter scales, layering structure often varies at the scale of several to 100s of meters. Hence, a geoacoustic survey based on sequential measurements/inversions along a track requires the ability to estimate the vertical and lateral variability of the environment from noisy and incomplete data (e.g., measurements which are limited in frequency and/or angular coverage at each survey point). Such data cause uncertainty in the parameter estimation. In a sequential Bayesian approach, it is crucial to clearly define and differentiate between variability and uncertainty. Variability is a measure of the inherent spatial and/or temporal heterogeneity in an environmental property. It is an intrinsic property of the environment, and cannot be reduced by improved experimental or data-analysis techniques (although improved techniques may improve our estimate of variability). Uncertainty is a measure of our knowledge of an environmental parameter value, and is quantified as a probability density in a Bayesian approach. Uncertainty is a property of our knowledge of the environment, not of the environment itself, and can be reduced by improved experimental and data-analysis techniques. Since quantifying sediment variability over a survey area is the ultimate goal for this work, rigorous uncertainty estimation is a prerequisite to resolving variability that can be ideally addressed by Bayesian inversion.

It is important to note that uncertainties from geoacoustic inversion quantify the accuracy of parameter estimates for the particular model adopted to represent the environment, and can depend strongly on that choice. Therefore, it is desirable to estimate the model from the data in a rigorous and objective manner (a process referred to as model selection). This requires

automated adaptation of the sediment model to the local environment and data information, including a changing number of sediment layers and variable local noise characteristics. This adaptation must avoid both over-parameterization (too many layers, resulting in unconstrained model structure) and under-parameterization (too few layers, leaving structure unresolved and biased). This requirement for parsimony is intrinsically satisfied by Bayes' theorem [11] and can be addressed efficiently by trans-dimensional (trans-D) models [16]. Trans-D models, based on a hierarchical Bayesian formulation, sample members of a group of models according to their support by the data and prior information. In this particular case, transitions between group members are carried out by adding/deleting layers (change of model dimension) using a reversible-jump MCMC (rjMCMC) algorithm [29]. The group of models in a trans-D model may contain multiple members that fit the data and should be considered jointly in uncertainty estimation. The result is a probability distribution which extends over all group members and provides ensemble parameter estimates with rigorous uncertainties that inherently include uncertainty due to this model selection ambiguity.

IV. Results and Discussion

Two major extensions were required to apply our geoaoustic remote-sensing method to sediment assessment for underwater munitions detection: (A) address the theoretical and computational demands of sequential Bayesian inversion for many data sets along a survey track, and (B) design a prototype geoaoustic sediment survey (p-GeoSS) system for the shallow water depths of interest. Significant successes in both of these are described below.

A. Bayesian Inference

In past research we have developed a highly effective trans-D Bayesian inversion for single-location data. However, addressing large sequential data sets along a survey track requires an efficient sequential inversion algorithm which automatically adapts the model (allows the number of layers to change) based on data information, and takes advantage of results at one location in initializing the inversion at a subsequent location (sequential importance sampling). We have already developed an initial sequential inversion for survey data collected by a moving platform (e.g., an AUV with towed source and receiver array) which employs such sequential Monte Carlo techniques [15].

1. Progress

At the beginning of the project, the algorithm had been applied mainly to simulated plane-wave reflection-coefficient data for water depths greater than 60 m and limited sediment thickness. However, full spherical-wave reflection modeling (i.e., point source and point receiver at separation distance where wavefront curvature is non-negligible) is required for shallow-water applications, which is far more computationally intensive and up to now impractical. To address this, we have

- a. Employed state-of-the-art hybrid computer architecture.
- b. Made significant computational improvements to the forward (reflection) model.
- c. Generalized sequential inversion to improve parameter estimation and computational efficiency.

a. Employed hybrid computing to substantially improve efficiency

We designed, acquired and installed a new hybrid computing facility that combines 160 central processing units (CPUs) with 16 general purpose graphics processing units (GPUs). The hybrid computer is well-suited for the computationally intensive inversions in this project and is maintained and administrated by Jan Dettmer. The computer is jointly funded by the Office of Naval Research (15%), the Natural Sciences and Engineering Research Council (NSERC, 50%) of Canada and SERDP (35%). These resources have been harnessed for the statistical inference problem of quantifying the geoacoustic properties for supporting detection and classification of underwater munitions.

b. Made significant improvements in solving the Sommerfeld integral

The Sommerfeld integral prior to this project was solved using Simpson's rule and efficient determination of the sampling and limits of integration [14] which was implemented on a GPU for massive parallelization. The solution is now based on the Levin integration method [25], also implemented on a GPU. For a single evaluation of the integral, Simpson's method may be slightly faster. However for the large number of evaluations needed for sequential inversion, the Levin integration method is more accurate and substantially faster, roughly by a factor of 5.

This substantial increase in speed led to improvements in the inversions by: 1) eliminating ad-hoc approximation in the integral, i.e., an interpolation scheme which worked reasonably well in some but not all cases, 2) including 6 center frequencies in each inversion; in previous work the computational demands limited the inversion to 3 center frequencies, and 3) representing band-averaging about the center frequency more accurately. In previous work, the number of frequencies for representing a sub-band was typically 3 which has been increased to 5, leading to more accurate data predictions.

c. Generalized sequential inversion to improve parameter estimation and computational efficiency

Brute force inversion for multiple data sets would solve the full inversion problem (10^6 forward models) for each consecutive source transmission. Sequential inversion exploits the fact that in many (but not all) cases, the seabed from one transmission to the next has some similarities. That is, the posterior probability density (PPD) from one ping can inform the solution for the next ping. This can greatly increase the speed (i.e., fewer forward model evaluations are required) while retaining the same accuracy of the solution and associated uncertainties.

Substantial progress was made in the efficiency of our sequential inversion approach as well as in the quality of the uncertainty quantification. The progress is based on an advance in defining more informative priors (adopted from other recent work of our group) and on a novel particle filter developed for this project. These are discussed below.

i. Defining more informative priors

The new method includes three prior components that can improve the quality of uncertainty estimates. First, the prior bounds take into account correlations between sound velocity and density based on a large compilation of observations [27]. This prior constrains the seabed model to physically meaningful profiles. Second, the method includes a background model and inverts for perturbations about that model so that the prior on parameters can effectively include dependence on depth [28]. This addition can substantially improve inversion stability where data information is limited. Third, the prior for the seabed complexity is based on even numbered

order statistics (ENOS) and a Poisson distribution [29], [30]. The seabed complexity is given by the number of sediment interfaces (n) for each data set which is considered to be unknown (estimated from the data) and uncertain (given by a probability density function). In our previous work, the prior on n was treated as uniform which can be shown to result in the inversion results including many thin layers that increase uncertainty. However, many of these layers are below the resolution limit of the data we consider in this work and it may be desirable to exclude these from our analysis. The even numbered order statistics provides a formal approach to achieve this and results in simpler seabed models and higher computational efficiency.

ii. Development and implementation of a new particle filter

The most significant new advance under this project is a novel particle filter that includes bridging distributions via trans-D parallel tempering (PT). We originally proposed to develop better bridging based on annealed importance sampling (AIS). A key limitation in our previous work with AIS was that it does not allow for trans-D steps (i.e., the number of sediment interfaces in the model cannot change during bridging). So far, our efforts to devise a trans-D AIS algorithm have been unsuccessful, which led to the alternative path of applying PT as a bridging algorithm. The success of implementing PT within the particle filter resulted in a significant gain in computational efficiency. The PT implementation (Figure 1) includes trans-D steps for every component of the algorithm and is intrinsically parallel which leads to efficient use of our new computer hardware.

Particle filters quantify information content of consecutive data sets by considering results from previous data sets along a survey track to inform the importance sampling at the current point. Significant challenges arise from rapid changes in the environment along a track where both the complexity of sediment layers as well as their properties can change. Adapting to the seabed complexity at a new position along the track is addressed by including reversible jump Markov chain Monte Carlo (rjMCMC) steps which allow the layering to change along a track. The efficiency of adaptation is improved through tempering the likelihood function (i.e., relaxing the required fit to the data) which is achieved by raising the likelihood function to a power of <1 (Figure 1, middle column). The algorithm applies tempering to subsets of particles during rjMCMC steps which results in some particles exploring the parameter space more widely than others. In addition, exchange moves are included between particles (PT bridging). The exchange moves swap the seabed parameter vectors between particles that explores widely and particles that explore locally, which results in more efficient exploration for the whole particle cloud. During this bridging, the specific tempering scheme (degree of relaxation applied to various particles) is adapted to the severity of environmental change. To avoid overly complex models during this phase of the algorithm, the PT initially employs the Bayesian information criterion (BIC) instead of a formal likelihood function. The BIC strongly penalizes model complexity during the bridging and predominantly encourages exploration of simple models which has a dramatic effect on efficiency [31].

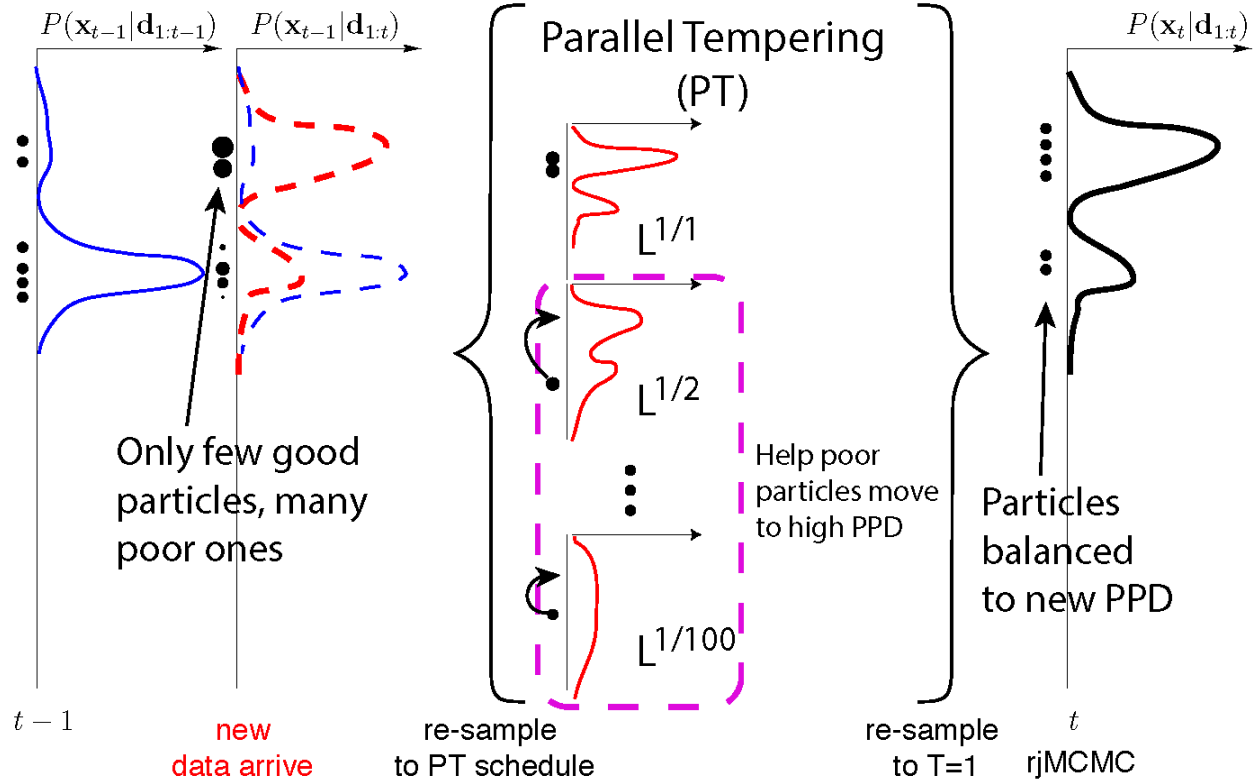


Figure 1. Schematic of the PT particle filter implementation for a progression from data set $t-1$ to t . All steps of the algorithm are trans-D. As new data are introduced, many particles exhibit poor fits and must migrate to higher-likelihood regions of the new posterior. To facilitate this migration, some particles are re-sampled onto a tempered distribution to move more freely around parameter space. Finally, all particles are re-sampled to the target distribution of $L^{1/1}$.

The particle filter is implemented on the hybrid computer and employs both multiple CPUs and multiple GPUs. Three levels of parallelism are exploited: (1) The computation of spherical reflection coefficients is based on the parallel implementation of Levin integration on a GPU (via the compute unified device architecture—CUDA). (2) PT particle updates are carried out by many concurrent CPU processes which exchange information via the message passing interface (MPI) based on an automatic load balancing algorithm. (3) The concurrent CPU processes access multiple GPUs in a staggered sequence via the CUDA multi-process service such that communication between CPUs and GPUs (a major bottleneck) overlaps with GPU computation for the various MPI processes.

2. Test of Bayesian inference advances using synthetic data

The new sequential algorithm described above was applied to simulated spherical reflection coefficients for 170 data sets along a track of 7 km length. The environment, Figure 2, was employed in previous work [15] and provides several challenging geologic features, including: change in geoacoustic properties within a layer along the track, change in the number of layers, and two abrupt changes simulating a geological fault and an erosional channel.

Spherical reflection coefficients for each position along the track are simulated for a realistic survey acquisition design [14] where an AUV tows a chirp source and a 32 element hydrophone array 10 m above the seabed. It is known that the spherical wave effects are significant for this geometry [14]. Over the source band, 975 to 2700 Hz, the inversion is performed on 6 discrete frequency bands. Each band has a 75-Hz bandwidth, intensity averaged over 5 continuous-wave frequencies per band. The 32 hydrophones mean that the reflection coefficient is sampled at 32 angles. Therefore, the current inversion example considers 160,000 reflection-coefficient “units” over the track length of 170 pings (see Table 1 for details). Once the simulated data were generated for each of the pings, random Gaussian noise of standard deviation 0.03 was added to each data set to create the noisy simulated data.

The inversion algorithm employs a particle filter. First, the algorithm is initiated by populating the particle cloud. At this point, a random sub-sample of the Bayesian posterior for the first ping is utilized by carrying out an initial Markov chain Monte Carlo inversion. The particle filter then progresses through all data sets sequentially. For each data set, the particle cloud is initiated with a sub-sample of the previous result. The filter then applies the following steps to complete the inference process for one data set:

- 1) Update likelihood values for the new data set.
- 2) Update the particle cloud with 5 rjMCMC steps and apply PT exchange moves to the whole cloud based on the BIC objective function.
- 3) Update the particle cloud with 5 rjMCMC steps and PT based on the likelihood function.
- 4) Resample all particles to $\beta=1$ where β is an annealing parameter
- 5) Update each particle with 10 rjMCMC steps; each step is saved to the posterior sample.

