Sound in the Sea: Hands-on Experience with NOAA VENTS Program

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***Abstract* –Pacific Environmental Lab of National Oceanic and Atmospheric Administration (PMEL/NOAA), with support from Ocean Exploration, has extended its hydrophone monitoring capability to the eastern Pacific by installing "Pioneer Seamount Acoustic Observatory" off California. Recently in the western Pacific, five moored autonomous hydrophones have been added to explore and monitor volcanic activity in the Mariana Islands. As a result, our passive autonomous hydrophone networks cover vast areas of the global oceans, and currently collect acoustic data at a rate of approximately 1 GByte/day. These data allow detection of low-magnitude seismicity associated with volcanic activity with more accurate source locations than from land-based seismic networks. The data are also used to study the distribution of large baleen whales in the open ocean, which is otherwise expensive to access. Drawing on our extensive collection of acoustic data and expertise in hydrophone technology development, in 2002 we created and executed a public outreach program called "Sound in the Sea." The program teaches middle and high school students the fundamentals of ocean acoustics. Using actual PMEL/NOAA hydrophone data, students explore epicenters of underwater earthquakes and identities of different species of whales based on their vocalization characteristics. Students also learn how to make a simple hydrophone using glue and a plastic eggshell (the "Easter egg hydrophone"), which they test dockside in Yaquina Bay, Oregon. The "Sound in the Sea" program provides an exciting hands-on experience.**

I. INTRODUCTION

Pacific Marine Environmental Lab of National Oceanic Atmospheric Administration (PMEL/NOAA) began passive acoustic monitoring of the Juan de Fuca Ridge (JdFR) in 1991 using the U.S. Navy's SOund Surveillance System (SOSUS), a network of hydrophone arrays in the northeast Pacific Ocean. Taking advantage of the sound propagation properties of the ocean and the multi-channel cabled hydrophone signals available at Whidbey Island Naval Air Station, the program has been successful for the last decade in detecting tertiary phase waves (T-phase Wave) generated by low level seismicity in JdFR [1, 2] and locating epicenters. In 1993, the system was expanded to collect beam-formed data and to transmit the data in real-time over a dedicated T-1 line to NOAA laboratories in Newport, Oregon. The SOSUS hydrophone data are essential for the NSF (National Science Foundation) event response for seismic/tectonic events in JdFR area.

In order to monitor the mid-ocean ridges, the areas too remote for the cabled hydrophones, NOAA/OSU (Oregon State University) have developed a different strategy, which is to monitor the area of interest with multiple moored autonomous hydrophones (AUH) instead of cabled hydrophones. A self-contained, battery-operated instrument was developed to record one-channel acoustic data up to 2 years. Housed in a titanium pressure case, it is designed to turn around with minimum service required at sea [3]. These instruments have the advantage of portability; that is, they can be deployed anywhere in the world oceans, but cannot provide the data in real time; one must wait until a ship revisits the deployment site and recovers the instrument. Another advantage is that these instruments are relatively inexpensive compared to a cabled system such as SOSUS. Using multiple AUHs, in 1996, NOAA began monitoring the eastern Equatorial Pacific. The coverage of the AUH array was expanded to the Gulf of Alaska in 1999 for the acoustic behavioral study of large whale species [4]. In 1999, NOAA/OSU began coverage of the Mid Atlantic Ridge (MAR) between 15^o and 35^oN [5] and later in 2002 up to 50^oN. Monitoring of the Mariana Back Arc Basin (14^o-20^oN, 143^o-145^oE), western Pacific began in 2003.

This paper presents the progress we have made so far including Pioneer Seamount Acoustic Observatory, and participation in the "*Ring of Fire"* (*RoF*) cruise supported by Ocean Exploration program. We also discuss the public outreach aspect of our joint NOAA/OSU facility in Newport, OR. Our goal is to make the research we do more accessible to students and the general public by providing an interactive web site and hands-on educational curricula.

