Time Reversal Ocean Acoustic Experiments At 3.5 kHz: Applications To Active Sonar And Undersea Communications

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Abstract. We have conducted a series of time-reversal experiments at a center frequency of 3.5 kHz with a 1 kHz bandwidth. These experiments and follow-up analysis suggest applications to active sonar and undersea communications. In the area of active sonar, time reversal physics points to procedures to minimize reverberation and therefore enhance the echo-to-reverberation ratio. These ideas have been confirmed under limited circumstances in our shallow-water acoustic experiments. For undersea communications, time reversal provides an opportunity to implement space-time multiplexing in complex environments. Our experiments indicate that vertical aperture provides a capability for implementing multiple input/multiple output (MIMO) communications. We also have demonstrated experimentally that a moving source and/or receiver can communicate by establishing a synthesized horizontal aperture time-reversal mirror.

INTRODUCTION

Over the last 40 years, time-reversal mirrors (TRMs) have been investigated for various applications [1-4]. This is a process that was first demonstrated in nonlinear optics, then in ultrasonic laboratory acoustic experiments, and most recently in ocean acoustics. A TRM takes advantage of reciprocity, a property of wave propagation in a static medium and a consequence of the linear wave equation invariance to time reversal. Therefore, phase conjugation in the frequency domain can be implemented in the time domain by a TRM.

Recently we have conducted a series of time-reversal experiments at a center frequency of 3.5 kHz with a 1 kHz bandwidth. These experiments and follow-up analysis suggest potential applications to active sonar and underwater communications. In the area of active sonar, a TRM focuses acoustic energy on a target enhancing the target echo while minimizing the reverberation from the boundaries below and above the focus, thereby resulting in echo-to-reverberation enhancement. These ideas have been confirmed under limited circumstances in our shallow-water acoustic experiments including active reverberation nulling [5-6].

For undersea communications, time-reversal provides an opportunity to implement space-time multiplexing in complex environments [7]. A recent time reversal experiment demonstrated that multiple foci can be projected from an array of sources to the same range but at different depths [8]. This Multiple Input/Multiple Output (MIMO) process potentially can improve the information data rate. We have also experimentally demonstrated that a moving source and/or receiver can communicate by establishing a synthetic, horizontal aperture, time-reversal mirror.

TRM AND ACTIVE SONAR

For active sonars, reverberation is defined as that portion of the received signal which is scattered by rough ocean boundaries or by volume inhomogeneities. Experiments have shown that when the focus is placed in the middle of water column, there is very little energy projected on the boundaries below and above the focus at the focal range (typically 20 dB down from the focal region). Hence, an echo return from a TRM focus will have a minimal reverberation at the echo range cell, resulting in an echo-to-reverberation enhancement.

Figure 1(a) shows the experimental configuration for reverberation measurements [5]. Figure 1(b) and (c) show the time-reversal (TR) focusing and the broadside (BS) transmission measured by the Vertical Receive Array (VRA). Broadside transmission is an excitation of the Source/Receive array (SRA) with equal amplitudes. Note that an enhancement in the ensonification level at the probe source (PS) location (60 m) by TR is approximately 5 dB as compared to the BS transmission which fills the water column.

