Recent Results from Ocean Acoustic Time Reversal Experiments

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Summary

Acoustic time reversal has been, in one form or another, investigated over the last forty years. From 1996 onward, we have conducted a series of four at-sea experiments. Equipments central to the research effort were (ONR/MPL) two vertical source-receive arrays (SRA's), centered at 450 Hz and 3500 Hz that implemented the Time Reversal Mirrors (TRM's), and extremely sophisticated, remotely operated vertical receive arrays (SACLANTCEN) as wells SACLANTCEN's ships, the R/V Alliance and the Manning. The higher frequency SRA was operated remotely from a buoy such that the SRA was a node on a 2.4 GHz local area network (LAN). The properties of the phase conjugate focus fields and their relationship to the ocean environment were experimentally studied: potential focal ranges and range shifts, focal size, and stability. Some preliminary system concepts have also been investigated experimentally: active sonar and undersea communications. Much of this work has been reported earlier and in this paper we present a short, selected review and outline recent progress.

1. TRM Experiments 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 multi-path 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 due to the waveguide nature of acoustic propagation in the ocean.

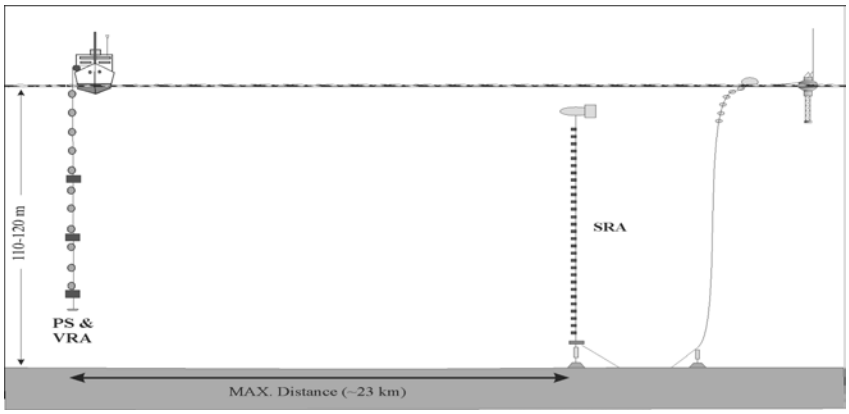

Figure 1. Experimental setup of generic time reversal mirror experiment in the ocean

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 [10]. Furthermore, it can be shown that for propagation to and from a probe source upslope of the TRM, the resulting focus is tighter than if the probe source was in the same depth water as the TRM. An example is shown in Fig.2 indicating a 3 dB focus in depth of order 1 m approximately 10 km from the TRM.

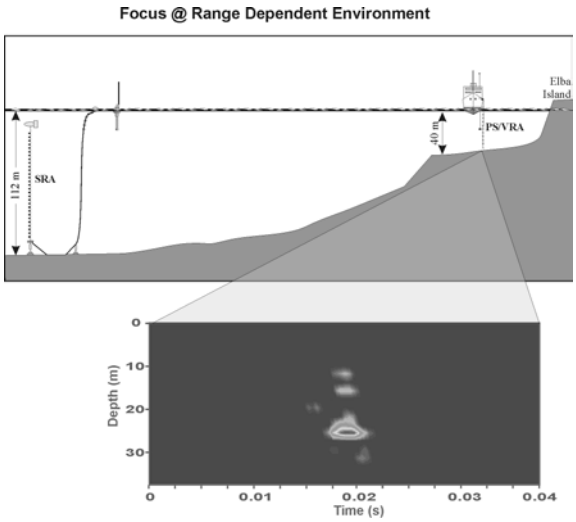

Figure 2. Geometry and data example for the range dependent TRM experiment.

Figure 3 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 [10].

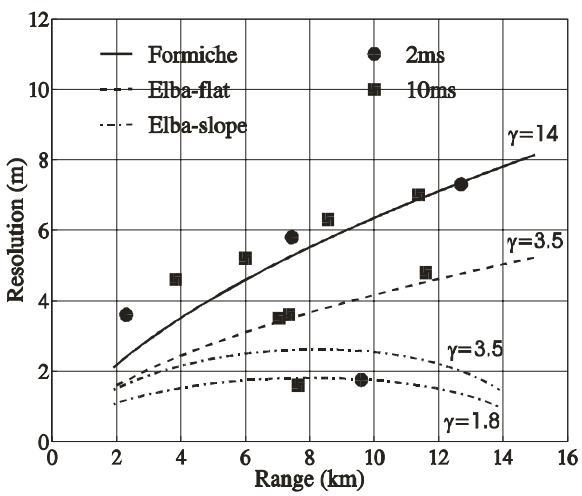

Figure 3. Comparison between the measured and the calculated resolution at 3500 Hz for different sites.

