PAPER

Hawaii Experimental Acoustics Range for Shallow Water Applications

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ABSTRACT

Shallow water acoustics provide a means for monitoring and surveillance of near-shore environments. This paper describes the current and future capabilities of the low- to high-frequency Hawaii Experimental Acoustics Range (HEAR) that was designed to facilitate a wide range of different shallow water acoustics experiments and allow researchers from various institutions to test various array components and configurations. HEAR is a portable facility that consists of multiple hydrophones (12–16) cabled independently to a common central node. The design allows for variable array configurations and deployments in three modes: experimental (off boats and piers), autonomous, and cabled. An application of HEAR is illustrated by the results from a deployment at Makai Research Pier, Oahu, Hawaii. In this deployment, HEAR was configured as a long-baseline range of two volumetric subarrays to study passive acoustic tracking capabilities in a shallow water environment.

Keywords: passive acoustics, shallow water, surveillance, hydrophone array, time difference of arrival, likehood, data acquisition

Introduction

The Hawaii Experimental Acoustics Range (HEAR) is a newly built, low- to high-frequency (10 Hz–60 kHz) shallow-water portable acoustics facility. HEAR was designed and built by Fedenczuk and is operated by the HEAR Lab in the Department of Ocean and Resources Engineering through the Center for Island, Maritime, and Extreme Environment Security (CIMES) at the University of Hawaii (UH). The purpose of the range is to provide a high-sensitivity, reconfigurable, multinode acoustic system that can be deployed in various shallow water environments for operation in autonomous, shore, and cabled observatory modes. Its modular design allows for swapping (and thus testing) of various multi-vendor components including hydrophones, filters, data acquisition systems, and cables. This paper describes the current and future capabilities of HEAR and presents results from a deployment.

