Predictions of Time Reversing Array Performance in Shallow Ocean Waters

David R. Dowling
Department of Mechanical Engineering
University of Michigan, Ann Arbor, MI 48109-2121
phone: (734) 936-0423 fax: (734) 764-4256 email: drd@engin.umich.edu

Award #: N00014-96-1-0040
http://www.personal.engin.umich.edu/~drd/

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 water 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 to enhance the performance of active and passive sonar systems in unknown environments.

OBJECTIVES

This project seeks to quantitatively predict TRA performance 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. While past work on this project has concentrated on narrowband signals in dynamic [1,2] and noisy [3] environments having weak azimuthal scattering [4], the current effort emphasizes array orientation [5], broadband signals [6], and the effects of source and array motion [7,8]. Three-dimensional effects, moving media, and variants of time reversal are also being explored.

APPROACH

This project exploits narrowband and broadband formulations of a time-reversing array, and analytic and computational propagation models. In particular, analytical propagation models are used for free-space (single path) and stably-stratified two-fluid (two path) environments. TRA performance in a 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, Karim G. Sabra, is using a customized version of RAM that allows us to recover the amplitude and phase of the computed field. Broadband simulations are conducted via a superposition of computed single frequency results. Simulations involving moving sources are conducted via a spatial superposition of fixed source results. Extension of these efforts to

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **30 SEP 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE **Predictions of Time Reversing Array Performance in Shallow Ocean Waters**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Mechanical Engineering,,University of Michigan,,Ann Arbor,,MI, 48109**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

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 water 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 to enhance the performance of active and passive sonar systems in unknown environments.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

three dimensional (3D) propagation has so far been handled with the N-by-2D approximation. However, arrangements have been made with Prof. Kevin Smith of the Naval Post-graduate School to obtain a range-depth-azimuth propagation code for future 3D propagation simulations of TRA performance when needed. In addition we have evaluated and adopted GCPEM (a PE code developed by Dr. Dimitri Nikhin of NOAA) for studies that include acoustic propagation in moving media.

WORK COMPLETED

During the past year, this project has had two main thrusts: i) completion of the formal prediction and simulation of TRA performance with broadband signals, moving sources, and moving arrays, and ii) the launch of work on TRA performance in shallow water sound channels when non-negligible ocean currents are present. In addition, we have begun preliminary work two fresh topics: 1) a new array processing technique, synthetic time reversal (STR), that exploits the features of ocean sound channel propagation to deconvolve multipath distortion from underwater sound signals transmitted through unknown environments, and 2) TRA performance degradation in the shallow ocean when the array elements are allowed to drift.

The broadband TRA performance predictions for moving sources and moving arrays have been completed, written-up, and submitted for publication [7,8]. The main results here are that a moving source does not impede acoustic time reversal as long as the source only moves a fraction of a center-frequency wavelength during its signal broadcast, and that the performance of a moving endifre horizontal TRA degrades rapidly with towing speed compared to towed arrays that are tilted or vertical (an idealized case).

The second thrust seeks to determine how array performance changes for different orientations of a time reversing array and a shallow ocean current. Prior work [9] has shown the location of the array-produced retrofocus will drift in the cross range direction for uniform currents in free space, and we are now simulating range-directed and cross-range directed currents between a source and a time reversing array.

Research on the new topics is in its infancy. However, we have explored enough of the available literature on blind-deconvolution to determine that STR appears to be a unique approach and that it may be widely applicable to waveguide acoustic propagation.

RESULTS

Figure 1 illustrates the type of results obtained for the performance of acoustic time reversal with a moving source. This is a range-depth plot of the difference in retrofocused signal energy in a shallow ocean sound channel between a linear vertical water-column spanning array responding to a stationary source and the same array responding to a source that is moving away from the array at a speed of 20 m/s (approximately 40 knots). In both cases, the source broadcasts a Gaussian windowed sine wave with a center frequency of 500 Hz and a 99%-signal-energy bandwidth of 258 Hz. Here, the water column is 65 m in depth with a downward refracting sound speed profile, the source is at a depth of 18 m, and the source-array range is 1 km. The energy differences shown on Fig. 1 are normalized the by the peak retrofocus energy for the stationary source case and converted to decibels. The energy differences that occur in the retrofocus field between stationary and moving sources under these conditions are 20 or more dB down from the retrofocus peak. Predicted signal correlations for these conditions are above 95%, but do show a small drop, a few percentage points, between the stationary and moving source cases.

