An Initial Demonstration of Underwater Acoustic Communication Using Time Reversal

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***Abstract*—In July 1999, an at-sea experiment to measure the focus of a 3.5-kHz centered time-reversal mirror (TRM) was conducted in three different environments: an absorptive bottom, a reflective bottom, and a sloping bottom. The experiment included a preliminary exploration of using a TRM to generate binary-phase shift keying communication sequences in each of these environments. Broadside communication transmissions were also made, and single-source communications were simulated using the measured-channel response. A comparison of the results is made and time reversal is shown to be an effective approach for mitigating inter-symbol interference caused by channel multipath.**

***Index Terms*—Communications, phase conjugation, time reversal.**

I. Introduction

A TIME-REVERSAL mirror (TRM) has been implemented in the laboratory [1] and [2] and in the ocean [3]–[6]. The application of time-reversal methods (phase conjugation in the frequency domain) for underwater acoustic communications has already been suggested [2], [5], [7] and some calculations for a 3500-Hz pulse with a kilohertz bandwidth has [8] demonstrated the temporal multipath recombination and sidelobe suppression needed for underwater communications.

Though much progress has been made in ocean acoustic telemetry in the past 30 years, reliable high-speed communications have remained elusive [9]. Adaptive channel equalization has been used in coherent underwater acoustic communication systems to deal with the inter-symbol interference (ISI) caused by time varying dispersive multipath environments [10], [11]. Time reversal is an approach that can be used independently of or in conjunction with adaptive channel equalization. The temporal compression of the time-reversal focus reduces the dispersion caused by the channel. The spatial focus of the TRM mitigates the effects of channel fading. Therefore, the receiver would not need spatial diversity, i.e., an array of receiving sensors. Thus, a TRM could be used in conjunction with a relatively simple receiver consisting of a single-channel adaptive equalizer which would have the benefit of reducing the overall complexity of the receiver structure when compared to that of a multichannel adaptive equalizer. Furthermore, since the time-reversal focus degrades slowly as the ocean changes, adaptive channel equalization could extend the period of reliable communication. Investigating the use of a TRM in conjunction with a single channel adaptive equalizer is a current area of research.

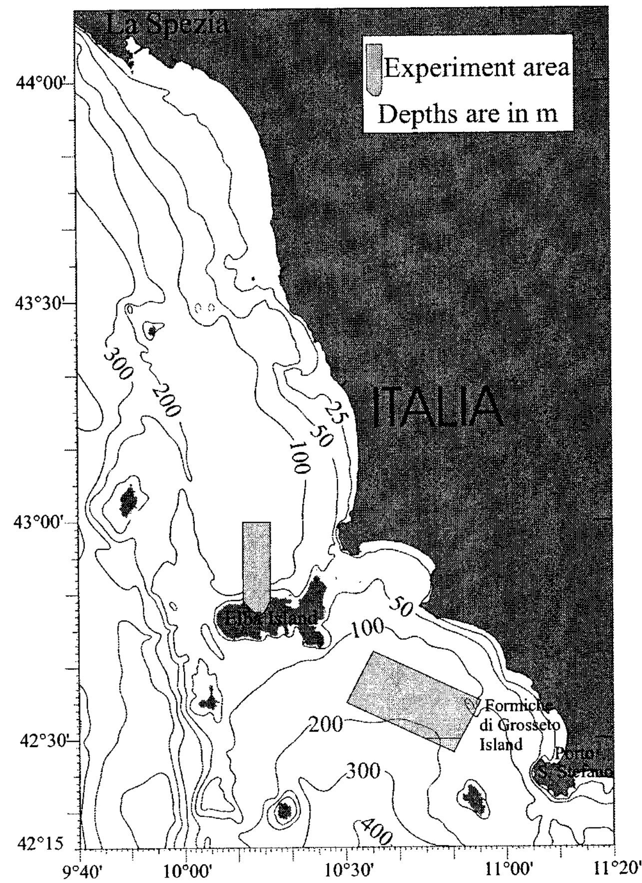

Fig. 1. TRM experiments were performed off the west coast of Italy. The TRM was deployed in 110–130 m deep water from the R/V ALLIANCE and the PS was deployed off the R/V Manning 11 km away. Measurements were made off the northern coast of Elba and near Formiche di Grosseto.

