

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 Number: 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, inversion for sound-speed in the water-column, and source localization, exploiting (fully or partially) the physics of the propagation medium. Algorithms are designed for inversion via the extraction features of the acoustic field.

OBJECTIVES

- Achieve accurate and computationally efficient inversion for propagation medium parameters and source localization by designing estimation schemes that combine acoustic field 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 Bayesian 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 source localization and water column sound speed estimation 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] and [4]; the latter paper is in press. The method is an extension of previous approaches developed by the PI, now using more advanced techniques. The initial goal 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

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 2012		2. REPORT TYPE N/A		3. DATES COVERED -	
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) Department of Mathematical Sciences New Jersey Institute of Technology 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 The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 7	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

which sound propagates. Even small discrepancies in arrival time and amplitude estimates can lead to significant errors in inferences on inversion. Accurate estimation, however, linked with physical models for sound propagation in the ocean, can lead to accurate source localization and inversion for properties of the propagation medium. As will be seen below, in addition to simple point estimates, our method facilitates the computation of posterior probability densities (PPDs) for arrival times, which can be used for uncertainty quantification in inversion (source localization and depth and sound speed estimation in the water column; sound speed estimation in the seabed has also been performed). These distributions can be multimodal, a fact that is not often revealed when different methods are used. It has also been shown in [1] that amplitude PPDs can be obtained in a straightforward manner; those can be used for seabed attenuation estimation.

More work was conducted on identifying arrival times and amplitudes of distinct frequencies in dispersion curve analysis (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 using dispersion curves has been extensively discussed in [5, 6, 7, 8].

WORK COMPLETED

Previously developed approaches were improved to provide more accurate estimates of arrival times and, subsequently, of source location, bathymetry, and the water-column sound speed profile. Specifically, in addition to conventional, forward particle filters, smoothing, backward mechanisms were employed, that reduced uncertainty. The arrival time tracking method was applied to synthetic and real data for source localization, and bathymetry and sound speed estimation in the water column and the seabed layer. Results were obtained by using the particle filtering results as input to the inverse problem; more results will be obtained this year by further improving and testing our approach. Passive fathometer processing with particle filters was also improved, with the developed methodology applied to seismic tremor tracking as well [9]. Additionally, the particle filtering method was applied to synthetic long-range data for dispersion curve extraction with results significantly improved in terms of resolution from those presented in [10].

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 inversion with arrival time estimates obtained with our method, we noticed that, in some cases, uncertainty in estimates can still be significant.

To improve our results, we further extended our arrival time tracking method to obtain tighter PPDs on arrival times. Reducing the variance in the arrival time PPDs is directly related to limiting the variance in source location and 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 employed backward-moving filters that improved results on initial states by moving backwards after estimation at all states/receivers was completed following the approach of [11]. We extended our work in this direction during the last year. Figure 1 shows results from an extensive performance evaluation of the smoothing process as compared to a standard forward only-filter.

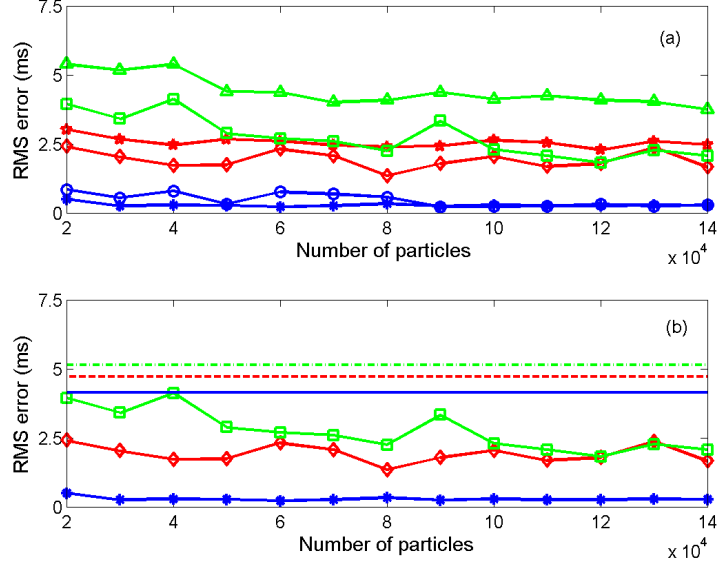


Figure 1: Demonstration of the advantage of a PF with smoothing over a simple PF for three paths at an SNR of 10 dB: (a) PF-MAP RMS errors for arrivals times from a forward PF for three paths (circles for D, stars for SR, and triangles for BR) and a forward-backward filter for the same paths (asterisks, diamonds, squares); (b) RMS errors for arrivals times for a forward-backward filter for the three paths (*) and GS-MAP results.

Specifically, the figure shows Root Mean Squared (RMS) errors for Maximum a Posteriori (MAP) arrival time estimates for three paths for (a) a forward filter and a forward-backward filter, and for (b) the same forward-backward filter and the Gibbs Sampling (GS)-MAP processor presented in [12]. Results show that the forward-backward filter is superior to both the forward-only filter and the conventional processor.