To ensure convergence for data sets along track sections of significant environmental change, step 2 is repeated up to 20 times until the likelihood values of the updated particles are within 10% of those from the previous step. For each repetition, the fraction of tempered particles in the cloud is increased. Increasing the fraction of tempered particles and repeating the PT step improves the chance of rapid convergence for challenging track sections at the cost of additional computational effort for some data sets. The inversion of 170 data sets was completed in 18.5 hours which equates to a rate of 1500 data sets per week on a single node of the new hardware [32]. This meets and exceeds the Go/No-go criterion.

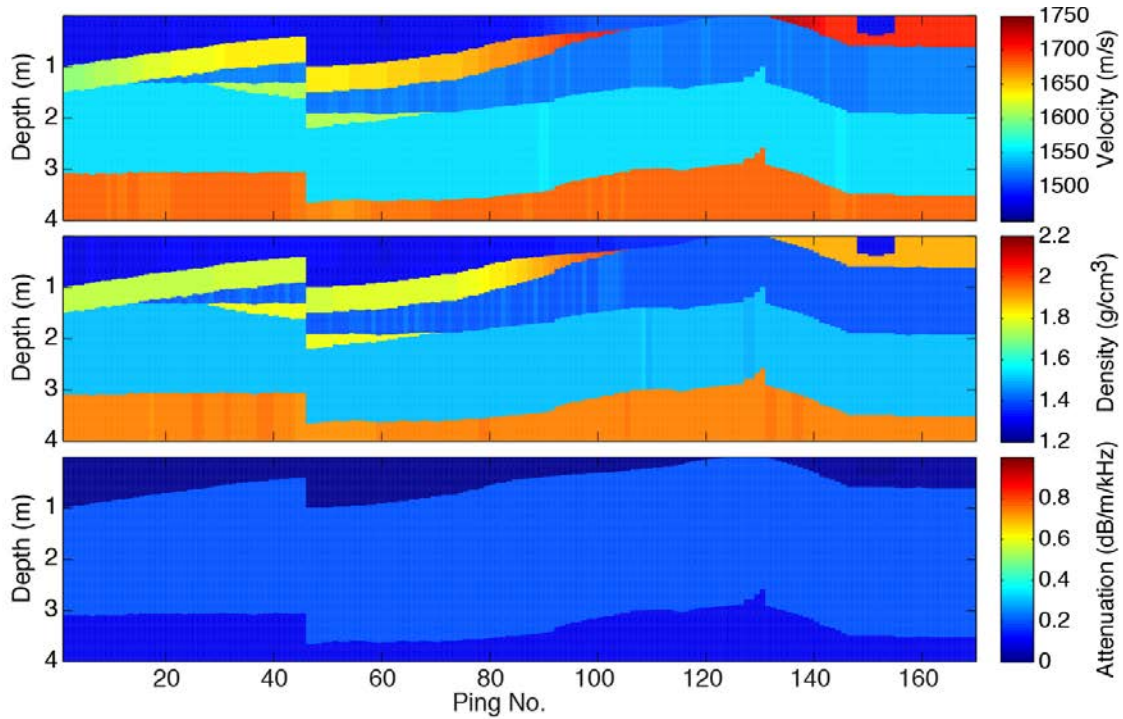


Figure 2. Simulated seabed environment along a 7 km track. Broadband spherical reflection coefficients at multiple angles (from 28-68°) are generated from this environment for each of 170 pings.

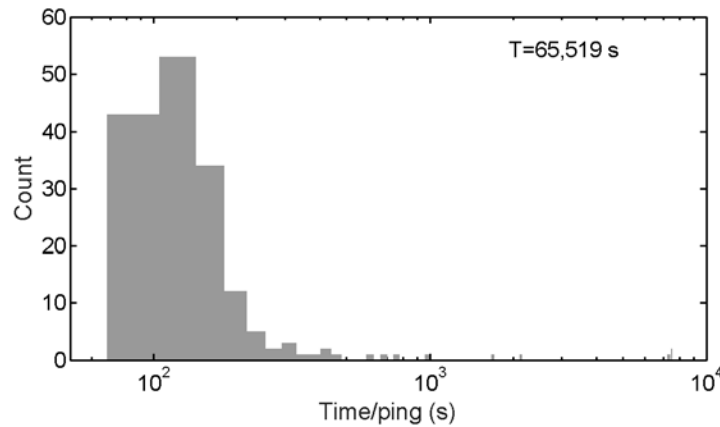


Figure 3. Histogram of algorithm timing, i.e. computation time per ping. Note that a small number of pings require a large fraction of the total computer time. This suggests that additional efficiency improvements are possible. The total computation time T is also shown.

Figure 3 shows a histogram of the time requirements per ping. While the vast majority of the 170 pings converge quickly, within a few tens of seconds, just 6 pings require about 9 hours, about half of the total computer time. The slow convergence for some pings is rooted in the PT repetition scheme outlined in the previous paragraph.

The most challenging section of the survey track is near ping 46, where seabed layering complexity and layer properties change rapidly. Figure 4 shows simulated data before and after

the fault along with predicted data for a large number of geoacoustic profiles from the ensemble solution. Interestingly, the inversion appears to adapt to the significantly changed data successfully. However, there is a trade-off between data fit and model complexity so that data fit alone is an insufficient criterion by which to judge inversion results.

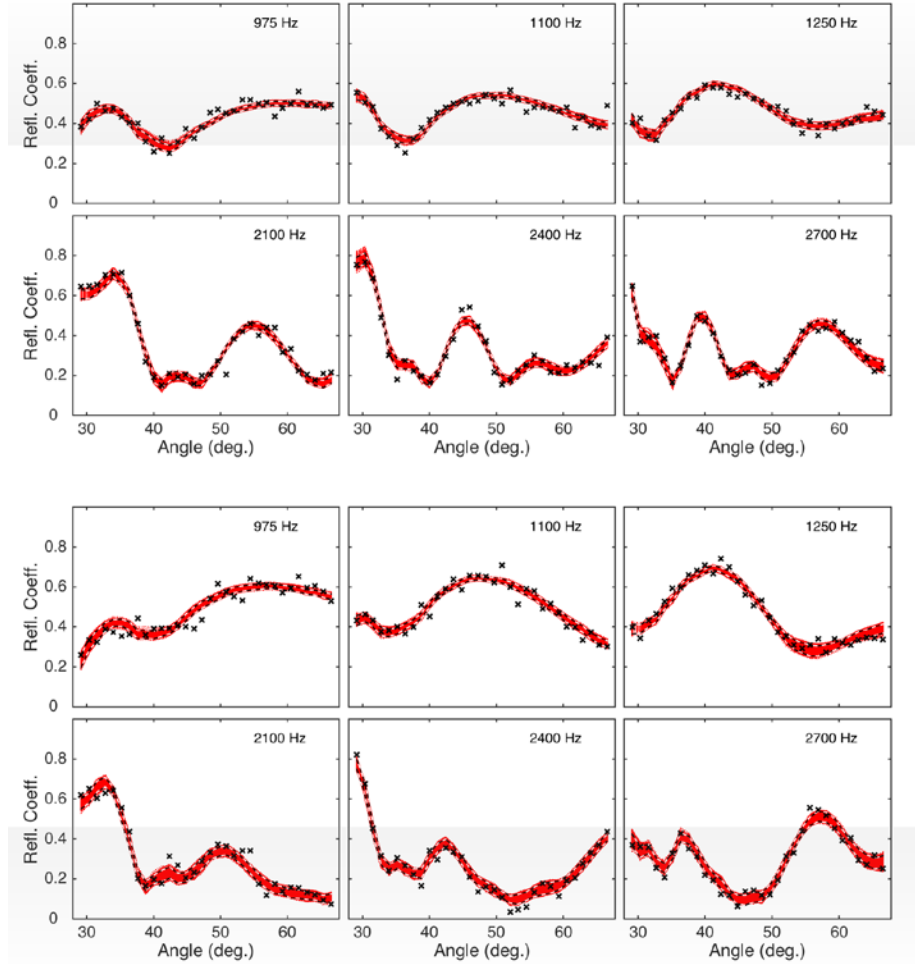


Figure 4. Simulated data for pings 45 and 56 (black x) and predicted data (red lines) sets for a large random subset of models from the Bayesian inversion. The predicted data capture the interference pattern of the simulated reflection coefficients well and quickly adjust to the rapid change in reflection coefficient values caused by the fault between these ping locations.

Figure 5 illustrates the problem in terms of marginal profiles and marginal distributions for the number of interfaces for pings 45 and 46. While seabed estimates are consistent with the true model at ping 45, the inversion over-estimates the complexity at ping 46, resulting in a poor representation of the true seabed properties. However, the algorithm has the ability to rapidly recover from this poor result. The results for ping 46 (Figure 4) are among the worst results along the track, i.e., are the furthest from the true values.

The true and inferred median sediment profiles for the complete track, Figure 6, show that high-quality estimates are obtained again for ping 48. Note that the other challenging features, e.g., the

layers with changing thickness, layers with changing properties, and the erosional channel are well-captured by the method. As a broad statement, the velocities have the lowest uncertainties (scaled by the true value), followed by density; attenuation generally has the greatest uncertainties.

As a side note, it is apparent from inspection of the results that the data have the lowest information content for the basement properties. This is a result of the physics of the problem: layers induce rapid variations in angle/frequency space which are high in information content, whereas the basement has a rather mild dependence on frequency and angle and thus is substantively lower in information content. Though the basement simulation results and the associated uncertainties are not unreasonable, this lack of sensitivity can be mitigated in practice by simply choosing the reflection coefficient integration time to sample a few meters deeper than the largest depth of interest. For the SERDP munitions problem, this is likely to be only a few meters.

In summary, the results in Figure 6 demonstrate that rapid uncertainty quantification is possible for large data volumes acquired by a moving survey system like GeoSS.

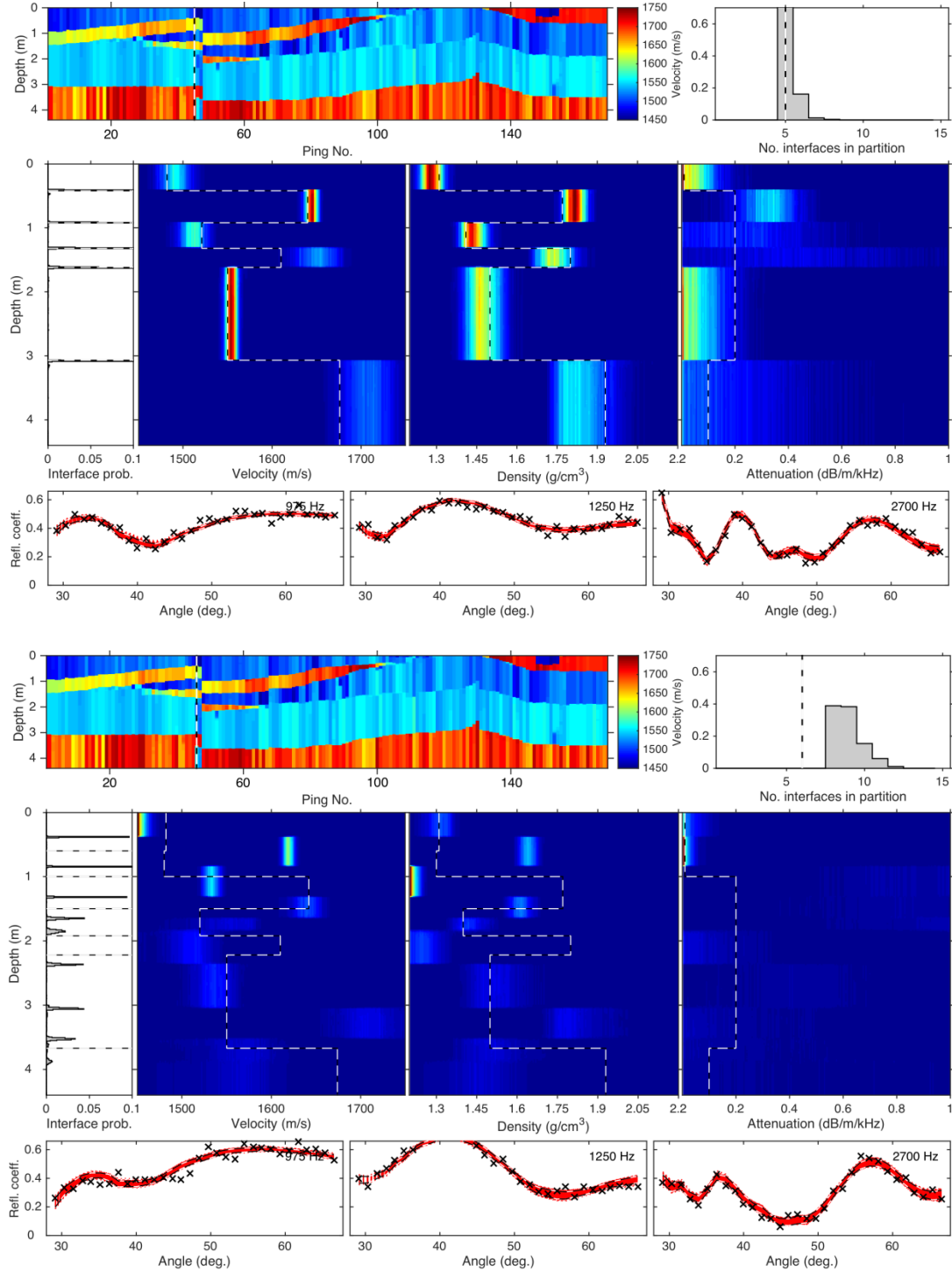


Figure 5. Geoacoustic uncertainty estimates for pings 45 (top) and 46 (bottom). Depth is relative to the seafloor and the true model is given by the dashed lines. The top left panel for each ping shows the velocity estimate for the complete track and the position of this particular ping along the track (dashed). The bottom rows of panels for each ping illustrate the data fit for 3 representative frequency bands (out of 6). The top right panel for each ping shows the true (dashed) and estimated seabed complexity (histogram). These uncertainty estimates are available

for all data sets along a survey track. The results for ping 45 are typical, those for ping 46 are among the worst along the track, i.e., are furthest from the true values.