II. PIONEER SEAMOUNT REAL-TIME HYDROPHONE

The Pioneer Seamount site offers the opportunity to install the first deep-water civilian hydrophone array for monitoring of ambient ocean noises and their effects on the marine environment. As part of NOAA's Ocean Exploration Program, NOAA has started re-using an existing undersea cable once used for ATOC to passively monitor the ocean for natural and man-made sounds. This

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cable extends about 95 km (Fig. 1) from shore to an undersea mountain known as Pioneer Seamount (37 21.1'N, 123 26.1'W). On August 31, 2001, a hydrophone array designed by University of Washington was installed on the summit of the seamount (998m depth), and the continuous recording of sounds from earthquakes, weather, whales, ships, etc. began.

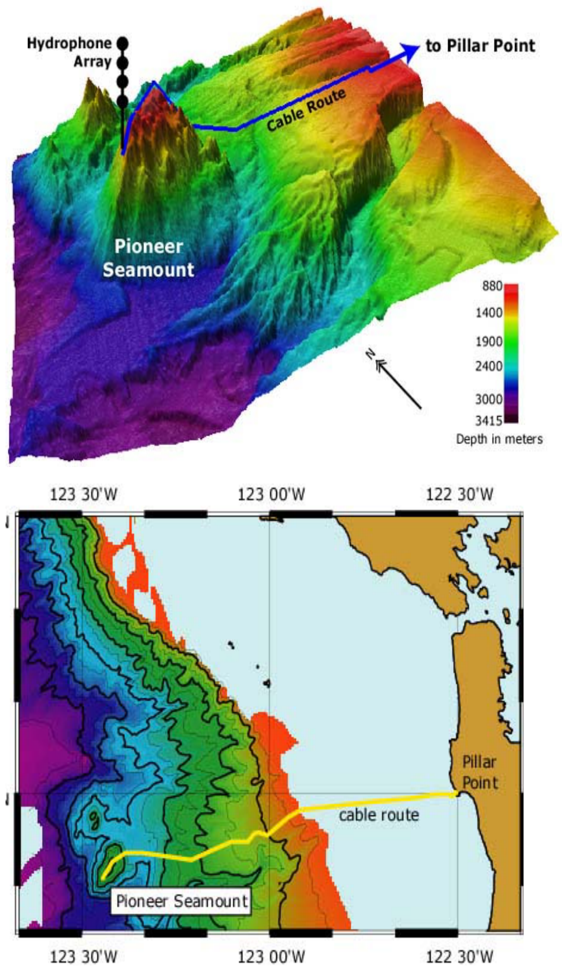

Fig. 1. Location of the submarine cable off the central California coast that is being used for the Sound in the Sea Project. This cable stretches from Pillar Point Air Force Station to an underwater seamount (Pioneer Seamount) and is approximately 95 km long. Four passive underwater hydrophones have been installed on the seaward end of the cable. Data on recorded sounds are sent along the cable to a station on land for processing.

In contrast to the multi-channel SOSUS data acquisition system (currently 48 channels), the signals from Pioneer Seamount Acoustic Observatory are four channels with 30-m vertical spacing between the elements in the water above the sea floor. The two-stage one-pole high-pass filter at 10Hz and 100Hz de-emphasize the typical low-frequency deep-water ambient noise [6], which otherwise dominates the signal. The four-channel analog signals are multiplexed and sent through an underwater cable to the shore station at Pillar Point Air Force Tracking Station, CA. At the shore station the signals are de-multiplexed to retrieve individual channels and digitized at 1kHz by 16-bit sigma-delta A/Ds, and stored at an internet-based network PC in the station. The data file is simultaneously uploaded through a commercial DSL to NOAA's Newport lab and made accessible to both scientists and the public via World Wide Web in real-time. Fig. 2 is a typical running spectrogram of three-channel data. It contains humpback whale calls in the two left channels and ship noise on the right channel. The signals are not suitable for beam forming or localization of the sound source, but sufficient for the study of ambient noise, whale calls, and assessment of various man-made noises [7, 8].

