I. INTRODUCTION

The basic problem encountered in ocean acoustic communications is the time-dependent, highly dispersive nature of the channel. While procedures have been developed for line-of-sight and some multipath ocean environments to ranges typically much less than 100 km, very long range propagation utilizing the deep sound channel is particularly problematic. For example, data from the acoustic engineering test (AET) of the acoustic thermometry of ocean climate project clearly highlight these difficulties. During the AET, the propagation of 37.5 Hz bandwidth pulses at a carrier frequency of 75 Hz was observed at long range. The effective pulse length of \(1/37.5 = 25\) ms at the transmitter exhibits a time spread at the receiver of greater than 5 sec at the range of 3250 km, or about 200 times the length of the original “symbol.”

The AET was originally conducted as a tomography experiment in which the early arriving, weaker but visible and identifiable wavefronts were used for inversion of ocean properties (see Fig. 2). Tomographers typically discard a majority of the energy that is concentrated near the sound channel axis because the arrival structure cannot be related to a background ocean acoustic model. However, it is just this complex, high-energy late-arrival structure that can be utilized by acoustic time reversal methods to enable very long range acoustic communications without the necessity of employing computationally formidable multichannel equalizers.

In this paper, we demonstrate using the AET array data that time reversal combined with frequent channel updates to accommodate channel variations over the 20-min long reception, followed by a single channel decision-feedback equalizer (DFE) provides almost error-free performance using all 20 array elements. Further, using data from a single receive element with multiple receptions provides similar almost error-free performance as in the single reception array case, but of course with the bit rate reduction associated with the number of repetitions integrated.

The paper is organized as follows. Section II reviews the time reversal communications. Section III describes the tomography experiment conducted during November 1994. Section IV investigates the temporal variations of the channel. The proposed time reversal receiver and the resulting performance are presented in Section V.

II. TIME REVERSAL COMMUNICATIONS

Over the past several years, time reversal (or phase conjugation in the frequency domain) communications has been discussed extensively in the literature. The approach exploits spatial diversity to achieve spatial and temporal focusing in complex multipath environments. The preliminary system concept has been demonstrated using experimental data collected in shallow water for both active and passive time reversal communications. Mathematically, the two approaches are equivalent with the communications link being in the opposite direction by invoking spatial reciprocity of wave propagation. Yang addressed the difference between passive phase conjugation (PPC) and the decision-feedback equalizer approach and Preisig compared the PPC and channel-estimate based DFE (CE-DFE).

While the temporal focusing (pulse compression) achieved by the time reversal approach reduces intersymbol interference (ISI) significantly, there always is some residual ISI that results in saturation of the performance at high SNR. As a result, the time reversal approach has been combined with adaptive channel equalization, which simulta-
neously removes the residual ISI and compensates for slow channel variations to yield better performance than is achieved by time reversal alone. Indeed, Song and Kim have confirmed that the combination offers nearly optimal performance using the theoretical performance bounds derived in Ref. 12. Furthermore, comparison between theory and data suggests that the theoretical performance can provide a useful upper bound for predicting performance of time reversal communications. The combined approach is referred to as the correlation-based DFE by Yang. Since the time reversal approach collapses multiple channels into a single channel, the complexity of the successive DFE remains unchanged as the number of array elements increases, resulting in low computational complexity.

Normally, the time reversal approach assumes that the channel is time invariant or slowly varying. Passive time reversal applies spatiotemporal matched filtering to combine multichannel data, using either measured channel responses from channel probes or initial channel estimates from training symbols at the beginning of the data packet. In dynamic ocean environments, however, the channel can vary substantially over time and the performance of time reversal communications will deteriorate due to the mismatch between the actual and assumed channel impulse responses. A simple approach to avoid the mismatch is frequent transmission of a channel probe signal at the expense of data rate. A more elaborate approach is to track continuously the channel using previously detected symbols (decision-directed mode) prior to matched filtering without compromising the data rate. In fact, time reversal alone with frequent channel updates has been proposed and referred to as decision-directed passive phase conjugation (DDPCC). More recently it has been demonstrated that continuous channel updates prior to time reversal combining followed by a single channel DFE significantly improve the performance in a time-varying channel due to environmental fluctuations. Separately, joint time reversal combining with channel updates and multichannel equalization has been discussed with emphasis on the use of low complexity multichannel algorithms.

