An Acoustically-Linked Deep-Ocean Observatory

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***Abstract* - A buoy-based observatory that uses acoustic communication to retrieve data from water column and seafloor instruments has been developed and deployed in 2362 m of water offshore Vancouver Island. The system uses high-rate (5000 bps) acoustic modems that are power-efficient (on order 1000 bits per joule) to telemeter data from an ocean bottom seismometer and a sensor monitoring a cold seep site near the Nootka fault. The buoy includes a Linux-based embedded controller, the modem base station and meteorological sensors. Data is off-loaded from the buoy using *ftp*, and remote login capability allows the acoustic communication schedule to be modified when instruments are added or removed from the network. The system has been operational for one year, typically transferring more than 500 Kbytes of data per day from two seafloor instruments.**

I. INTRODUCTION

Next-generation ocean observatories will provide communications infrastructure for sensors deployed throughout the world's oceans using submarine cables and surface buoys. Ocean observatories enable sampling over longer time scales and more expansive spatial ranges than what is possible using an expeditionary approach [1], and are thus planned over coastal, regional and global spatial scales [2].

Deep-water observatories fall into two broad categories, cabled and buoy-based. Regional cabled observatories such as NEPTUNE [3] will provide unparalleled access to the deep ocean, but because of the cost of installing cable, will likely be limited to areas within a few hundred kilometers of shore. In contrast, buoy-based systems that use satellite telemetry can be located almost anywhere in the world, and are thus complementary to cabled observatories. Two types of buoy-based observatories have been proposed, one is a "heavy-weight" design with a very high speed satellite link (Mbits/sec), diesel generator for power, and fiber optic connections to a seafloor junction box. These are ideal for high bandwidth sensors such as acoustic arrays or continuous seismic monitoring. A second "light-weight" approach is an acoustically-linked observatory with no electrical connection to instruments and low-rate satellite communications using Iridium. This approach is considerably less expensive than the high-bandwidth version and is well suited to support moderate numbers of sensors located over a 5-20 square kilometer area and may easily telemeter 1 Mbyte or more of data per day.

The overall performance of the system is related to communications power efficiency and cost of the acoustic and satellite telemetry systems. The efficiency of the acoustic link determines the size and cost of the sensor battery and its replacement rate which requires ship servicing. Solar cells on the buoy provide enough power for many hours of Iridium terminal operation each day, so the limitation of satellite data transfer is the cost associated with its use.

An important feature of all new ocean observatories is near real-time access and flexibility. The acoustically-linked observatory's usability for science is influenced by the ability of the operator to monitor and maintain the communications system based in the buoy, and the ease with which sensors can be added to the network. A key feature of the system presented here is that it provides connectivity between Internet Protocol (IP) sensors over the acoustic link. In addition, the use of IP over satellite link allows control software on the buoy to be updated from shore.

The observatory was deployed in 2004 near the Nootka Fault 80 km off the coast of Vancouver Island in 2362 m of water and is providing seismic and vent sensor data from the area. This acoustic network presented some unique implementation challenges but demonstrates the feasibility of a long-term operational observatory.

Deep-water systems that used buoys and acoustic communications include a prototype deployed in 1989 [4], and more recently, systems such as NeMO have demonstrated year-long deep water deployments with relatively low telemetry data rates (~600 bps) and near-real time uplink capability via Iridium satellite data link [5]. The acoustically-linked observatory described here is an improvement on previous designs by taking advantage of higher data rate (~5400bps) and longer range (~4km) acoustic telemetry and the availability of a low power Linux-based control system for remote configuration and operation.

The paper includes a description of the entire system, including the buoy, sensors, communications links and the protocols used for data transfer. Section II describes the hardware that makes up the system, in Section III the operation of the observatory is described, and in Section IV the performance of the system and some of the data collected are presented.

