MURI: Impact of Oceanographic Variability on Acoustic Communications

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LONG-TERM GOALS

Couple together analytical and numerical modeling of oceanographic and surface wave processes, acoustic propagation modeling, statistical descriptions of the waveguide impulse response between multiple sources and receivers, and the design and performance characterization of underwater acoustic digital data communication systems in shallow water.

OBJECTIVES

Develop analytical/numerical models, validated with experimental data, that relate short-term oceanographic variability and source/receiver motion to fluctuations in the waveguide acoustic impulse response between multiple sources and receivers and ultimately to the capacities of these channels along with space-time coding and adaptive modulation/demodulation algorithms that approach these capacities.

APPROACH

The focus of this research is on how to incorporate an understanding of short-term variability in the oceanographic environment and source/receiver motion into the design and performance characterization of underwater acoustic, diversity-exploiting, digital data communication systems. The underlying physics must relate the impact of a fluctuating oceanographic environment and source/receiver motion to fluctuations in the waveguide acoustic impulse response between multiple sources and receivers and ultimately to the channel capacity and the design and performance characterization of underwater acoustic digital data communication systems in shallow water. Our approach consists of the following thrusts.

1. Modeling short-term variability in the oceanographic environment.

The long-term (beyond scales of minutes) evolution of the physical oceanographic environment (e.g. due to currents and long period internal waves) imparts slow changes to the waveguide acoustic propagation characteristics. In contrast, surface waves driven by local winds and distant storms exhibit

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dynamics on much shorter scales (seconds to tens of seconds) and directly impact short-term acoustic fluctuations. In addition, shorter-period internal waves, finestructure, and turbulence also will contribute to propagation variability. An important question is the relative impact each of these has on short-term acoustic fluctuations. Here we will couple models of the background time-evolving oceanographic environment with models of the surface wave dynamics to provide realistic sound speed fields along with their spatiotemporal correlation structure.

2. Transformation of environmental fluctuations and source/receiver motion into waveguide acoustic impulse response fluctuations between multiple sources and receivers.

Both ray-based (Sonar Simulation Toolset and Bellhop) and full-wave (Parabolic Equation) propagation modeling methods will be used to transform simulated sound speed fields, surface wave dynamics, and source/receiver motion directly into dynamic acoustic pressure fields. A Monte Carlo approach will be used to simulate realistic time-varying impulse responses between multiple sources and receivers. As an alternative, adjoint methods quantify the sensitivity of the channel impulse response to oceanographic (and geometric) variability. The linear approximation inherent in the sensitivity kernel may be valid for only a limited dynamic range of the environmental fluctuations corresponding to just a few seconds at the frequencies of interest but might provide useful insight into the mapping between environmental and acoustic fluctuations and subsequently to estimating the environmentally-dependent acoustic channel capacity.

3. Spatiotemporal statistical descriptions of waveguide impulse response fluctuations.

Statistical descriptions summarizing the spatiotemporal relatedness of waveguide impulse response fluctuations provide insight into the influence of environmental dynamics and can be used for system design and performance evaluation purposes. The scattering function provides a useful description of the channel in time delay and Doppler. In addition to estimating the scattering function from ensembles of realizations of fluctuating impulse responses (either from realistic simulations or at-sea observations), we also will use the sensitivity kernel for the impulse response combined with the dynamics and statistics of the environmental fluctuations to estimate the scattering function.

4. Channel capacity and the design and performance characterization of underwater acoustic, diversity-exploiting, digital data communication systems.

Channel capacity sets an upper bound on the information rate that can be transmitted through a given channel. The capacity of the highly dispersive and fluctuating ocean environment cannot be derived in closed form but only simulated or derived from measurements. In addition, realistic (constrained) capacity bounds will be derived that include practical implementation issues such as those imposed by phase-coherent constellations and realizable equalization schemes. Based on multiple source and receiver channel models developed from measured waveguide characteristics, we will assess the capacity of underwater acoustic channels and these will serve as goals for the design of space-time coding techniques and adaptive modulation/demodulation algorithms. An especially challenging problem in multipath-rich waveguides is the design of coherent communication schemes between moving platforms.

5. Benchmark simulations and validating experimental data.

A set of benchmark simulation cases will be defined for use in exploring transmitter/receiver design and performance characterization in the deployment of diversity-exploiting digital data telemetry systems (point-to-point and networked). Both fixed-fixed (stationary) and moving source and/or receiver scenarios will be considered across bands of frequencies in the range 1-50 kHz. Multiple source and receiver cases (MIMO) will be of particular interest. Validating experimental data will be obtained during the ONR acoustic communications experiment in summer 2008 and other follow-on experiments.