Methods

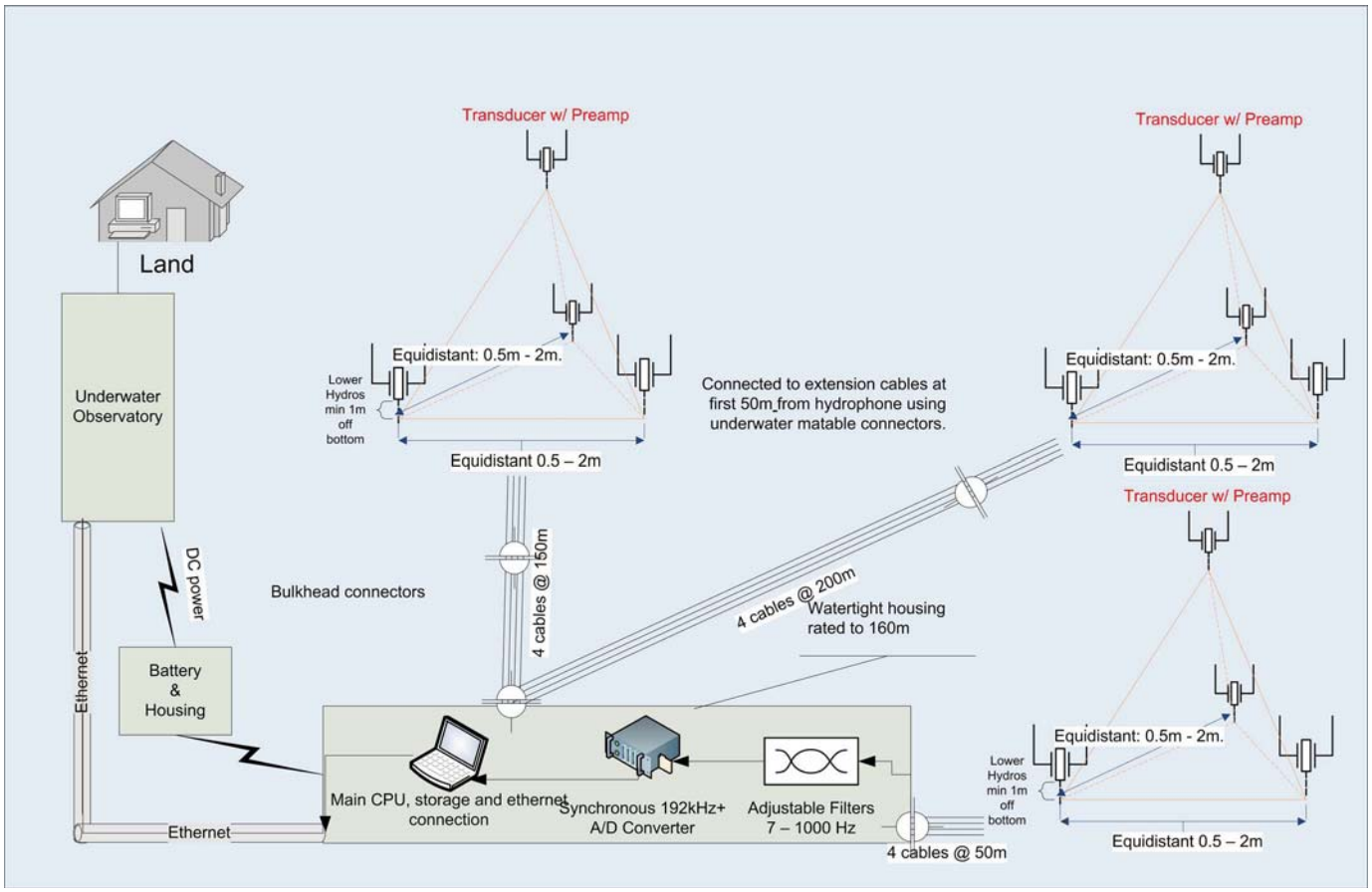
The key design specifications for HEAR were flexible configuration and modular design. The flexibility facilitates experiments using receiver arrays of various dimensions, spacing, and configurations (such as line, cross, widely spaced, and volumetric arrays). The modular design allows various hydrophones, digitizers, filters, and attenuators to be used. This enables performance testing of individual components and allows the range to be customized for different experiments. The range also needed to operate in several modes: (1) land-based mode for direct connectivity and control from piers and boats, (2) autonomous mode for long-term deployments in remote setting; and (3) cabled observatory mode that allows the system to be plugged into existing underwater observatories that provide power and data transfer capabilities. For reference, Figure 1 shows a schematic for one possible configuration of the HEAR system.

Electronic Design

When possible, commercial off-the-shelf (COTS) components were used (e.g., preamplified hydrophones). Since we could not find a COTS data acquisition system that satisfied all of HEAR's requirements, a custom data acquisition system was designed and built. The data acquisition system allows for both differential and single ended signaling and accommodates a variety of analog-digital (A/D) converters including Texas Instruments PCM3204 and PCM1804. Each channel has a dedicated A/D converter connected to a common clock. Channels are digitized synchronously at a minimum of 192 kHz (unless intentionally lowered by the user) to avoid timing errors associated with nonsynchronous multiplexed sampling (one A/D converter iteratively sampling each channel at a faster rate).

FIGURE 1

Schematic of the HEAR system in one possible observatory-based configuration with three spatially separated tetrahedral subarrays.



Software-adjustable attenuators and physical plug-type attenuators control the input voltage window for each channel on the acquisition system. Analog high-pass filters, with cutoff frequencies that range from 7 to 1,000 Hz, can be adjusted remotely to remove unwanted low-frequency noise. The acquisition system has on-board signal processing and computational capabilities to perform basic tasks such as fast Fourier transform analysis and digital filtering. This on-board processing relieves the computational burden from the main controlling CPU.