This paper will discuss a July 1999 experiment in which an acoustic source/receiver array transmitted communication sequences to a vertical receiver array (VRA) that was 11 km away. Communication sequences were transmitted in two shallow-water environments ranging from 110 to 130 m water depth. The first was north of Formiche di Grosseto, the second was off the northern coast of Elba as shown in Fig. 1. Using a probe source (PS) frequency of 3500 Hz, a vertical focus of less than 10 m was achieved at the desired focal depths of

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60 and 80 m. Short broadside and time-reversal communication sequences were transmitted in the two environments. Single-source communications were also simulated using experimentally measured channel responses. Time reversal is a two-way communications technique, first measuring the channel response with a PS, and then transmitting the communication sequences. Both single-source and broadside communications are one-way transmission techniques. The time-reversal approach is shown to be an effective approach for ISI due to channel multipath. However, the data are limited and are not sufficient for a statistical bit-error analysis. Single source transmissions were the most prone to the negative effects of dispersion. Section II provides an overview of the theory of time reversal. Section III will discuss the experimental setup, data, and communications results for both range-independent and range-dependent sloping environments. Section IV will contain concluding remarks.

II. Theory of Time Reversal

The theory behind time reversal [7], [12]–[14] has been presented earlier. time reversal can be seen as implementing a matched filter of the impulse response of the waveguide [15]. When a known signal $s(t)$ is transmitted from a source in a waveguide, it is convolved with the impulse response of the waveguide, $h_i(t)$ and the signal $r_i(t) = s(t) * h_i(t)$ is received on the ith element of the TRM, an array of N source/receiver transducers. The TRM receives $r_i(t)$ and retransmits the time reversed version of the signal, $r_i(-t)$. Thus, time reversal implements a linear matched filter yielding the autocorrelation of the impulse response of the waveguide. The signal received back at the original source location, $s_r(t)$, can be written as

$$s_r(t) = \sum_{i=1}^{N} s(-t) * (h_i(-t) * h_i(t)). \tag{1}$$

The strength of the time-reversal focus depends on the number of echoes received and the number of TRM elements N. For illustration purposes, first consider a simplified case where the impulse response is made up of M equal amplitude echoes. Presuming the multipath structure is not periodic, the autocorrelation of this multipath has a peak level that is M times higher than the sidelobes. Combining the autocorrelation functions from all N elements and assuming the sidelobes occur at different times, we have a peak to sidelobe gain of $M * N$. However, in realistic waveguides, later multipaths typically are attenuated heavily and thus contribute little to the total field [16]. In general, longer impulse responses increase the peak to sidelobe ratio but also increase the temporal span of the sidelobes. In the context of applying time reversal to communications systems, this means there will be a trade off between increased peak to sidelobe ratio and increased ISI.

The resolution and sidelobe suppression issues for time reversal are the same as they are for linear broadband matched field processing [17], since match field processing is the computational implementation of time reversal [18]. A simple way to compute resolution is to recognize that a water-column spanning array can produce a vertical focus on the order of the water depth divided by the number of contributing modes. In many environments, the highest modes correspond to the later multipaths arriving in the impulse response. Receiving more multipaths indicates that the higher modes are strongly contributing to the pressure field and a sharp resolution can be achieved [19]. A dense array reduces the sidelobes of the time-reversal focus [20]. As previously mentioned, increasing the number of TRM elements N, increases the number of averages and improves the time-reversal focus. From the modal point of view, a more

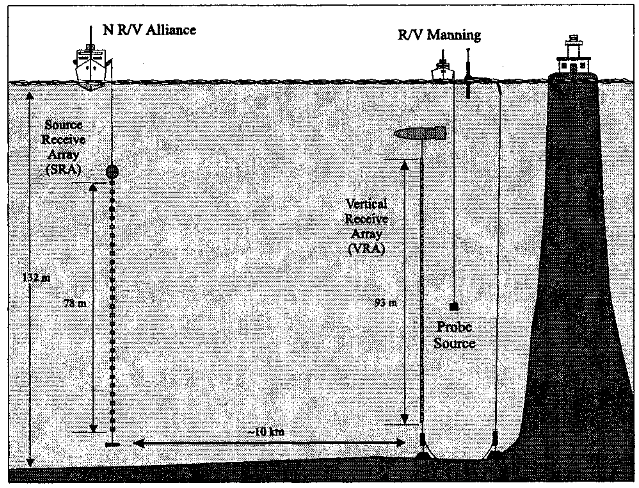

Fig. 2. Time-reversal experimental setup. The time-reversal mirror was deployed from the R/V ALLIANCE. Communication sequences were transmitted from the time-reversal mirror (SRA) to the VRA collocated with the PS deployed from the R/V MANNING.

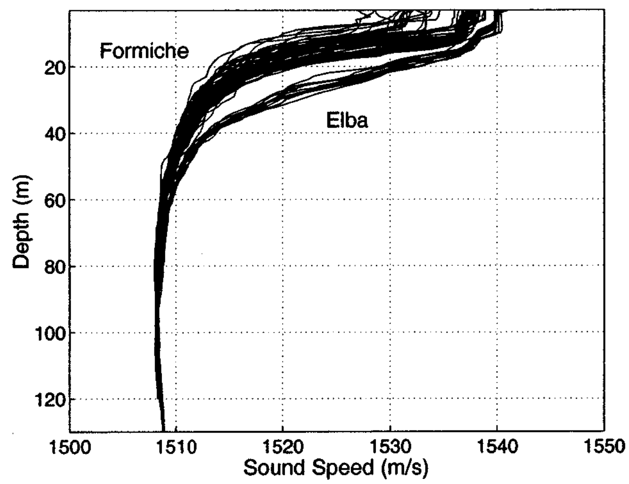

Fig. 3. Downward refracting sound-speed profiles were measured by taking CTD casts from the R/V ALLIANCE in both the Elba and Formiche areas.

