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ECHO-TO-REVERBERATION ENHANCEMENT USING A TIME REVERSAL MIRROR

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Reverberation from rough ocean boundaries often degrades the performance of active sonar systems in the ocean. The focusing capability of the time-reversal method provides a new approach to this problem. A time reversal mirror (TRM) focuses acoustic energy on a target enhancing the target echo while shadowing the boundaries below and above the focus in a waveguide, thereby reducing reverberation. The resulting echo-to-reverberation enhancement has been demonstrated experimentally using a time reversal in the 3-4 kHz band in shallow water.

1. INTRODUCTION

A time reversal mirror (TRM) retransmits a received signal in time-reversed order (backpropagation) resulting in a focus at the origin of the signal [1]. Focusing can be achieved effectively with a vertical source/receiver array (SRA) in a waveguide, where most acoustic energy is confined within the waveguide by reflection from the boundaries and refraction from the inhomogeneous sound-speed environment. In a range-independent environment, a vertical SRA generates an azimuthally symmetric focal structure.

The focusing capability of a TRM suggests potential applications to the active detection problem in the ocean where backscattering from rough ocean boundaries often masks a weak target echo and degrades detection performance. In a waveguide, a TRM can generate a focused acoustic field at the origin of a probe source and, as we demonstrate, less energy at the rough ocean boundaries below and above the focus which is referred to as shadowing in this paper. This property can be used to enhance the echo-to-reverberation ratio in the returning backscattered field, resulting in improved detection performance.

In this paper, we first use numerical simulations to demonstrate time-reversal focusing and shadowing and the resulting reduced reverberation. Then we present experimental results obtained in shallow water north of Elba Island, Italy, demonstrating the echo-to-reverberation enhancement.

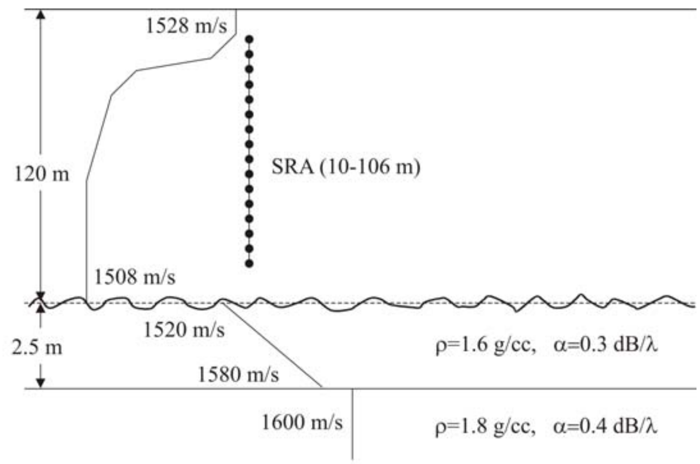

Fig. 1. Ocean environmental model used for backscattered field simulations. The bottom roughness has 0.1 m rms height and 15 m correlation length with a Goff-Jordan spectrum.

2. NUMERICAL SIMULATIONS

We consider an environment similar to that of the experimental results that will be discussed in the next section. To calculate the reverberation from a rough interface in a waveguide, a normal mode scattering model based on the perturbation method [2] is implemented for realistic shallow water environments.

2.1. Environmental Model

Figure 1 shows the waveguide environmental model used for backscattered field simulations. The SRA consists of 33 elements spanning the water column from 10 to 106 m with 3 m inter-element spacing in the 120 m deep water. The sound-speed profile indicates a typical downward refracting environment with the thermocline spanning 20-50 m depth resulting in substantial interaction with the ocean bottom. The ocean-sediment interface has a roughness of 0.1 m rms and 15 m correlation length generated using a power law spectrum. We use a 100-ms Gaussian shaped pulse with a center frequency of 3.5 kHz. The vector time series transmitted by the SRA is normalized such that the maximum value across all the elements and time is equal to the maximum element source level of 174 dB re 1 μPa used during the experiment. This results in approximately 8 dB less energy being transmitted by the SRA for the time-reversal (TR) transmission compared to the conventional broadside (BS) transmission.