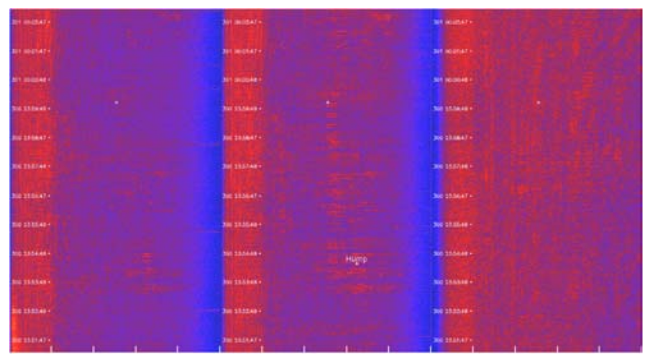

Fig. 2. Running spectrogram of three hydrophones. Each column represents different hydrophones with time spaced vertically at one-minute time interval. The frequency of the first two left columns ranges from 0 to 440Hz and the third from 0 to 100Hz.

The cut-off frequencies for the anti-aliasing filter are set to 440Hz. On NOAA's "Sound in the Sea" web site the user can listen the live audio file by clicking the appropriate button. To hear a sound such as a blue whale vocalization or typical T-phase waves, both of which are below 50Hz and inaudible to human ears, the wave file is played back at four to ten times the normal speed. For science educators and students, the same web site also provides sound clips of various origins including earthquake, whale calls, and mysterious sounds observed at the Pioneer Seamount.

The data were analyzed at the Newport lab for identification of whale species. Species recognition is normally not problematic, as enough is now known about the general characteristics of call types to recognize which species is vocalizing [9]. For instance, blue whales produce long, slowly-changing, tonal calls at 15-30 Hz, fin whales produce repetitive short pulses in the 20-40 Hz range, and humpback, whales make a wide variety of frequency modulated calls. We detected calls from blue whales, fin whales, humpback whales and sperm whales. An example of humpback whale call occurrence per month is shown in Fig. 3. The bar graph indicates the seasonal changes in detected vocalizations, indicating either a movement of animals into and out of range of the array, or a seasonal change in vocalization rate of humpback whales. Based on what we know of humpback whale behavior, the detected seasonal trend is likely due to both of these factors, as humpback whales migrate into the Pioneer Array area during the spring and fall, and male humpback whales sing complex "songs" as part of a winter breeding. The next challenge would be to take a detailed look at the vocalizations collected from these species. Recent research [10, 11] has demonstrated the existence of distinct acoustic populations of some species of cetaceans in a given area that produce vocalization(s) distinct from other populations.

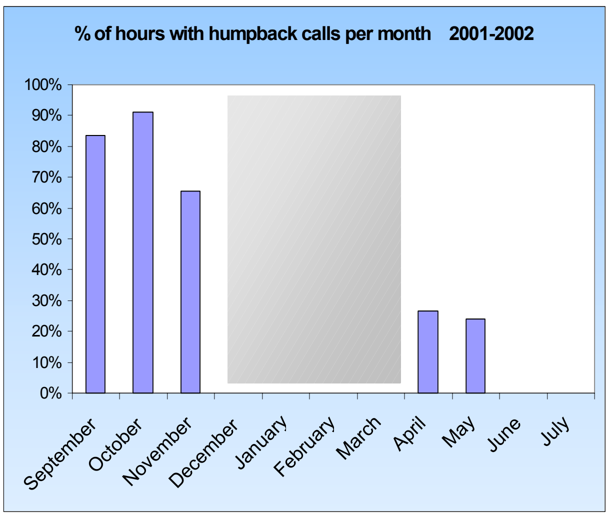

Fig. 3. An example of percent of hours that humpback whale calls were observed from September of 2001 to May of 2002. Shaded area is where no data are available due to a cable break.

With the addition of the Pioneer Seamount hydrophones, we now can acoustically survey an area that is a migratory corridor for a number of cetaceans. However, acoustic signals ceased on September 25, 2002. Testing by UW engineers indicated a cable failure approximately 40 km offshore. A remotely operated vehicle (ROV) from MBARI is scheduled to survey and photograph the cable in the summer of 2003. If survey data indicate repair of the cable is reasonably feasible and if funding can be obtained to repair the cable, then the live data display will be restored.