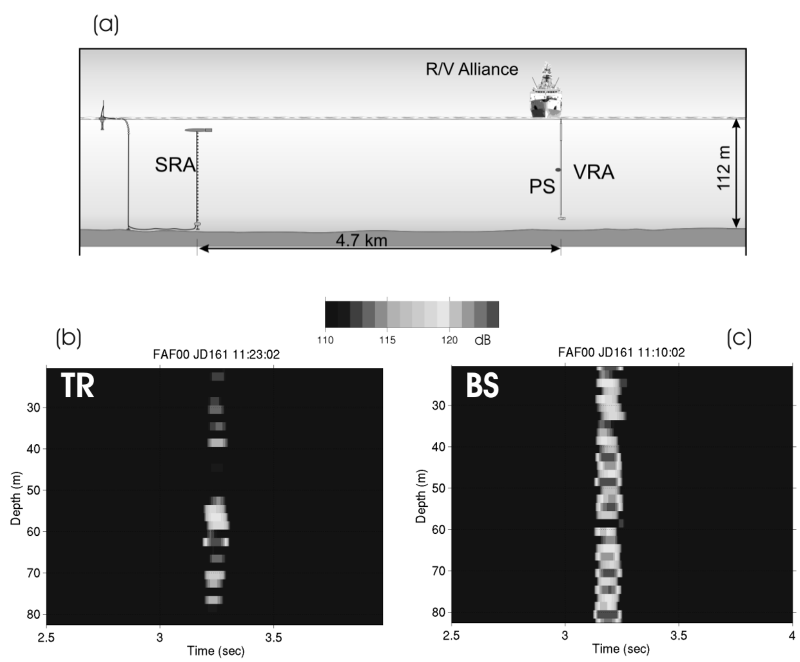


FIGURE 1. (a) Experimental configuration for reverberation measurements carried out north of Elba Island off the west coast of Italy. The PS was deployed from the R/V Alliance at 60 m depth and 4.7 km range away from the SRA. The PS pulse was a 100-ms long pulse at 3.75 kHz. (b) TR focusing recorded by the VRA near the PS. For comparison purposes, (c) shows a BS transmission received by the VRA which fills the water column.

The returning backscatter from these transmissions was recorded monostatically by the SRA. Figure 2 shows the measured reverberation fields: (a) BS and (b) TR transmission. The ambient noise level is also shown in (c) as a reference. The existence of a reverberation notch approximately 400-m wide and about 3 dB is evident. Note that the BS level is about 5 dB higher than that of TR due to the difference in transmitted level.

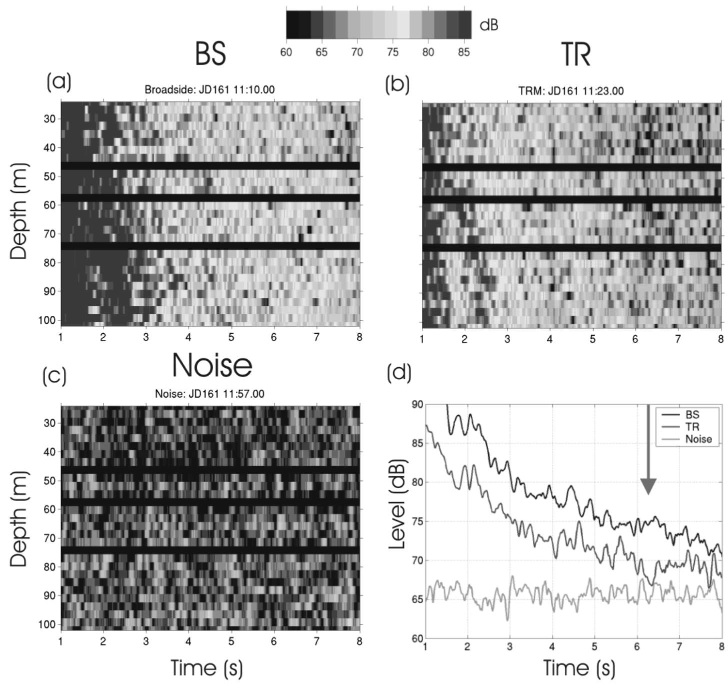


FIGURE 2. Measured backscattered field at the SRA: (a) BS transmission and (b) TR transmission. The ambient noise field is also displayed in (c) as a reference. (d) shows the corresponding reverberation level incoherently averaged across the upper SRA elements along with ambient noise level. The TR reverberation indicates about a 3 dB notch around 6.3 sec corresponding to the PS range of 4.7 km.

REVERBERATION NULLING

Backscattering from the rough water-bottom interface can serve as a surrogate probe source (PS) in time reversal. A time-gated portion of the reverberation then is refocused to the bottom interface at the corresponding range [9]. Here, reverberation nulling is investigated to enhance active target detection. The basic idea is to minimize the acoustic energy incident on the corresponding scattering interface by applying an excitation weight vector on the time-reversal mirror which is in the complementary subspace orthogonal to the focusing vector [6].

