Simulations of Time Reversing Arrays in Shallow Ocean Waters

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LONG-TERM GOAL

The long term goals of this project are: i) to predict and understand time reversing array (TRA) retrofocus size and longevity in shallow water ocean waters, and ii) to deduce the effectiveness of using a TRA for monitoring and/or determining the acoustic characteristics of unknown environments.

OBJECTIVES

This project seeks to quantitatively predict TRA retrofocus size and longevity in the presence of dynamic random shallow-water internal-waves, noise, bottom losses, and three-dimensional acoustic scattering typical of the shallow ocean. In particular, the influence of acoustic frequency, source array range, and propagation complexities in a dynamic mulitpath sound-channel on time-reversing array retrofocusing is not completely understood and the phenomena primarily responsible for TRA retrofocusing persistence and limitations are not entirely identified. The challenge here is to ascertain generic features and scaling laws in the presence of wide natural variability. Such results are the essential inputs for the design of practical TRA systems. While past work on this project has dealt with simple dynamic environments [1], the current effort incorporates realistic oceanic sound propagation to a much greater degree through the use of modern computational tools.

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 wide-angle parabolic-equation code RAM (by Dr. Michael Collins of NRL). My students and I are using a customized version of RAM that allows us to recover the amplitude and phase of the computed field. We have also developed Monte-Carlo simulation techniques for TRA simulations involving random super-positions of linear internal waves, random bottom roughness, and noise. Broadband simulations are conducted via a superposition of narrowband results.

WORK COMPLETED

This project has two main thrusts: TRA simulations involving acoustic scattering from internal waves and bottom roughness, and TRA simulations of narrowband and broadband signals in the presence of noise.

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For the first thrust, Monte-Carlo models of random shallow-water internal waves and bottom roughness have been generated and imported into RAM. The internal-wave model is based on measured temperature and salinity profiles from the SWARM '95 experiment and the Garrett-Munk spectral form. The scaling exponents were adjusted to match a displacement spectrum also measured at the SWARM site. The SWARM data was provided by Dr. Steven Finette of NRL. The bottom roughness model is based on a power law spectrum deduced from classical oceanic measurements.

Both the internal wave model and the bottom roughness model have been used in RAM to predict TRA retrofocus properties as a function of acoustic frequency, range, and bottom absorption. The internal wave results have been written up and submitted for publication [2]. The bottom roughness investigations are now underway.

For the second thrust, a general scaling law for TRA operations in a noisy environment has been developed that incorporates the source strength of the original transmission, the power output from the the array, the noise level, and the propagation characteristics of the sound channel to predict the probability of that a retrofocus is formed. Here, only simple omni-directional noise fields have been considered but the formulation could be extended to directional noise noise fields.

This theoretical scaling law has been compared to Monte-Carlo simulations of TRA retrofocusing performance in noisy free-space and shallow-water sound-channel environments. The results are good and have been written up and submitted for publication [3]. Current efforts are now focused on extension of this work to retrofocusing of short broadband pulses.

RESULTS

The TRA simulations in a shallow water sound channel show that the size and amplitude of the retrofocus are both degraded by increasing source-array range, and bottom absorption. Interestingly, the ultimate range for obtaining a good retrofocus is found to increase with increasing acoustic frequency for frequencies from 100 Hz to 1kHz when the original source is placed in the upper region of the water column. This unexpected result is due to modal absorption in a shallow water sound channel. The quality of the TRA retrofocus is better when more modes form the retrofocus. Higher acoustic frequencies lead to more modes having little interaction with the bottom and these modes sustain the TRA retrofocus at longer ranges.

When internal-waves are included in the simulations, they aid retrofocusing for short periods of time before they cause it to dissappear. The duration of the retrofocus generally decreases with increasing acoustic frequency and source-array range.

Some of our most recent results for bottom-roughness-based retrofocusing from a vertical water-column spanning TRA are shown on Figure 1. Here, there are no internal-wave dynamics in the simulations so retrofocus duration is not an issue. The horizontal axis on Fig. 1 is the source array range. The vertical axis on Fig. 1 is the azimuthal angular extent of the retrofocus in the cross-range horizontal direction at the depth of the retrofocus. In the absence of bottom roughness this would be 360°. Thus this figure shows that bottom roughness provides horizontal beamforming even when the array can not. The extent of this roughness-induced beamfroming increases (i.e. the angular size of the retrofocus decreases) until a range of 10 km or so where the effects of bottom absroption begin to degrade the retrofocus.

