Fluctuations of Mid-to-High Frequency Acoustic Waves in Shallow Water

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LONG-TERM GOALS

The long-term goal of this project is to obtain quantitative understanding of the physics governing broadband frequency (50 Hz to 50 kHz) acoustic signal propagation, reflection, refraction and scattering in shallow water and coastal regions in the presence of temporal and spatial ocean variability.

OBJECTIVES

The scientific objective of this research is to understand acoustic wave propagation in a dynamic environment in two different frequency bands: Low (50 Hz to 500 Hz) and Mid-to-High (500 Hz to 25 kHz). The priority for the low frequency band is to assess the effect of environmental anisotropy on acoustic wave propagation, with an emphasis on the separation of different effects due to horizontal refraction and mode coupling from adiabatic regimes. The priority for the mid-to-high frequency band is to assess the effects of water column and sea surface variability on acoustic wave propagation for underwater acoustic communications and tomography applications.

APPROACH

Combined experimental, theoretical, and modeling efforts are devoted to gain understanding of broadband acoustic wave propagation in shallow water. We aim to learn in detail about the channel impulse response (CIR) function with respect to environmental variations. Studies carried out in the low frequency band have been focused on the analysis of archival data as well as field data during the SW06 experiment [1, 15]. We have investigated different mechanisms that can explain sound intensity fluctuations in the presence of an internal solitary wave packet.

The mid-to-high frequency band part of our research is based on the experimental data collected during KauaiEx 2003 [2], MakaiEx 2005, and the recent KAM'08 [3]. The effects of sea surface and water column variability on acoustic wave propagation have been studied to understand the physics of the waveguide for 5-30 kHz frequency band for underwater acoustic communications application.

WORK COMPLETED

1) *Low Frequency Acoustic Wave Propagation.* Progress has been made in understanding the three-dimensional (3-D) effect of low frequency propagation in shallow water in the presence of internal

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14. ABSTRACT

The long-term goal of this project is to obtain quantitative understanding of the physics governing broadband frequency (50 Hz to 50 kHz) acoustic signal propagation, reflection, refraction and scattering in shallow water and coastal regions in the presence of temporal and spatial ocean variability.

15. SUBJECT TERMS

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waves [4-9]. The effects due to horizontal refraction are separated from those due to mode coupling and adiabatic conditions. Based on these results, a hypothesis is developed for further investigation and the SW06 experiment data has been analyzed to test the theory [8, 9].

2) *High Frequency Acoustics.* We have participated in the Kauai Acomms MURI 2008 (KAM'08) experiment. During the joint efforts with the Marine Physical Laboratory (MPL), Scripps Institution of Oceanography, the Ocean Acoustics Laboratory, University of Delaware deployed two tripod tranmission/receiving systems multiple times as well as providing contiunous environmental measurements in the three week at-sea experiment. The data analyis of KauaiEx 2003, MakaiEx 2005, and KAM’08 has been another focus of high frequency acoustics research to assess the effects of the environment on the acoustic wave propagation. Our studies show the temporal and spatial changes in the water column and the sea surface have significant effects on acoustic wave propagation and acoustic communications.

3) *Instrumentation.* We have developed two acoustic transmission/receiving systems that were deployed in the KAM’08 experiment.

RESULTS

In the following sections, results for both low and high frequency bands are presented. These highlights are based on papers and reports resulting from our existing research grants [1-14].

A. Low Frequency Acoustic Wave Propagation in the Presence of Shallow Water Internal Waves

Previous studies [4-6] suggest that there are three different mechanisms that can explain intensity variations in the presence of internal solitary waves (ISW). The adiabatic regime corresponds to fluctuations of the sound field due to local variations of the water column (i.e. sound speed and/or depth) at the position of the source or the receiver. The mode coupling regime corresponds to the interaction of the sound field with the internal waves, causing energy transfer between different modes which in turn can result in fluctuations in the intensity. The horizontal refraction regime corresponds to the distribution of the sound field in the horizontal plane, which can cause fluctuations in the measured field. The last two situations result in more significant signal intensity fluctuations than the first [4-6].

We separate propagation regimes depending on the angle between the ISW wave front and the direction of the acoustic track. Here we present a data set from the SW06 experiment where the acoustic track angle is kept unchanged while the internal wave slowly transects the acoustic track. When the ISW train is starting to cover the receiver array only and does not occupy all (or a significant part of) the acoustic track, we have the adiabatic regime. As the train continues to cover the acoustic track, propagation changes to the horizontal refraction regime. Thus, we can isolate the transition between the two regimes.

