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

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propagation characteristics. In contrast, surface waves driven by local winds and distant storms exhibit 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 be scheduled in the future.

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 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. 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 adaptive modulation and the characterization of channel capacity for sparse ISI channels.

Publications related to this MURI include journal articles [1-25] and conference publications [26-49].

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.

A set of mooring locations were defined with PMRF. These are shown in Fig. 1 adjacent to the 100 m isobath along with the deployment positions of the acoustic sources, receiving arrays, and environmental moorings. Environmental moorings deployed included a thermistor string at Sta04 and a waverider buoy at Sta06. Also, self-recording thermistors were attached to the receive arrays at Sta08 and Sta16.

Two source arrays were deployed. The first was a large-aperture, 8-element source array deployed at Sta02. The second was a small-aperture, 4-element source array deployed at Sta03. In addition two near-seafloor sources were deployed for shorter periods at Sta05 and Sta07 along with collocated small-aperture, 8-element vertical receive arrays. Two large-aperture, 16-element vertical receive arrays were deployed at Sta08 and Sta16 along with two shorter-aperture, 24-element vertical receive arrays at Sta09 and Sta17. Lastly, a small-aperture, 4-element vertical receive array was deployed from an RF buoy at Sta05 then later at Sta11 for receiving adaptive modulation transmissions from a ship-deployed, small-aperture, 4-element source array. In addition to the fixed-source transmissions, source tows were carried out in the area. These included tows close to and at long range from the receive arrays. The acoustic transmissions from all sources deployed in KAM11 were in three bands covering 3.5-35 kHz and included both environmental probing waveforms as well as communication transmissions.

Examples of the dynamic water column environment observed during KAM11 are shown in Figs. 2-3. The mixed layer depth changes from as little as 20 m to as much as 60 m or more over the course of 24 hours. Similarly, the wind speed and sea surface conditions exhibited a daily pattern. Fig. 4 shows wind speed and direction data along with waverider-derived sea surface wave spectra for the first seven days of the experiment.

The channel impulse response (CIR) was estimated using various waveforms (e.g. FM chirps and MLS sequences). In addition, the CIR naturally was estimated as part of the processing of communication waveform transmissions. Fig. 5 shows an example of the impulse response and demodulation results from one of the sources in the vertical source array deployed at Sta03 being received by the near-seafloor, 8-element receive array at Sta07. The center frequency was 13 kHz and the source-receiver range was 2 km. The CIR shows significant variations over the 10 s packet duration. The QPSK transmission was received with a data rate of 12 kilobits/s and a bit-error-rate of 0.3%.

