Ocean Variability Effects on Underwater Acoustic Communications

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Award Number: N00014-06-1-0193
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LONG-TERM GOALS

This proposed research seeks to identify, explain, and ultimately predict, the factors that significantly alter the operational effectiveness of underwater acoustic communications through experimental work and theoretical analysis. The long-term goal is to develop reliable, high throughput transceivers customized for coherent underwater acoustic communications.

OBJECTIVES

The research objective is to investigate the relationship between environmental fluctuations and the performance of coherent underwater acoustic communications at high frequencies (8-50 kHz) through experimental research and data analysis.

APPROACH

Several studies have been conducted in recent years that show correlation between high frequency acoustic fluctuations and environmental parameters. For example, effects of tidally driven temperature fluctuations on underwater coherent acoustic communications were studied for a carrier frequency of 18 kHz [1]. However, the relationship between environmental fluctuations and the performance of coherent underwater acoustic communications is not fully understood yet.

Underwater acoustic channels are challenging for coherent digital communications because of severe multi-path spread and limited bandwidth. Furthermore, the variability of the ocean environment can cause fast fluctuations of acoustic channels and these fluctuations result in additional limitations on digital communications. To study the environmental fluctuation effects over an extended period, a low complexity receiver that is able to accommodate fast channel fluctuations at high frequencies (8-50 kHz), including time-varying Doppler and fast phase variations, is needed.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2007**	2. REPORT TYPE **Annual**	3. DATES COVERED **00-00-2007 to 00-00-2007**

4. TITLE AND SUBTITLE **Ocean Variability Effects On Underwater Acoustic Communications**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Delaware,College of Marine and Earth Studies,,114 Robinson Hall,Newark,DE,19716**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
This proposed research seeks to identify, explain, and ultimately predict, the factors that significantly alter the operational effectiveness of underwater acoustic communications through experimental work and theoretical analysis. The long-term goal is to develop reliable, high throughput transceivers customized for coherent underwater acoustic communications.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

WORK COMPLETED

Based on the experimental research conducted by Ocean Acoustics Laboratory (OAL), the University of Delaware, we have developed a multi-channel combiner/decision feedback equalizer (DFE) for underwater acoustic channels. With the developed receiver, different types of PSK signals over an extended period in the Kauai experiment (KauaiEx) have been processed.

RESULTS

KauaiEx [2, 3] was conducted west of Kauai, HI, in 100 m deep water during June-July of 2003. As shown in Fig. 1, the bottom-mounted Telesonar Testbed acoustic source was deployed 5 m above the sea bottom. At about 3 km range, the 16-element Marine Physical Laboratory (MPL) autonomous receiving array spanned the entire water column. An extended period (27 hours) of acoustic measurements were conducted from 04:00 GMT on July 2 to 07:00 GMT on July 3, 2003, while the ocean environment was monitored in order to understand the role of environmental parameters in high frequency underwater acoustic communications. The surface wave spectrum and the water temperature profile were measured by a wave-rider buoy and a thermistor chain deployed along the propagation path. The wave-rider buoy was deployed about 1.2 km away from the source. The thermistor chain shown was about 400 m away from the MPL array.