Cables

HEAR cables include standard 50-m lengths that attach directly to the hydrophones as well as extension cables that range in length from 100 to 150 m. Even though most hydrophones require three to five contact points, HEAR cables and connectors all have six contact points. The customized six contact wiring removes vendor and model-specific cabling restrictions and allows for connectivity to many different hydrophone types. Although the six conductor cable is standard for differential hydrophones with calibration signals, the wiring configurations for different hydrophones/vendors are not the same. Our cables are specially wired to allow us to use the same cables and connectors with components from different vendors. This feature was designed directly into the wet-mateable connectors and into the custom-built universal connectors for use with various acquisition cards. This setup enables other researchers and labs to test their equipment using HEAR (including the cables and connectors).

Underwater mateable connectors enable at-depth coupling and decoupling of cables from one another and from the underwater housing that encases the data acquisition system. For connectors left uncoupled underwater for more than several hours, dummy plugs are used to cap the connectors and prevent corrosion. Instead of shipping damaged connectors and their cables back to their factories (which can take several months) or using temporary splices (introducing weakness and possible noise), connectors can

be quickly replaced using a field-capable molding kit.

Although neoprene cable jackets were recommended for strength and durability by laboratories located in colder climates, polyurethane jackets were chosen after local researchers advised that neoprene cables have a tendency to receive biogenic punctures, possibly attributed to sea urchins (K. Millikan, personal communication). The high surf encountered in Hawaiian coastal water (including on the south shore) causes chafing in response to wave energy. This damages the cables by physically moving them against sand and reef or by moving suspended sand and other debris against them. In longer duration deployments (more than several days) and/or in highly dynamic environments, sections of cable (and other components) that are vulnerable to wave or current effects are reinforced with additional protective jackets. Depending on conditions and requirements, these can range from vendor-specific protective chafing strips to simple water pipe insulation tubing acquired from a local hardware store.

Power and Housings

HEAR operates from a 24-V DC source that comes either from a 120-V AC shore connection (via AC/DC converter), a 24-V ship/ocean observatory connection, or a separate 24-V underwater battery and housing. Although most of the electronics (including the acquisition system) run directly from 24 V, the voltage is further regulated to reduce noise and stepped down for some models of hydrophones that require 9–12 V. The underwater battery can be used as the sole source of power for autonomous experiments or as a backup power source and regulator for experiments with land or underwater observatory connectivity. Housing the battery inside of its own underwater case decreases the size of the main housing, making the system more portable. It also permits use of various sized batteries and housings based on the duration of deployment and power needs. Endurance of the system on the batteries has not been fully evaluated. Unlike other underwater acoustic systems that are exclusively built for autonomous recording, HEAR was not design with strict power consumption parameters and it is not intended for long-term deployments. Its autonomous mode is designed for testing in short term deployments (hours to days rather than months).

The main underwater housing is currently being built and is made of schedule 80 PVC pipe. The end caps are made of a 316 stainless steel plate (3/8 inch thick) and have O-ring seals for access. The stainless steel acts as a heat sink and is connected to a chassis that secures all of the equipment and further dissipates heat from the electronics and power supplies. The square end caps have holes in the four corners for threaded rods that run the length of the housing on the outside. Eye nuts on the ends of these rods mechanically fasten the housing to an underwater anchor, preventing accidental loss of ballast. Bulkhead connectors on the end caps permit hydrophones, Ethernet, and power connections.

Various types of hydrophone platforms have been built to accommodate a wide variety of possible array configurations. These include rigid structures made of steel as well as lines to which hydrophones can be tethered. For rigid node experiments requiring portability, we use collapsible survey-grade tripods that are modified to support volumetric clusters consisting of four to six hydrophones each. Metal tangs have been machined for the joints of each tripod leg to lock it at a desired angle.