In SW06 experiment both acoustic and environmental data were collected simultaneously. On August 17, 2006, the ISW surface signatures were also captured continuously by the on-board radars of two research vessels prior to the arrival of, and during the passing of, the ISW packet over the acoustic track. The water depth along the acoustic track was about 80 m. The acoustic source (NRL 300Hz) was located on the mooring denoted SW45. The source was 72 m below the sea surface and 10.5 m above the sea floor, and linear frequency modulating (LFM) signals were transmitted. A vertical and horizontal receiver array (the “Shark VHLA”) was located on mooring SW54 about 20.2 km south of the NRL source. The vertical and horizontal part of the receiver array consisted of 16 and 32 hydrophones respectively. The acoustic track and the locations of the source and receiver as well as the horizontal and vertical array configurations are shown in Fig. 1 [8].

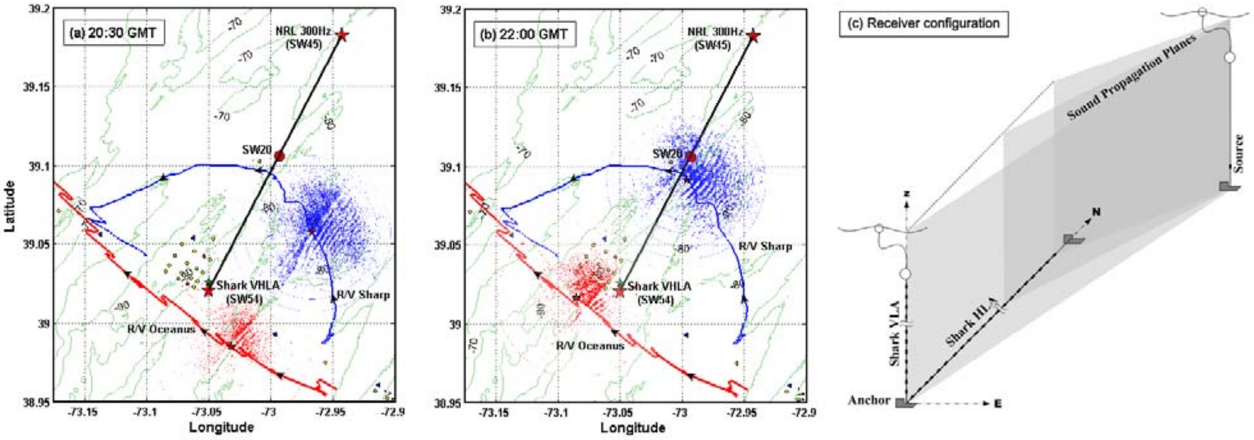


Figure 1: Map of the experiment location showing the positions of the acoustic source (NRL 300 Hz on SW45 mooring), the receiver array (Shark VHLA on SW54 mooring) and a midpoint thermistor array (SW20) together with the two research vessels (R/V Sharp and R/V Oceanus) at two separate geotimes. Times are (a) 20:30 GMT when the ISW has not reached the acoustic track, (b) 22:00 GMT when the ISW has occupied a large portion of the acoustic track including the receiver array. Ship tracks and radar images of R/V Sharp and R/V Oceanus are shown. The configuration of the receiver Shark VLA and Shark HLA is shown in (c).

On August 17, 2006 at about 18:00 GMT, the R/V Sharp from the University of Delaware and the R/V Oceanus from the Woods Hole Oceanographic Institution (WHOI) observed the origination of an ISW near the shelf break. This event was named Event 50 on R/V Sharp and Rosey on R/V Oceanus. Figures 1(a) and 1(b) show the track of each vessel following this event from 18:00 GMT on August 17 to 02:00 GMT on August 18, 2006. The two ships observed different parts of the ISW front, thus providing a large spatial coverage. The surface signatures of the ISW were digitally recorded by on-board ship radar images every 30 seconds. Combined radar images from the two vessels, each about 11.1 km in diameter, covered the receiver and about two thirds of the acoustic track. In this study we discuss two situations: (1) when the ISW packet had not reached the acoustic track [time period Tg_1 (20:30 to 20:37 GMT)] and (2) when the ISW occupied most of the acoustic track [time period Tg_2 (22:00 to 22:07 GMT)]. The radar images from both vessels at 20:30 GMT and 22:00 GMT are shown in Figs. 1(a) and 1(b) respectively.

