# Nulling crosstalk in underwater communication with an adaptive time-reversal mirror

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***Abstract*-Since the concept of adaptivity has been introduced into the time-reversal mirror (TRM) in order to steer nulls and is referred to as the adaptive time-reversal mirror (ATRM), the ATRM has been applied to focus selectively on a weak target and to have multiple focusing simultaneously. In this study, the ATRM is applied to nulling the crosstalk between receivers in underwater communication when independent symbol sequences are sent simultaneously to different receivers. The nulling process utilizes probe source transmissions from the receiving locations in order to find the ATRM weight vectors to be backpropagated. The algorithm is applied to long-range underwater acoustic communication to show, via simulation, that the crosstalk at multiple receiving locations can be cancelled.**

## I. INTRODUCTION

It is well known that a time-reversal mirror (TRM) uses the received signal from a probe source to refocus the signal at the probe source location by backpropagating the time-reversed version of the received signal. Since TRM has been demonstrated in ultrasonics [1] [2] and in ocean acoustics [3] [4] [5], a specific application of TRM to achieve low error bit rate in underwater communication was successfully demonstrated [6].

Since the concept of adaptivity was introduced to time-reversal mirror (TRM) and referred to as an adaptive time-reversal mirror (ATRM) [7], the applicability of ATRM has been demonstrated in selective focusing onto a weak scatterer among the two scatterers [7] and multiple focusing [8] with an application to underwater communication for self-equalization at multiple receiving locations.

In the present study, ATRM is extended to independent multiple focusing in an ocean waveguide by imposing a set of constraints in the formulation to find the weight vectors. Subsequently, the developed algorithm is, via simulation, applied to the self-equalization process at the multiple receiving locations without crosstalk in the long-range underwater acoustic communication, where the characteristics of the channel is dispersive and multi-pathed resulting in a severe signal distortion.

In Sec. II, the formulation of TRM and ATRM is reviewed, and ATRM is extended to the independent multiple focusing algorithm. Simulation results are presented in Sec. III for TRM and ATRM in an ocean waveguide in the context of underwater communication. A summary of the work presented is found in Sec. IV.

## II. THEORY

### *A. Review of TRM*

In order to review the adaptive TRM, we follow the convention in Kim [7]. As described in Fig. 1, the phase-conjugate field at the field location $\vec{r}$ in frequency domain is written as

$$p(\vec{r}) = \sum_{j=1}^{N} g^*(\vec{r}_i \mid \vec{r}_{\rm ps}) g(\vec{r} \mid \vec{r}_j)$$

$$= \mathbf{g}^+(\mathbf{r}_{\rm array} \mid \vec{r}_{\rm ps}) \mathbf{g}(\vec{r} \mid \mathbf{r}_{\rm array}), \qquad (1)$$

where $g(\vec{r}_i \mid \vec{r}_{\rm ps})$ represents the received acoustic pressure at the *i*th array element location $\vec{r}_i$ propagated from the probe source position $\vec{r}_{\rm ps}$. Likewise, $g(\vec{r} \mid \vec{r}_i)$ represents the field propagated from the *i*th array element location $\vec{r}_i$ to the arbitrary receiver location $\vec{r}$ as shown in Fig. 1. $N$ is the number of array elements. Superscripts $()^*$ and $()^+$

denote complex conjugate and Hermitian transpose, respectively. In a vector notation, $\mathbf{g}$ and $\mathbf{r}_{\text{array}}$ are $(N \times 1)$ column vectors representing the Green's function and array element positions respectively. Note that the position vectors are written in *italic* letters with arrows and the column vectors and matrices are written in boldface letters.

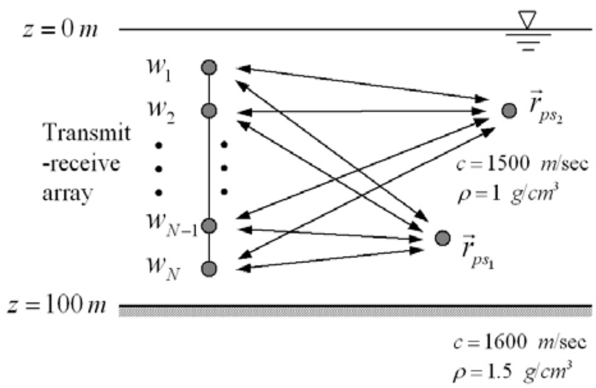



FIG. 1. Description of Pekeris waveguide for ATRM.

