Acoustic multipath arrival time estimation via blind channel estimation

Brendan Rideout, Eva-Marie Nosal, & Anders Host-Madsen

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SCHOOL OF OCEAN AND EARTH SCIENCE AND TECHNOLOGY
UNIVERSITY OF HAWAIʻI AT MĀNOA

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Objective and Background

- Objective: Estimate multipath arrival times by blindly calculating underwater acoustic impulse responses using marine mammal vocalizations
  - Blind?
    - No knowledge of source signal required
    - No assumptions on environment (e.g., no range-independent assumption); non-parametric
  - Potential uses include:
    - Localization of both impulsive and non-impulsive marine mammal vocalizations
    - Ocean tomography via unknown sources

What is an impulse response (IR)?

- The output (or response) of a system when the input is a unit impulse
- Given the system IR, the system output given any input signal is:

$$x(t) = h(t) \otimes s(t)$$

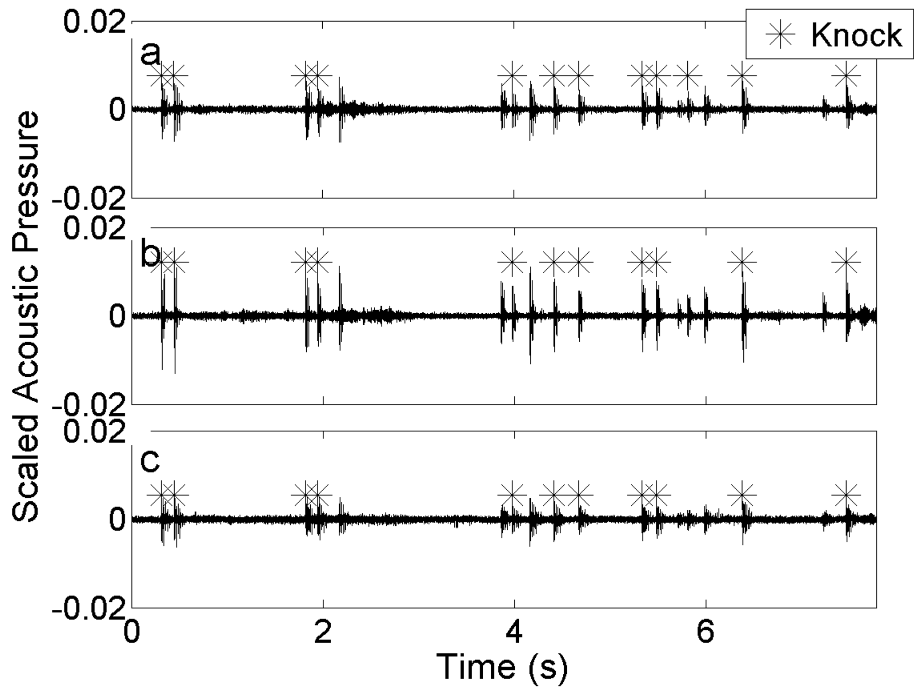
$x(t)$ = system output
$h(t)$ = impulse response
$s(t)$ = system input

Impulse Responses and Marine Mammals

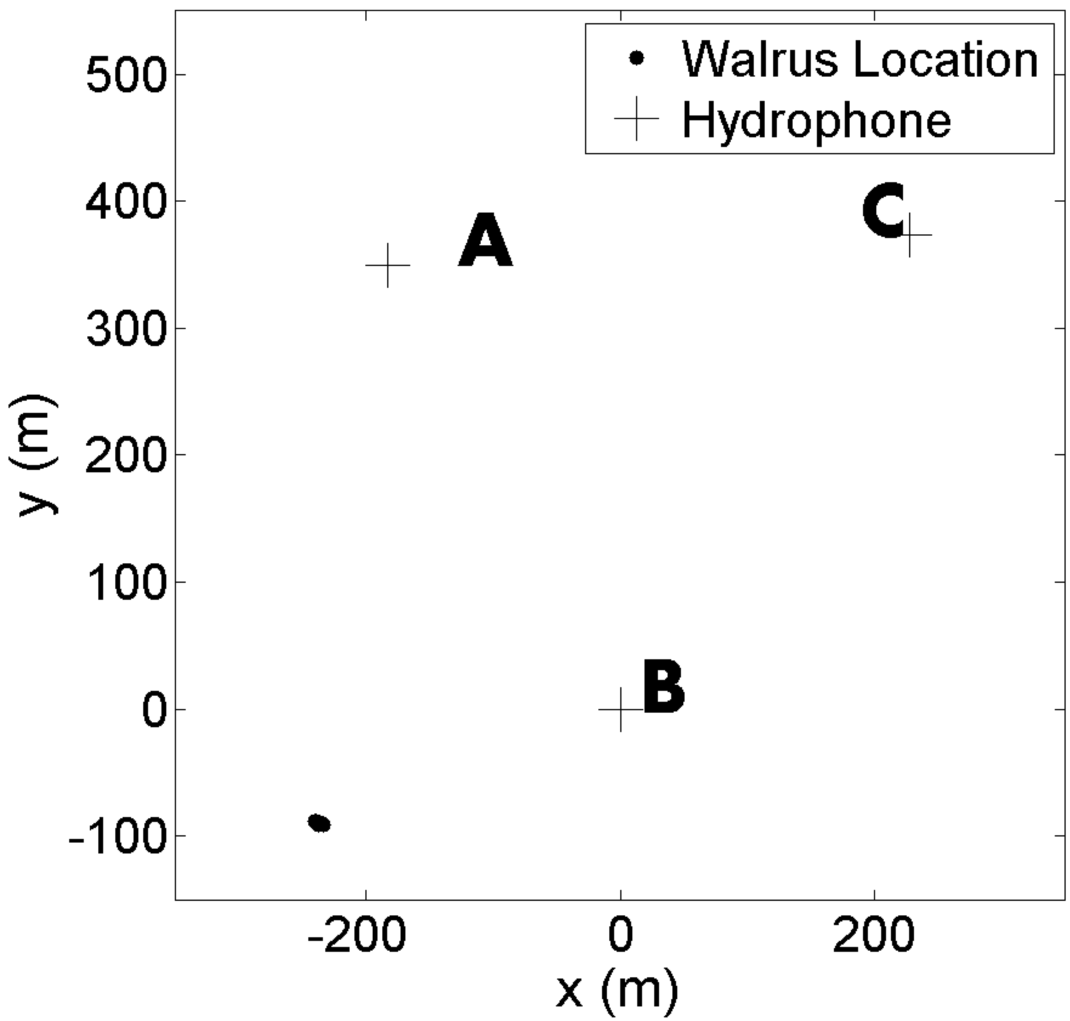
- Consider the case of a walrus (or sperm whale) producing impulsive vocalizations
- Effectively, the received signals from these animals is an approximation of the impulse responses for the acoustic channels between the animal and the receiver
- One impulse response for each source:receiver pair

Walrus Vocalizations

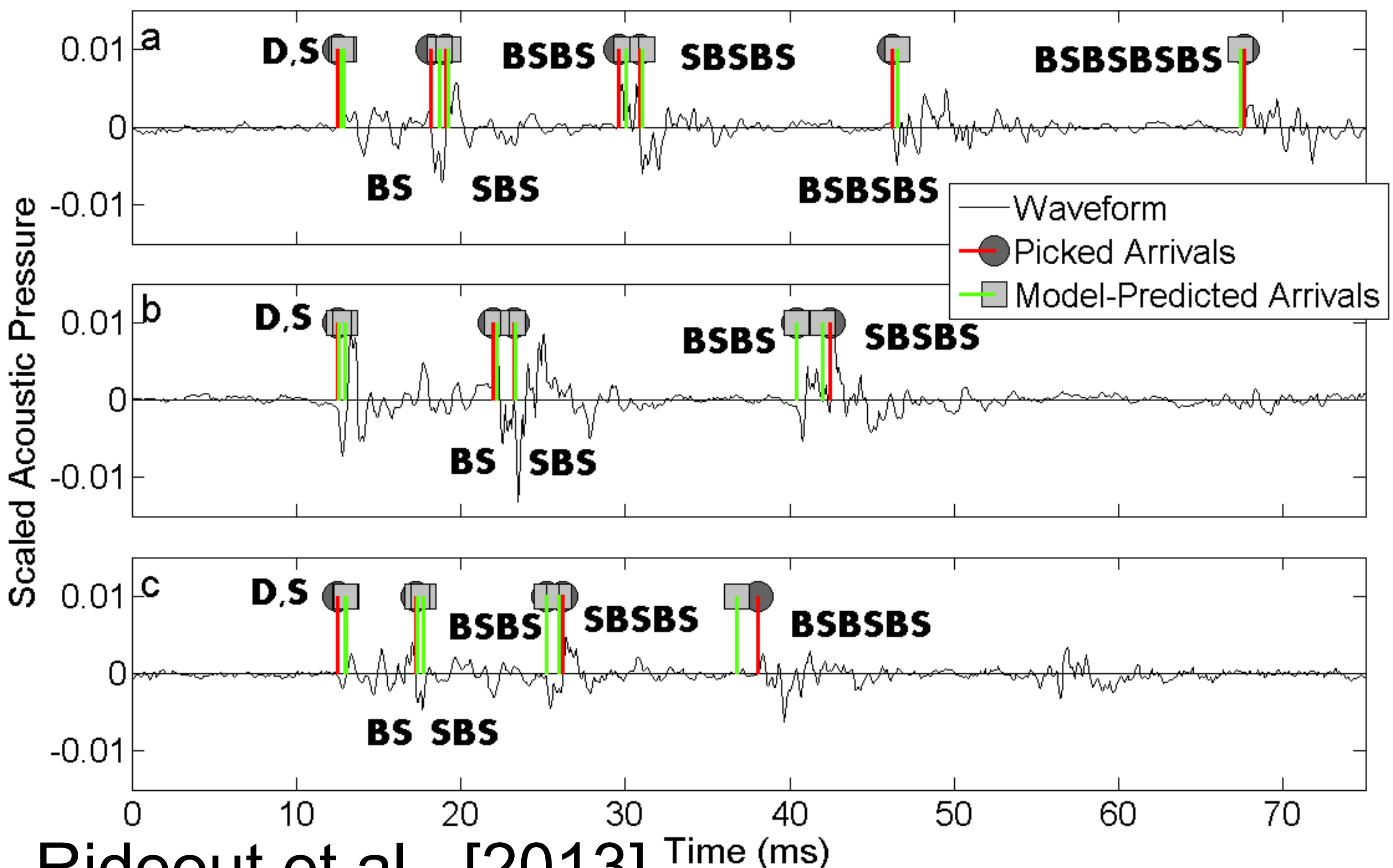
- Walrus vocalizations include knocks, grunts, and bells
- Knocks are impulsive vocalizations made underwater, primarily by male walruses



