Predicting Time Reversing Array Performance in Shallow Ocean Waters

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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 water ocean waters, and ii) to deduce the effectiveness of using a TRA for underwater communication and for surveillance of the acoustic characteristics of known or 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 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 [6,7], the effects of source and array motion, and three-dimensional environments.

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). My current student, Karim G. Sabra, is using a customized version of RAM that allows us to recover the amplitude and phase of the computed field, and we are now in the process of evaluating OASES (by Prof. Henrik Schmidt of MIT) for our simulation efforts. Broadband simulations are conducted via a superposition of computed single frequency results. Simulations involving moving sources and moving arrays are conducted via a spatial superposition of fixed source and receiver results. Extension of these efforts to 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.

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14. ABSTRACT

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15. SUBJECT TERMS

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In May of 2000, we participated in a shallow water experiment conducted by Drs. Daniel Rouseff, Warren Fox and colleagues at the Applied Physics Laboratory of the University of Washington that involved testing passive time reversal as an underwater communications technique. A publication covering this effort will appear soon [6].

WORK COMPLETED

During the past year, this project has had three main thrusts: i) completion of the formal prediction and simulation of broadband TRA performance in the presence of noise, ii) continued work on simulations of narrowband linear horizontal TRA performance in shallow water sound channels, and iii) preliminary work on TRA retrofocusing with broadband signals and moving sources.

The broadband TRA noise-rejection performance work has been completed, written-up, submitted, reviewed, revised, and resubmitted for publication [7]. The main result is an algebraic relationship for the signal-to-noise ratio achieved at the TRA retrofocus in terms of the signal-to-noise ratio received by the TRA, the characteristics of: the source broadcast, the array's transducers, the noise at the source and the array, and the sound-channel.

The second thrust seeks to determine changes in array performance caused by different array orientations and geometries. Over the last year, our work has emphasized the simplest possible shallow-water sound-channel propagation model: the modal sum for the Pekeris waveguide. However, extension of this effort to more realistic sound channels having non-uniform sound speed profile, and bottom absorption is now underway.

The third thrust is in its infancy and we are still examining a variety of simulation tools to handle broadband pulses, source and array motion, and range-independent and range-dependent environments. However we have completed a first set of TRA simulations with a moving source.

RESULTS

The highlight of the effort to predict the retrofocus-field signal-to-noise ratio, SNR_f, produced by a TRA operating in a noisy environment is the algebraic formula obtained when the electronic amplification factor for the array is set by an average broadcast power limitation, and the noise is uncorrelated between elements of the TRA and between array elements and the retrofocus location. The final formula includes the variance σ_r^2 of the noise field that is accidentally recorded by the array, and the variance σ_f^2 of noise that is present at the intended retrofocus location.

$$SNR_f(\vec{r}_s) = 2B \cdot T_r \cdot N \cdot SNR_r \Big/ \left[1 + \frac{\Pi_s T_s}{N \Pi_e T_r} \left(\frac{1 + SNR_r}{SNR_r} \right) \cdot \frac{\sigma_f^2}{\sigma_r^2} \right] \qquad (1)$$

Here, $\bullet_s$ and $\bullet_e$ are the source and array-element acoustic powers, T_s is the duration of the original signal, T_r is the time interval necessary to receive 99% of the signal energy after the signal propagates through the sound channel, B is the one-sided bandwidth of the signal that captures 99% of the signal energy, N is the number of array elements, and SNR_r is the average received signal-to-noise ratio for a single element of the TRA. This formula should be useful for preliminary design studies of TRA applications.

The investigations into the performance of horizontal TRAs have proceeded slowly over the last year because the AASERT award that was supporting them ended in August 2000 and the graduate student, Michael R. Dungan, successfully completed his Ph.D. in early fall 2000. However, we continue to pursue RAM calculations in this area and hope to soon revise and resubmit our paper [5].

An interesting early result of our recent broadband simulations of TRA retrofocusing on moving sources is shown below on Figure 1, a range-depth slice of the TRA's retrofocus field obtained when the original source was moving horizontally toward the array at 20 m/s (Mach no. = 0.013) in a range-independent sound channel of 65 meter depth. The color contours denote the correlation of the retrofocused signal with the time-inverted original signal. The correlation field is high (i.e. red) in a broad region near the intended retrofocus location: depth = 27 m, range = 1000 m. For this case, the acoustic energy (not shown) is strongly peaked near the retrofocus location with a vertical and horizontal extent of only a few meters and a few tens of meters, respectively. Interestingly, Fig. 1 and an equivalent correlation field for a stationary source are essentially identical.