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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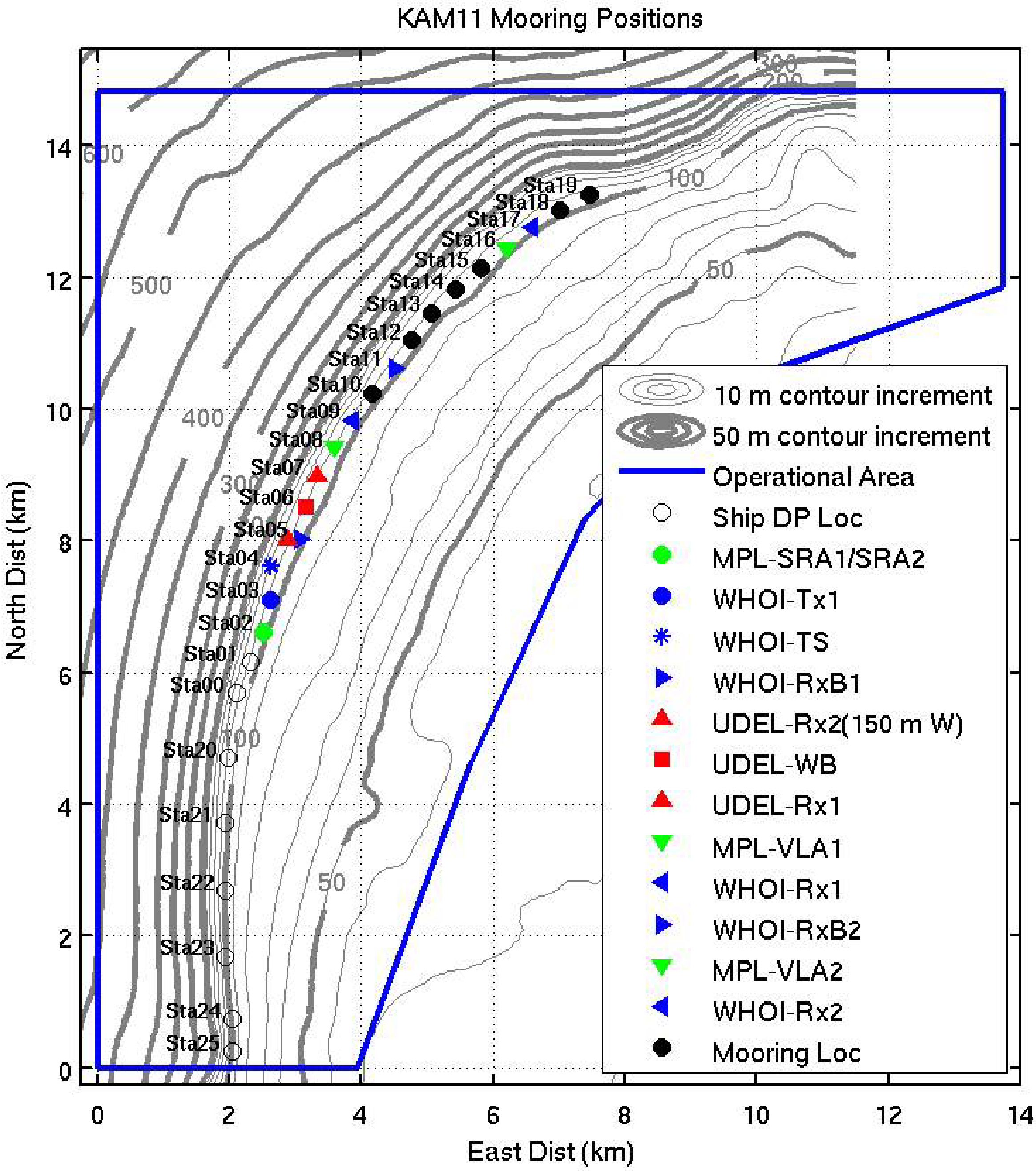
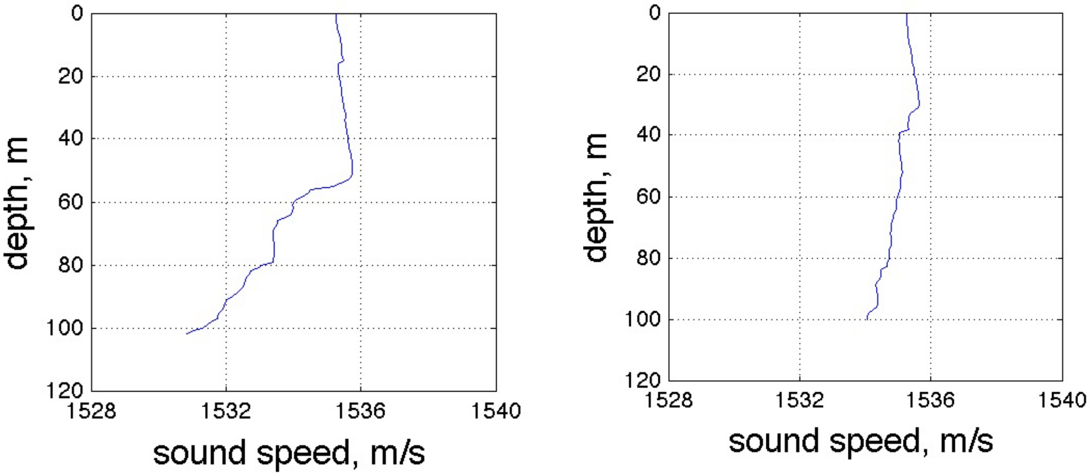
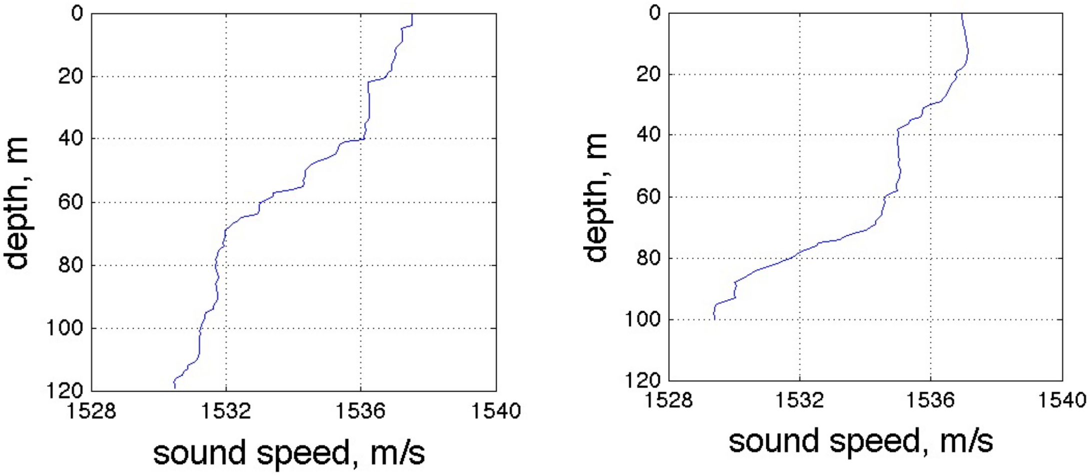