To further illustrate the power of the process, we show in Figures 2 and 3 source localization and bathymetry estimation PPD results from applying the method of [12] and the new method to the Haro Strait data. Figure 2 shows PPDs obtained with the GS method of [12]. Figure 3 presents results obtained with the new filter. The reduction of the uncertainty in the PPDs, evident by comparing Figures 2 and 3, is significant.

Additional work was carried out by applying particle filters to real data for sound speed estimation. 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 illustrates estimation of the sound speed profile for the water column using the ray path arrival time PPDs such as those shown in [2]. Specifically, Figure 4 shows the PPD of the coefficient of the first EOF, which is in agreement with results presented in [13]. Note that the PPD is bimodal, which is not evident in results previously presented in work with the same data. The resulting sound speed profile was similar to the profile shown in [14].

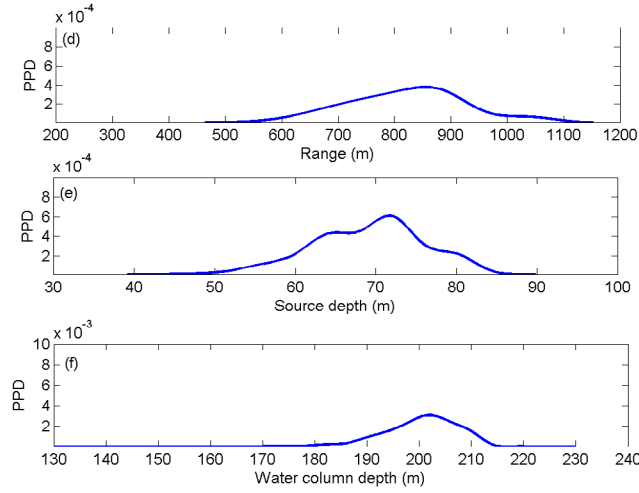


Figure 2: PPDs of (a) source range and (b) depth and (c) water column depth estimates with the Gibbs Sampling method of [13].

The PI's particle filtering method for dispersion tracking was improved working along similar lines. The new method was applied to synthetic long-range data for dispersion curve extraction with results significantly improved from those presented in [10]. These results are shown in Figure 4, where MAP estimates are superimposed on a spectrogram. The method detects modal trajectories that exit at low frequencies and new that appear at high frequencies. The continuous or interrupted nature of the curve captures the degree of reliability of specific modal behaviors in inversion.

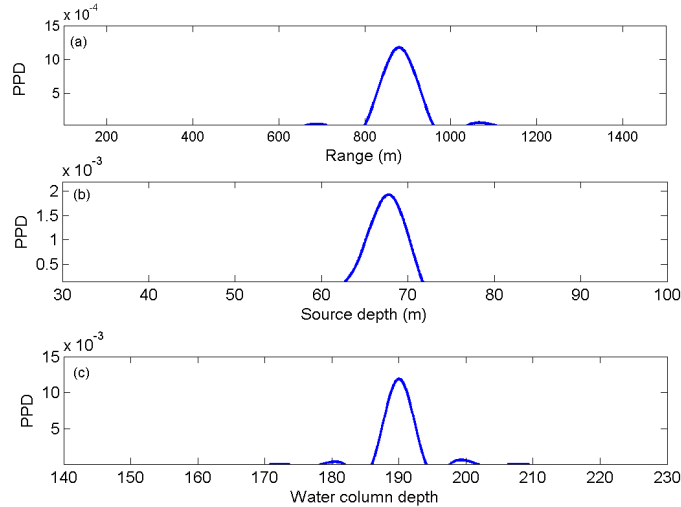


Figure 3: PPDs of (a) source range and (b) depth and (c) water column depth estimates with particle filtering.

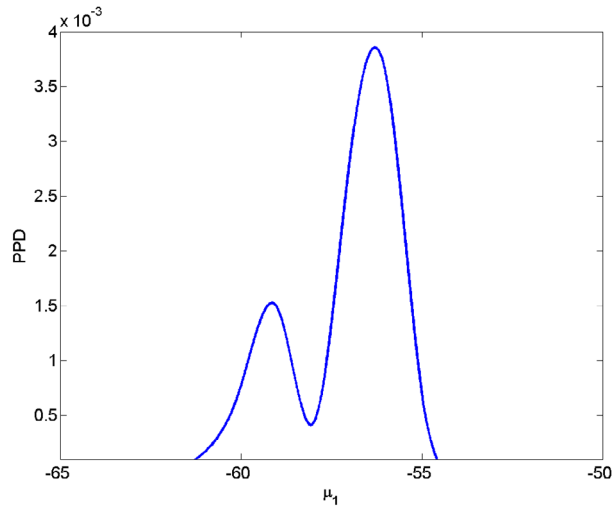


Figure 4: Sound speed estimation for the SW06 experiment using arrival times extracted by the particle filter and used as input to the inverse problem: the figure shows the PPD of the coefficient of the first EOF. The results are in agreement with those presented in [13,14].

