Sequential Geoacoustic Filtering and Geoacoustic Inversion

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LONG-TERM GOALS

The development of new geoacoustic inversion methods, their use in the analysis of shallow water experimental data, and evaluation of geoacoustic model and parameter uncertainties including the mapping of these uncertainties through to system performance uncertainties.

OBJECTIVES

Analysis of geoacoustic inversion data collected from various experiments. Of specific technical interest are: (1) development of methods to track the environmental parameters using sequential filtering, (2) use of ambient noise for estimation of seafloor structure parameters, and (3) the development of new inversion methods for use into the kHz frequency regime.

APPROACH

1. Sequential filtering

A common feature of inverse problems in ocean acoustics is that estimates of underlying physical parameters are extracted from measured acoustic data. Geoacoustic inversion has been approached in the same framework, estimating, in addition to source location, ocean environment parameters and their uncertainty. Often, those parameters evolve in time or space, with acoustic data arriving at consecutive steps. Information on parameter values and uncertainty at preceding steps can be invaluable for the determination of future estimates but is often ignored.

Sequential Bayesian filtering, tying together information on parameter evolution, a physical model relating acoustic field measurements to the unknown quantities, and a statistical model describing random perturbations in the field observations, offers a framework for the solution of such problems.

2. Extracting information from noise cross-correlations

We have focused extensively on extracting information from noise in ocean acoustics with both theoretical work as well as experimental work. The passive fathometer is based on relating the down- and up-going signals received on an array and can be implemented in the time or frequency domain.

Here, we are exploring the passive fathometer by aligning arrivals using phase information from the fathometer (currently only the magnitude is used). We have evidence that the vertical fathometer array moves with the waves on the sea surface. Thus if we can correct for this movement it will be possible to align the reflections better and then average the reflection time series with phase as opposed to just using the envelope. This should give sharper definition of the seafloor and sub bottom reflections and enables estimating environmental geoacoustic parameters in addition to depths of reflecting layers.

For noise cross-correlation in general, we are exploring accelerating convergence for the noise cross-correlation by various signal processing strategies, e.g. averaging, rejecting interference dominated time series, eigenvalue/eigenvector decomposition, and focusing on specific arrivals using beamforming.

3. Compressive sensing

Many inverse problems in the ocean are inherently sparse, we recently have become interested in this topic as it is applicable to many problems. A simple example is beamforming, here we know that there are only a few sources, but when using conventional beamforming this information is not used.

WORK COMPLETED

We have worked on the basic compressive sensing concepts [Xenaki 2014], grid free compressive sensing [Xenaki 2014], and multiple window compressive sensing [Gerstoft 2015]. Direction-of-arrival (DOA) estimation refers to the localization of several sources from noisy measurements of the wavefield with an array of sensors. Thus, DOA estimation is expressible as a linear underdetermined problem with a sparsity constraint enforced on its solution. The compressive sensing (CS) framework asserts that this is solved efficiently with a convex optimization procedure that promotes sparse solutions.

Typically, matched-field inversion experiments use large-aperture arrays and powerful transmissions with high SNR. However, single-receiver/synthetic aperture inversion methods are preferable operationally due to ease of deployment. Furthermore, low SNR methods are attractive due to their ability to use low powered sources, e.g., battery powered acoustic sources, resulting in less disturbance to marine mammals. Tan el [2013, 2014, 2015] focuses on matched field inversion for mobile, single source-receiver configurations in low SNR conditions.

RESULTS

Compressive beamforming

In DOA estimation, CS achieves high-resolution acoustic imaging, outperforming traditional methods. Unlike the subspace DOA estimation methods, which also offer super-resolution, DOA estimation with CS is reliable even with a single snapshot [Mecklenbrauker 2013].

For multiple snapshots, CS has benefits over other high-resolution beamformers:

1) It does not require the arrivals to be incoherent.

2) It can be formulated with any number of snapshots, in contrast to, e.g., the Minimum Variance Distortionless Response (MVDR) beamformer.
3) Its flexibility in the problem formulation enables extensions to sequential processing, and online algorithms.

We show here that CS obtains higher resolution than MVDR, even in scenarios, which favor classical high-resolution methods.