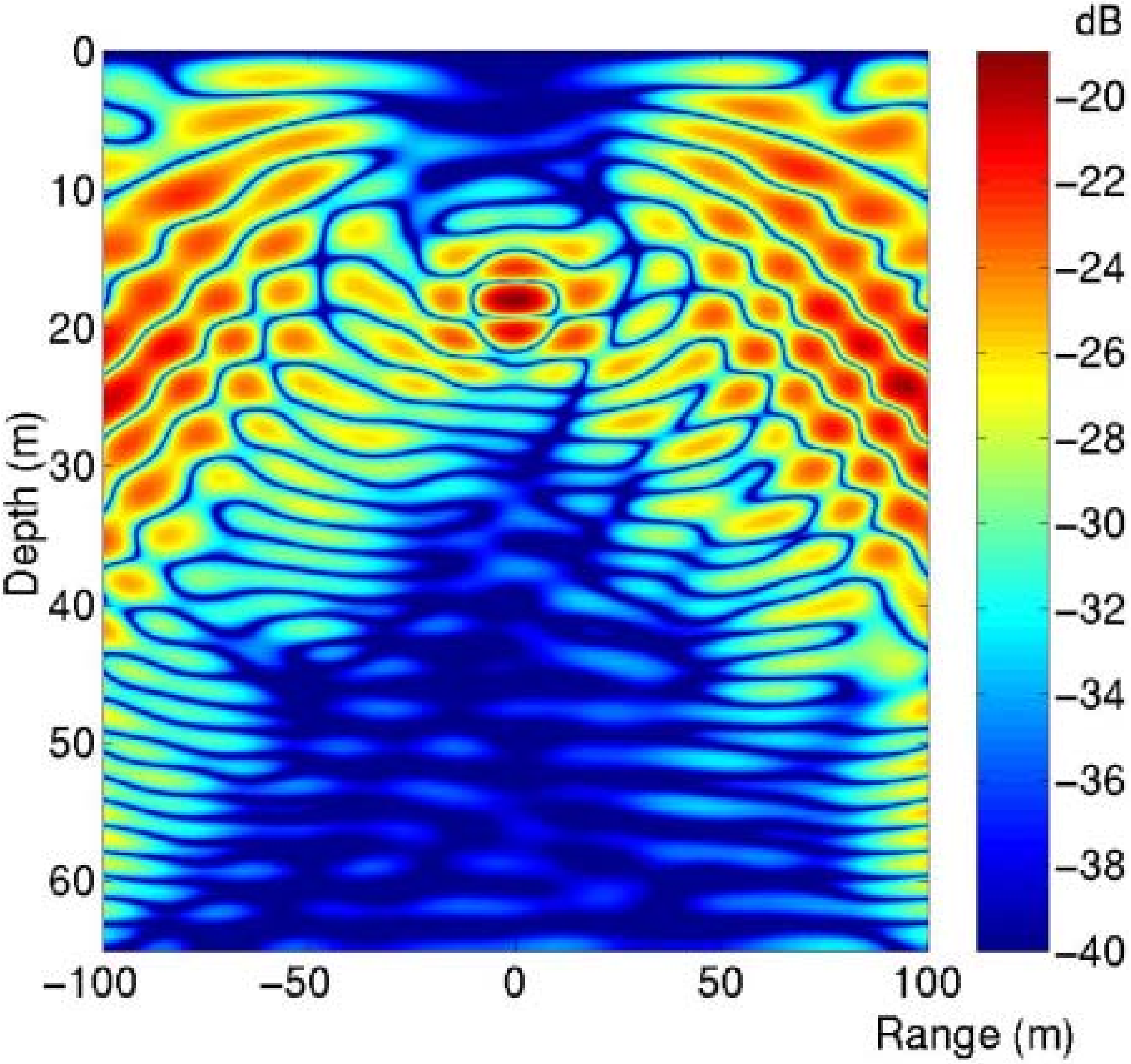

Figure 1. The difference in the retrofocused signal energy in a shallow ocean sound channel between a TRA responding to a stationary source at 18 m depth and a source moving away from the array at 20 m/s. The energy values are normalized by the retrofocus peak energy for the stationary source case and converted to dB. The signal pulse was a Gaussian-windowed sine wave with a center frequency of 500 Hz and a 99%-energy bandwidth of 258 Hz. The vertical axis is the water depth in meters. The horizontal axis is the range in meters measured from the original source location. Although the largest differences are predicted to occur near the original source location, these differences are relatively small.