Impulse Response Information Content



Impulse Responses and Marine Mammals, cont'd.



- Rideout et al., [2013]

Theory: Problem Formulation

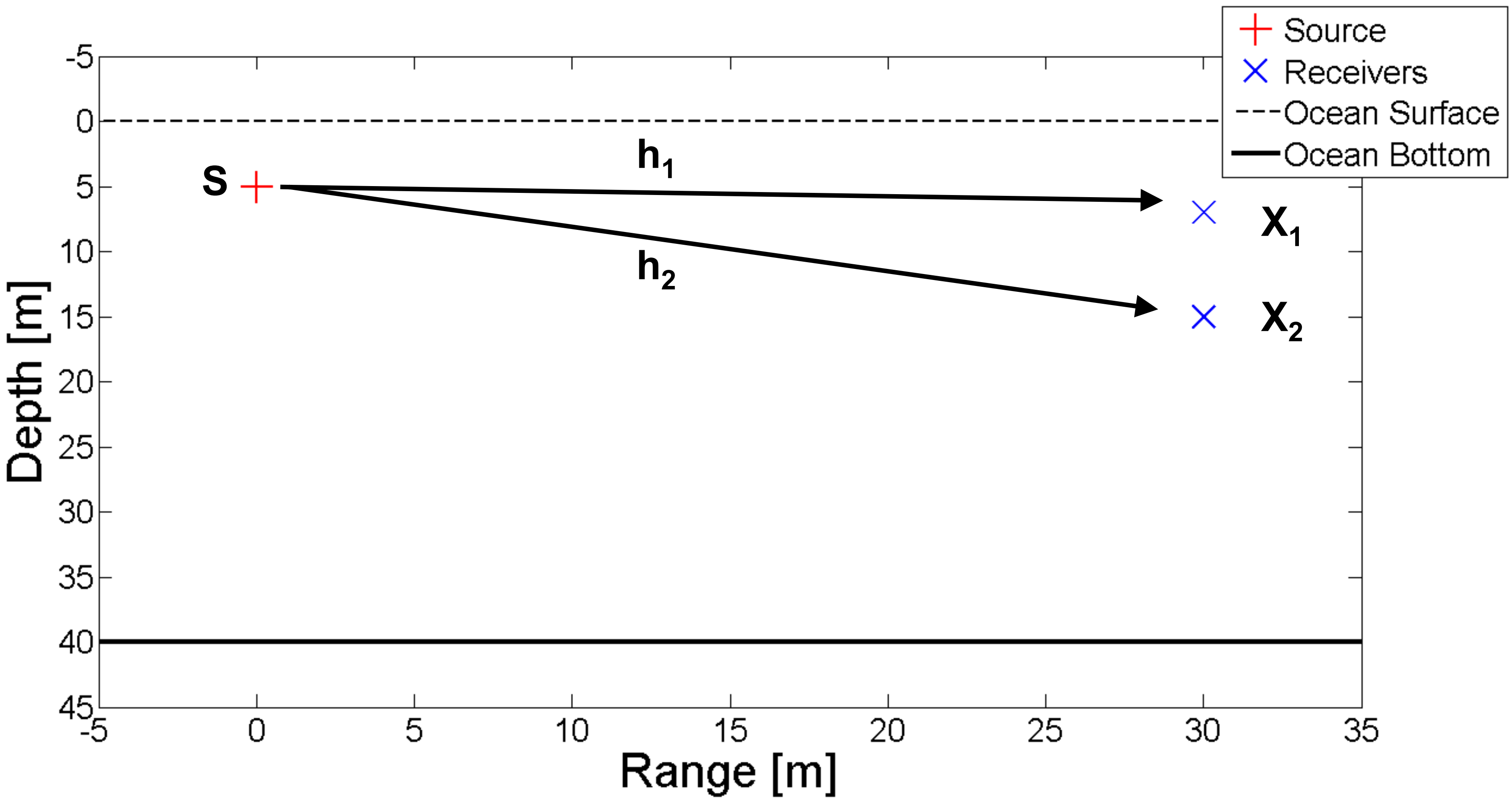
- Received data:

$$x_1(k) = h_1(k) \otimes s(k)$$
$$x_2(k) = h_2(k) \otimes s(k)$$

- If the channels share a common source:

$$\begin{aligned} h_2(k) \otimes x_1(k) &= h_2(k) \otimes \left[h_1(k) \otimes s(k)\right] \\ &= h_1(k) \otimes \left[h_2(k) \otimes s(k)\right] \\ &= h_1(k) \otimes x_2(k) \end{aligned}$$
$$h_2(k) \otimes x_1(k) - h_1(k) \otimes x_2(k) = 0$$

Theory: Problem Formulation, cont' d.



Theory: Problem Formulation, cont' d.

- Convolution can be expressed as a system of equations (L = # samples in the channels, N = # data):

$$\left[X_1(L) \vdots - X_2(L)\right]\begin{bmatrix} h_2 \\ h_1 \end{bmatrix} = 0 \qquad X(L)h = 0$$

- Where

$$h_m \equiv \left[h_m(L), \cdots, h_m(1)\right] \qquad X_m(L) \equiv \begin{bmatrix} x_m(1) & x_m(2) & \cdots & x_m(L) \\ x_m(2) & x_m(3) & \cdots & x_m(L+1) \\ \vdots & \vdots & \ddots & \vdots \\ x_m(N-L) & x_m(N-L+1) & \cdots & x_m(N) \end{bmatrix}$$

- Solve the homogeneous system of equations for the IR vector, h
- Generalizable to any number of receivers