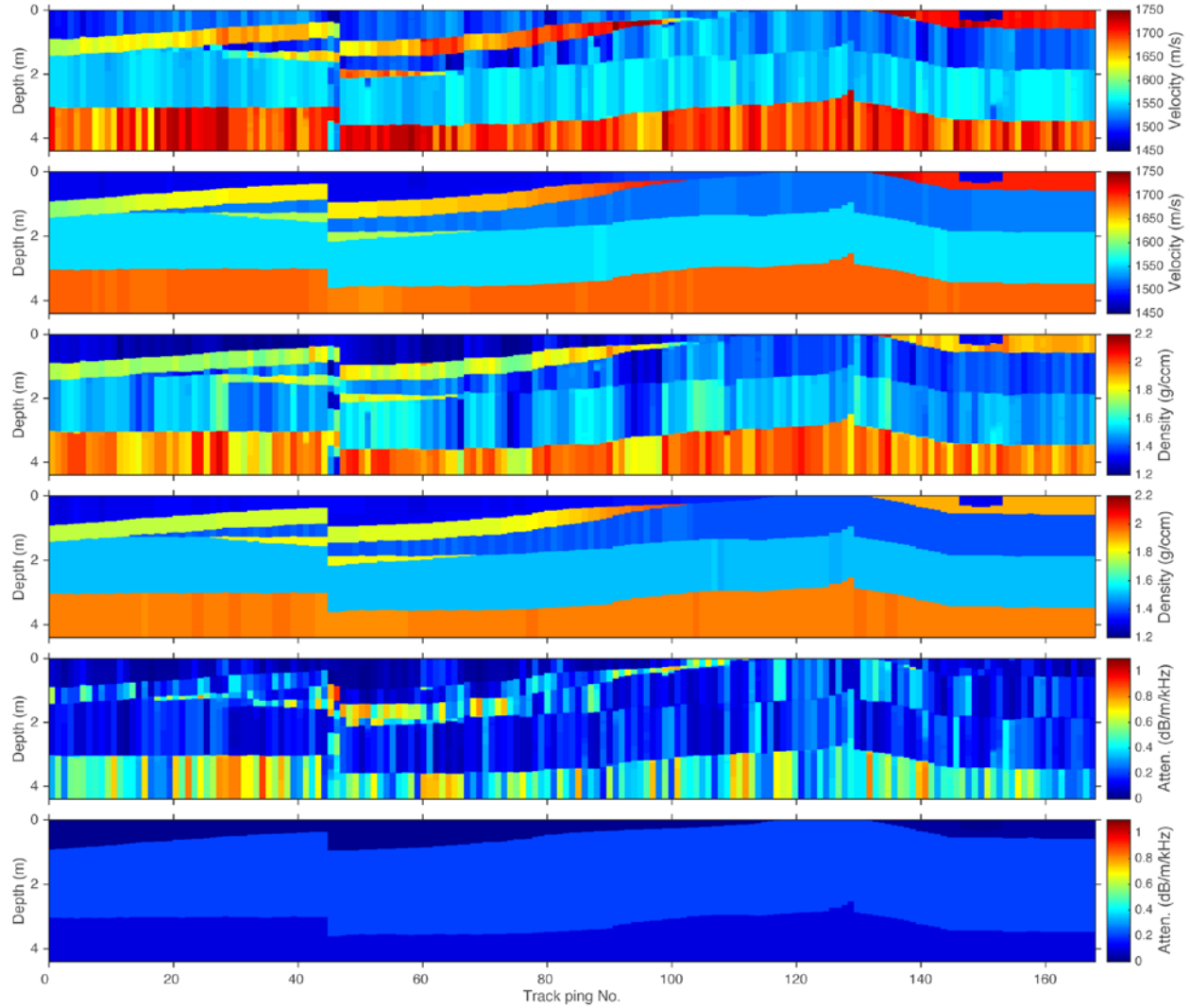


Figure 6. Comparison of true and Inversion results in terms of posterior median models along the track consisting of 170 data sets. The velocity density and attenuation results (rows 1,3,5) are compared with the actual properties used in the simulation (in rows 2,4,6).

To examine the efficiency gains in more detail, Tables 1-3 quantify the simulation results in terms of reflection-coefficient units, CPU hours of computational effort and cost of the computer hardware required for the problem. The tables also compare our current capabilities to our capabilities in 2011. Table 1 shows that the current simulation considers 17 times the reflection-coefficient units compared to previous efforts. At the same time, the algorithm analyses the problem 70 times faster in terms of CPU hours. Together the advances constitute an efficiency gain of 3 orders of magnitude. While precise and isolated benchmarking is beyond the scope of this project, various efficiency gains were observed during the algorithm development. The gains are mainly due to:

- 1) Levin integration (~5 times more efficient for this application);

- 2) GPU implementation (~40 times more efficient for this survey geometry and source);
- 3) Utilization of multi-process parallelism (~2 times more efficient by overlapping CPU-GPU communication with GPU computation);
- 4) Trans-D parallel tempering (~3 times more efficient than annealed importance sampling used in the previous algorithm)

While points 2 and 3 can be described as being partially due to hardware advances in the new computer, note that exploiting these new hardware features is not trivial and requires substantial algorithm design and research efforts in understanding how the physical system and inference algorithm can make optimal use of the available hardware. In addition, note that the method is not only more efficient but also more accurate in that the ad-hoc and environment-dependent interpolation scheme was completely removed and replaced by rigorous Levin integration. Finally, the GPU implementation scales extremely well with the number of angles and frequencies in the reflection-coefficient data, resulting in the new method being highly adaptable to future acquisition systems with more channels and larger source bandwidth.

Table 1. Comparison of computational domain from 2011 to 2016

	2011 capability	2017 capability	Factor
Frequencies	9 (3 per 3 bands)	30 (5 per 6 bands)	
Angles	32	32	
Sub-sampling	0.3	1	
No. pings	100	170	
RC units	9,600	163,200	17

Table 2. Comparison of performance gains from 2011 to 2016

	2011 capability	2017 capability	Factor
No. CPUs	168	20 + 2 GPU	
Walltime (hrs)	168	18.6	
Total CPU-hours	28,224	372 + 37	1/70

Table 3. Comparison of computer costs

	2011	2016	Factor
Computer cost	\$50,000	\$10,000	1/5

3. Test of Bayesian inference advances using measured data

Considerable efforts were made in creating the simulations to make them as realistic as possible, including complex, but stylized geologic features as well as noise levels similar to that observed in measured data. Nevertheless, the physics behind the simulations is largely the same physics that are assumed in the forward model. Thus, the importance of testing the algorithm with

measured at-sea data is to test all our assumptions under naturally occurring seabed conditions that may or may not conform to our assumptions.

Our data collection efforts over the past decades have been focused on seabed reflection measurements at individual sites on the mid to outer continental shelf, 80-150 m water depth. Such measurements were conducted at many tens of locations. A small number (4) of sequential data sets, i.e., seabed reflection data along a track, were collected at similar water depths,;however, in the past it was not possible to analyze them except in very short sections. With advances made under this project, it is now possible to infer the geoacoustic properties along any or all of those tracks, tens of kilometers in length. In 3 of the 4 data sets the source and/or receiver were far above the seabed (combined height of 100-200 m). In one data set, the source and receiver were quite close to the seabed, ~ 12 m. This data set was chosen to test our algorithm because it was the closest geometry to that which might be performed at SERDP sites of interest (less than 35 m water depth). Also, beyond just a reasonable match with the experimental geometry, the close proximity to the seabed tends to play a very significant role in the physics of the problem and under some conditions may compromise the ability to infer sediment properties (see Sec. IV.B). Thus, this data set was by far the strongest candidate for testing, because we expected that it would not only test our algorithms, but also our underlying assumptions under experimental conditions similar to what might be expected at SERDP site water depths.

The selected data set was collected along a 14 km seabed survey track on the Malta Plateau, south of Sicily, Mediterranean Sea, as part of the Clutter09 experiment (Figure 7). At these water depths, the enabling technology of an autonomous undersea vehicle (AUV) permitted towing a source and receiver close to the seabed, Figure 8. The AUV speed over ground was ~ 1 m/s and was in bottom-following mode, keeping a 12 m altitude along the track.

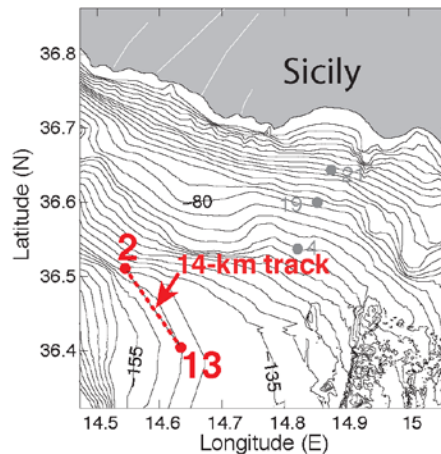


Figure 7. Location of 14 km seabed reflection track on the Malta Plateau in the Straits of Sicily.

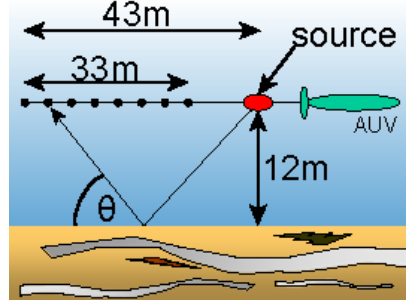


Figure 8. *Cartoon of source and receiver geometry for the seabed reflection experiment*

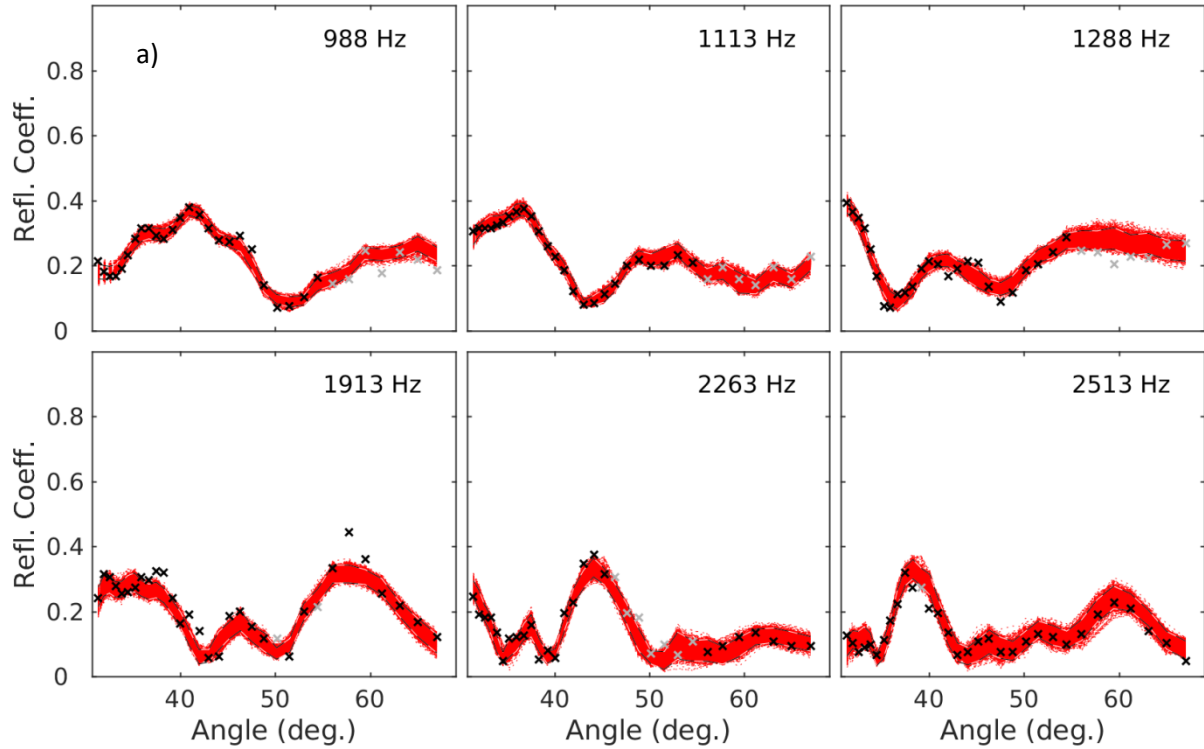
The source consisted of two cylindrical transducers mounted in a spheroidal-shaped tow body. Two simultaneous linear frequency modulated pulses were broadcast from 800-1400 Hz (termed LF) and 1600-3500 Hz (termed MF) with a pulse length of 1 s at a 3 s pulse repetition rate. The simultaneous transmission permits analysis of the reflection coefficient over the full band, including LF and MF. The receiver was a horizontal 32 element hydrophone array with 1.05 m spacing with a total array length of 32.55 m. The distance between the AUV and the source was 2.6 m and the first hydrophone was 10.38 m from the source.

Given the source-receiver geometry, specular grazing angles at the seabed were 29° – 67° and reflection-coefficient data were computed (see [14]) as a function of frequency and grazing angle. The reflection coefficients were intensity averaged over 75 Hz wide frequency bands resulting in 8 LF bands and 25 MF bands. Our previous research at single sites has shown that the high information content in the reflection data can be retained with a subset of the frequencies; in other words, closely spaced frequencies do not provide independent data. In the analysis that follows, a total of six bands were employed, with band centers at 988, 1113, 1288, 1913, 2263, and 2513 Hz.

Previous studies of these data have shown a few unusual reflection coefficient features including ‘speckle’ or high amplitude reflectivity at a single angle and interference patterns that do not evolve smoothly as predicted by theory, but rather follow a ‘stair-step’ trajectory. Both of these effects can be explained by various scales of interface curvature ([41], [42], [36]). These effects cannot be modeled with the plane-layered reflection model (eq. (2)) applied here; nevertheless, it was shown that suitable spatial averaging would minimize these effects. Therefore, data from 10 consecutive pings were stacked so that each stacked data point is averaged over roughly 30 m of seabed. Of the 3500 data stacks, every second stack (a total of 1750) is used for the inversion. The variability between data sets in the stacking process was used to estimate a noise level that is representative of theory error due to seabed complexity. The standard deviation of data noise is assumed to be estimated by the standard deviation of the stacked data at each angle and frequency. In addition, the variability of stack members was employed to screen for sections along the track that exhibit extreme reflection variability. These sections are caused by rapid sediment variability that could not be treated with our forward model and thus were not analyzed. After excluding these sections, a total of 1488 stacks remain which are inverted for high-resolution seabed structure. Finally, there was persistent evidence of biases caused by source beam pattern errors at some frequencies/angles, and in this case, the un-biased data were kept and only the relatively few biased points for a given stack were ignored (i.e., removed). The stacking procedure is summarized in “video data_stacks.mp4”.