Figure 2 presents normalized TRA retrofocus energy vs. array towing speed and summarizes our performance predictions for several moving TRA configurations in a range-independent shallow ocean sound channel. Here, each curve is normalized by the peak retrofocus energy for that array configuration when the towing speed is zero. In all cases, the moving TRA is responding to a stationary source. The figure contains results from idealized-vertical (a), horizontal-endfire (b,c,d), and tilted (f,g,h) TRAs. Curve e) is a theoretical far-field prediction for the horizontal arrays.

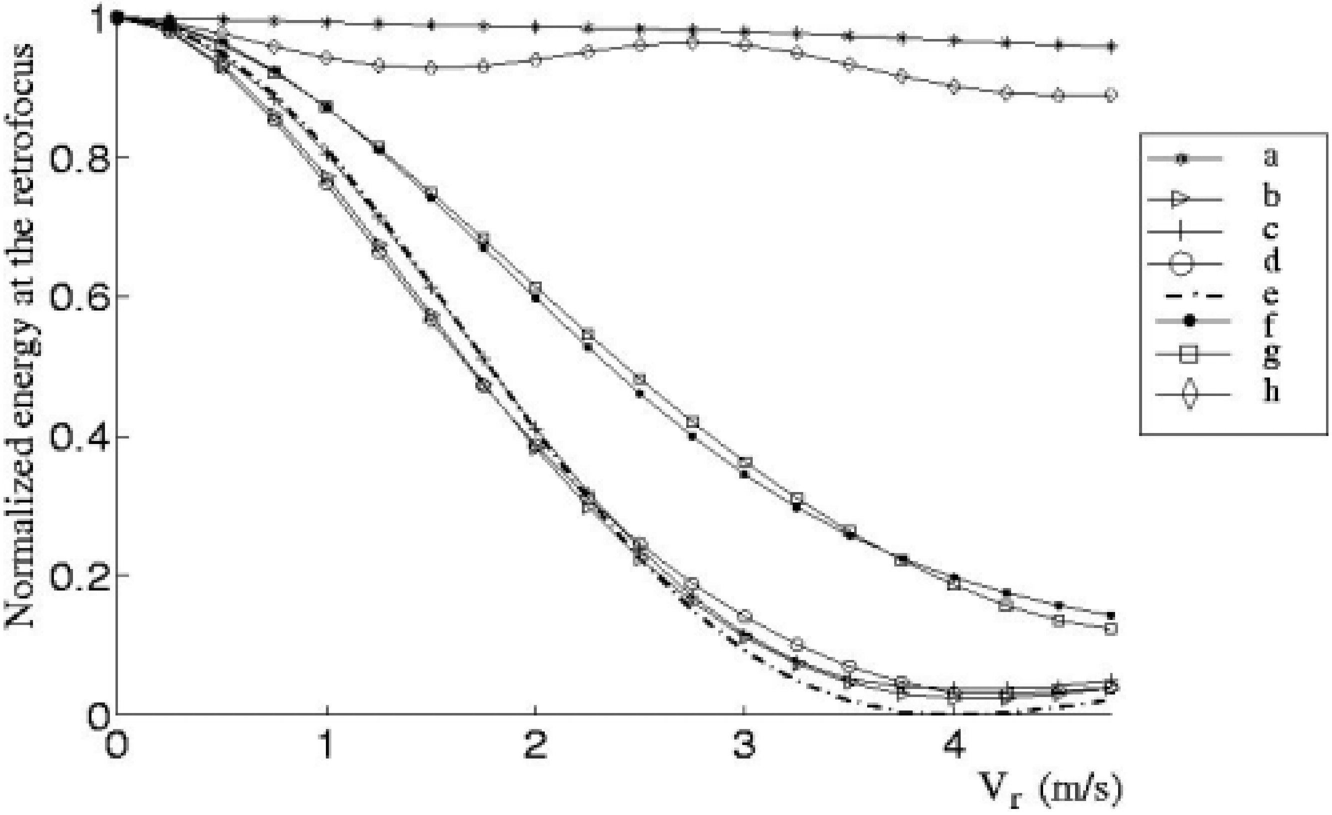

Figure 2. Peak retrofocused signal energy produced by a TRA towed in a shallow ocean sound channel normalized by the peak energy when the array is stationary vs. array towing speed. In each case the array has 21 elements. Case a) is for an idealized water-column-spanning vertical array. Cases b), c) and d) are for endfire horizontal arrays towed at mid water column at source-array ranges from 1.5 km to 5.0 km. Case e) is a theoretical far-field prediction for the endfire horizontal arrays. Cases f), g) and h) are for tilted TRAs directed along the endfire azimuth with case h) representing the shortest and most vertical array. Clearly, horizontal TRA performance degrades the most rapidly with towing speed.

IMPACT/APPLICATION

These results show that time reversing arrays may be able to function well in shallow ocean waters even when the source is moving. This suggests that phase-coherent underwater communications are possible between a fixed array and a maneuvering underwater vehicle or diver. Therefore, TRA-based techniques may be well suited for tetherless underwater acoustic communication systems.

However, the towed array TRA performance results paint a less optimistic picture. In this case, array performance depends strongly on source-array configuration and towing speed. Consequently, full utilization of the benefits of acoustic time reversal in towed active sonar systems will require careful parametric choices.

TRANSITIONS