In ocean acoustics, CS has found application in high resolution vertical array processing and in coherent passive fathometry for inferring the depths of sediment interfaces and their number (as discussed below). Various wave propagation phenomena from a single source (refraction, diffraction, scattering, ducting, reflection) lead to multiple partially coherent arrivals received by the array. These coherent arrivals are a problem for typical high-resolution beamformers.

We use least squares optimization with an L1-norm regularization term, also known as the least absolute shrinkage and selection operator (LASSO) to formulate the DOA estimation problem. The LASSO formulation complies with statistical models as it provides a maximum a posteriori (MAP) estimate, assuming Gaussian data likelihood and a Laplacian prior distribution for the source acoustic pressure. The LASSO is known to be a convex minimization problem and solved efficiently by interior point methods. In the LASSO formulation, the reconstruction accuracy depends on the choice of the regularization parameter, which controls the balance between the data fit and the sparsity of the solution. The regularization parameter can be found from the properties of the LASSO path (i.e. the evolution of the LASSO solution versus the regularization parameter).

There are limitations of CS that affect reconstruction quality such as basis mismatch which occurs when the DOAs do not coincide with the look directions of the angular spectrum. Grid refinement alleviates basis mismatch at the expense of increased computational complexity, especially in large two-dimensional or three-dimensional geoacoustic inversion problems such as seismic imaging. Importantly, grid refinement causes increased coherence between the steering vectors (basis coherence), which induces bias in the estimate. An example from [Gerstoft 2015] shows how CS with multiple windows actually performs better than conventional beamforming and MVDR/MUSIC (see Figs. 1-2).

Compressive geoacoustic inversion

Geoacoustic inversion estimates ocean environment parameters such as the water column sound speed profile (SSP) and seafloor parameters such as the sediment layer thick-nesses, sound speed profiles, density and attenuation values. Here we introduce a passive geoacoustic inversion algorithm for use with drifting vertical line array (VLA) data and is based on Yardim et al [2014]. The sea-surface generated ambient noise observed by the VLA is used to invert for the sediment parameters. This inversion algorithm has two important features.

First, passive fathometry and bottom loss measurements are used together. Passive fathometry is a coherent technique that depends on the cross-correlation of upward and downward pointing beams and the bottom loss method is an incoherent technique that depends on the ratio of noise levels coming from different matched pairs of vertical arrival angles. Inversion methods that use either one of these have different properties and performance characteristics. Thus, using both of them together is an attractive combination. Here, the fathometer is used to estimate the water depth, the number of layers, and sediment thicknesses. This is followed by an inversion that uses incoherent bottom loss measurements, estimating the sound speed, attenuation, and density profiles in addition to refining the previously obtained sediment thickness values.

Second, compressive sensing (CS) is incorporated in the fathometer inversion. Here we take advantage of the sparse nature of sediment formations where there is a finite number of layer interfaces that create strong reflections. CS provides a theoretical framework that enables expressing the problem as a convex optimization problem which then can be solved efficiently.

Adaptive fathometry based on the minimum variance distortionless response (MVDR) and the white noise constrained (WNC) beamformers has been shown to outperform fathometry that uses conventional beamforming. This is due to the fact that the adaptive beamformers are able to suppress much better noise coming from unwanted angles. Here MVDR fathometry is used together with CS to estimate the water depth and sediment thicknesses using the Boundary 2003 data.

Passive fathometer data processing is a coherent ambient noise processing technique that enables passive ocean bottom profiling. The fathometer output is the cross- correlation of downward traveling sea surface noise generated just above the VLA with the upward traveling reflection of itself from the seabed, see Fig. 3(a). To achieve this, conventional or adaptive beamforming is used on the VLA data. Beamforming allows the array to look up and down while rejecting arrivals from other angles, particularly the higher level arrivals coming from around the horizontal direction (e.g. due to regional shipping activity). Adaptive beamforming such as MVDR and WNC beamforming were used to improve the fathometer results. Figure 4 from [Yardim 2014] shows how the sparse solution varies with the regularization parameter λ.

IMPACT / APPLICATIONS

Geoacoustic inversion techniques are of general interest for the estimation of waveguide parameters thus facilitating system performance prediction in shallow water. Natural transition paths for these results will be the PEO-C4I Battlespace Awareness and Information Operations Program Office (PMW-120) and the Naval Oceanographic Office.

