Efficient Inversion in Underwater Acoustics with Analytic, 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: N000141310077
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 of features of the acoustic field and optimization. The potential of analytic approaches is also investigated.

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.
- Develop analytic techniques for sediment sound speed estimation.

APPROACH

We first worked on a new sediment sound speed estimation scheme based on Stickler's inverse problem approach [1, 2]. As we will mention in the next section, we managed to estimate sediment sound speed and thickness in a synthetic waveguide using an analytic method, improving on previously obtained results with a similar but simpler approach.

<table>
<tr><td colspan="3">Report Documentation Page</td><td colspan="2">Form Approved
OMB No. 0704-0188</td></tr>
<tr><td colspan="5">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.</td></tr>
<tr><td>1. REPORT DATE
30 SEP 2014</td><td colspan="2">2. REPORT TYPE</td><td colspan="2">3. DATES COVERED
00-00-2014 to 00-00-2014</td></tr>
<tr><td colspan="3" rowspan="3">4. TITLE AND SUBTITLE
Efficient Inversion in Underwater Acoustics with Analytic, Iterative, and Sequential Bayesian Methods</td><td colspan="2">5a. CONTRACT NUMBER</td></tr>
<tr><td colspan="2">5b. GRANT NUMBER</td></tr>
<tr><td colspan="2">5c. PROGRAM ELEMENT NUMBER</td></tr>
<tr><td colspan="3" rowspan="3">6. AUTHOR(S)</td><td colspan="2">5d. PROJECT NUMBER</td></tr>
<tr><td colspan="2">5e. TASK NUMBER</td></tr>
<tr><td colspan="2">5f. WORK UNIT NUMBER</td></tr>
<tr><td colspan="3">7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
New Jersey Institute of Technology,Department of Mathematical Sciences,Newark,NJ,07102</td><td colspan="2">8. PERFORMING ORGANIZATION REPORT NUMBER</td></tr>
<tr><td colspan="3" rowspan="2">9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</td><td colspan="2">10. SPONSOR/MONITOR’S ACRONYM(S)</td></tr>
<tr><td colspan="2">11. SPONSOR/MONITOR’S REPORT NUMBER(S)</td></tr>
<tr><td colspan="5">12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited</td></tr>
<tr><td colspan="5">13. SUPPLEMENTARY NOTES</td></tr>
<tr><td colspan="5">14. ABSTRACT</td></tr>
<tr><td colspan="5">15. SUBJECT TERMS</td></tr>
<tr><td colspan="3">16. SECURITY CLASSIFICATION OF:</td><td rowspan="2">17. LIMITATION OF ABSTRACT
Same as Report (SAR)</td><td rowspan="2">18. NUMBER OF PAGES
7</td></tr>
<tr><td>a. REPORT
unclassified</td><td>b. ABSTRACT
unclassified</td><td>c. THIS PAGE
unclassified</td></tr>
</table>

19a. NAME OF RESPONSIBLE PERSON

Also, 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. We extended work on the development of a quasilinear model for source location, bathymetry, and water column sound speed profile estimation. We demonstrated via a comparison to simulated annealing that our approach is superior to global optimization: although the method is much faster, the accuracy in the estimation is not compromised.

More work with a new statistical model more accurately describing dispersion in the ocean was conducted for 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 using dispersion curves has been extensively discussed in [3,4,5].

WORK COMPLETED

Sediment sound speed was estimated using a new efficient analytic method. Despite low frequencies used for the inversion, high resolution was attained with sediment sound speeds and thicknesses accurately extracted.

We extended work on the development of our quasilinear model for source location, bathymetry, and water column sound speed profile estimation and demonstrated that it is superior in terms of efficiency to global optimization in terms of efficiency by comparing it to fast simulated annealing.

More work was conducted on extracting dispersion curves for long-range propagation with a new statistical model. Results show that the new model offers higher reliability in the estimation of dispersion than conventional spectrogram methods and allows us to perform an accurate inversion for sediment sound speed. A new and more accurate statistical model than the simple Gaussian one that had been previously used was developed.

RESULTS

Figure 1 shows sound speed estimation in sediments and the corresponding sediment thickness employing the method mentioned in the past section. The interpolant approach developed in our work provides closer profiles to the true one than other approaches, with the improvement mostly evident at the interfaces between different sediments. This feature is the one that allows accurate estimation of the sediment thickness.

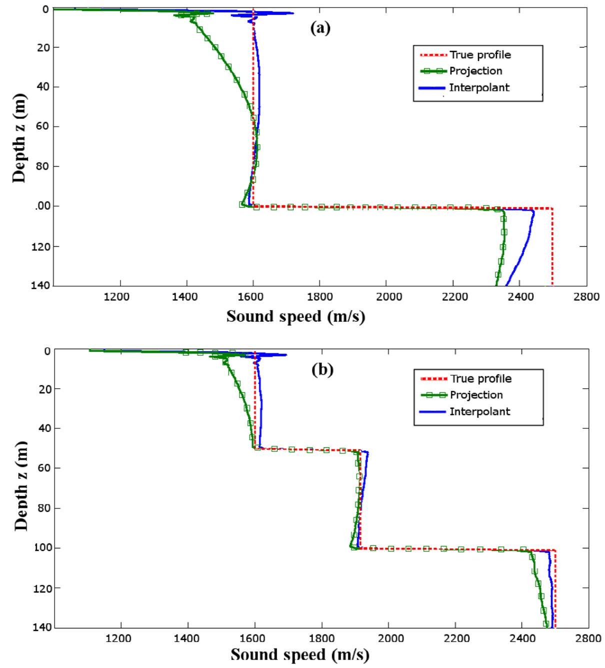

Figure 1: Sediment sound speed and thickness estimation with an analytic method, improving on results previously obtained from similar techniques with two different profiles. Profile discontinuities are well tracked, providing estimates both for sound speed and sediment thickness.