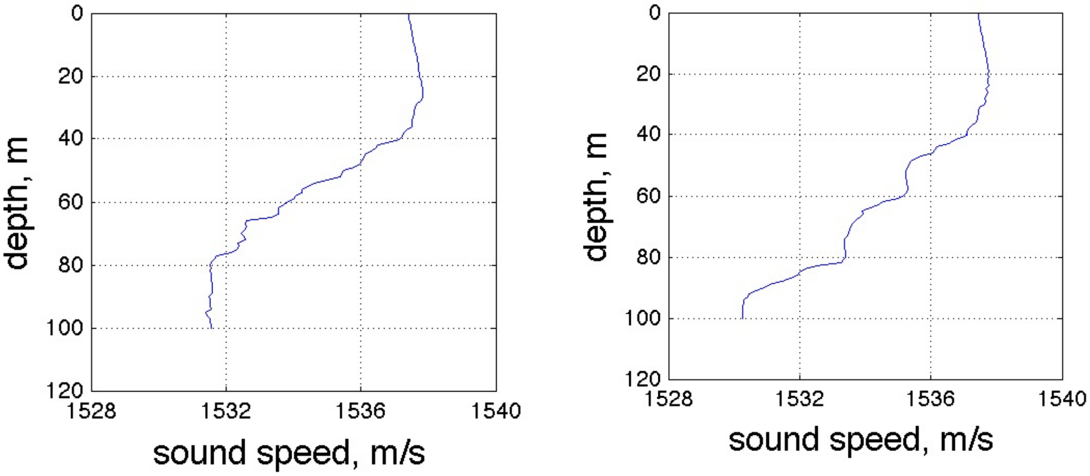
Figure 1. Mooring deployment positions in km with respect to the southwest corner of the KAM11 operational area (22˚04'N, 159˚50'W). Indicated are the deployment locations of both the environmental and acoustic hardware: TS (thermistor string), WB (waverider buoy), SRA (source-receive array), Tx (source array), RxB (receive array buoy), Rx (receive array), and VLA (vertical line array).