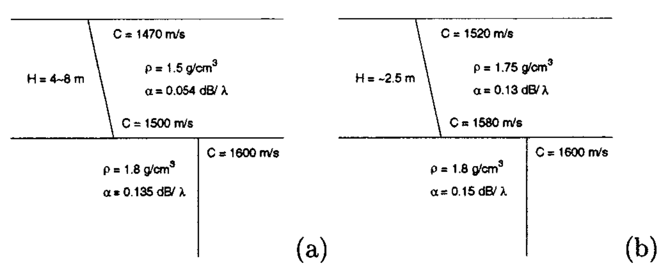

Fig. 4. Two-layer geoacoustic models for: (a) Formiche di Grosseto (slow bottom); (b) north Elba (fast bottom), in the Mediterranean [22].

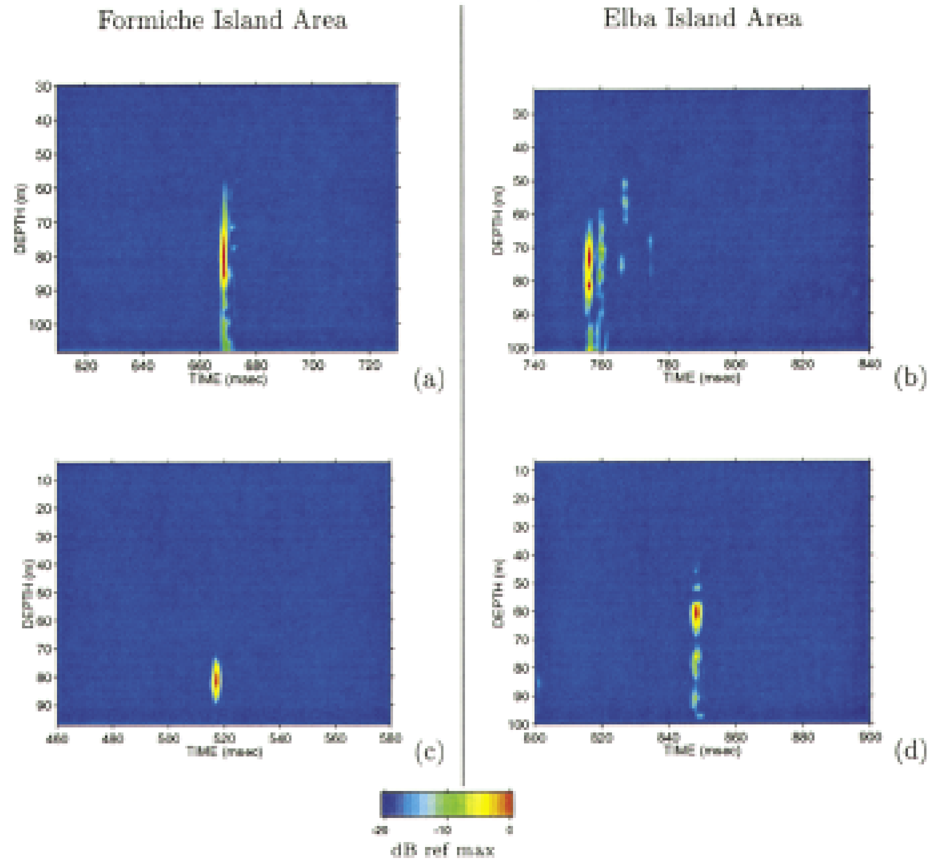

Fig. 5. Panels (a) and (b) show the channel response from a 2-ms, 3.5-kHz PS pulse received by the TRM are shown in . The PS was 80 m deep near Formiche and 60 m deep north of Elba. The received channel responses are time reversed and retransmitted from the TRM. The time-reversed signal refocuses both spatially and temporally, back to the original PS locations as shown in panels (c) and (d):.

dense TRM samples the water column sufficiently to capture and retransmit the higher order modes that contribute to side-lobe suppression.