To address the issue of underwater acoustic digital data communication in a fluctuating environment, we have brought together a multidisciplinary research team consisting of oceanographers, ocean acousticians, and signal processors. Team members consist of faculty and researchers from four universities and unfunded collaborators from private industry and a navy laboratory:

- University of California, San Diego (UCSD) - W.S. Hodgkiss, W.A. Kuperman, H.C. Song, B.D. Cornuelle, and J.G. Proakis
- University of Washington (UW) - D. Rouseff and R. Goddard
- University of Delaware (UDel) - M. Badiey and J. Kirby
- Arizona State University (ASU) - T. Duman
- Heat, Light, and Sound (HLS) - M. Porter, P. Hursky, and M. Siderius (Portland State University)
- SPAWAR Systems Center – San Diego (SSC-SD) – V.K. McDonald and M. Stevenson

WORK COMPLETED

A second shallow water acoustic communications experiment (KAM11) was conducted in early summer 2011 off the western side of Kauai, Hawaii (in the same location as KAM08). Both fixed and towed source transmissions were carried out to multiple receiving arrays over ranges of 1-8 km along with additional towed source transmissions out to 14 km range. The acoustic transmissions were in three bands covering 3.5 to 35 kHz. Substantial environmental data was collected including water column sound speed structure (CTDs and thermistor strings), sea surface directional wave field (waverider buoy), and local wind speed and direction.

Analysis of the previous KAM08 and new KAM11 experiment data this past year has included both fixed and moving source transmissions. Environmental analysis has included incorporating the impact of a time-varying sea surface into modeling of the fluctuating channel impulse response using both ray and Parabolic Equation (PE) acoustic models. Communication receiver design has included processors for orthogonal frequency division multiplexing (OFDM), multiple-input/multiple-output (MIMO) transmissions, and multi-user single-input/multiple-output (SIMO) communications. Lastly, progress has been made on the design aspects of adaptive modulation based on OFDM using as the design criterion maximizing system throughput in the channel for a specific target bit error rate.

Publications related to this MURI include journal articles [1-35] and conference publications [36-62].

RESULTS

The Kauai Acomms MURI 2011 (KAM11) Experiment was conducted in shallow water (80-200 m) west of Kauai, Hawaii, at the at the Pacific Missile Range Facility (PMRF) over the period 23 June – 12 July 2011. The objective of KAM11 was to collect acoustic and environmental data appropriate for studying the coupling of oceanography, acoustics, and underwater communications. The focus was on fluctuations over scales of a few seconds to a few tens of seconds that directly affect the reception of a data packet and packet-to-packet variability. The experiment region exhibited substantial daily oceanographic variability.

Reciprocal transmissions were conducted during KAM11 between two acoustic transceivers mounted on the seafloor at a depth of 100 m (see Fig. 1) [33]. As shown in Fig. 2, the passage of moving surface wave crests generated focused and intense coherent acoustic returns that had increasing or decreasing delay depending on the direction of propagation relative to the direction of surface wave crests. A rough surface, two-dimensional parabolic equation model has been developed to address acoustic scattering and reflection from a moving sea surface and associated subsurface bubbles [32]. As shown in Fig. 3, the model can produce qualitative agreement with data for the dynamic surface returns.

Data appropriate for testing multiuser acoustic communication receiver design also was collected during KAM11 (see Fig. 4) [28]. The receiver block diagram is shown in Fig. 5 and consists of an adaptive time reversal (ATR) multichannel combiner embedded within an iterative successive interference cancellation (SIC) framework. With the addition of matching pursuit (MP), a sparse channel estimation technique, the receiver provides both temporal interference cancellation as well as spatial interference suppression in decoding simultaneous transmissions from separate users in a time-varying environment. The decoding performance is illustrated in Fig. 6 where a comparison is made between single user performance (only one user transmitting) and multiuser performance (packets from both users added together). In addition, it is shown that ATR alone would not have achieved satisfactory results.

IMPACT/APPLICATIONS

Acoustic data communications is of broad interest for the retrieval of environmental data from in situ sensors, the exchange of data and control information between AUVs (autonomous undersea vehicles) and other off-board/distributed sensing systems and relay nodes (e.g. surface buoys), and submarine communications.