(a) CTD #01, Sta13 (JD175 1945Z). (b) CTD #03, Sta03 (JD176 1915Z).



CTD #05, Sta04 (JD184 2037Z). CTD #08, Sta16 (JD185 0250Z).



CTD #09, Sta06 (JD187 0540Z). CTD #10, Sta04 (JD187 0633Z).

Figure 2. Sound speed structure derived from CTD casts at various locations and times.

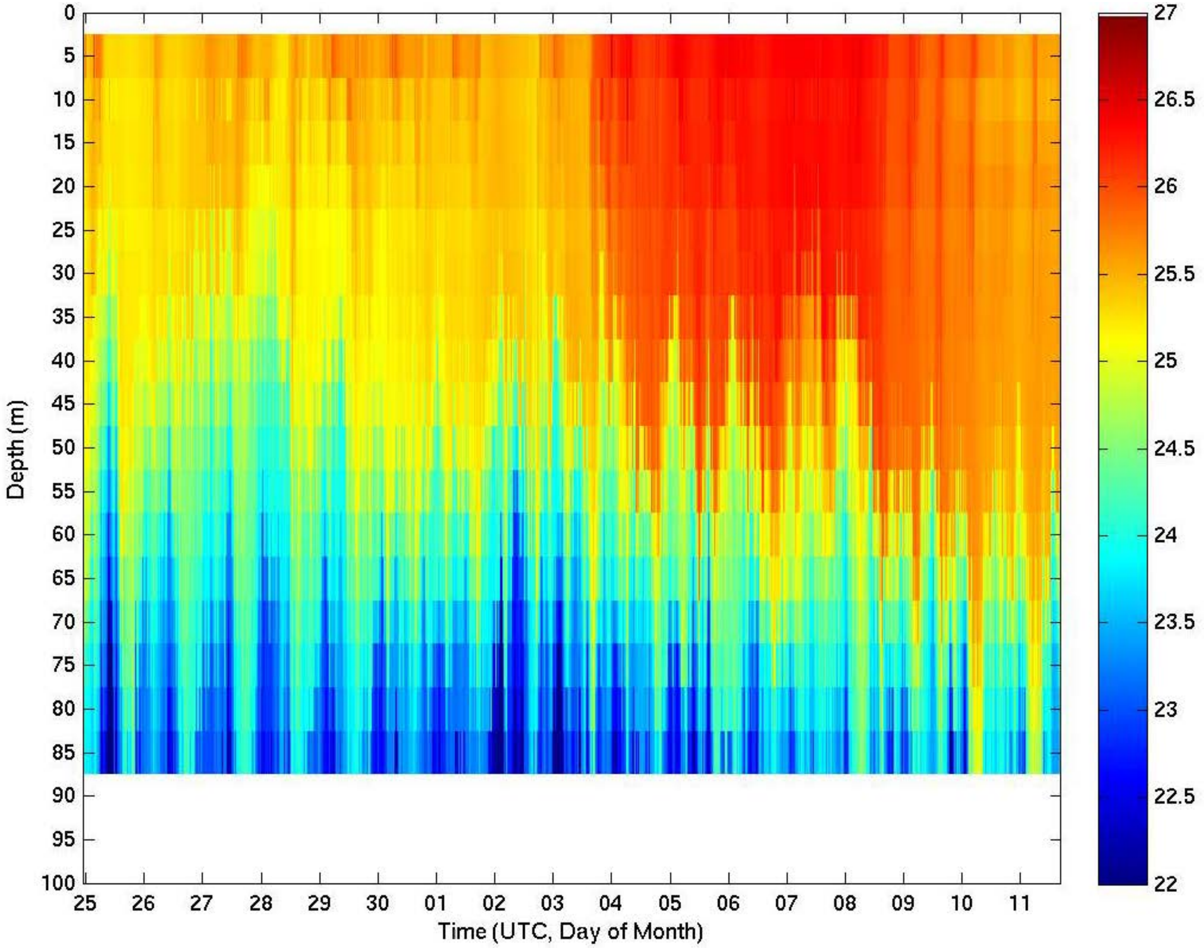


Figure 3. Temperature profiles recorded on the thermistor string deployed at Sta04 on 24 June 2011 (UTC).

