

**A Final Report to the Office of Naval Research:**

**Acoustic Time Reversal in the Shallow Ocean**

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**Abstract**

Acoustic time reversal is of interest to the United States Navy because it is an effective means for focusing sound in unknown underwater environments. For the last nine years, the Office of Naval Research has supported theoretical and numerical investigations at the University of Michigan into the performance of time reversing arrays in the ocean. This report summarizes the research accomplishments of these investigations.

**Introduction**

The United States Navy must often operate in unknown ocean environments. Sonar is its primary means for underwater remote sensing. Acoustic time reversal is a robust technique for focusing sound in unknown ocean environment and is therefore of interest for improving the capabilities of current and future Naval sonar systems. At the present time, acoustic time reversal is currently being pursued for applications in active sonar, passive sonar, and underwater communication systems.

This project began almost a decade ago when much less was known about acoustic time reversal and its possible underwater applications. The project started in October of 1995 and continued through December of 2004. From June of 1997 through August of 2000 it was supplemented by an AASERT grant (ONR Grant number N00014-97-1-0628). Results from both efforts are summarized in this report. Three graduate students, Drs. S. Khosla, M. Dungan, and K. Sabra, earned their doctoral degrees while working on these projects. A fourth research student, Ms. I. Lebron-Duran, was supported by this project for approximately 18 months but she did not complete a Ph.D. degree. During the course of this project acoustic time reversal grew from being a theoretical novelty into a mainstream technique, and many underwater-acoustics research groups, including ones at Scripps Institution of Oceanography, Penn State Applied Research Laboratory, and the Naval Research Laboratory, to name a few, have been attracted to the study of acoustic time reversal.

## Summary of Research Accomplishments

This project primarily involved theoretical and numerical predictions of the focusing performance of time reversing transducer arrays (TRAs). The technical accomplishments of this project are documented in detail in the references<sup>1-12</sup>. The following paragraphs summarize the main results from these archival journal papers.

The studies supported by this project began with a simplified analysis into how well acoustic time reversal would work in simple dynamic environments containing a superposition of linear internal waves, a single soliton-type internal wave, and ocean surface waves<sup>4</sup>. This work involved analytic propagation modeling. The primary findings here were that internal waves are likely to move slowly enough to allow effective use of acoustic time reversal, but that surface waves move too rapidly.

The findings concerning linear internal waves were further refined through the use of modern numerical propagation models in computational environments that were matched to measured at-sea conditions<sup>1</sup>. Here, a variety of parameter studies involving acoustic frequency and internal wave strength showed that acoustic time reversal would work well in the shallow ocean under all but the most extreme internal-wave conditions.

To enhance the realism of these investigations, an analysis of how noise impacts acoustic time reversal was undertaken<sup>5</sup>. Because acoustic time reversal requires reception and transmission of the signal before final focusing, noise has the opportunity to affect array performance twice. The main result of this study was a narrowband theory that was validated by Monte-Carlo narrowband simulations.

Up to this point, all focusing studies of time reversal in the ocean considered vertical transducer arrays for producing the time-reversed sound waves and looked for focal characteristics in range-depth planes. However, when the ocean environment has three-dimensional variations, vertical time-reversing arrays can still produce azimuthal focusing<sup>2</sup>. The main results here are in the form of scaling laws for TRA focusing in shallow oceans with random internal wave fluctuations or randomly rough bottoms.

To more thoroughly assess the impact of noise on acoustic time reversal, an investigation involving broadband signals and noise was conducted for TRAs operating in ocean environments<sup>7</sup>. Here the final results are cast in terms of an algebraic law that predicts the signal-to-noise ratio of the focused field in terms of the array and noise characteristics, the time-bandwidth product of the signal, and the time spreading caused by multipath propagation in the underwater sound channel.

Another important step toward realism was taken by investigating how the geometry of a linear TRA affects its focusing performance<sup>3</sup>. Here, three orientations within an ocean sound channel – vertical, horizontal endfire, and horizontal broadside – were contrasted and compared. The final results mirror those of matched field processing investigations but also identified reasons for the production of larger side lobes by horizontal arrays when compared to vertical arrays.

To address concerns associated with the use of TRAs for active sonar and underwater acoustic communication with a maneuvering vehicle, the focusing performance of a TRA responding to a broadband point source was analyzed and simulated<sup>10</sup>. The basic finding here was that TRA performance is not strongly altered by a moving source since nearly all relevant vehicle speeds lead to small underwater Mach numbers.

The study of source motion was followed by one involving uniform array motion to assess the performance impact of towing a TRA<sup>8</sup>. This study revealed that idealized towed vertical TRAs would be nearly insensitive to motion, but that equivalent towed horizontal arrays would suffer performance penalties even at towing speeds of only a few knots. Thus, the main impact of the reported analysis is to suggest a means of element phasing to correct for the detrimental effects of a non-zero array-towing speed.

These studies of source and array motion were followed by another theoretical and numerical investigation into the effect of ocean currents on TRA performance in shallow ocean waters<sup>9</sup>. Here it was found that a towed array deployed in a nominally still ocean, and a stationary array deployed in an ocean current have much in common. In addition, this work addressed surface (wind-driven) and tidal (bulk motion) currents and assessed when TRA systems might be useful for remotely measuring ocean or river current speeds.

The fourth investigation of motion and TRA performance involved a TRA having elements that drifted randomly between the signal reception time and the time-reversed broadcast time<sup>11</sup>. Here, as expected, horizontal element drift in range caused focusing degradation faster than vertical element drift. In addition, scaling the results with an appropriately-averaged wave number successfully collapsed focusing results from different acoustic frequencies.

The final two investigations explored applications of passive time reversal. The first of these involved a genuine shallow water experiment on underwater acoustic communication using passive time reversal processing<sup>6</sup>. This experiment was conducted in Puget Sound by a team headed by Dr. D. Rouseff from the Applied Physics laboratory of the University of Washington. The present project provided travel support for D. Dowling and K. Sabra to participate in the experiment. The primary experimental outcome was good; data streams were transmitted error free at rates above 2 kbits per second over distances up to several kilometers.

The final investigation addressed application of passive time reversal to blind deconvolution of signals transmitted through an unknown shallow ocean sound channel<sup>12</sup>. The goal here is to collect array-measured sounds in an ocean sound channel and the convert them into the original signal from a remote source without the cooperation of the source or any explicit knowledge of the ocean sound channel. Time reversal and a modal-phase-matching technique allow this to be done with near 100% correlation using simulated data and up to 95% correlation using ocean-measured array data provided by Dr. W. Kuperman's group at Scripps Institution of Oceanography.

## Conclusion

Acoustic time reversal is now well known throughout the underwater acoustics research community. The results from this project have identified and predicted the potential performance of this technique for a wide variety of oceanic and operational scenarios.

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