DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Efficient Inversion in Underwater Acoustics with Iterative and Sequential Bayesian Methods

Zoi-Heleni Michalopoulou
Department of Mathematical Sciences
New Jersey Institute of Technology
Newark, NJ 07102
Telephone Number: (973) 596 8395
Fax Number: (973) 596 5591
E-mail: michalop@njit.edu
URL: http://www.math.njit.edu/~elmich

Award Numbers: N000140710521, N000141010073
Category of research: shallow water acoustics

LONG TERM GOALS

The long term goal of this project is to develop efficient inversion algorithms for successful geoacoustic parameter estimation and source localization, exploiting (fully or partially) the physics of the propagation medium. Algorithms are designed for geoacoustic inversion via the extraction features of the acoustic field.

OBJECTIVES

- Achieve accurate and computationally efficient geoacoustic inversion and source localization by designing estimation schemes that combine acoustic field modeling and statistical modeling.
- Develop methods for passive localization and inversion of environmental parameters that select features of propagation that are essential to model for accurate inversion.
- Implement sequential filtering methods that provide dynamic and efficient solutions for the first two objectives.

APPROACH

Continuing efforts from previous years, we worked with Bayesian approaches applied to sound signals for the extraction of acoustic features using a combination of physics and statistical signal processing.

One of the topics approached this past year was geoacoustic inversion using arrival time estimation for propagation in multipath environments with sequential Monte Carlo methods, namely, particle filtering. Some of our results have been presented in [1,2,3]. The idea is to estimate accurately arrival times and corresponding amplitudes of sound paths in shallow water environments. Arrival times as well as amplitudes of corresponding paths provide critical information on the geometry and environment in which sound propagates. Even small discrepancies in arrival time estimates can lead to significant errors to inferences made on inversion. Accurate estimation, however, linked with

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the 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 the 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 Washington Headquarters Services, Directorate for Information Operations and Reports, 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 a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **SEP 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**

4. TITLE AND SUBTITLE **Efficient Inversion in Underwater Acoustics with Iterative and Sequential Bayesian Methods**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **New Jersey Institute of Technology,Department of Mathematical Sciences,Newark,NJ,07102**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

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

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

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

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

physical models for sound propagation in the ocean, can lead to accurate geoacoustic inversion. In addition to simple point estimates, our method facilitates the computation of posterior probability density functions (PDFs) for arrival times which can be used for uncertainty estimation in geoacoustic inversion.

More work was also done on identifying arrival times and amplitudes of distinct frequencies (within a single mode or across different modes). Those characteristics provide significant information on properties of the propagation medium and source location. The importance of modal arrival times and amplitudes in geoacoustic inversion and source localization has been discussed in [4, 5, 6, 7]. Towards this goal, the method developed by the PI for modal decomposition of a received signal and modal arrival time estimation [8,9] was applied for geoacoustic inversion.

WORK COMPLETED

The described approaches were improved to provide more accurate estimates of arrival times and geoacoustic parameter estimates. Specifically, in addition to conventional, forward particle filters, smoothing backward mechanisms were employed, reducing uncertainty. The arrival time tracking method was applied to synthetic and real data both for source localization and sound speed estimation in a seabed layer. The method was also adapted for use with passive fathometer data [10,11], tracking seabed reflectors. The particle filtering method for tracking trajectories in time-frequency representations was combined with an acoustic model for sound speed inversion.

RESULTS

Results that we have previously reported illustrated how we can extract arrival time estimates from sound signals in the ocean that are more accurate than those computed with conventional methods. However, performing geoacoustic inversion with arrival time estimates obtained with our method for some cases, we noticed that uncertainty in geoacoustic estimate results can still be significant. An example is shown in Fig. 1, where using multipath arrivals extracted with particle filtering, we estimated sound speed in a seabed layer. Although the mode of the PDF is very close to the true sound speed value (1645 m/s), substantial uncertainty is present, manifested as an extensive spread of the PDF.