Makai Research Pier Experiment (Makai-X)

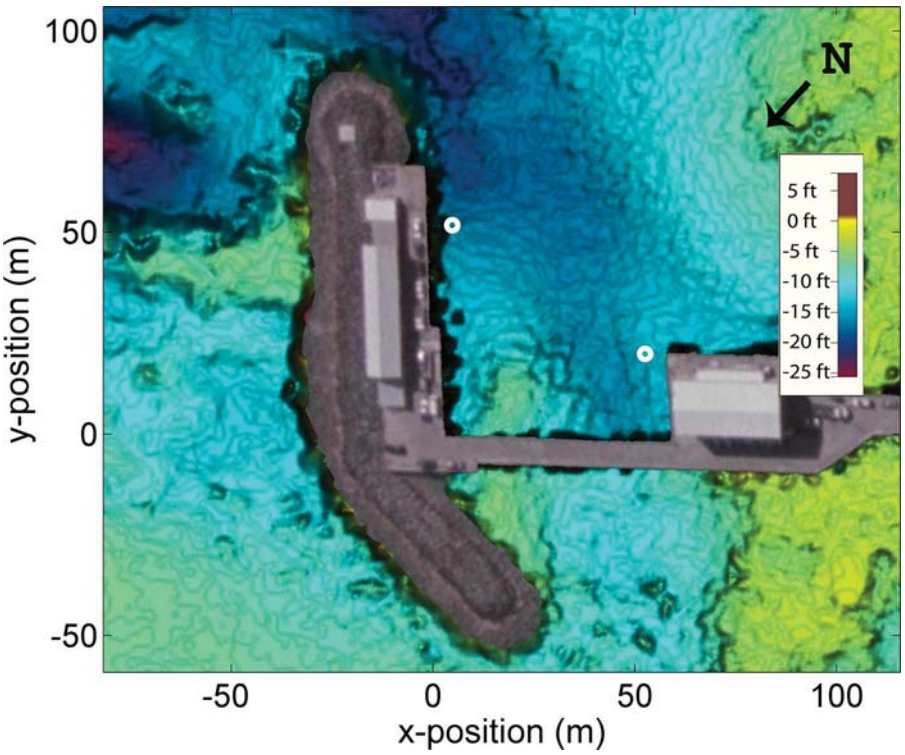
A pier-based deployment of HEAR occurred in December of 2010 off the Makai Research Pier in Oahu, Hawaii. The purpose of the deployment was to test HEAR and to gather controlled experimental data for use in sound source detection and tracking algorithm development. The Makai Research Pier was chosen due to its proximity and accessibility. The L-shaped pier provides convenient access, allowing arrays to be easily deployed and recovered. A private portion of the pier acts as a convenient staging area and nearby facilities (water, electricity) are easily accessible. Water depth at the site varies from about 2 to 8 m (Figure 2).

Experiment

The deployment used 10 channels of the data acquisition system that synchronously sampled each channel at 192 kHz and digitized at 24 bits. An anti-aliasing filter and 10-Hz high pass filter physically blocked frequencies that were not compatible with either the hydrophone sensor or the data acquisition system. The 10-V input on the acquisition system permitted the full range of signals to be acquired without being clipped (the output of the hydrophones was 6 V rms). Wet-mateable connectors were mated with reciprocating bulkhead connectors that were then wired to DIN connectors. (This setup was chosen in anticipation of an underwater housing that required the wet-mateable connectors.

FIGURE 2

Bathymetry and experimental layout at Makai Research Pier. Locations of hydrophone subarrays are indicated with white circles.

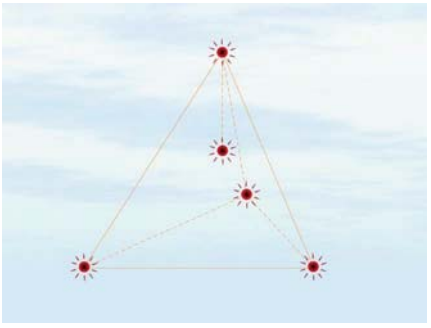


The internal DIN connectors permitted generic connectivity to different acquisition cards.) Preamplifier power to each channel was input individually at 24 V. The current draw was negligible (in the mV range). The data acquisition system was connected via an express card port to a laptop running Windows XP. Data were recorded via custom software that permitted control of channel configuration, sampling rate, and acquisition length as well as immediate spectrum visualization in MATLAB. Scripts were written in-house and included data capture, conversion, filtering, segmentation, and visualization.