The development of the massively parallel SMC algorithm (Figure 1 and Sec. IV.A.1.c) provided the efficiency to analyze such a large number of data sets for the first time. In all, 1488 stacked data sets were analyzed with fully nonlinear uncertainty quantification (UQ) while accounting for full wave-field effects, an approach that was considered close to intractable even for a single data set a decade ago [9]. This section will discuss the results from this UQ study.

Figure 9 shows representative data fits for two stacks (number 10 and 3148) that are achieved during the inversion. The six frequency bands used in the inversion are shown and observed reflection coefficients are shown as black crosses. Those reflection-coefficient values that are not used in the inversion are shown in gray. The significant change in reflection coefficient values between the two stacks indicates substantial spatial variability of the sediment between the start and the end of the track. The data predictions for a representative ensemble of models (1000) from the posterior density are shown in red and indicate that most data features are captured by the predictions. The quality of these data fits is a strong indication that the inversion results are consistent with the observed data.



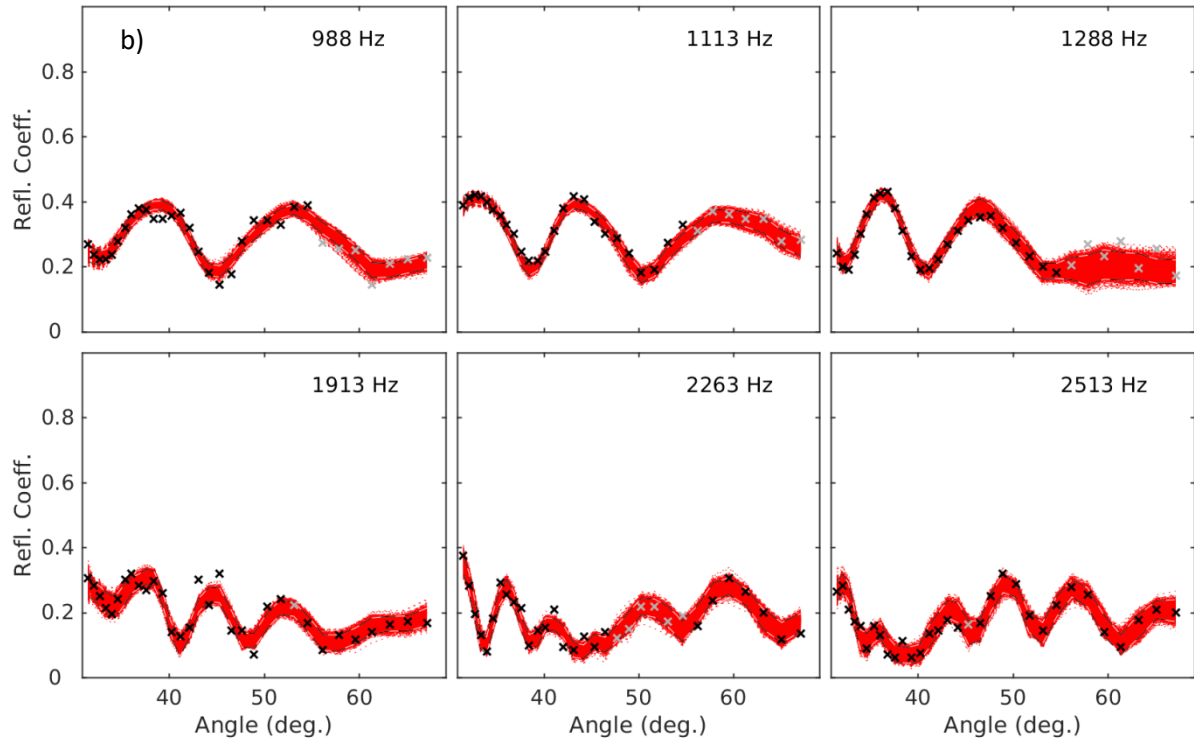


Figure 9. Data fits for two stacks: a) number 10 and b) number 3148

Figure 10 represents one of the main study results. Posterior mean models for compressional velocity, density and compressional attenuation are shown for the 1488 data sets along the entire length of the survey track. The depth profiles are presented with the bathymetry which is obtained from independent measurements (dashed line). Some gaps are visible in the data which stem from unusable sections that were removed during the stacking process. The results show unprecedented resolution of seabed features in both the vertical and horizontal directions. In addition, the ability of the trans-D model to adapt to the seabed complexity (number of layers) along the track is clear. Several interesting seabed features are resolved along the track:

- (1) A low-velocity, low-density wedge, likely a muddy material, is observed with a thickness of 1 m near the start that thins out to ~ 10 cm thickness at the end of the survey. The remarkable vertical resolution of the method is evident in the resolution of this thin, water saturated, muddy layer with properties that are difficult to distinguish from seawater (velocity of ~ 1460 m/s and density of 1.25 g/cm³). Near the beginning of the track, where this layer is close to 1 m thick, attenuation is inferred to be 0.025 dB/m/kHz, a value that agrees with a highly-sensitive nearby measurement in the same sedimentary layer [43].
- (2) A high-velocity, high-density layer is visible at the start of the track (near 36.5° N) at 3.5m depth. This layer is visible along the entire track, reaches a maximum burial depth of 5.5 m (near 36.45° N) and then becomes shallower again. In addition, the properties of

the layer change along the track with the highest velocities and densities near the middle of the survey.

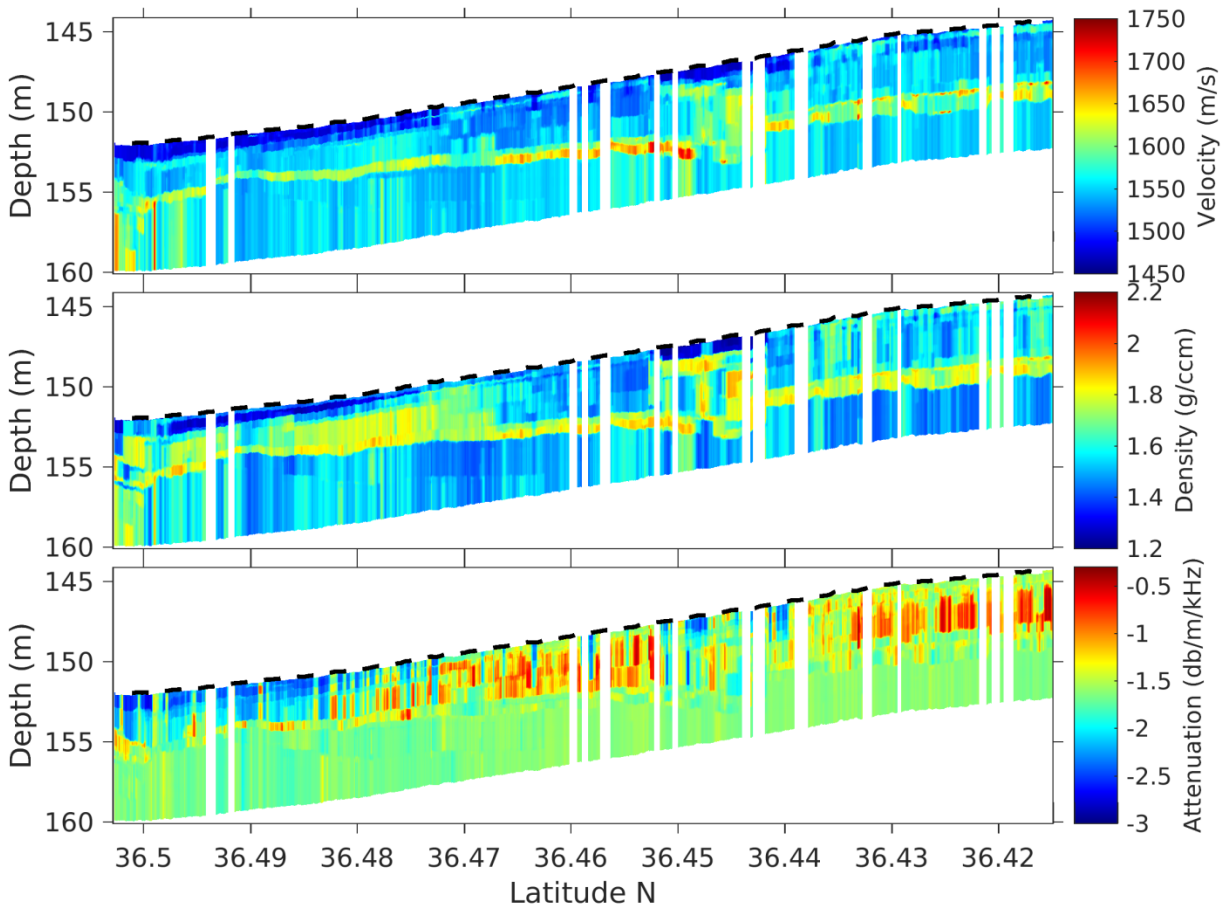


Figure 10. *Posterior mean geoaoustic results for the 14 km track*

Figure 11 shows the uncertainty in terms of 95% credibility interval widths estimated for the geoaoustic properties in Figure 10. General trends that are observed are that uncertainty increases with penetration depth for all parameters and that thicker layers typically exhibit lower uncertainty. In addition, velocity is the best-resolved parameter relative to the width of the prior distributions and attenuation shows generally large uncertainty. Density is a parameter that is widely believed to be difficult to resolve with acoustic methods, yet is resolved well in the upper ~4 m of the sediment and exhibits particularly low uncertainty in thicker layers. Finally, note that the uncertainty of attenuation is lowest in the thick part of the mud wedge, which provides confidence in the attenuation estimate of 0.025 dB/m/kHz.

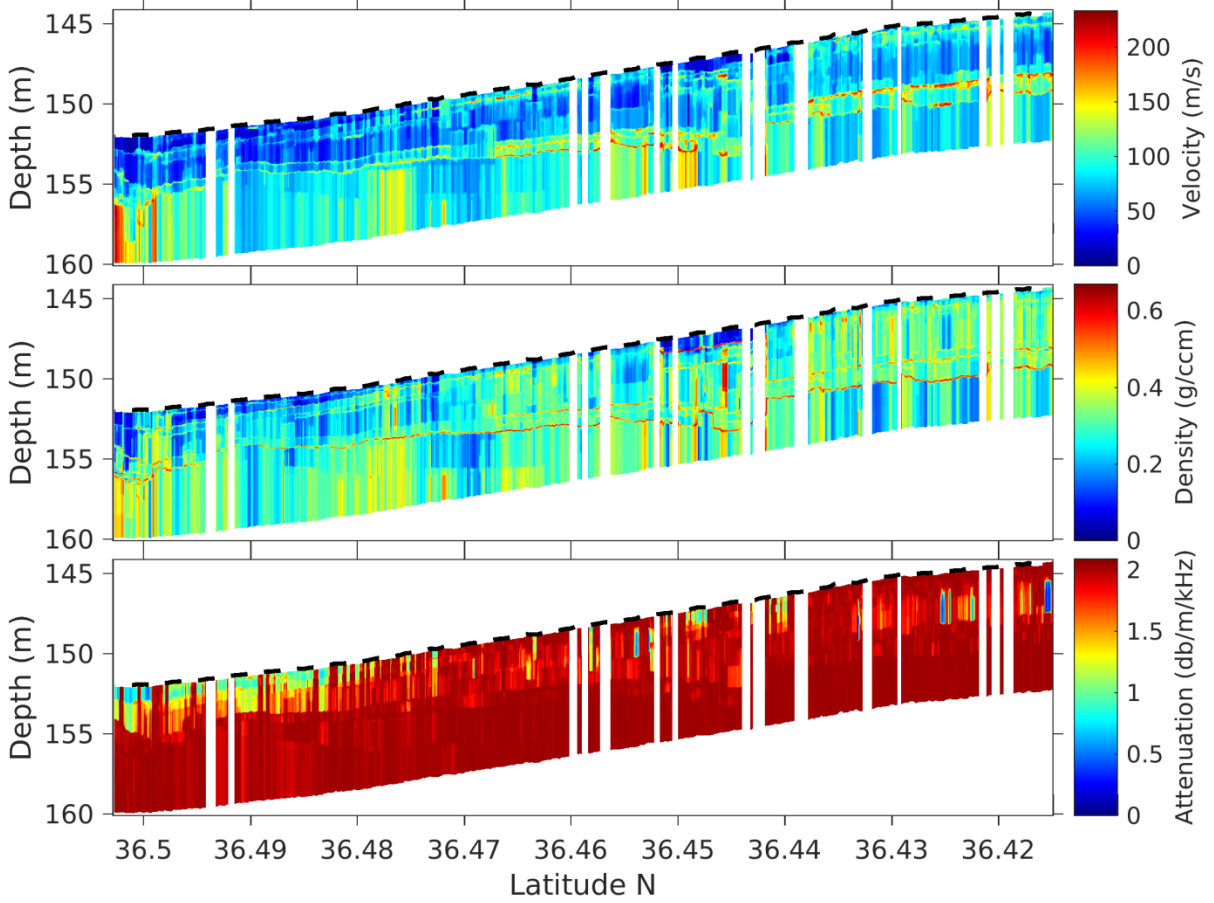


Figure 11. *Geoacoustic uncertainties for the results in Figure 10 quantified as 95% credibility interval widths.*

While the focus of this study are AUV data, previous at-sea experiments have also provided data measured with a surface-towed source and a fixed hydrophone for the start (site 2) [1] and end of the track (site 13) [11]. These fixed-receiver measurements contain a wider angular and frequency range than the AUV data which yield even higher resolution and lower uncertainties than the AUV data [11], [16]. In addition, during those experiments seabed gravity and piston cores were collected that provide independent estimates of seabed parameters. Figure 12 (a) and (b) compare the AUV estimates to the core estimates at these two sites. For the AUV estimates, two stacks were picked that are in the closest proximity to the locations where the cores were taken (stacks 82 and 3338). Both AUV-reflection estimates show quite good agreement with core estimates on both velocity and density. It should be noted that the core velocity data at Site 2 (Figure 12a), is badly biased below 1.2 m sub-bottom. Below 1.2 m, there were shells and shell fragments with a size of order and larger than the wavelength used to measure time of flight across the core, which led to multiple scattering and the expected decrease in sound speed (discussed in more detail in [6]).

For further comparison, Figure 13 shows the inversion results obtained from the fixed-receiver data. While these results feature higher resolution and lower uncertainty than the results from AUV data, there is close agreement between the methods.