In what follows we will present results that provide a foundation for applications of TRM based system concepts. The areas covered are reverberation and communication.

2. TRM and Reverberation

There are a number of interesting issues concerning reverberation and communications.

2.1 Reverberation when focusing within the water column

Our basic experiments have shown that when we place a focus in the water column, there is very little energy (typically 20 dB down from the focal region) projected on the boundaries above and below the focus at the focal range. Hence, an echo return from a TRM focus will have minimal reverberation at the echo range cell.

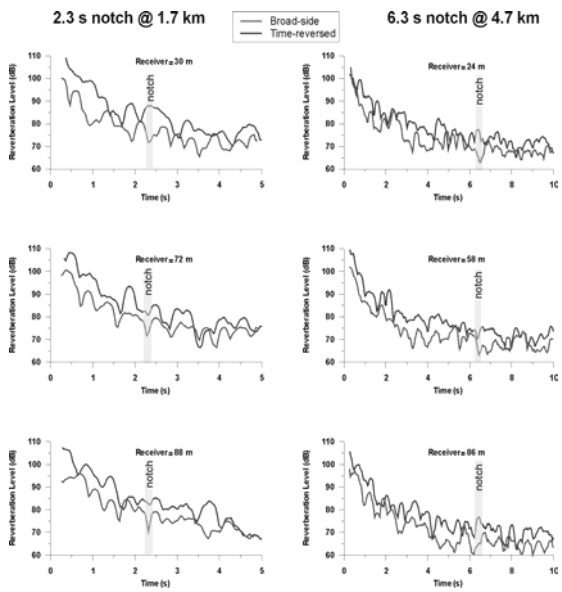

Figure 4. Examples of echo-to-reverberation enhancement compared to reverberation from a broadside transmission. The position of notch indicated the range at which the SRA was focusing.

Figure 4 shows examples of 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 (TR) 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.

2.2 Time Reversal without a Probe Source

Boundary reverberation, for example, caused by bottom roughness, can serve as a surrogate probe source. That is, a time gated portion of the reverberation could be refocused to the bottom at the range corresponding to the reverberation interval that has been time reversed. This idea has been investigated in Ref. [7]. Figure 5 and 6 summarize this concept with simulation. The method can either be a straightforward time reversal of the gated time interval or an application of the time-reversal operator technique.

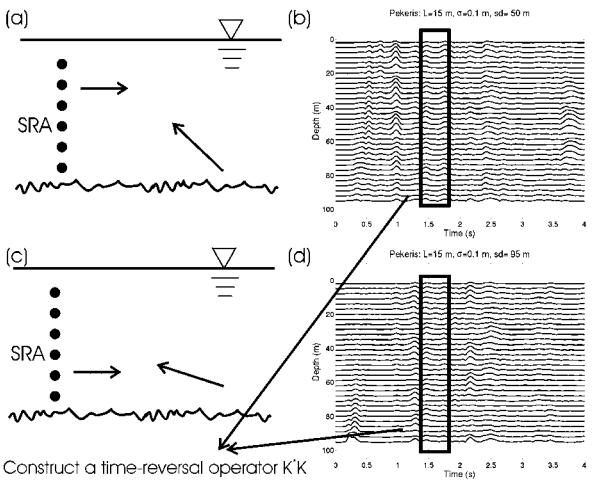

Figure 5. A time interval corresponding to a particular range interval is used to construct the time-reversal operator. The largest eigenvalue(s) are used to select the eigenvector weights of the SRA which then emits signals that focus on the origin of the reverberation.

2.3 Reverberation Nulling

We have previously derived [8] that a TRM can be used to produce a null at a focus given a field on the TRM from a probe source. Combining this idea with the use of reverberation as a probe source, it is then possible to produce a null rather than focused energy at the origin of the time gated reverberation [11]. Just as in the reverberation focusing, a slice of reverberation corresponding to the range cell is extracted for processing – but this time to produce a null.