Based on the theory proposed in our previous work [5], the angle between the ISW fronts and the acoustic track determines the mechanism of the intensity fluctuations. Small angles provide horizontal refraction and focusing while larger angles cause mode coupling. Between these limits, there is an angular region for which the propagation is adiabatic. During internal wave Event 50, the ISW fronts passed through the acoustic track at an angle of about 5^{o}, providing the condition for horizontal refraction.

To show a focusing event, we again consider two geotimes: Tg_1 and Tg_2. We calculate the total intensity integrated over the depth H as [8]

$$I(T) = \int_0^H I(z,T)dz \tag{1}$$

where $I(z,T) = \frac{1}{\rho c}\int_{\tau}^{\tau+\Delta\tau} p^2(z,T,t)dt$ is the intensity of the signal arrivals integrated over a pulse length $\Delta\tau$ at a given depth z, where p is acoustic pressure, ρ is water density, and c is sound speed.

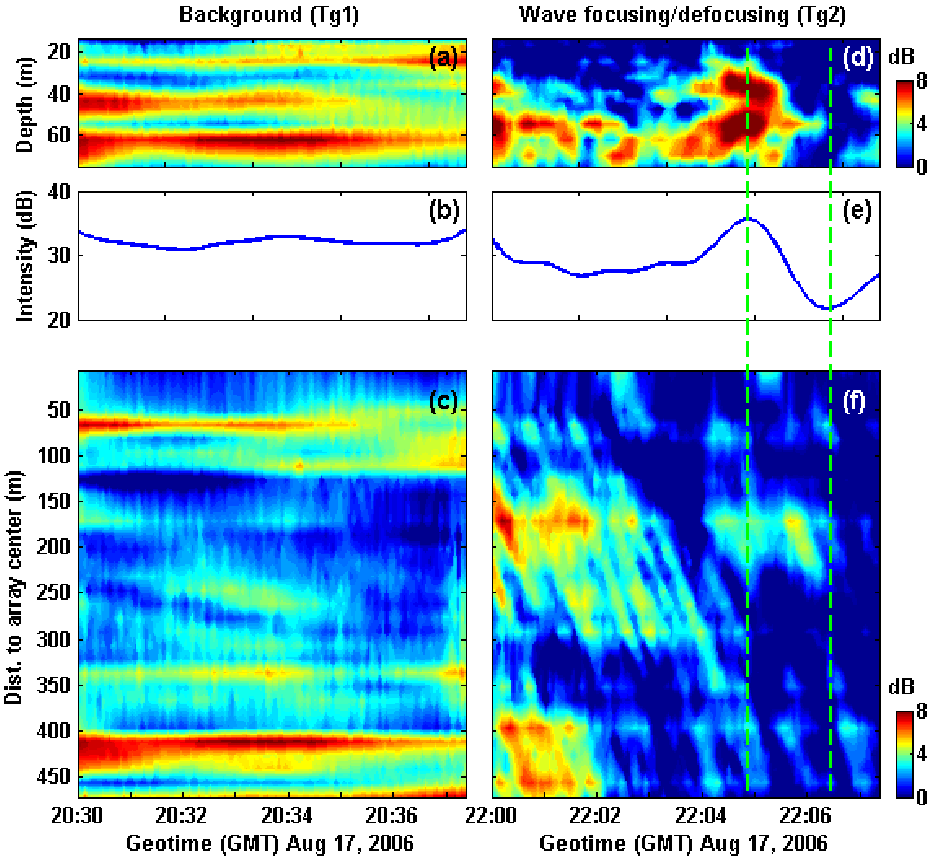


Figure 2: Received acoustic intensity during a 440 sec (~ 7.33 mins) transmission period for two geotimes, Tg_1 (from 20:30:00 to 20:37:20 GMT): (a) depth distribution of total intensity per pulse I(z,T), (b) depth integrated intensity, I(T) for VLA, (c) total intensity I(x,T) for HLA; and Tg_2 (22:00:00 to 22:07:20 GMT): (d) depth distribution of total intensity per pulse I(z,T), (e) depth integrated intensity, I(T) for VLA, (f) total intensity I(x,T) for HLA.