RELATED PROJECTS

In addition to other ONR Code 322OA and Code 321US projects investigating various aspects of acoustic data communications from both an ocean acoustics and signal processing perspective, a second MURI also is focused on acoustic communications (J. Preisig, “Underwater Acoustic Propagation and Communications: A Coupled Research Program”).

PUBLICATIONS

Journals

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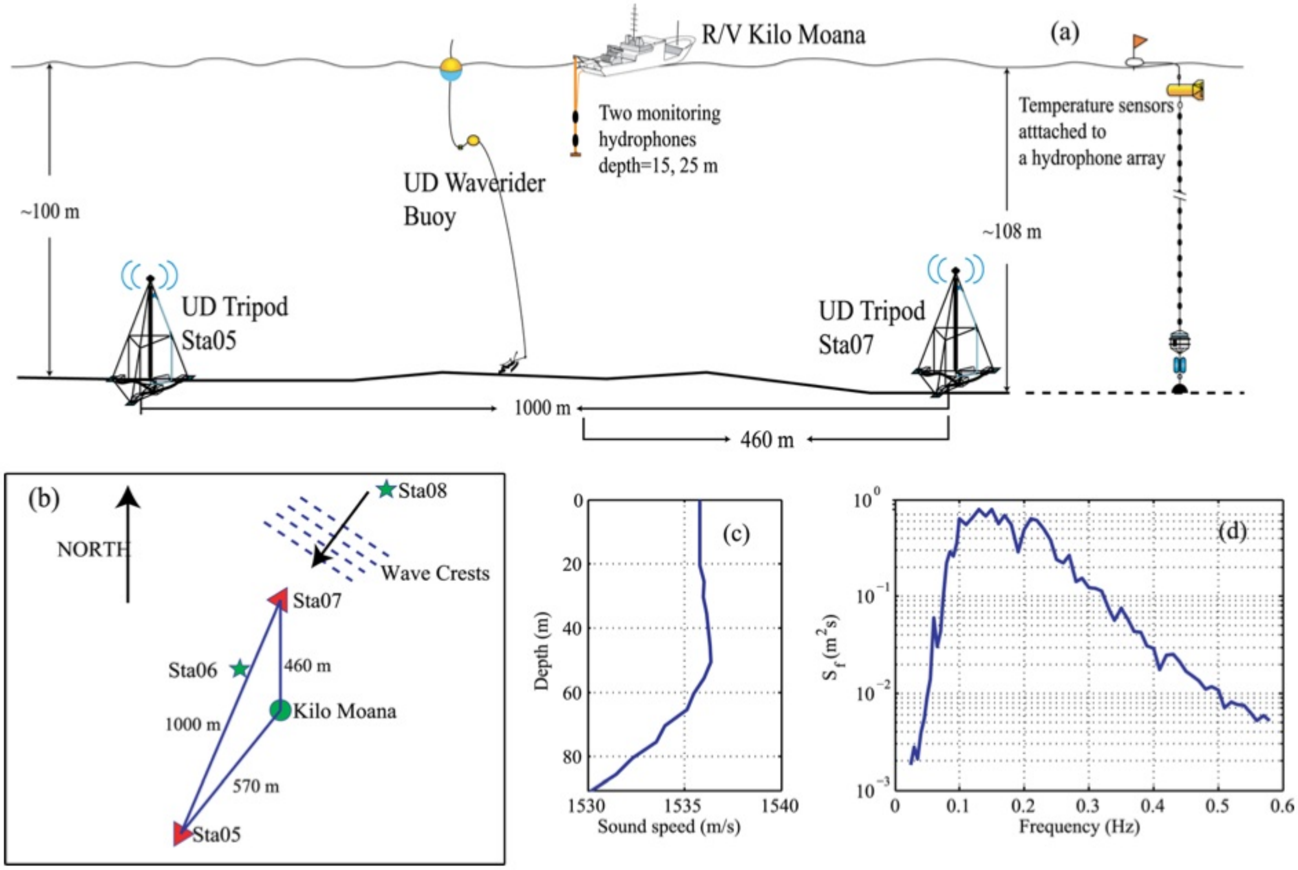


Figure 1. High frequency acoustic reciprocal transmissions under variable surface gravity waves during the KAM11 experiment. (a) Experiment setting. (b) Top view of source-receiver positions, surface waverider buoy, and monitoring hydrophones tethered to R/V Kilo Moana, with respect to the surface wave propagation. (c) Measured sound speed profile. (d) Measured surface gravity wave spectrum showing a strong wind-driven component at 0.1-0.2 Hz.