Figure 3 shows the reverberation nulling experiment at 3.5 kHz conducted in April 2003 near the Elba Island, Italy. The SRA was deployed in 105-meter water near Elba Island. Initially, we generated reverberation time series from 100-ms CW broadside transmission of the SRA (before). Due to the proximity of the SRA to the Island, the two prominent peaks around 4.25 km and 5.85 km result from the interaction with the

Island corresponding to the concentric circles denoted in the upper left panel. The peak at 2.5 km, however, is due to a seamount at the corresponding range which is visible in the bottom topography (small circle). Thus the peak at 2.5 km range provides a good candidate for reverberation nulling. The resulting reverberation nulling (after) is superimposed in the lower left panel, indicating the reduction of reverberation level to the background level by 2 dB. On the other hand, the reverberation return from the interaction with the island has increased at 5.8 km range.

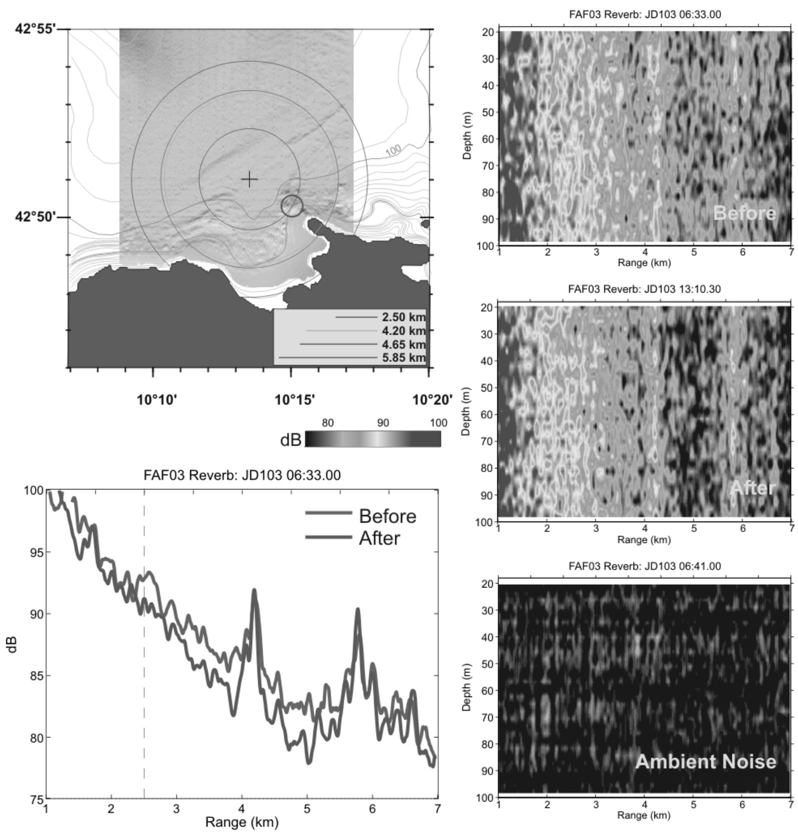


FIGURE 3. Experimental demonstration of reverberation nulling at 3.5 kHz. Note the reduction of reverberation level at the intended 2.5 km range as compared to the original reverberation from a broadside transmission (BT) of the SRA (bottom left). Right column: Reverberation level in time and depth along with ambient noise level.

MULTIPLE-INPUT MULTIPLE-OUTPUT (MIMO)

Time reversal can be implemented between a transmit and receive array without invoking reciprocity. This technique has been used in ultrasonic laboratory experiment, but never at sea. We refer to this approach as the "round robin" technique [8]. The process requires connectivity between the two arrays but does not require a Probe Source (PS) collocated with the receiver array as in a conventional TRM configuration as shown in Figure 1.

The procedure is illustrated in Fig. 4 in which a pulse is separately sent out from each SRA transducer and received on the VRA at a specific depth. This information is transferred to the SRA, and each respective pulse is synchronized, time reversed and sent out from the SRA simultaneously. Since the round robin procedure involved receiving all depths simultaneously on the VRA, the time reverse sequence for focusing at each depth is captured almost simultaneously.