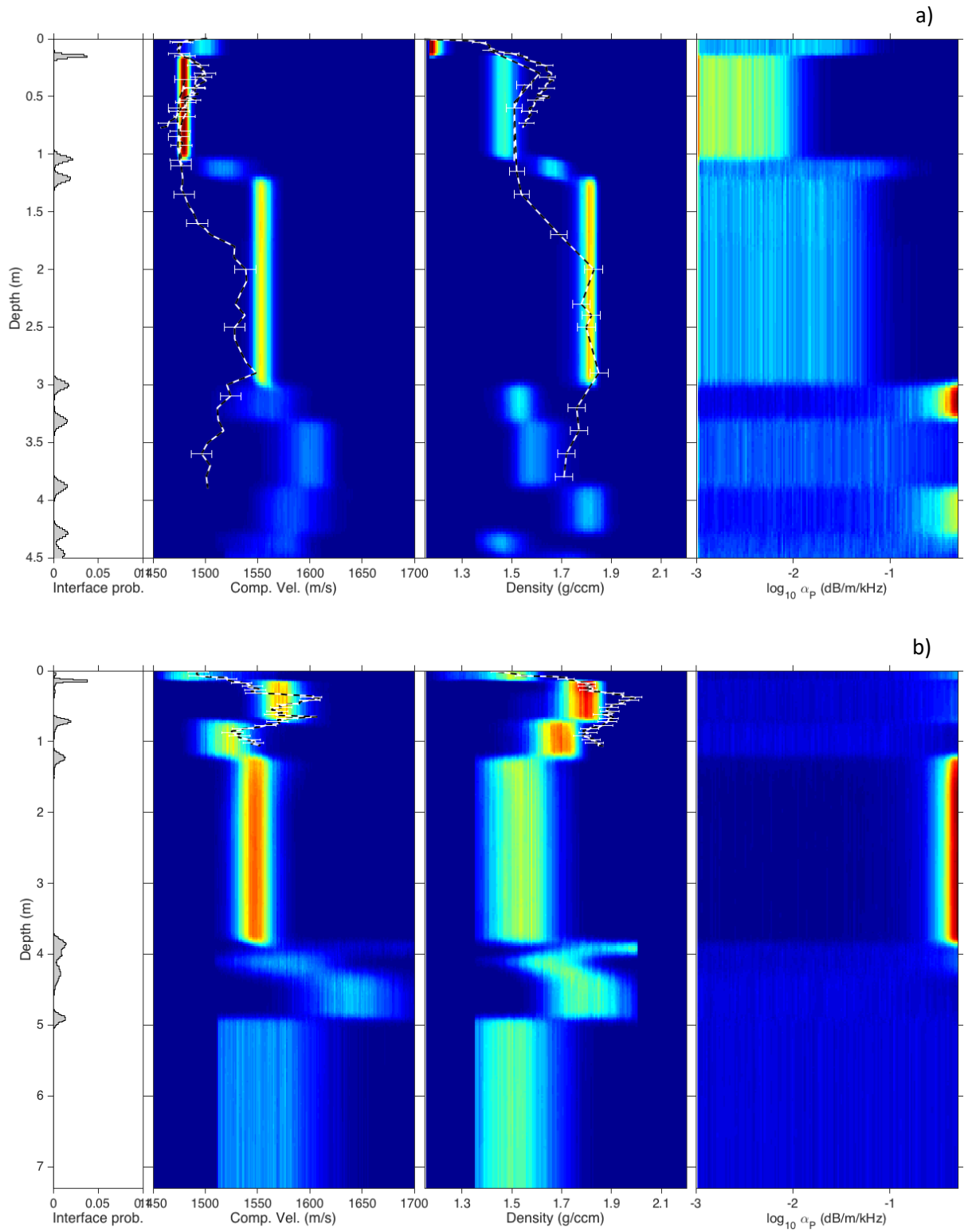


Figure 12. Comparison of estimated geoaoustic properties with core data estimates.

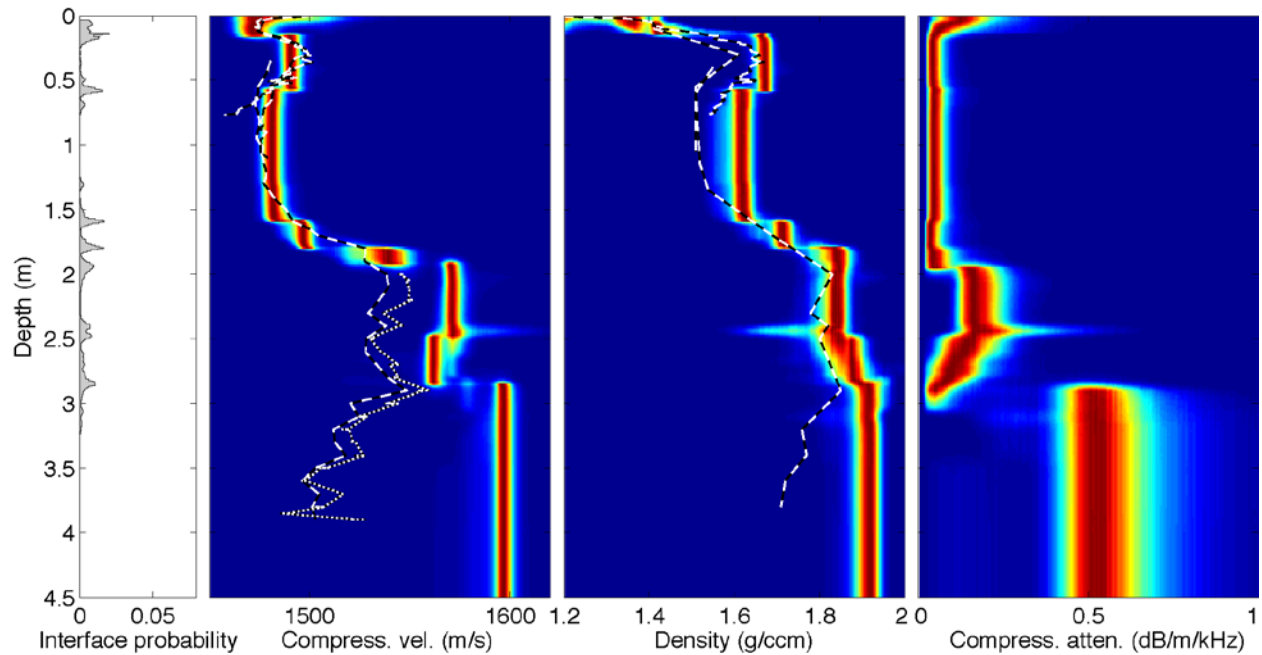


Figure 13. Comparison of layering structure (from the reflection data in the frequency-angle domain) with time domain normal incidence seismic profiling data along nearly the same track.

Figure 14 shows a comparison of the posterior-mean velocity along the track overlaid with vertical seismic profiles obtained with a surface-towed source along the same track. While the AUV results provide much more information in terms of quantitative velocity, density, attenuation, and depth results, the comparison to the seismic time-domain section is useful in illustrating that similar structural features are imaged. Many of the layers that are visible in the seismic section are also resolved as seabed layers by the AUV.

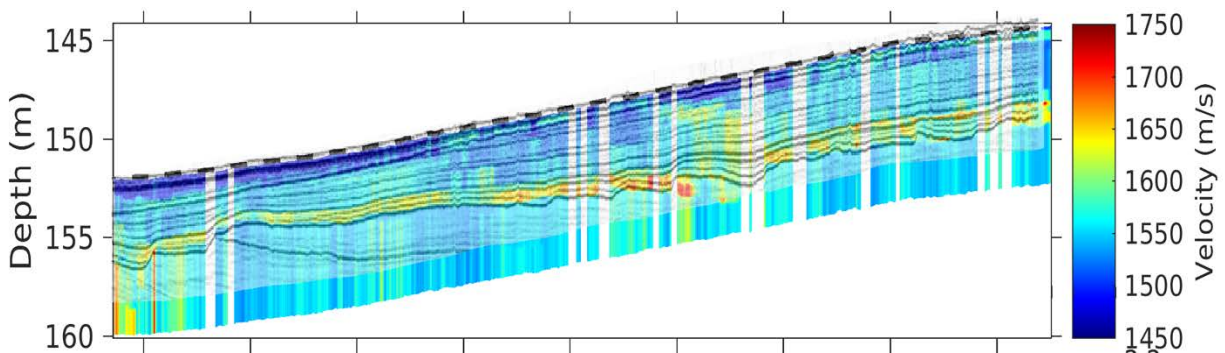


Figure 14. Comparison of layering structure (from the reflection data in the frequency-angle domain) with time domain normal incidence seismic profiling data nearly along the same track.

B. Prototype GeoSS high level design

It would be straightforward to develop a p-GeoSS design based on the premise that the assumptions in our data analysis would always be justified. However, this would tend to lead to an overly optimistic design, and perhaps to a less capable system. Thus, our design considerations contemplate issues that arise when our assumptions are not met. In the following we address some physics that are crucial to designing a robust p-GeoSS system.

A significant assumption in the uncertainty quantification comes from the forward model assumption of a plane-layered medium with smooth boundaries. While this has been a good assumption for all of our experiments in deeper water (60-180 m), it may or may not hold in very shallow water (10-35 m), where sediment layer interface roughness spectra may contain scales that limit our ability to measure/interpret the reflection coefficient.

In order to explore the effects of roughness on our ability to quantify sediment geoacoustic properties, we model the effects of a layered medium with rough boundaries on our observable - the reflection coefficient. The goal of the simulations is to show the effects of unmodeled physics in our approach and point to a design that can minimize those effects. The computational strategy closely follows the field measurements and processing. That is, the reflected field was first computed [34] in the time domain from a point source and receivers above a layered seafloor (with roughness on each layer), then the reflected time series data were processed in the same manner as our measured data (see [2]). The principal approximations in the model (see [34]) are the tangent-plane approximation, the Born approximation (multiple reflections between interfaces are neglected) and the flat-interface approximation for computing the transmitted field. The latter two approximations follow closely from Langston [35] and thus the model will be referred to as the Langston-Kirchhoff model.

The roughness at the top and bottom of the layer is parameterized assuming a von Karman spectrum, $W(k)=w/(k^2+L^{-2})^{\gamma/2}$ where k is the spatial wavenumber, w is spectral strength, γ is spectral exponent and L is the spectral cut-off length. In the simulations, two sets of roughness parameters were used, both derived from measurements in a 20 m water depth; a) $w_1=0.0039$ and $\gamma_2=4.43$ based on laser line measurements [37] and b) $w_1=1.2e-5$ and $\gamma_2=2.85$ based on multibeam bathymetry data (see Appendix in Ref [36]). The geoacoustic model consists of a 0.65 m thick layer at 1555 m/s, 0.45 dB/m/kHz and 1.6 g/cc over a basement of 1680 m/s, 0.2 dB/m/kHz and 1.9 g/cc. The reflection simulations for case a) are shown in Figure 15. Note that the high reflectivity values (red) in the lower and upper left corners of each plot are artifacts and should be ignored.

Before discussing the simulations, it is helpful to consider effects of the Fresnel zone, or the size of the insonified region on the rough surface (see Figure 16). The smallest in-plane Fresnel radius is about 1 m, which occurs at the highest angle and frequency. The largest in-plane Fresnel radius is about 10 m which occurs at the lowest angle and frequency. The Fresnel radius is an important spatial scale that significantly affects how the roughness influences reflection. Returning to the reflection simulation with rough boundaries (Figure 15) the results in the first row, $L=0.03$ m, indicate that roughness has practically no effect on the reflection coefficient at all angles and frequencies. This can be understood by comparing $2\pi L$ with the Fresnel radius, ξ . When the Fresnel zone is much larger than the cut-off scale, ($\xi \gg 2\pi L$), the acoustic field at the

receiver is averaged across many roughness scales, and the roughness has little net effect on the reflection coefficient.

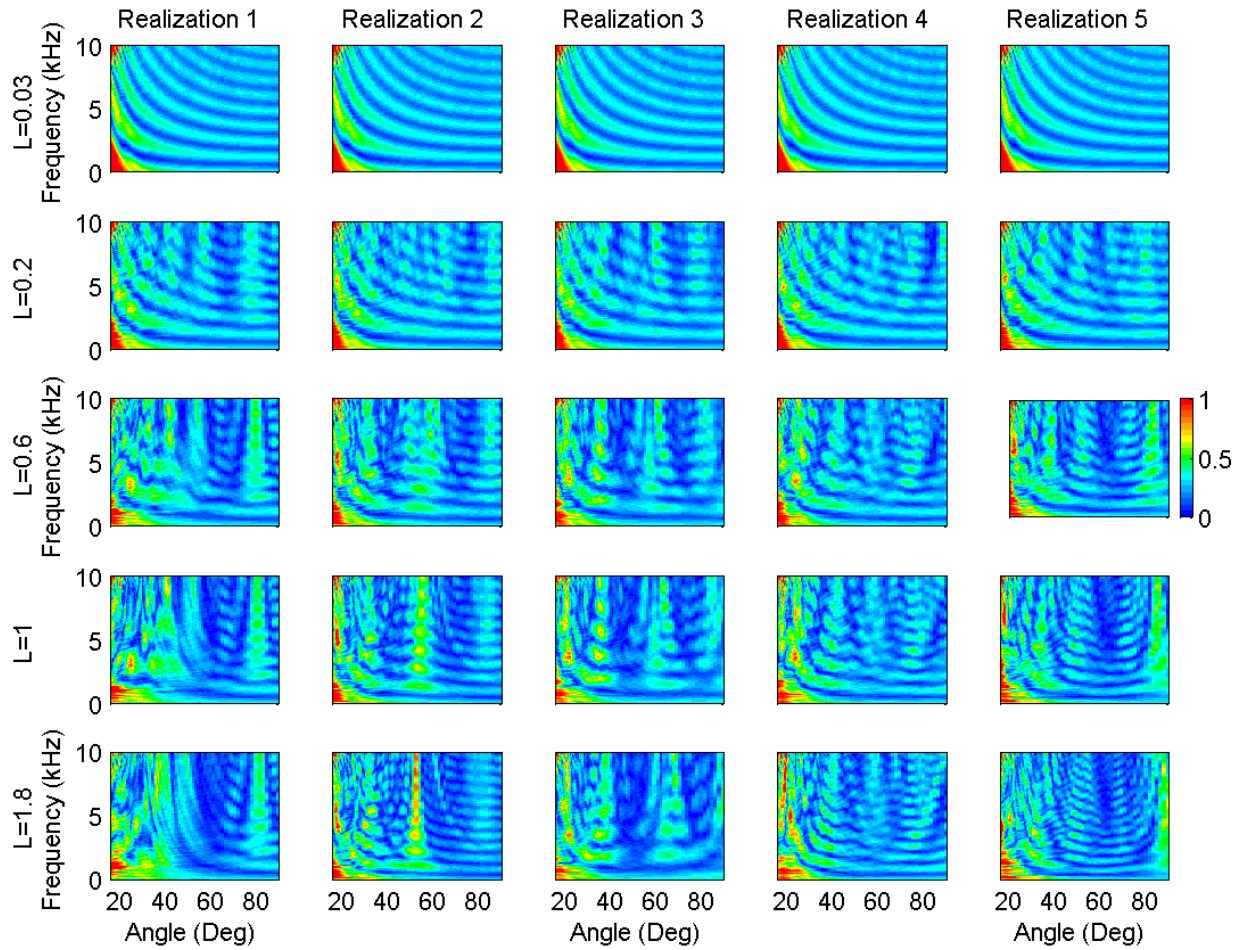


Figure 15. Simulation of experiment data, i.e., using the same experiment geometry, with estimated roughness values from laser line scanner data, for various realizations (columns) and values of spectral cut-off, L (rows). The source plus receiver height above the boundary is 17 m.