III. Experimental Results

The experimental setup already has been discussed in detail previously [5], [21] and is shown in Fig. 2. A PS is nearly collocated with a VRA which has 32 elements with 3-m spacing. The PS has a center frequency of 3.5 kHz which corresponds to a wavelength (λ) of 0.43 m in the ocean. The source receive array (SRA) consists of 29 source/receiver transducers with an inter-element spacing of 2.78 m for a total aperture of 78 m or 181 λ. The transducers essentially have a bandwidth of 1 kHz centered at 3.5 kHz. The PS in Fig. 2 transmits a 2-ms pure tone pulse centered at 3.5 kHz. The signal is received on the SRA, digitized, time reversed (phase-conjugated) and retransmitted. The turn-around time from PS ping to retransmission was approximately 2 min. The backpropagated time series will refocus at the PS location where the VRA will be used to measure the vertical structure of the field. The VRA element closest to the PS depth will be used as the single element receiver in our TRM communication system. Sound speed profiles for the two experimental environments, Elba and Formiche, are shown in Fig. 3. Their respective bottom properties are shown in Fig. 4 [22]. The Formiche area has an absorptive bottom and the area near the northern coast of Elba has a more reflective bottom. A

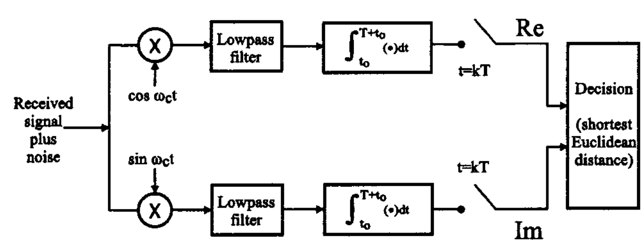

Fig. 6. Block diagram of the single element BPSK receiver system. The received signal and noise are separated into their quadrature components. The output of the receiver, every $T = 2$ ms, is the position of a single bit in the complex plane. The logical decision is the closest Euclidean distance to either $\pm i$. The original bit was coded with a phase of $\pm 90°$ representing either a 1 or 0.

reflective bottom produces greater multipath dispersion than an absorptive bottom.

Measurements were made in both range-dependent and range-independent environments. We will first discuss the range-independent results. Panel (a) of Fig. 5 shows the Formiche channel response recorded on the TRM. The PS was at 80-m depth at 11-km range. The sediment layer around Formiche has a lower sound speed than the water column, and energy tends to become trapped within it. Thus, the Formiche area is minimally dispersive with few multipath arrivals so the original 2-ms pulse has spread only a few milliseconds. The Elba channel was excited by the same PS and recorded in panel (b). The PS was at a depth of 60 m and at 11-km range. The

