Time-Reversal Acoustics

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Abstract

Phase conjugation (PC) has been demonstrated in nonlinear optics, laboratory ultrasonics and most recently, in ocean acoustics. PC can be implemented in the time domain by a "time reversal mirror." A brief review of the physics of a TRM is presented. This is followed by a presentation of the results of a set of ocean acoustic experiments in which a TRM was implemented. Applications of the TRM process are discussed.

Introduction

Phase conjugation (PC) is a process that has been first demonstrated in nonlinear optics [1] and then in ultrasonic laboratory acoustic experiments [2], and most recently in ocean acoustics [3]. PC takes advantage of reciprocity, a property of wave propagation in a static medium and a consequence of the invariance of the linear wave equation to time reversal. Therefore, PC in the frequency domain can be implemented in the time domain by a time reversal mirror (TRM) or phase conjugate mirror.

In this paper, we briefly review the physics of a TRM and then present the results from a series of ocean acoustic experiments in which a TRM was implemented. Possible applications are discussed.

Review of TRM

Excellent overview articles on TRM can be found in Refs. 2 and 4. We briefly review the TRM in the context of ocean acoustics.

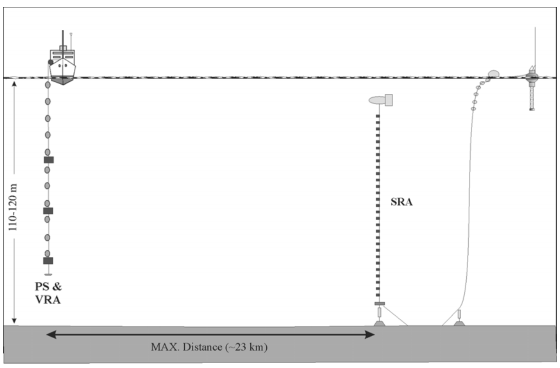

Figure 1. Experimental setup of generic time reversal mirror experiment in the ocean.

Figure 1 illustrates the components of a TRM experiment in the ocean. A probe source (PS) indicated by one of the rectangles on the vertical receive array (VRA), sends out a pulse that is received at the source-receive array (SRA). The dispersed signal with all its multipath structure is time reversed and retransmitted by the SRA. The resulting signal multipath structure collapses to a spatial and temporal focus (original PS pulse length) at the original PS position that is co-located in range with the VRA.

The size of the focal region depends on the wavelength and the effective aperture of the SRA which increases due to the waveguide nature of acoustic propagation in the ocean over the free space. Analysis using image methods, including attenuation effects of the ocean bottom, indicates that the diffraction limit on the size of the focal region was reached experimentally [5].

PC or TRM is relevant to the recent trends in acoustic signal processing which have emphasized utilizing knowledge of the environment, e.g., matched field processing (MFP) [6]. However, MFP requires accurate knowledge of the environment along the propagation path. Phase conjugation is an environmentally self-adaptive process that can be applicable to localization and communication in complicated ocean environment. The fact that a TRM both spatially and temporally refocuses energy with the aid of a probe suggests that ocean self-equalization with respect to communication processing is possible [5]. In fact, this self-equalization process was demonstrated experimentally as described below.

TRM experiments in the ocean

We have conducted a series of four ocean acoustic experiments off the west coast of Italy (see Fig. 2). The first two in 1996 and 1997 used a 450 Hz SRA which was hardwired to Formiche Island. These experiments were the first to implement and demonstrate the TRM process in the ocean [3,7,8]. At 450 Hz, focal distances out to 30 km were demonstrated, the multi-day stability of focal region was demonstrated and a new process to shift the focal range was derived and experimentally confirmed.