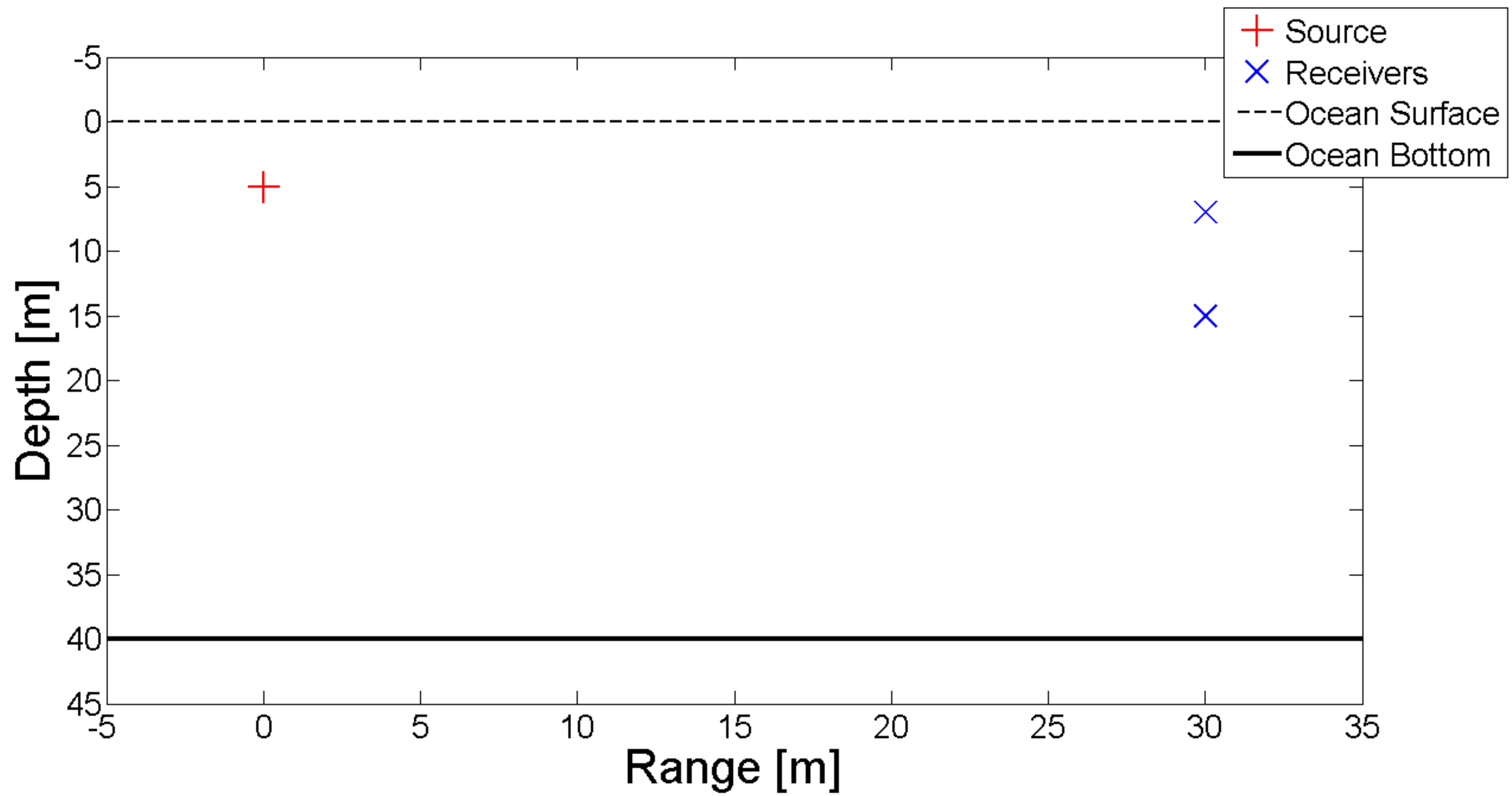
Theory: Optimization Algorithm

- To solve the over-determined system of equations $X(L)h = 0$ (i.e., estimate the IRs), an iterative, L1 optimization routine called NESTA (Becker et al., 2011) is used.
  - Designed to efficiently acquire compressible signals, and adapted to estimate IRs
  - Doesn't require precise knowledge of channel length, nor knowledge of number of significant non-zero IR samples

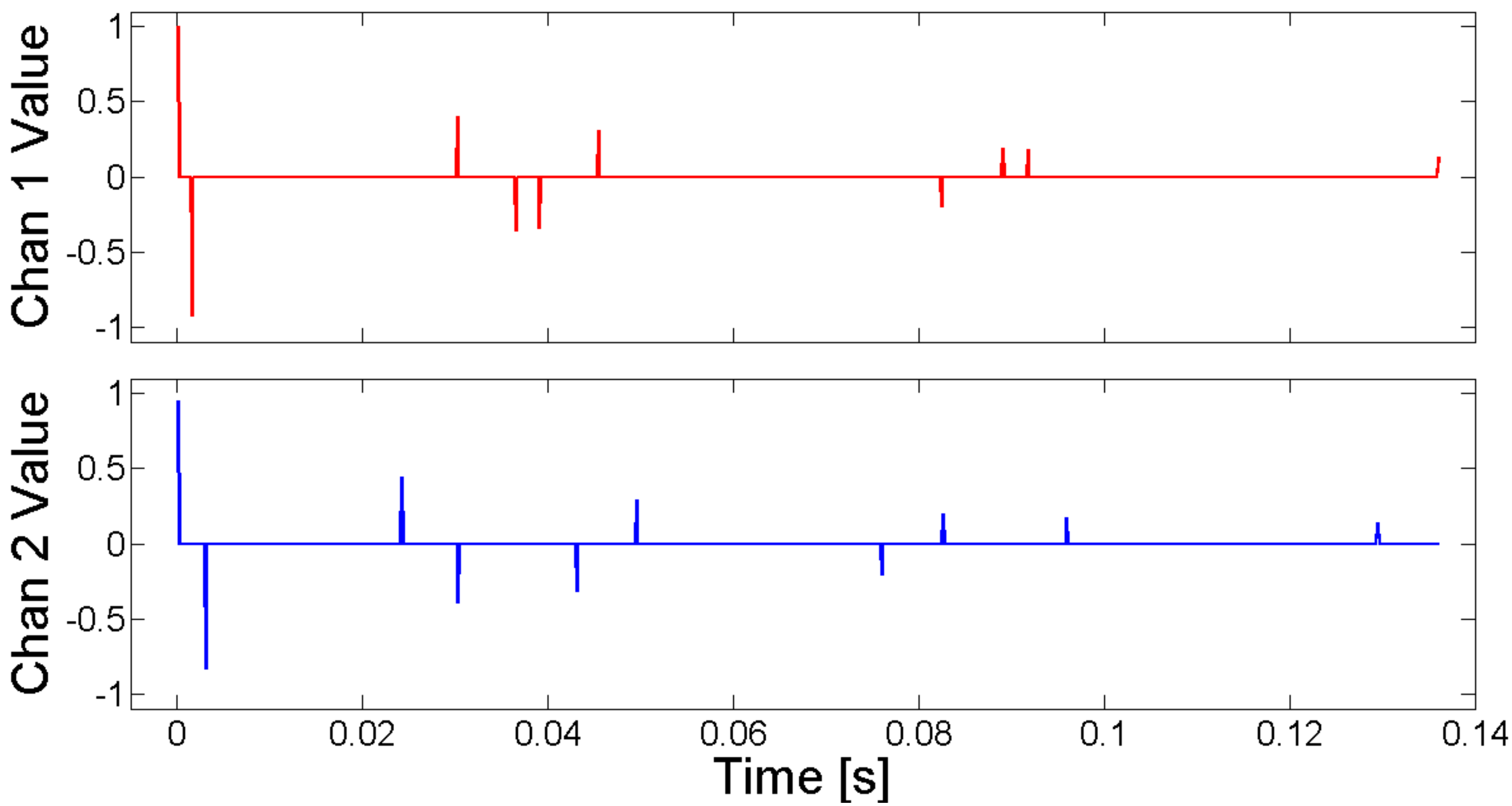
Theory: Optimization Algorithm, cont’d.

- NESTA (Nesterov’s Algorithm)
  - Application of compressed sensing which builds upon classical Basis Pursuit techniques
    - Compressed Sensing
      - Identification of smallest number of signal components containing the most information
    - Basis Pursuit
      - Decomposition of a signal (e.g., IR) into an ‘optimal’ (i.e., minimum l1 norm) combination of components
  - Estimated IRs balance data fit with solution size using tradeoff parameter
    - Cost Function = $\lambda \|x\|_{\ell_1} + \frac{1}{2}\|b - Ax\|_{\ell_2}^2$
  - Tradeoff parameter proportional to noise power
    - As noise increases, smaller solutions preferred