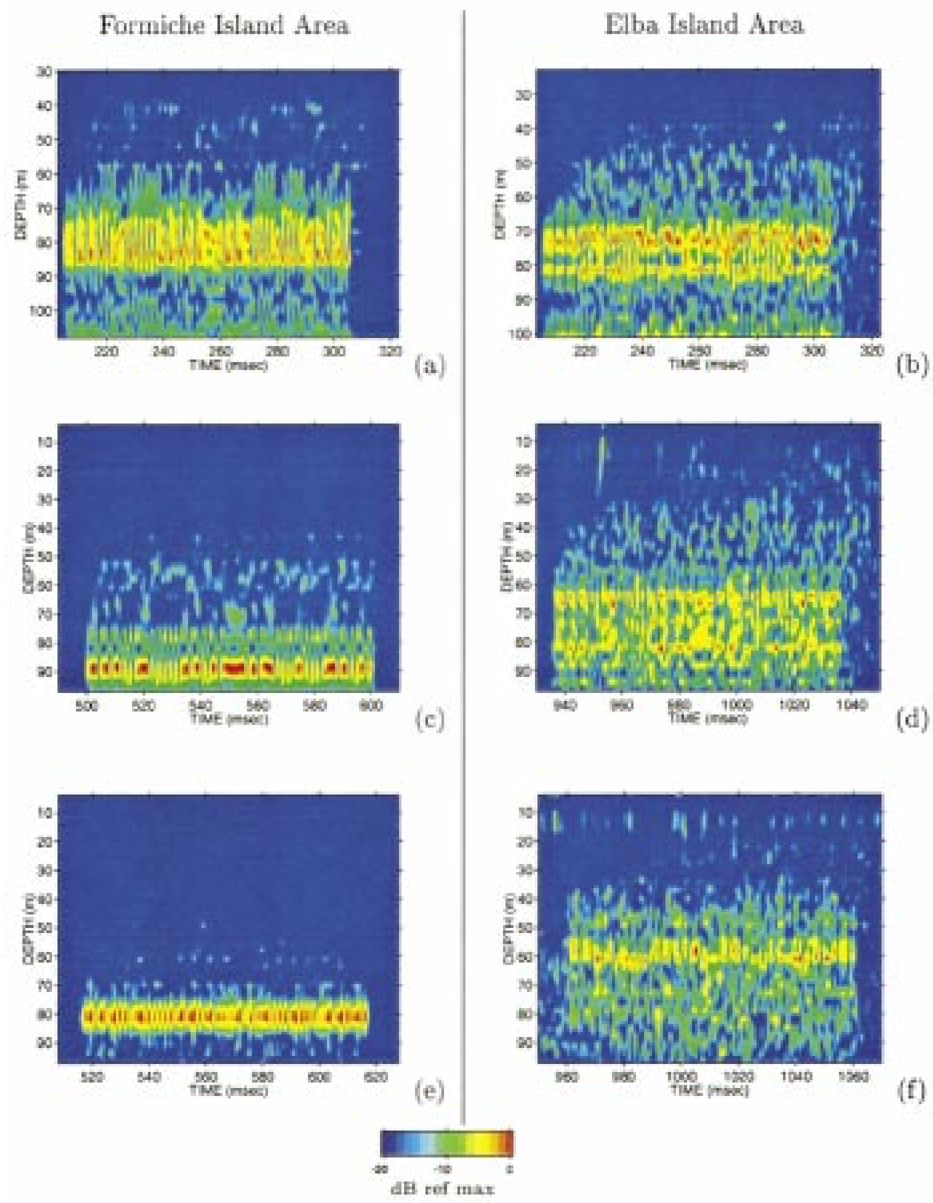

Fig. 7. Communications time series received on the VRA 11 km away from the TRM. Data-derived simulations of transmissions from a single source are shown in panels (a) and (b). One-way broadside communication sequences are shown in panels(c) and (d). Two-way time-reversal transmissions are shown in panels (e) and (f).

Elba area has a reflective bottom resulting in many multipath arrivals. The TRM recorded the initial 2-ms pulse as well as 20-ms of dispersive multipath arrivals. Panel (c) shows the time-reversed pulse as received by the VRA in the Formiche environment. Thus, the Formiche channel response shown in panel (a) has been time reversed and retransmitted and received on the VRA. The acoustic field has been compressed both spatially and temporally back to the original PS depth of 80 m. Panel (d) shows the Elba time-reversal focus at the PS depth of 60 m.

A. Communications—Range Independent

We first will consider transmitting communication sequences in two range-independent environments. Binary-phase shift keying (BPSK) was used to encode digital information in the phase of a transmitted pulse with a bit rate of 500 b/s. Each 2-ms pulse represents either a 1 or 0 by changing the phase of the pulse by 180°. All decoding was done with a single element, synchronized integrate-and-dump receiver shown in Fig. 6. No array processing or adaptive channel equalization was used. The depth of the PS will be considered the desired target depth for communications. Thus communication results will be shown for a reception depth of 80 m near Formiche and 60 m near Elba. The bit-error rate cannot be measured statistically since the sequence length is only 50 b. Therefore, only an initial preview of the potential of time reversal applied to communications can be presented here. The short 50-b span of the communication sequence was only due to equipment limitations and not channel physics. Section III-A-1 will discuss communications from a point source to a VRA receiver element. Section III-A-2 will discuss communications from the source array to a VRA receiver element using broadside transmissions. Section III-A-3 will discuss communication from the source array to a VRA receiver element using time-reversal transmissions.

1) Simulation of Single Source Transmissions: Simple one-way acoustic communications can be carried out by a single source transmitting to a single receiver element. Due to limited experimental time, communication sequences sent by a single source were not made. Simulations of these communication sequences were made from the measured channel responses shown in panels (a) and (b) of Fig. 5. In each case, the 50-b BPSK communication sequence was synthesized by taking 50 copies of the channel response, each separated by 2 ms, and encoding them with either a ± 1 polarity with no additional noise. This simulated single source communication sequences are shown in panels (a) and (b) of Fig. 7 for the Formiche and Elba areas, respectively. Because of the limited multipath in the Formiche area, there are few dispersive arrivals and therefore little ISI. Using the simple receiver design in Fig. 6, we were able to correctly receive 50/50 b that were transmitted. There is greater ISI in the Elba area because of the large number of multipaths. Only 40/50 b were correctly received. Note also that the received acoustic energy has been spread vertically across the water column.

2) Broadside Transmissions: Another method of one-way communications is to use all the elements of the SRA to transmit the same communications sequence on all channels simultaneously (i.e., a broadside beam). Broadside transmission excites preferentially only the first few waveguide modes. For the purpose of communication, transmitting a single mode would suppress dispersion and therefore ISI. Exciting exactly a single mode in shallow water experiments has proven quite difficult and requires more complicated feedback control systems [23]. After propagation, attenuation further emphasizes the lower order modes. At the depth of the first mode peak there is little dispersion and high SNR since the first mode dominates the field. But off this peak, the other lower order modes are contributing significantly to the total field and, thus, there is dispersion and ISI. The same 50-b BPSK communication sequence, consisting of 50 individual 2-ms pulses, was transmitted using all 29 sources of the TRM with each source transmitting at the same level. The experimental results from this one-way transmission in the Formiche and Elba areas from the TRM to the VRA are shown in panels (c) and (d), respectively of Fig. 7. Note how the acoustic energy is lower in the waveguide and in the Formiche area can be seen to take on the shape of the first mode. Using the same single-element receiver design at the PS depth, we were able to correctly receive 50/50 of the transmitted bits from both the Formiche as well as the Elba data. While broadside transmissions can suppress dispersion, they concentrate energy vertically at the peak of the first mode which might not be the desired receiver position.