Hydrophones were arranged in two 5-element tetrahedral subarrays that were deployed on opposite ends of the pier with approximately 60-m separation (Figure 2). The configuration of the each subarray is shown in Figure 3; four hydrophones were placed at the vertices of a regular tetrahedron and the fifth hydrophone was placed at the center. Subarray 1 had an edge length of 1.6 m and was 0.5 m off the seafloor. Subarray 2 had an edge length of 0.9 m and was 0.6 m off the seafloor. Two HEAR Lab SCUBA divers leveled the subarrays so that the base edges were horizontal. The orientation of the arrays is shown in Figure 4.

FIGURE 3

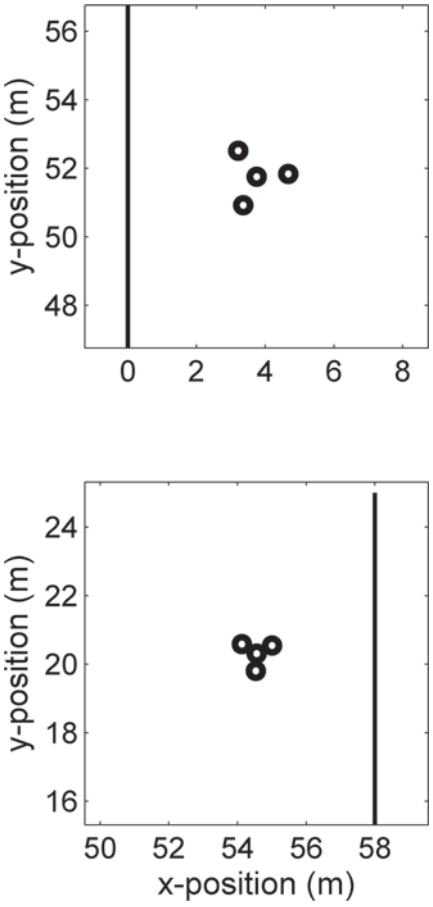
Subarray configuration: four hydrophones are at the vertices of a regular tetrahedron and a fifth hydrophone is in the center.



To create controlled sound sources, HEAR Lab researchers on shore followed a course along the pier from the first subarray to the second. Over the course, a transducer was lowered into the water to a depth of 1 m at approximately 10-m intervals along the pier. The transducer emitted 20-40 kHz linear up-chirps with 150-ms duration. Source levels were kept low (~90 dB re. 1 µPa) to avoid any environmental impact issues. The exact locations of the hydrophones, divers,

FIGURE 4

Orientation of Subarray 1 (top) and Subarray 2 (bottom). The pier is shown with a solid black line, and hydrophones are indicated by circles.



artificial sources, and key landmarks on the pier were determined using a total station (an electronic instrument that includes integrates a survey transit (theodolite) with an electronic distance meter). Sound speed was measured with a sound velocity profiler lowered from several positions along the pier; it was almost constant with position and depth at 1,535 m/s.

Data Analysis

In the following analysis, the positions of the control sources were assumed unknown and a localization algorithm based on time of arrivals was applied to find the sources. Signals were band-pass filtered to reduce noise and then cross-correlated between hydrophone pairs. The peak of the envelope of the cross-correlation function was recorded as the measured difference in arrival time (TDOA) for the hydrophone pair being considered. Likelihood surfaces were formed by comparing measured TDOAs to modeled TDOAs in a manner similar to the procedure outlined in Nosal and Frazer (2007):

$$L_{TDOA}(\bar{s}) = \frac{1}{\left(2\pi\sigma_{TDOA}^2\right)^{N/2}} \exp\left[\frac{-1}{2\sigma_{TDOA}^2}\sum_j\left(\overline{TDOA}_j(\bar{s}) - TDOA\right)\right]$$

where N is the number of receiver pairs, $\bar{s}$ is the candidate source position, $TDOA_j$ and $\overline{TDOA}_j$ are the measured and modeled TDOAs for receiver pair j, and σ_{TDOA} is the standard deviation in the measured TDOAs due uncertainties in receiver position, sound speed, and cross-correlation peak position. The maximum in the likelihood surface is the estimated source position.

