Efficient Inversion in Underwater Acoustics with Analytic, Iterative, and Sequential Bayesian Methods

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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 and optimization. The potential of analytic approaches are 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

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, bathymetry, and water column sound speed estimation using arrival time estimates for propagation in multipath environments with sequential Monte Carlo methods, namely, particle filtering, tied with a linearization method with novel features. Some of our results have been presented in [1, 2, 3, 4] and [5]; the latter paper, focusing on the linearization approach, is currently under review. The method is an extension of previous methods developed by the PI, now using more advanced techniques. The initial goal is to estimate accurately arrival times of sound paths in shallow water environments. Then, we propagate these arrival times and their posterior probability density functions (PDFs) through a quasilinear model for source location, bathymetry, and water column sound speed profile estimation.

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 [6, 7, 8, 9].

Finally, we worked on a new sediment sound speed estimation scheme based on Stickler's inverse problem approach [10, 11]. As we will mention in the next section, we managed to estimate sediment sound speed in a synthetic waveguide using an analytic method, improving on previously obtained results with a similar but simpler approach.

WORK COMPLETED

Previous, approaches developed by the PI 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 SW06 *lfm* data. It was combined with a new linearization technique that now includes differentiation with respect to EOF coefficients rather than sound speed directly. Source localization, bathymetry, and sound speed profile results were obtained in terms of both point estimates and posterior PDFs, which will be shown later.

Additionally, the PI's particle filtering method was applied to both synthetic and real long-range data for dispersion curve extraction with a new and more accurate statistical model than the simple Gaussian one that had been previously used. Bathymetry estimates were extracted using the estimated dispersion curves for the synthetic case (more work is currently conducted with the real data).

Finally, we estimated sediment sound speed using a new analytic method, building on work presented in [10, 11].

RESULTS

As mentioned in the previous section, we used the particle filtering method along with a linearization scheme that related arrival time estimates to source range and depth, water column depth, sound speed profile in the water column, and tilt. The Jacobian matrix necessary for linearization can become complex if differentiation with respect to the depth dependent sound speed is performed. We developed an alternative scheme, where the Jacobian matrix includes derivatives with respect to EOFs instead of sound speed directly. PDFs for source localization, water column depth, and sound speed profile EOF coefficients obtained with this method are shown in Figure 1. The method required only a few iterations for convergence and the results were in agreement with estimates obtained at nearby sites [12, 13] with more computationally demanding global optimization techniques. It should be noted that no inversion results have been previously presented from the *lfm* data used in this work.

Figure 2 shows (a) the mean sound speed profile as calculated by CTD measurements at the site and the sound speed profile constructed with the MAP estimates obtained from the extracted arrival time PDFs and linearization and (b) the profiles of (a) with superimposed sound speed profiles constructed from distinct arrival time particles.

Figure 3 shows the real data time-series (solid lines) and synthetic time-series (dotted lines) generated using the parameter estimates from the filtering/linearization scheme. The synthetic time-series agree closely with the true data, strongly indicating that our estimates are close to the true values.

It was previously mentioned that work was performed on extracting dispersion curves for long-range propagation with a new statistical model. Preliminary results show that the new model offers higher reliability in the estimation of dispersion.

Lastly, Figure 4 shows sound speed estimation in sediments 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.

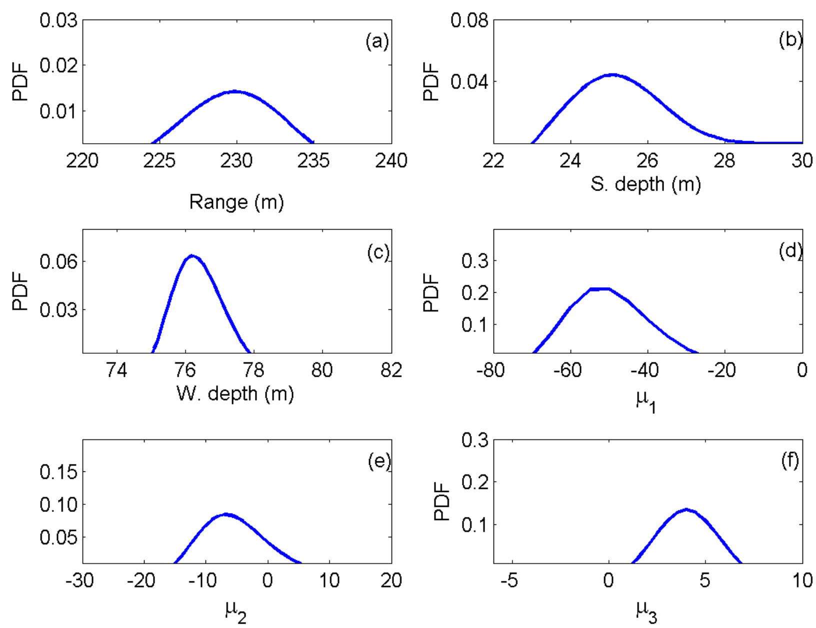

Figure 1: PDFs of (a) source range, (b) source depth, (c) water column depth, (d) μ_1, (e) μ_2, (f) μ_3 for real data.