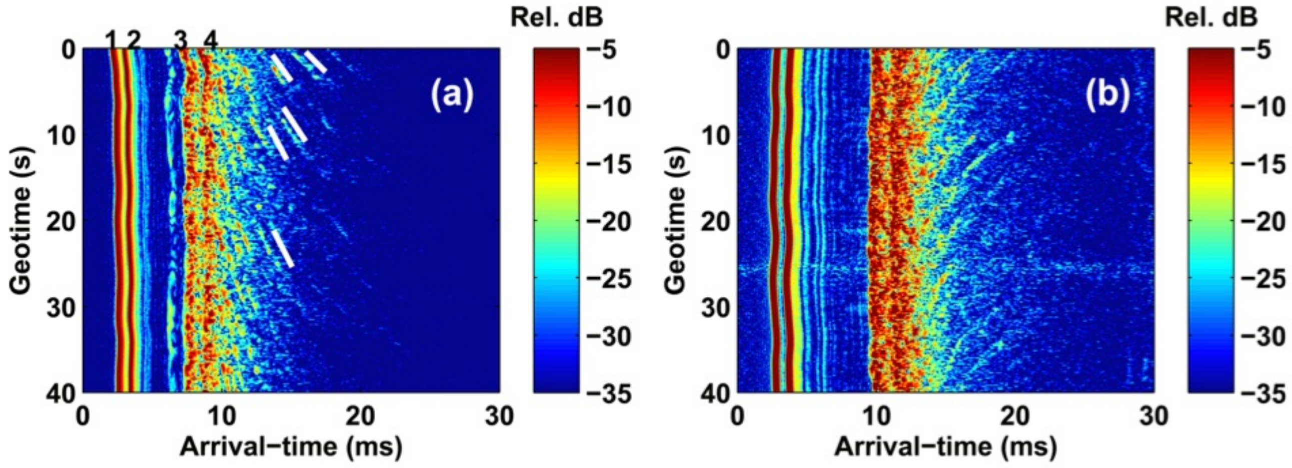


Figure 2. Measured acoustic signals at a hydrophone in the upper water column from left and right transmission stations in Fig. 1(a). Surface paths show a strong intensity and arrival-time fluctuations of surface paths, resulting from focusing effects of surface gravity waves. Extended fringe pattern shows intensity highlights for the surface reflected acoustic paths as the surface gravity water waves propagate above the source-receiver track.

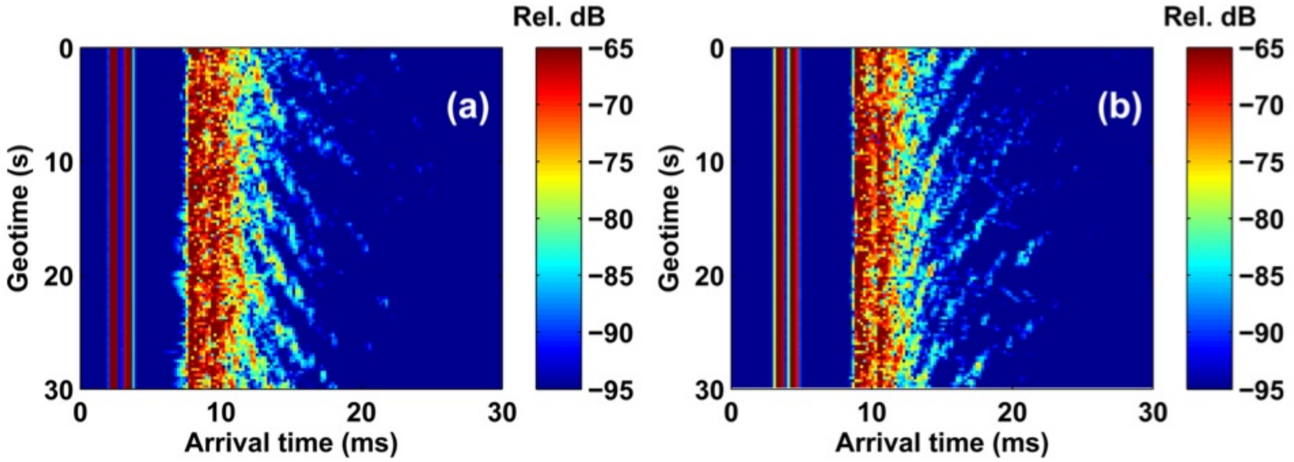


Figure 3. Two dimensional parabolic equation modeling results generate similar fluctuating characteristics of the surface returns seen in Fig. 2 with similar extended fringe patterns.