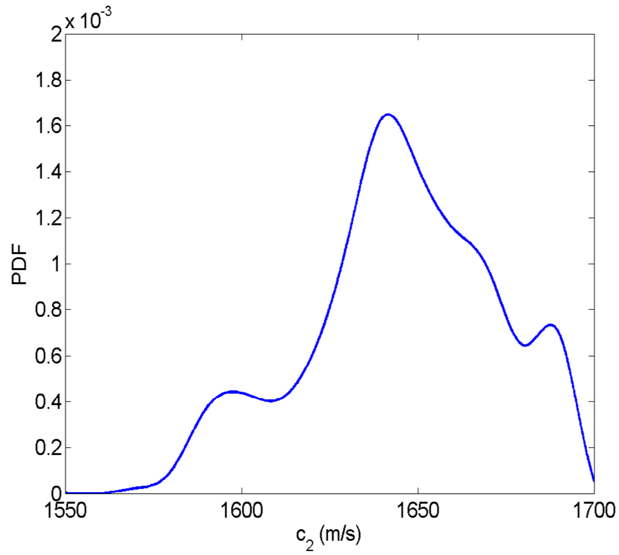

Figure 1: PDF of sediment sound speed estimated using arrival times of ray paths extracted with particle filters.

To improve our geoacoustic parameter estimates, we further extended our arrival time tracking method to obtain tighter PDFs on the arrival times. Reducing the variance in the arrival time PDFs is directly related to limiting the variance in environmental parameter estimates. We observed that a portion of the uncertainty in our arrival time estimation is a result of limited prior information in the initial states of the filtering process. To mitigate this problem, we implemented backward-moving filters, that improved results on initial states by moving backwards after estimation at all states/receivers was complete [12]. Figure 2(a) shows the arrival time PDFs for a specific ray path at a receiving phone. The correct arrival time is 49. The PDF that we calculate is multimodal with a large variance. The main mode is close to the true arrival time. Figure 2(b) shows the PDF for the same path after smoothing. Multimodality in the PDF has been removed and variance has been reduced (however, there seems to be a small trade-off between uncertainty reduction and a bias, which shifts the main mode slightly to the right).

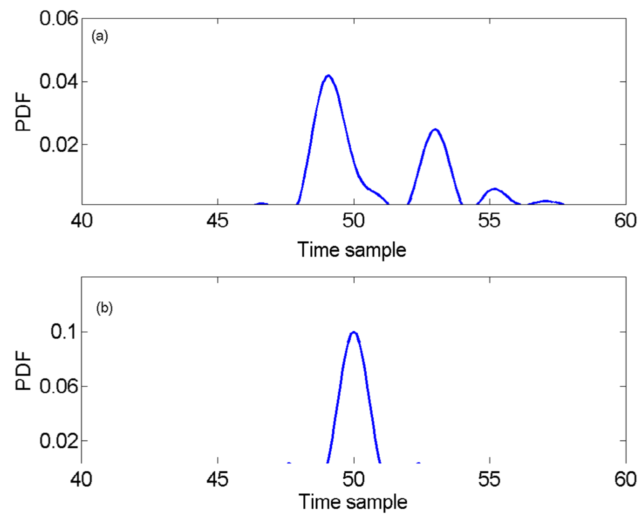

Figure 2: PDFs of arrival time estimates of the same path for (a) a simple particle filter and (b) a particle filter combined with smoothing.

Similar to the example of Figure 2 but now using arrival time PDFs obtained after smoothing, we calculated new estimates of the sound speed in the layer. The new PDF is shown in Figure 3. The probability density is now concentrated around the true sound speed value with a much reduced variance.

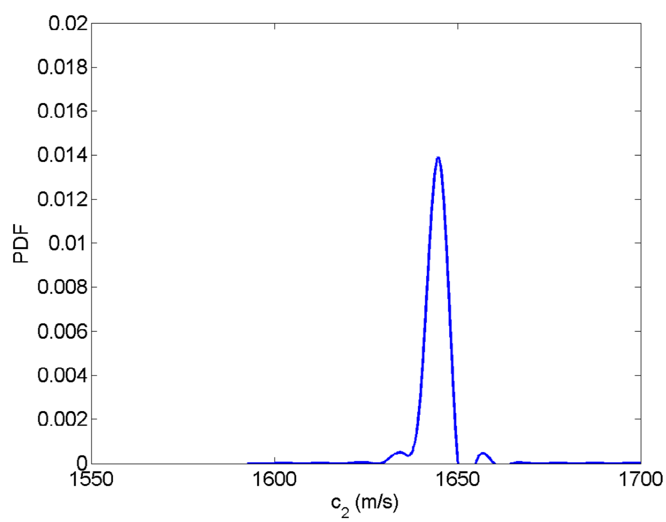

Figure 3: PDF of sediment sound speed estimated using arrival times of ray paths extracted with particle filters after smoothing.