The combination of robustness from the self-averaging time reversal process and low computational complexity from both a single channel DFE and a significantly reduced number of taps due to temporal compression appears promising for challenging underwater acoustic communications. To date, however, time reversal communications has been demonstrated mostly in shallow water environments on the order of 100-m depth and up to 20-km range. Interestingly, Dowling suggested in the early 1990s that time reversal pulse compression would be beneficial for communications in deep water where the multipath spread is relatively long by analyzing deep-ocean propagation measurements (IWAC’90) conducted at 272 km range at 460 Hz.

In this paper, we investigate the feasibility of time reversal communications at long ranges in deep water. This is partly motivated by an earlier effort where acoustic tomography transmissions over a 3250 km path in the North Pacific Ocean at 75 Hz were examined using an adaptive multichannel DFE with integrated phase tracking and Doppler compensation. We will analyze the same data set using a temporally adaptive time reversal approach, i.e., multichannel time reversal combining with continuous channel updates followed by a single channel DFE.

### III. ACOUSTIC ENGINEERING TEST (AET)

As a preliminary test of the acoustic thermometry of ocean climate (ATOC) project, the acoustic engineering test was conducted for 7 days in November 1994 in the eastern North Pacific Ocean as shown in Fig. 1. A detailed description of the experiment can be found in Ref. 4 and here we review the main parameters relevant for our discussion.

The 75-Hz acoustic source $S$ was suspended at 652-m depth, near the sound-channel axis, from the floating instrument platform R/P FLIP moored off San Diego, California in 4000 m deep water. The source level was 195 dB re 1 $\mu$Pa at 1 m. The receiver denoted by $R$ was an autonomous vertical line array moored just east of Hawaii in water about 5300 m deep. The vertical receiving array consists of 20 hydrophones at 35-m spacing (1.75 wavelengths at 75 Hz) between 900- and 1600-m depth, below the sound-channel axis (650-m). The receiving array is located 3250 km away from the source. The geodesic acoustic path is depicted in Fig. 1 along with the bathymetry, indicating no significant feature. Sound speed profiles between the source and receiving array can be found in Fig. 5 of Ref. 4.

The tomography source transmitted a phase-modulated maximal-length shift-register sequence ($m$-sequence) at the carrier frequency of 75 Hz with a bandwidth of $W = 37.5$ Hz. The $m$-sequence contains 1023 binary digits (or chips) and the period of the sequence is 27.28 s with each digit consisting of two carrier cycles. The number of periods for each transmission was a mix of 20, 40, or 80 correspond-

![Image](https://via.placeholder.com/150)
The received data are complex demodulated to baseband and then rate of 37.5 bits every 27.28 s. In this paper, we will analyze the tomography signal is treated as a BPSK communication. It is possible to track the channel continuously that the tomography signal is treated as a BPSK communciation signal, it is possible to track the channel continuously about 6 sec. The early arriving wavefronts are visible but weak, while a majority of the energy is concentrated on the later arrivals while the final 1 s of the arrival exhibits a highly variable complicated structure associated with scattering of near-axial energy by internal waves. The 3-s delay spread is displayed in Fig. 2 for a single receiver (Ch#1) at the top of the vertical array (935-m). Note that about 3-s delay spread captures all the significant arrivals within 10 dB from the maximum. This truncated version of the channel response will be used for time reversal processing in Sec. V.

Figure 2 shows two 20-min AET receptions in time/depth format on JD321 and JD322 (28 h apart), respectively, displaying distinctive arrival patterns. The delay spread is about 6 sec. The early arriving wavefronts are visible but weak while a majority of the energy is concentrated on the later arrivals associated with low-order modes propagating near the sound-channel axis. The later arrivals with significant energy will be utilized for acoustic communications as opposed to the early identifiable rays used for typical acoustic tomography data analysis.

The binary m-sequence can be interpreted as a binary-phase shift-keying (BPSK) communication signal with an information rate of 37.5 bits/s. Alternatively, it can be treated as a direct sequence (DS) or pseudo-noise (PN) spread spectrum signal where each 1023 chip sequence represents a single information bit with a much slower data rate, i.e., 1 bit every 27.28 s. In this paper, we will analyze the m-sequence as a BPSK communication signal with a data rate of 37.5 bits/s. For communications processing, the received data are complex demodulated to baseband and then sampled at twice the symbol rate (i.e., 75 Hz) facilitating use of a fractionally sampled DFE in Sec. V.