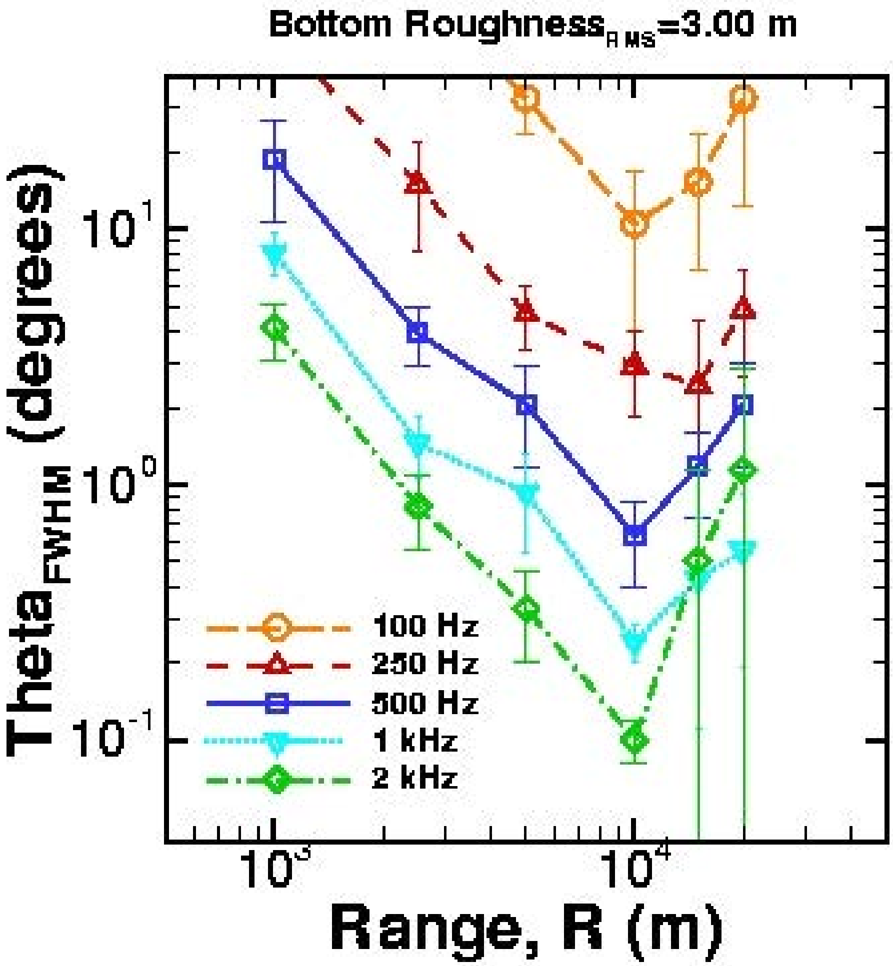

Figure 1. Azimuthal TRA retrofocus angular size (full width at half maximum, FWHM) vs. Source-Array Range (R) for five acoustic frequencies when the root-mean-square height of the bottom roughness is 3 m.

Studies at other bottom roughness levels yield similar results. We are now working on comparing how the retrofocus size and duration are effected by internal waves and bottom roughness.

Our results from the investigations into the effects of noise on TRA retrofocusing suggest that there are two limiting regimes for TRA operations in noisy environments that correspond to the two propagation passes necessary for use of a TRA. The first propagation step consists of sound traveling from the source to the array. In a noisy environment this sound is received with a finite signal-to-noise ratio and some of the recorded noise is broadcast by the TRA when it transmits the recorded and time-reversed versions of the initial signal. The TRA's rebroadcast of the recorded sound occurs in the same environment and travels from the array back to the source where it may be recorded or sampled, perhaps as part of an underwater communication system. Again, in a noisy environment, this retrofocused sound is received with a finite signal-to-noise ratio. A portion of the noise received at the retrofocus comes from the unintentionally TRA-broadcast noise, and a portion of it comes from ambient noise at the retrofocus location, and either noise term may dominate.

These regimes are illustrated in Figure 2, which is drawn from a submitted paper [3]. The horizontal axis displays the variable X = the average TRA broadcast signal-to-noise ratio. The vertical axis displays the variable Y = the average signal-to-noise ratio of the received signal at the TRA.

