Acoustic Blind Deconvolution and Source Localization in Shallow Ocean Environments

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LONG-TERM GOALS

The overall long-term goal for this project is to develop engineering tools that are useful to the Navy as it operates in uncertain, partially known, or unknown ocean environments. During the last year, this project has focused on further determining the utility of a time-reversal-based technique for blind deconvolution of recorded sounds broadcast by a remote source with emphasis on determining if and how the results might be used for classification, localization, tracking, and/or identification of remote sources in poorly known or unknown multipath waveguide environments.

The long term goals of this project are: *i*) to determine the effectiveness of artificial time reversal (ATR) for the purposes of blind deconvolution in noisy unknown ocean sound channels, *ii*) to effectively apply ATR to marine mammal sounds recorded in the ocean with vertical and/or horizontal arrays, and *iii*) to utilize the ATR-estimated signals and ocean-sound-channel impulse responses to identify, localize, and/or track individual marine mammals (or other sound sources of interest).

OBJECTIVES

Since early 2009 this project has focused on developing an acoustic-ray-based version of artificial time reversal (ATR), a technique for recovering the original signal and the source-to-array-element impulse responses for a remote unknown sound source in an unknown underwater waveguide [1,2,3]. The specific objectives are to: *a*) determine ATR performance as a function of the signal-to-noise, array size, and array element number using acoustic propagation simulations, *b*) verify these findings with simple airborne- or water-borne acoustic laboratory experiments involving multiple receivers and multiple ray paths, *c*) obtain and process underwater array recordings of remote-but-cooperative sound sources, and *d*) obtain and process marine mammal vocalizations for the purposes of marine mammal tracking and identification. This research effort extends the past mode-based version of ATR [1] to higher frequencies and smaller receiving arrays.

APPROACH

Over the last year, this project has primarily focused on processing results from two different sets of underwater sound measurements to understand the capabilities and limitations of ATR. The primary focus of this processing effort is data from CAPEX09, an experiment conducted by Dr. Daniel Rouseff

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and collaborators at the University of Washington - Applied Physics Laboratory (UW-APL) in 60 m of water in Lake Washington, just east of Seattle. In this experiment chirp signals with a bandwidth of 1.5 kHz to 4.0 kHz were broadcast from a depth of 30 m and recorded by a 7-m-long 32-element receiving array at source-array ranges of 100 m, 250 m, 500 m, and 1.0 km. This experiment represents an ideal test bed for ray-based ATR because the environment is relatively simple, the number of array elements used in the processing may be varied over a wide range, and because the ATR results are excellent at the shortest range and decrease in quality with increasing range. Thus, fundamental limitations of ATR may be deduced from this data set, and such limitations have been found and understood in the last year.

A second data set from the arctic ocean off the north coast of Alaska was obtained from Dr. Aaron Thode of the Scripps Institution of Oceanography (SIO). This data set includes air-gun pulses from seismic surveying and whale calls recorded on a vertical array with eight elements in 35 meters of water. This data set is more complicated than that from CAPEX09, and after a month or so of focused effort little progress had been made without the direct intervention of Dr. Thode. Thus, further processing of this data set in Ann Arbor was put on hold, but arrangements have been made for the current doctoral student on this project, Ms. Shima H. Abadi, to spend a semester with Dr. Thode at SIO in La Jolla to develop genuine expertise understanding and processing recordings of marine mammal sounds. Ms. Abadi should advance to PhD candidacy within the next month.

In addition, a third data set is currently being assessed for use in this project. It comes from a laboratory cylindrical-water-tank experiment (1.07 m diameter and depth) funded by the Naval Engineering Education Center and involves three-dimensional multipath propagation (reverberation), signals in the 50 kHz to 120 kHz bandwidth, and recordings from a 16-element receiving array (sampled at 1 MHz per channel). The technical goal with this data set will be to determine ATR performance with a near-field source and variable array geometry.

