Ocean Variability Effects on Underwater Acoustic Communications

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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 rate 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. High rate communication methods are to be developed based on the understanding of acoustic propagation physics in dynamic shallow water environments.

APPROACH

The acoustic channel is regarded as one of the most challenging environments for data communication. Often cited difficulties include extended multipath, fast temporal fluctuations, and large Doppler spread [1]. These characteristics are challenging not only to receiver design, but also to channel modeling efforts. During the past year, we have dealt with both aspects, communication receiver design for high data rates and channel modeling for predicting modem performance in the dynamic ocean environment, based on our experimental data collected in shallow water regions in Kauai Island, HI.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
2012	**N/A**	**-**

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)
114C Robinson Hall College of Marine and Earth Studies, University of Delaware

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
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

WORK COMPLETED

1) Development of multiband time reversal transceivers for the underwater acoustic channel. As an alternative to orthogonal frequency-division multiplexing (OFDM) [2], we developed a multiband transceiver, where a wide frequency band is divided into multiple separated sub-bands. These sub-bands are several kilohertz in width, much wider than OFDM sub-carriers used in underwater channels. Intersymbol interference still exists for individual sub-bands. Time reversal acoustic communication is performed for each sub-band. The transceiver scheme has low complexity at both the transmitter and the receiver. Multiband time reversal communication demonstrated high data rates through the use of experimental data collected during 2011.

2) Development and validation of an acoustic channel model through the use of parabolic equations. While there is on-going work [3-4], the research community is still lacking adequate models that can provide realistic representations of the dynamic channel in the ocean. Advancements in underwater acoustic communication technology mainly rely on at-sea experiments, which are very costly. A realistic channel model not only can facilitate receiver design, help investigate channel limits, and aid in communication algorithm validation and comparison, it also can provide a basis for network level studies. We have developed a parabolic equation model combined with a surface model to generate realistic time-varying impulse responses of the acoustic channel. The channel model has been validated with our recent experimental data collected during 2008.

RESULTS

1) ***Multiband time reversal communication.*** During the KAM11 experiment (its setting illustrated in Fig. 1(a)), a frequency band of 10-32 kHz was utilized by ITC-1001 transducers. The transducers of a ship-tethered source array transmitted communication signals at four sub-bands, each of which was 4.5 kHz in width. The four sub-bands were centered at 12, 18, 24, and 30 kHz, respectively. The communication sequence at each sub-band had a symbol rate of 4 kHz. The 4.5 kHz sub-bands were separated by guard bands of 1.5 kHz in width. The spectrum of the transmitted signal is shown in Fig. 1(b).

A 16-element receive array was deployed 3 km from the source array. Time reversal decision-feedback equalizers (DFEs) were used to demodulate communication sequences at individual sub-bands. In the time reversal DFE (Fig.1(c)), time reversal combined the received multichannel signals into a single composite signal. The receiver estimated impulse responses and used them in time reversal combining to accommodate channel fluctuations [5]. Then an adaptive DFE was applied to equalize the ISI in the composite signal. The adaptation of the DFE coefficients was implemented by a recursive least-squares algorithm. Sparse channel estimation via the matching pursuit algorithm was employed to take advantage of the sparse property of the underwater channel. Due to the low transducer response at high frequencies, the received intensity at the 30 kHz band was 10 dB lower. This was reflected in the lower intensity of the impulse responses shown in Fig.1(e) than those in Fig.1(d). The advantage of the matching pursuit algorithm over the least squares method was apparent for a sub-band at 30 kHz, which had low raw SNRs. With least squares methods, the time reversal receiver failed at the sub-band of 30 kHz. By contrast, the receiver with the matching pursuit algorithm demodulated the communication sequence at 30 kHz at a low bit-error-rate (BER, 1.7%).

With matching pursuit channel estimation, the time reversal receiver demodulated multiband QPSK packets at low BERs (0.4%) across four sub-bands. A data rate of 32 kblits/s was achieved for the multiband quadrature phase-shift keying (QPSK) packets over the 20-32 kHz band.