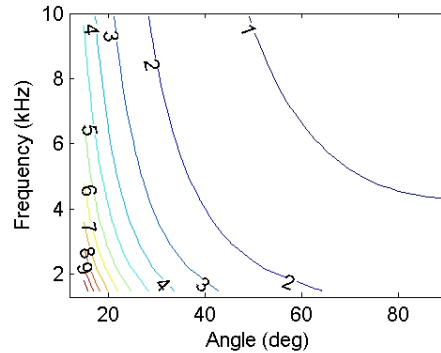


Figure 16. The in-plane Fresnel zone radius for the experimental geometry employed in the reflection measurements. The source plus receiver height above the boundary is 17 m.

When $2\pi L$ is on the order of and larger than the Fresnel zone and there is sufficient power in the low wavenumber part of the heterogeneity spectrum, the roughness plays a more significant role and the interference pattern is perturbed. This can be seen in row 2, $L=0.2$ m, for the high angles and high frequencies (above ~ 5 kHz) where the interference pattern is perturbed. Note that at low angles and frequencies, however, the interference pattern is not perturbed much, since in that region $\xi \gg 2\pi L$.

As the spectral cut-off increases further, e.g., $L=0.6$ m in row 3 Figure 10, more of the frequency-angle domain is affected by the roughness and broad patterns emerge. For example, in row 3 realization 1, there are reflection peaks at 30, 40, 50 80 deg that can be seen across a range of frequencies. The broadband nature can be explained by focusing from seabed curvature (from either layer interface). Theory predicts that the reflection amplitude due to focusing increases with increasing frequency. For example, above a concave hemi-spherical boundary the focused field amplitude (i.e., reflection) at a distance equal to the radius increases linearly with frequency (e.g., [38]). This amplitude increase is simply a manifestation of conservation of energy, where the size of the ‘focal spot’ decreases with increasing frequency. One example of this can be seen in row 5, realization 2 at about 55 deg, where the high reflection coefficient due to focusing increases in amplitude and narrows in angular range with increasing frequency (due to the diminishing in size of the focal spot). The oscillatory behavior of the frequency dependence in this (and other examples in Figure 10) are caused by the interaction of the focusing with the layer interference pattern.

Adjacent to the broadband focusing highlights there are broadband nulls. These are caused by defocusing (convex regions of the seafloor within the Fresnel zone). For each roughness realization, the focusing/defocusing regions move to different locations in angle space (as expected). The salient point here is that interface curvature can perturb (or even destroy) the interference pattern, hence reduce our ability to estimate geoacoustic properties.

In addition to the roughness parameters from the laser line scanner (spatial resolution 4 mm), it was desirable to also use roughness parameters from multibeam bathymetry data [36] (spatial resolution 1 m). The bathymetric roughness spectra yielded a spectral exponent of $\gamma_2 = 2.83$, closer to a ‘typical’ value of $\gamma_2 = 3$ for sandy sediments. These parameters were employed the same reflection simulation as described for Figure 15, but showed a weak or non-existent perturbation of the interference pattern for all values of L . This occurs because for a more normal spectral exponent, the small-scale roughness (high wavenumbers) imposed on the large-scale curvature (low wavenumbers) prevent high coherence required for significant focusing.

In summary, the simulations show that in some instances layer roughness does not greatly perturb the reflection coefficient (with respect to assumed flat interface assumption). In these cases the small-scale roughness is averaged out over the Fresnel zone and our uncertainty quantification approach will perform well. However, when 2 special conditions are both met:

- 1) there is a very large spectral exponent, (here $\gamma_2 > 4$), and
- 2) the spatial correlation length of the roughness is greater than the Fresnel zone, $2\pi L \sim \xi$,

then focusing and defocusing of the acoustic field occurs cause strong perturbations in the reflection coefficient. This would result in strong biases in the resulting geoacoustic parameters.

While it is not known how many of the SERDP sites would have both these conditions that lead to focusing and defocusing, our design for the p-GeoSS system is informed by the need to reduce the impact of focusing/defocusing. This can be done by increasing the Fresnel zone, ξ , which is a function of frequency f and grazing angle θ and can be written approximately as

$$\left\{ \left[(r_s + \xi_x)^2 + \xi_y^2 \right] + h_s^2 \right\}^{\frac{1}{2}} + \left\{ \left[(r_r - \xi_x)^2 + \xi_y^2 \right] + h_r^2 \right\}^{\frac{1}{2}} = \frac{c}{2f} + \frac{h_s + h_r}{\sin \theta}$$

where the subscripts x,y on the Fresnel zone ξ are the in-plane and out-of-plane directions respectively. It can be seen by inspection that the Fresnel zone size can be increased by any or all of the following: decreasing frequency, increasing source or receiver height, and decreasing grazing angle. This suggests:

- frequencies in the hundreds of hertz, possibly low kilohertz would be a favorable regime at least from the point of view of Fresnel zone size in regions with a very high roughness spectral exponent.
- moving the source and/or receiver as far as possible from the boundaries.
 - From a practical point of view, it is undesirable to tow the receiver near the sea surface given the deleterious impact on the tow stability and the deleterious effect of sea surface reflection/ scattering (which would tend to mask the seabed reflection and render high accuracy reflection processing impossible).
 - Using a surface-towed source with broad but downward-looking beam, would be a much better solution with respect to increasing the Fresnel zone size. We have extensive experience with such a source that has yielded high accuracy reflection data at single sites. It should be noted though that our extensive prior use of this source in water depths 70-180 m was not intended for maximizing Fresnel zone size, rather the source was attractive because it yielded a broadband stable pulse and is small, light, easy to operate, easy to deploy and recover and easy/inexpensive to ship.
- Low grazing angles can be achieved by either
 - placing source and/or receiver near the seabed (however this is contrary to Fresnel zone considerations above) or
 - by placing source and receivers far apart in horizontal offset. This is the more practical of the 2 options.

In the following, high-level design factors are considered for the p-GeoSS system.

1. Source

a. Source Frequency range

The frequency range largely determines what physics will and will not be important in the measurements (examined in detail in the previous section). Selection of the frequency range should also take into account the frequencies at which the key parameters (compressional and shear wave velocities and attenuations and density) are most sensitive, i.e., estimated with the lowest uncertainties, what frequencies can be robustly modeled, and what frequencies are practical from ocean engineering limitations (e.g., weight, power, and tow considerations).

One of the most highly informative regions of data space (frequency and angle) is where oscillations due to layering occur. This is the Bragg condition and can be written (for destructive interference),

$$k_z d = m\pi/2, m=1,2,\dots$$

where $k_z = 2\pi f/c \sin\theta$ is the vertical component of the wavenumber, c is layer sound speed, θ is the grazing angle, and d is layer thickness. We can estimate a rough upper bound for the frequency by selecting rough bounds for the various parameters. For example, to resolve layer thicknesses d to ~ 0.1 m near normal incidence, then the frequency that satisfies the Bragg condition is 2.5 times the layer sound speed, or about 4 kHz for a typical sand 1650 m/s and 4.5 kHz for a very coarse sand/gravel. Thus an upper frequency of about 5 kHz should permit adequate measurement of layer interference patterns. This is, in fact, a conservative estimate of the frequency range for a given resolution. Theory and our past experience with measured data show that layers can be detected to about half the first Bragg minimum criterion. That is, the behavior of the reflection coefficient across frequency and angle provides enough information to identify the layer with certainty without less than first minimum or maximum being measured.

b. Source Directionality

Source directionality is another important design parameter. On one hand, greater source directionality can reduce multipath contamination. On the other hand, a source with strong directionality can lead to bias errors if the source orientation is known imperfectly. For example, in the analysis of measured data using a directional coherent source towed behind an AUV (see Section IV.A.3), there were regions of the data space where reflection data were biased due to lack of knowledge of the exact source positioning. The only practical recourse was to remove those data, though fortuitously the removal of the biased data did not reduce the information very much. In general, this result cannot be counted on, and there is a clear reason to employ a source with slowly varying three dimensional beam patterns.

c. Pulse repetition rate

The simplest approach for mapping the data to angle and position on the seabed is to use one ping received on all 32 receivers to obtain $|R_s(\theta)|$. For straight line ray paths, the spatial separation of the specular points along the seabed is simply $d/2$, where d is the inter-element array spacing. Thus, this approach laterally averages over a distance on the seabed of approximately one half the receiver length (16 m) plus the Fresnel zone radius at the lowest and highest angle. The Fresnel radius depends upon frequency, source/receiver separation and altitude. As an example at 2000 Hz, for the source/receiver combined height above the seabed of 24 m, the averaging ‘footprint’ on the seabed is about 24 m with this approach.

Another approach is to use common depth point (CDP) processing (e.g., [33]) in which the specular point on the seabed for all angles is nearly identical. CDP trades angular resolution for improved spatial resolution. In CDP, a single receiver is used from each ping and by constraining the maximum distance between the specular angles to be less than $d/2$, the resulting footprint is about 8 m at 2000 Hz, a factor of 3 improvement in spatial resolution over the simple approach. The number of pings or angles possible (N_{CDP}) for $|R_s(\theta, f)|$ is

$$N_{CDP} = d N_{rec} \Omega / 2v + 1 \quad (3)$$

where N_{rec} is number of receivers, v is speed over ground and pulse repetition rate, Ω . For nominal values of $N_{rec}=36$, $d=1$, and $v=1.5$ m/s, $N_{CDP} \sim 12\Omega$. A reasonable pulse repetition rate of 3 Hz would lead to $N_{CDP} = N_{rec} = 36$ angles per stack. This would provide a sufficient number of angles to achieve obtain quantitative geoacoustic properties at relatively small uncertainties.

Since one of the assumptions in our forward model is that the seabed is nearly uniform across the illuminated region, the better horizontal spatial resolution from CDP processing is important because it allows a wider range of spatial variability to be properly mapped. Thus, the main factor in the determining the pulse repetition rate is that it should be sufficient so that CDP processing will yield a reasonable number of angles.

d. Source height above the seabed

The dominant consideration here was discussed in the opening paragraphs of Section IV.B, where the need to maximize the Fresnel zone size informs the source height to be as close to the sea surface as practical.

e. Recommended Source

Taking into account the above discussion, a practical solution is a commercially available Uniboom source, which has the following characteristics:

- It is towed very near the sea surface, typically a few tens of centimeters (which is important for maximizing the Fresnel zone size).
- It transmits a repeatable pulse that can be broadcast at 3 pulses per second, which would yield good CDP results at tow speeds of 3 knots.
- It has a source plate of radius of 0.19 m and weighs only 18 kg in air. It is towed on a small catamaran of approximate dimension 0.8 x 1.6 x 0.5 m, with power requirements that make it convenient to work off of even small coastal vessels.
- It has a broadband signature, 0.2-10 kHz.

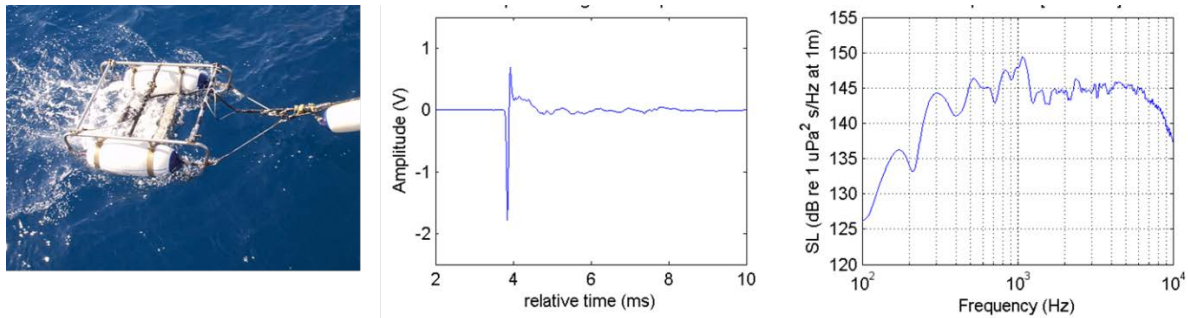


Figure 17. From left to right: photograph of Uniboomer source mounted on a catamaran, example of source pulse measured on axis at sea, and the resulting spectrum.

2. Receiver

Each source-receiver position represents a different angle for the reflection coefficient. Thus, determining the number of receivers and their layout should be guided by the expected information content in the angular domain.

A potentially highly informative angle is that associated with the critical angle of the sediment, defined as $\theta_c = \cos^{-1}(c_w/c_s)$. If the water sound speed c_w is known, then measuring the critical angle can directly yield the sediment sound speed, c_s . In unconsolidated sediments expected at these water depths, critical angles vary roughly from 0-33 deg. In practice, a classical critical angle is not always apparent, either because there is no critical angle (e.g., in the case of thick low-velocity silty-clayey sediment) or because the presence of nearly ubiquitous sedimentary layering perturbs its behavior.

Taking a layered medium as the most likely scenario, we can examine angular information content by considering the Bragg condition $2\pi f d / (c \sin\theta) = m\pi/2$, $m=1,2,\dots$. Our first interest is in the layer sound speed c . The Bragg condition indicates that c cannot be gleaned from a single angle θ , rather it can only be obtained over a range of angles where the function $1/\sin\theta$ has a sufficient variation. This function varies slowly at steep angles (near normal incidence) and rapidly at low angles, for example from 90 to 60 deg it varies only 15%, but from 90 to 30 deg it varies by 100% (factor of 2). An example of the reflection coefficient is shown in Figure 18 where the interference pattern $f/\sin\theta$ is clearly seen. Also note the relatively slow change with angle of R_s near 90 deg at a given frequency and the more rapid changes below about 60 deg. Our models, as well as previous measurement results, show that a range of angles from 30-90 deg, or even 30-70 deg, provide sufficient information to extract layer sound velocity with small uncertainties, less than about 1%.

