

# Array-Based Uses of Underwater Sound in Unknown Ocean Environments

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## LONG-TERM GOALS

The long term goals of this project are: i) to predict and understand the characteristics of active and passive time reversing array (TRA) performance in shallow ocean waters, ii) to deduce the effectiveness of using a TRA for underwater communication and for surveillance of the acoustic characteristics of known or unknown environments, and iii) to determine how to exploit the generic propagation characteristics of underwater sound channels in order to enhance the performance of active and passive sonar systems in unknown environments.

## OBJECTIVES

This project seeks to quantitatively determine how well active and passive implementations of acoustic time reversal perform in shallow ocean environments. Here performance includes: retrofocus field amplitude, location, size, and longevity; and the correlation of the retrofocused signal with the original signal. The intent is to predict these quantities as a function of signal frequency and bandwidth, source-array range, array orientation, noise level, source motion, array motion, and array configuration in shallow ocean sound channels containing realistic propagation complexities. Such complexities include depth dependent speed of sound profiles, dynamic random shallow-water internal-waves, noise, bottom losses, and three-dimensional acoustic scattering. The challenge here is to ascertain generic features and scaling laws in the presence of wide natural variability. Such results form the starting point for the design of practical TRA systems. Past efforts conducted as part of this project included narrowband signals in dynamic [1,2] and noisy [3] environments, weak azimuthal scattering [4], different array orientations [5], broadband signals [6], and the effects of source and array motion [7,8]. During the past year, the effects of shallow ocean currents [9] and drifting array elements [10] on TRA performance [9] have been explored, along with and a novel passive implementation of acoustic time reversal [11].

## APPROACH

This project exploits narrowband and broadband transducer-array formulations of active and passive acoustic time reversal, analytic and computational propagation models, and ocean measurements made by another ONR-supported research team [12,13]. In particular, analytical propagation models are used for free-space (single path) and stably-stratified two-fluid (two path) environments. TRA performance in an ocean sound channel is simulated with the range-depth (2D) wide-angle parabolic-equation code RAM (by Dr. Michael Collins of NRL) and the mode-based propagation code KRAKEN (by Dr. Michael Porter). My current graduate student, Ivelysse Lebrón Durán, and her predecessor Karim Sabra who completed his Ph.D. in April 2003, have exploited a simple Fourier

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superposition of single-frequency results to synthesize broadband signals. In addition, a first-order-in-mach-number perturbation theory [14] has been used in to explore the effects of low-Mach number ocean currents.

## **WORK COMPLETED**

During the past year, this project has had three main thrusts: i) completion of the formal prediction and simulation of TRA performance in the shallow ocean when a non-trivial current is present, ii) specification of the formal basis for, and completion of the initial parametric exploration of, artificial time reversal (ATR), a new technique for blind deconvolution of signals in ocean sound channels, and iii) investigation of the influence of randomly drifting array elements on the time reversal process. In addition, preliminary consideration has begun on potentially augmenting the ATR investigations with additional experiments, and possibly expanding the research horizons of this project to include probability-density-function based techniques for describing acoustic propagation in uncertain environments.