IMPACT

The significance of accurate arrival time estimation in source localization and water-column sound speed estimation has been studied with the goal of producing accurate parameter estimates and measures of the uncertainty in the estimation process. The reliability of arrival time estimation methods is intimately tied to the quality of the inversion process. The new approaches facilitate arrival time extraction and the association between paths/modes and detected arrivals and also produce PPDs of arrival times, modal frequencies, and corresponding amplitudes.

RELATED PROJECTS

The PI is collaborating with Drs. Yardim and Gerstoft on sequential filtering in ocean acoustics. The PI is also collaborating with Dr. Leon Cohen on comparing numerical and analytical descriptions of dispersion in ocean environments and is involved in discussions with Dr. Ross Chapman on inversion for attenuation.

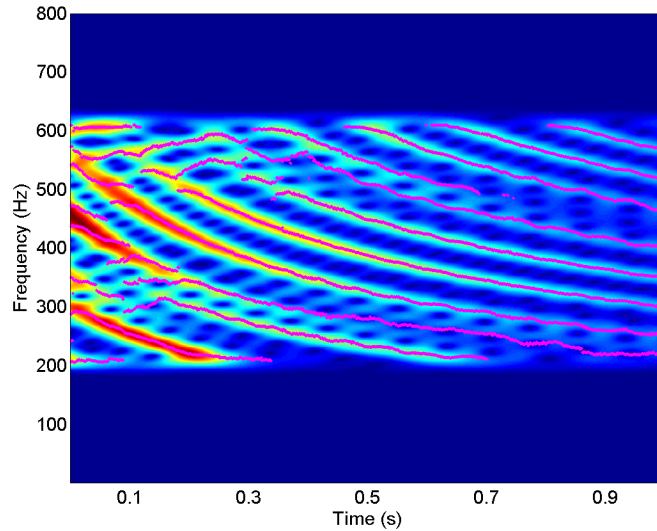


Figure 5: *Dispersion curves estimated with particle filtering from a synthetic environment simulating the environment of the Gulf of Mexico experiment.*

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*, October 2011.
4. Z.-H Michalopoulou and R. Jain, Particle filtering for arrival time tracking in space and source localization, *Journal of the Acoustical Society of America*, in press.
5. 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.
6. J. Lynch, S. Rajan, and G. Frisk, “A comparison of broad band and narrow band modal inversions for bottom geoaoustic properties at a site near Corpus Christi, Texas, *Journal of the Acoustical Society of America*, vol. 89, p. 648-665, October 1991.
7. 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.
8. 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.
9. C. Yardim, P. Gerstoft, and Z.-H. Michalopoulou, Geophysical Signal Processing Using Sequential Bayesian Technique, *Geophysics*, under review.
10. 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.

11. 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.
12. Zoi-Heleni Michalopoulou and Michele Picarelli, Gibbs sampling for time-delay-and amplitude estimation in underwater acoustics, *Journal of the Acoustical Society of America*, vol. 117, pp.799-808, 2005.
13. Chen-Fen Huang, Peter Gerstoft, and William S. Hodgkiss, Effect of ocean sound speed uncertainty on matched-field geoacoustic inversion, *Journal of the Acoustical Society of America*, vol. 123, pp. EL162-168, 2008.
14. Yong-Min Jiang, N. Ross Chapman, and Peter Gerstoft, Short range travel time geoacoustic inversion with vertical line array, *Journal of the Acoustical Society of America*, vol. 124, pp. EL135-140, 2008.

PUBLICATIONS

- Z.-H Michalopoulou and R. Jain, Particle filtering for arrival time tracking in space and source localization, *Journal of the Acoustical Society of America*, in press. [refereed]
- Z.-H. Michalopoulou, C. Yardim, and P. Gerstoft, Particle Filtering for Passive Fathometer Tracking, *Journal of the Acoustical Society of America*, vol. 171, pp. EL74--EL80, December 2011 [refereed]
- E. Sullivan, Z.-H. Michalopoulou, and C. Yardim, Model-based ocean acoustic signal processing, *Acoustics Today*, vol. 7, issue 3, pp. 8-16, October 2011.
- C. Yardim, P. Gerstoft, and Z.-H. Michalopoulou, Geophysical Signal Processing Using Sequential Bayesian Technique, *Geophysics*, under review [refereed].
- 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].
- Z.-H. Michalopoulou, Optimizing receiver and source positioning in the ocean: Lessons from nature, *Journal of the Acoustical Society of America*, vol. 132, pp. 2055, October 2012.
- T. Lin and Z.-H. Michalopoulou, Sound speed estimation and source localization with particle filtering and a linearization approach, *Journal of the Acoustical Society of America*, vol. 132, pp. 2055, October 2012.
- T. Lin and Z.-H. Michalopoulou, An inverse method for estimating sediment sound speed in the ocean, *Journal of the Acoustical Society of America*, vol. 132, pp. 2094, October 2012.