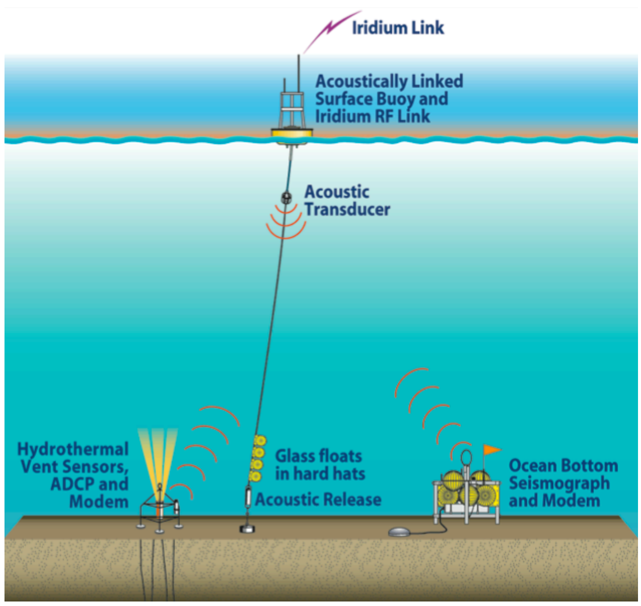

Fig. 1. Conceptual drawing of an acoustically-linked observatory.

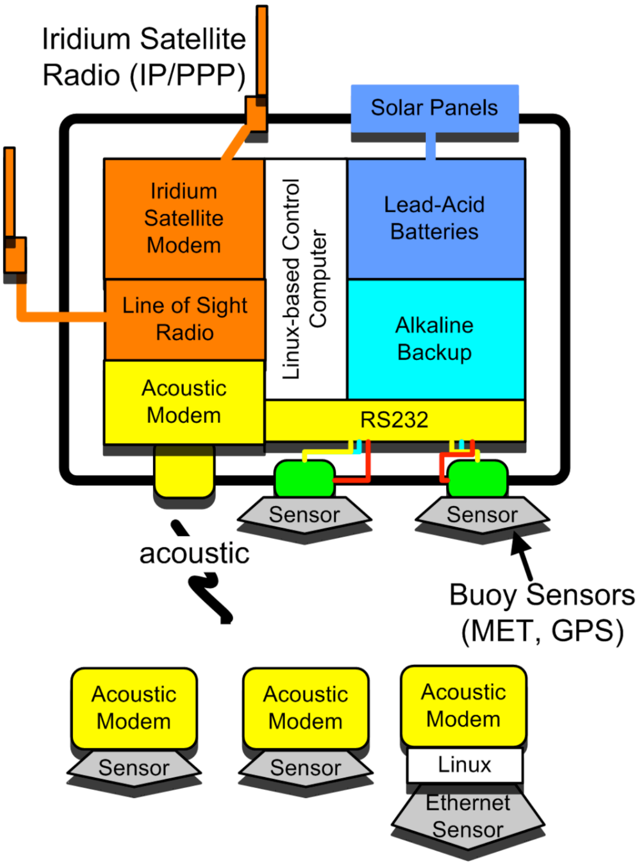

Fig. 2. Functional components of the buoy-based observatory (figure courtesy of A. Maffei, WHOI).

II. SYSTEM DESCRIPTION

The system is represented functionally as shown in Fig. 2 where the primary components of the system are shown. The buoy houses the control computer, radio, satellite, and acoustic modems plus surface sensors. Multiple remote sensors (up to 15) in the water column or on the seafloor can be addressed by the surface modem. The individual hardware elements are described in detail below.

A. Buoy and Mooring

The surface mooring (Figure 3) deployed in 2362 m of water about 80 km off the coast of Vancouver Island is an inverse catenary design with a scope of 1.08 as shown. This low scope design was chosen to minimize the diameter of the buoy's watch circle and thus keep the buoy within acoustic range of the seafloor instruments. The mooring uses 7/16 inch plastic-jacketed, torque-balanced wire rope in the upper 1000 m and a combination of 7/8 inch plaited nylon and 1-1/8 inch plaited polypropylene line below this point. It is anchored with 7700 pounds of steel and employs dual acoustic releases for recovery. Back-up buoyancy is provided by 48, 17-inch glass balls. The surface buoy consists of a Surlyn flotation module with 15,000 pounds of net buoyancy mounted on an aluminum structure that includes a tower for mounting instruments and antennas and a large removable instrument well.