*B. Review of ATRM*

Introducing a signal vector for backpropagation

$$\mathbf{w} = \begin{bmatrix} w_1 \\ w_2 \\ ,\vdots \\ w_{N-1} \\ w_N \end{bmatrix} \tag{2}$$

Eq. (1) can, more generally, be written as

$$p(\vec{r}) = \sum_{i=1}^{N} w_i^* g(\vec{r} \mid \vec{r}_i) = \mathbf{w}^+ \mathbf{g}(\vec{r} \mid \mathbf{r}_{\text{array}}), \tag{3}$$

where $\mathbf{w}$ reduces to $\mathbf{g}(\mathbf{r}_{\text{array}} \mid \vec{r}_{\text{ps}})$ in a conventional time-reversal mirror.

The weight vector $\mathbf{w}$ can be chosen for specific purpose. Generally, the formulation to find $\mathbf{w}$ is based on the optimization problem of the following objective function:

$$\min_{\mathbf{w}} \mathbf{w}^+ \mathbf{K} \mathbf{w} \tag{4}$$

with the distortionless response constraint at the focal location, which can be expressed as

$$\mathbf{w}^+ \mathbf{g}(\vec{r}_{\text{ps}} \mid \mathbf{r}_{\text{array}}) = 1 \tag{5}$$

This optimization problem has a well known solution referred to as the minimum variance in the adaptive array signal processing [9] [10] [11], which is

$$\mathbf{w} = \frac{\mathbf{K}^{-1}\mathbf{d}}{\mathbf{d}^+ \mathbf{K}^{-1} \mathbf{d}} \tag{6}$$

where $\mathbf{d}$ is the steering vector for the look direction, or the signal vector from the focal point in the context of TRM, or the replica vector in matched field processing (MFP). More specific examples of ATRM are summarized in the followings.

*C. Steering Nulls with ATRM*

In order to find the signal vector $\mathbf{w}$ to steer a null to $\vec{r}_{\text{ps2}}$, the crossspectral density matrix (CSDM) in Eq.(6) is defined as [7]

$$\mathbf{K} = \mathbf{d}_{\text{ps1}} \mathbf{d}_{\text{ps1}}^+ + \mathbf{d}_{\text{ps2}} \mathbf{d}_{\text{ps2}}^+ \tag{7}$$

with a constraint

$$\mathbf{w}^+ \mathbf{g}(\vec{r}_{\text{ps1}} \mid \mathbf{r}_{\text{array}}) = 1, \tag{8}$$

where the location with distortionless response is denoted as $\vec{r}_{\text{ps1}}$ and the location of nulling is $\vec{r}_{\text{ps2}}$. The signal vector $\mathbf{w}$ for backpropagation is found from

$$\mathbf{w} = \frac{\mathbf{K}^{-1}\mathbf{d}_{\text{ps1}}}{\mathbf{d}_{\text{ps1}}^+ \mathbf{K}^{-1} \mathbf{d}_{\text{ps1}}} \tag{9}$$

where $\mathbf{d}_{\text{ps1}}$ is a signal vector from $\vec{r}_{\text{ps1}}$ to the array location $\mathbf{r}_{\text{array}}$.