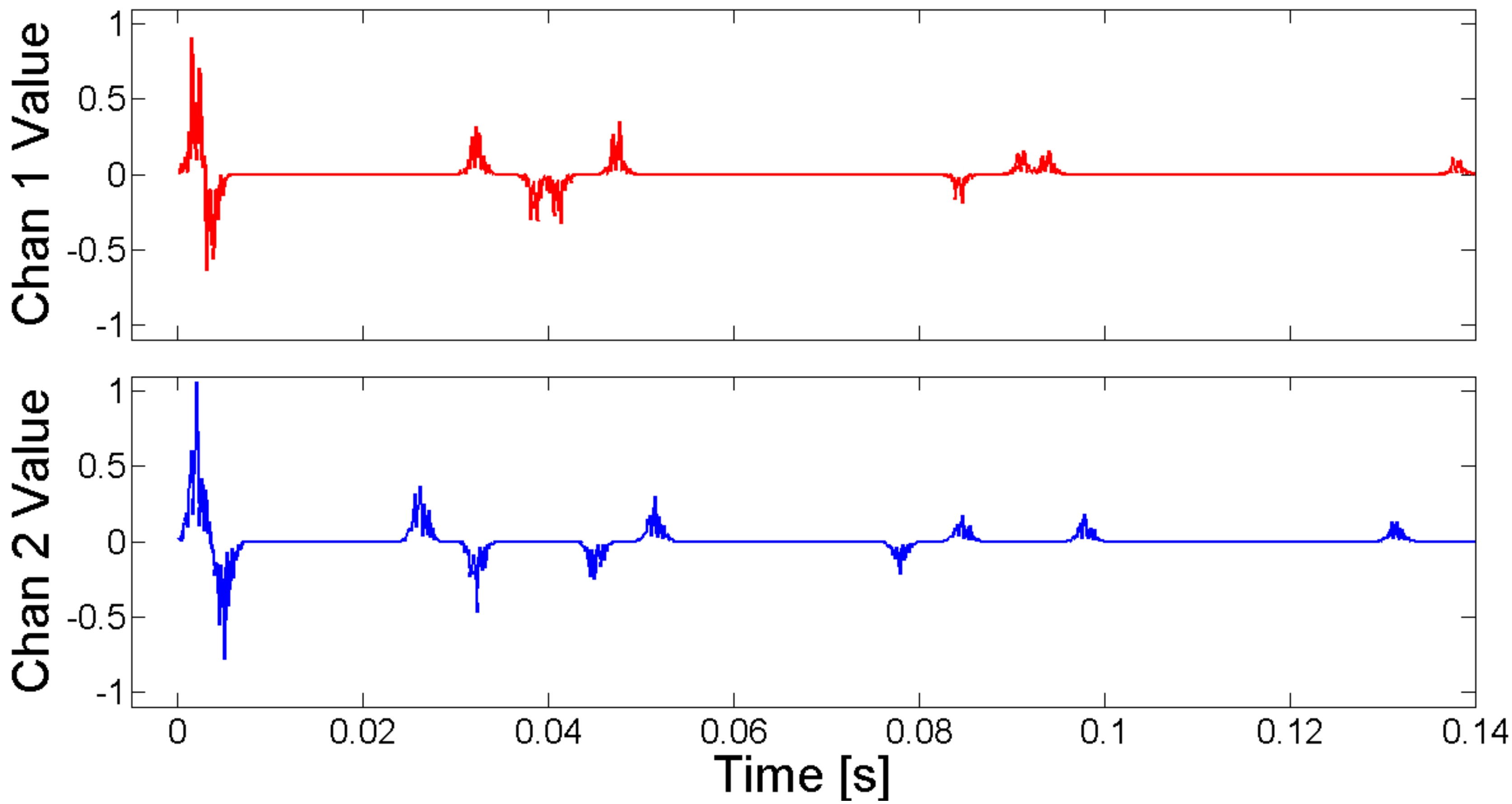
Simulation: Environment



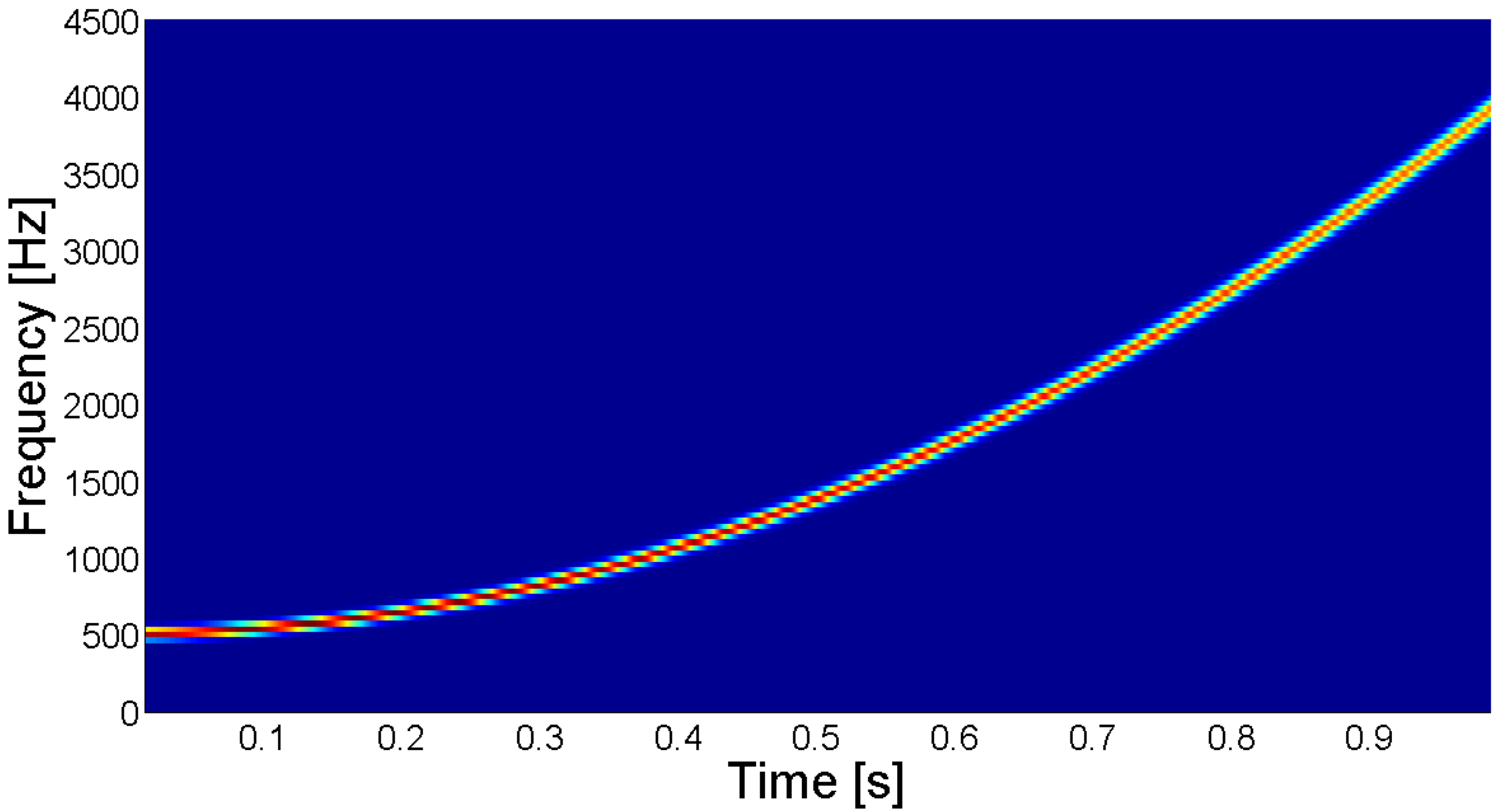
Simulation: Calculated IR

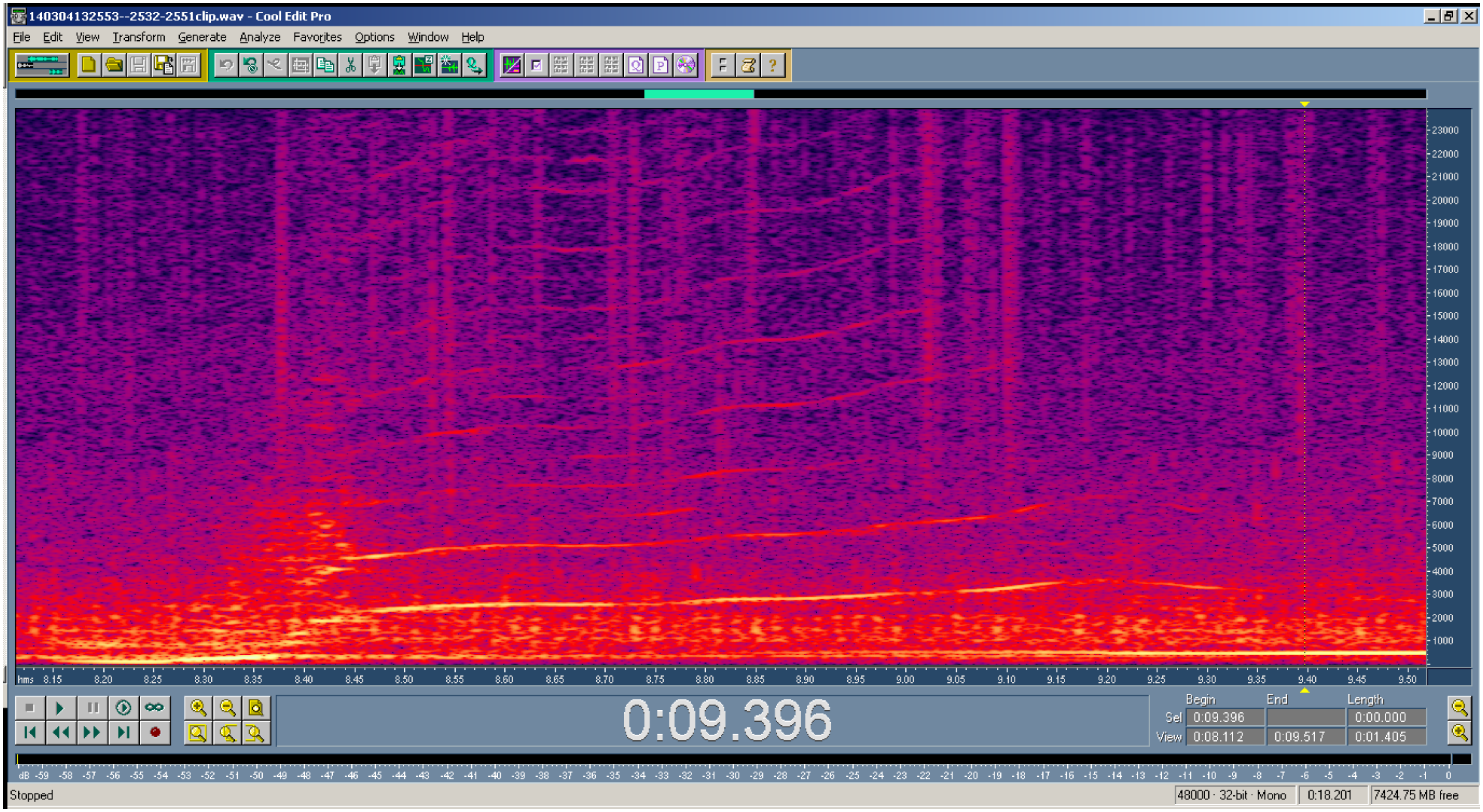


Simulation: IR with Scattering Model



Simulation: Source Waveform

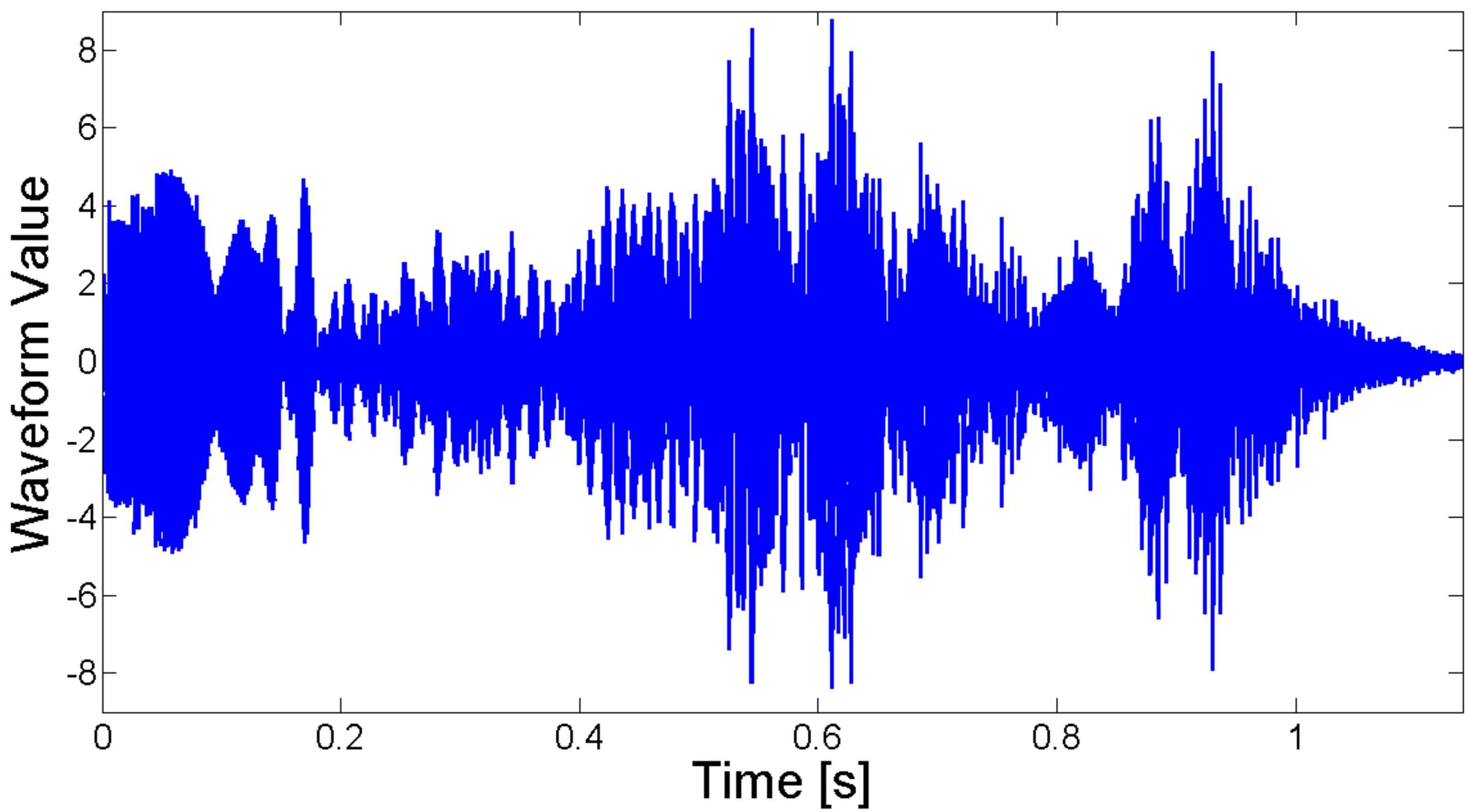




- Chen et al., [unpublished]

