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. In an ONR Graduate Traineeship Award we address using random matrix theory in ocean acoustics.

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.

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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.

WORK COMPLETED

One application of passive estimation of the time-domain Green's function is in the use of cross-correlations of upward and downward pointing vertical line array beams observing ambient noise to extract seabed layer structure (i.e. a passive fathometer) [Traer et al., 2011, 2012]. This passive fathometer technique exploits the naturally occurring acoustic sounds generated on the sea-surface, primarily from breaking waves. The method is based on the cross-correlation of noise from the ocean surface with its echo from the seabed, which recovers travel times to significant seabed reflectors. To limit averaging time and make this practical, beamforming is used with a vertical array of hydrophones to reduce interference from horizontally propagating noise. The initial development used conventional beamforming, but significant improvements have been realized using adaptive techniques. An analytical model is presented in [Traer et al., 2011] for the passive fathometer response to ocean surface noise, interfering discrete noise sources, and locally uncorrelated noise in an ideal waveguide. The leading order term from the ocean surface noise produces the cross-correlation of vertical multipaths, yielding the depth of sub-bottom reflectors.

We have explored incorporating Kalman and particle filter tracking techniques into the geoacoustic inversion problem [Yardim 2011a, 2011b, 2012, 2013, Michalopoulou 2012]. This enables spatial and temporal tracking of environmental parameters and their underlying probability densities, making geoacoustic tracking a natural extension to geoacoustic inversion techniques.

RESULTS

Geoacoustic tracking

In many cases, it is of interest to estimate geoacoustic parameters over a larger spatial region rather than just the parameters characterizing propagation between a fixed source and receiver (or receiving array) location. Data might be available at a moored vertical receiving array from a towed acoustic sound source or a source might be received by a towed horizontal array. In both cases, the typical approach would be to treat each record of data independently of the others and carry out a full geoacoustic inversion for every record resulting in a sequence of geoacoustic parameter estimates and, in some cases, posteriori probability densities of the environmental parameters. The latter enables the environmental uncertainty to be projected into other waveguide characterizations such as propagation loss and its uncertainty.

In a review paper we have studied the basis and use of sequential filtering in ocean acoustics [Yardim 2011]. Sequential filtering provides a consistent framework for estimating and updating the unknown parameters of a system as data become available, see Figs. 1-2. Despite significant progress in the general theory and implementation, sequential Bayesian filters have been sparsely applied to geoacoustic inversion in ocean acoustics. The foundations of sequential Bayesian filtering with emphasis on practical issues are first presented covering both Kalman and particle filter approaches. Filtering becomes a powerful estimation tool, employing prediction from previous estimates and updates stemming from physical and statistical models that relate acoustic measurements to the unknown parameters. Ocean acoustic applications are then reviewed focusing on the estimation of environmental parameters evolving in time or space. Some possible scenarios for geoacoustic inversion are shown in Fig. 3.

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.

Compressive sensing is a technique that solves sparse inversion problems by taking advantage of the sparseness of the solution. Introducing the Lagrange multiplier λ, the problem becomes:

$$\hat{\mathbf{x}} = \underset{\mathbf{x}}{\mathbf{argmin}}\left[\left\|\mathbf{b}-\mathbf{S}\mathbf{x}\right\|_2 + \lambda\left\|\mathbf{x}\right\|_1\right]$$

In this equation $\mathbf{b}$ is the fathometer output (a real valued time series), $\mathbf{S}$ is a matrix of time-delayed sinc-functions, translating the sparse reflections at depth $\mathbf{x}$ to the fathometer output $\mathbf{b}$.

In recent years, CS has been used in diverse fields. In addition to some early applications, recent underwater acoustic work includes sensor network representations, compressive channel sensing for underwater communication, beamforming, and matched-field processing.