In Fig. 2(a) we show a plot of *I(z,T)* for the VLA at Tg_1. It is shown that for a repeated pulse of the same radiated intensity, only minor temporal intensity variation exists. In Fig. 2(b) we plot the depth integrated intensity for all geotimes, *I(T).* The very small fluctuations (~ 3 dB) at Tg_1 indicate a quiescent condition without ISWs in the track. This means that during this period of observation there is no redistribution of sound energy in the horizontal plane, i.e. there is no horizontal refraction. Small variations of the depth distribution of the sound intensity correspond to the adiabatic case. Figure 2(c) shows the acoustic intensity on the HLA. There are no apparent temporal intensity variations on the HLA during this geotime.

I(z,T) for Tg_2 is plotted in Fig. 2(d). Here we see increasing and decreasing trends in sound intensity over the VLA, which are synchronous in depth. The average intensity *I(T)* peaks to ~ 35 dB around 22:04:30 to 22:05:00 GMT, and decreases to ~ 20 dB around 22:06:37 GMT as shown in Fig. 2(e). This significant fluctuation corresponds to redistribution of the acoustic energy in the horizontal plane, which in the limit can be referred to as focusing or defocusing events and is related to the position of the source and/or receiver with respect to the internal wave crests. In this case (i.e. Tg_2), the receiver is between two adjacent maxima of the thermocline displacement, and the high intensity fluctuations (~ 15 dB peak to peak) are due to horizontal refraction effects similar to those shown in previous studies [5]. The fluctuations in the presence of internal waves (i.e. at Tg_2) are about 15 dB, which are much larger than those of Tg_1 (~ 3 dB), with no internal wave in the acoustic track.

As in the quiescent case shown above, Fig. 2(f) shows the acoustic intensity on the HLA for the active period (Tg_2). During the geotime of about 7.33 minutes, we see the variation of the sound field at the horizontal array. For the variation observed during the first 3 minutes, there are two large intensity maxima observed at the HLA. These become weaker and disappear during the second half of the time period (after 22:03 GMT). This behavior, in our opinion, is a manifestation of horizontal redistribution of the sound intensity, which we label as focusing/defocusing phenomena.

In addition to the results shown above, we have further worked on the intensity fluctuations due to mode coupling. The results are being considered for publication in JASA [9]. Future work will include mode and frequency filtering of this acoustic data as well as modeling to establish the transition of acoustic field behavior from adiabatic to other mechanisms when an ISW passes an acoustic track.

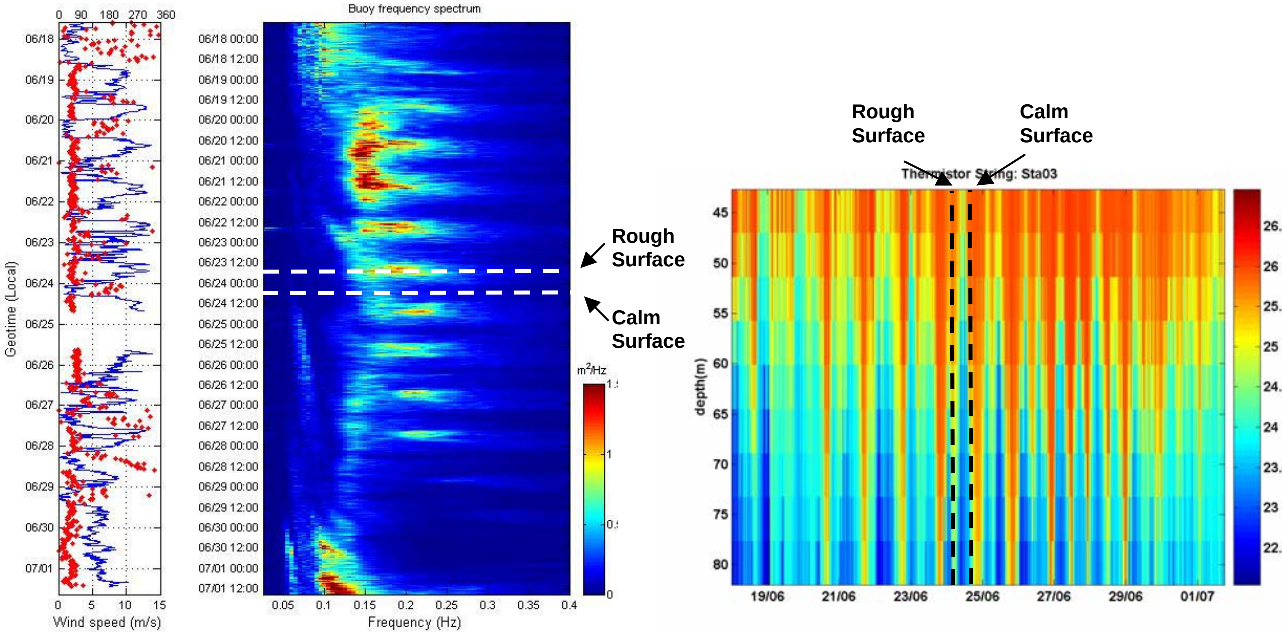
B. High Frequency Acoustics - KAM'08 Experiment

