OCEAN ACOUSTIC TIME-REVERSAL MIRROR

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Two ocean acoustics experiments demonstrating the implementation of a time reversal mirror have been conducted. Pulsed sound (50-ms with center frequency 445 Hz) was refocused to the position of a probe source out to ranges as great as 30 km in 125-m deep water. In addition, a technique to refocus at ranges other than that of the probe source also was demonstrated. These results are summarized along with examples illustrating the temporal stability of the focused field. Finally, theoretical considerations are discussed for a time reversal mirror operating at an order of magnitude higher frequency.

1. INTRODUCTION

Two recent experiments [1,2] demonstrated the implementation of an acoustic time-reversal mirror (TRM) in the ocean. A TRM [3], also referred to as the process of phase conjugation, focuses sound from a source-receive array (SRA) back to the probe source (PS) which ensonified the SRA. The SRA receives the probe source pulse field, time-reverses it and then uses the time-reversed data as the excitation of an array of sources which are collocated with the receiving hydrophones. If the ocean environment does not changes significantly during the two-way travel time, the phase conjugate field will refocus regardless of the complexity of the medium with the caveat that excessive loss in the system degrades the process. The focus is both spatial and temporal, undoing the multipath from the first part of the transmission. Since this process offers an approach to compensate for multipath interference and other distortion through a complex medium, it may be applicable to various adaptive sonar and communication concepts.

This paper describes the results from the two phase conjugation experiments. Theoretical considerations also are discussed for a time-reversal mirror operating at an order of magnitude higher frequency.

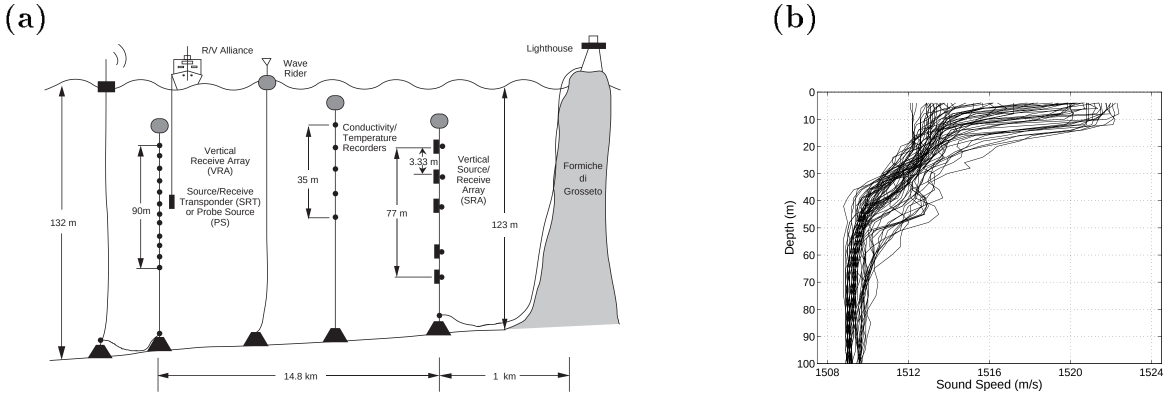

Figure 1: (a) Experimental setup of phase conjugation experiment. (b) Sound speed profiles derived from CTD's for the period of May 11-24, 1997.

2. TRM EXPERIMENTS IN THE OCEAN

The TRM experiments were performed off the west coast of Italy in April 1996 [1] and May 1997 [2]. Fig. 1(a) is a schematic of the experiments and indicates the type of measurements that were made. Fig. 1(b) is a collection of the sound speed profiles obtained from CTD as an indication of variability over the duration of the May 1997 experiment. The TRM was implemented by a 77 m source-receive array (SRA) in 123-m deep water which was hardwired to the Isola di Formica di Grosseto. The SRA consisted of 24 hydrophones with 24 collocated sources with resonance frequency of 445 Hz. The received signals were digitized, time reversed and retransmitted. A probe source (PS) was deployed from the NATO research vessel ALLIANCE. The ALLIANCE also deployed a 48 element vertical receive array (VRA) spanning 90 m. The VRA radio telemetered all individual element data back to the ALLIANCE. For the runs in which we simultaneously varied the range of PS and the VRA in May 1997, the VRA was suspended from the ALLIANCE to ensure its being very close to the probe source.