Unique features of the buoy and mooring include a universal joint between the buoy and the mooring that provides for up to about 60 degrees of motion in two planes. A central hole in the universal provides an unbending pathway for conductors that pass through the universal. Below the universal is a 10 m chain and urethane composite that has 12 electrical conductors coiled around it. The purpose of this component is to protect the conductors from bending strain produced by the motion of the buoy in severe sea states. The conductors connect two acoustic transducers, which are mounted at the bottom of the chain/urethane segment on an aluminum plate to electronics in the surface buoy.

Fig. 3. Buoy with solar panels, meteorological sensors and antennas.

B. Power System

Primary power is generated on the buoy by four vertically mounted 150 watt solar panels and stored in a bank of eight 100 watt lead acid batteries. An alkaline backup battery of 512 D Cells is capable of providing power to the system for up to 3 months during long periods without sunshine. Average buoy power consumption including the communication systems is approximately 5 watts.

C. Controller

The controller is a low-power computer (called the Bitsy from Applied Data Systems) which is StrongARM based. It runs Linux and takes less than 1 Watt when operating. The low power operation means that it can be operated continuously. The Linux kernel running on the Bitsy is customized for the hardware and allows the system to control power to the radios and other sub-systems.

D. Buoy Sensors

Meteorological conditions are measured every 10 minutes by ASIMET wind, barometric pressure and relative humidity sensors. A GPS incorporated in the primary Iridium unit provides position information once per hour.

E. Satellite and Line-of-Sight Links

Two-way communications to shore are accomplished using two Iridium 9505 satellite modems. The connection speed for the Iridium modems is 2400 baud. A 900 MHz spread-spectrum FreeWave radio modem with a link speed of 38400 baud and a range of several miles is used during testing and deployment. Both Iridium and RF links use PPP (point to point protocol) to run IP (Internet Protocol) which allows the use of standard networking tools for communication and file transfer. Multiple connections are possible which make remote monitoring and system management possible.

F. Acoustic Modems

The acoustic communications system uses multiple data rates for control and data telemetry. Low-rate (80 bps) frequency-hopping, frequency-shift keying (FSK) is used for all control functions, and high-rate (300-5300 bps) phase-shift keying (PSK) is used for data uplink from the sensors. The link protocol is simple time-division, multiple-access (TDMA), which is controlled from the surface. Two modems are used on the surface buoy, one Micro-Modem, and one Utility Acoustic Modem (UAM), both developed at WHOI. The Micro-Modem is used for all network control functions, and the UAM receives and decodes the PSK uplink at one of four possible rates. For simplicity and redundancy two separate transducers are used. The UAM capability is now available in a compact co-processor that fits on top of the Micro-Modem, so future deployments will not need two different modems. The remote sensors all use the Micro-Modem.

The modems all use directional transducers with 60 degree beams. Use of directional transducers provides high efficiency at modest power levels. The source level is 190 dB and the transmit power is approximately 8 Watts. When the modems are not transmitting they require 100 mW, but may also be put asleep by acoustic or local commands to reduce power consumption to less than 1 mW.

Three other important modem capabilities are used in the system. One, the modem can be commanded to toggle a hardware control line to turn on power to a sensor or computer. Two, the modems can ping each other to ensure that another unit is awake and within range. The ping command also returns the acoustic travel time which allows the distance to be computed. Third, the modems have an acknowledge mode whereby the transmitting party sets a bit in the packet indicating that an acknowledgement is requested. The acknowledgement packet is sent automatically when a good packet is received (i.e. the checksum checks) and this bit is set. At the originating device the acknowledgement serves as notice that the data which were transmitted can be taken off the outgoing queue and new data can be sent in the next packet.