3) Time-Reversal Transmissions: Time-reversal communications is a two-way method that takes advantage of the focusing ability of the time-reversal mirror. A channel is excited by a PS and its channel response can be recorded as shown in Fig. 5

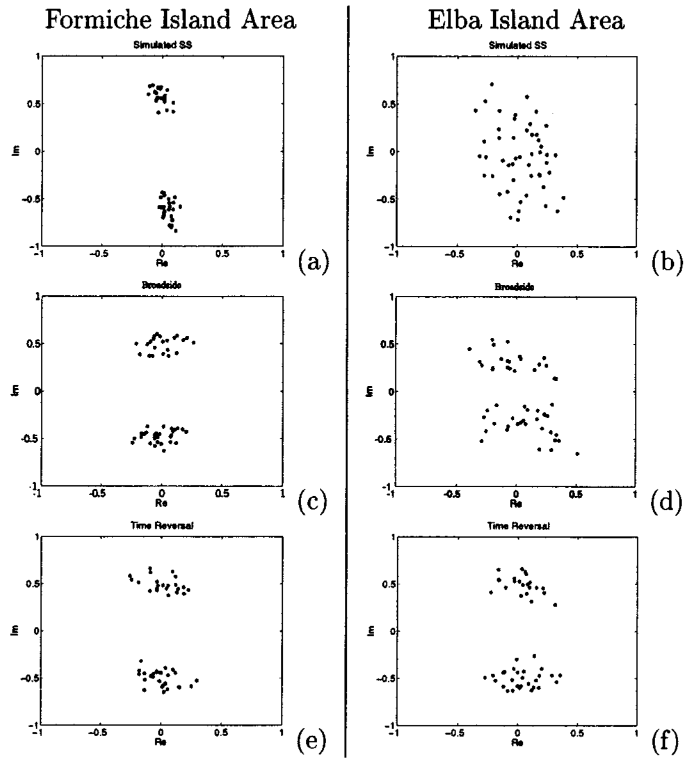

Fig. 8. Performance results are shown for the three BPSK communication types as decoded by the single-element receiver. The left-hand column contains data from Formiche, where the PS (receiver) is at 80-m depth, while the right-hand column contains data from Elba, where the PS (receiver) is at a 60-m depth. (a) and (b) Performance results for data-simulated-one-way-single-source communications. (c) and (d) Results for one-way broadside communications. (e) and (f) Results for two-way-time-reversed communications.

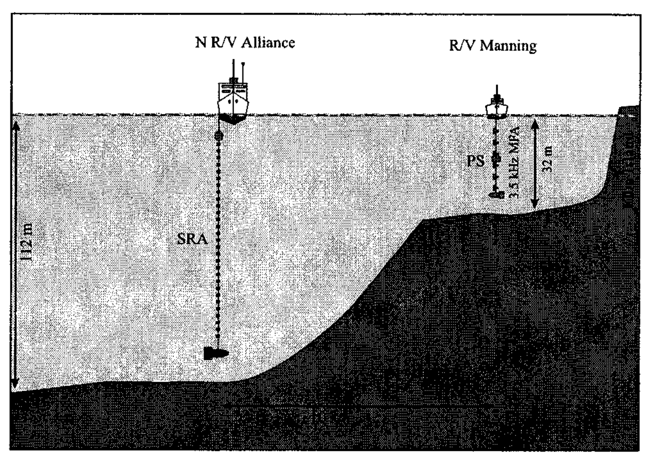

Fig. 9. Experimental setup for the upslope Elba communications experiment. The bathymetry changed from 112 m to 32 m over the 10-km range.

on the TRM. No data transmission is taking place during the PS ping capture phase. Time-reversed BPSK encoding uses the time-reversed channel response as a single bit, encoded with either a ± 1 polarity. The communication sequence is normalized by the maximum amplitude (across all time and depth). The entire time-reversed channel response is copied every 2 ms, with the copies substantially overlapping each other. After transmission through the ocean, the individual bits are compressed nicely