Further work was carried out by applying our method to real data. Specifically, we worked with data from the SW06 experiment, collected at the 16-element MPL-VLA1 array (because of low SNR at the 15th and 16th phones, data at only the 14 lower phones were used) [2]. The source signal was a linear frequency modulated pulse with frequencies between 100 and 900 Hz. Figure 4 (a) illustrates ray path arrival time PDFs in a case where the number of paths arriving within a certain observation time window is varying. Figures 4 (b), (c), (d) show PDFs for the number of observed arrivals within the given window at three different phones.

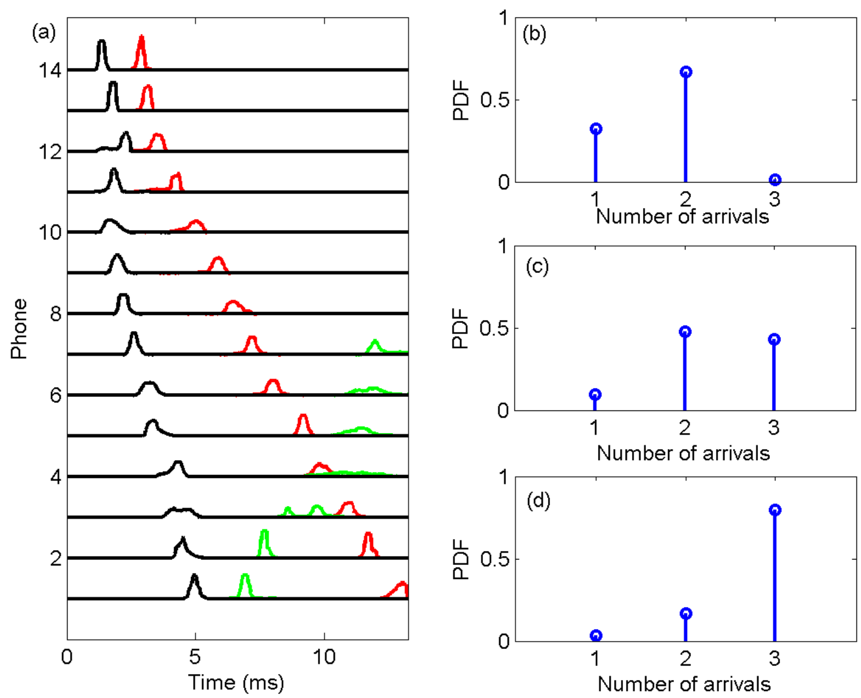

Figure 4: ***(a) PDFs for arrival times of three paths calculated with particle filtering applied to the time series of Fig. 1. (b) Probability Mass Functions for the number of arrivals in an observation window for receivers 9, 8, and 7 [2].***

As previously mentioned, this approach is highly applicable to data produced by passive fathometer data processing [10,11]. The presence of wavelets in the estimate of the medium's Green's function corresponds to the location of reflectors in the seabed. Figure 5 shows how the particle filtering method tracks reflectors from data from the Boundary 2003 Experiment, after both conventional and MVDR processing. This work was done in collaboration with Drs. Peter Gerstoft and Caglar Yardim from Scripps.

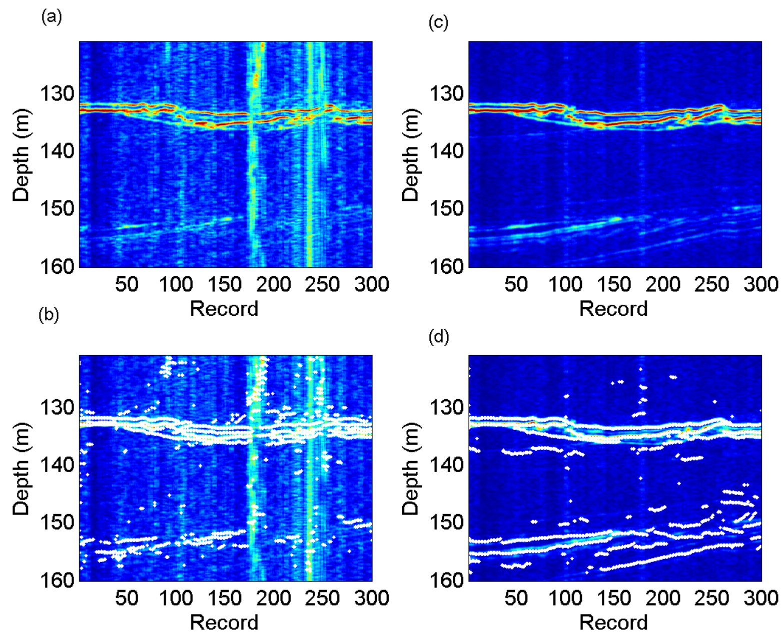

Figure 5: (a) Conventional and (b) MVDR fathometer results for Boundary 2003 data. (c) Conventional and (d) MVDR fathometer results for Boundary 2003 data with particle-filtering tracks superimposed (white dots).