An alternative formulation can be used, where the CSDM is defined as (3)

$$\mathbf{K} = \mathbf{d}_{\text{ps1}} \mathbf{d}_{\text{ps1}}^+ \tag{10}$$

and the constraints are

$$\mathbf{w}^+ \mathbf{g}(\vec{r}_{\text{ps1}} \mid \mathbf{r}_{\text{array}}) = 1 \tag{11}$$

and

$$\mathbf{w}^{+}\mathbf{g}(\vec{r}_{\text{ps2}} \mid \mathbf{r}_{\text{array}}) = 0 \quad (12)$$

which is known as a multiple constraints method (MCM). In matrix form, the constraints in Eq.(11) and (12) can be expressed as $\mathbf{M}^{+}\mathbf{w} = \mathbf{c}$, where $\mathbf{M} = [\mathbf{d}_{\text{ps1}} \quad \mathbf{d}_{\text{ps2}}]$ and

$$\mathbf{c} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}. \quad (13)$$

The signal vector $\mathbf{w}$ for backpropagation is found from

$$\mathbf{w} = \mathbf{K}^{-1}\mathbf{M}[\mathbf{M}^{+}\mathbf{K}^{-1}\mathbf{M}]^{-1}\mathbf{c}. \quad (14)$$

*D. Multiple focusing with ATRM: Broadcasting the same symbol sequences to multiple receiving locations*

In the previous study [8], a formulation for the signal vector $\mathbf{w}$ to have the multiple focusing points was derived and applied to the long-range underwater communication in the ocean waveguide in order to demonstrate the self-equalization process at multiple receiving locations. Weight vector $\mathbf{w}$ in Eq. (6) gives a distortionless response for one probe source only. We want to achieve simultaneous multiple focusing with distortionless response in multiple probe source locations. For this purpose, the multiple linear constraint ATRM is applied. That is, the multiple focusing is achieved by merely replacing the constraint matrix in Eq.(14) as

$$\mathbf{c} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}. \quad (15)$$

The response vector associated with constraint matrix has ones for its all element for each probe source locations. However, the value of the response matrix can be prescribed to monitor the relative strength of the focused field.

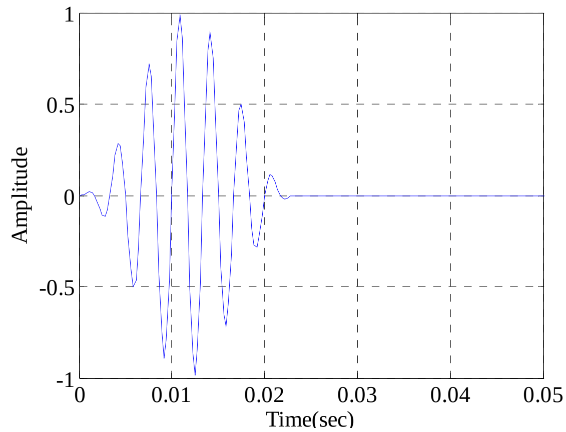
*E. Multiple focusing with ATRM: Broadcasting the different symbol sequences to multiple receiving locations*

In order to send the different symbol sequences to multiple receiving locations, the procedures to find the signal vector $\mathbf{w}$ are as follows. First, the formulation presented in *Sec. II.C* is used to have a distortionless response at one location and nulls at the other locations. For example, supposing two receiver locations such A and B, the signal vector $\mathbf{w}$ is found so that the distortionless response is achieved at A and a null at B from Eq.(14). Next, another signal vector $\mathbf{w}$ that satisfies the distortionless response at A and a null at B are found from the same Eq.(14). Now, the two signal vectors are linearly superposed for the entire frequency bins and inversely Fourier transformed to generate the bit signal sequences at the transmit/receive array. Finally, the signals are transmitted to the ocean resulting in a multiple focusing without crosstalk between the multiple receiving locations even when the different bit sequences are broadcasted simultaneously.

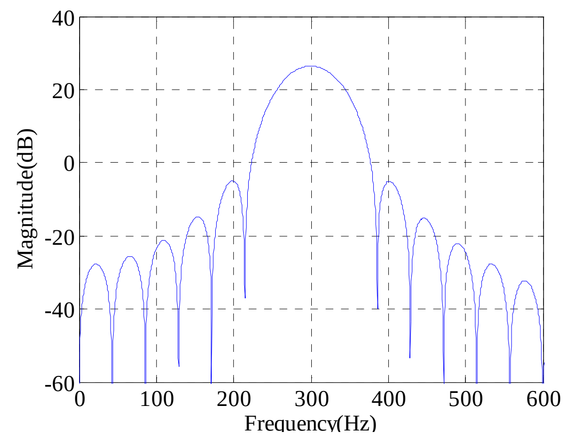
## III. SIMULATION

In this section, an independent multiple focusing is demonstrated in Pekeris waveguide which is shown in Fig. 1.