3. LONG RANGE TRM

The April 1996 experiment first demonstrated that a time reversal mirror (or phase conjugate array) can be implemented to spatially and temporally refocus an incident acoustic field back to its origin at a range of 6.3 km [1]. The May 1997 experiment extended the results of the earlier experiment [2]. New results included: 1) extending the range of focus from the earlier result of 6 km out to 30 km, 2) verifying a new technique to refocus at ranges other than that of the probe source [4], and 3) demonstrating that probe pulse pulses up to one week old can be refocused successfully.

Fig. 2 shows the results for PS at 81 m depth for three different ranges from the SRA: 4.5 km, 15 km and 30 km. As expected, the temporal focus remains compact while the spatial focus broadens with range due to mode stripping.

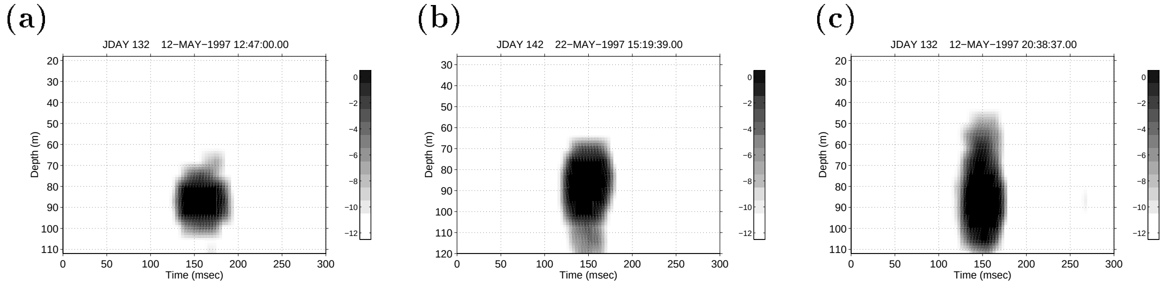

Figure 2: Experimental results for 50-ms, 445 Hz center frequency probe source (PS) at 81 m depth and various ranges, R, between the PS and SRA. (a) R =4.5 km. (b) R=15 km. (c) $R = 30$ km. Both the VRA and PS were suspended from the ALLIANCE except (b) which was from a RF-telemetered VRA at 15 km range. Note the slightly different y-axis of (b).

4. TRM WITH VARIABLE RANGE FOCUSING

Fig. 3 displays results which experimentally confirm a technique to change the range of focus of a TRM based on the frequency-range invariant property in a waveguide [4]. The technique involves retransmitting the data at a shifted frequency according to the desired change in focal range, such that

$$(\Delta\omega/\omega) = \beta\,(\Delta R/R)\,. \tag{1}$$

The invariant β determined by the properties of the medium is approximately equal to 1 in a shallow water acoustic waveguide. The frequency shift can be implemented easily in near real-time by a FFT bin shift prior to retransmission. Fig. 3(a) shows the out-of-focus results for the PS at a depth of 82 m when the VRA was 700 m outbound of the probe source. A +30 Hz frequency shift brought the focus back as shown in Fig. 3(b).