G. Acoustically Linked Sensors

Two types of sensors are accommodated in the observatory, "dumb" raw serial instruments and those with programmable controllers, possibly running Linux or a similar operating system. Raw serial instruments are handled using a Micro-Modem with internal buffering to store data until it is requested from the surface. For this deployment the raw sensor used was a Falmouth Scientific current meter located on the mooring line and programmed to provide data at a regular rate to the modem.

An ocean bottom seismometer (OBS) was the primary data source for this deployment. The seismometer includes a network-based data logger, the Quanterra Q330 Baler, recently developed for land-based applications, but adopted by the WHOI OBS group for seafloor deployments. The transfer of data from the OBS is done using another embedded Linux computer (the same Bitsy hardware used on the buoy), which runs software to handle the modem data interface. Data from the OBS is offloaded by first requesting, via HTTP, a data segment, for example 1 Hertz data for a 6 hour period, then using a network file copy command from a remote computer. Because the data request originates at the surface or possibly on-shore, the time, resolution, and seismometer source of the data can be varied at time of request. This allows the OBS to be operated as a near real-time observatory sensor: measurements are requested as desired, and parameters can be modified as desired by the user. On several occasions this capability was used to offload high resolution data from known seismic events shortly after they occurred.

In order to accommodate this type of control a sophisticated command execution and file transfer system that can run on Linux or Unix operating systems was developed as described in Section III.

III. OBSERVATORY OPERATION

A. Buoy Control and Schedule

Using the *telnet* protocol over Iridium link, a user can log in to the buoy and have complete control over the system. This capability allows schedules to be modified, firmware for the acoustic modems to be upgraded and if necessary the entire operating system to be replaced through the Iridium link. Installation of an instrument developed by the University of Washington and Scripps occurred several months after the deployment of the buoy system. Modification of the buoy schedule, installation of new data processing software and acoustic link verification were all performed remotely from WHOI.

Scheduling of all tasks performed by the buoy controller are managed using the Linux *crond* daemon. All activities are scheduled to occur at specific times during the day. For this deployment the system is scheduled on a 6 hour cycle that is shown in Figure 4. Taking advantage of the Linux OS, most tasks can occur simultaneously with the exception of the acoustic link. The acoustic link is only able to communicate with one instrument at a time and thus acoustic tasks must not be scheduled to overlap.

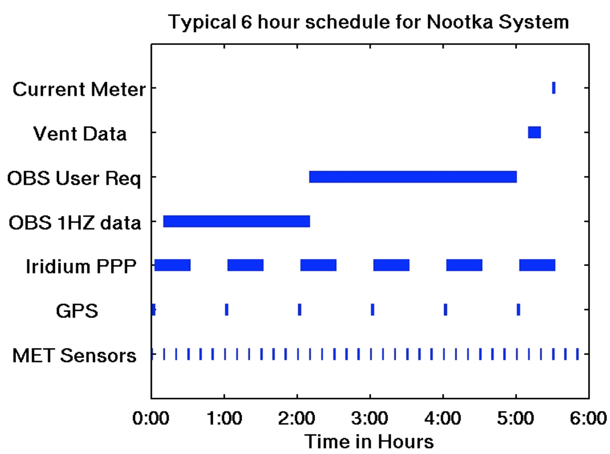

Figure 4. Sampling Schedule for acoustically-linked observatory.

A Linux daemon was created to manage the acoustic links. This daemon, called *modemd*, maintains serial connections to the Micro-Modem and UAM on the buoy, configures the modems as required for each subsurface node session, logs performance of acoustic links, and facilitates link control and file transfer by means of a Linux command line interface. The daemon is also used in the remote OBS system. It runs on the Linux computer that is used to manage the data transfer from the OBS and the acoustic modem.