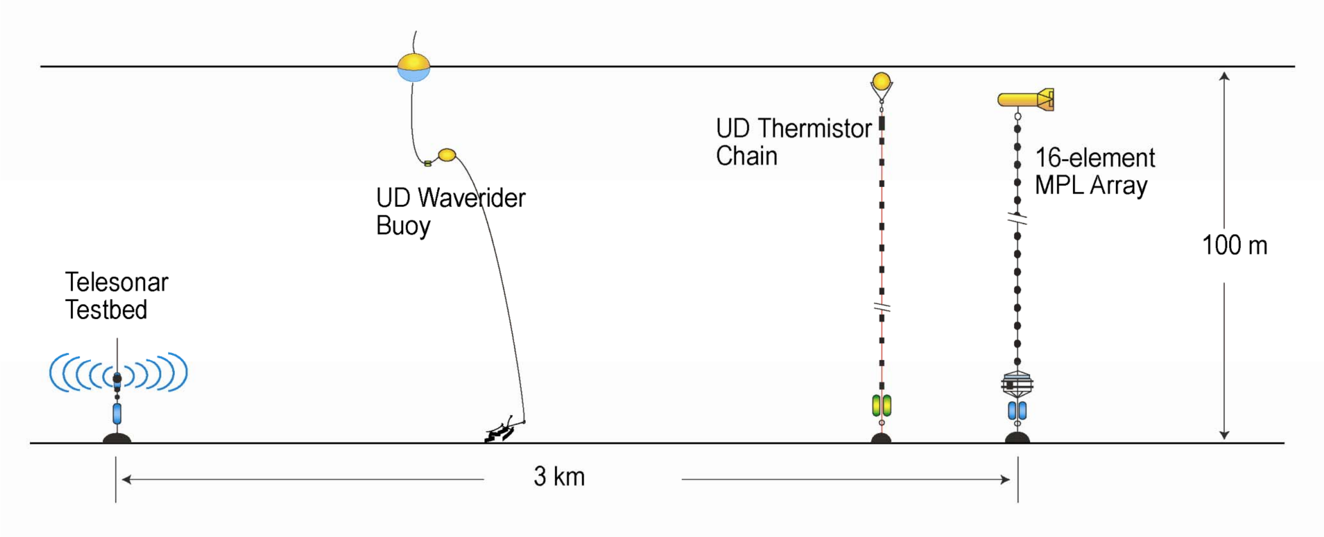

Fig. 1. In KauaiEx, the water depth was 100 m. The bottom-mounted Telesonar Testbed acoustic source was deployed 5 m above the sea bottom. At about 3 km range, the 16-element MPL autonomous receiving array spanned the entire water column. The surface wave spectrum and the water temperature profile were measured by a wave-rider buoy and a thermistor chain along the propagation path. The wave-rider buoy was deployed about 1.2 km away from the source. The thermistor chain shown was about 400 m away from the MPL array.

Along with acoustic measurements, the surface wave spectrum and the 2-D water temperature profile were measured by a wave-rider buoy and a series of thermistor chains deployed along the propagation path. As shown in the middle panel of Fig. 2, the wind speed underwent a late morning (Hawaii local time 10:00AM, e.g. 20:00 GMT) increase and a late night decrease as indicated by the sea surface wave spectrum. The corresponding significant wave height varied from 1.4 m to 1.0 m as shown in the top panel of Fig. 2. The water temperature profile shown in the bottom panel of Fig. 2 was measured by a thermistor chain deployed about 400 m away from the MPL array. Note that for most of the time the water column was well mixed down to about 50 m depth. A cold layer (about 4-5 degree lower than the mixed layer) emerged at nearly tidal cycles. The salinity was measured and can be treated as constant in the propagation field. Mainly acoustic data during two environmental conditions marked as A and B in Fig. 2 will be discussed. Case A corresponds to around 12:00 GMT on July 2 when the sea surface was relatively calm and the water column was well mixed. The significant wave height during case A was about 1.1 m. Case B is from 21:00 GMT on July 2 to 03:00 GMT on July 3 when the sea surface was rougher and the water column was layered. The significant wave height during case B was about 1.3 m.