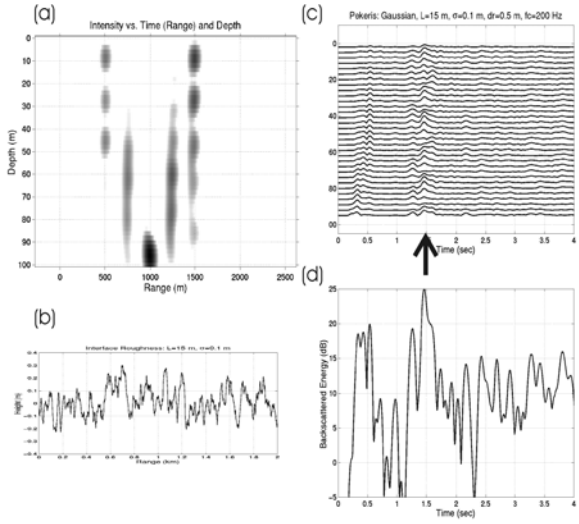

Figure 6. The upper left panel (a) is the simulation results showing a focus at the bottom caused by refocusing the energy in the gated time interval shown in Fig. 5. The time record of the reverberation is shown in the upper right hand panel (c) and below that is a plot of the signal energy summed over all the hydrophones (d). Also shown is the bottom roughness (b).

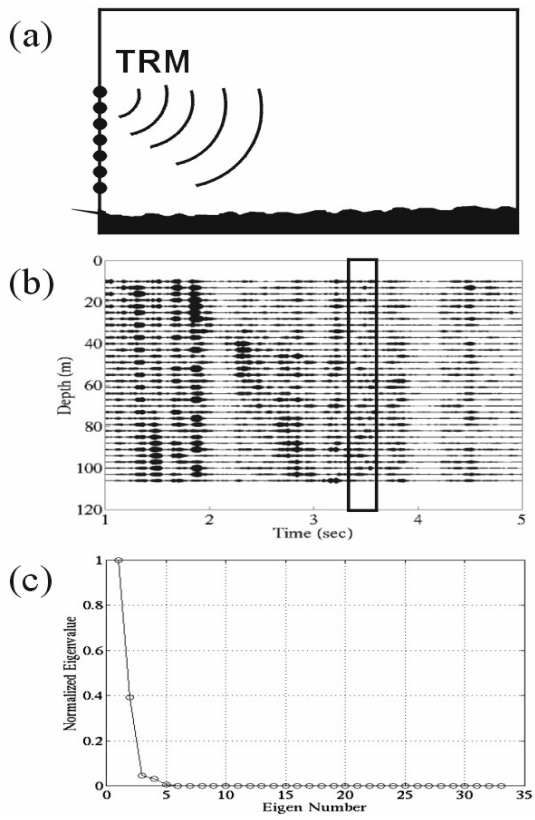

Figure 7. (a) Schematic of the reverberation geometry. (b) A slice of the reverberation is extracted just as in the reverberation focusing procedure and (c) an eigenvector decomposition is done (at each frequency).

The eigenvector/eigenvalue decomposition of this slice is shown in Fig. 7. The first few eigenvectors correspond to the reverberation whereas the eigenvectors with negligible eigenvalues represent a shading across the array that is orthogonal the reverberation return at the selected range. Figures 8 and 9 are simulation and data examples.

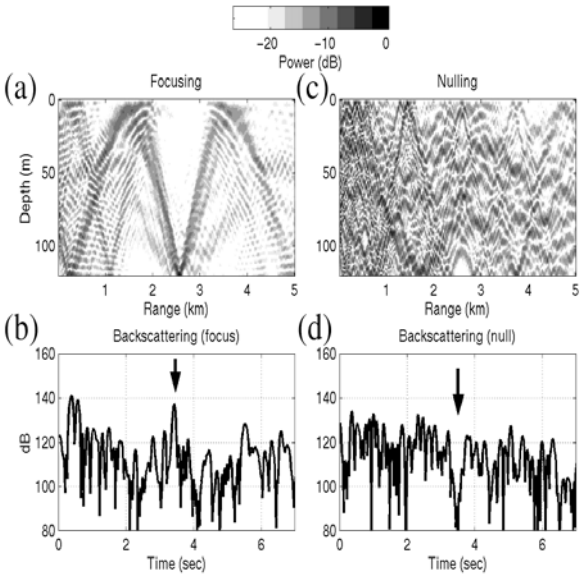

Figure 8. Simulation of reverberation focusing and reverberation nulling using eigenvectors corresponding to the reverberation and orthogonal to the reverberation, respectively, across the array for the selected time interval shown in Fig. 7.