III. EXPANDING HYDROPHONE COVERRAGE BEYOND CABLED ARRAY

A. History :1991 to 2002

In 1991, NOAA began continuous recording of digital data from the Navy's fixed hydrophone array (SOSUS) systems in the northeast Pacific. Improved digital signal processing, and developments in ocean environmental models, combined with tremendous increase in computer power have served to increase the detection rate of T-phases. For JdFR area, using beam-formed SOSUS, the estimated detection threshold is approximately magnitude 2.0, and the raw SOSUS hydrophone it is about 2.5, compared to the global seismic network's threshold of magnitude 4.2 [1]. SOSUS raw time series data remains classified, however the epicenter map is available at NOAA's web site http://www.pmel.noaa.gov/vents/acoustics/seismicity/seismicity.html. The web site is updated quarterly.

In 1996, NOAA took a different approach to monitoring a remote area of the ocean. An array of six self-contained, battery-operated hydrophones (AUH) was deployed in the eastern equatorial Pacific to monitor the East Pacific Rise (10S-10N and 95W-110W) for tectonic and seismic events. Each hydrophone was moored in the sound channel depth and separated by approximately 10 to 15 degrees of latitude and longitude. During the first few years of monitoring, the array was serviced at six-month intervals. As battery technology and hard disk capacity improved over the last several years, the servicing interval became longer, and in 2002 we began servicing the array in two-year intervals. Data quality also has improved over the years. Early data from AUH are 8-bit sampled at 100Hz. The newer data sets have a 16-bit data resolution sampled at 250Hz. With the higher resolution, we hope to lower the detection threshold and widen the monitoring capability of marine mammal species with a higher sampling rate

Monitoring of the Gulf of Alaska for the acoustic behavior of large marine mammal species began in 1999 using six AUHs. In 2002, the monitoring effort stopped due to a lack of funding. In February of 1999, in collaboration with WHOI, NOAA/OSU began monitoring the mid-Atlantic Ridge between 15N and 35N with six AUHs. These hydrophones are serviced on a yearly schedule, and the data are processed within six months after the recovery. The experiment will continue at least through 2007. In collaboration with French and Portuguese scientists, we began another monitoring program in the northern mid-Atlantic between 40N to 50N. This array will be recovered in September of 2003.

The locations of these hydrophones are plotted in Fig. 4. Except for the Gulf of Alaska data, both the epicenter maps and time series of these AUHs are available at our web site http://newportftp.pmel.noaa.gov:1776/phonedata/GetTPDbyTimes.html. Depending on the purpose and the software that individual intends to use, three types of data formats are available online including NOAA's internal, CSS 3.0, or WAV file formats. Users may, by specifying either the time range or 1-day file of the specific hydrophone, download the file from our web site.

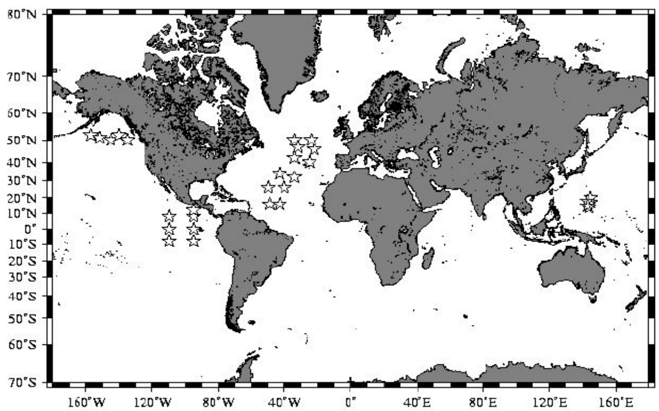

Fig. 4. Area covered by autonomous hydrophone arrays. Stars mark the AUH deployment moorings maintained by NOAA/OSU.

B. 2003 Mariana array

In February 2003, NOAA/OSU deployed five more AUHs along the Mariana Island during the OE supported *RoF* cruise. The goal of the experiment was to discover the extent and character of active hydrothermal vents and recent volcanic activity, thereby prioritizing targets for an ROV sampling expedition in 2004. Addition of five more AUHs is expected to improve substantially the earthquake and tremor detection and location capability of the U.S. Navy SOSUS hydrophones in the western Pacific Ocean.