Each remote node has its own link configuration. The data rate, time between packets, packet timeout, data rate and number of retries are entered in a link configuration file on the surface buoy controller. These parameters vary with the type of sensor and its location. The link file is modified whenever a new sensor is added to the observatory. For example, a node placed a great distance from the buoy would have a link file entry with a longer packet timeout, and a sensor node with a more data to send would require a higher data rate.

B. *Acoustic Remote Command Execution*

The first step for a networked instrument is to send a command to prepare data for subsequent acoustic transmission. This may be optionally preceded by a command to turn on the power to an adjacent device. The command execution capability is provided by a function modeled after the Unix remote shell (*rsh*) command, called *ash*, for acoustic remote shell. Using this capability a user, or more typically, a shell script running on the surface buoy, can send a shell command to an acoustically-linked remote computer for execution. For the OBS system a *perl* script is executed on the remote computer. The script performs the local HTTP-based file transfer from the OBS to the modem control computer in preparation for acoustic transfer to the surface.

C. *Acoustic File Transfer to Buoy*

Files are transferred between computers over the acoustic modem at the rate specified in the link control file. Control originates at the surface and the data is “pulled” from the remote computer. The surface requests data from a remote unit until all files in the acoustic “outbox” are transferred, or until the maximum number of retries or the maximum connection time has been exceeded. The connection is loss-less: all packets that make up a file must be received and be error-free (as determined by a cyclic-redundancy check) for a file transfer to be completed successfully. The acknowledgement capability is used on a packet by packet basis to guarantee reliable data transfer.

D. *Satellite File Transfer to Shore*

Data is transferred to shore using a file based transfer scheme similar to email. Files to be transferred are placed in an incoming or outgoing directory on the buoy or shore computer. Once per hour, the buoy initiates a PPP connection and transfers all files using FTP. Data on the shore computer is made available via a web page located at http://fathom2.whoi.edu/.

IV. PERFORMANCE AND RESULTS

The system was deployed in May 2004 near the Nootka fault offshore Vancouver Island. It operated for more than a month before the high-rate data stopped being received by the buoy. However, the digital signal processor (DSP) in the Utility Acoustic Modem was still operating, so the problem was determined to be somewhere in the analog receive path from the transducer to the DSP. A number of options were considered in order to repair the system, including recovering the buoy and replacing the transducer and external wiring. However, it was first decided to attempt a fix by changing the firmware on the Micro-Modem, the UAM, and the control program *modemd*.

Fortunately, two identical transducers were installed below the buoy, one for each of the modems. The Micro-Modem transducer was still operating well and could communicate at the low data rate. However, the Micro-Modem does not have the capability to run the sophisticated decision feedback equalizer used to receive the high-rate phase-coherent data. The Micro-Modem *does* have the capability to detect and demodulate the high-rate data from passband to baseband to reduce the amount of raw data per packet, though it cannot decode it. Thus the Micro-Modem firmware was modified to detect and store the baseband PSK signals, then transfer them to the Linux computer, which then uploaded them to the UAM DSP for processing. Making these changes to all three processors took time, but the modifications were ultimately successful. The impact on system operation was in total throughput. The burst rate remained the same, but moving the data between processors using the serial ports (which operate at 115 kbps) took many seconds for each transfer. The system was restored to operation in late September 2004, and has been operating well since.

The bathymetry in the deployment area and the estimated watch circle of the system are shown in Figure 5. The acoustic coverage area varies with the position of the buoy on the surface. Sensors located on the mooring line or within the watch circle of the buoy have the highest probability of good connectivity, though the coverage area is considerably larger. The point labeled “Proposed UW Site” is the seep site where another sensor was deployed. Connectivity at this site is not possible 100% of the time, but depends upon the location of the buoy which is forced by currents and local winds. Thus an important consideration for sensors on the edge of the coverage area is sufficient data buffering to allow storage through periods when the buoy is not in acoustic range.