2.2. Reverberation Calculation

Here we simulate the reverberation reduction using a time reversal. First, consider non-TRM reverberation from a broadside (BS) SRA transmission. BS is an excitation of the SRA with equal amplitudes. Figure 2(a) shows one-way BS transmission loss in rang and depth at 3.5 kHz. On the other hand, (b) shows two-way TR focusing when the PS is at a 4.7 km range and 60 m depth. Note the triangle-shaped shadow zones formed above and below the focus.

Fig.2(c) and (d) are vertical slices of (a) and (b), respectively, at the PS range, displaying the energy distribution across the depth. The TR field in the shadow of (d) is lower than that of the focus by 15-20 dB, consistent with the experimental results.

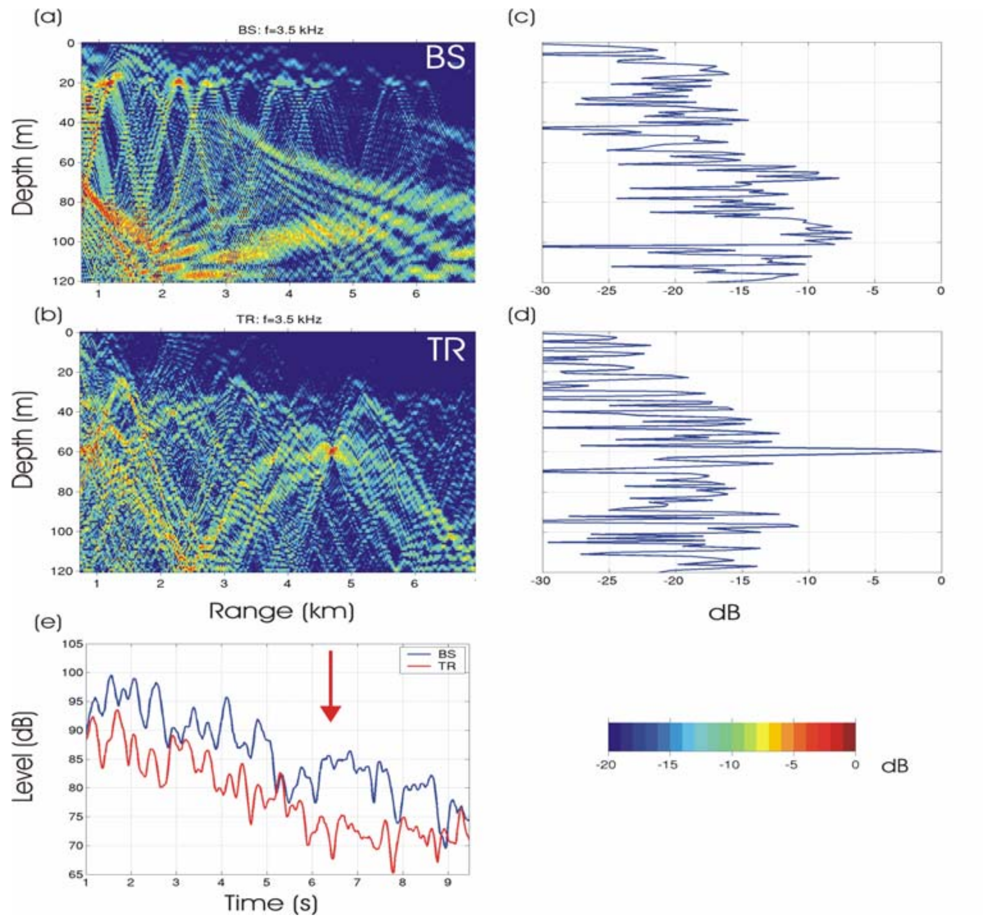

Fig. 2. Normalized transmission loss at the center frequency of 3.5 kHz: (a) BS and (b) TR focusing with a PS at 4.7 km range and 60 m depth. (c) and (d) are vertical slices of (a) and (d) at the PS range of 4.7 km. The curves in (e) show the reverberation level using a 100 ms Gaussian pulse. The TR reverberation (red) shows about a 5 dB reverberation notch around 6.4 sec, corresponding to the PS range. Note that the overall level of BS is 5-10 dB higher than the TR due to the normalization at the SRA.