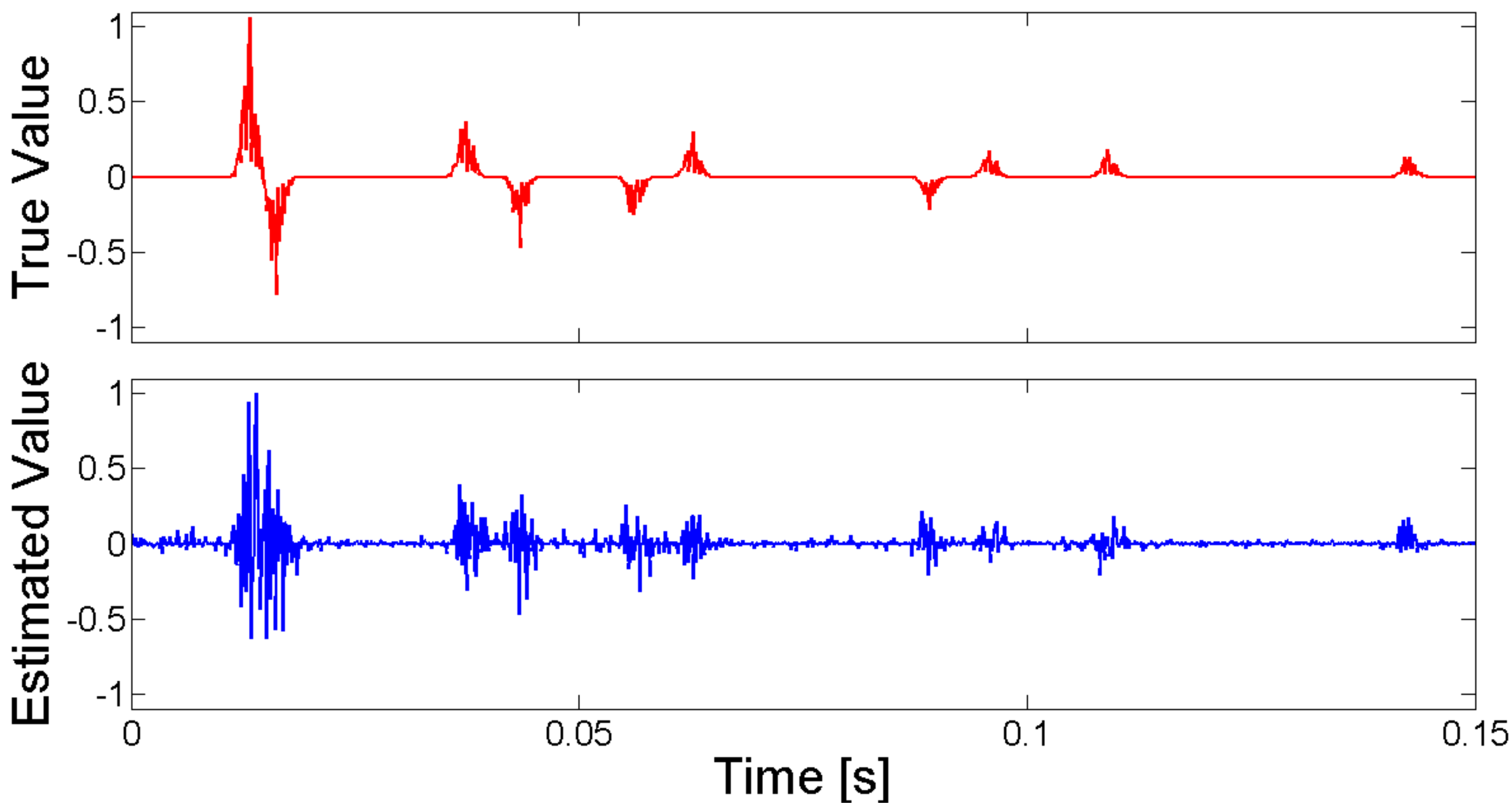
Simulation: Received Waveform

- SNR= = ~44dB



Simulation: True & Estimated Channels

- Channel 2



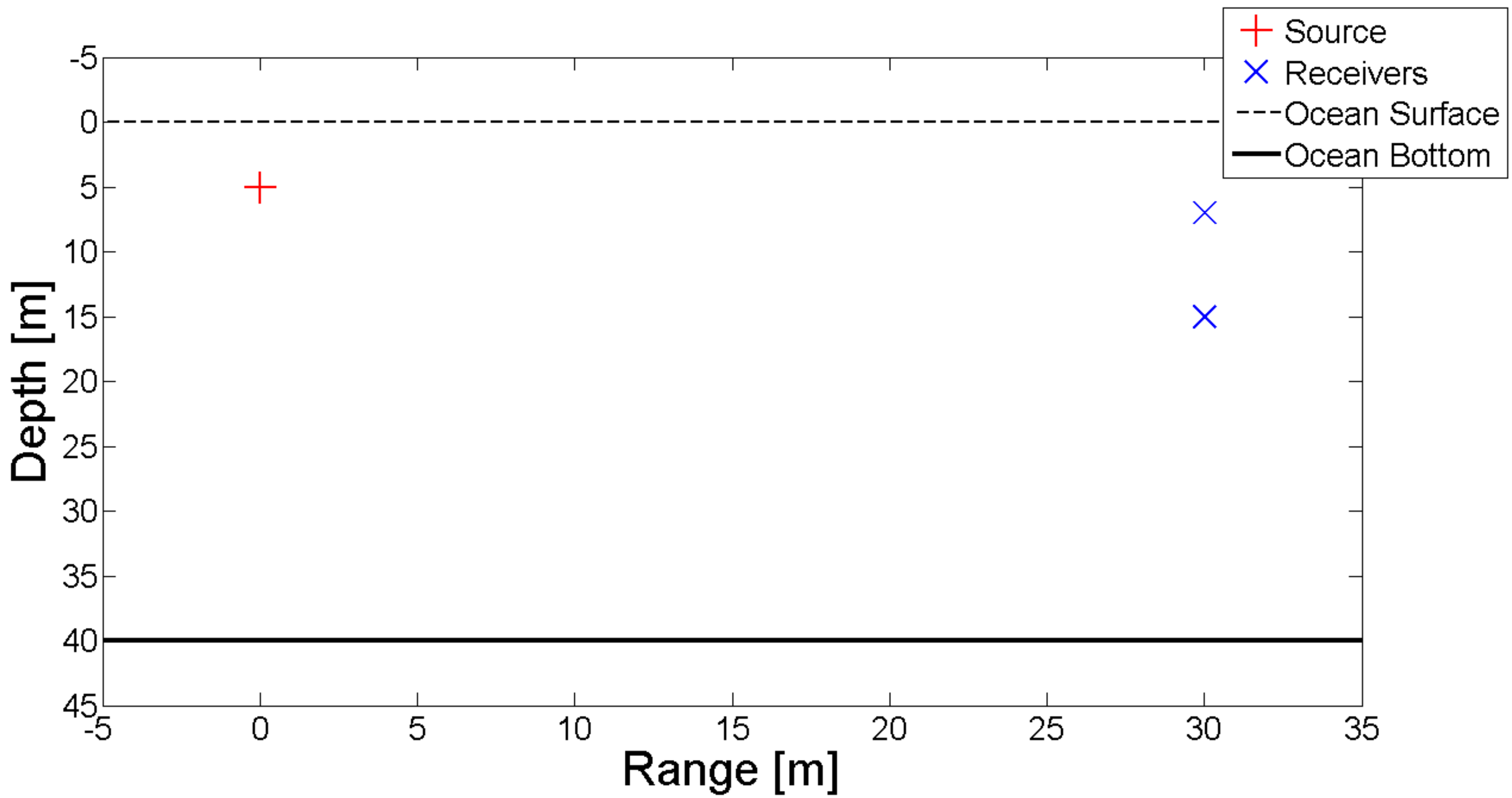
Summary and Next Steps

- Adapted a blind channel estimation algorithm to estimate underwater acoustic channel impulse responses using bioacoustic signals
- Simulations show promising results
  - Identification of multipath arrival times possible in estimated IR
- Currently working to process measured data

Questions?

