Blind channel estimation of underwater acoustic waveguide impulse responses using marine mammal vocalizations

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1 Introduction

This paper presents results from an ongoing research project aimed at improving the reliability of tracking underwater marine mammals. In particular, this project aims to expand the usefulness of specific high-performance tracking approaches (e.g., those using time of arrival-based localization) to a wider range of species, including humpback whales, than is currently possible. This expansion will facilitate the identification of critical habitat for marine sanctuaries and allow sound-producing oceanic activities, including scientific, industrial, and military endeavors, to be more responsibly conducted.

A sound that is heard underwater is a function of both the sound made by the source and the environment the sound passes through in traveling from source to receiver. These environmental influences include ocean surface wave conditions, ocean bottom sediment properties, and relative source & receiver locations. The net effect of all these influences is called the impulse response for the acoustic channel between the source and receiver. Knowledge of the underwater acoustic impulse response permits source localization, and potentially ocean environmental parameter estimation, in many cases. In this work, a technique called Blind Channel Estimation (BCE) is employed to estimate the impulse responses, where blind refers to the estimation algorithm not requiring *a priori* knowledge of the source waveform. BCE was originally conceived as a way to improve cell phone reception as the user moves through a complicated environment (e.g., between tall buildings).

2 Theory

This section will present a brief development of the theory behind BCE for a one source/two receiver case. Vectors (e.g., $\mathbf{h}_i$) and matrices (e.g., $\mathbf{X}$) are shown in lower and uppercase boldface characters, respectively. This approach is generalizable to any number of receivers.

For the one source/two receiver case, as shown in Xu et al. (1995), the received (i.e., sampled) waveforms ($\mathbf{x}_i$ and $\mathbf{x}_j$) are expressed as

$$\mathbf{x}_i(k) = \mathbf{h}_i(k) \otimes \mathbf{s}(k)$$
$$\mathbf{x}_j(k) = \mathbf{h}_j(k) \otimes \mathbf{s}(k)$$

where $\mathbf{h}_i(k)$ is the impulse response for the i^{th} receiver, and $\mathbf{s}(k)$ is the source waveform. These two equations can be expressed as

$$\mathbf{h}_i(k) \otimes \mathbf{x}_j(k) = \mathbf{h}_i(k) \otimes \big(\mathbf{h}_j(k) \otimes \mathbf{s}(k)\big)$$
$$\mathbf{h}_i(k) \otimes \mathbf{x}_j(k) = \mathbf{h}_j(k) \otimes \big(\mathbf{h}_i(k) \otimes \mathbf{s}(k)\big)$$
$$\mathbf{h}_i(k) \otimes \mathbf{x}_j(k) = \mathbf{h}_j(k) \otimes \mathbf{x}_i(k)$$
$$\mathbf{h}_i(k) \otimes \mathbf{x}_j(k) - \mathbf{h}_j(k) \otimes \mathbf{x}_i(k) = 0$$

This convolution relationship can be expressed as a system of linear equations:

$$\begin{pmatrix} \mathbf{X}_j(L) & -\mathbf{X}_i(L) \end{pmatrix} \begin{pmatrix} \mathbf{h}_i \\ \mathbf{h}_j \end{pmatrix} = 0$$
$$\mathbf{X}(L)\mathbf{h} = 0 \tag{1}$$

where

$$\mathbf{X}_j(L) = \begin{pmatrix} x_j(L) & x_j(L+1) & \dots & x_j(2L) \\ x_j(L+1) & x_j(L+2) & \dots & x_j(2L+1) \\ \vdots & \vdots & \ddots & \vdots \\ x_j(N-L) & x_j(N-L+1) & \dots & x_j(N) \end{pmatrix}$$

$$\mathbf{h}_i \equiv [h_i(L), \dots, h_i(0)]^T$$

and $L+1$ is the length of the longest IR in the set.

Due to the ambiguities inherent to the problem formulation in Equation (1), BCE is unable to resolve the start time and scaling factor for the channels being estimated. In acoustical terms, there is magnitude and phase ambiguity in the solution. The literature presents at least two possibilities to resolve this ambiguity. In Xu et al. (1995), the constraint $|\mathbf{h}|_1 = 1$ is presented. This addresses the scaling factor but not the phase ambiguity. In Zeng et al. (2013), the ℓ^{th} entry in $\mathbf{h}$ is defined to be equal to 1. All other values of $\mathbf{h}$ are estimated relative to this value. To achieve this, the ℓ^{th} column of $\mathbf{X}$ is defined as $\mathbf{b}$ and ℓ is set equal to some constant (frequently, $(L+1)/2$). Thus, the governing equation becomes (for the two channel case):

$$\mathbf{A}\mathbf{c} = \mathbf{b} \tag{2}$$

where

$$\mathbf{c} = [[h_1(L), \dots, h_1(\ell+1), h_1(\ell-1), \dots, h_1(0)], \mathbf{h}_2^T]$$

$\mathbf{b}$ is the ℓ^{th} column of $\mathbf{X}$, and $\mathbf{A}$ is obtained by removing the l^{th} column of $\mathbf{X}$.