Sound velocity and layer thickness are coupled in the Bragg condition, and in fact the measurement of the interference pattern over that angular range provides sufficient information content to extract both c and d via the frequency-angle evolution of the peaks and valleys associated with the interference pattern, see Figure 18.

In addition to evolution of the pattern in frequency-angle space, the amplitude of the peaks and valleys for example at a single angle, contain a great deal of information about (i.e., are highly sensitive to) the layer density contrast and attenuation. The ability to obtain accurate information about sediment layer sound speed, density and attenuation from the interference pattern of measured reflection data has been demonstrated numerous times in field data (e.g., [1]-[4],[6]-[19]).

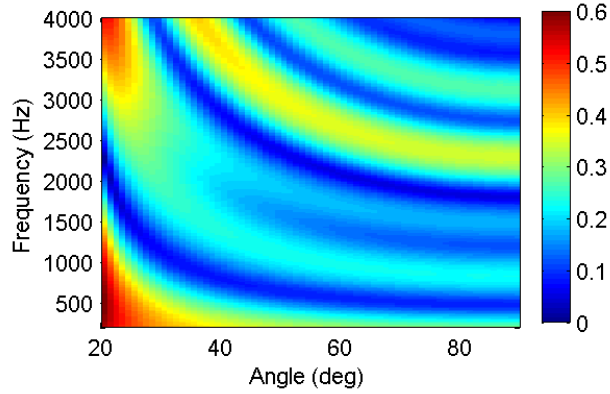


Figure 18. Reflection coefficient, $|R_s|$, for two layers 0.3 m and 0.7 m over a halfspace. The information content is in both the pattern (evolution of constant R_s over frequency-angle space) and in the amplitude oscillations from the peaks to troughs.

a. Number and layout of receivers

How many angles are required to provide sufficient information about the sediment properties? This depends on both the particular sedimentary environment (hence angular dependence of the reflection coefficient) as well as the range of angles that are measured. While the latter can be controlled, the angular dependency we are trying to measure will of course not be known, *a priori*. Thus, we draw heavily on past experience where results have shown that roughly 30 angle observations can provide highly detailed and accurate geoacoustic properties (as just one of many examples, see [14]).

There are several considerations in determining the receiver spacing. Since each receiver represents a different seabed angle, the receiver spacing could be such that it yields evenly spaced angles. In this design, the inter-hydrophone distances will be smallest towards the front of the array (i.e., closest to the source). However, in the discussion above it was shown that there is generally higher information at lower grazing angles where the interference pattern changes more rapidly with angle. This suggests that a better strategy is to design the inter-hydrophone spacing such that the angular resolution is highest at the lowest grazing angles. From a practical point of view we recommend a constant inter-phone spacing. This yields the desired higher angular resolution at lower angles and also provides needed flexibility for adjusting to different water depths. Figure 19 shows the angles and the angular resolution for a receive array of 36 hydrophones evenly spaced with a 1 m separation. Note that at steep angles (close to the source), the angular resolution changes rapidly about 4 deg, from phone to phone, while at low angles (at large source –receiver offsets) the angles change by about 1 deg.

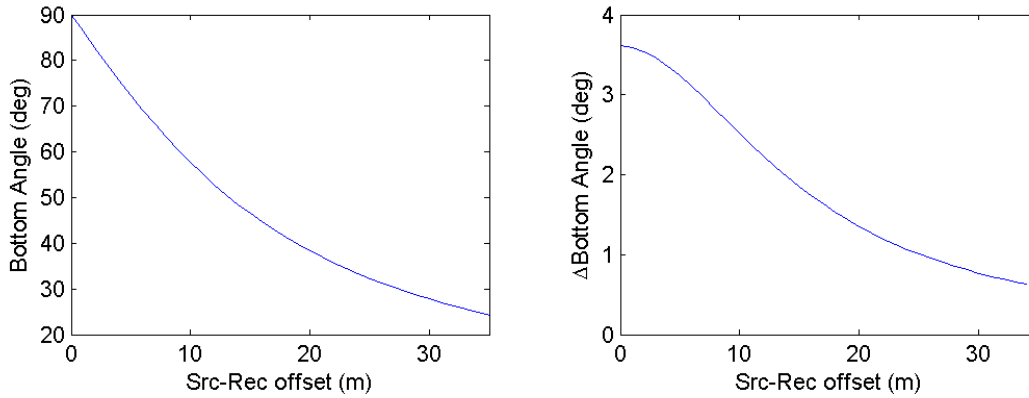


Figure 19. Seabed reflection angles (left panel), and phone-to-phone angle resolution (right panel) for a water depth of 10 m and evenly spaced hydrophones. Note that the difference in angles from phone to phone is about 4 times smaller at lower angles than at normal incidence. This provides a better sampling of the information content in the angular domain.

An additional consideration for the receiver layout is that it would be advantageous to also measure seabed scattering via beamforming. While our primary observable is the reflection coefficient, scattering would provide diagnostic information in case of large roughness scales that could disrupt reflection coefficient analysis (e.g., see Figure 15). Diagnostic information means that scattering measured from the short array section could identify the roughness scales that are present. Scattering could potentially also be a useful quantity to provide to the detection/classification sonar systems. The nominal 1 m spacing permits beamforming at frequencies up to 750 Hz. A short aperture of more closely spaced hydrophones, 0.25 m would provide beamforming capability up to 3 kHz. The greater frequency range, permitted by two nested inter-phone spacings, improves the ability to estimate the spectral roughness parameters. The short aperture should be placed at the head of the array, not for purposes of increased angular resolution, but rather for a more monostatic geometry, i.e., closest to the source. The monostatic geometry yields the greatest opportunity for measuring scattering close to the array.

b. Receiver directionality

One of the challenges of measuring the seabed reflection coefficient in very shallow water is separating multipaths, i.e., direct, bottom, and sea surface. Figure 20 shows travel time differences (assuming isovelocity and $c=1500$ m/s) for a 10 m water depth, a source depth of 0.3 m and two receiver depths 4 m (blue) and 6 m (red). The solid line is the travel time difference (TTD) between the direct and bottom reflected paths, the dash-dotted line is the TTD between bottom and sea surface reflected paths. Note that for the deeper receiver depth, the direct and bottom arrivals are less than 4 ms apart at angles below about 60 deg (red solid). The 4 ms line indicates the length of the boomer pulse, including ring-down. Thus, in 10 m water depth, multipath separation could not be achieved; hence, no reflection data could be obtained below 60 deg. This limited angular would severely compromise the geoacoustic information. The angular coverage could be improved a bit by changing the receiver depth to 4 m. In this case the direct-bottom and bottom-sea surface TTD cross the threshold of 4 ms at about the same angle, which optimizes the possible angular coverage. However, even in this case, the lowest angle is 45 deg, which again would substantively compromise the geoacoustic information. Also, it should be

noted that Figure 20 is an idealized and optimistic prediction, especially for the sea surface, which is rough. A rough sea surface means that in practice the sea surface arrival will be spread in time, so the actual travel time differences will be somewhat smaller than predicted here.

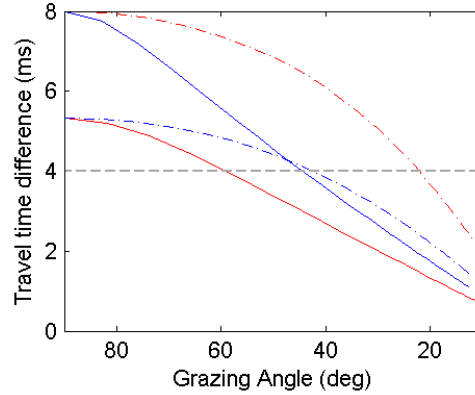


Figure 20. *travel time differences between the direct and bottom reflected (solid line) and the bottom reflected and sea surface reflected (dash dot line) for a water depth of 10 m. The source depth is 0.3 m and results for two receiver depths are shown, 4 m (blue) and 6 m (red).*

The implication of this analysis is that omni-directional receivers will not provide the necessary range of reflection angles in water depths shallower than about 15 m. Traditional or advanced beamforming on a linear array is not a robust option, since at low angles where multi-path rejection is a problem, the angles of arrival are relatively close and the direct and surface reflected paths will both have a much higher amplitude than the bottom reflected path in many instances.

A more robust approach to multipath rejection is to employ receiver directivity using tetrahedral receiver elements, i.e., a set of 4 hydrophones arranged in a tetrahedral fashion. This can be thought of as an incremental extension to cardioid elements, which have been used for undersea towed arrays for some time, e.g., [40]. A cardioid element consists of 3 in-plane hydrophones spaced at 120 deg, a roll sensor allows their position to be accurately known. The tetrahedral element would comprise a cardioid configuration plus one extra phone along the axis of the array. Figure 21 shows the arrangement of the four hydrophones comprising the tetrahedral element along with the roll sensor.

An additional benefit of the tetrahedral elements is that they can be used for reducing the impact of unwanted noise (e.g., nearby ships).

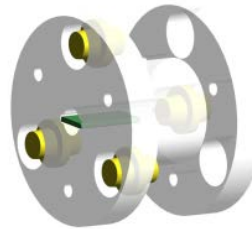


Figure 21. *Tetrahedral hydro-phone (yellow) positions and roll sensor (green).*

c. Receiver height above seabed considerations

The tow height at a specific site will be governed by trade-offs between (in order of importance):

- consideration of bottom bathymetry and/or hazards,
- maximizing the angular coverage,
- maximizing the Fresnel zone size (opposite dependency as angular coverage).

d. Recommended receiver

Understanding of the information content in the angular regime, as described above, needs to be considered in light of engineering limitations for a practical receiver. These practical limitations are a maximum array length of 40 m, and maximum total number of channels of 192 with a maximum sampling frequency of 50 kHz. These are not absolute limitations, but staying within these constraints allows use of existing hardware/technology and keeps the array size and weight and handling requirements commensurate with the capability of a small coastal vessel.

Our high-level design for the receive array is shown in Figure 22 and consists of 48 tetrahedral elements (total of 192 channels) with 16 elements spaced at 0.25 m at the front of the array and 32 elements spaced at 1 m. The total array aperture is 35 m. The dynamic range on the receivers should be 20 bits or greater. This permits measurement of both the direct blast from the source as well as low-amplitude reflections from the seabed.

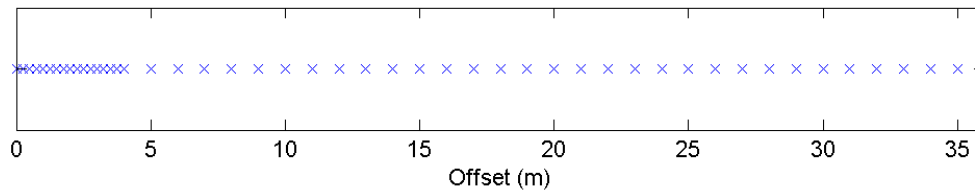


Figure 22. *prototype GeoSS receiver array layout, with 48 tetrahedral elements. Each tetrahedral element (indicated by x) is comprised of 4 hydrophones. There are 36 elements spaced at 1 m, and a nested array at 0.25 m spacing at the front of the array.*

3. Towing platform

In the measured reflection data that we used to test our sequential algorithm, (Sec IV.A.3) an AUV was used as a very stable platform to place source and receiver near the seabed. In the shallow water depths of interest to SERDP (< 35 m), while use of an AUV with a towed source and receiver may be possible, it seems impractical. The most compelling consideration dictating the choice of tow platform is that the physics of the sediment reflection problem indicate that a surface towed source and a subsurface towed receive array will provide the highest quality data. This configuration is very suitable for a small coastal vessel, but highly impractical for an AUV.

4. Data acquisition system

The data acquisition system must be capable of acquiring 192 channels with 24 bit precision at 50 kHz and much lower bandwidth non-acoustic sensor data including roll, pitch, heading and depth. The data acquisition system can either be housed on the wet side (in the array) or on the

dry side (coastal vessel). The data storage should be sufficient to allow storage for at least up to 12-14 hours of survey data per day.

5. Summary p-GeoSS design comments

Two important considerations in the p-GeoSS system were maximizing Fresnel zone size and maximizing the angular range. The first condition is predicated upon meeting the assumptions in the uncertainty quantification processing (the forward model), and the second condition is predicated upon collecting sufficiently informative data to obtain reasonably low uncertainties. These two considerations have opposite dependencies in terms of source/receiver height above the seabed. The first and second considerations would maximize and minimize their heights respectively. For reasons explained above, it is advantageous to maximize the source height and use the receiver height (and scope) to obtain the desired angular coverage, while meeting other considerations, e.g., equipment safety.

The use of tetrahedral elements was necessitated by the requirement of multi-path separation. The limits on multi-path separation were defined by the choice of source (Uniboomer), which in turn was selected to maximize Fresnel zone size on the sediment. Another source, e.g., a coherent source, could be designed with a higher pulse resolution, and thus potentially remove the need for the tetrahedral elements. However, such a source would need to be towed at a deeper depth than the Uniboom. This would not only decrease the Fresnel zone size, but make deployment and towing considerably more challenging. Having an additional sub-surface tow cable would make the towing more difficult and possibly compromise equipment safety in all but the most benign conditions. Alternatively, placing the source on the same cable as the receiver would add considerable engineering complexity and cost, as well as making the compromise between Fresnel zone size and angular coverage more difficult to resolve. In terms of practical usage, the combination of the surface-towed Uniboom and the tetrahedral elements appears to be the best compromise for a system that eventually will be used operationally.

V. Conclusions and Implications for Future Research/Implementation

At the beginning of the project there were two main gaps in capability:

1. it was not possible to perform sequential Bayesian inversion for track lengths more than a few hundred meters (far too short to be useful for surveys needed for SERDP application)
2. There was a gap in knowledge in how to design geoacoustic survey system for the scales and water depths pertinent to the SERDP munitions problem.

The first gap was closed successfully and beyond expectations. By improving both the accuracy and speed of the forward model (solving the Sommerfeld integral), and by incorporating a more informative prior for seabed complexity based on even numbered order statistics and a Poisson distribution, and by developing a novel particle filter that includes bridging distributions via trans-D parallel tempering that carefully exploited new hardware, more than 1500 data sets could be processed in one week. This result was 50% more computationally efficient (faster) than our projections at the beginning of the project. In summary, we could not process sequential

reflection data for a reasonable survey lengths at the beginning of the project. At the end of the project, reflection survey data can now be readily processed. This is a significant advance in capability.