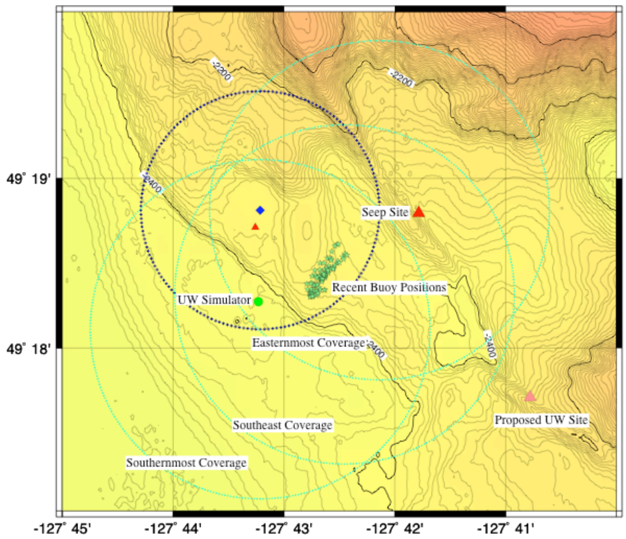

Figure 5. Deployment area near Nootka fault, showing watch circle (blue), and common acoustic coverage areas (cyan).

A. *Acoustic Data Throughput*

The total amount of data that is transferred each day using the acoustic modem depends upon how the system is configured. Considerably flexibility is available in scheduling data uploads, and the volume of data depends on the number of channels of 1 Hz seismic data that are requested. The approach used at the start of the deployment was to telemeter four channels of 1 Hz data every day, and then request 40 Hz data from all channels for specific events that were detected by shore stations. The exact amount of data transferred depends upon how much compression can be done on the data. The compression is an integral part of the data format that is used by the Quanterra Q330. The amount of data transmitted from the OBS per day is shown in figure 6. Prior to the acoustic repair the system averaged 782 Kb per day. After the repair the number of channels was reduced from four to two, and the average amount of data transmitted reduced to 554 Kb per day on average.

The amount of data from the vent-monitoring instrument is approximately 25 KBytes per day. This data load does not take a significant time to transfer, and thus was not reduced by th modifications described above.

B. Iridium Data Throughput

Since deployment in May 2004, more than 150 Mb of data from acoustically linked instruments have been transferred via Iridium. Average data throughput for each transfer has ranged between 220-240 Bytes/second depending on file length. Remote management of the vent instrument installation and acoustic modem repair were made possible by the reliability of the Iridium link.

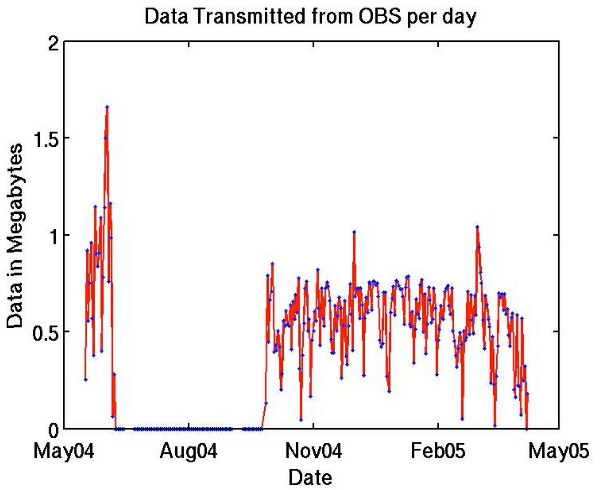

Figure 6. Daily data transmission, showing when data transfer stopped, and then was regained after repairs were effected remotely.

C. OBS Data

The most important feature of the acoustic observatory is the ability to get data in real time from an OBS and the nearby vent sensor. The data would normally be unavailable until they are recovered, possibly a year after an event of interest. While it is impractical to acoustically transmit all of the 40 Hz data from the OBS, it is very feasible to send broadband data from selected events. The data can generally be acquired within a few hours of an event.