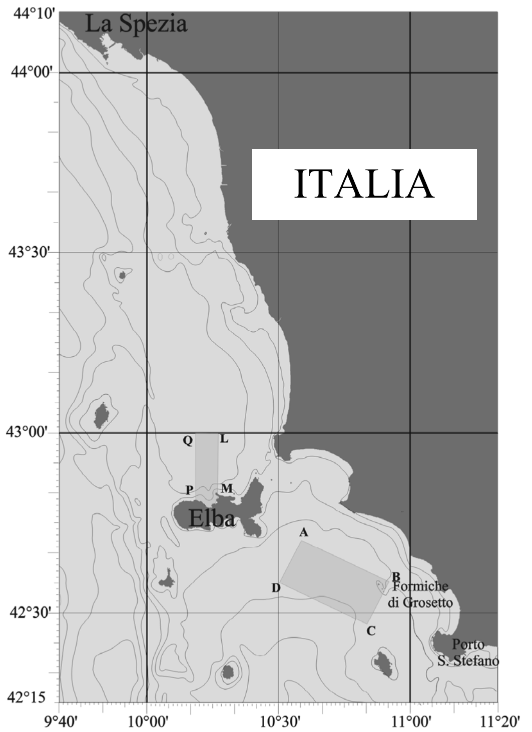

Figure 2. Location of ocean acoustic time reversal mirror experiements off the west cost of Italy.

The third experiment conducted in 1999 used a 3500 Hz array [5]. The SRA was moored and tethered to a remote, self-contained buoy system with all electronics/computers so that it functioned as a node on the local area network (LAN). However, the probe source was not fixed to the VRA so that field measurements were often not obtained at the precise focal position. Focal ranges out to about 15 km were demonstrated (the maximum LAN range at that time). Data in the Formiche and Elba areas with different bottom types were taken and markedly different dispersion characteristics were observed. The totality of the data indicates that both for the 450 Hz and 3500 Hz experiments the diffraction limit on the focal size was achieved. A short communication sequence indicated communication utility, though in this first communication exploration, the quantity of data was insufficient to perform statistical bit error analysis [5]. Finally, an up-slope experiment with the SRA in 100 m, PS in 30 m of water at a range of 10 km demonstrated a remarkable focusing ability with 3 dB extent of only 1 m.

The fourth experiment was carried out recently north of Elba in between May 19 and June 13, 2000 using 3500 Hz SRA. Some of the goals include: 1. To obtain sufficient data to characterize the error rate of the self-equalization undersea process as applicable to undersea acoustic communication. 2. To perform TRM measurements to provide data to begin to explore applications of focused acoustic fields to active sonar concepts. In particular, echo to reverberation enhancement are studied. 3. To measure stability and fluctuation properties of the focused field out to significant ranges in both flat and sloping regions.

Ocean Acoustic Environment

The ocean environment was quite variable throughout the experiment. An example of the spatio-temporal variability is shown in Fig. 3 for 9 CTD sites north of Elba on three consecutive days. There is a very distinct spatial dependence on the profiles. Additional data from oceanographic moorings will provide valuable environmental data set. In addition, hydrosweep bathymetry, seismic profiling, expendable bottom penetrometer (XBP) measurements and cores were taken during the experiment along with acoustic transmission loss (TL) runs.

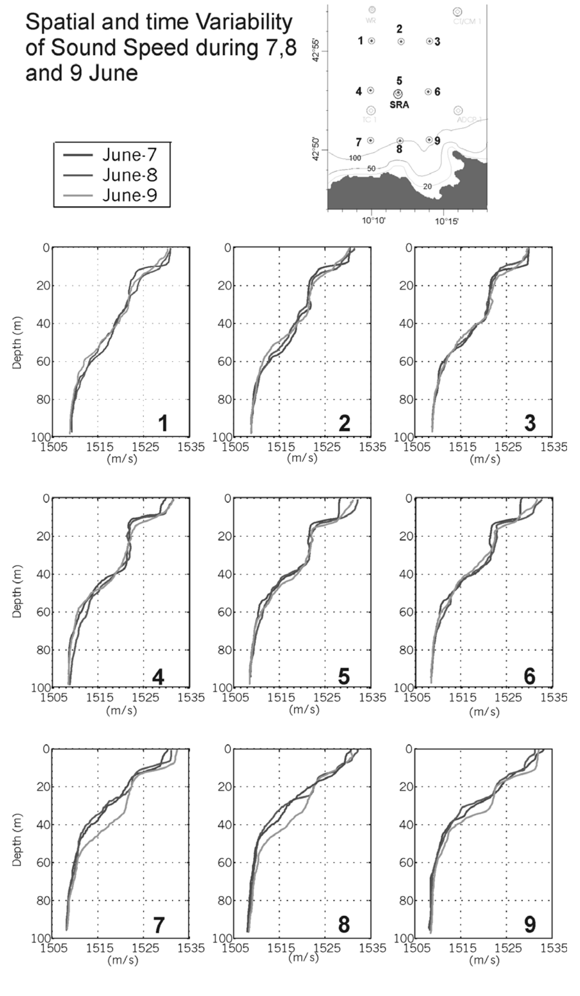

Figure 3. Sound speed profiles on three consecutive days at nine different positions north of Elba derived from CTDs.