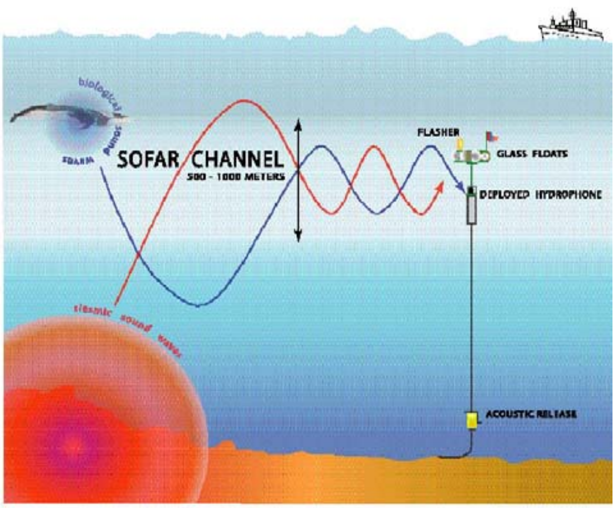

Fig. 5. Mooring diagram of Autonomous Hydrophone (AUH). Mooring consists of an acoustic release, portable hydrophone with self-recording package, and float. The hydrophone is moored at SOFAR channel depth.

On May 10 2003, only three months after five AUHs were deployed in Mariana, Anatahan Island (16.35N, 145.67E), a volcano along the northern Mariana Island chain north of Saipan, erupted; spewing a column of ash2500 meters above sea level. Analysis of seismometer records in the region shows that the explosive activity was preceded by hundreds of earthquakes starting roughly 12 hours before the eruption began. During the first two days of the eruption, the seismic records were dominated by as many as 100 earthquakes per hour with the largest earthquake having a magnitude of 3 [12]. Anatahan Island is still in an active eruption phase, with a lava dome having formed in the volcano's east crater.

One of the AUHs is only 50km north of Anatahan Island, and we expect that all the hydrophones will record the acoustic phases of earthquakes and volcanic tremor that have propagated through the ocean during the eruption. Due to the hydrophones' proximity to the source, it is anticipated that Mariana AUHs will give us unprecedented new insights into the source dynamics of T-phases produced by volcanic activity. In addition, an international collaboration was established with the Korean Ocean Research and Development Institute (KORDI) to recover the Mariana hydrophones off the

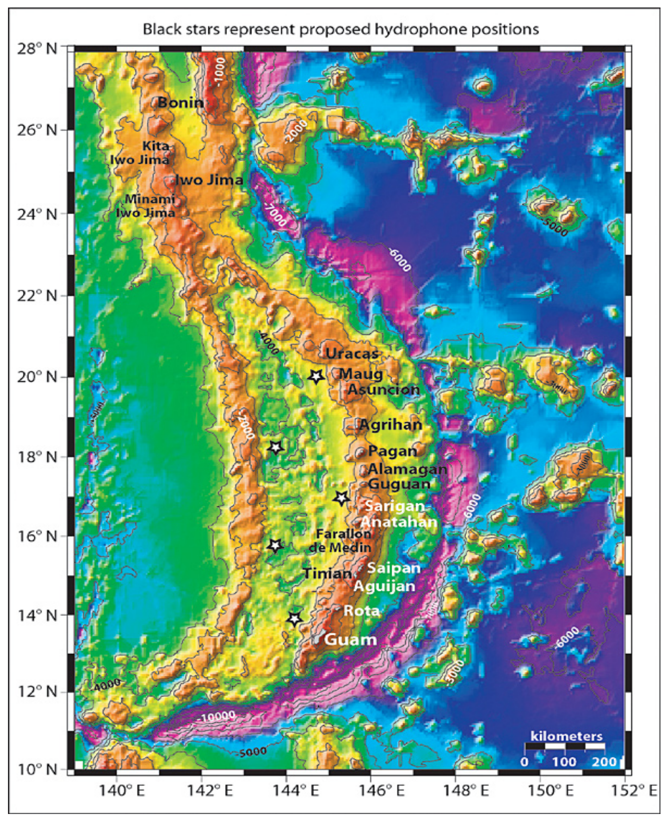

Fig. 5. Five autonomous hydrophones (AUH) mooring locations indicated by star signs between Maug and Guam in Mariana Arc. One of AUHs was deployed 50km north of Anatahan Island, which has been actively erupting since May 10, 2003.