Ocean acoustic passive fathometry [Gerstoft et al., 2008, Siderius 2011. Traer et al 2009, 2011, 2012] is a coherent method that computes the cross- correlation between the upward and downward propagating noise. A geoacoustic inversion algorithm based on passive fathometry then can be used to infer the sediment properties. This approach to fathometry is a passive method since it only uses the surface-generated noise field. It requires the decomposition of the ambient noise wave field into its upward and downward propagating components. A common way of achieving this is using beamforming to steer the VLA. 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. A multiple model particle filter is used in [Michalopoulou et al 2012] to track the range-dependent sediment thicknesses in an environment where the number of interfaces change. 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. 4(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.

The CS inversion results also can be compared with l2-norm inversions with regularization at 00:00 hr. The pseudo-inverse solution in Fig. 5(a) yields a noisy reflection coefficient sequence with clusters of larger amplitudes at 131–135 m (water-sediment interface and the top sediment layer) and 153–157 m (a secondary series of interfaces). The synthetic fathometer output using the pseudo-inverse estimated environment matches well the measured fathometer response except for the small mismatch around 132 m, see Fig. 5(a). Three CS inversion results with increased sparseness are given in Fig. 5(b–d). The results with $\lambda = 0.2$ show many reflectors with small but non-zero reflection, $\lambda = 0.3$ focuses well on the distinct interface regions with no reflectors in between, and finally $\lambda = 0.55$ mostly misses the reflectors at 150–160 m entirely and only does a good job of estimating the reflectors around 130–135 m. The synthetic fathometer outputs for all three values of λ give a better match to the fathometer response than does the pseudo-inverse method, demonstrating the advantages of using CS over classical l2-norm based inversions for the fathometer inversion problem.

Broadband synthetic aperture geoacoustic inversion

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] focuses on matched field inversion for mobile, single source-receiver configurations in low SNR conditions.

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

2014:

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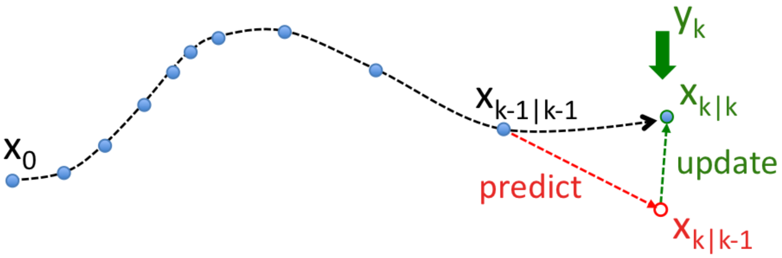

Figure 1. Sequential Bayesian filtering. From state x_{k-1}, state x_k is first predicted via the state equation, providing $x_{k|k-1}$. As data y_k becomes available, the observation equation is employed to update state $x_{k|k-1}$, providing $x_{k|k}$.

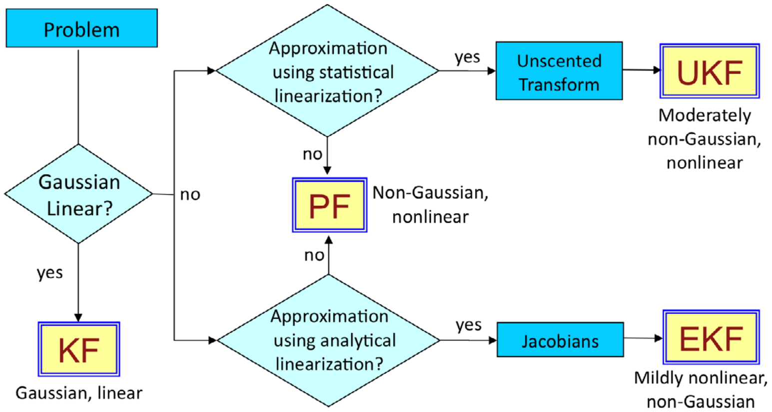

Figure 2. A quick guide to filter selection leading to the Kalman filter (KF), extended Kalman filter (EKF), unscented Kalman filter (UKF), and particle filter (PF).