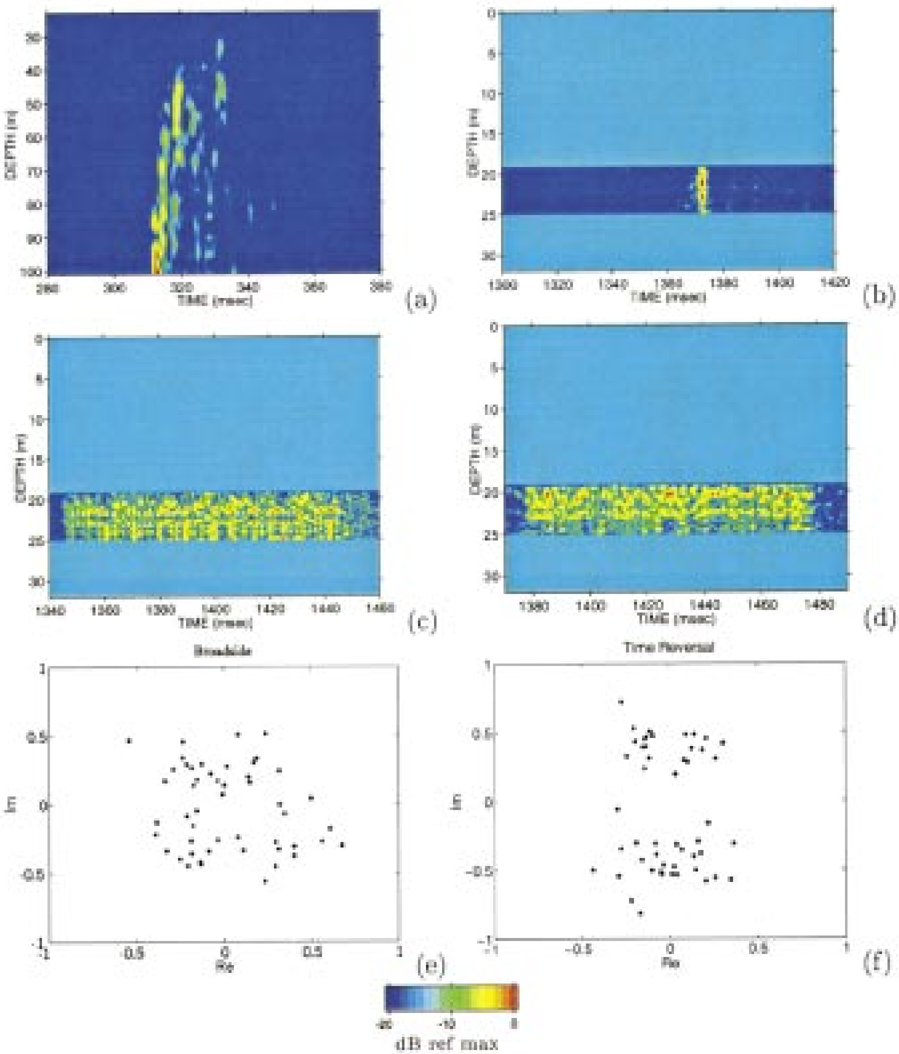

Fig. 10. (a) Channel-response data in the range-dependent Elba upslope environment. The original 2-ms pulse has spread about 40 ms. (b) Time-reversed focus received on the MFA. The original PS was located at a depth of about 22 m. (c) Reception of the broadside transmission. (d) Reception of time-reversal transmission. (e) and (f) Scatter plots for broadside and time reversal, respectively.

back to their original 2 ms duration as shown in panels (e) and (f) of Fig. 7. Note the focus of energy at the desired PS depth. The scintillation seen in the time-reversal communication transmission is caused by the constructive and destructive interference of the sidelobes of each separate time-reversal focus. The time-reversal focus from the Elba area has more sidelobes thus produces a more complicated scintillation. Again, 50/50 of the transmitted bits were received correctly and decoded at the PS depth for both the Formiche and Elba data.

4) Symbol Scatter Plots: The performance results for the three transmission types in the Formiche and Elba areas are shown in Fig. 8 as scatter plots of the estimated data symbols for BPSK encoding. The real and imaginary outputs of the receiver shown in Fig. 6 for each bit are depicted as dots in the complex plane. Recall that the receiver is a single element collocated with the PS. Without noise or ISI there would only be two points, 180 degrees apart in the complex plane, representing a received “1” or a “0.” The left hand column presents data from Formiche, while the right hand column presents data from Elba. Panels (a) and (b) show performance results for simulated one-way single source communications. Panels (c) and (d) show one-way broadside communication results. Lastly, panels (e) and (f) show performance results for two-way time-reversal communications. The small scatter depicted in (a) is caused by the small dispersion of the Formiche environment. For Formiche, the broadside transmission in (c) and the time-reversal transmission in (e) show comparable results. For Elba, the simulated single source transmission results in (b) show large scatter since we wish to receive at a depth where very little of the signal energy is located. Comparing the broadside results in (d) to the time-reversal results in (f), shows that there is an improved grouping in the time-reversal scatter plot.