Likelihood surfaces were created using hydrophones in Subarray 1 only ($L1_{TDOA}$), hydrophones in Subarray 2 only ($L2_{TDOA}$), and one hydrophone from each subarray (LC_{TDOA}). For the entire system, the likelihood surface (L_{TDOA}) was created as

$$L_{TDOA}(\bar{s}) = L1_{TDOA}(\bar{s}) \times L2_{TDOA}(\bar{s}) \times LC_{TDOA}(\bar{s})$$

Figure 5 shows the resulting likelihood surface (cross-section at 1-m depth) for a control source at (2 m, 2 m, 1 m). Based on the width of the cross-correlation peaks, relative and absolute uncertainties in receiver positions (2 cm and 1 m, respectively), and uncertainty in sound speed (1 m/s), σ_{TDOA} was set as 0.1 ms $L1_{TDOA}$ and $L2_{TDOA}$ and as 5 ms for LC_{TDOA}. Grid spacing was 1 and 0.1 m horizontal position and depth, respectively. With each of the subarrays independently ($L1_{TDOA}$ and $L2_{TDOA}$), azimuth and elevation of the source is found, but not range. With one hydrophone from each array (LC_{TDOA}), the source can lie anywhere along a hyperbolic surface. When the full system is used to localize the source (L_{TDOA}), the position is found unambiguously. For the case in Figure 5, (2 m, 4 m, 4 m) is the likelihood surface maximum (and hence the estimated source position). The horizontal and vertical position estimates miss the correct position by 2 and 3 m, respectively. Results for other control-source positions are similar, with likelihood surfaces for five different source positions are shown in Figure 6.

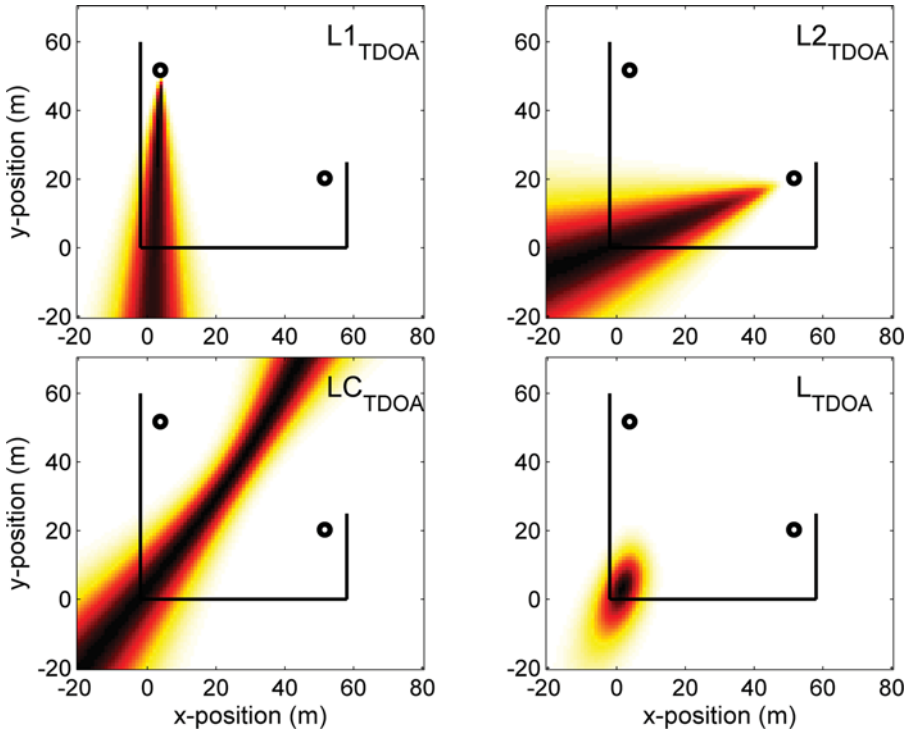
In the next stage of the analysis, hydrophone signals were autocorrelated to find secondary peaks that correspond to reflected arrivals. Strong secondary peaks occurring close to the primary (direct arrival) peak were classified as surface-reflected and used to estimate the difference in time between the direct arrival and the surface-reflected arrival (DRTD). Likelihood surfaces using these surface reflections were created as