The second gap was also successfully closed. Through modeling and advances and insights accrued during application of sequential inversion to both simulated and measured data, we have developed a high-level design for a prototype Geoacoustic Sediment Survey system. The design includes a commercial broadband surface-towed source and a towed receive array consisting of a 48 tetrahedral elements arranged to provide seabed reflection data at high accuracy and high information content.

Remaining research question

- Is there sufficient information content in reflection measurements to extract information about the elastic properties of marine sediments?

Sediment shear waves are excited in the sediments by compressional waves in the water. Generally, their amplitude is sufficiently small that the sediment is treated as an effective fluid medium such that shear wave effects are biased into other parameters, primarily attenuation. This is nearly always a reasonable simplification of the full-physics of the problem and the biases are often small. Nevertheless, there are reasons to pursue the above question, not only for scientific purposes but also for more applied reasons, inasmuch as robust shear-wave velocity estimates might be useful for estimating, perhaps via empirical relations, the shear resistance/strength of sediments which is relevant to burial mechanics.

The question posed here has direct relevance, but should not be considered as critical to the fielding and operation of a p-GeoSS system.

Other uses for products from this work

Results of the research conducted under this project can be applied to basic research questions about lateral variability of sediment physical properties. Until now, it has been difficult to measure quantitative geoacoustic variability down to scales of 10 m. The most common form of acoustic remote sensing for geoacoustic properties typically averages over scales of km to tens of km. In addition, the advances made here can be used for applied problems for example in geohazard mapping in support of offshore construction of pipelines and rigs.

VI. References

- [1] Holland C.W. and J. Osler, High resolution geoacoustic inversion in shallow water: A joint time and frequency domain technique, *J. Acoust. Soc. Am.*, 107, 1263-1279, 2000.
- [2] Holland C.W., Seabed reflection measurement uncertainty, *J. Acoust. Soc. Am.*, 114, 1861-1873, 2003.
- [3] Holland C.W., Coupled scattering and reflection measurements in shallow water, *IEEE J. of Oceanic Eng.*, 27, 454-470, 2002.
- [4] Holland C.W., Geoacoustic inversion for fine-grained sediments, *J. Acoust. Soc. Am.*, 111, 1560-1564, 2002.
- [5] Dosso S.E., Quantifying uncertainty in geoacoustic inversion. I. A fast Gibbs sampler approach, *J. Acoust. Soc. Am.* 111, 129-142, 2002.
- [6] Holland C.W., Dettmer J. and Dosso S.E., Remote sensing of sediment density and velocity gradients in the transition layer, *J. Acoust. Soc. Am.*, 118, 163-177, 2005.
- [7] Dosso S. E. and C.W. Holland, Geoacoustic uncertainties from viscoelastic inversion of seabed reflection data, *IEEE J. Ocean Eng.*, 31, 657-671, 2006.
- [8] Holland C.W., S.E. Dosso, and J. Dettmer, A technique for measuring in-situ compressional wave velocity dispersion in marine sediments, *IEEE J. Oceanic Eng.*, 30, 748-763, 2005.
- [9] Dettmer J., S.E. Dosso and C.W. Holland, Full-wavefield reflection coefficient inversion, *J. Acoust. Soc. Am.*, 122, 3327-3337, 2007.
- [10] Dettmer J., S.E. Dosso and C.W. Holland, Uncertainty estimation in seismo-acoustic reflection travel-time inversion, *J. Acoust. Soc. Am.*, 122, 161-176, 2007.
- [11] Dettmer J., S.E. Dosso and C.W. Holland, Model selection and Bayesian inference for high resolution seabed reflection inversion, *J. Acoust. Soc. Am.*, 125, 706-716, 2009.
- [12] Dettmer J., S.E. Dosso and C.W. Holland, Joint time/frequency-domain inversion of reflection data for seabed geoacoustic profiles, *J. Acoust. Soc. Am.*, 123, 1306-1317, 2008.
- [13] Dosso S. E., C.W. Holland and M. Sambridge, Parallel tempering in strongly nonlinear geoacoustic inversion, *J. Acoust. Soc. Am.*, 132, 3030-3040, 2012.
- [14] Holland C.W., P.L. Nielsen, J. Dettmer and S.E. Dosso, Resolving meso-scale seabed variability using reflection measurements from an autonomous underwater vehicle, *J. Acoust. Soc. Am.*, 131, 1066-1078, 2012.

- [15] Dettmer J., S.E. Dosso and C.W. Holland, Sequential trans-dimensional Monte Carlo for range-dependent geoacoustic inversion, *J. Acoust. Soc. Am.* 129, 1794 -1806, 2011.
- [16] Dettmer J., S.E. Dosso and C.W. Holland, Trans-dimensional geoacoustic inversion, *J. Acoust. Soc. Am.*, 128, 3393-3405, 2011.
- [17] Dettmer J., C.W. Holland and S.E. Dosso, Resolving lateral seabed variability by Bayesian inference of seabed reflection inversions, *J. Acoust. Soc. Am.*, 126, 56-69, 2009.
- [18] Dettmer J., C.W. Holland and S.E. Dosso, Trans-dimensional uncertainty estimation for dispersive seabed sediments, *Geophysics*, 78, WB63-WB76, 2013.
- [19] Holland C.W. and J. Dettmer, In-situ sediment dispersion estimates in the presence of discrete layers and gradients, *J. Acoust. Soc. Am.*, 133, 50-61, 2013.
- [20] Steininger G., C.W. Holland, S. Dosso and J. Dettmer, Seabed roughness parameters from joint backscatter and reflection inversion on the Malta Plateau, *J. Acoust. Soc. Am.*, 134, 1833-1842, 2013.
- [21] Chu, P.C., Mine Impact Burial Prediction From One to Three Dimensions, *Transactions of the ASME*, 62, 010802-1 to 25, 2009, doi:10.1115/1.3013823.
- [22] Bennett, R.H., R.W. Faas and C.W. Curry, 2004. Geotechnical Mine Burial Prediction Technique and Database Generation for Development of Mine Burial Maps, Coastal Shallow-Water Fine-Grained Sediments. SEAPROBE, Inc. Technical Report Number SI-0004-01, 89p., Companion Rept. with SEAPROBE, Inc. Technical Report Number SI-0004-02, 89p.
- [23] Barbu C., P. Valent, M. Richardson, A. Abelev and N. Plant, A Probabilistic Approach for Mine Burial Prediction, in *Detection and Remediation Technologies for Mines and Minelike Targets IX*, ed. by R. S. Harmon, J. T. Broach, J. H. Holloway, Jr., *Proc. of SPIE Vol. 5415*, 2004.
- [24] Brekhovskikh L.M. and O.A. Godin, *Acoustics of Layered Media II: Point Sources and Bounded Beams*, Springer-Verlag, Berlin, 1999.
- [25] Quijano J. E., S. E. Dosso, J. Dettmer, and C.W. Holland, Fast computation of seabed spherical-wave reflection coefficients in geoacoustic inversion, *J. Acoust. Soc. Am.*, 138, 2106-2117, 2015.
- [26] Martinelli S. and C.W. Holland, Effects of seabed curvature on the scattered acoustic field, *Acoust. Soc. Am.*, May 2016, Salt Lake City, UT.
- [27] Steininger G., J. Dettmer, S. E. Dosso, and C.W. Holland, Trans-dimensional joint inversion of seabed scattering and reflection data, *J. Acoust. Soc. Am.*, 133, 1347-1357, 2013.

- [28] Dettmer J., S. E. Dosso, T. Bodin, J. Stipčević, and P. R. Cummins. Direct-seismogram inversion for receiver-side structure with uncertain source-time functions. *Geophys. J. Int.*, 1373–1387, 2015.
- [29] Green P.J., Reversible jump Markov chain Monte Carlo computation and Bayesian model determination, *Biometrika*, 82, 711-732, 1995.
- [30] Dettmer J. and S. Dosso, Probabilistic Geoacoustic Inversion in Complex Environments, ONR Annual Report, 2015.
- [31] Kim S., J. Dettmer, J. Rhie, and H. Tkalcic. Efficient trans-dimensional optimization and Bayesian uncertainty estimation in joint surface wave dispersion and receiver function inversion: application for the southern Korean Peninsula. *Geophys. J. Int.*, in review.
- [32] The specific case reported here is typical of many inversion test cases were carried out.
- [33] Schneider W.A., The common depth point stack, *Proc. of the IEEE*, 72(10),1238-1254, 1984.
- [34] Pinson S., J. Cordioli and L. Guillon, Spherical wave reflection in layered media with rough interfaces: three dimensional modeling, *J. Acoust. Soc. Am.*, 140, 1108-1115, 2016.
- [35] Langston C. A. , The effect of planar dipping structure on source and receiver responses for constant ray parameter, *Bulletin of the Seismological Society of America*, 67(4), 1029-1050, 1977.
- [36] Holland C.W., S. Pinson, C. Smith, P. Hines., D. Olson, S. E. Dosso and J. Dettmer, Seabed structure inferences from TREX13 reflection measurements, *IEEE J. Oceanic Eng.*, 42, 268-288, 2017.
- [37] Hefner T. and DJ Tang, Seafloor Laser Scanner Measurements at TREX13, *IEEE J. Oceanic Eng.*, 42,110-1124, 2017.
- [38] Vercammen M., The reflection of sound by curved surfaces, *Proc. Acoustics'08*, Paris, 3473-3478, 2008.
- [39] de Moustier C. and B.J. Kraft, Bathymetry and 400-kHz seafloor acoustic backscatter imagery offshore Panama City Beach, FL, *to be published in IEEE J. Ocean Eng.*
- [40] Preston, J. , Using Triplet Arrays for Broadband Reverberation Analysis and Inversions, *IEEE J. of Oceanic Engineering*, 32, 879-896, 2007.
- [41] Holland C.W., Estimating seabed structure from perturbed layer resonance fringes (A), *J. Acoust. Soc. Am.*, 2016.

[42] Martinelli S. and C.W. Holland, Effects of seabed curvature on the scattered field (A), J. Acoust. Soc. Am., 2016.

[43] Holland C.W. and S.E. Dosso, Mid frequency shallow-water fine-grained sediment attenuation from waveguide reverberation, J. Acoust. Soc. Am., 134, 131-134, 2013.

Appendix A. Supporting Data

There were no data collected during this 2-year proof-of-concept phase. The data that were used were collected during a prior research grant. The analyses performed on those data are provided in Section IV.A.3 of this report.

Appendix B. List of Scientific/Technical Publications

1. Mandolesi E., J. Dettmer, S. E. Dosso, and C. W. Holland, Trans-dimensional Bayesian inference for large sequential data sets, Amer. Geophysical Union, San Francisco, 2015.
2. Dettmer J., J. Quijano, S.E. Dosso, C.W. Holland and E. Mandolesi, Efficient estimation of range-dependent seabed properties from large data volumes of a towed source and receiver-array, Can. Acoust. Assoc., Vancouver, 2016.
3. Martinelli S. and C.W. Holland, Effects of seabed curvature on the scattered field (A), J. Acoust. Soc. Am., Salt Lake City, 2016.
4. Dosso S.E., J.D. Dettmer, C.W. Holland and E. Mandolesi, Seabed properties estimation from acoustic recordings by an autonomous underwater vehicle, European Geophysical Union meeting, Vienna, Austria 2016.
5. Dettmer J., J. Quijano, S.E. Dosso, C.W. Holland, and E. Mandolesi, Uncertainty quantification of seabed parameters for large data volumes along survey tracks with a tempered particle filter, Am. Geophysical Union, 2016.
6. Dettmer J., C.W. Holland, E. Mandolesi, and S.E. Dosso, Spatial variability of seabed properties on the Malta Plateau inferred by an autonomous moving system (A), J. Acoust. Soc. Am., 2016.
7. Mandolesi E., J. Dettmer, S. E. Dosso, and C. W. Holland, Efficient Sequential Monte Carlo estimation of range-dependent seabed properties (A), J. Acoust. Soc. Am., 2016.
8. Dettmer J., C.W. Holland, S.E. Dosso and E. Mandolesi, Geoacoustic inversion to study spatial variability and uncertainty along a 14-km seabed survey on the Malta Plateau (A), J. Acoust. Soc. Am., 2017.

Appendix C. Other supporting Material

Two videos are provided that give insights into (1) the reflection-coefficient data processed along the survey track and (2) the inversion results in terms of full uncertainty quantification along the track. More details about the measured data can be found in Section IV.A.3

1. Reflection-coefficient Stacking

As described in Section IV.A.3, the reflection coefficients were stacked along the track to address the issue of speckle in the data which is due to interface curvature not captured by the forward model. Video “video_data_stacks.mp4” illustrates which pings were stacked along the track. The 6 panels from top left to bottom right show the data for the 6 frequency bands chosen for the inversion (988, 1113, 1288, 1913, 2263, and 2513 Hz). The ping number on which the stack is centered is also shown. On each panel, the colored lines show the reflection coefficients

for 10 consecutive pings. Red and green distinguish the data for adjacent frequency bins. All these data are stacked to produce the black lines which are the data employed in inversion. The gaps in the black data are sections that are excluded due to excessive ping-to-ping variability. Note that the ping number will sometimes jump to larger values during the video. Those jumps are due to sections of track being excluded from the analysis due to rapid spatial variability along the track which cannot be met by the assumptions of our method. This occurs for a total of 451 pings along the track length of 3428 pings.

In addition, the dashed lines show to estimates of noise, the black dashed line indicating the standard deviation of all red and green curves and the red dashed line indicating the average of two standard deviation values calculated separately for the red and green lines. The inversion results in this report employ the red dashed line as an estimate for data noise.

2. Inversion results along the survey track

The video “video_AUV_results.mp4” summarizes the full uncertainty quantification along the track. The results are organized in three rows and multiple panels per row. The top row, left panel shows the posterior mean velocity estimate for the track as a function of depth below seafloor and ping number. The vertical dashed line indicated the position along the track (the current ping) for the other information in this video. The right panel in the top row quantifies the seabed complexity at the current ping in terms of a PDF for the number of layers. The seabed complexity is observed to change significantly along this survey.

The 4 panels in the middle row show (from left to right) marginal of interface probability, and then profile marginal densities for velocity, density and the base-10 logarithm of attenuation. The profile marginal represent a rigorous quantification of uncertainty for those parameters and can be observed to vary significantly along the track.

The panels in the bottom row show data fits for every second frequency band considered in the inversion. Black crosses represent the observed and stacked data. The red lines are data predictions for 5000 randomly chosen models from the posterior which illustrate the range of data predictions produced by the posterior ensemble of models. Note that the predictions fit the data well everywhere along the track, even when changes in the environment are rapid (e.g., when a data gap is encountered).