As seen in Fig. 2, the transmitted probe pulse for BPSK (Binary Phase Shift Keying) has a center frequency $f_c = 300\,\text{Hz}$ and a ping duration $\tau = 23.33\,\text{ms}$. In Fig. 3, the pulse for FSK (Frequency Shift Keying) is shown with center frequency 257.1 Hz and 342.9 Hz, respectively. The sampling frequency is 3600 Hz, FFT size is 8192, so that the time duration is 2.3 s long. This time duration is long enough to prevent aliasing in time as a pulse propagates in the ocean and stretches in time due to multipath propagation and dispersion. The probe sources are located at A: $\vec{r}_{\text{ps}_1} = (5800\,\text{m}, 80\,\text{m})$ and B: $\vec{r}_{\text{ps}_2} = (6200\ \text{m}, 20\ \text{m})$, respectively. The vertical transmit/receive array consists of 17 elements with an inter-element spacing of 5 m ranging from 10 m to 90 m in depth. The description of an ocean waveguide is shown in Fig. 1. As a propagation model, KRAKEN[12] was used throughout the simulation.

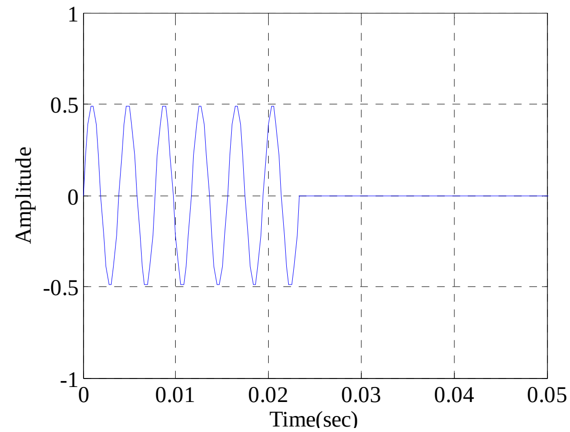



(a)

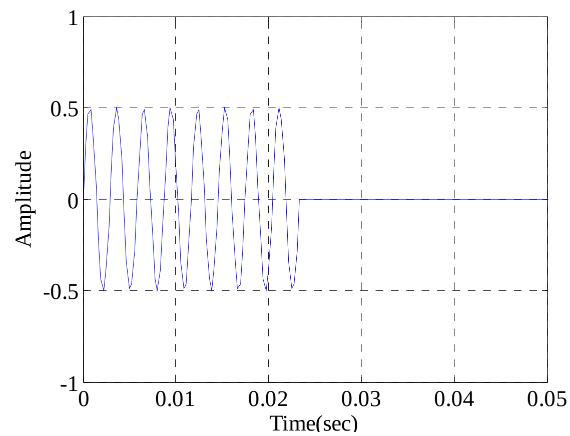



(b)

FIG. 2. Symbol for BPSK, (a) signal and (b) spectrum.




(a)




(b)

FIG. 3. Symbols for FSK: (a) a bit sequence with center frequency of 257 Hz, (b) a bit sequence with center frequency of 343 Hz,

*A. Superimposed Transmission with Crosstalk*

Figure 4 shows the acoustic field at 300 Hz, when the time-reversed signals from the individual probe sources at A and B are superposed and simultaneously transmitted. Since the individually focused signals are superposed, there is crosstalk between the receivers at A: (5800 m, 80 m) and B: (6200 m, 20 m) as can be seen in Fig. 5 and 6. In the numerical experiment for Fig. 5 and 6, FSK signal sequences in Fig. 3 are used as a probe signal to focus (or, self-equalization) at A, and BPSK singal sequences in Fig. 2 are used to focus at B.