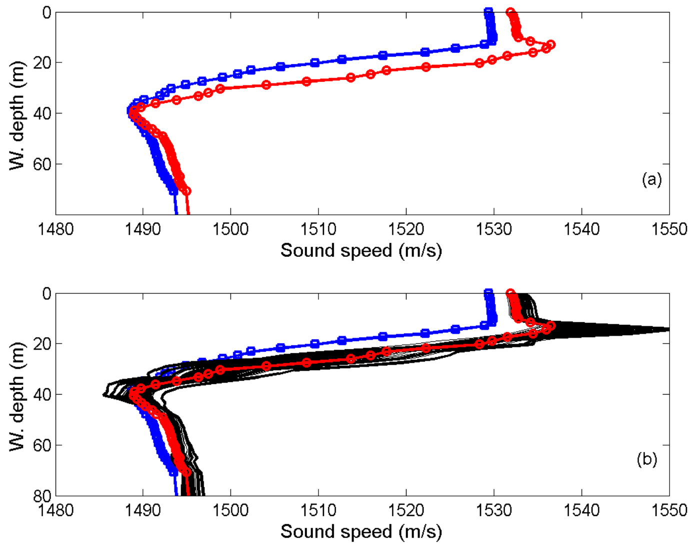

Figure 2: (a) The mean sound speed profile as calculated by the CTD measurements (squares) and the sound speed profile constructed with the MAP estimates obtained from the extracted arrival time PDFs (circles). (b) The profiles of (a) with superimposed sound speed profiles constructed from distinct arrival time particles (solid curves).

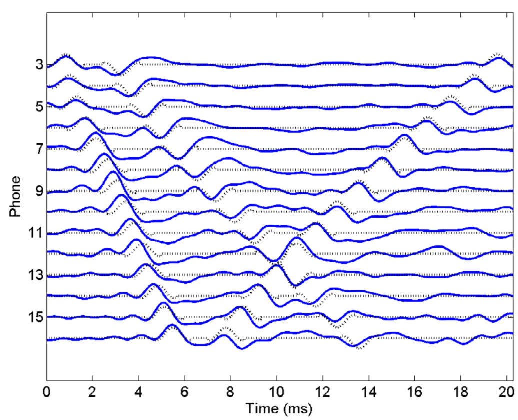

Figure 3: Real data (solid lines) and synthetic time-series (dotted lines) generated using the linearization estimates.

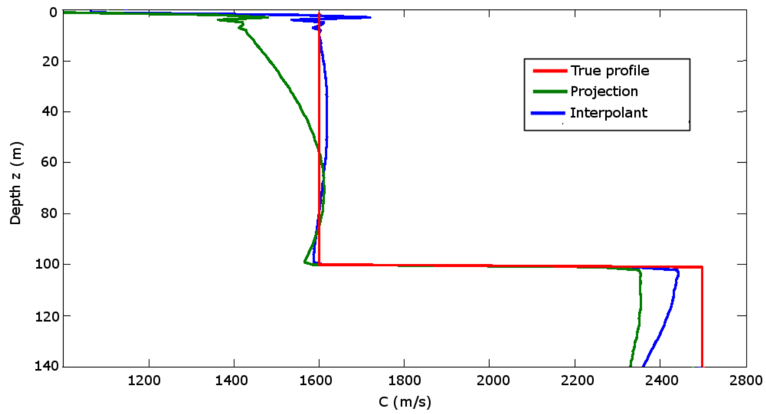

Figure 4: Sediment sound speed estimation with an analytic method, improving on results previously obtained from similar techniques.

IMPACT

Accurate arrival time estimation and fast inversion methods for source localization and water-column sound speed estimation have been studied with the goal of producing accurate parameter estimates and measures of the uncertainty in the inversion process. new approaches facilitate arrival time extraction and the association between paths/modes and detected arrivals and also produce PDFs of arrival times, modal frequencies, and corresponding amplitudes. These are critical features in estimating inversion parameters efficiently and accurately. The linearization method also impacts favorably inversion adding to the efficiency and accuracy just mentioned. Also, the development of a new inversion technique 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.

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. 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*, Volume 132, Issue 5, pp. 3041-3052, 2012.

5. Tao Lin and Z.-H Michalopoulou, Sound speed estimation and source localization with linearization and particle filtering, submitted to the *Journal of the Acoustical Society of America,* August 2013.
6. 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.
7. 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.
8. 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.
9. 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.
10. 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.
11. D. C. Stickler, "A shallow-water ocean acoustics inverse problem," *Acoustic Research Letters Online,* vol. 6, pp. 287-290, 2005.
12. C.-F. Huang, P. Gerstoft, and W. 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.
13. C. Yardim, P. Gerstoft, and W. S. Hodgkiss, Sequential geoacoustic inversion at the continental shelfbreak, *Journal of the Acoustical Society of America*, vol. 131, pp. 1722-1732, 2012.

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*, Volume 132, Issue 5, pp. 3041-3052, 2012 [refereed]

Tao Lin and Z.-H Michalopoulou, Sound speed estimation and source localization with linearization and particle filtering, submitted to the *Journal of the Acoustical Society of America,* August 2013. [refereed, under review]

C. Yardim, P. Gestoft, and Z.-H. Michalopoulou, Geophysical Signal Processing Using Sequential Bayesian Technique, *Geophysics*, 78:V87-V100, 2013 [refereed].

T. Lin and Z.-H. Michalopoulou, Sampling methods for uncertainty quantification in source localization and geoacoustic inversion in the ocean, *POMA*, Volume 19, pp.1-4, 2013.

N. Aunsri and Z.-H. Michalopoulou, Time-frequency analysis with Bayesian filtering methods for dispersion tracking, *POMA*, Volume 19, pp.1-4, 2013.

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.