WORK COMPLETED

The ATR technique uses measured signals from a known array of receiving phones to separately estimate the original source signal and the source-to-array-element transfer functions from an unknown remote source in an unknown multipath environment. Unfortunately, ATR does not provide absolute timing or amplitude information so simple distance-equals-speed-times-time or amplitude-decay ranging is not possible from ATR results alone. However, when ATR performs well, the estimated source-signal waveform and the transfer-function waveforms are accurately recovered.

The work completed in the past year has involved improving the understanding of how the operational parameters (number of receivers, signal-to-noise ratio, number of identifiable paths, source-array range, etc.) influence ATR performance for chirp signals having frequencies in the 1.5 to 4.0 kHz range. The primary performance parameter for original-source-signal reconstruction has been the cross correlation coefficient between the original and ATR-reconstructed signals. In addition, a simple and robust means of using the ATR-estimated transfer functions for remote unknown source localization has been developed and tested with the CAPEX09 data set. The primary finding in the last year is that ray-based ATR is successful and can be used to unambiguously localize a remote source when at least one ray-path arrival persists throughout the bandwidth of the signal. These results have been submitted for publication [3].

RESULTS

To date, this investigation has determined the following about the ATR-estimated source-signal waveform using the CAPEX09 data set. (*i*) The cross-correlation coefficient with the original signal may be at or above 98% when the SNR is above 8 dB, and at or above 90% when the SNR is as low as 2 dB when all 32 receiving phones are used. (*ii*) The cross-correlation coefficient with the original signal may be above 98% when 6 to 8 receivers are used, and above 90% when as few as 3-4 receivers are used. (*iii*) A coherent combination of ATR results using different reference rays may lead to an improved cross-correlation coefficient with the original signal when the individual-ray ATR results are comparable. (*iv*) The likely success of ATR can be assessed by the presence (or absence) of ray-path arrivals deduced from the beam-formed array measurements that persist at the same angle throughout the bandwidth of interest. When such paths are present, ATR works well. When such paths are absent, ATR struggles or fails.

To date, this investigation has also determined that the ATR-estimated transfer functions can be used to robustly estimate the source-array range and source depth in a weakly-range-dependent multipath environment when the water column depth and speed of sound profile are known at the receiving array location. The ATR-estimated transfer functions do not recover the propagation time from the source to the array, but they do provide the arrival time differences for the various ray paths that reach the array. Thus, a simple ray-based back-propagation technique based on acoustic time reversal (or phase conjugation in the frequency domain) is possible. First, the environmental information and the ray arrival angles are used to compute *M* ray trajectories launched at angles θ_m starting from the center of the array and extending out to the largest array-source range of interest, about 600 m in the current investigation using the CAPEX09 data. Here, the Gaussian beam code *Bellhop* from HLS Inc. was used for this task. Next, the ATR-determined impulse response is idealized as a series of perfect impulses that occur with the ATR-determined arrival-time differences. This series of impulses is then time reversed and each impulse is launched along its associated ray path from the array. As the various impulses, located at range-depth coordinates (r_m, z_m) propagate away from the array along their corresponding rays, the root-mean-square (rms) impulse position,

$\zeta = \left[(1/M)\sum_{m=1}^{M}\left((r_m - R)^2 + (z_m - Z)^2\right)\right]^{1/2}$, based on Euclidian distances from the impulse centroid $(R,Z) = (1/M)\sum_{m=1}^{M}(r_m, z_m)$, is monitored. The centroid location with the minimum ζ within the domain of interest provides an estimate of the source location.

The results of such calculations using the CAPEX09 data are shown on Figure 1, where the standard deviation of impulse-marker position, ζ, is plotted as a function of range from the receiving array for array-source ranges of 100 m, 250 m, and 500 m. Here an unambiguous minimum in ζ occurs at or very near the actual array-source range, and the source depths estimated by this technique are within a few meters of the actual source depth. Thus, the relative timing information in the ATR-estimated transfer functions can be used to successfully localize the CAPEX09 source using only the environmental information at the array and a ray-propagation code.