The results of this project should aid in the design of further experiments, and eventually, active and or passive TRA sonar hardware. To this end, discussions have been held with Dr. Charles Gaumond of the Naval Research Laboratory to determine the applicability of a variety of time reversal schemes to anti-submarine warfare. In addition, researchers at the Naval Surface Warfare Center - Carderock Division have taken an interest in passive acoustic time reversal as a means for studying low event rate cavitation. Continuing discussions on this topic are under way.

RELATED PROJECTS

1. - This research effort is now being loosely coordinated with the work of Drs. Charles Gaumond and David Fromm of the Naval Research Laboratory.

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). A chapter for the senior-level ocean acoustics textbook now being assembled by Dr. Hermin Medwin is being co-authored by the author of this report and Dr. HeeChun Song from the SIO time-reversal team.

REFERENCES AND PUBLICATIONS

[1] S. R. Khosla and D.R. Dowling, "Time reversing array retrofocusing in simple dynamic underwater environments," J. Acoust. Soc. Am., Vol. 104, 3339-3350, 1998.

[2] M.R. Dungan and D.R. Dowling, "Computed time-reversing array retrofocusing in a dynamic shallow ocean," J. Acoust. Soc. Am., Vol. 107, 3101-3112, 2000.

[3] S.R. Khosla., and D.R. Dowling "Time-reversing array retrofocusing in noisy environments," Vol. 109, 538-546, 2001.

[4] Dungan, M.R. and Dowling, D.R., "Computed narrowband azimuthal time-reversing array retrofocusing in shallow water," J. Acoust. Soc. Am. Vol. 110, 1931-1942, 2001

[5] Dungan, M.R. and Dowling, D.R., "Orientation effects on linear time reversing array retrofocusing in shallow water," in press J. Acoust. Soc. Am., 2002.

[6] Sabra, K.G., Khosla, S.R., and Dowling, D.R., "Broadband time reversing array retrofocusing in noisy environments," J. Acoust. Soc. Am. Vol. 111, 823-830, 2002

[7] Sabra, K.G., and Dowling, D.R., "Broadband performance of a time reversing array with a moving source," submitted to J. Acoust. Soc. Am, Sept. 2002.

[8] Sabra, K.G., and Dowling, D.R., "Broadband performance of a moving time reversing array," submitted to J. Acoust. Soc. Am, Sept. 2002.

[9] Dowling, D.R. "Phase-conjugate array focusing in a moving medium," J. Acoust. Soc. Am. Vol. 94, 1716-1718, 1993.