PUBLICATIONS

2015:

Gerstoft, Xenaki, Mecklenbräuker, Multiple and single snapshot compressive beamforming, J Acoust. Soc. Am., 138, DOI: 10.1121/1.4929941 [published, refereed]

Tan, Gerstoft, Yardim, Hodgkiss (2014), Change-point detection for recursive Bayesian geoacoustic inversions, J Acoust. Soc. Am., 137, 1962-1970, [published, refereed]

Xenaki, Gerstoft, Grid-free compressive beamforming, J Acoust. Soc. Am., 137, 1923-1935 [published, refereed]

2014:

Carriere, Gerstoft, Hodgkiss (2014), Spatial filtering in ambient noise interferometry, J Acoust. Soc. Am. 135, 1186-1196, [published, refereed]

Perrot, Brehmer, Roudaut, Gerstoft, Josse, Efficient multibeam sonar calibration and performance evaluation, Int J Eng Science Innov Tech (IJESIT) Vol 3 (4), July 2014 [published, refereed]

Tan, Gerstoft, Yardim, Hodgkiss (2014), Recursive Bayesian synthetic aperture geoacoustic inversion in the presence of motion dynamics, J Acoust. Soc. Am., 136, 1187-98, [published, refereed]

Xenaki, Gerstoft, Mosegaard (2014), Compressive beamforming, J Acoust. Soc. Am., 136, 260-271. [published, refereed]

Yardim, Gerstoft, Hodgkiss, Traer (2014), Compressive geoacoustic inversion, J Acoust. Soc. Am. 135, 1245-1255 [published, refereed]

2013:

Menon, Gerstoft, Hodgkiss (2013), Effect of medium attenuation on the asymptotic eigenvalues of noise covariance matrices, IEEE Signal Proc Lett, 20, 435-438, [published, refereed]

Tan, Gerstoft, Yardim, Hodgkiss (2013), Broadband synthetic aperture geoacoustic inversion, J Acoust. Soc. Am., 131, 312-322. [published, refereed]

Xenaki, Gerstoft, Mosegaard (2013), Modeling and detection of oil in sea water, J Acoust. Soc. Am.,134, 2790-2798. [published, refereed]

Yardim, Gerstoft, Michalopoulou (2013), Geophysical signal processing using sequential Bayesian techniques. Geophysics 78, V87-V100, [published, refereed]

Yardim, Gerstoft, Hodgkiss (2013), Particle smoothers in sequential geoacoustic inversion, J Acoust. Soc. Am. 134 p 971-981, [published, refereed]

2012:

Gerstoft, Menon, Hodgkiss, Mecklenbräuker, Eigenvalues of the sample covariance matrix for a towed array, J Acoust. Soc. Am., 132, 2388-2396. [published, refereed]

Menon, R, P Gerstoft, WS. Hodgkiss (2012a), Asymptotic Eigenvalue Density of Noise Covariance Matrices, IEEE Signal processing. 60, 3415-3424, [published, refereed]

Menon, Gerstoft, Hodgkiss (2012b), Cross-correlations of diffuse noise in an ocean environment using eigenvalue based statistical inference, J Acoust. Soc. Am., 132, Nov 2012. [published, refereed]

Michalopoulou, Yardim, Gerstoft (2012), Passive Fathometer Tracking, J Acoust. Soc. Am EL.131, EL74-EL80. [published, refereed]

Traer, James and Peter Gerstoft, 2012, Coherent averaging of the passive fathometer response using short correlation time, J Acoust. Soc. Am, 131, 3633-3641, [Published, refereed]

Yardim, Gerstoft, Hodgkiss (2012), Sequential geoacoustic inversion at the continental shelfbreak, J Acoust. Soc. Am, 131, 1722-1732. [published, refereed].