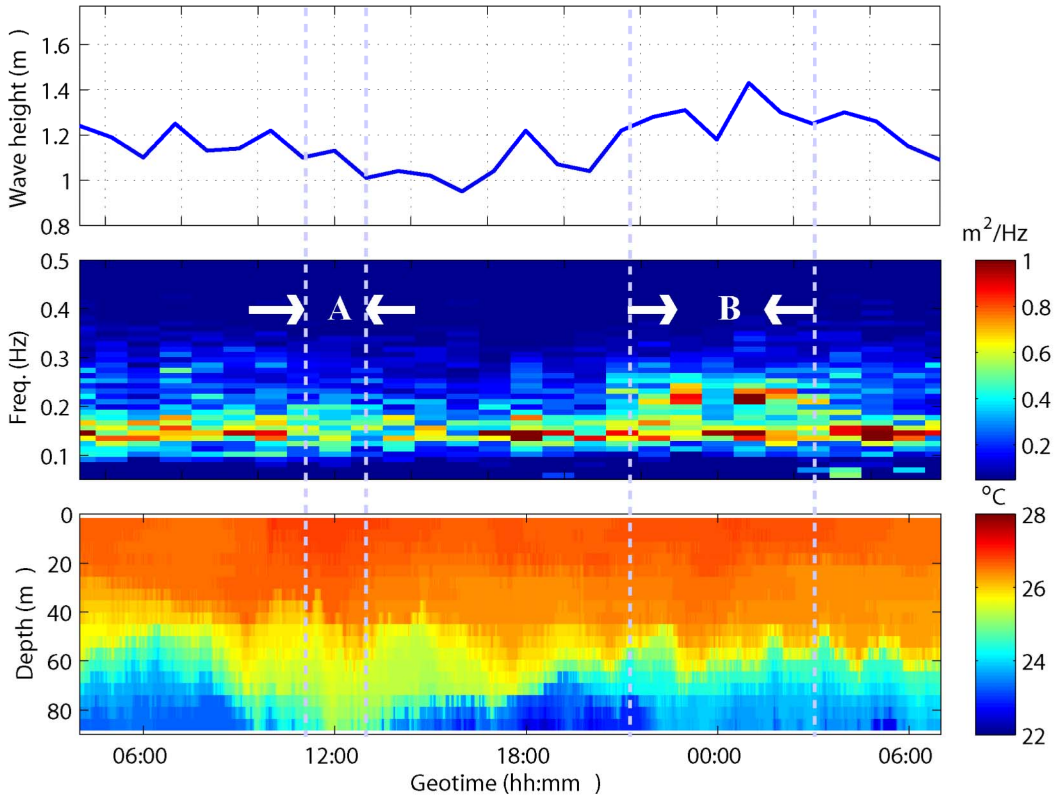

Fig. 2. Top panel: measured significant wave height; Middle panel: measured surface wave spectrum; Bottom panel: measured temperature profile from 04:00 GMT on July 2 to 07:00 GMT on July 3, 2003, in KauaiEx. Note around 12:00 GMT on July 2 (environmental case A), the water column was well mixed and the sea surface was relatively calm. From 21:00 GMT on July 2 to 03:00 GMT on July 3 (environmental case B), the water column was layered and the sea surface was rougher.

To recover the transmitted symbols which have been passed through the time-varying multi-path acoustic channels, a new multichannel receiver structure is proposed. Several features are incorporated into the receiver structure: (1) continuous Doppler tracking and correction is used to minimize the Doppler effects, (2) frequent channel estimation is used to track channel fluctuations [4-6], and (3) compensation for residual phase fluctuations and inter-symbol interference after time reversal combining is done using a DFE [7]. As shown in Fig. 3, the receiver consists of three parts: Doppler tracking and correction, channel estimation and time reversal multichannel combining, and single channel DFE.