Multiple time reversal focal spots then can be achieved simultaneously in the water column. Figure 5(a) shows the time-reversed focused field sequentially at every element of the VRA and (b) shows an example of simultaneous multiple focal spots at six different depths.

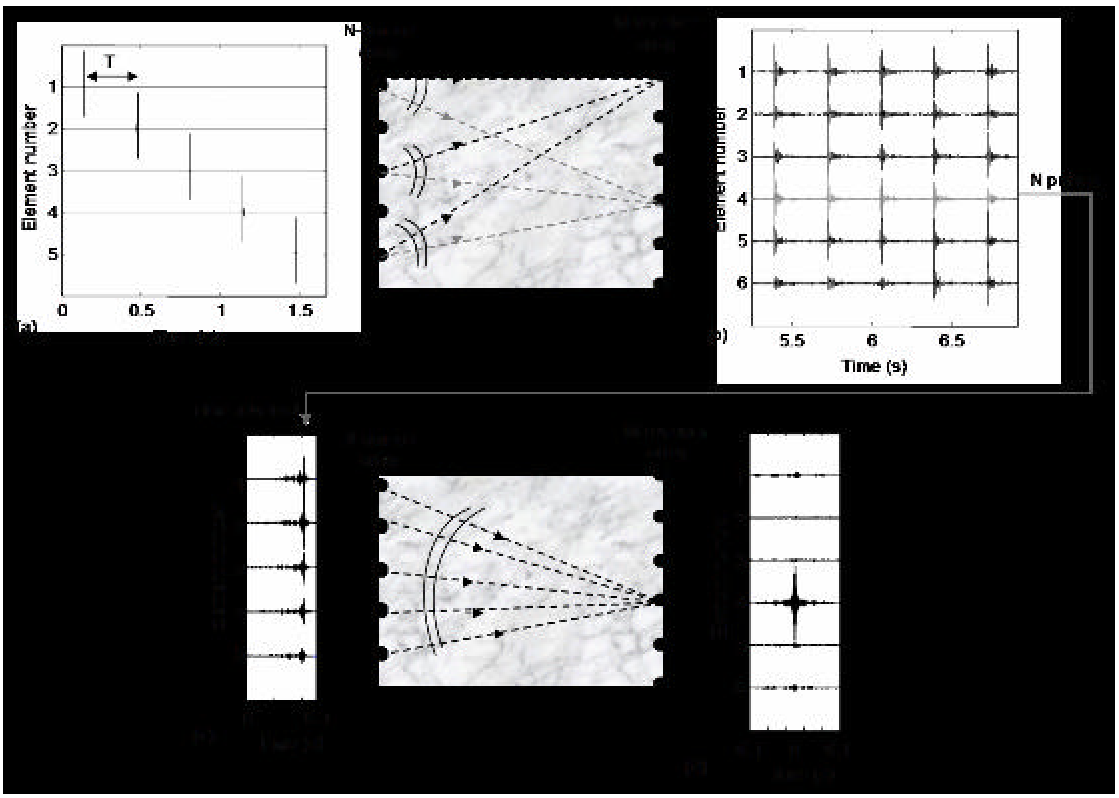
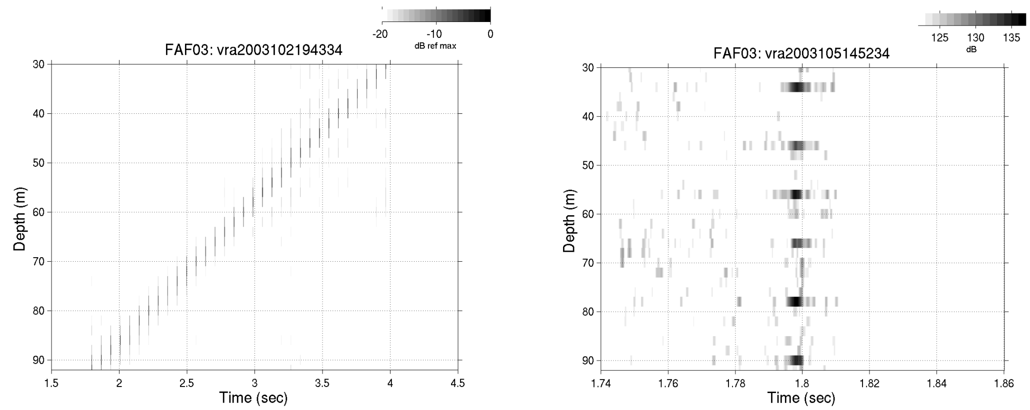