The same method was applied to noisy data. Several numerical issues were addressed with the development of a suitable regularization technique. The final results show that, even in noisy environments, the new method can estimate sediment sound speed. Sediment thickness was also estimated in most cases. In other cases, smoothing occurred, blurring the boundaries between sediments. Results are presented in Figure 2 for three different Signal-to-Noise Ratios. Experiments were performed with a variety of environments with similar results [6].

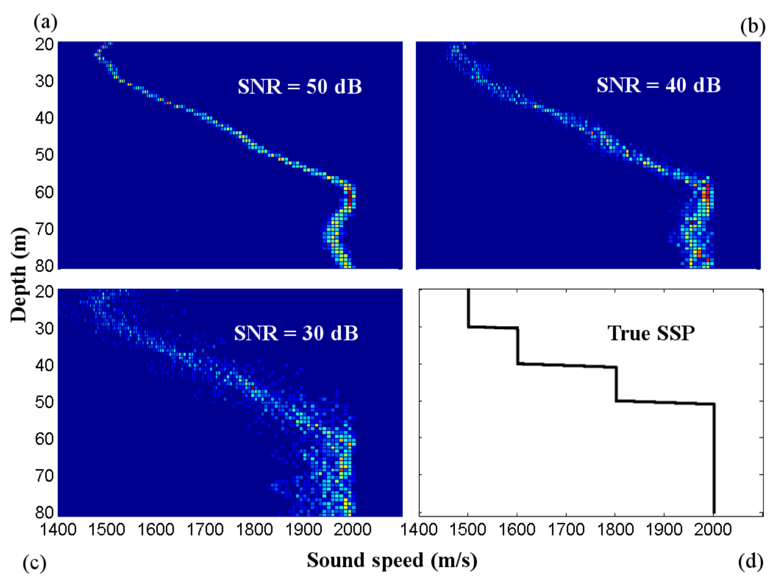

Figure 2: Performance of the analytic inversion method at three different noise levels.

Using Shallow Water 06 data, we compared our linearization/particle filtering approach to inversion using simulated annealing. A comparison for two sets of arrival times for three paths (direct, first surface reflection, and first bottom reflection) is presented in Table 1. The results are practically identical. However, our method required six iterations per case whereas the simulated annealing method required from a few hundred to a few thousand iterations [7]. Figure 3 illustrates the simulated annealing estimation process, showing the number of iterations necessary for convergence. The new feature of including EOF coefficients in the linearization process facilitated the estimation of water column sound speed profiles.

Table 1: Comparison of the particle filtering/linearization method and simulated annealing (range r, source depth z_s, water column depth WD, EOF coefficients μ_1, μ_2, and μ_3, and tilt.

Parameter	Lin. Estimate	SA Estimate	Lin. Estimate	SA Estimate
r (m)	228	232	229	228
z_s (m)	26	26	27	27
WD (m)	76	76	77	77
μ_1	-54	-56	-42	-43
μ_2	-10	-12	-7	-7
μ_3	2	1	2	-2
tilt (deg)	0	0	0	0

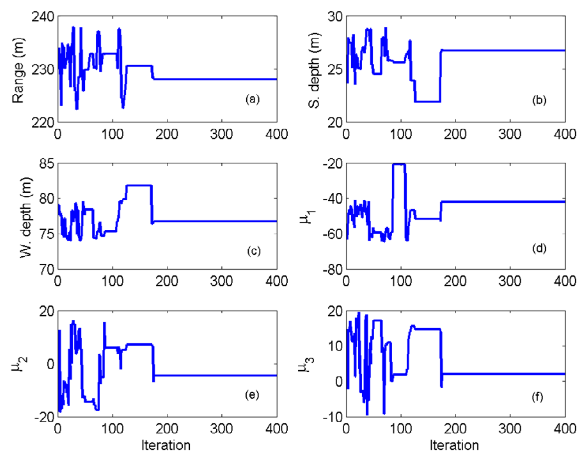

Figure 3: Simulated annealing results for (a) and (b) source location, (c) bathymetry, and (d), (e), and (f) EOF coefficients.

For the dispersion problem, dispersion curves were extracted from broadband data, with dispersion tracks identified even for weak modes, as shown in Figure 4.