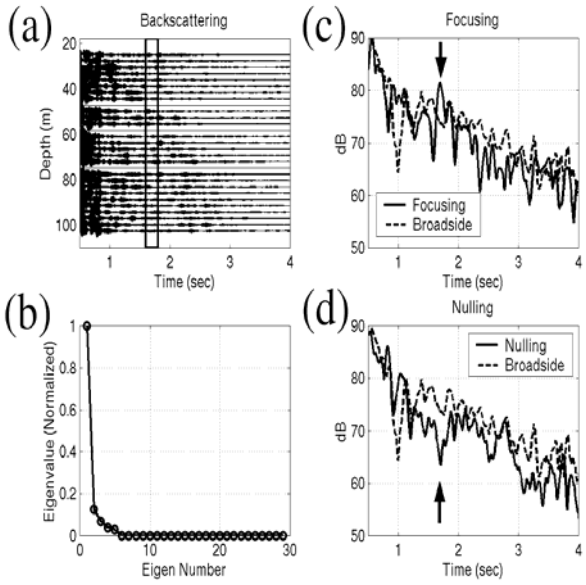

Figure 9. example corresponding to the processing described in Figs. 7 and 8.

3. Underwater Communications with a TRM

The time reversal process refocuses the signal present at an array back to originating signal probe source. The focus is both in space and time; the latter means that any multipath structure is recombined to produce the time reversed signature of the signal at the probe source position. Therefore, the TRM deals with one of the major difficulties associated with underwater communications: intersymbol interference caused by multipath time spread [4]. This issue is illustrated in Fig. 10 where the first panel shows the time spread of a point source signal. The time reversal recompresses the signal at the probe source as shown in the second panel. The bottom panel shows a sequence of signals ("bits") sent from the TRM; each is the time spread signal from the probe source – the superposition being quite a mess. Nevertheless, each time spread signal recompresses resulting in distinct bits at the probe source position. Note the time spread signal are displaced in time by the original pulse width. In the example shown, an Autonomous Underwater Vehicle (AUV) is envisioned as carrying the probe source.

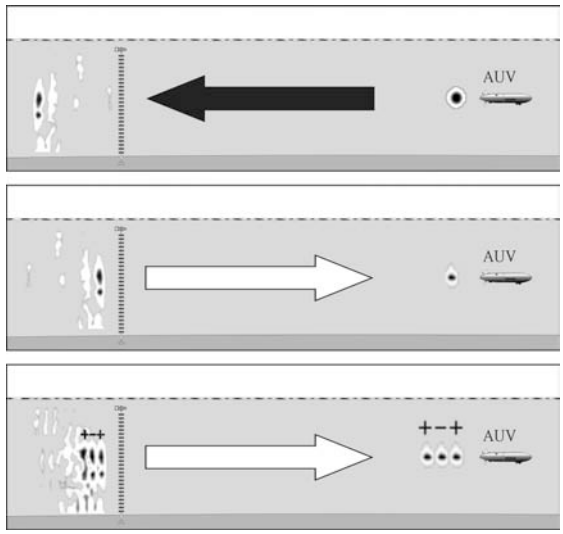

Figure 10. Illustration of time reversal communications. First, the AUV sends a PS pulse to the TRM. Normally, the channel response would be time-reversed and retransmitted as shown in the second panel. For communications, the lengthy time-reversed channel response is treated as one symbol. That symbol is phase shift encoded and combined into a communication sequence. Though there is considerable overlap at the TRM, the individual symbols compress temporally and spatially at the AUV.