KAM'08 Experiment was conducted off the western side of Kauai, HI, from June 16, 2008 to July 2, 2008, in depths of up to 100 m. This experiment focused on acoustic and environmental data used to study ocean variability effects on the high frequency bands, and is explained in more detail in an accompanying report [3]. As shown by our previous studies [10, 11], high frequency acoustic propagation is affected by the temporal and spatial changes in the water column and the sea surface. It is also shown that the ocean variability impacts arrival rays differently depending on their travel paths. These ocean variability effects on acoustic wave propagation in turn have significant implication on high rate underwater acoustic communications and high frequency current tomography. The measurements from KAM'08 provide abundant data for these studies.

Two University of Delaware autonomous high frequency acoustic transmission/reception seafloor tripod systems were deployed. Each tripod had provisions for an acoustic source at the top and a small-aperture, 5 to 8-element vertical line array of receivers with 2 feet inter-element spacing. The hydrophones had a sampling rate of f_s = 80 kHz per element and the total continuous record duration of each tripod was 40 hours. The maximum source level from these transducers was 180 dB re μPa. During KAM'08, one tripod was configured to "receive-only" and the other tripod was configured to "transmit-only". These tripods were further supplemented by acoustic sources and vertical line arrays that were operated by MPL.

To measure the sea surface waves, UDel Datawell directional waverider model DWG-G7/316 was deployed using a seafloor mooring and soft tether to the buoy. The waverider buoy transmitted its data over RF back to the ship. Figure 3(a) plots the measured surface wave frequency spectrum together with recorded wind speed and direction. A period of ~ 24 hours is apparent, and during high wind conditions, the wind mostly came from NE.

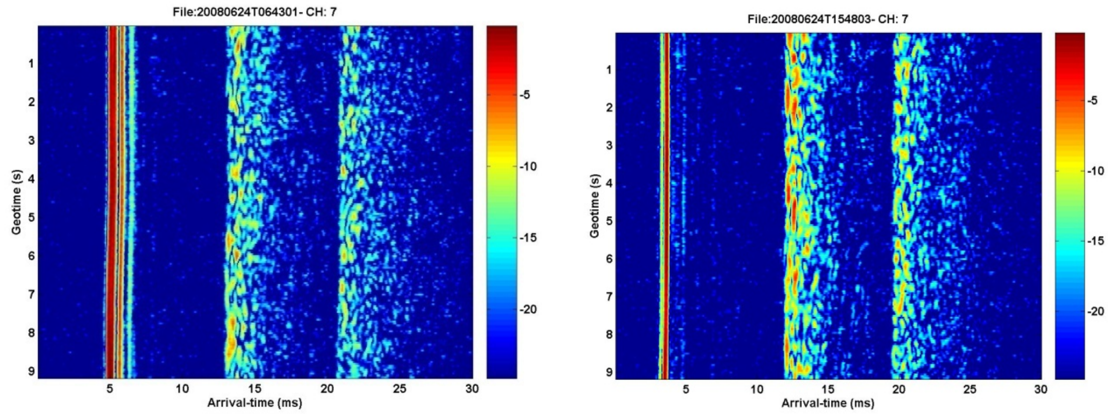
UDel thermistor string (TS), consists of 16 Star Oddi Starmon-mini temperature loggers were deployed near one of the tripods. In addition to the moored TS, a set of UDel and Heat, Light, and Sound (HLS) temperature loggers were attached along both MPL VLAs (15 on each VLA) and 4 HLS temperature loggers were also attached to the source array. The UDel sensors were Star Oddi Starmon-mini temperature loggers and the HLS sensors were Onset Computer Tidbits. Figure 3(b) shows the temperature profiles recorded on UDel TS from 18:00 on June 18 to 18:00 on July 01, 2008, UTC.