Figure 7 shows the location of the plates and faults in the North East Pacific. A series of three earthquakes occurred at the edge of the Nootka fault on February 28th, 2005. The data were uploaded from the buoy and are shown in Figure 8. These vertical-component, ground-motion data show arrivals from three moderate-sized, strike-slip earthquakes and from other smaller events. The source-receiver distances for the events labeled with moment magnitude (Mw) values are, in time progressive order, 179 km, 222 km, and 173 km. The 20 Hz data are band-pass filtered from 5-9 Hz for this plot.

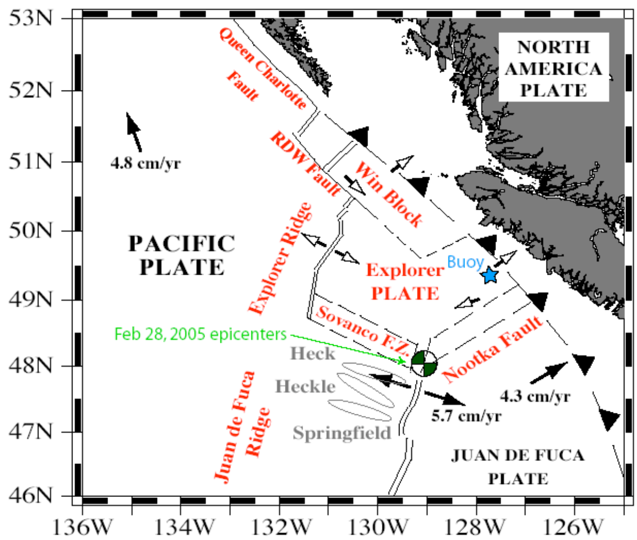

Fig. 7. Tectonic framework of North East Pacific showing locations of the buoy and Nootka Fault and the epicentral locations of the three earthquakes shown in Figure 8.

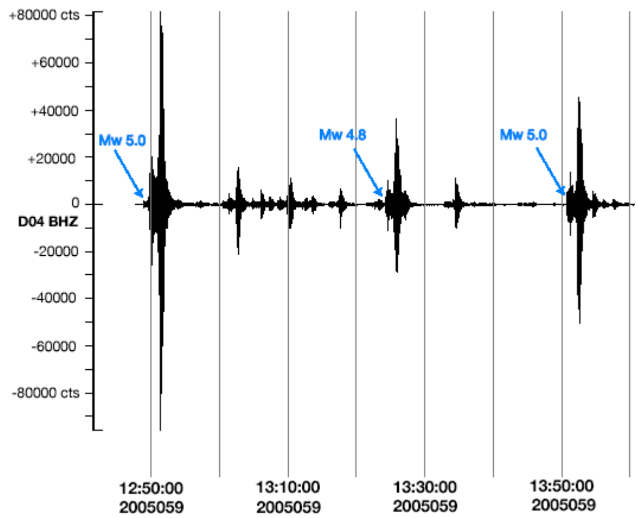

Fig. 8. Seismograms recorded on February 28, 2005 by the WHOI OBS deployed in the immediate vicinity of the buoy anchor.

V. CONCLUSIONS

The acoustically-linked observatory can play a significant role in providing near real-time data from the water column and the seafloor. The strength of the “light-weight” buoy approach is its low cost relative to the large buoy, though it is envisioned that a combination of both will be necessary in the ORION infrastructure. The amount of data that can be transmitted over the acoustic link is actually similar to what is practical (and affordable) to send over the Iridium link. The OBS is an excellent example of a high bandwidth sensor whose data can be selectively uploaded in response to events observed on other sensors on shore (and in the future on the cabled regional observatory). Large numbers of other sensors that produce less data per day (on the order of 50-100 Kbytes) can be accommodated without difficulty, and the flexibility and remote configuration capability of the system allows them to be added to the network easily.

Acknowledgments

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