Using Equation (2) as a starting point, the blind channel estimation problem can be formulated as a quadratically

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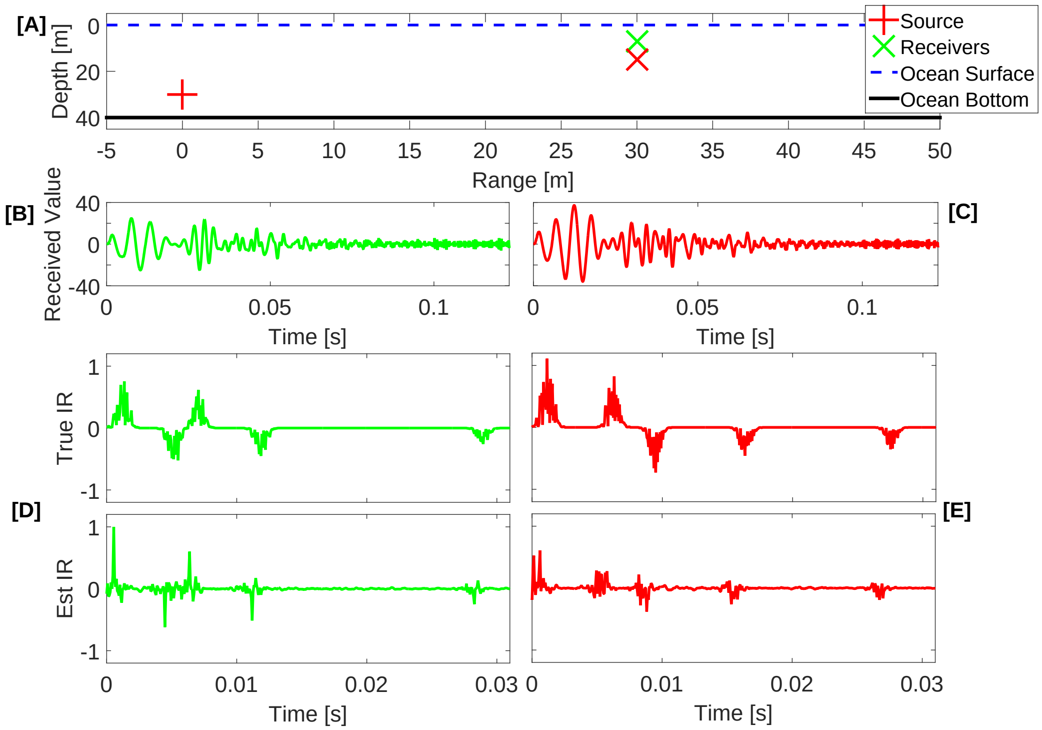

Figure 1: BCE performance under simulated ocean conditions. [A] Simulation conditions, with a uniform water depth of 40 m, a single source 30 m below the surface, and two receivers 30 m away from the source and at depths of 7 and 15 m, respectively. Received waveforms at the top and bottom are shown in [B] and [C], respectively. The true and estimated impulse responses for the top receiver are shown in [D], while those for the bottom receiver are shown in [E].

constrained ℓ_1-minimization problem (as per Equation 1.2 in Becker (2011)):

$$\min \parallel c \parallel_{\ell_1} \text{ subject to } \parallel \mathbf{Ac} - \mathbf{b} \parallel_{\ell_2} \leq \epsilon \qquad (3)$$

where $\mathbf{c} \epsilon R^p$ and $p = 2 * (L + 1) - 1$ (for the two channel case). This type of problem can be solved using established optimization approaches (e.g., Becker (2011)).

3 Simulation Results

To test the performance of the BCE approach using realistic marine mammal vocalizations, a set of simulations were carried out. For this paper, the source is a frequency sweep (i.e., a chirp) from 100-4300 Hz, modeled after a humpback whale call recorded offshore of Maui in May 2015. Figure 1 shows the results of this simulation. The ocean environment used for this simulation is shown in subplot **[A]**. The chirp is observed by the shallow and deeper simulated receivers as shown in **[B]** and **[C]**, respectively. The estimated, and true, impulse responses for each of the two channels are shown in **[D]** and **[E]**. The good match between true and estimated channels suggests that blind channel estimation can reveal enough about the impulse response to allow the sound source to then be located. It is likely that some environmental conditions and source characteristics are better suited for estimating the underlying impulse responses than others. For instance, if the underlying channels have significant time-varying components (e.g., due to ocean surface waves or relative motion between the source and receivers) the estimated impulse responses tend to be less informative.

4 References

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Acknowledgments

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