FIGURE 4. Schematic of a round-robin time-reversal implementation. A pulse is separately sent out from each SRA transducer and received on the VRA at a specific depth (e.g., element #4). This information is transferred to the SRA (lower plot), and each respective pulse is synchronized, time reversed and sent out from the SRA simultaneously.

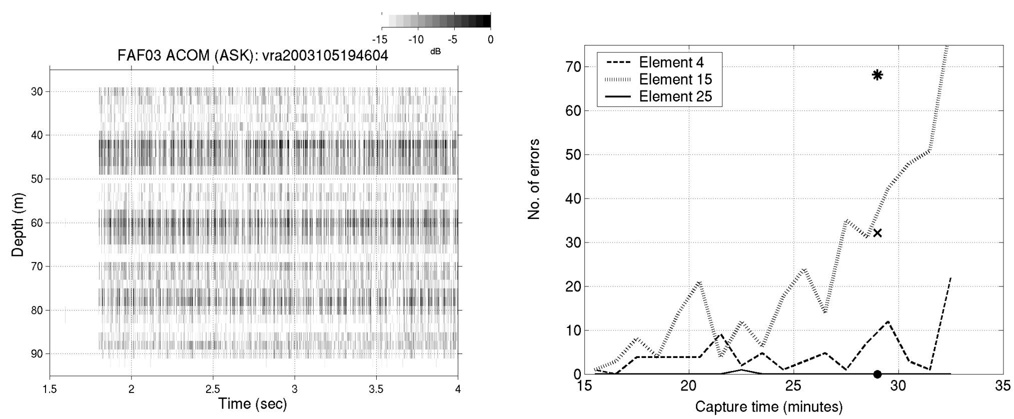
UNDERWATER COMMUNICATIONS

With the at-sea, multiple-focal-spot demonstration with a TRM, spatial encoding of communication sequences is feasible. Here we demonstrate that different communication sequences can be simultaneously sent to and decoded at individual receivers on a vertical array using a simple binary Amplitude Shift Keying (ASK) modulation scheme. Although inefficient, the incoherent ASK modulation allows for initial feasibility study of MIMO communications.



(a) (b)

FIGURE 5. (a) Sequential focusing at every element of the VRA. (b) Simultaneous multiple focal spots at six depths.



(a) (b)

FIGURE 6. (a) The first 2 sec of measured binary ASK data to the three depths of VRA (42 m, 60 m and 78 m). (b) BER out of 4,900 bits as a function of time at three different focal depths using an incoherent binary ASK modulation. The results are from simulated ASK sequences based on 40-minute round-robin channel response data and decoded using passive time reversal. The dots denote the BER of active time reversal ASK communication data.

Figure 6(b) shows the Bit Error Rates (BER) for 4,900 bits transferred at three different depths as a function of time. These results are from simulated binary ASK sequences based on 40-minute round-robin channel response data and decoded using passive phase conjugation [10]. In comparison, the three dots at minute 29 denote the BER of active time reversal communication data. Simultaneous, multiple-depth, coherent communications currently are being investigated.

SYNTHETIC HORIZONTAL APERTURE TRM

An ultrasonic, synthetic aperture, endfire array has been constructed in our ultrasonic laboratory to study its time-reversal properties. The minimal hardware configuration of a synthetic endfire time-reversal array using only one transmitter and one receiver makes communications a viable application. In a recent TRM experiment, we investigated the synthetic aperture time-reversal communications.