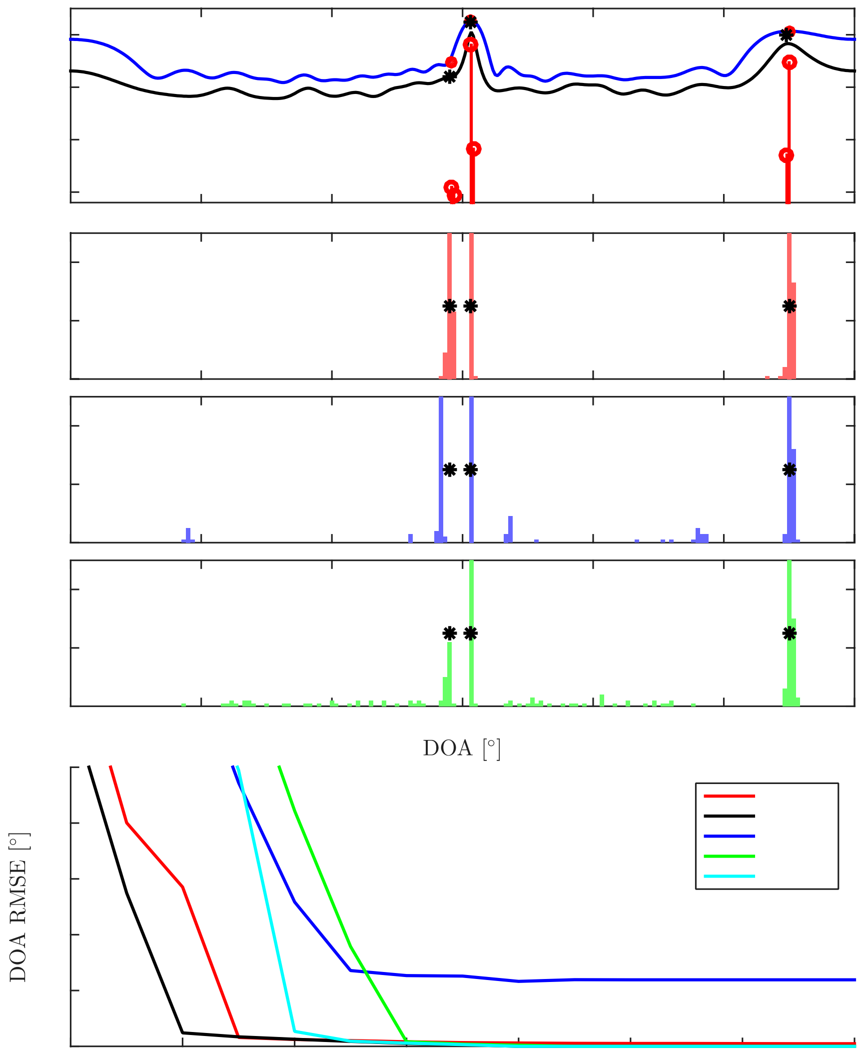

Figure 1: Multiple L = 50 snapshot example for 3 sources at DOAs [−3°, 2°, 75°] with magnitudes [12, 22, 20] dB. At array SNR = 0 dB: a) spectra for CBF, MVDR, and CS (o) and unbiased CS (o, higher levels), b) CS,(CBF, and MVDR histograms based on 100 Monte Carlo simulations, and c)(CS, exhaustive-search, CBF, MVDR, and MUSIC performance versus SNR. The true source positions (*) are indicated in a) and b). See [Gerstoft, 2015] for further details.