(a) **(b)**

Figure 3: (a) Measured surface wave frequency spectrum together with wind speed and direction during the KAM'08 experiment from 14:00 on June 17 to14:00 on July1, 2008, local time (UTC-10 hrs). (b) Temperature profile recorded on UDel TS from 18:00 on June 18 to 18:00 on July 01, 2008, UTC. Note: two dashed lines in (a) and (b) denote the time when the sea surface was rough (JD176 06:50 UTC) and calm (JD176 15:50 UTC).

Fig. 4 shows channel impulse response functions at the Udel tripod VLA for two geotimes. The sea surface was relatively rough at JD176, 06:50 UTC in Fig. 4(a) while it was relatively calmer at JD176, 15:50 UTC in Fig. 4(b). The water column condition was also distinct between these two cases. At JD176, 06:50, there were multiple bottom-interacting rays because of the downward reflecting sound speed profile. Because of the sea surface condition, the surface arrivals had stronger intensity and larger coherence at JD176, 15:50. As a consequence, the communication comperformance through use of the Udel tripod VLA shows difference in the output SNR between these two geotimes. As shown in Fig. 5, there is about 2 dB difference in the output SNR when the time reversal receiver [12] with the same parameters was used in demodulation.


(a) JD 176, 06:50 UTC

(b) JD 176, 15:50 UTC

Figure 4: CIR function at the Udel tripod VLA for two geotimes. CH-7 was about 2 m above the sea floor. A 10 s BPSK sequence with R=4 kilosymbols/s and fc=16 kHz was used to estimate the channel. The sea surface was relatively rough at 06:50 while it was calmer at 15:50. The source was the bottom transducer at 82.5 m depth of MPL SRA. The source/receiver range was 1 km.

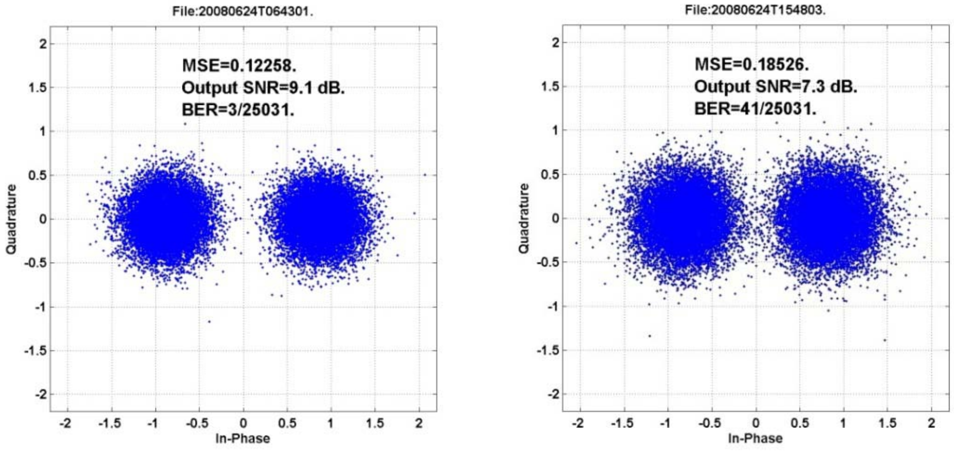


Figure 5: Soft demodulation of the BPSK signal at the tripod VLA moored at Sta02 for the two geotimes shown previously. 5 channels are used to demodulate the signal. The symbol rate of these signals is 4 kilosymbols/s and the carrier frequency is 16 kHz. Note there is a ~2 dB difference in the output SNR when the same set of receiver parameters was used in demodulation.

C. Instrumentation

Two autonomous high frequency acoustic transmission/reception tripod systems for underwater research were designed and fabricated [14]. In KAM’08 experiment, high quality acoustic data were collected by these systems. Figure 6 shows the system diagram for the DAU and the photo of the system being assembled during KAM’08 experiment.