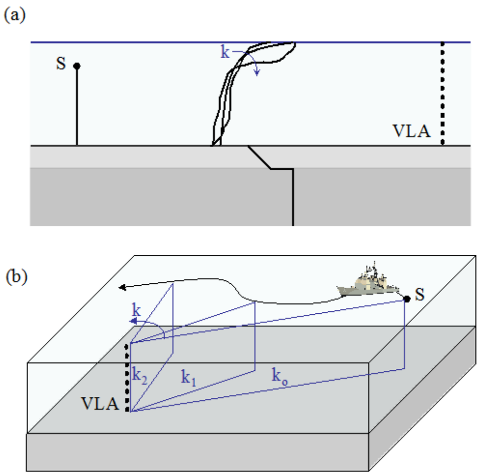

Figure 3. Geoacoustic environmental tracking: (a) Temporal tracking of the ocean sound speed profile for a fixed-receiver and a fixed-source and (b) tracking of the changing environment between the receiver and a moving source. Here shown for a vertical line array (VLA) of receivers.

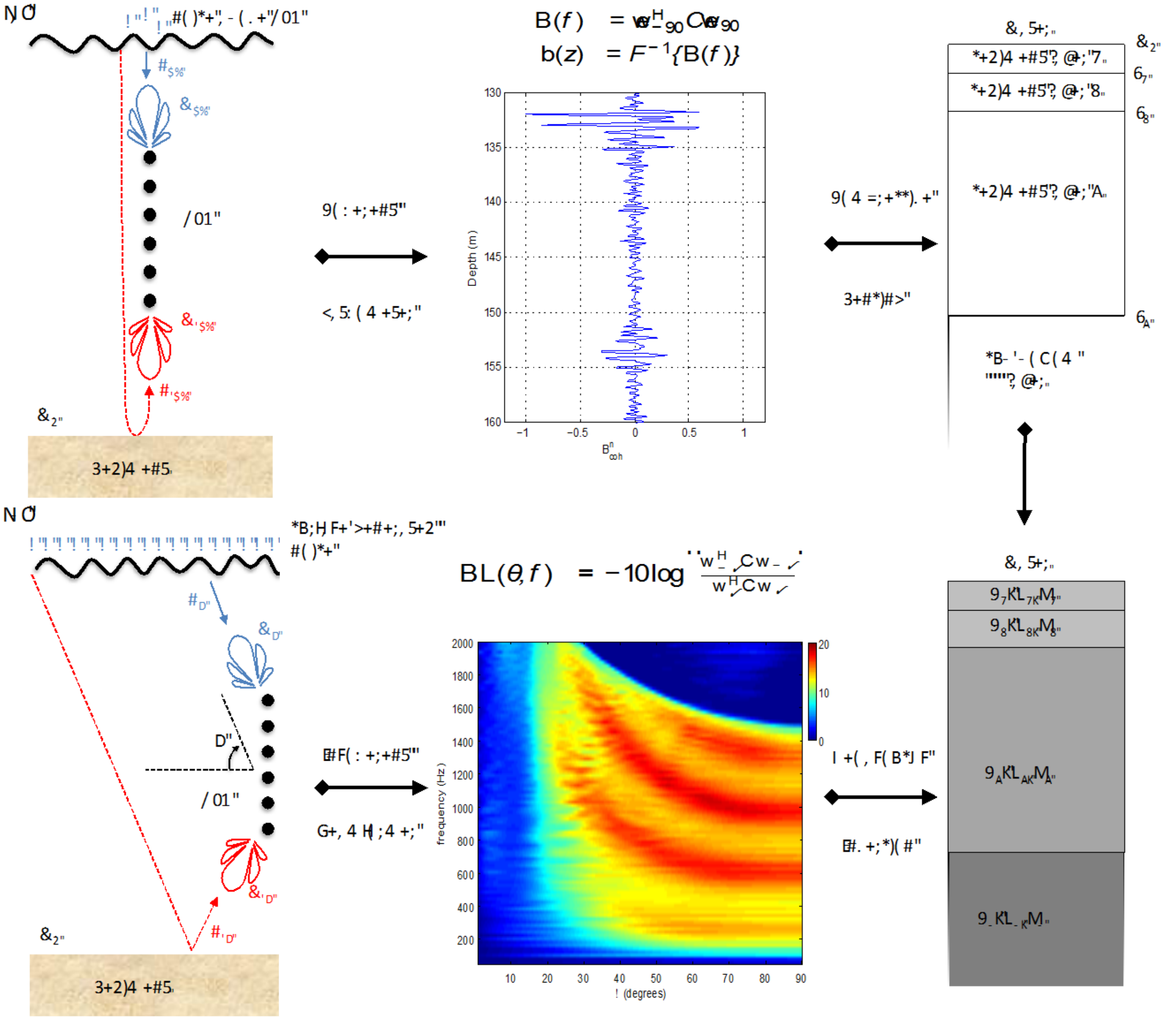

Figure 4. Description of the method: (a) Coherent fathometer processing by cross-correlating the upward and downward propagating surface-generated noise. The number of interfaces and their locations are estimated using