Size of the focal region in up-slope environment

The size of the focal region in a range-independent waveguide is analyzed using an image approach in Ref. [5]. Here we extend the analysis to a range-dependent upslope waveguide where extremely sharp focal regions are obtained as shown in Fig. 4.

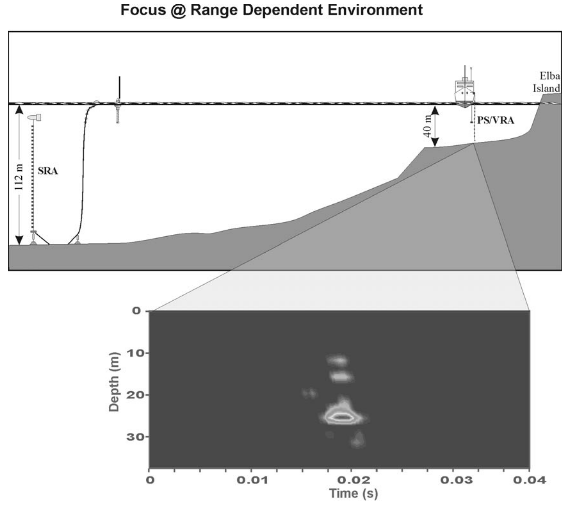

Figure 4. Geometry and data example for the range dependent TRM experiment.

Figure 5 shows measured focal sizes at 3500 Hz for three different environments: the Formiche, flat Elba and sloping Elba areas. Superimposed are the theoretical predictions based on the image approach, which are in good agreements with the measured ones.

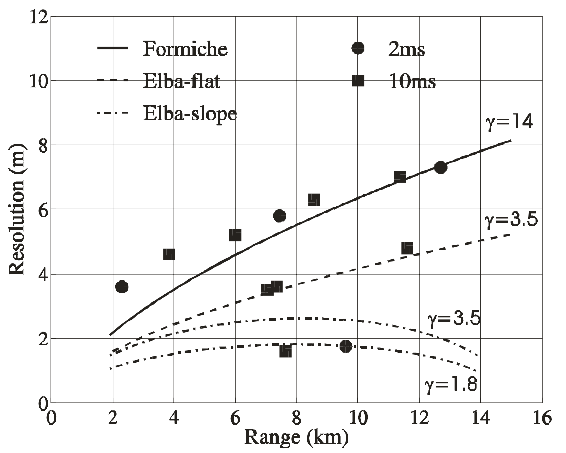

Figure 5. Comparison between the measured vertical focal sizes and the calculated resolution based on the image aperture method with appropriate bottom attenuation for 3500 Hz in three different environments.

The resolution is determined by the effective aperture of the array L_e, i.e., effective angle θ_e which depends on the water depth D, range R, and bottom attenuation. In flat bottom as shown in Fig. 6(a), $\theta_e \approx \sqrt{D/2\gamma R}$ where the factor 2 accounts for two-way propagation and γ is a parameter determined from the bottom characteristics [5]. For a wedge shaped ocean, the effective angle θ_w can be defined as

$$\theta_w \approx \sqrt{DR_0 / 2\gamma R(R-R_0)},$$

where R_0 is the range to the apex and the slope of the bottom is defined as $\alpha \approx D/R_0$ (see Fig. 6(b)). In a wedge ocean, each bounce of sound propagating from a PS to a time reversal array reduces the reflection angle by 2α, decreasing the overall attenuation in the two-way propagation which results in $\theta_w > \theta_e$.