The system includes a modular high-frequency hydrophone array (1-8 elements), a mid-frequency transducer (10 kHz), a central electronics unit in underwater pressure housing, deep sea batteries, and a scaffold tripod for seafloor deployment. The sensitivity of the hydrophone is -165 dB re: 1 V/µPa, and its frequency band is from 2 Hz to 30 kHz. The central electronics unit consists of an AXIOMTEK signal board computer (SBC), a General Standards PMC66-16AISS8AO4 PCI data acquisition card and a power amplifier. The data acquisition card provides 16-bit 8-channel analog input and 4-channel analog output capabilities. Eight input channels are digitized simultaneously at rates up to 2MHz per channel. The control software was developed on a customized release of Linux operating system to achieve stability while keeping the size small. During underwater missions, the system is powered by three deep sea batteries through a junction box. When on deck, power can be supplied directly by the AC-DC power converter and the batteries can be left to recharge.

The central electronics unit is placed inside a Prevco underwater pressure housing rated at 1100-meter depth. The housing, three deep sea batteries and an electrical junction box are all mounted on a scaffold tripod frame, the height of which is about 18 feet and the triangular base is about 12 feet. Three SeaBattery SB-12/80 deep sea batteries (12 volt, 80 amp hour) can provide approximately 72 hours continuous recording time.

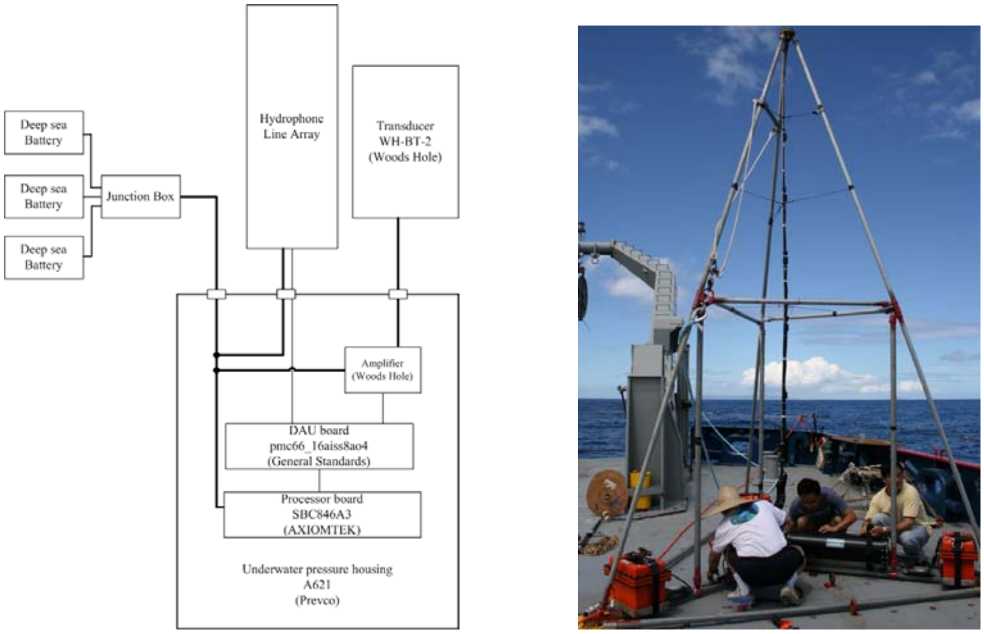


Figure 6: Left: system diagram for the DAU.
Right: photo of the DAU system being assembled during KAM’08.

IMPACT/APPLICATIONS

The low frequency part of our research benefits the science of understanding sound propagation in complex shallow water regions. We have developed a theory to explain the fluctuations of the arrival time and the intensity caused by internal solitons. The high frequency part of our research has impacts on the development of new underwater communications systems with more efficient decoding capabilities.

RELATED PROJECTS

In the low frequency band research, we have been working with Drs. J. Lynch at Woods Hole Oceanographic Institute (WHOI) and B. Katsnelson from University of Voronezh, Russia. For the research work in the high frequency band, we are collaborating with colleagues from Scripps Institution of Oceanography (Drs. W. Hodgkiss, H.-C. Song, and W. Kuperman), Applied Physics Laboratory-University of Washington (Dr. D. Rouseff), and Heat, Light, and Sound Research Inc. (Dr. M. Porter).

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