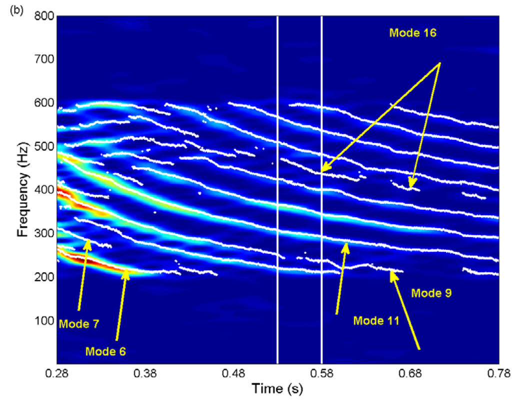

Figure 4: Spectrogram of a noisy synthetic signal and the dispersion tracks as estimated by a particle filter superimposed.

We then propagated probability density functions (PDFs) of arriving frequencies at particular times for two modes through a normal modes model to identify which sediment sound speeds would generate the measured time differences; that is, we exploited group velocities for inversion. At the output of our method, we obtain a PDF of the sediment sound speed. Results are shown in Figure 5. The impact of noise and mode misidentification on the results was also investigated [8].

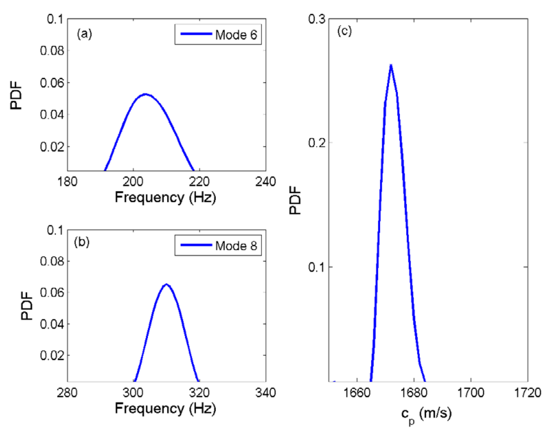

Figure 5: (a) and (b): PDFs of two arriving modal frequencies at a particular time as estimated by the Particle Filter. (c) The PDF of the sediment sound speed using the frequency PDFs of (a) and (b).

IMPACT

The development of the new inversion has a significant impact on the problem of geoacoustic parameter estimation, because of its potential to estimate sound speed in sediments in an exact, fast, analytic fashion. The method relies on limited prior information (sensitivity to assumptions is currently being further investigated).

Also the importance of dispersion analysis in geoacosutic inversion has been long established, with excellent results demonstrated with real data. Our method appears to produce superior results in comparison to conventional methods and provides narrow PDFs of sediment sound speed.

Lastly, our inversion method with multipath arrival times and linearization is fast and accurate, allowing for effective inversion in real time.

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.

REFERENCES

1. D. C. Stickler and P. A. Deift, “Inverse problem for a stratified ocean and bottom,” *Journal of the Acoustical Society of America,* vol. 70, pp. 1723-1727, 1981.
2. D. C. Stickler, “A shallow-water ocean acoustics inverse problem,” *Acoustic Research Letters Online,* vol. 6, pp. 287-290, 2005.
3. 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.
4. 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.
5. 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.
6. Tao Lin and Zoi-Heleni Michalopoulou, An inverse method for the estimation of sediment sound speed in the ocean, submitted to the *Journal of the Acoustical Society of America,* 2014.
7. Tao Lin and Z.-H Michalopoulou, Sound speed estimation and source localization with linearization and particle filtering, *Journal of the Acoustical Society of America,* 135, 1115-1126, 2014.
8. Nattapol Aunsri and Zoi-Heleni Michalopoulou, Sequential filtering for dispersion tracking and sediment sound speed inversion, *Journal of the Acoustical Society of America,* in press, 2014.

PUBLICATIONS

Tao Lin and Zoi-Heleni Michalopoulou, Sound speed estimation and source localization with linearization and particle filtering, *Journal of the Acoustical Society of America,* 135, 1115-1126, 2014 [refereed].

Nattapol Aunsri and Zoi-Heleni Michalopoulou, Sequential filtering for dispersion tracking and sediment sound speed inversion, *Journal of the Acoustical Society of America,* in press, 2014 [refereed].

Tao Lin and Zoi-Heleni Michalopoulou, An inverse method for the estimation of sediment sound speed in the ocean, submitted to the *Journal of the Acoustical Society of America* (currently under review), 2014 [refereed].

Tao Lin and Zoi-Heleni Michalopoulou, An inverse method for estimating sediment sound speed, *Journal of the Acoustical Society of America,* 134, 4241, 2013 (the corresponding presentation earned second place in the student award competition at the Fall Meeting of the Acoustical Society of America, 2013).

Nattapol Aunsri and Zoi-Heleni Michalopoulou, Stochastic characterization of acoustic signals for sequential dispersion tracking and geoacoustic inversion, *Journal of the Acoustical Society of America,* 135, 2306, 2014.

HONORS/AWARDS/PRIZES

- Zoi-Heleni Michalopoulou: College of Science and Liberal Arts Award for Excellence in Research, New Jersey Institute of Technology, 2014.
- Tao-Lin: second place in the Acoustical Oceanography student award competition at the Fall Meeting of the Acoustical Society of America, 2013.