Inversion was also conducted using time-frequency particle filtering [8]. Figures 6 and 7 show sound speed PDF estimates (at one depth in the water column and within the first sediment) for synthetic data. The ellipses indicate the true values of the sound speed. The inversion was done using frequency-arrival time estimates and linearization. Ill-conditioning issues presented us with challenges which we are currently investigating.

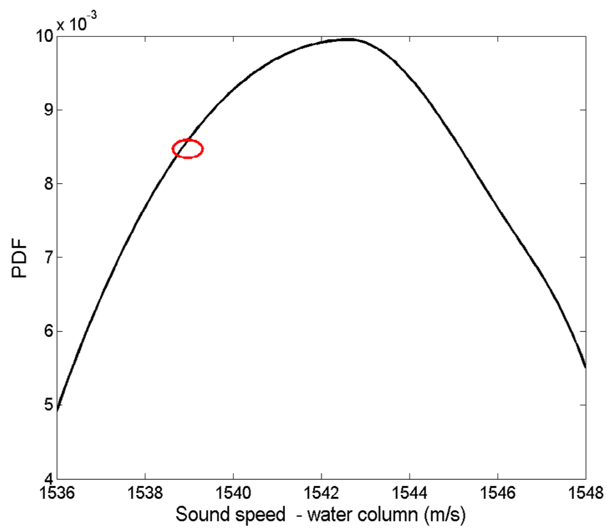

Figure 6: PDF of water column sound speed at a selected depth calculated using particle filtering and time-frequency analysis.

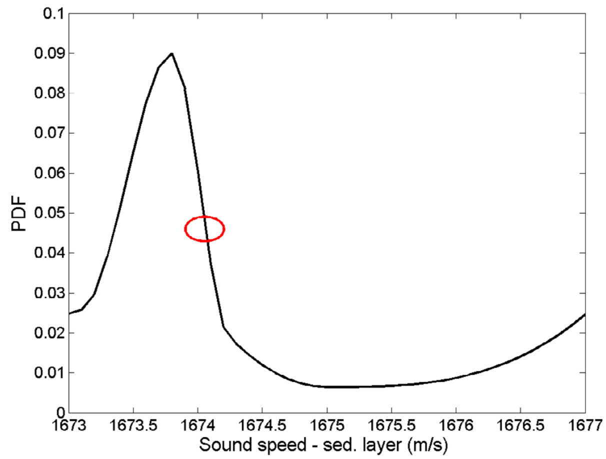

Figure 7: PDF of sediment sound speed calculated using particle filtering and time-frequency analysis.

IMPACT

The significance of accurate arrival time estimation in geoacoustic inversion has been studied with several methods designed for producing geoacoustic parameter estimates and measures of the uncertainty in the estimation process. The reliability of these methods is intimately tied to the ability to accurately extracting and identifying arrival times. The new methods facilitate this extraction and the association between paths/modes and detected arrivals and also produce posterior probability distributions of modal frequencies or arrival times. These distributions can then be employed to quantify uncertainty in the estimation of geoacoustic parameters as demonstrated in Figures 3, 6, and 7. The success of the developed approach in reflector tracking using passive fathometer data is encouraging, as this is an emerging field with a vast potential for the understanding of the seabed structure.

RELATED PROJECTS

The PI is collaborating with Drs. Yardim and Gerstoft on sequential filtering in ocean acoustics. A collaboration is also underway with Dr. Lisa Zurk and Dr. Helen Ou (Portland State University) on tracking as it relates to the waveguide invariance principle. Additionally, the PI is collaborating with Dr. Leon Cohen on comparing numerical and analytical descriptions of dispersion in ocean environments.