Figure 2(e) shows calculated reverberation levels for both BS and TR transmission. The reverberation field is averaged incoherently across the SRA elements. Two important observations can be made. First, the overall level of BS (blue) is higher than the TR level (red) due to the normalization. Second, the TR retransmission produces about a 5 dB reverberation notch around 6.4 sec corresponding to the PS range of 4.7 km.

The inherent assumption in our numerical modelling of bottom reverberation is that both the environment and interface roughness is axisymmetric so that there is no out-of-plane scattering. In addition, we neglect volume scattering and ocean surface scattering. These assumptions certainly are unrealistic in general and we do not attempt to do direct model/data comparisons in this paper. Therefore, the absolute levels are not intended to be comparable. However, the experimental results below confirm the existence of the notch.

3. EXPERIMENTAL RESULTS

3.1. Reverberation Reduction

A time-reversal experiment was performed May/June 2000 north of Elba off the west coast of Italy as shows in Fig. 3(a). The SRA had 29 transducers spanning a 78 m aperture with a center frequency of 3.5 kHz and 1 kHz bandwidth. During this part of the experiment, the SRA was operated at 3.75 kHz to avoid some unexpected self-noise around 3.5 kHz. We also deployed a 32 element vertical receiver array (VRA) to measure bistatic reverberation as well as to monitor the time reversal focus [3].

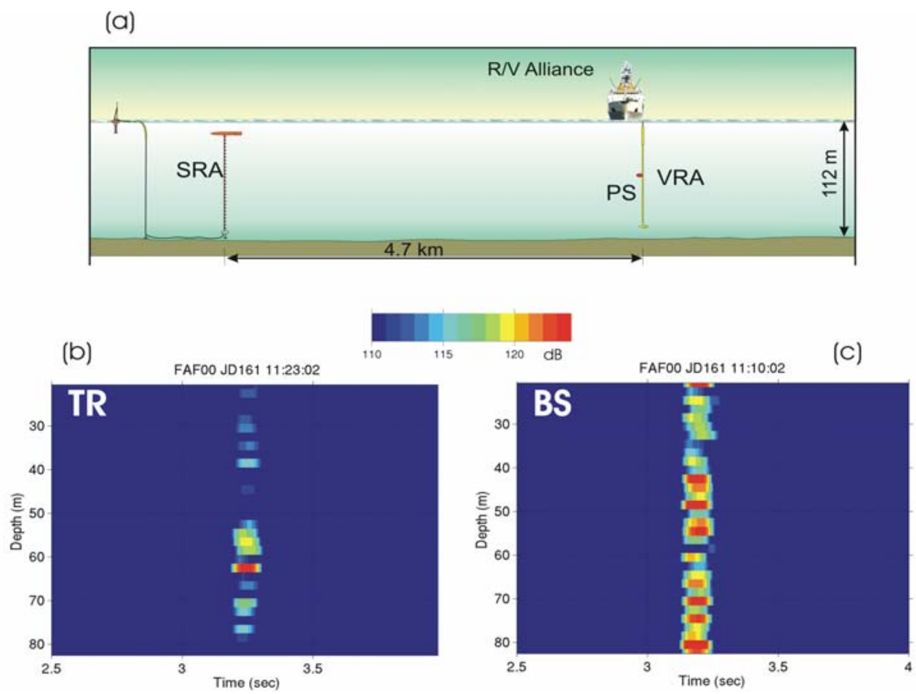

Fig. 3. Experimental configuration for reverberation measurements. The PS was deployed from the R/V Alliance at 60 m depth and 4.7 km range. The pulse was a 100 ms pure tone at 3.75 kHz. (b) TR focusing recorded by the VRA near the PS. For comparison purposes, (c) shows a BS transmission which fills the water column.