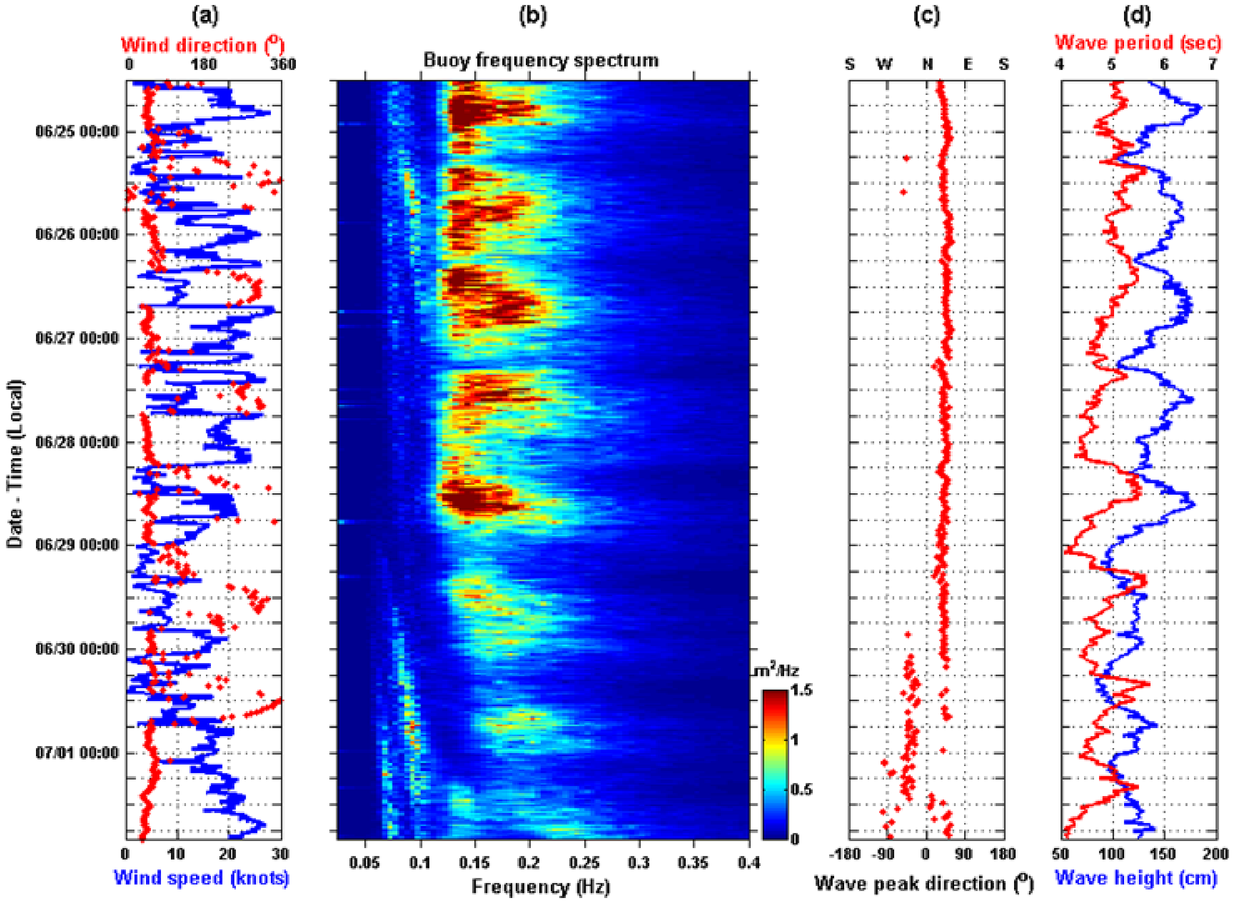


Figure 4. Ship wind speed and direction data along with waverider derived sea surface wave spectra, significant wave height, and wave period during first deployment of the waverider buoy 1200L on 24 June through 2000L on 1 July.