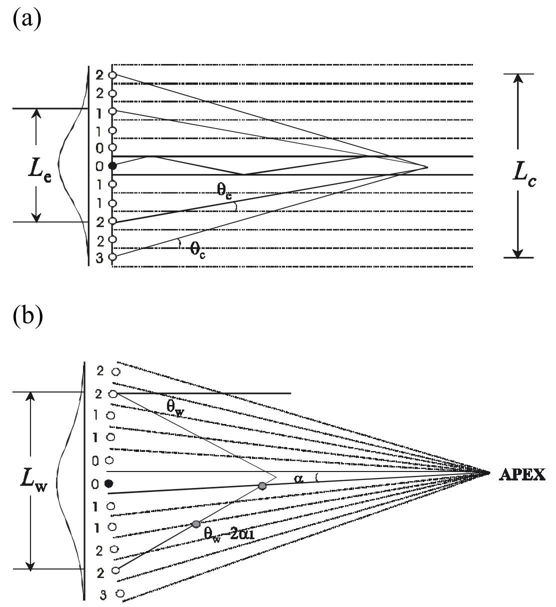

Figure 6: Schematic of image arrays: (a) for Pekeris waveguide and (b) for a sloping environment. The image aperture L_c is determined by the critical angle θ_c of the bottom. The effective aperture L_e is smaller due to attenuation in the ocean bottom that causes the shading of the image sources. In a sloping environment, the grazing angles changes by 2α for each bounce with the bottom which results in a difference in the effective aperture L_w. The labels at the image sources indicate the number of interaction with the bottom.

Self-equalization underwater communications

The communication experiments were performed in the fixed-fixed configuration with both the SRA and VRA operated remotely. A 2-ms CW probe source signal was received at the SRA, time reversed thereby creating the basic symbol for the communication sequence. This TR bit is then copied onto a random sequence (plus and minus ones) to produce a 10 second, 5000 bit coded communication sequence for acosutic transmission to the VRA at a range of 8 km. The communication terminology for this coding is Binary Phase Shift Keying (BPSK). One way broadside and single source control communications experiments were also performed. A subset of the BPSK focused results as received at the VRA is shown in Figure 7 along with broadside and single source control examples. Decoding was done by the synchronized correlator receiver or matched filter as shown in Figure 8. The dot plots on the right are an indication of the robustness of the communication process. With no noise or ocean variability, one would expect only two dots on the imaginary axis at plus and minus one. Preliminary analysis suggests successful decoding with the best results from the time-reversed process. Data were also taken for other types of coding: BPSK, QPSK, 8-PSK and 8-QAM in order to explore the potential for higher bit rate communications.

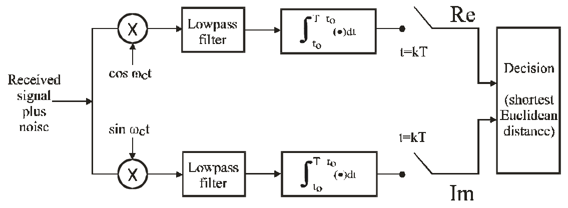

Figure 8. Block diagram of a BPSK decoding system. The received signal and noise is separated into its quadrature components. They are both filtered and passed through a synchronized integrate-and-dump receiver. The output of the receiver, every T=2 ms, is the position of a single bit in the complex plane. The logical decision is the closest Euclidian distance to either $\pm i$. The original bit was coded with a phase of $\pm 180^\circ$ representing either 1 or 0.

The communications experiments were also conducted in the upslope range-dependent environment in Fig. 4 where the SRA was operated remotely and the PS/VRA was 9.8 m away in 40-m water. Figure 9 shows again the performance of two-way time reversal communication is better than one-way single source and broadside communications.