B. Communications—Range Dependent

Range-dependent measurements were made in the upslope region off the northern coast of Elba. The channel is characterized by many multipath arrivals. Fig. 9 shows that during

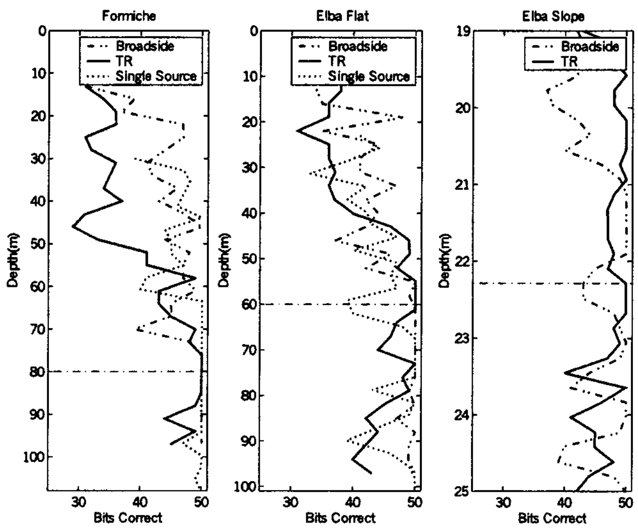

Fig. 11. The number of bits correct out of 50 transmitted, versus depth for the three transmission types in the three environments. The horizontal dashed line is the depth of the PS.

this portion of the experiment, the TRM was deployed from the drifting R/V ALLIANCE in 112 m water depth. The medium frequency array (MFA), a short 6-m long array with 0.18 m spacing, was used instead of the VRA to give a high resolution look at the TR focus. Deployed from the side of the anchored R/V MANNING, the MFA and PS were nearly collocated in shallow water 32 m deep. The two ships were separated by 10 km.

Panel (a) of Fig. 10 shows the 2-ms PS pulse spreads to about 40 ms as received by the SRA. The time-reversal focus shown in panel (b) is at the original PS depth of about 22 m with a vertical focal size less than 1 m. The water column not spanned by the array is depicted in light blue. Although the best foci were obtained during the upslope experiment, the communications data were collected during a time of fast drifting, so the results are somewhat out of focus. The reception at the MFA of the broadside transmission is shown in panel (c). The energy is spread through the water column. The reception of the time-reversal transmission is shown in panel (d). Panel (e) shows the scatter plot from broadside transmission and panel (f) shows the the scatter plot results for time reversal transmission. A tighter grouping can be seen in the time-reversal results. In the broadside transmission, 43/50 b were decoded correctly while for the time-reversal transmission, 50/50 b were decoded correctly.

C. Communications—Channel Fading

Often, it is impractical to have an array of receiver elements that span a large enough portion of the water column to mitigate channel fading For example, an autonomous underwater vehicle has a limited vertical aperture for receiving elements. The effect of channel fading on the three transmission types can be seen in Fig. 11 as a function of the number of bits correct out of 50 versus depth. The PS depth is shown as a dashed line. The single-source transmission has energy distributed throughout the water column and was subject to dispersion. The broadside transmission will excite the lower order modes and especially the first mode. After propagation, the weakly excited modes are attenuated. By looking at Fig. 11, it can be seen that the broadside communication works best around the peak of the first mode. This is because the first mode dominates, thus fighting dispersion and channel fading. Away from the peak of the first mode, the other excited modes begin to contribute significantly to the field and there is significant dispersion in the signal. Broadside transmission works well at the peak of the first mode but that might not be where the receiver is located. Time reversal provides control over the the vertical acoustic energy distribution thus potentially facilitating communication with receivers at any depth. The number of bits correct versus depth for time reversal tends to reproduce the focal shape.

Another characteristic of time reversal is that the focus quickly decays, both in depth and temporal focus, at positions other than that of the PS. This suggests that a receiver attempting to listen at another location would not benefit from the SNR and dispersion reduction available at the time-reversal focus.

IV. Conclusion

We have shown that as a matched filter to the channel impulse response, time reversal potentially is an effective communications technique that mitigates the ISI caused by multipath dispersion. Preliminary evidence demonstrates a substantial advantage of time reversal over one way single source communications and, to a lesser extent, advantage over one-way broadside (nearly single mode) communications.

The time-reversal approach enables focusing the transmitted energy in both range and depth. Furthermore, it was demonstrated that focusing of communication sequences can be accomplished over substantial range-dependent bathymetry.

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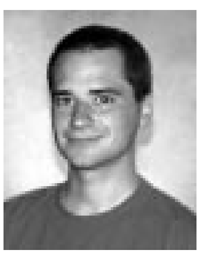

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T. Akal, photograph and biography not available at the time of publication.

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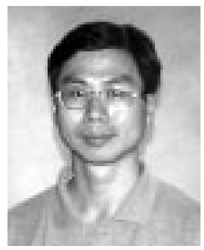

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