KORDI research vessel *Onnuri* during September 2003 and to benefit from the T-phase modeling expertise of the researchers at KORDI.

IV. HANDS-ON EXPERIENCE: " SOUND IN THE SEA AS AN EDUCATIONAL TOOL

A. Classroom

Besides providing web based educational materials, including sound clips, NOAA puts emphasis on the hands-on experience through 2-day classes co-sponsored by Saturday Academy at Oregon State University. This is the second year we sponsored the "Sound in the Sea" class. The class was taught by volunteers from OSU faculties and NOAA employees and was offered on two consecutive Saturdays in the spring. Classroom size was limited to approximately 10, and included a mixture of both high school and middle school students.

On the first week, students learn a brief history of the principles of sound and the background of the Piezo element. Students are then exposed to the concepts of frequency, wavelength and sound speed. More acoustic terms including refraction and reflection are introduced. Acoustic impedance, which is an ambiguous term even for a college student is explained. Before building the hydrophone, students are introduced to the basics of electronics including Ohm's law, electronics component, and how to use a soldering iron.

Students are given the option of assembly one of two types of hydrophones: rubber molding (Fig. 7) or oil-filled type (Fig. 8). Rubber molding the Piezo element with a plastic Easter egg shell is a messy process and needs close supervision by instructors, but otherwise students are left to assemble at their own pace. The rubber used has the sound velocity of 1430m/s and density of 1078kg/m^3. The oil-filled hydrophone made of PVC pipe fittings, available at any hardware store, is less messy but requires more skill to build. The cavity of PVC fitting was filled with Canola oil, which has the sound velocity of 1440m/s and density of 940kg/m^3.

Each student solders the two-stage pre-amp by themselves and instructors help to test each unit before connecting the 9-V battery. The pre-amp consists of two separate boards, and pre-assembled at NOAA. Each board is robust and easy to solder, yet a low noise design. It has a variable gain between 40 to 70dB with frequency range of 50Hz to 15kHz. The Piezo element has a sensitivity of –200dBV re micro Pa with 10nF of capacitance. Total cost for the kit including the pre-amp, headphones and 30 feet of cable is approximately $35/unit.

An assignment to the student was to download "Ishmael" from http://cetus.pmel.noaa.gov/cgi-bin/MobySoft.pl and to install on his/her PC at home. Ishmael is the software used to record and analyze the sound with a Windows based PC, The program was developed by an OSU scientist and was provided at no cost to the student. It was modified for the ease of use for anyone with a high school level physics background. After installing Ishmael, students were encouraged to practice running the software on their own. For example, recording their own voices and analyzing the resulting spectrogram helped them to understand the concepts of Fourier Transform, fundamental tone and harmonics.