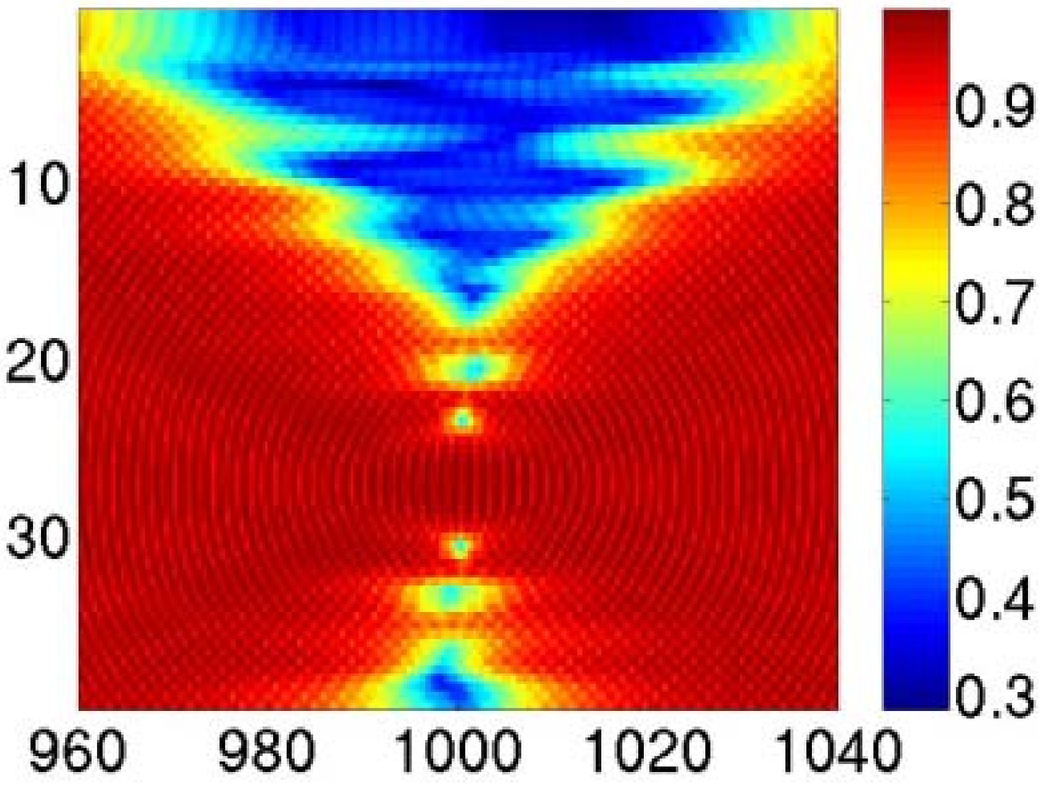

Figure 1. The correlation of the retrofocused signal with the time-inverted original signal pulse in a range-independent waveguide of depth65m at a range of 1 km. The source was moving horizontally toward the time-reversing array at a speed of 20 m/s and a depth of 27 m. The signal pulse was a Gaussian-windowed 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. For this source speed, the correlation with the original signal is high in a large region near the intended retrofocus location (depth = 27 m, range = 1000 m)

IMPACT/APPLICATION

These results show that time reversing arrays may be able to function well in shallow ocean waters because TRAs can exploit multipath propagation to enhance the focal point signal-to-noise ratio. This result is apparent in Eq. (1) above because SNR_f is primarily proportional to the time-bandwidth product of the received signal which – because of temporal multipath signal spreading – may be much larger than the time-bandwidth product of the original signal. Therefore, TRA-based techniques may be well suited for tetherless underwater acoustic communication systems.

In addition, the preliminary results for TRA performance with moving sources suggest that TRA performance is relatively insensitive to source motion for source speeds of approximately 40 knots or less. Thus, TRA-based tetherless underwater acoustic communication with a moving autonomous underwater vehicle (AUV) should be nearly unaffected by AUV motion.

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 of addressing several longstanding problems associated with Naval propulsion systems. Continuing discussions are under way. And finally, a research group at Science Applications International Corporation is following up on the passive phase conjugation (or passive time-reversal) concept that was suggested for underwater communication a few years ago [8].

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. - A research group headed by Dr. Daniel Rouseff at the Applied Physics Laboratory of the University of Washington completed an experiment on underwater acoustic communication using passive acoustic time reversal. Mr. K. Sabra and I participated on the experiment and have agreed to work with these APL researchers again on their next experiment on this topic.

3 - 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.

PUBLICATIONS

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