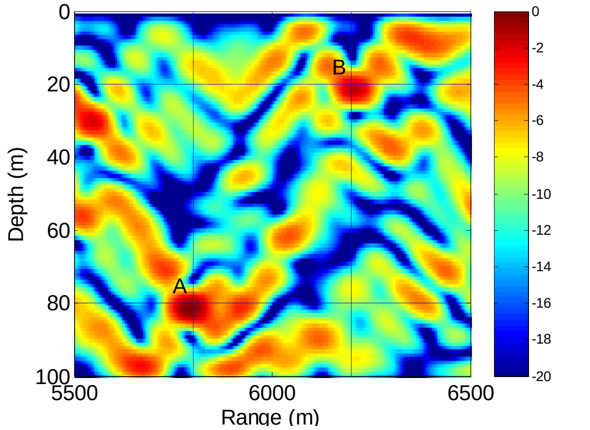
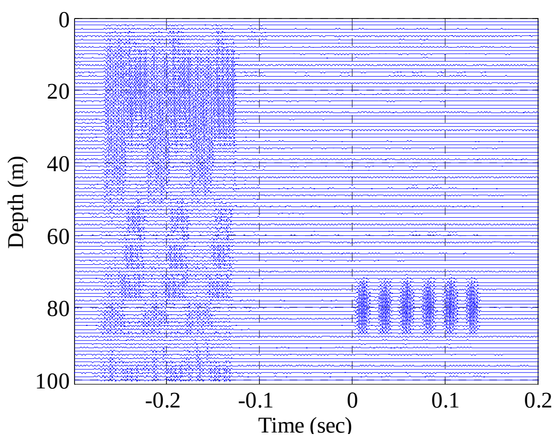
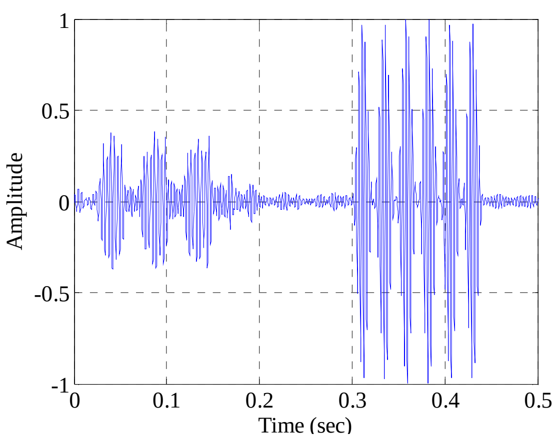



FIG. 4. Superposed contour plot of the acoustic field at the center frequency 300 Hz.



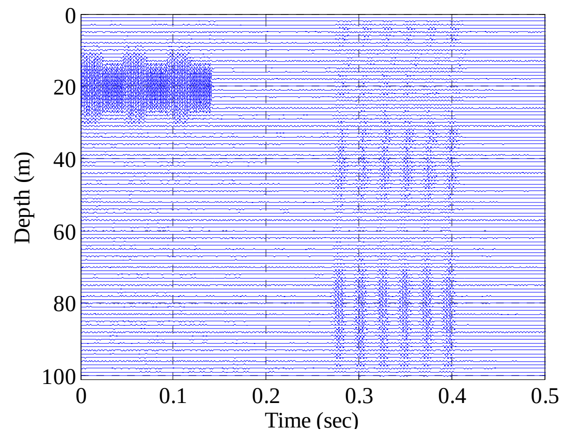

(a)



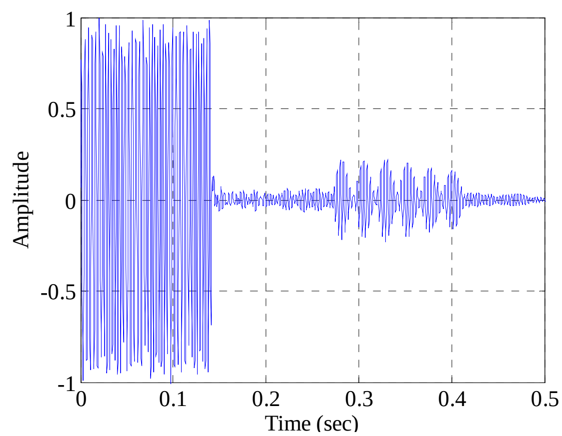

(b)

FIG. 5. Signals received at A: (a) Depth-stacked signals at range 5800 m, (b) signal at A

For this case, six FSK and BPSK bit sequences are used. As can be seen in Fig. 5(b) and Fig. 6(b), there is crosstalk. In Fig. 5(b), the BPSK signal sequences are focused at A and the FSK signal sequences are the unwanted cros stalk.