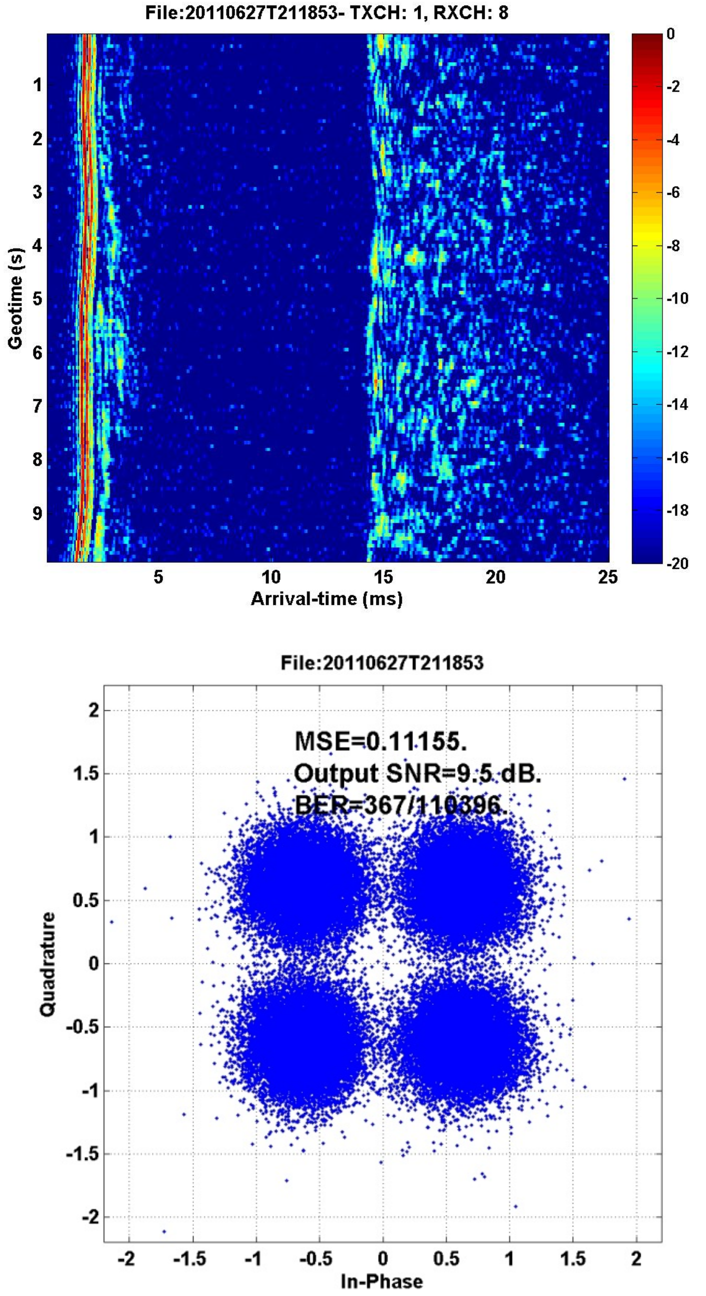


Figure 5. Example impulse response and demodulation results from a fixed source (Sta03, source depth 15 m) to a near-seafloor receive array (Sta07). The center frequency was 13 kHz. The source-receiver range was 2 km. (Top) Impulse response function at receiver depth 107 m. (Bottom) QPSK demodulation results at the 8-elment receive array with a data rate of 12 kilobits/s and a bit-error-rate of 0.3%.