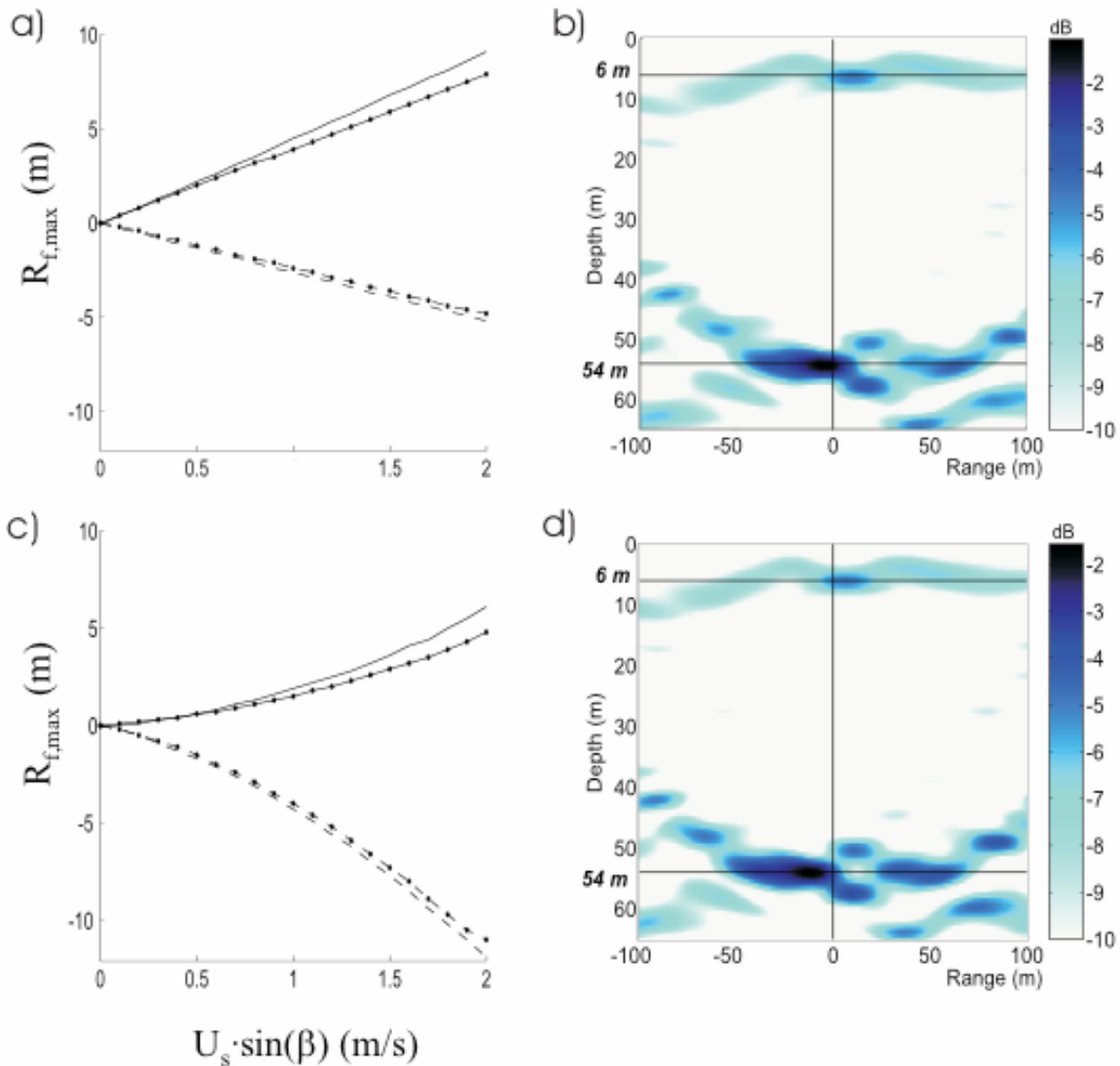
The TRA performance study involving shallow ocean currents has been completed, written-up, submitted for publication, reviewed, revised, and resubmitted [9]. We are currently awaiting final acceptance for publication. The main predictions of this study are that currents may cause either upstream or downstream focal shifts, and that, depending on orientation, horizontal arrays may be much more sensitive to ocean currents than vertical arrays.

The second research thrust on ATR, a novel passive implementation of acoustic time reversal, has been written-up and submitted for publication [11]. Because this technique was discovered unexpectedly, the main point of progress last year was to understand and formalize the reasons for its success. In addition, the technique has been tested on synthetic and measured ocean propagation data.

The third research thrust involves some relatively statistical predictions that are verified by numerical propagation simulations. It also has been written up and submitted for publication [10].