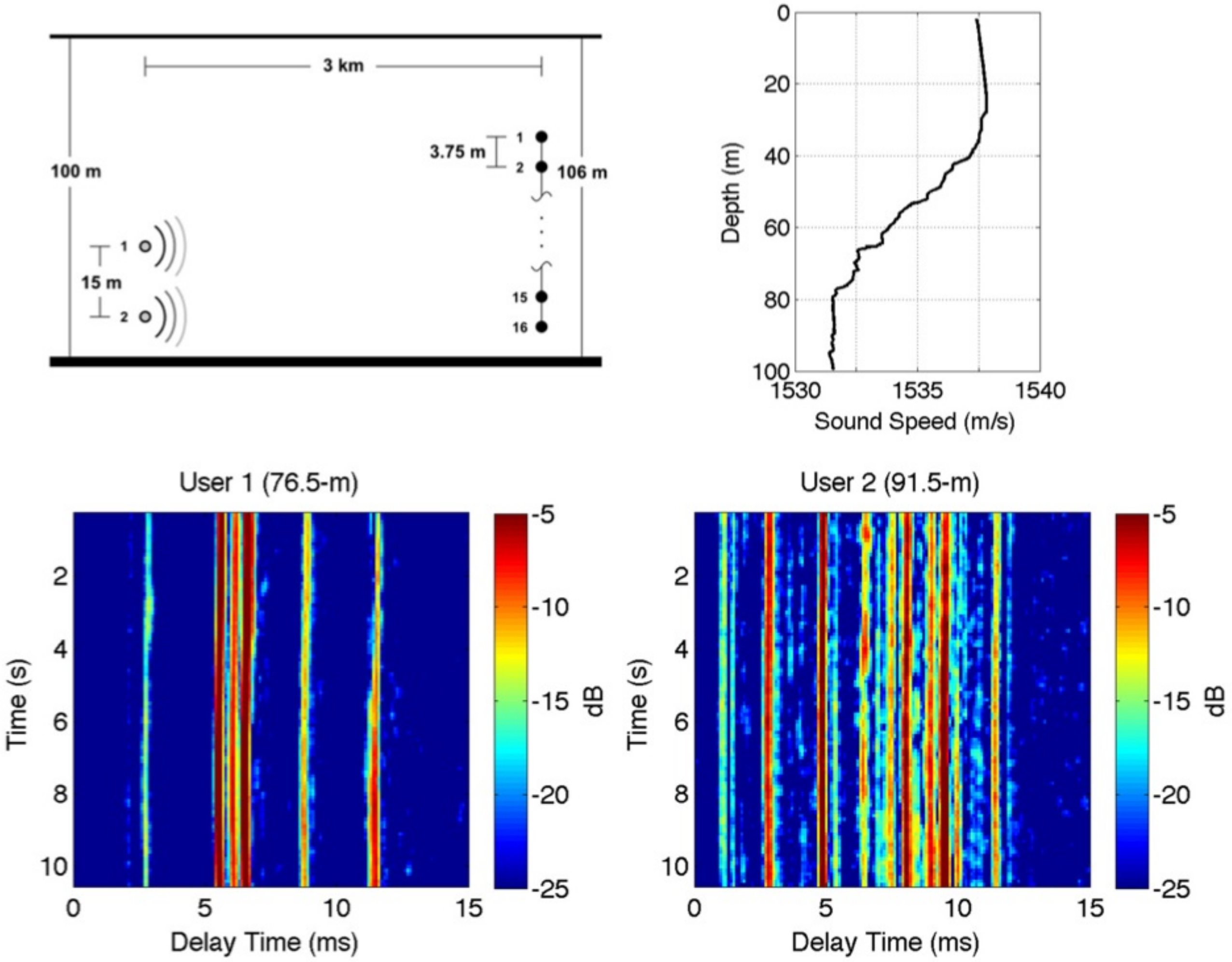
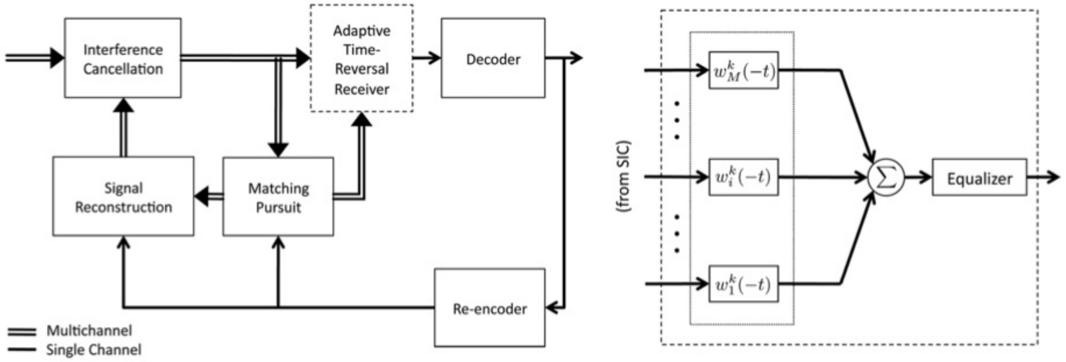
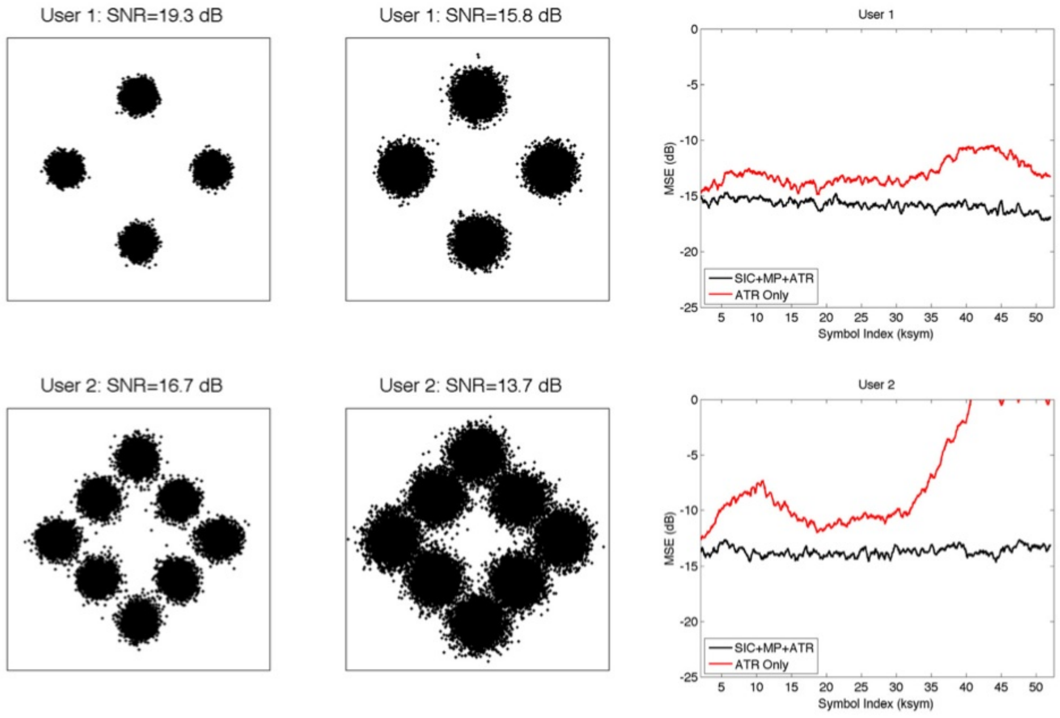


Figure 4. KAM11 experiment configuration and environmental conditions during collection of multiuser data: (top) Diagram of the KAM11 experiment in which two users transmit to a 16-element receiving array in 100-m deep water and an example sound speed profile collected during the experiment illustrating the downward refracting environment; (bottom) Example channel impulse responses between User 1 (left) and User 2 (right) and a single element at 74-m depth of the receiving array taken from the output of matching pursuit (MP) during single-user processing.



(a) (b)

Figure 5. (a) A receiver block diagram with adaptive time reversal (ATR) and matching pursuit (MP) embedded in the successive interference cancellation (SIC) framework. (b) The ATR receiver for decoding user k. The filter weights are designed to minimize crosstalk from competing users without distorting the signal from user k.



(a) (b) (c)

Figure 6. Decoding performance for User 1 (top row) and User 2 (bottom row) from data collected during KAM11: (a) soft symbol estimates from decoding the packets in a single-user setting, (b) final soft symbol estimates after four iterations of the combined receiver from decoding the multiuser packet, (c) mean-squared error comparison between the ATR only receiver (without channel updates) and the proposed receiver.