compressive sensing. (b) Incoherent bottom loss estimation using beamforming. The 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.

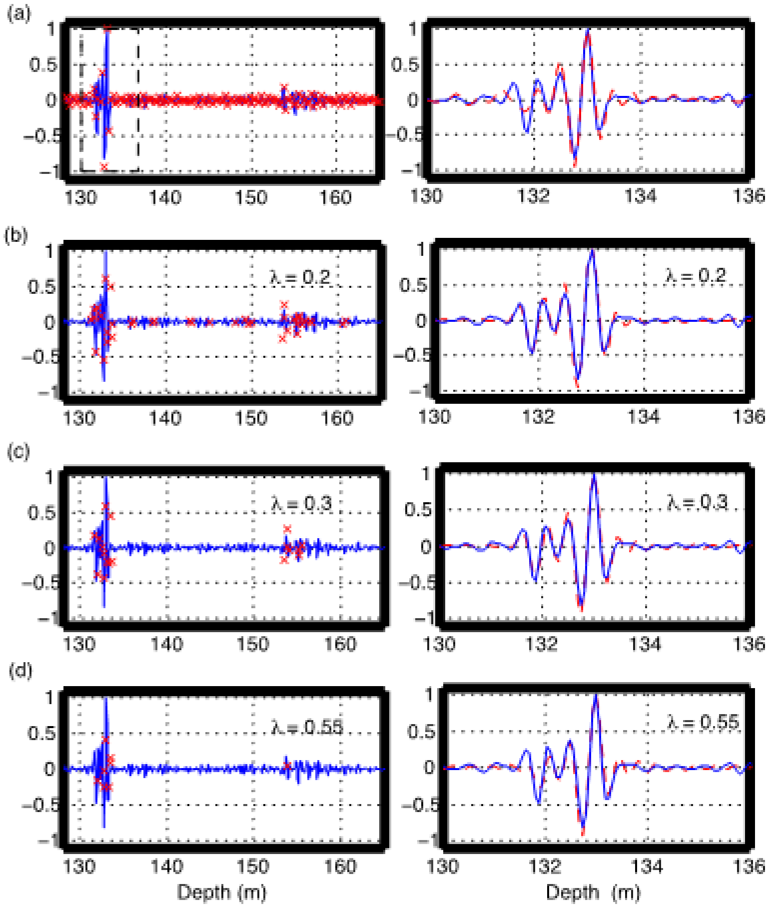

Figure 5: Four inversion results (×) using the MVDR fathometer output at 00:00 hr with two-way travel time converted into depth using c = 1500 m/s: (a) l2-norm inversion with regularization, and CS inversions with (b) λ = 0.2, (c) λ = 0.3, and (d) λ = 0.55. The right column plots are zoomed (rectangle in (a)) sections of the time-series where b(x) (dashed) is compared to the observed fathometer output (solid).