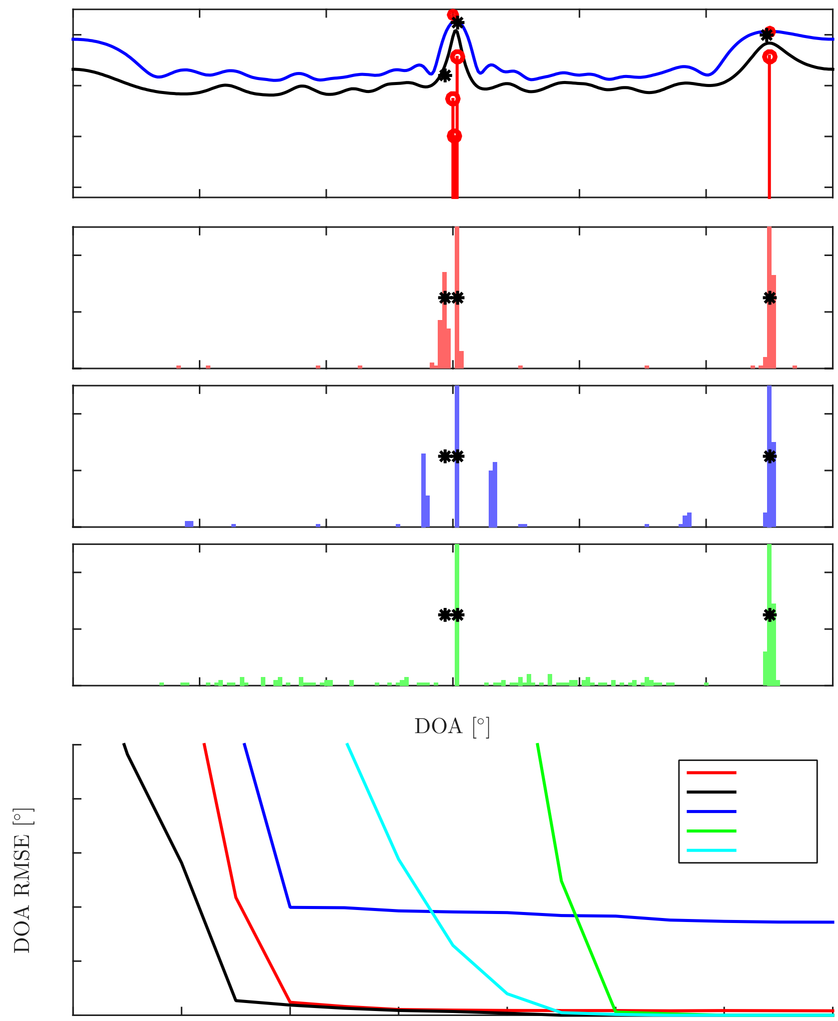

Figure 2: Same scenario as Fig. 1 but with closer spaced sources [−2°, 1°, 75°]. See [Gerstoft, 2015] for further details.