For comparison, the same experimental signals were used for incoherent and coherent Bartlett matched field processing (MFP) assuming (again) a range-independent environment identical to that found at the array. The incoherent results, a combination of harmonic MFP results at six frequencies (1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 kHz), are shown on Figure 2 for array-source ranges of 100 m, 250 m, and 500 m.

A black diamond marks the source location in each frame. At the two shorter ranges, Fig. 2 a) and b), ridges in the MFP ambiguity surface are concentrated along the most-direct ray path between the source and the array. Unfortunately, the inevitable actual-vs.-simulated propagation mismatch leads to multiple ambiguity surface maxima at the two shorter ranges, and no obvious localization result at the 500 m range. The coherent MFP results are similar to these incoherent ones. The overall finding here is that neither MFP calculation is more accurate than the simple ray-trace results even though the computational effort to produce Figure 2 was substantially greater than that necessary to produce Figure 1. The simpler localization scheme is more robust in this case because it is much less sensitive to phase mismatch between the actual and simulated acoustic propagation than MFP.

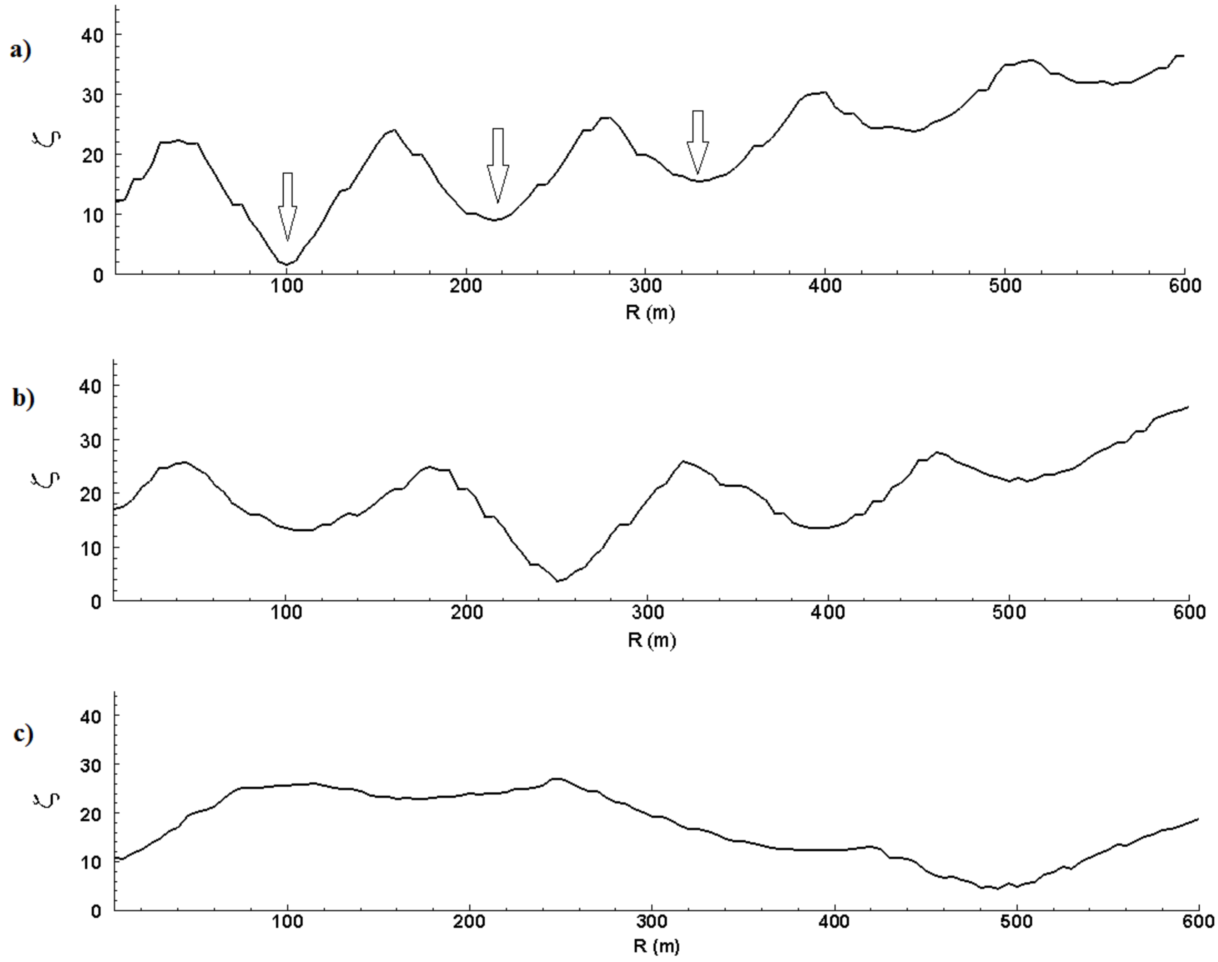

Figure 1. Standard deviation of impulse-marker locations vs. array-source ranges of 100 m (a), 250 m (b), and 500 m (c) using three rays from the CAPEX09 data. The array lies at zero range. The minimum of the standard deviation ζ indicates the most likely range between the source and the array. In each case there is one clear unambiguous minimum out to a range of 600 m. The arrows in panel a) indicate places where the three rays cross close to each other.

IMPACT/APPLICATION

In broad terms, this project ultimately seeks to determine what is possible for a sonar system when the environmental information is absent, incomplete, or uncertain. The capabilities of future Naval sonar systems will be enhanced when sonar techniques are developed that do not rely on detailed knowledge of the acoustic environment. Thus, this research effort into the effectiveness and utility of ray-based artificial time reversal, a relatively-new blind deconvolution scheme, may eventually impact how transducer (array) measurements are processed for detection, classification, localization, tracking, and identification of remote unknown sound sources.

TRANSITIONS

The results of this research effort should aid in the design of sonar signal processors for tactical decision aids. However, at this time no direct transition links have been established with more applied research or development programs. Once the current results are more firmly established and validated, a transition path through NRL or one of the Navy's Warfare Centers will be sought.