IV. CHANNEL ESTIMATION

Acoustic tomography processing coherently combines multiple periods of the m-sequence in order to extract the low-level signal at long ranges as presented in Fig. 2. Now that the tomography signal is treated as a BPSK communication signal, it is possible to track the channel continuously at the symbol rate (37.5 Hz) so that we can evaluate how rapidly the channel is evolving. In the analysis that follows, the 40-period, 20-min long transmission on JD321 shown in Fig. 2(a) will be examined.

Using the known sequence of symbols, the temporal evolution of the channel response over the first 5-min period is shown in Fig. 3 for a single receiver (Ch#1) at the top of the vertical array (935-m). Note that about 3-s delay spread captures all the significant arrivals within 10 dB from the maximum. This truncated version of the channel response will be used for time reversal processing in Sec. V.

To further examine the temporal variations of the channel, the channel response can be correlated with the initial channel estimate, equivalent to the generalized $q(t)$ function for a single channel (i.e., $M=1$) such that

$$q(t; \tau) = g(-t; 0) * g(t; \tau),$$

where $g(t; \tau)$ is the response of the channel at delay time $t$ to an impulse applied at time $\tau$ and $*$ denotes convolution. The magnitude (correlation) and phase of the complex basebanded version of $q(0; \tau)$ function is displayed in Fig. 4. It should be mentioned that the phase tracking result shown in Fig. 4 (lower panel) is similar to the one presented in Ref. 5. The initial phase slope up to 300 s corresponds to a Doppler shift of $f_d=0.0015$ Hz.

As expected, the channel correlation steadily deteriorates and reduces to 3 dB at around 800 s (or 13-min). Incidentally, Worcester et al. reported that the coherence time for acoustic tomography is on the order of 13 min (about 28 periods). Our analysis of other AET transmissions, however, indicates that the coherence time measured by the 3-dB down criterion could be much shorter. For example, the data
corresponding to Fig. 2(b) are found to have the coherence time less than 5-min (12 periods). Thus, the plots in Fig. 2 are obtained from coherent averaging of just 12 periods of the \( m \)-sequence after appropriate Doppler processing.\(^4\)

Of course the 3-dB loss is not acceptable for this low-energy signal and requires more frequent channel updates to minimize the mismatch between the actual and assumed channels over the 20-min long reception. In fact, the channel updates will be performed every one or two periods for best performance as shown in Sec. V.

**V. RECEIVER AND PERFORMANCE**

The proposed receiver for processing the AET data is illustrated in Fig. 5 where passive time reversal multichannel combining is followed by a single channel decision-feedback equalizer.\(^8\) The spatiotemporal matched filter or demodulation filter corresponds to the channel response \( G_i(f) = G_0(f)H^*_i(f) \) where \( G_0(f) \) is the signal transmitted (i.e., rectangular envelope) and \( H_i(f) \) is the channel impulse response, since the received data are a convolution of the two signals. In our approach, phase tracking is conducted prior to the DFE so that the DFE focuses mainly on eliminating the residual ISI. We employ a decision-feedback carrier phase estimate based on the maximum likelihood (ML) criterion.\(^24\)

To accommodate the channel variations addressed in Sec. IV, frequent channel updates will be incorporated as illustrated in Fig. 6. The initial channel estimates from the \( N_T \) training symbols are applied as matched filters to the next block of \( L \) symbols for time reversal demodulation using the receiver in Fig. 5. The estimated \( L \) symbols are used for updating the channel estimates, which are then applied to the next block of \( L \) symbols for demodulation, and so on. For the channel estimates, we will use the least mean square (LMS)
algorithm for faster execution\textsuperscript{24} while the single channel fractionally sampled DFE ($K=2$) employs the RLS algorithm in our analysis. This hybrid approach allows for keeping the computational complexity minimal.