$$L_{DRTD}(\bar{s}) = \frac{1}{\left(2\pi\sigma_{DRTD}^2\right)^{M/2}} \exp\left[\frac{-1}{2\sigma_{DRTD}^2}\sum_j\left(\overline{DRTD}_j(\bar{s}) - DRTD\right)\right]$$

where M is the number of receivers for which surface reflections can be identified, $\bar{s}$ is the candidate source position, $DRTD_j$ and $\overline{DRTD}_j$ are the measured and modeled DRTDs at receiver j, and σ_{DRTD} is the standard deviation in the measured DRTDs due uncertainties in receiver position, sound speed, cross-correlation peaks, and variability due to surface waves.

FIGURE 5

Likelihood surfaces (white/black shows low/high probability of source present) at 1-m depth for a chirp control source at position (2 m, 2 m, 1 m). Surfaces are shown for each subarray individually ($L1_{TDOA}$ and $L2_{TDOA}$), "cross arrays" (LC_{TDOA}, using one hydrophone from each subarray), and both subarrays used together (L_{TDOA}). The pier is shown with a solid black line, and subarrays are indicated by circles.



Likelihood surfaces were created for each of the subarrays independently ($L1_{DRTD}$ and $L2_{DRTD}$). Due to the calm surface conditions at the time of the experiment, the effect of waves on DRTD was negligible and σ_{DRTD} was set to 0.1 ms (the same value as σ_{TDOA} used to compute $L1_{DRTD}$ and $L2_{DRTD}$). $L1_{DRTD}$ and $L2_{DRTD}$ were multiplied by $L1_{TDOA}$ and $L2_{TDOA}$, respectively, to create likelihood surfaces $L1$ and $L2$ that use both TDOAs and DRTDs for each subarray:

$$L1(\bar{s}) = L1_{TDOA}(\bar{s}) \times L1_{DRTD}(\bar{s})$$
$$L2(\bar{s}) = L2_{TDOA}(\bar{s}) \times L2_{DRTD}(\bar{s})$$

The results for the case from Figure 5 are shown in Figure 7. By using surface reflections, range (in addition to azimuth and elevation) is found by each of the subarrays independently.

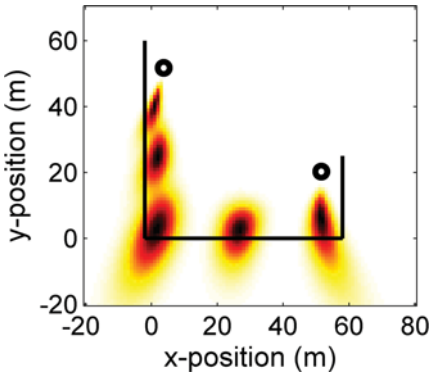
Likelihood surfaces that include surface reflections were computed for the full system as

$$L(\bar{s}) = L1_{TDOA}(\bar{s}) \times L2_{TDOA}(\bar{s}) \times LC_{TDOA}(\bar{s}) \times L1_{DRTD}(\bar{s}) \times L2_{DRTD}(\bar{s})$$

The most important effect of including surface reflections on the full system likelihood surface is to reduce the width of the likelihood peak along the vertical axis. That is, including surface reflection reduces uncertainties in source depth by effectively increasing the vertical aperture of the array. For the case considered in Figures 5 and 7, the estimated source depth was 4 m when only TDOAs were used (L_{TDOA}) but 1.1 m when TDOAs and DRTDs were used together (L). The correct source depth was 1 m, demonstrating the significant improvement in source depth estimate when reflections are used.