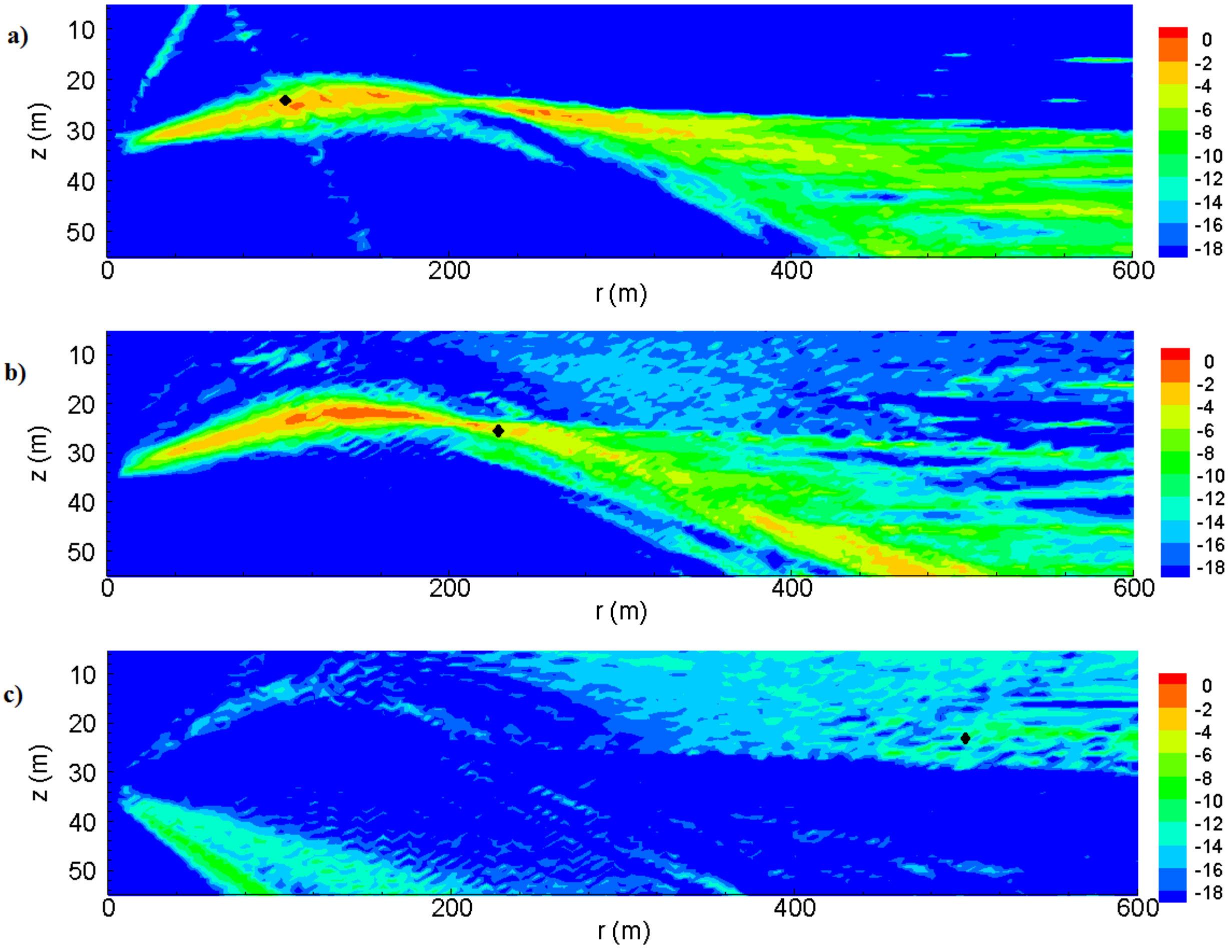

Figure 2. Incoherent Bartlett Matched Field Processing (MFP) ambiguity surfaces for the same experimental data used to produce Figure 1. Here, the ray-based propagation code Bellhop was used, and harmonic MFP results from 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 kHz were incoherently combined. The actual source location is indicated by a black diamond in each figure. The well-known problems with MFP propagation mismatch lead to ambiguous or indeterminate source localization results.

RELATED PROJECTS

This project is currently using acoustic array recordings of known man-made sounds made available by Dr. Daniel Rouseff of the UW-APL from the CAPEX09 experiment. In addition, Dr. Aaron Thode of SIO has provided acoustic array data collected in the arctic that includes man-made and marine mammal sounds. Dr. H.-C. Song of SIO has also used artificial time reversal for processing underwater communication sequences and has agreed to share data for further investigation of ATR in the future. In addition, the use of blind deconvolution for the recovery of free-field sound source signatures from measurements made in reverberant laboratory test facilities is also of interest for hydro-acoustic testing at the Naval Surface Warfare Center - Carderock Division which is supporting the laboratory-water-tank experiments mentioned above.

REFERENCES

[1] Sabra, K.G., and Dowling, D.R. (2004), "Blind deconvolution in ocean waveguides using artificial time reversal," *Journal of the Acoustical Society of America*, Vol. 116, 262-271.

[2] Sabra, K.G., Song, H.-C., and Dowling, D.R. 2010 "Ray-based blind deconvolution in ocean sound channels," *Journal of the Acoustical Society of America – Express Letters*, Vol. 127, EL42-EL47.

[3] Abadi, S.H., Rouseff, D., and Dowling D.R. "Blind deconvolution for robust signal estimation and approximate source localization," submitted to Journal of the Acoustical Society of America, August 2011.

PUBLICATIONS

[1] Kundu, P.K., Cohen, I.M., and Dowling, D.R., *Fluid Mechanics, 5th Ed.* (Academic Press, Oxford, 2012), 891 pages.