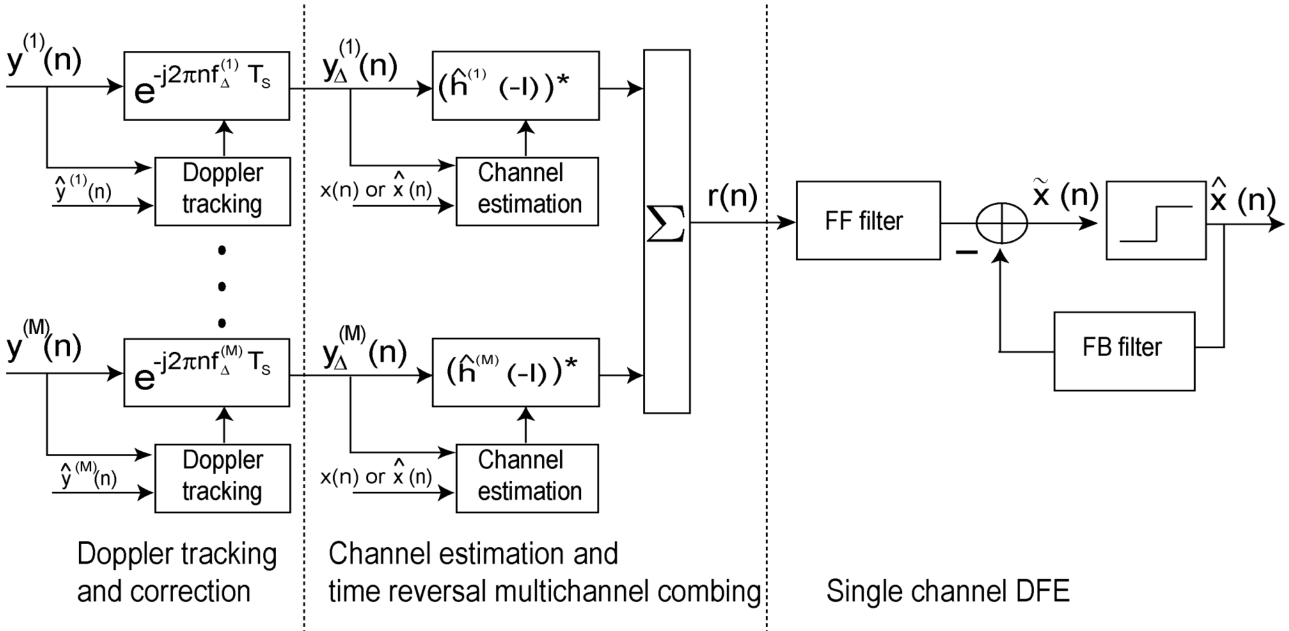

Fig. 3. The proposed receiver is composed of three parts: Doppler tracking and correction, channel estimation and time reversal multichannel combining, and single channel DFE.

In the literature, existing DFE approaches include: (1) multichannel DFEs developed by Stojanovic, *et al.* [4, 7-8] and (2) time reversal DFEs [9-11]. Although time reversal based, the proposed receiver has a different structure than the referenced time reversal DFEs where multichannel combining is performed based on channel probes or the known symbols at the beginning of the data packet. Phase tracking or Doppler tracking usually is performed after time reversal combining. Then an adaptive DFE is used to compensate for channel fluctuations. Compared with the referenced time reversal DFEs, the proposed receiver performs continuous Doppler tracking and channel estimation to combat fast carrier phase changes and channel fluctuations at the individual channels.

In the multichannel DFEs developed by Stojanovic *et al.*, feedforward filters are applied to the individual channels and their outputs are combined [4, 8]. Phase synchronization at the individual channels is optimized jointly with the equalizer tap weights. The number of total adaptive feedforward filter taps increases with the number of channels. Compared with the multichannel DFEs developed by Stojanovic *et al.*, the proposed receiver uses a single channel DFE after time reversal multichannel combining.

The proposed receiver is equivalent to the optimum diversity combiner/DFE [12] under the assumption that the channel can be estimated perfectly and the noise is spatially and temporally independent Gaussian with the same spectral density. An advantage of the proposed receiver structure is its low complexity. Since the time reversal combining converts multiple channels into a single channel, the complexity of the successive DFE will not change when the number of hydrophone channels increases. The complexity of the receiver grows only linearly with the number of hydrophone channels because the complexity of the channel estimators grows linearly with the number of hydrophone channels if a fast least squares algorithm, such as the LSQR algorithm [5], is employed.