The theory on which this shift is dependent is valid only over the frequency range in which the mode shapes do not change significantly. Frequency shifts of greater than about 10 % violate this condition. A practical limitation also comes from the transducer

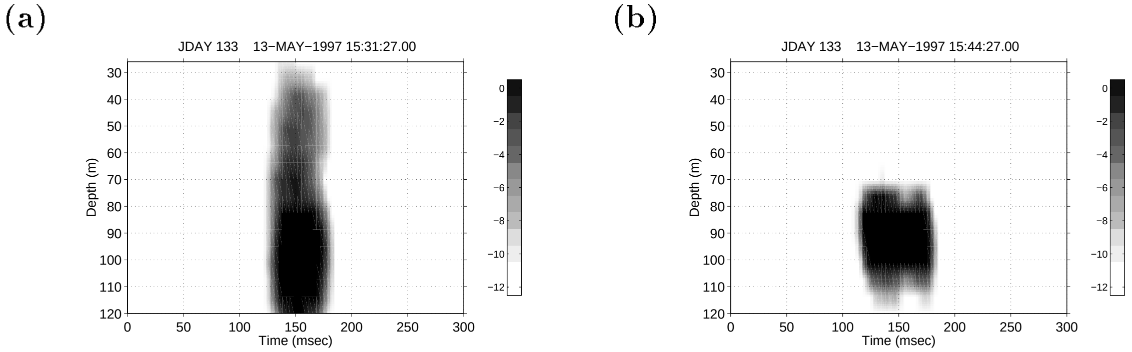

Figure 3: Experimental results for the PS at a depth of 82 m. (a) Out-of-focus results on the VRA when the VRA is 700 m outbound of the PS. (b) Same as (a) except a +30 Hz frequency shift has been applied to the data at the SRA prior to retransmission. Note that the focus is brought back on the VRA.