(a)




(b)

FIG. 6. Signals received at B: (a) Depth-stacked signals at range 6200 m, (b) signal at B

### *B. Superimposed Transmission without Crosstalk*

When the symbol sequences generated in *Sec. II.E* are superposed at Transmit/Receive array and backpropagated, the field at 300 Hz is shown in Fig. 7 and the symbols received at A: (5800 m, 80 m) is shown in Fig. 8. As expected, the FSK symbol sequencs do not appear at A. Only the BPSK symbol sequences are transmitted to A without interfering with FSK symbol sequences.

The same plots are shown in Fig. 9 for the receiver at B: (6200 m, 20 m).

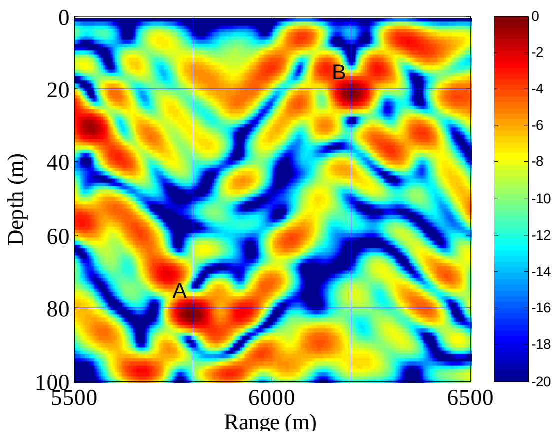
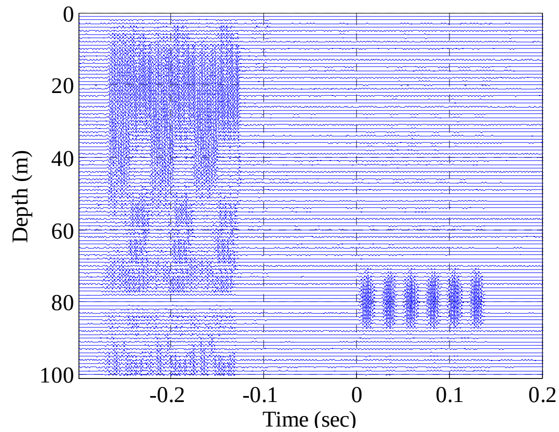
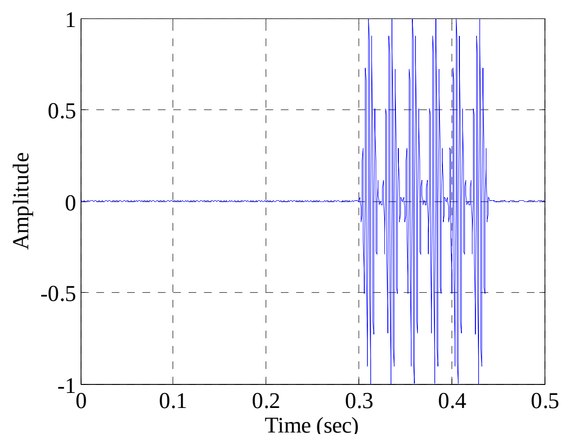



FIG. 7. Superposed field at the center frequency 300 Hz. (a) contour plot, (b) range vs. dB plot at focal point A, (c) depth vs. dB plot at focal point A, (d) depth vs. dB plot at focal point B, and (e) depth vs. dB plot at focal point B.