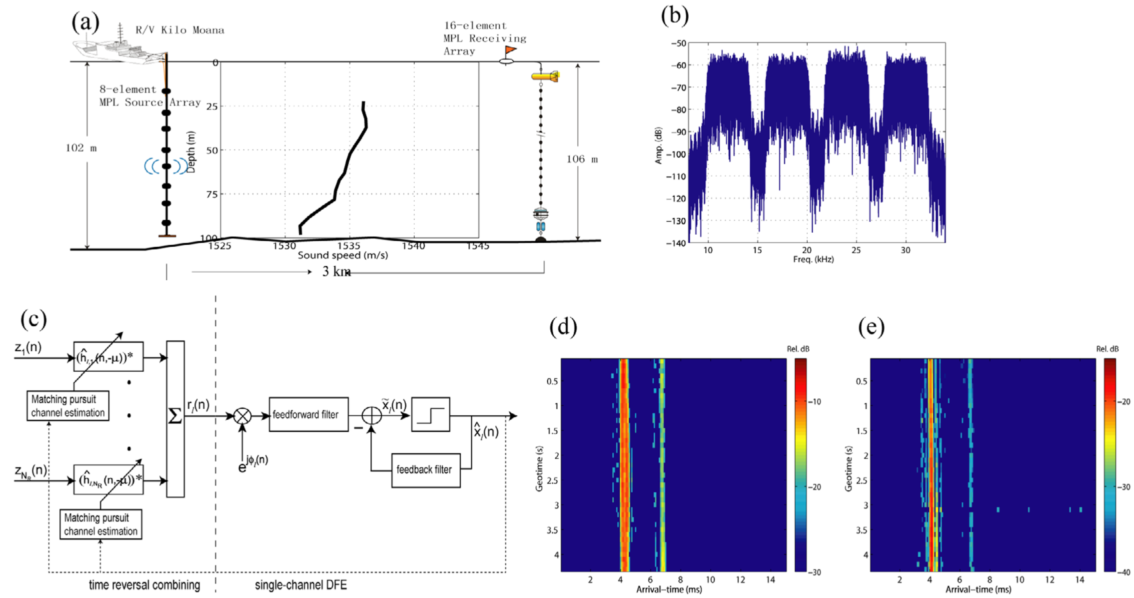

Figure 1. Multiband acoustic communication during KAM11. (a) KAM11 experimental setting. (b) Spectrum of the multiband transmission. (c) Time reversal DFE with matching pursuit as the channel estimation algorithm. (d) Estimated impulse responses at 24 kHz. (e) Estimated impulse responses at 30 kHz. Note that the color scale in (e) is 10 dB weaker than those in (d).

2) ***Communication channel model through parabolic equations.*** A communication channel simulator has been developed through the use of parabolic equation modeling of acoustic propagation and scattering. Specifically, the simulator uses the Monterey-Miami Parabolic Equation (MMPE) model [6] augmented with a linear surface wave model [7]. The linear surface wave model generates an evolving surface based on theoretical or experimental directional surface spectrum and feed the surface displacement and its derivatives to the acoustic model. Inferred from the surface roughness, a subsurface bubble layer is generated and fed to the MMPE model to account for scattering and reflection through bubble cloud [8]. The time-varying acoustic field is then calculated using successive MMPE runs when the ocean evolves in time. At each single run, the model accounts for surface scattering effects based on the surface input. It also accounts for propagation through the water column and through the sediment based on other environmental measurements such as sound speed profile, bathymetry, and bottom properties.