## **RESULTS**

Figure 1 illustrates the type of results obtained for shallow- and deep-source retrofocusing from a vertical water-column spanning TRA in a downward refracting sound channel when a tidal current (a,b) or wind-driven surface current (c,d) is present. The source-array range is 2.5 km and the water channel depth is 65 m. The shallow and deep sources are 6 m and 54 m below the ocean surface. Figure 1a) shows the retrofocus shifts as function of the maximum current speed in the source array direction for a tidal current that extends to very near the ocean bottom. Figure 1b) is a sample field amplitude plot for a peak tidal current speed of 2 m/s. The solid lines on Fig. 1a) are for the shallow source; the dashed lines are for the deep source. The plain curves are for a narrowband signal at 500 Hz while the curves with dots are for a Gaussian-windowed sine pulse with a center frequency of 500 Hz and a 99%-signal-energy bandwidth of 258 Hz. Figure 1c) and d) are similar to Fig. 1a) and b), except that Fig. 1c) and d) are for a wind-driven surface that only influences the upper ~20% of the water column. For both Fig. 1b) and d), the vertical TRA is off to the right of the field plot. The main results show that: 1) ocean currents may cause retrofocus shifts of several wavelengths, 2) these shifts may be in the upstream or downstream directions depending on the source depth, and 3) broadband and narrowband signals in the same frequency range are shifted similarly.



**Figure 1. TRA Retrofocus shifts and field plots for deep and shallow sources, and tidal and surface currents in a 65 m deep sound channel at a source array range of 2.5 km. The TRA is linear and vertical.  $U_s \sin(\beta)$  is the ocean current component directed between the source and the array. Frame a) shows retrofocus shifts,  $R_{f,max}$  vs. current speed is for a tidal current. The plain lines are for single frequency signals at 500 Hz. The dotted curves are for broadband pulses with a center frequency of 500 Hz. The solid lines are for a shallow source (6m depth). The dashed lines are for a deep source (54m depth). Frame b) is a sample field plot showing shallow and deep retrofocus field amplitudes for the tidal current when  $U_s \sin(\beta) = 2.0$  m/s. Frames c) and d) are the same as frames a) and b) except that they are the results for a wind-driven surface current.**

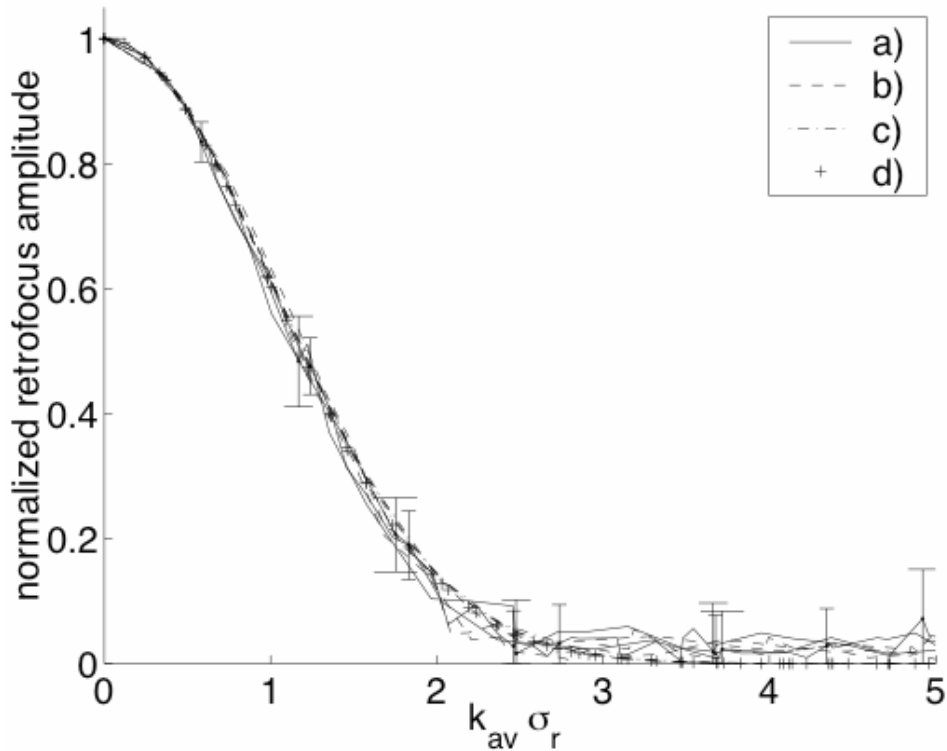
Artificial time reversal is a technique for reconstructing acoustic signals that have been distorted by passage through an unknown multipath underwater sound channel. The technique relies on accurately determining the frequency dependence of the phase of one (or more) propagating modes from a weighted sum of array measured signals. Table 1 presents the peak correlation results between ATR reconstructed signals and an estimate of the original broadcast signal based on oceanic measurements from the successful time reversal experiments recently conducted in the Mediterranean Sea [12,13] for

source-array ranges of 3.75 km, 15 m, and 20 km. The middle four columns of the table are denoted by the array-weighting scheme used in that implementation of ATR. The final column presents the correlation values achieved by active time reversal conducted in the ocean. The ATR correlation results are generally good and are equal or superior to genuine time reversal in every case.