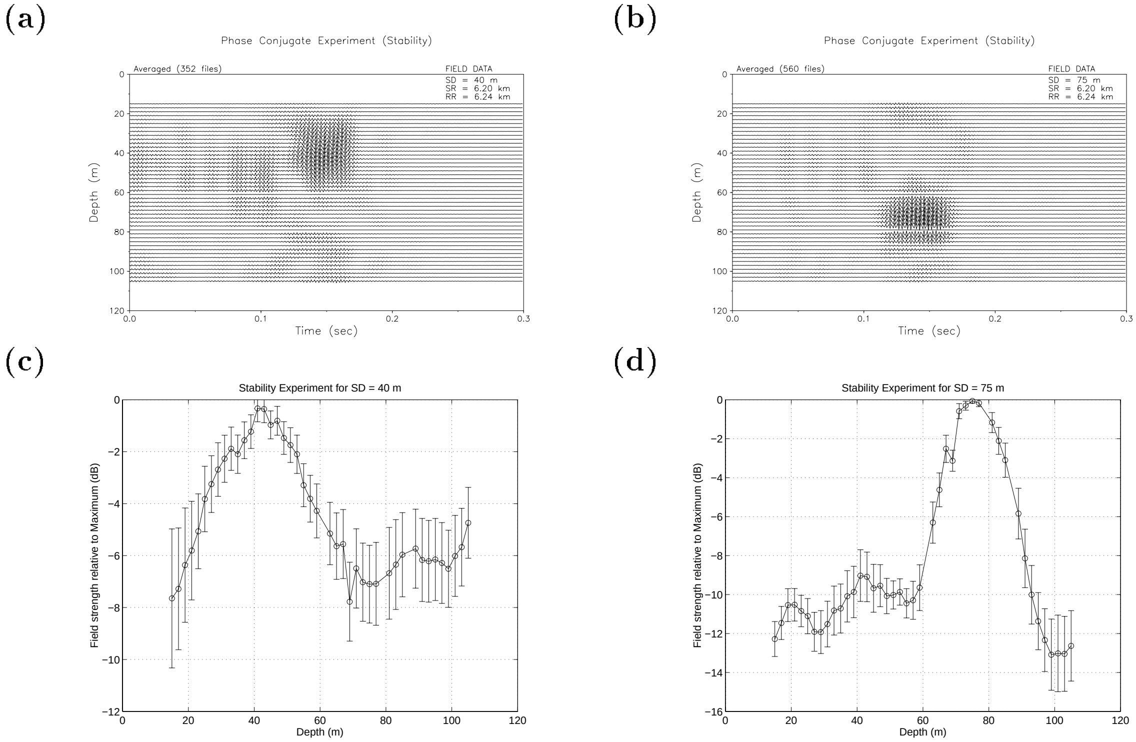

Figure 4: Resutls on stability of the focal region. (a) Pulse arrival structure at VRA for probe source at 40-m depth averaged over 1 h. (b) Pulse arrival structure at VRA for probe source at 75-m depth averaged over 2 h. (c) Mean and standard deviation of energy in a 0.3-s window for 40-m probe source. (d) Mean and standard deviation of energy in a 0.3-s window for 75-m probe source.

characteristics of the SRA whose 3 dB bandwidth is approximately 35 Hz centered at 445 Hz. Therefore, it is difficult to excite the transducer at a frequency more than 10 % offset from the original carrier frequency.

5. TRM WITH LONG TIME MEMORY

For a time independent medium, one could use stored probe pulses to focus on specific locations. However, the temporal variability of the ocean is expected to limit such a procedure. In the April 1996 experiment we found the medium stable for at least three hours (the duration of this portion of the experiment was limited). Over this period, a single probe pulse could be used to provide a stable focus as shown in Fig. 4. These plots indicate that the focus was considerably more stable for the deep probe source versus the shallower probe source and that the focus is broader for the shallower probe source.

In the May 1997 experiment we found that probe pulses up to one week old (limited by duration of the experiment) still produced a significant focus at the original probe source location. Fig. 5(a) shows the original data received on the VRA. Fig. 5(b) and (c) show the result on the VRA one day and one week later, respectively. The biggest environmental change that occurred during this experiment was a gradual warming of

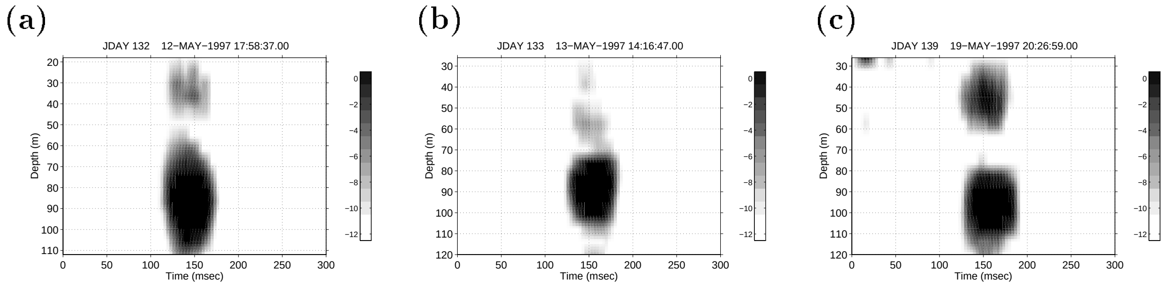

Figure 5: Experimental results illustrating the retransmission of old pings. (a) The original data received on the VRA when the PS and VRA were at the same range of 15.2 km and the PS was at a depth of 81 m. (b) The results on the VRA one day later. The VRA was 400 m inbound of the PS. (c) The results on the VRA one week later. The VRA was 300 m inbound of the PS and a −16 Hz frequency shift has been applied prior to retransmission. Note the slightly different y-axis of (a).

the surface layer resulting in an increase in sound speed near the surface as shown in Fig. 1(b). Therefore, the results from a deeper source will be less sensitive to the environmental variation over the period than those from a shallow source. It is surprising that a one-day old ping apparently shows better focusing as seen in Fig. 5(b). Though the focus is degraded significantly after a week with a sidelobe in the upper water column, the TRM clearly retains a memory. These results suggest that the repetition rate required to retain a stable focus may be less than originally suspected.