The performance of time reversal communications with continuous channel update applied to the data [JD321003800, Fig. 2(a)] is displayed as a scatter plot in Fig. 7(a). The output SNR is 7.3 dB using all 20 elements of the vertical array ($M=20$) with a bit error rate (BER) of 49/34782. For the same data set, Ref. 5 employed a multichannel DFE with integrated phase tracking and Doppler compensation and reported 6.3 dB output SNR. Note that explicit Doppler processing (resampling) was not required in our approach although phase tracking was carried out by a decision-directed carrier phase estimate. The number of fractionally spaced feed-forward taps in the equalizer is chosen to be 60 corresponding to about 0.8 s, which is much shorter than the 3-s delay spread (see Fig. 3) resulting from temporal compression of time reversal. The number of feedback taps in the equalizer is set to 30. The LMS step size for channel estimation is $\Delta=0.00025$ and the RMS forgetting factor for the adaptive DFE is $\lambda=0.9995$. The number of training symbols and update block size are $N_f=3 \times 1023$ (3 periods) and $L=2 \times 1023$ (2 periods), respectively.

In terms of computational complexity, the total number of parameters for the adaptive DFE is 90(=60+30) in addition to the channel estimation computations. Since the fast LMS algorithm is employed for channel estimation, it takes about 5-min on a conventional desktop workstation to process the 20-min long transmission using all 20 array elements. In contrast, the multichannel DFE approach in Ref. 5 involved 3600 parameters when using all 20 elements and, thus, used the LMS algorithm for the DFE. As pointed out in Sec. II, the impact of the number of receivers in the time reversal approach is minimal due to the subsequent processing by a single channel DFE.

The performance of time reversal communications for a number of different transmissions over a 2-day period (JD321–JD322) is presented in Fig. 8 in terms of BER when $M=20$ (circles) and $M=10$ (triangles). Transmission 1 refers to the data analyzed above [JD321003800, Fig. 2(a)]. The BERs are on the order of $10^{-3}$ using $M=20$ and increase to approximately $10^{-2}$ when using only 10 elements ($M=10$). The best performance with a BER of 1/34782 and 9.3 dB output SNR using $M=20$ is obtained from transmission 5 (JD322043800) shown in Fig. 2(b).

To this point, time reversal communications at basin scale has been demonstrated exploiting the spatial diversity of a vertical array for individual 20-min long transmissions. It might also be possible to achieve similar diversity from temporal variations of the channel, provided that the channel responses are sufficiently uncorrelated with each other. Recall from Sec. IV that the channel coherence time for the
AET data is in the vicinity of 5–13 min. To examine temporal diversity, we have selected a single element (Ch#1) and combined a total of 17 transmissions made over a 2-day period (JD321–JD322) with transmissions separated by 2 or 4 hr (two of them are shown in Fig. 2). In other words, this is single receive element communications with diversity being obtained from the multiple transmissions separated much longer than the coherence time. The resulting scatter plot is shown in Fig. 7(b) with a comparable performance of 7.3 dB and BER of 16/19368. Some of the 17 transmissions were only 10-min long and, thus, we processed just the first 10-min of data for each transmission. Note that all the parameters employed are identical except that the update block size is reduced by a half, i.e., \( L=1 \times 1023 \) (one period) to compensate for some fast-varying receptions.

VI. SUMMARY AND CONCLUSIONS

During November 1994, broadband acoustic signals were transmitted from a 75-Hz source to a 20-element, 700-m vertical array at approximately 3250 km range in the eastern North Pacific Ocean as part of the acoustic engineering test of the acoustic thermometry of ocean climate project. The AET tomography signal consisted of repetitions of a \( m \)-sequence containing 1023 digits with two carrier cycles per digit, which was treated as a BPSK communication signal with an information rate of 37.5 bits/s. Although the multipath arrivals spanned 5–8 sec, most of the energy was contained by the later arrivals associated with low-order modes in the last 2–3 sec. The AET array data were processed using time reversal multichannel combining with frequent channel updates to accommodate channel variations over the 20-min receptions, followed by a single channel fractionally sampled DFE. The excellent performance using all 20 elements (vertical spatial diversity) with low computational complexity demonstrated the feasibility of time reversal communications even at basin scale. In addition, the comparable performance of single receive element communications using multiple transmissions illustrated that temporal diversity is as effective as spatial diversity.

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