FIGURE 6

Likelihood surfaces (L_{TDOA}) for sources at different positions along the pier (in the interest of space, the five surfaces for five different source positions were summed and displayed on the same figure). L_{TDOA} maxima are all within 3 m of the correct source position.



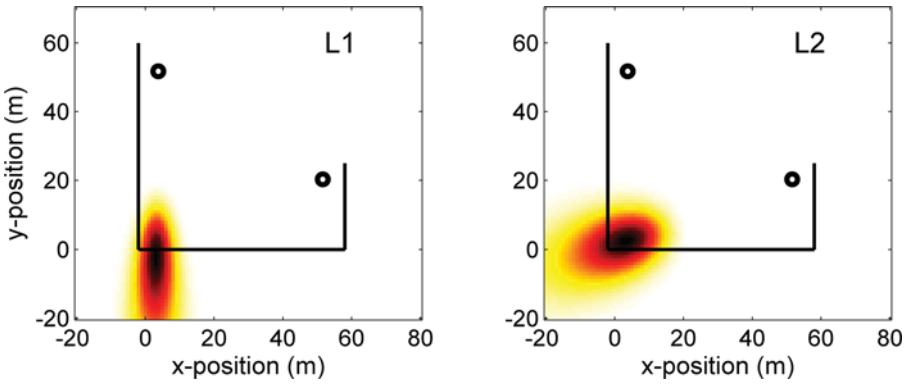
The use of surface reflections was possible due to the calm conditions that prevailed during Makai-X. With increasing wind and/or background swell, the standard deviation in the measured DRTDs (σ_{DRTD}) increases due to variable surface conditions. σ_{DRTD} can quickly become so large that surface reflections no longer contribute useful information about source position.

Discussion

HEAR was designed to support a wide variety of acoustics experiments.

FIGURE 7

Likelihood surfaces (*L1* and *L2*) for each subarray using TDOAs and surface reflections for the case shown in Figure 5. Source position is now estimated unambiguously for each subarray.



Its flexibility means that it is ideally suited for experimental and developmental work. However, this also means that it is not optimally suited to any one configuration or application. For example, single hydrophone recording systems that have been built specifically for long-term autonomous deployments can be smaller and more energy efficient.

The array is intended for shallow water applications and has a depth limit of 180 m. This limit is set only by the underwater housing; all other components are rated to 600 m or deeper. Because many harbor and near-shore environments are shallow, most HEAR deployments will be at depths of 20 m or less. These depths allow for the deployment, retrieval, and adjustments using small boats and divers. The HEAR Lab currently has four in-house-certified scientific divers qualified to use variable gas mixtures. It operates a 19-feet research vessel and has access to larger UH-operated vessels including the 96-feet *R/V Klaus Wyrtki* (McClain, 2006). These factors minimize deployment costs and allow for quick deployment using in-house resources.

Future Plans

Current development and upgrades that are scheduled to be finished within a year include building the designed underwater housing and backup systems for connectivity to cabled underwater ocean observing platforms. Access to the Kilo Nalu underwater ocean observatory (Pawlak et al., 2009) allows for long-term deployments with real-time data streaming from a strategic location at the mouth of Kewalo Harbor, Honolulu. The observatory's Ethernet connection enables remote access and control of the data acquisition system, filter, and other settings. Testing the entire system will continue indefinitely as parts are continually changed to measure performance differences between various components and configurations.

Conclusions

HEAR was developed to facilitate shallow water acoustics research by providing a reconfigurable range that can be deployed in various environments in autonomous, shore, and cabled observatory modes. A modular design allows components to be swapped and replaced. It has been used successfully in several configurations (Nosal and Fedenczuk 2010; this paper) and will continue to serve in studies of shallow water acoustic propagation and experiments that test passive acoustic monitoring techniques.

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