REFERENCES

1. R. Jain and Z.-H. Michalopoulou, A particle filtering approach for spatial arrival time tracking in ocean acoustics, *Journal of the Acoustical Society of America Express Letters*, Volume 129, Issue 6, pp. EL237-EL241, June 2011.

2. C. Yardim, Z.-H. Michalopoulou, and P. Gerstoft, An Overview of Sequential Bayesian Filtering in Ocean Acoustics, *IEEE Journal of Oceanic Engineering*, Volume 36, Issue 1, pp. 71 – 89, January 2011.
3. E. Sullivan, Z.-H. Michalopoulou, and C. Yardim, Model-based ocean acoustic signal processing, *Acoustics Today*, in press.
4. T. C. Yang, “Dispersion and ranging of transient signals in the Arctic Ocean,” *Journal of the Acoustical Society of America*, vol. 76, p. 262-273, October 1984.
5. J. Lynch, S. Rajan, and G. Frisk, “A comparison of broad band and narrow band modal inversions for bottom geoacoustic properties at a site near Corpus Christi, Texas, *Journal of the Acoustical Society of America*, vol. 89, p. 648-665, October 1991.
6. G. Potty, J. H. Miller, J. Lynch, K. Smith, “Tomographic inversion for sediment parameters in shallow water,” *Journal of the Acoustical Society of America*, vol. 108, p. 973-986, September 2000.
7. J. H. Miller and G. Potty, “Attenuation inversions in the East China Sea,” *Journal of the Acoustical Society of America*, vol. 114, p. 2343, October 2003.
8. Ivan Zorych, Zoi-Heleni Michalopoulou, “Particle filtering for dispersion curve tracking in ocean acoustics,” *Journal of the Acoustical Society of America*, vol. 124, pp. EL45-50, 2008.
9. Z.-H. Michalopoulou, “A Bayesian approach to modal decomposition in ocean acoustics,” *Journal of the Acoustical Society of America,* Volume 126, Issue 5, pp. EL147-EL152, November 2009.
10. M. Siderius, C. H. Harrison, and M. B. Porter, “A passive fathometer technique for imaging seabed layering using ambient noise,” *Journal of the Acoustical Society of America*, vol. 120, pp. 1315-1323, 2006.
11. P. Gerstoft, W. S. Hodgkiss, M. Siderius, C.-F. Huang, and C. H. Harrison, “Passive fathometer processing,” *Journal of the Acoustical Society of America*, vol. 123, pp. 1297-1305, 2008.
12. Simon J. Godsill, Arnaud Doucet, and Mike West, “Monte Carlo smoothing for non-linear time series,” Journal of the American Statistical Association, vol. 99, pp. 156-168, 2004.

PUBLICATIONS

Z.-H. Michalopoulou, C. Yardim, and P. Gerstoft, Particle Filtering for Passive Fathometer Tracking, *Journal of the Acoustical Society of America Express Letters*, submitted.

R. Jain and Z.-H. Michalopoulou, A particle filtering approach for spatial arrival time tracking in ocean acoustics, *Journal of the Acoustical Society of America Express Letters*, Volume 129, Issue 6, pp. EL237-EL241, June 2011 [refereed].

C. Yardim, Z.-H. Michalopoulou, and P. Gerstoft, An Overview of Sequential Bayesian Filtering in Ocean Acoustics, *IEEE Journal of Oceanic Engineering*, Volume 36, Issue 1, pp. 71 – 89, January 2011 [refereed].

E. Sullivan, Z.-H. Michalopoulou, and C. Yardim, Model-based ocean acoustic signal processing, *Acoustics Today*, in press.

Z.-H. Michalopoulou, Peter Gerstoft, and Caglar Yardim, A summary of filtering approaches in ocean acoustics, *Journal of the Acoustical Society of America*, Volume 128, Issue 4, pp. 2463, November 2010.

Z.-H. Michalopoulou, Tracking in ocean acoustics for geoacoustic inversion, *Journal of the Acoustical Society of America*, Volume 129, Issue 4, pp. 2598, May 2011.

L. Zurk, Z.-H. Michalopoulou, and D. Roussef, Active invariance structure in deep water towed array data, *Journal of the Acoustical Society of America*, Volume 128, Issue 4, pp. 2462, November 2010.

Z.-H. Michalopoulou, Model-based estimation and uncertainty characterization of modal arrival times and amplitudes in ocean acoustics, *Journal of the Acoustical Society of America*, Volume 128, Issue 4, pp. 2463, November 2010.