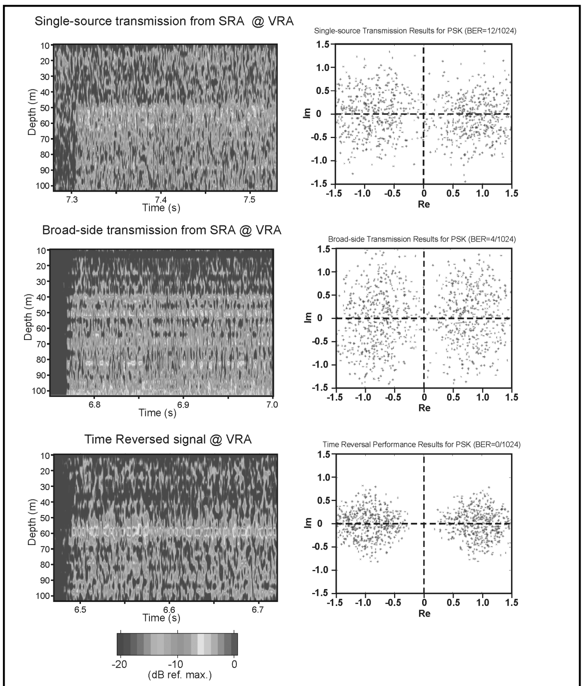

Figure 7. Range-independent: An example of time reversal communication result compared to one-way transmission control examples: single source and broadside. Bit error is denoted by BER.

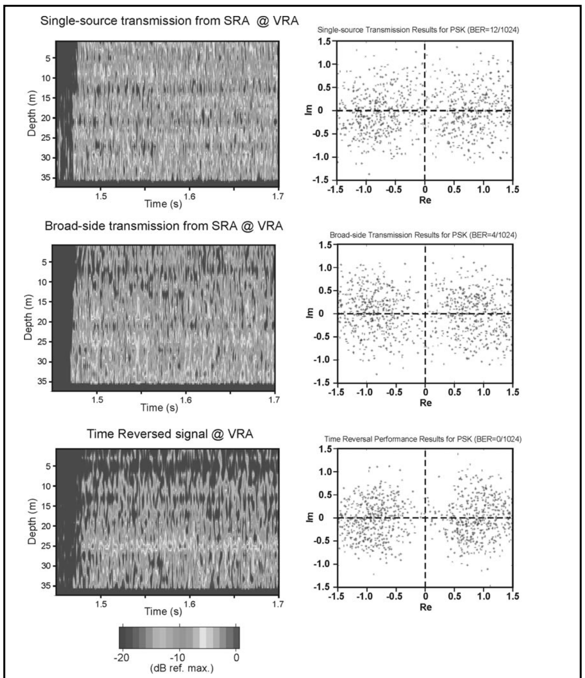

Figure 9. Same as Fig. 7 except in upslope range dependent environment as shown in Fig. 4. The two-way time-reversal communication shows a better performance than one-way single source and broadside communications.

Echo to Reverberation enhancement

The main goal was to demonstrate that (bottom) reverberation is minimized from the range where there is a time reversed (TR) produced focus in the water column. For example, Figure 10 shows this effect. The R/V Alliance deployed the probe source at 60-m depth and foci were produced at various ranges, while, at the same time, reverberation from the outgoing time-reversed SRA signal was recorded by the SRA. We see a decrease in the TR reverberation (notch) at that time which corresponds to the TR focus at 1.7 km and 4.7 km range in the example. Single source, monostatic reverberation measurements for cw tones and LFM chirps were also taken. Finally a set of towed probe source runs were made in conjunction with the SRA to determine if we can trace out a path of minimum bottom reverberation return related to the moving focal range.

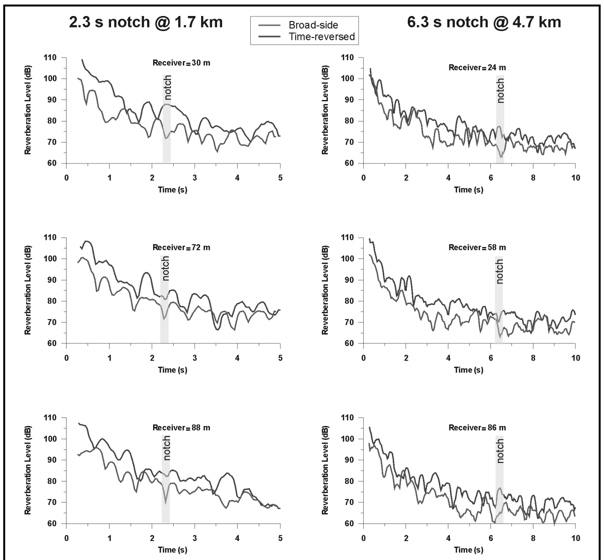

Figure 10. Examples of echo -to-reverberation enhancement compared to reverberation from a broadside transmission. The position of notch indicated the range at which the SRA was focusing.