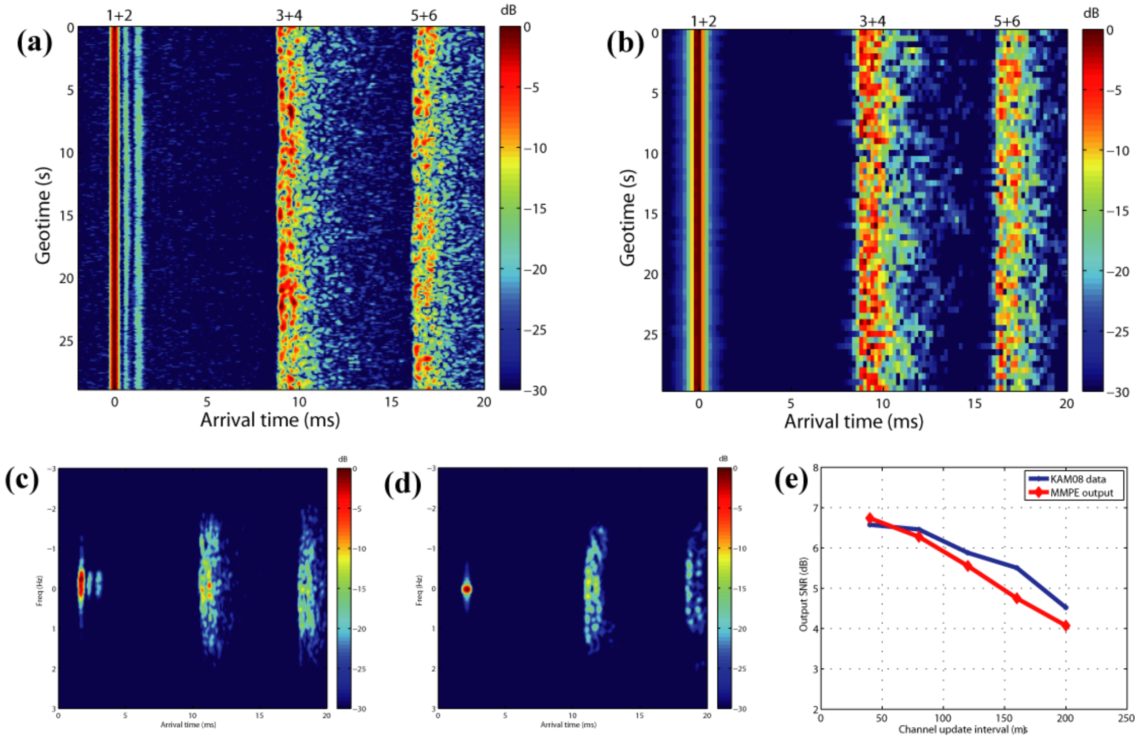

Figure 2. Acoustic channel simulation for KAM08. (a) Measurement impulse response over 30 seconds. (b) Simulated impulse responses. (c) Scattering function from measurement. (d) Scattering function from the simulation. (e) Communication performance comparison between measurements and simulations using time reversal demodulation versus different channel update intervals in the receiver.

The channel simulator is calibrated by experimental data obtained in KAM08 [8-10]. The source and receiver, separated by 1 km, were both placed in the lower water column of the ocean. The water depth was about 100 m. The surface model simulated a time-evolving surface from the directional surface spectrum obtained by a Waverider buoy in the experiment. Based on the surface input and other environmental measurements, the channel simulator generated realistic time-varying impulse responses for different ocean conditions.

Figure 2(a) show the measured impulse reseponses over 30 seconds between a source and a receiver, both of which were placed close to the seafloor. The combined direct and bottom returns marked as "1+2" were strong and had minimum spread over the arrival time axis. The surface returns marked as "3+4" or "5+6" show dispersive characteristics over the arrival time. These surface returns were also highly fluctuctuating. The model output (Fig. 2(b)) agreed well with the acoustic measurements (Fig. 2(a)) in terms of arrival time structure and intensity profile. Figure 2(c) and 2(d) show the scattering functions calculated from the experimental and simulated data. The arrival time structure of the experimental measurement was re-produced in the model results. For both experimental and simulated data, the combined direct and bottom returns, which correspond to the focused areas before 5 ms arrival time, were strong and had minimum spread over the Doppler axis. The surface returns in Fig. 2(c) nd 2(d) show dispersive characteristics both in the arrival time and Doppler axes. The Doppler spreads of the surface returns were similar in two subplots.

Our high frequency time reversal receiver [5] was applied to both the simulated data and the experimental data. The resulting acoustic communication performance comparison showed good agreement, with similar output signal-to-noise ratios (SNRs) and BERs. When the channel update interval adjusted in the receiver, the performances from the computer simulation and from the experimental data followed each other closely, as shown in Fig. 2(e).

IMPACT/APPLICATIONS

The developed acoustic modem software can perform robust, high data rate digital communications in shallow water environments. The developed channel simulator can predict acoustic modem performance in the dynamic ocean environment. These advancements have direct impacts on defense appliations since underwater acoustic modems are critical to a number of naval operations.

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