Table 1. Peak ATR Correlation Percentages Using Experimental Measurements

Range	Mode-1	Mode-2	Binary-1	Binary-2	Time Reversal
3.75 km	88.5	92	80	93	80
15 km	95	93	94	95	93
20 km	91	93	93	91	91

Sample results from the TRA performance study involving randomly drifting array elements are shown on Fig. 2. Here, the normalized TRA retrofocus energy is plotted vs. the product of the average



**Figure 2. TRA retrofocus signal amplitude vs. the product of the average horizontal wavenumber and the root-mean-square horizontal element displacement. Curves a) and b) are from 100 Monte-Carlo simulations of vertical and horizontal arrays. Curve c) and points d) are theoretical results.**

horizontal wavenumber of the first 10 propagating modes of the sound channel, and the root-mean-square horizontal displacement of the TRA elements occurring between signal reception and time reversed broadcast. Results for 100 Monte-Carlo trials at frequencies of 250 Hz, 500 Hz, and 750 Hz are shown for both vertical (a) and horizontal (b) arrays. The c) and d) curves on Fig. 2 are theoretical predictions for the same conditions predicted by a second moment analysis of the propagated fields. The error bars indicate the uncertainty level of the Monte-Carlo calculations. Overall, the theory-simulation agreement is excellent.

## **IMPACT/APPLICATION**

These results show that active time reversing arrays may be able to function well in shallow ocean waters even when the medium is moving, and that active TRA performance should degrade predictably if its elements are allowed to drift. This suggests that phase-coherent underwater communications are possible with TRAs since they are well suited for tetherless underwater acoustic communication systems.

The passive TRA work involving ATR potentially provides an important new means for removing multipath distortion from measured ocean-acoustic signals before attempting signal identification or classification. ATR may also be suitable for underwater communications.

## **TRANSITIONS**

The results of this project should aid in the design of further experiments, and eventually, active and or passive TRA sonar hardware. In addition, ONR's hydroacoustics group in Code 33 and researchers at the Naval Surface Warfare Center - Carderock Division are interested in using passive time reversal techniques to detect and localize subvisual cavitation events during hydrodynamic tests. Funds for such an effort covering personnel and hardware costs have been committed by ONR Code 33.

## **RELATED PROJECTS**

1. This research project is being coordinated with an experimental effort to detect, localize, and identify hydroacoustic sound sources during hydrodynamic tests of Navy relevant models and hardware.
2. This research project runs parallel to the time-reversal experiments and analysis of the international research team headed by Drs. William Kuperman and William Hodgkiss of Scripps Institution of Oceanography (SIO). Data from their landmark experiments has been shared for use in the study of ATR, and a chapter for the senior-level ocean acoustics textbook now being assembled by Dr. Hermin Medwin has been co-authored by the author of this report and Dr. HeeChun Song from the SIO time-reversal team.
3. A verbal agreement is in place with Dr. George Smith of NRL-Stennis to coordinate and collaborate on future blind deconvolution efforts.

## **PUBLICATIONS**

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[9] Sabra, K.G., and Dowling, D.R., "Effect of ocean currents on the performance of a time reversing array in shallow water," revised for the J. Acoust. Soc. Am., August 2003.

[10] Sabra, K.G., and Dowling, D.R., "Effects of time reversing array deformation in an ocean waveguide," submitted to J. Acoust. Soc. Am., May 2003.

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## **HONORS/AWARDS/PRIZES**

David R. Dowling of the University of Michigan was elected a Fellow of the Acoustical Society of America, May 2003.