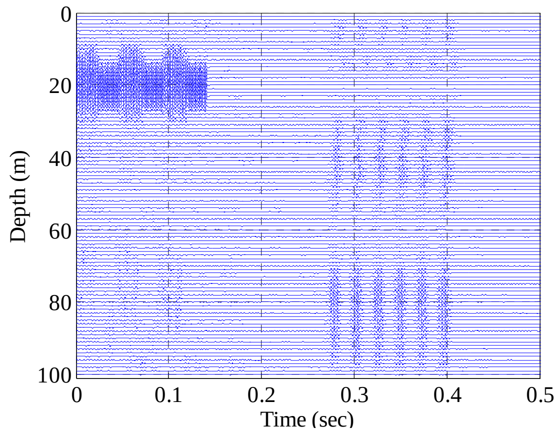



(a)

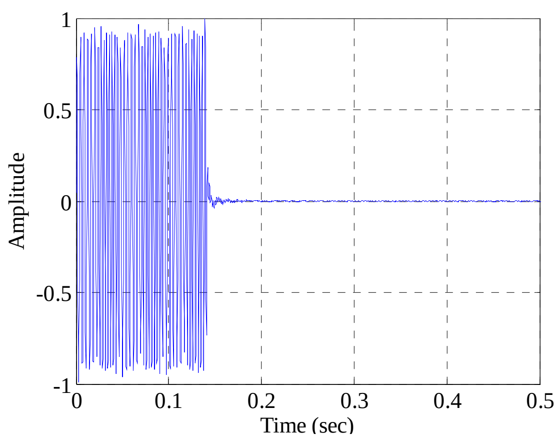



(b)

FIG. 8. Signals received at A: (a) Depth-stacked signals at range 5800 m, (b) signal at A.




(a)




(b)

FIG. 9. Signals received at B: (a) Depth-stacked signals at range 6200 m, (b) signal at B. (comm2/t_noct/noct.m)

## VI. SUMMARY

Based on ATRM, an underwater communication algorithm to cancel crosstalks between multiple receiving locations, while transmitting the different bit symbol sequences to different receiver locations, is developed and demonstrated through simulation.


### Acknowdgments

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## REFERENCE


[1] Mathias Fink, “Time –reversal mirror,” J. Phys. D 26, 1330-1350 (1993).

[2] Mathias Fink, “Time Reversed Acoustics,” Physics Today 50, 34-40 (1997).

[3] D. R. Jackson and D. R. Dowling, “Phase conjugation in Underwater Acoustics.” J. Acoust. Soc. Am. 89, 171-181 (1991).

[4] W. A. Kuperman, W. S. Hodgkiss, H. C. Song, T. Akal, C. Ferla, and D. R. Jackson, “Phase conjugation in the ocean: Experimental demonstration of an acoustic time reversal mirror,” J. Acoust. Soc. Am. 103, 25-40 (1998).

[5] W. S. Hodgkiss, H. C. Song, W. A. Kuperman, T. Akal, C. Ferla, and D. R. Jackson, “A Long-Range and Variable Focus Phase-Conjugation Experiment in Shallow Water,” J. Acoust. Soc. Am. 103, 25-40 (1999).

[6] G. F. Edelmann, W. S. Hodgkiss, S. Kim, W. A. Kuperman, H. C. Song, and T. Akal, “Underwater acoustic communication using time-reversal,” Proceeding of Oceans 2001, pp793-798 (2001).

[7] J.S. Kim, H.C. Song, and W.A. Kuperman, “Adaptive time-reversal mirror,” J. Acoust. Soc. Am. 109, 1817-1825 (2001)

[8] J.S. Kim and K.C. Shin, “Multiple focusing with adaptive time-reversal mirror”, Submitted to JASA (2002)

[9] Don H. Johnson and Dan E. Dudgeon, *Array Signal Processing-Concepts and Techniques,* Prentice-Hall Signal Processing Series, Alan V. Oppenheim, Series Editor (Prentice Hall, Englewood Cliffs, HN, 1993).

[10] H. Cox, “Robust adaptive beamforming,” IEEE Trans. Acoust., Speech, Signal Prcess. ASSP-35, 1365-1376 (1987).

[11] J. Capon, “High resolution frequency wavenumber spectrum analysis,” Proc. IEEE 58, 1408-1418 (1969).

[12] M. Porter, KRAKEN: User's Manual