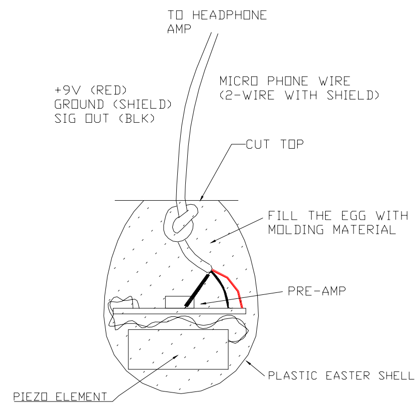

Fig. 7. Easter-egg type hydrophone

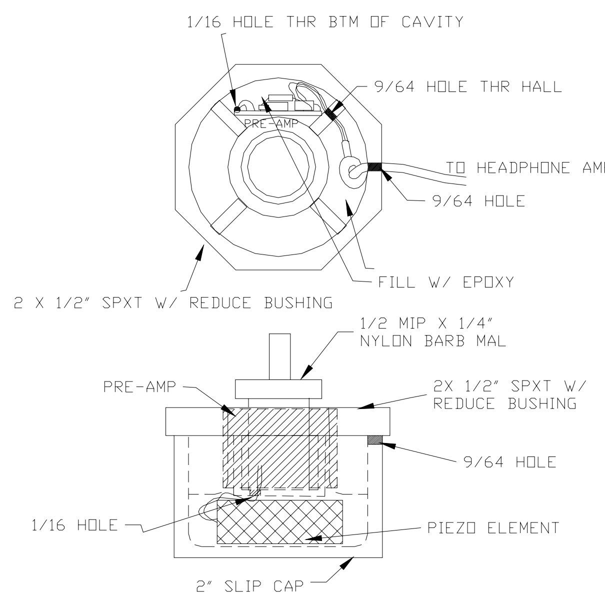

Fig. 8. PVC pipe-fitting type hydrophone

Using real acoustic data collected by autonomous hydrophones students learn how underwater earthquakes are located or how the species of a whale is identified by underwater sound. The concepts of frequency, amplitude, phase, etc. are reinforced during this lecture. OSU staff also review some of the surprising results of their acoustic surveys; for instance, sperm whales were detected quite frequently on both the Pioneer and Gulf of Alaska arrays, and blue whale calls were recorded regularly in the fall off the Oregon Coast. Students are asked to determine the advantages and disadvantages of such remote experiments, and are asked to hypothesize the source of some of our collected "mystery" sounds. This usually results in a lively discussion and reinforces the concept of the scientist as a detective.

B. Outdoor experiment and student response

On the second week, students tested their hydrophones at the OSU pier. Students were encouraged to bring their own laptop PC's or tape recorders so that the sound recorded at the pier could be analyzed with Ishmael later. In the field, students applied the techniques learned in class on how to use spectrogram display effectively. One of the features of Ishmael is that it records the sound and displays the "spectrogram" at the same time. An option of Ishmael, "spectrogram equalization," is particularly useful for bringing up a weak signal against the consistent background noise in the bay including a 60Hz noise. Some sound frequencies in the bay were below 50Hz and too low to be heard by the human ear. The program displays these inaudible frequencies as it changes in time. Students were instructed to observe how the ship noise changed as it sped up or how its pitch changed as it got closer or moved away. Sounds that students might have heard or seen on the spectrogram included a foghorn or ship horn in the bay transmitted through the water, low-frequency vibration of the pier floor, and the snapping of shrimps in the bay.

Students were asked how to make a better hydrophone; is Epoxy better than the hard rubber? Or is there better oil than Canola for PVC fitting type hydrophone? How to isolate the wave action so that the hydrophone would not be sensitive to the vertical motion, etc.?

2003 is the second year we offered the Sound in the Sea class. 12 students participated in the first class of 2002. 25 participated in the summer camp class sponsored by OSU. 8 enrolled in the 2003 Saturday Academy. Student ages are mixed from 8 grade to senior in high school. Although two-day class covered from basic underwater acoustics, math, electronics to bioacoustics, the contents did not seem to overwhelm any of the students, partly due to the excitement of building own hydrophone. Mixing hard engineering content with bioacoustics did not scare away any students. The class had a 60% to 40% ratio of female to male participants.

DISCUSSION

The "Sound in the Sea" project focuses on exploring the global ocean using passive underwater hydrophone arrays. Public outreach and education are important aspects of "Sound in the Sea," and the public response has been remarkably active, with one of the most often visited sited on the OE web site.

The following are the responses of the 2003 students who took "Sound in the Sea" class. (5-agree, 1- disagree)

Did you find the class interesting for you?	*4.7*
Was the class content too difficult for you?	*2.7*
Was the math too difficult?	*2.5*
Was the physics too difficult?	*3.0*
Was the class registration fee to high?	*2.7*
Was the assembly easy?	*2.2*
Was the 2-day class too long?	*2.5*
Would you take a similar class again?	*4.5*

The majority of students enjoyed the class and showed strong interests in taking a similar class again if it were offered in the proximity of their school district. If the funding is provided, it is our plan to develop curricula for science educators so that the educators themselves teach the "Sound in the Sea" class using the material developed by NOAA. However, participation of an educator in the program is imperative to develop a high school level curricula.

Picture 1. High school students dipping their hydrophones in the Yaquina Bay

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