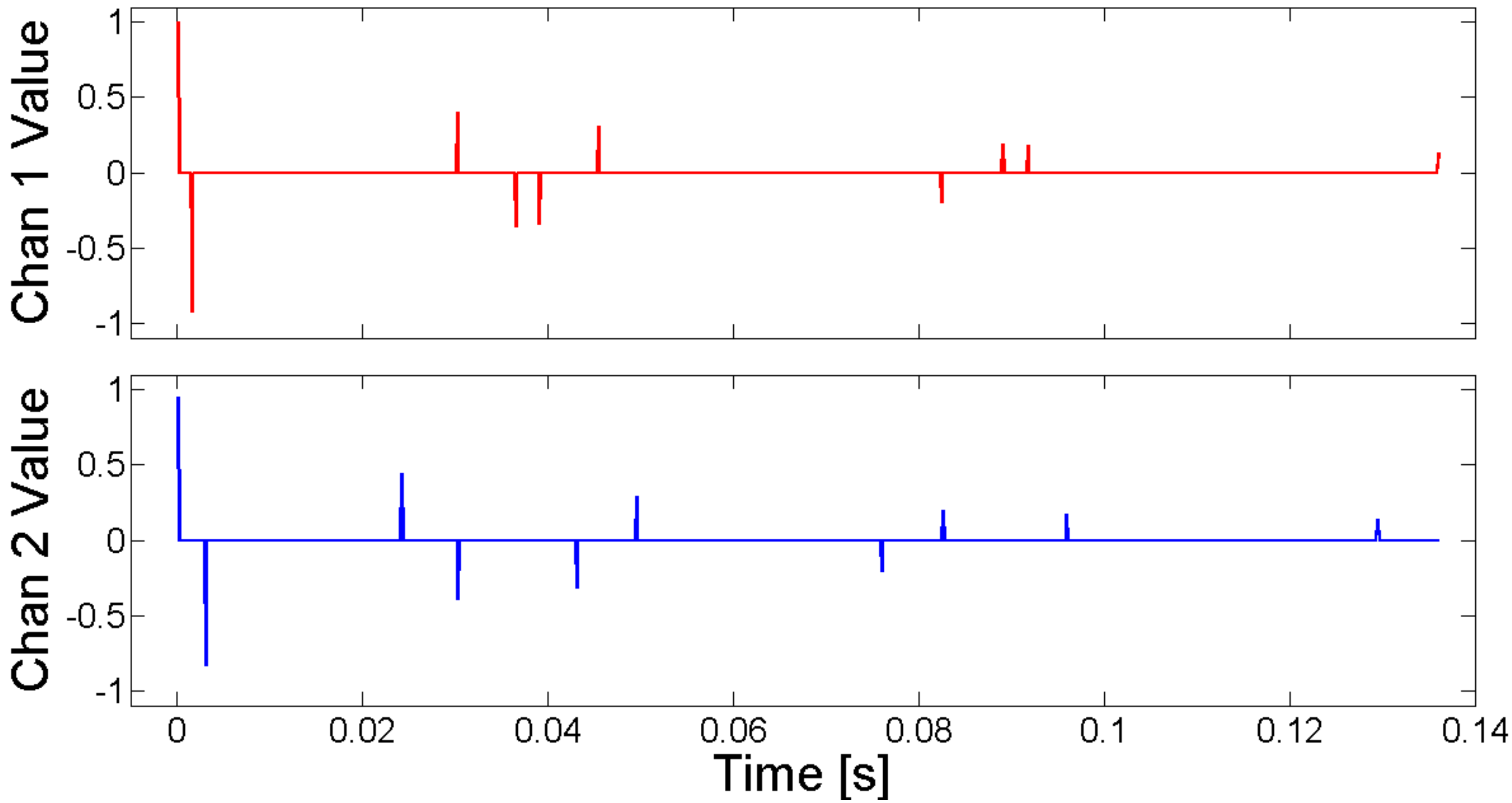
Simulated Impulse Response Calculation

- 1. Define Environment



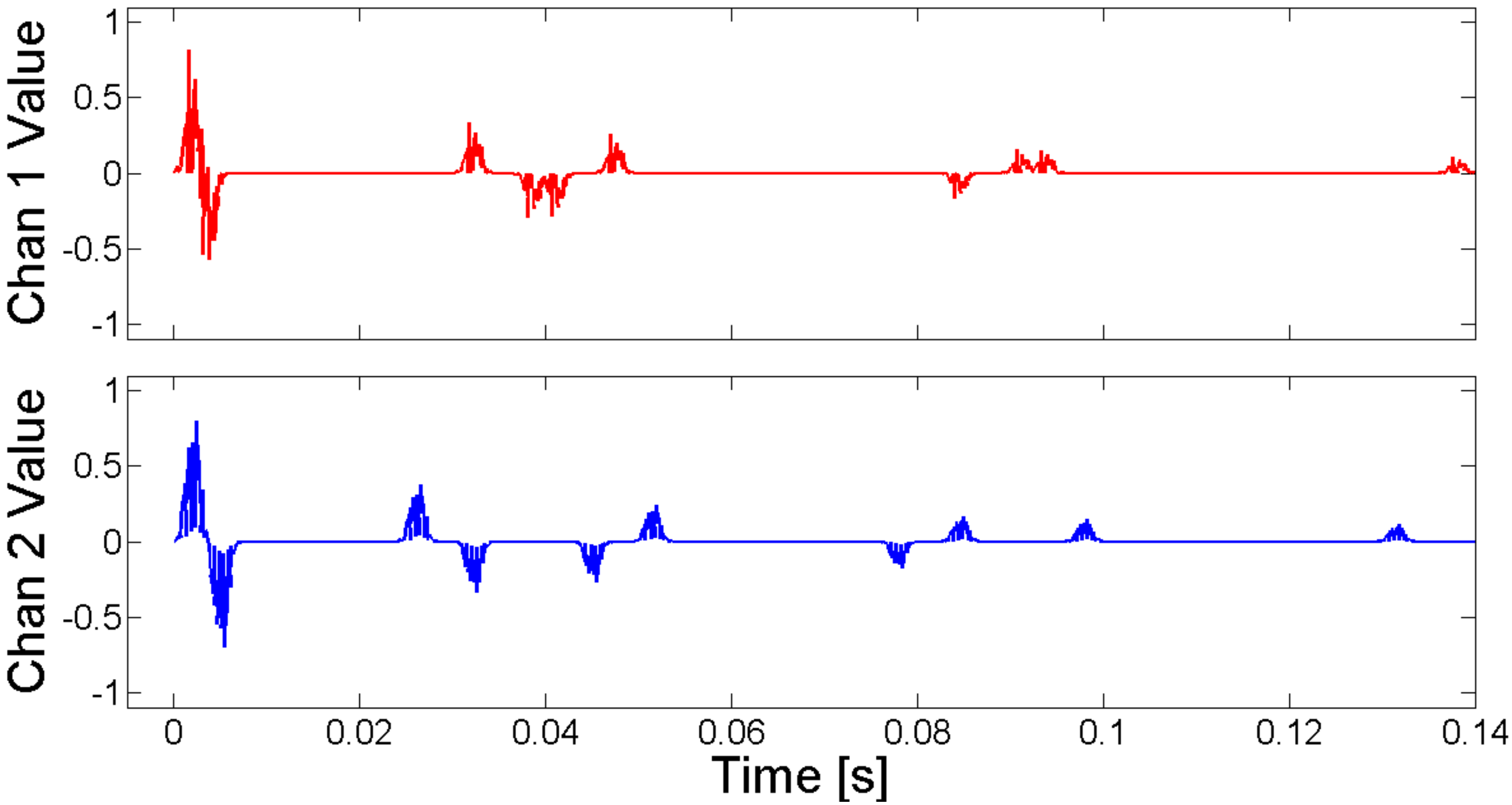
Simulated Impulse Response Calculation

- 2. Calculate arrival times and TL



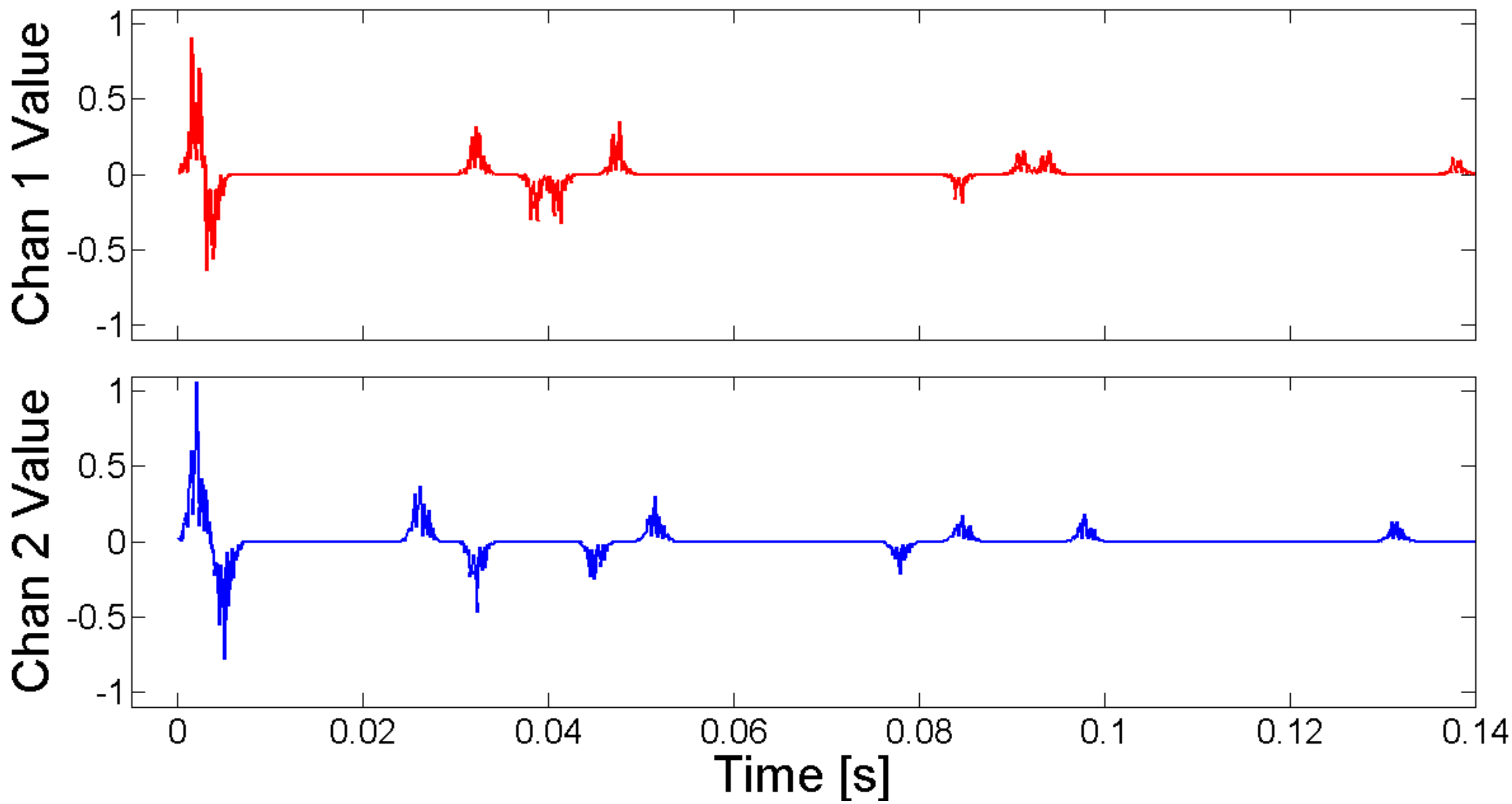