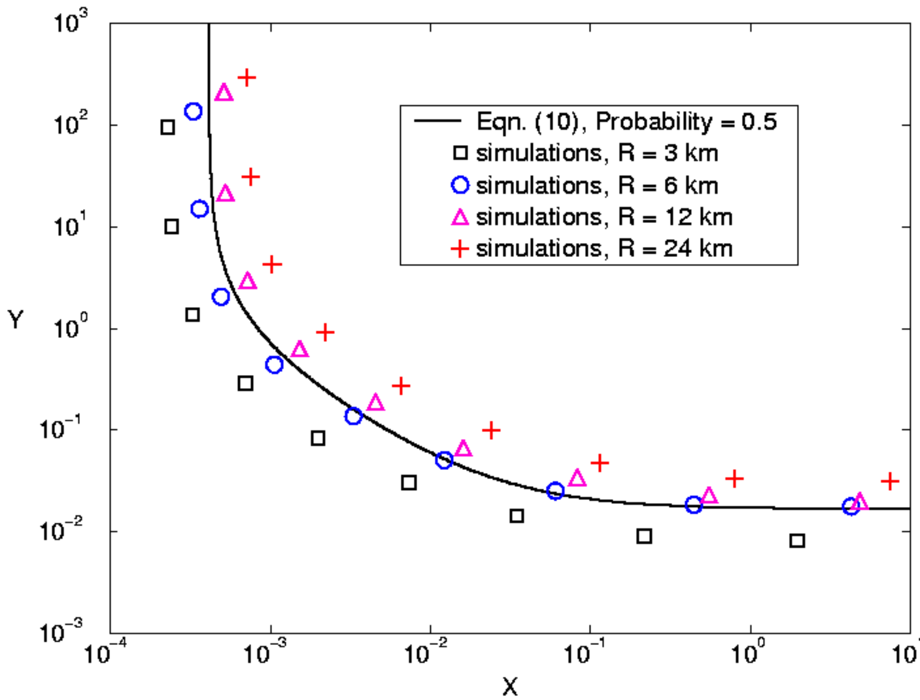

Figure2. TRA-broadcast SNR (X) vs. TRA-received SNR (Y) for several ranges in a shallow water sound channel. The symbols represent Monte-Carlo simulation results for the parametric location of 50% probability of retrofocusing. The solid line is a prediction of the parametric location of 50% probability of retrofocusing.

The reception-strength-limited case of TRA operation (rebroadcast-noise dominated) occurs when Y is small and X is large. The ambient noise limited case of TRA operation (weak rebroadcast or long ranges) occurs when X is small and Y is large. TRAs are guarenteed to work well when both X and Y are large. TRAs will not retrofocus when X and Y are small. The dividing line where TRA operations are marginal occurs when there is only a 50% probability of a retrofocus forming. The solid line on Fig. 2 is the prediction of the theoretical scaling law for the parameteric location of 50% probability of retrofocusing. The individual points are the results of Monte-Carlo simulations in a noisy shallow water sound channel. The simulation theory comparison is good and we believe that we understand how noise influences TRA operations.

IMPACT/APPLICATION

These results show that time reversing arrays may be able to function well in shallow ocean waters because TRAs can exploit variations in the bottom to give vertical arrays horizontal directivity. And, because the phase structure of the mulitpath propagation is not entirely destroyed by shallow water internal waves for time periods of several minutes to tens of minutes, TRAs could be exploited in active sonar systems and in underwater communications. Morever, the sensitivity of TRAs to environmental details may make it possible for them to be exploited in a variety of remote sensing applications.

Our current results suggest that (with appropriate modification) the noise results appear to be valid in any environment. Thus, they provide an ideal basis for detailed design of sonar systems incorporating TRAs.

TRANSITIONS

The results of this project should aid in the design of further experiments, and eventually, TRA sonar hardware. To this end exploratory discussions with personnel from the MIT Lincoln laboratory have been held. In addition, researchers at the Naval Surface Warfare Center - Carderock Division have taken an interest in acoustic time reversal as a means of addressing several longstanding problems associated with Naval propulsion systems. Continuing discussions are are now under way

RELATED PROJECTS

1 - This project runs parallel to the on-going nonlinear acoustic retrofocusing studies under the direction of Dr. Ronald Roy at Boston University and Dr. Steve Kargl at APL-UW.

2 - This research project runs parallel to the retrofocusing experiments and analysis of the international research team headed by Drs. William Kuperman and William Hodgkiss of SIO.

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.

[2] M.R. Dungan and D.R. Dowling, "Computed time-reversing array retrofocusing in a dynamic shallow ocean," in revision for J. Acoust. Soc. Am, October 1999.

[3] S.R. Khosla., and D.R. Dowling,"Time-reversing array retrofocusing in noisy environments," submitted to J. Acoust. Soc. Am, August 1999.

PATENTS

Dowling, D.R., and Yonak S.H. "Multiple microphone photoacoustic leak detection and localization system and method," filed October 1998, now pending. [Although this patent was not directly supported by ONR, the essential idea in this patent is **acoustic time reversal**.]