6. HIGH FREQUENCY TRM

In this section, we briefly discuss theoretical considerations for a time-reversal mirror operating at an order of magnitude higher frequency (*e.g.*, 3.5 kHz) for possible applications to adaptive sonar and communication problems. The major issue is spatial sampling—both array aperture and element spacing. In our TRM experiments, we used a 24-element SRA spaced 3.33 m (approximately λ at the frequency 445 Hz) spanning 77 m of a 123-m water column. If the same number of SRA elements is used with element spacing λ (0.4 m) at 3.5 kHz, then the SRA covers less than one tenth of the water column. In a TRM, however, we need to keep the array aperture as large as possible without spatial aliasing. Fig. 6(a) shows a simulation for a 2-ms Hanning windowed probe source pulse with center frequency 3.5 kHz as received at the SRA for the same geometry used in Fig. 1(a) with 24 elements spaced 3.3 m (corresponding to about 8 times λ at 3.5 kHz). Fig. 6(b) shows the pulse as transmitted back to the plane at a range of 5 km, the range of PS. There is a temporal dispersion of about 100 ms on the SRA due to multipath arrivals and significant energy throughout the water column but the time-reversed pulse received at the VRA is compressed (focused) to 2 ms along with small temporal sidelobes on both sides of the original pulse. The simulation results demonstrate good focusing even for these relatively large interelement separations (in terms of λ).

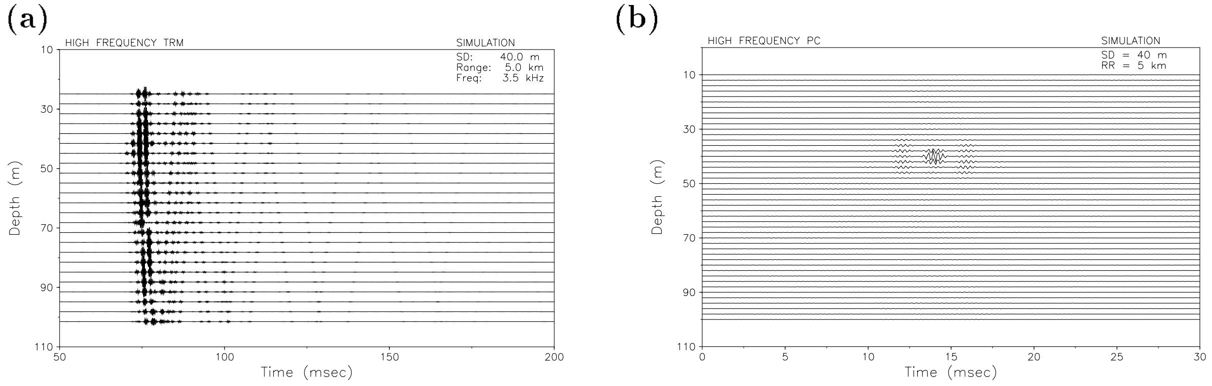

Figure 6: Simulation of a 3.5 kHz, 2-ms transmitted pulse for the geometry in Fig. 1(a) for a probe source located at a depth of 40 m. (a) Pulse received on the SRA at range of 5 km from the PS. There is a temporal dispersion of about 100 ms due to multipath arrivals and significant energy throughout the water column. (b) The focus of the time reversed pulse at the VRA. There is pulse compression back to the original 2-ms pulse duration as well as spatial focusing in depth. Note the small temporal sidelobes on both sides of the original pulse.

7. SUMMARY AND CONCLUSIONS

We have demonstrated that a time-reversal mirror produces a significant focus out to long ranges in a shallow water environment—30 km in a water depth on the order of 125 m. Furthermore, we have confirmed experimentally that the range of focus can be varied up to about 10 % around the nominal focal range. Finally, we have demonstrated that a time-reversal mirror can have substantial memory such that probe source pulses up to one week old could be refocused successfully. [Work supported by ONR.]

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