The configuration is shown in Fig. 7. A 10-sec communication sequence is transmitted from the ITC towed source every 30 seconds at a 2-knot tow speed (1 m/s). The communication sequence consists of binary ASK coding with a 1-ms preamble and 199-ms spacing for synchronization and Doppler compensation processing. The bit length is 1 ms so each sequence contains about 9800 bits. Figure 7(a) displays the impulse response due to a single bit and (b) shows the reception from communication sequences convolved with the time reversed version of the impulse response. By combining the transmissions to produce a synthetic aperture array, the BER was drastically reduced. For a single transmission, the error was 3915/9800; for 14 contiguous transmissions (each 30 sec apart), the bit error was 114/9800; for 14 sparsely-spaced transmissions (each 150 sec apart), the error was 1/9800; for all 66 transmissions, the error was 0/9800.

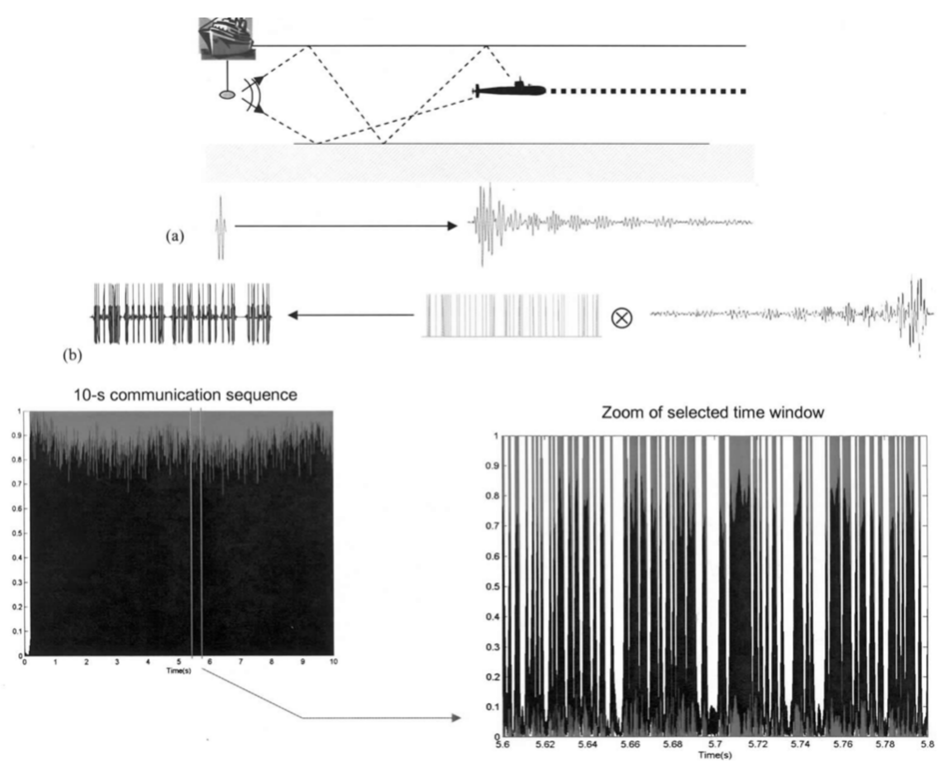


FIGURE 7. Synthetic, horizontal aperture communications. (a) Channel response due to a single bit. (b) Communication sequences convolved with a time-reversed version of the channel response. The bottom plots show decoded sequences after synchronization and Doppler compensation processing.

CONCLUSIONS

Recently a series of ocean acoustic experiments have been carried out confirming the robustness and potential utility of time reversal mirrors in underwater acoustics with applications in active sonar and undersea communications. In the area of active sonar, the echo-to-reverberation enhancement and reverberation nulling have been demonstrated using a time-reversal mirror in the 3-4 kHz band in shallow water.

For undersea communications, time reversal provides an opportunity to implement space-time multiplexing in complex environments. We demonstrated experimentally that multiple foci can be projected from an array of sources to the same range but at different depths. This MIMO process potentially can improve the information data rate. We also have demonstrated experimentally that a moving source and/or receiver can communicate by establishing a synthetic, horizontal aperture, time-reversal mirror.

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