Simulated Impulse Response Calculation

- 3. Random Gaussian Pulse Convolution



Simulated Impulse Response Calculation

- 4. Uniform Random Multiplication

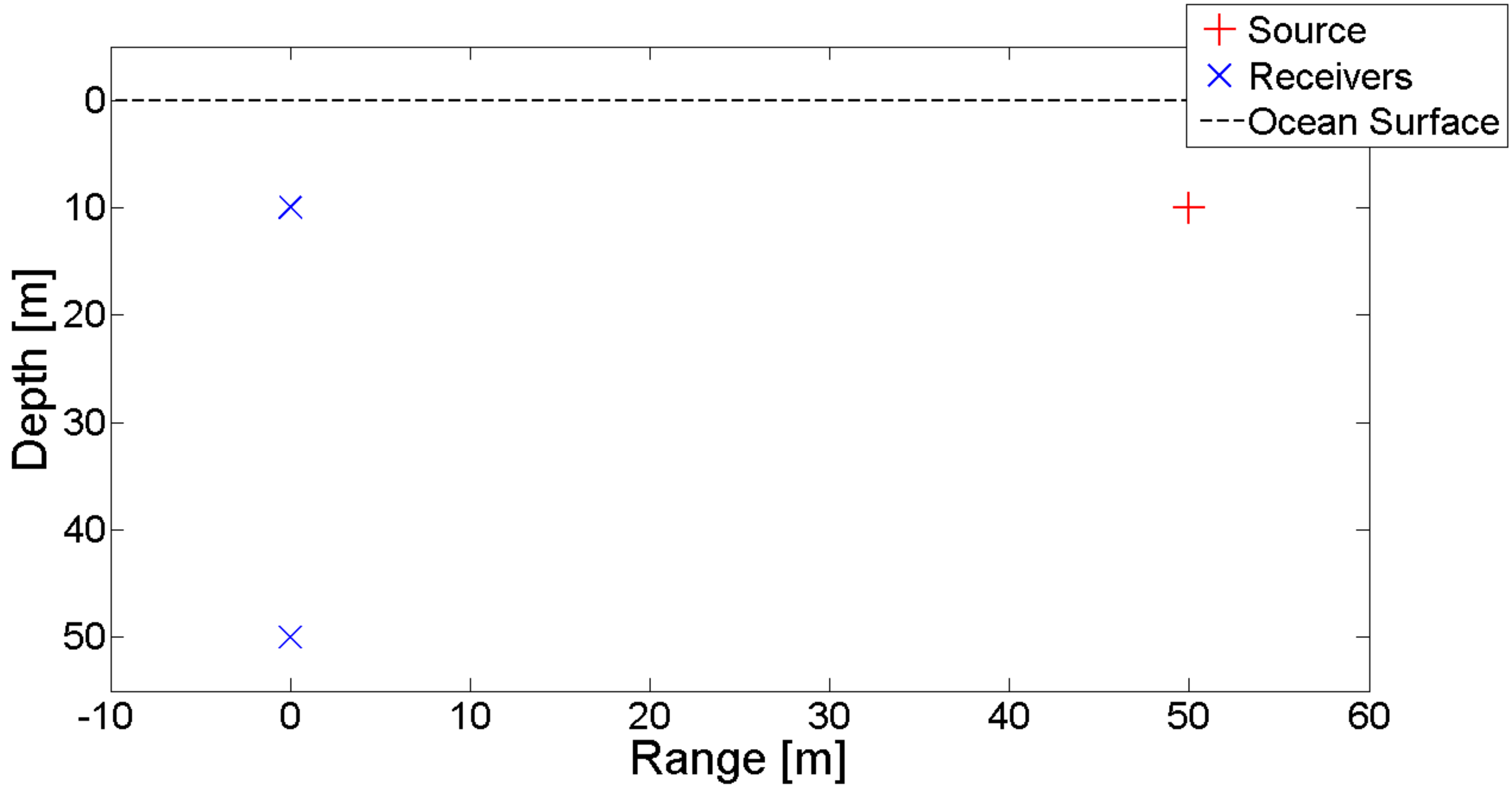


Processing Steps

- Recorded Waveform
- Estimate Impulse Responses
- Estimate Multipath Arrival Times