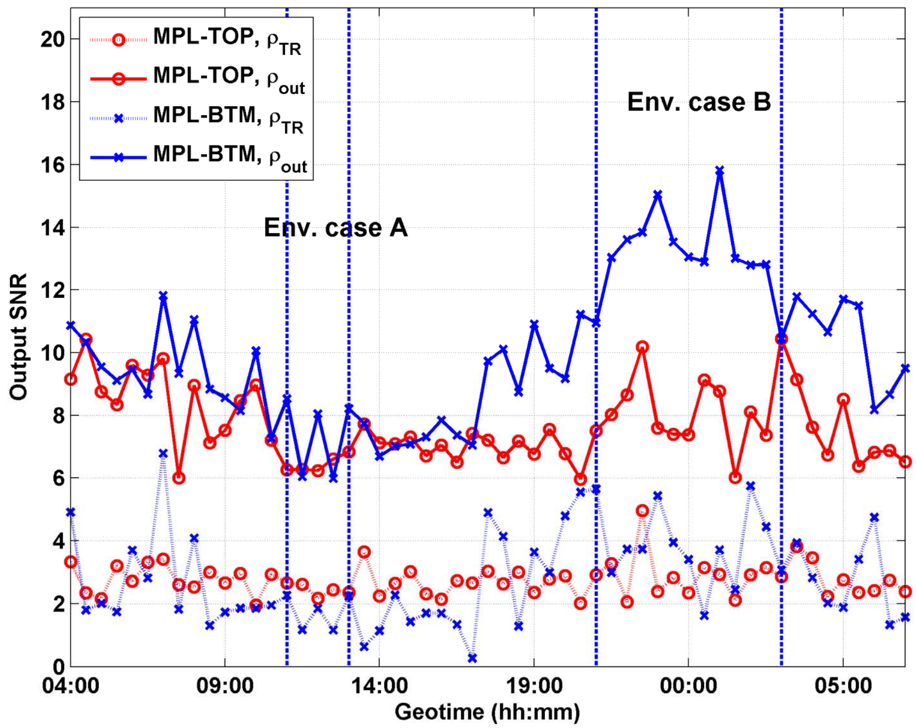

Fig. 4. The output SNR ρ_{out} on the MPL-TOP and MPL-BTM arrays over 27 hours from 04:00 GMT on July 2 to 07:00 GMT on July 3, 2003. The intermediate SNR results from time reversal combining also are shown as ρ_{TR}. Note the output SNR ρ_{out} on the MPL-BTM array during environmental case B is about 6 dB higher than that during enviromental case A.

Due to the large aperture and deployment range of the MPL array, the channel impulse response functions at the top and at the bottom of the array are different. To compare the performance of the communications data simultaneously recorded in the upper and the lower water column, the top 10 hydrophones of the MPL array (MPL-TOP) or the bottom 4 hydrophones of the MPL array (MPL-BTM) are considered as sub-arrays in the analysis because the CIR functions at these two sets of hydrophones show similarity among themselves. Fig. 4 shows the output SNR ρ_{out} on the MPL-TOP and MPL-BTM arrays for 27 hours. As mentioned, during the 27 hour MPL array recording period, the environment parameters underwent significant changes. Due to propagation variability, the performance of the receiver also experiences prominent changes. On the MPL-BTM array, the output SNR increases 5.8 dB during the change from environmental case A to environmental case B. In contrast, on the MPL-TOP array, the output SNR experiences a much smaller increase, 1.8 dB, when the environment changes from case A to case B.

The output after time reversal combining already provides an estimate for the transmitted symbols. The SNR in the output of time reversal combining after phase correction is defined as ρ_{TR}. Through a comparison between ρ_{TR} and ρ_{out}, the benefit of channel equalization can be seen. As shown in Fig. 4, post-processing with a DFE on the MPL-TOP and MPL-BTM arrays can improve the performance for all BPSK packets. For the MPL-TOP array, the improvement is 4.9 dB for the entire MPL array recording period and the improvement is roughly uniform along the geotime. In contrast, on the MPL-BTM array, the average improvement through use of a DFE is about 7.1 dB and the improvement varies during different environmental conditions. During environmental case B, the improvement is as high as 9.3 dB. The improvement of time reversal communications through use of a DFE has been discussed previously [11]. Here, the performance improvement is shown as a function of the ocean environmental parameters and the source/receiver geometry.

It is worthwhile to note that although the water column and sea surface condition varies during the 27 hour period, all BPSK packets can be demodulated successfully after the initial training preamble with a length of 1000 symbols both on the MPL-TOP and MPL-BTM arrays. However, even with ten hydrophones, the receiver with the MPL-TOP array usually has inferior performance to that with the MPL-BTM array, which only has four hydrophones. Such difference might be due to the fact most acoustic arrivals on the MPL-TOP array have sea surface interactions so that these arrivals are weaker and have shorter temporal coherence.

IMPACT/APPLICATIONS

The developed receiver is a robust structure for high data rate underwater digital communications at high frequencies. It can improve high data rate underwater acoustic modem design. The performance of coherent underwater acoustic communications indicates a strong correlation with the characteristics of the surrounding ocean environment which affects acoustic propagation. The exhibited relationship between environmental fluctuations and the performance of coherent underwater acoustic communications presents new insights into the operational effectiveness of underwater telemetry applications.

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