The experimental configuration for reverberation measurement is shown in Fig. 3(a). Fig. 3(b) and (c) show the TR focusing and BS transmission measured by the VRA, respectively. The sharp focus in (b) occurs at an apparent depth of 63 m (although the PS depth was 60 m, the difference may be due to a slight tilting of the VRA). The intensity decreases rapidly moving away from the focal depth. In contrast, the BS shows the acoustic field spreading over the water column.

Figure 4 shows the measured backscattered field: (a) BS and (b) TR transmission. Fig. 4(b) indicates that a lower level appears between 6 and 6.5 sec in the upper channel elements (8-29). The existence of the reverberation notch approximately 400 ms wide (red arrow) and about 3 dB is evident. Note also that the BS level (blue) is about 5 dB higher than that of the TR transmission.

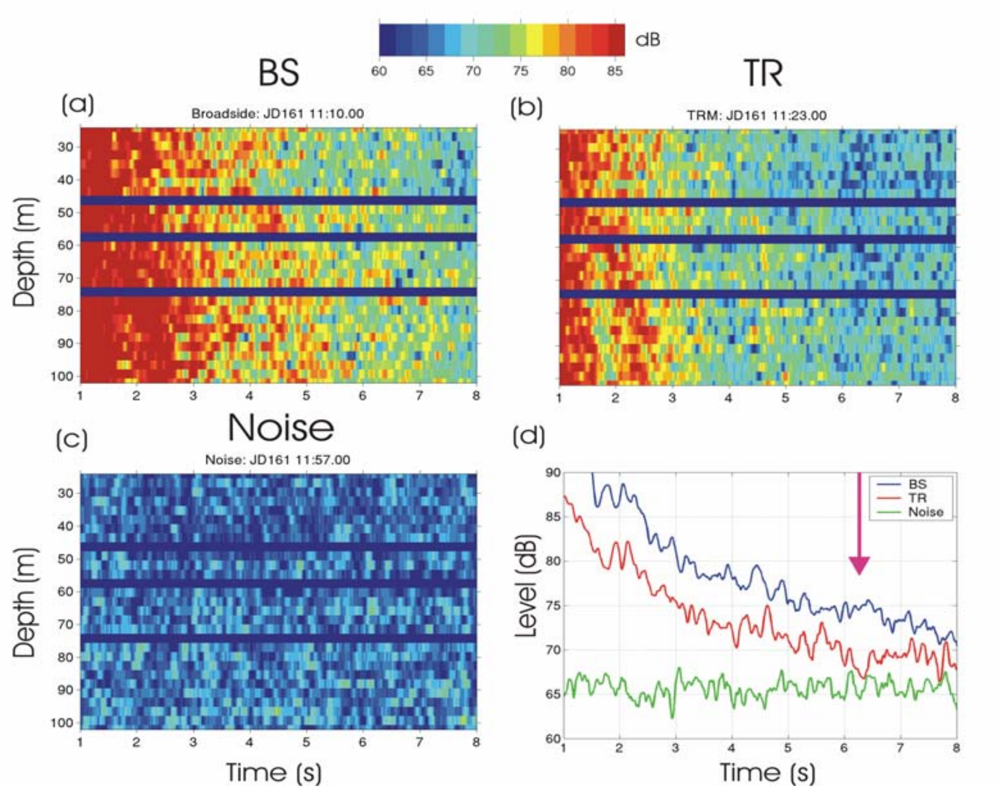

Fig. 4. Measured backscattered field at the SRA: (a) BS transmission and (b) TR transmission. The ambient noise field is also displayed in (c) as a reference. Plot (d) shows the corresponding reverberation level incoherently averaged across the upper (8-29) SRA elements: BS (blue), TR (red), and noise (Green). The TR indicates about a 3 dB notch around 6.3 sec corresponding to the PS range of 4.7 km.