TR Experiments including a target

An artificial target was deployed from the Manning together with a probe source. It consisted of a 30-m air-filled hose folded 7 times. Figure 11 shows the geometry of one of the experiments and Figure 12 shows a bistatic results: in which the Manning provided the probe source signal which was time reversed at the SRA, echoed off the target at the Manning with the echo shown being the VRA reception at the Alliance. The broadside control results do not show a target detection.

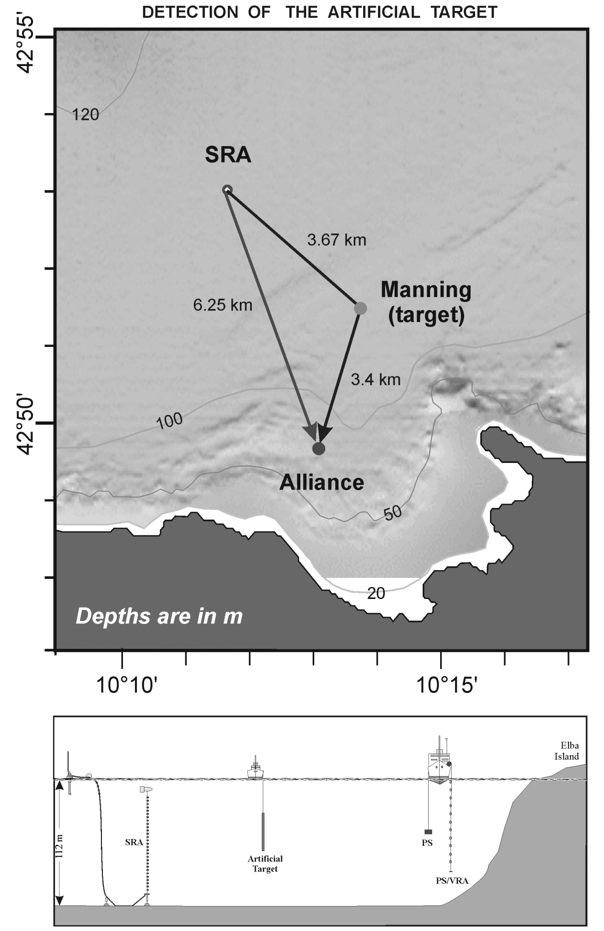

Figure 11. Bistatic scattering, time reversal geometry. Manning had an artificial "fire hose" target and a probe source.

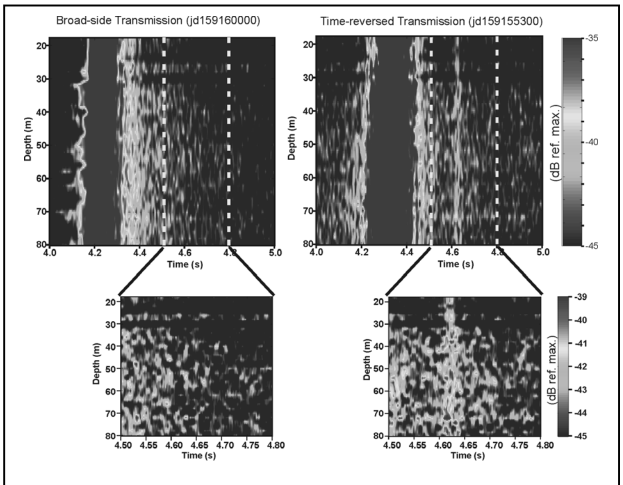

Figure 12. Example of data obtained using the bistatic configuration as shown in Figure 11.

Conclusions

We have implemented acoustic Time Reversal Mirrors in the ocean which perform as well as they would in an ideal laboratory setting. In particular, the measured focus size was shown to be at the diffraction limit, even for the complex ocean environments in which the experiments were performed. Furthermore, we have demonstrated the potential utility of the time reversal physics when applied to sonar and acoustic communications.

Acknowledgements

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