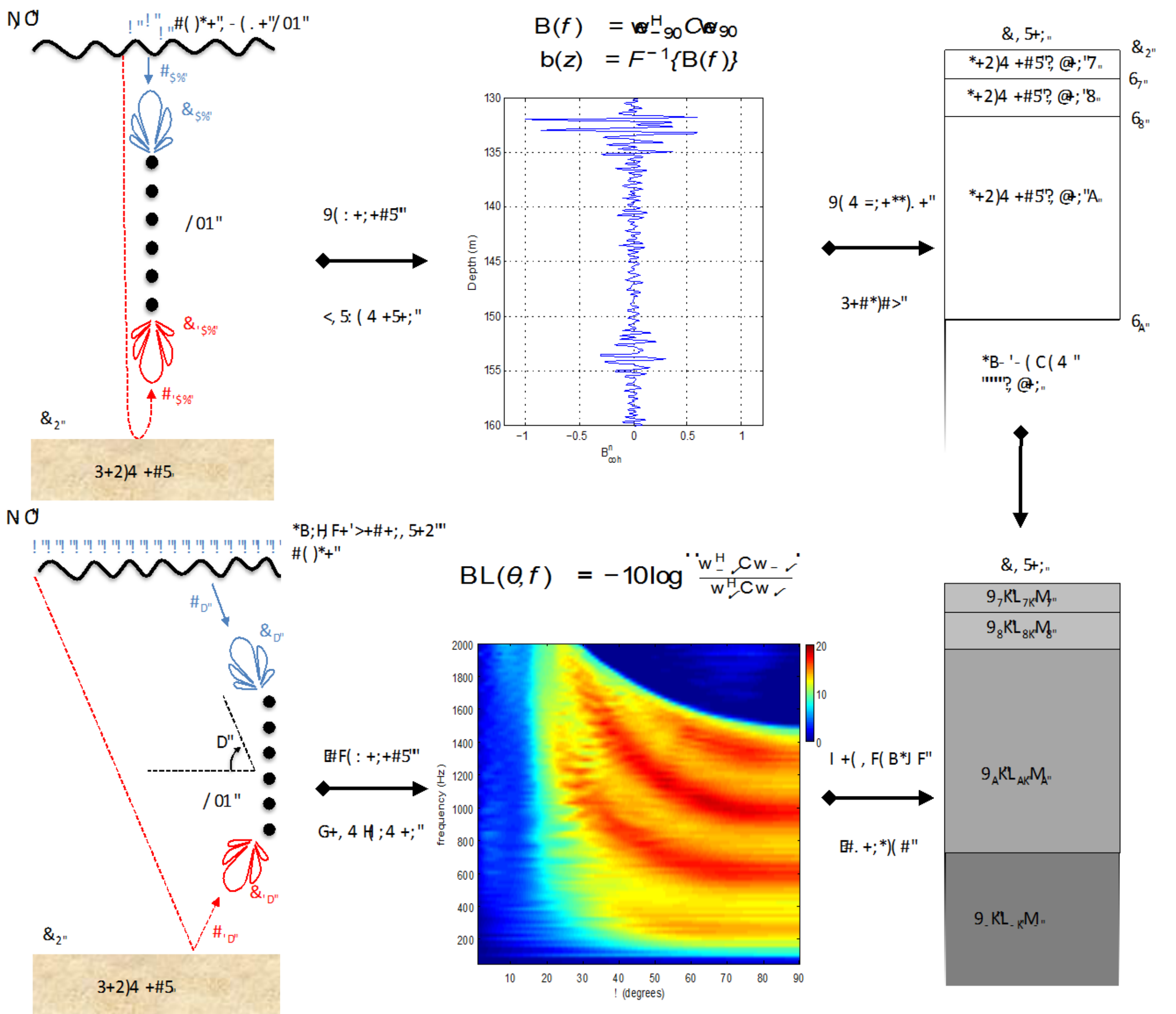

Figure 3. Description of the method: (a) Coherent fathometer processing by cross-correlating the upward and downward propagating surface-generated noise. The number of interfaces and their locations are estimated using compressive sensing. (b) Incoherent bottom loss estimation using beamforming. The bottom loss is obtained by dividing the bottom-reflected upward propagating noise by the downward propagating noise. This estimates bottom loss as a function of frequency and angle. Coupled with the layering information obtained from the fathometer results, a final geoacoustic inversion is performed. For further details see [Yardim 2014].

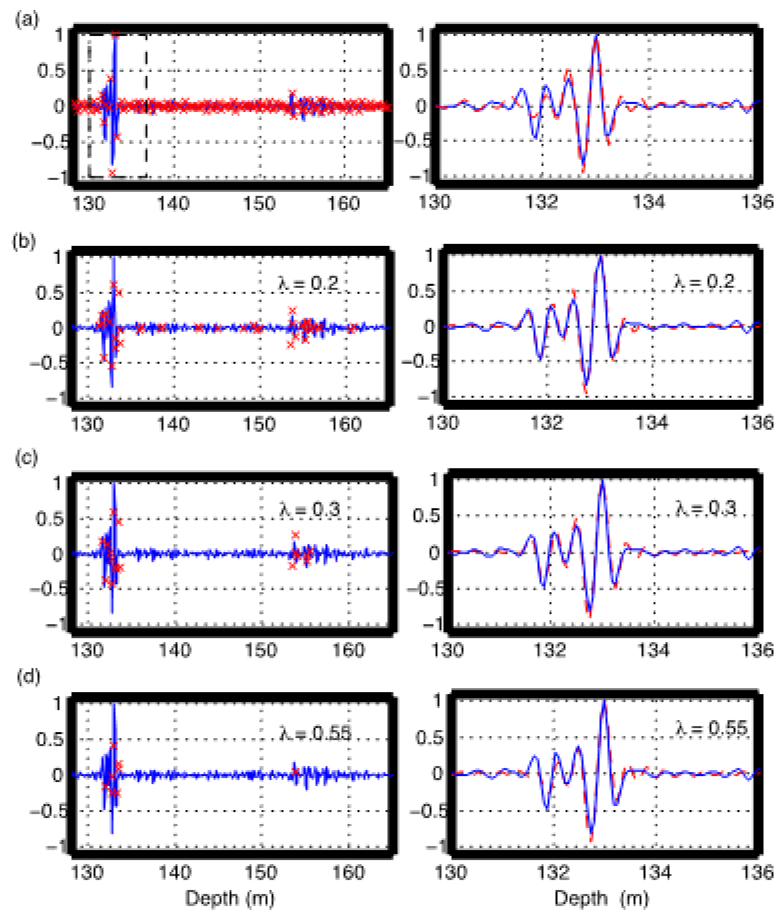

Figure 4: Four inversion results (×) using the MVDR fathometer output at 00:00 hr with two-way travel time converted into depth using c = 1500 m/s: (a) l2-norm inversion with regularization, and CS inversions with (b) λ = 0.2, (c) λ = 0.3, and (d) λ = 0.55. The right column plots are zoomed (rectangle in (a)) sections of the time-series where b(z) (dashed) is compared to the observed fathometer output (solid). For further details see [Yardim 2014].