3.2. Echo Enhancement

So far, we confirmed reduced reverberation using time-reversal process. The measurement in Fig. 3 also showed an increased level of ensonification at the PS (by approximately 5 dB) for the TR transmission over that of the BS transmission. Here we present experimental result including an artificial target showing improved target detectability with the time-reversal method.

Figure 5 shows the schematic for a bistatic scattering experiment. Figure 6 shows the results of the BS and TR transmission. The broad area around 4.2 s is the direct arrival from the SRA to the VRA. After this, the BS still produces high reverberation up to 4.8 s while the TR shows a relatively low level background level during the same time. An echo is visible around 4.52 sec in the TR (b), which is the expected time of the target arrival corresponding to a range of 6.84 km.

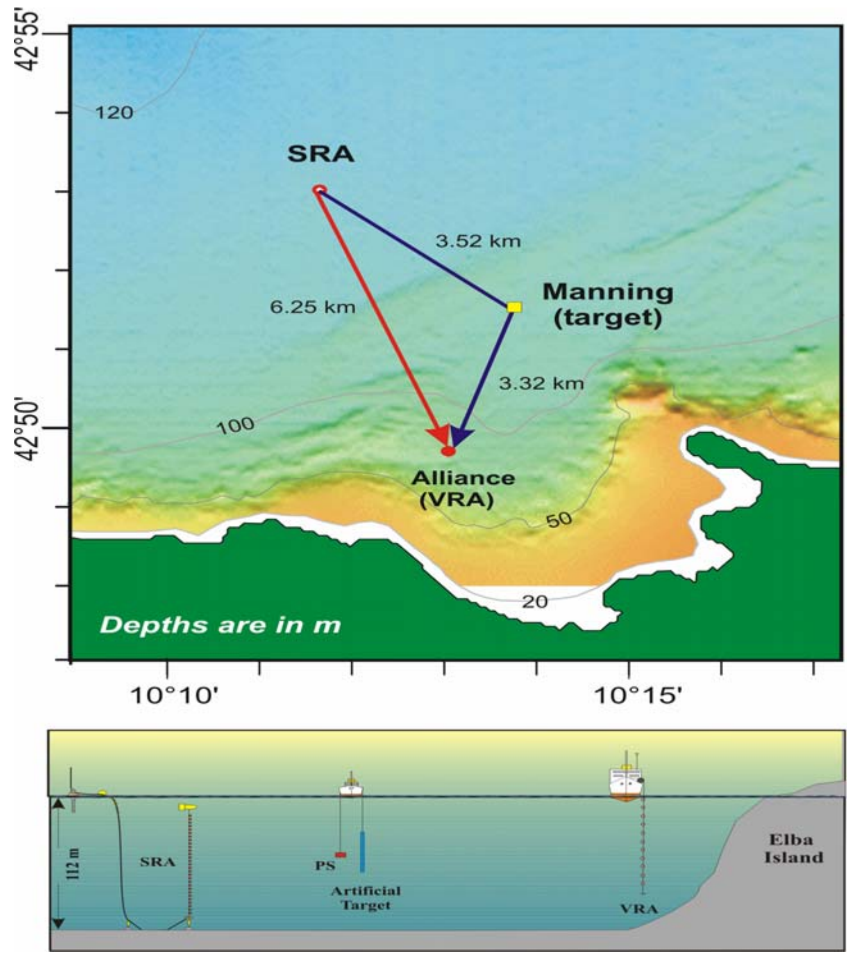

Fig. 5. Schematic for a bi-static scattering experiment. An air-filled tube simulating a target and a PS were deployed from the R/V Manning. The transmissions were monitored bistatically by the VRA deployed from the R/V Alliance.