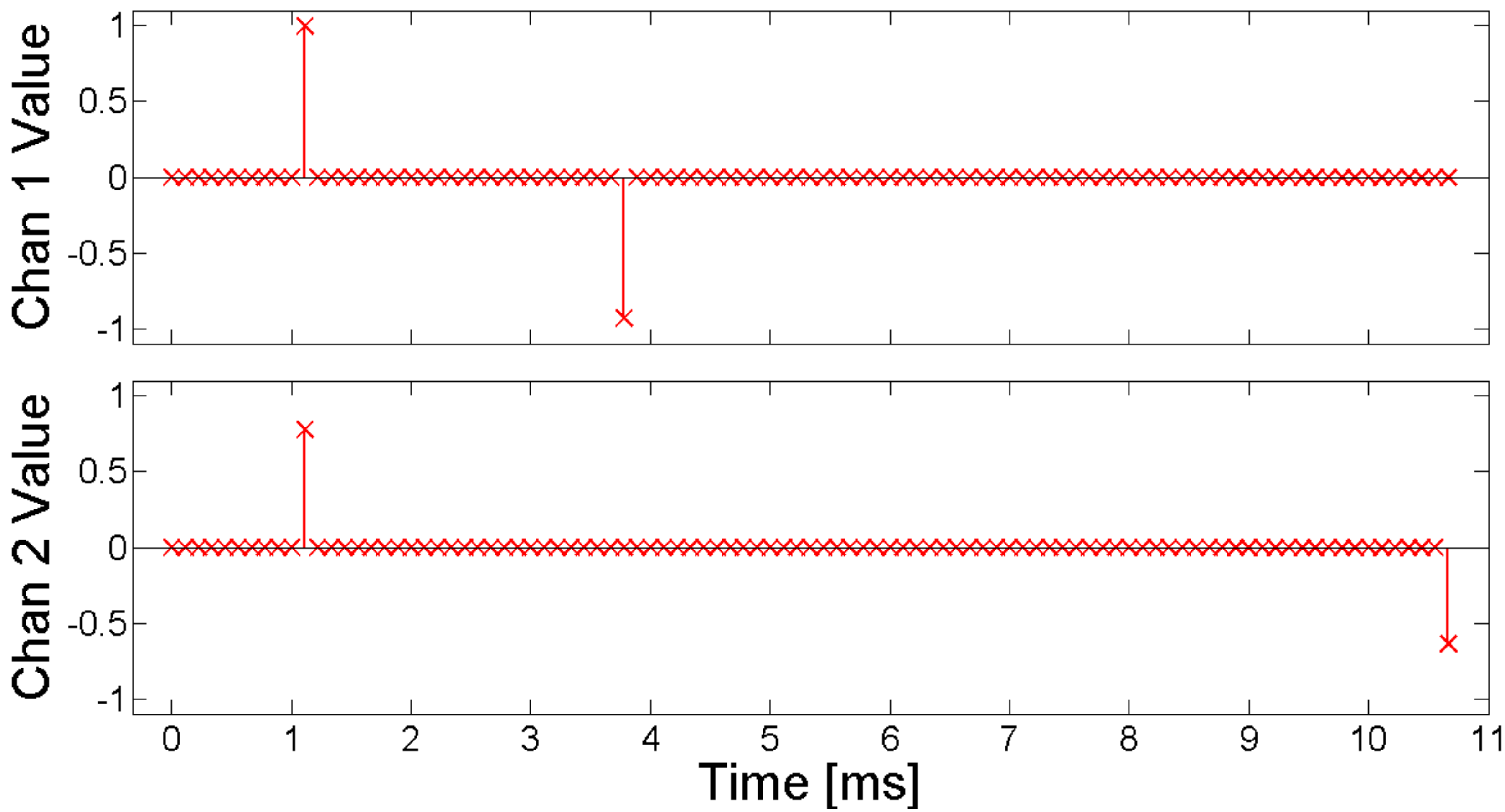
Theory: Cost Function Depiction

- Simulated Environment



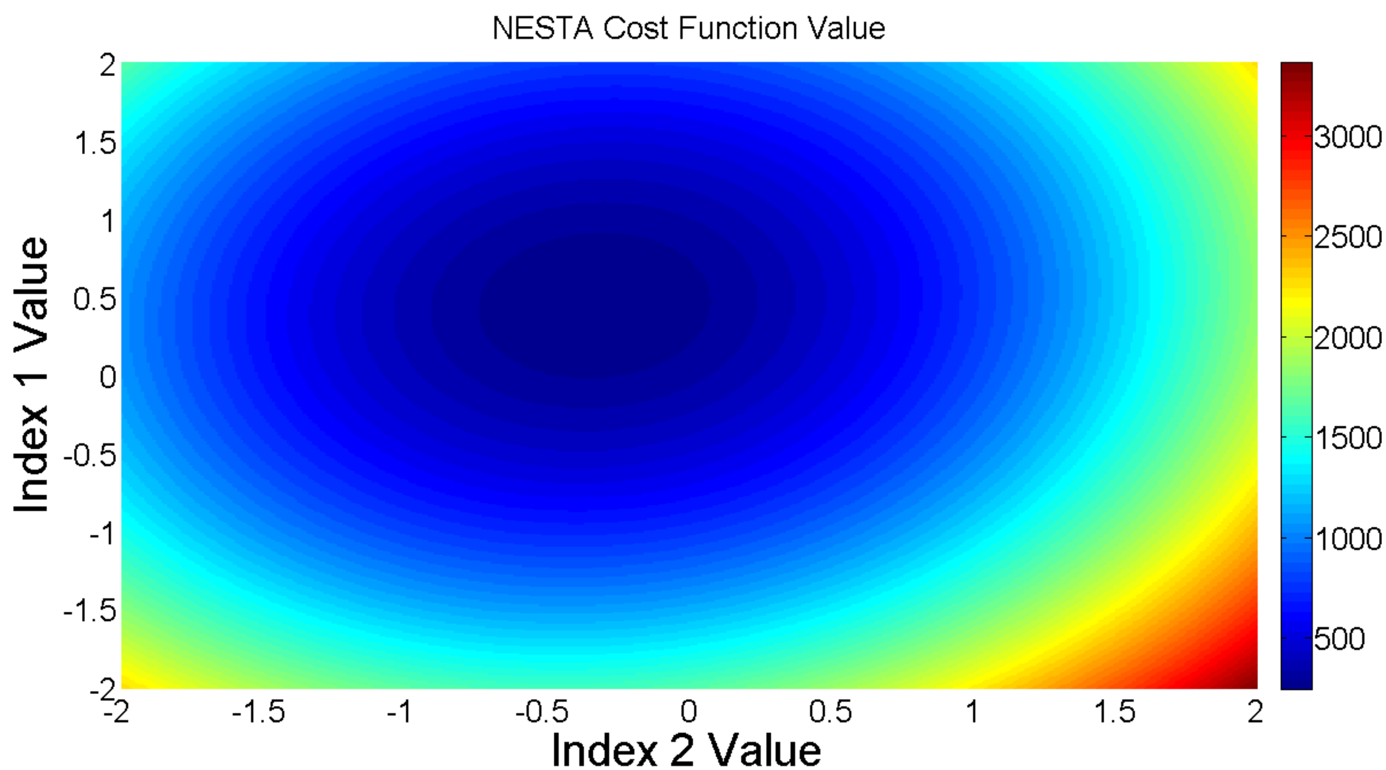
Theory: Cost Function Depiction, cont’d.

- True Impulse Responses (time shifted)



Theory: Cost Function Depiction, cont'd.

- Cost Function = $\lambda\|x\|_{\ell_1} + \frac{1}{2}\|b - Ax\|_{\ell_2}^2$
  SNR = -1dB
  True = [0.78, -0.64]   Est = [0.37, -0.34]



Theory: Performance Considerations

- For quality IR recovery,
  - Sparse channels (e.g., minimal scattering)
  - Wide bandwidth vocalizations
  - High signal-to-noise ratio

Impulse Responses and Marine Mammals, cont’d.