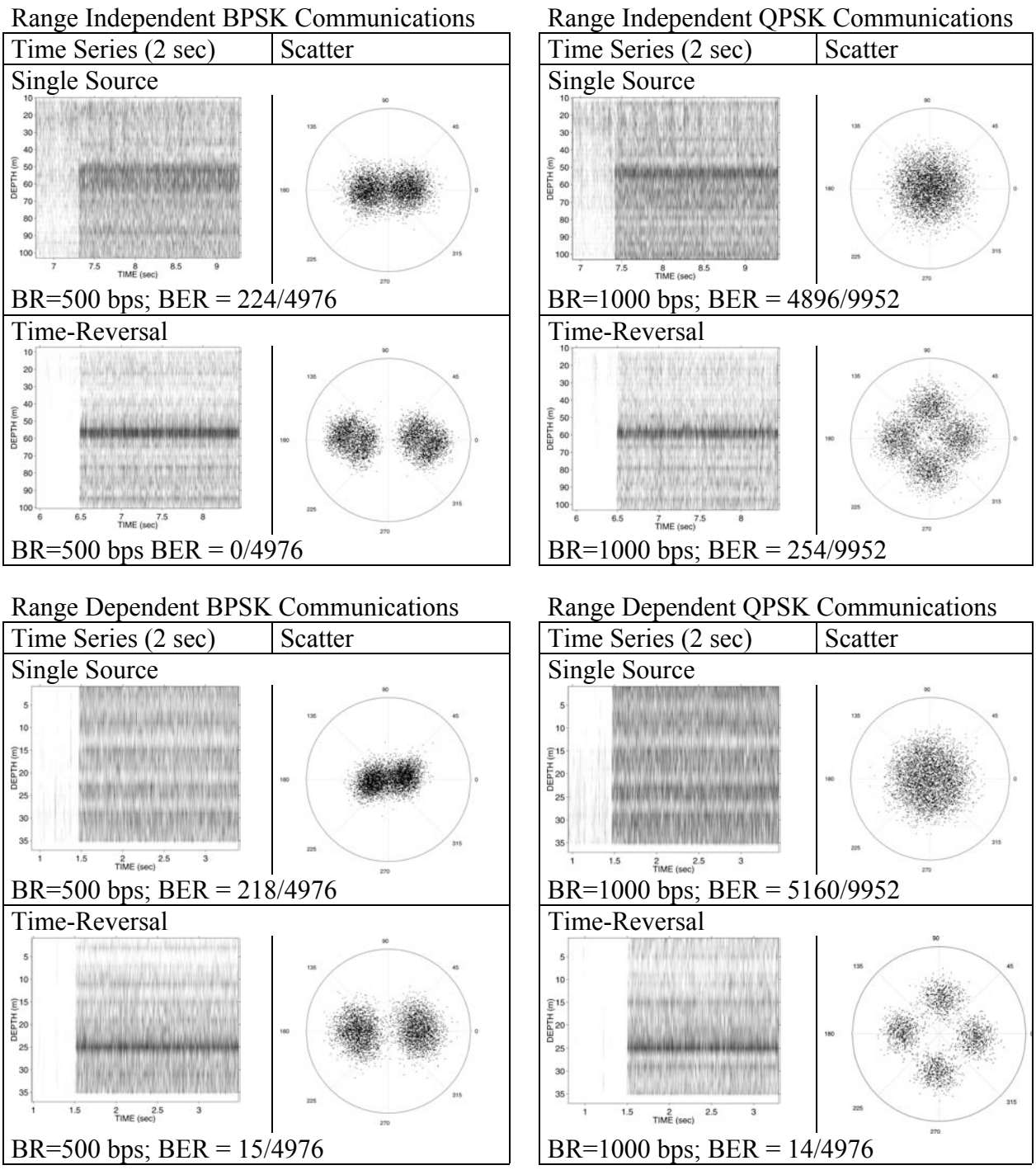

Figure 11. Contour and scatter plots of both communication types in both range independent and dependent shallow water environments. The contour plot depicts only the first 2 sec of data received on the VRA at a range of 10 km from the TRM. The scatter, or in-phase and quadrature plot depicts the performance of the single element integrate-and-dump receiver located at the same depth as the PS. Time reversal focuses energy to the PS depth. Note that there was insufficient SNR for the PLL to track the single source QPSK transmissions

In order to increase the bit rate, communications engineers further encode their signals by various schemes. One such scheme is to impose phase changes to represent bits. Binary phase shift keying (BPSK) simply uses plus and minus ones or phase shifts of one hundred eighty degrees to denote two different bits. Higher order schemes use more, but smaller phase shifts; for example QPSK uses ninety degree phase shift to encode four different bits.

Figure 11 shows experimental results for the above two schemes. Results are shown for a range independent environment and a range dependent environment similar to the one depicted in Fig. 2. This is a particularly challenging environment for underwater communications but the bit error rates are very encouraging. Not shown but presented elsewhere [4] are the non time-reversed control results indicating totally unacceptable bit error rates. Further, it has also been shown that the TRM bit error rate is a minimum at the depth of the probe source.

4. Summary

We first selectively reviewed previous TRM results that have already been reported in the literature [5,6,10,13,14]. We then presented some recent TRM theoretical and experimental results on reverberation [7,11] and acoustic communications [4]. These results suggest an assortment of system concepts for the TRM.

In particular, we have shown that reverberation can be used as a surrogate probe source and energy can be refocused to a selected region from which a portion of the reverberation has been received. We have also shown that rather than focus energy at the originating reverberating region, a null can be directed to the selected region with the use of a TRM that is appropriately shaded.

We have also discussed underwater communications with the use of a TRM. We have shown that the TRM effectively deals with intersymbol interference originating from multipath timespread and that this is particularly true in "challenging" acoustic environments. Further, we have demonstrated that the TRM can be combined with higher order communication schemes such as BPSK and QPSK and that the bit error rate is minimized at the focal depth.

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