4. CONCLUSIONS

Echo-to-reverberation enhancement using time reversal was demonstrated experimentally using monostatic and bistatic configurations in the 3-4 kHz bandwidth in a mildly range-dependent shallow water environment. The monostatic experiment showed a reverberation notch of about 3 dB depth at the PS range with a time-reversal transmission. This was in addition to an overall reverberation reduction of approximately 5 dB and an enhancement in the ensonification level at the PS location of approximately 5 dB. These experimental results are consistent qualitatively with numerical simulation results. The bistatic experiment with an artificial target also verified improved target detectability using the time-reversal method.

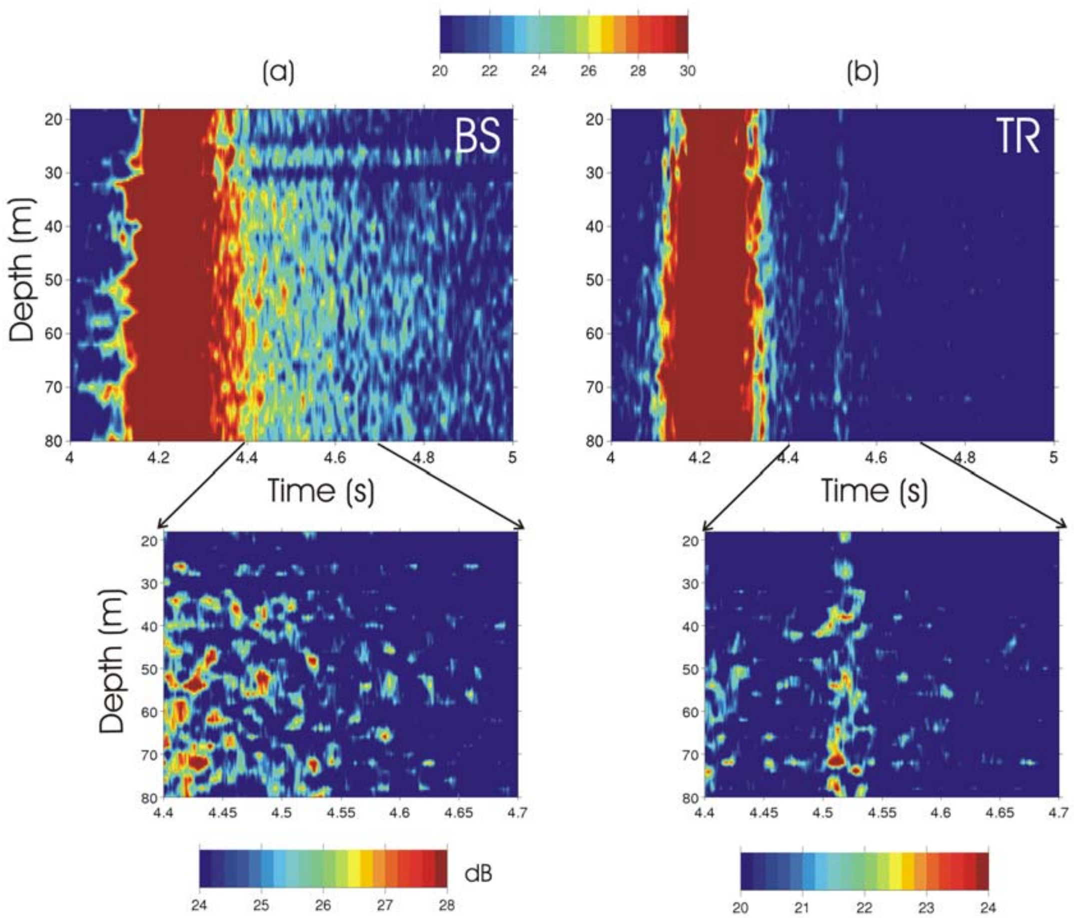

Fig. 6. Bistatic scattering measurements by the VRA: (a) BS and (b) TR. A signal presumed to be the target echo is visible at the expected time (4.52 s) with the TR transmission after the direct arrival (4.2 s).

5. ACKNOWLEDGEMENTS

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