

The WHOI Micro-Modem: An Acoustic Communications and Navigation System for Multiple Platforms

Lee Freitag, Matthew Grund, Sandipa Singh, James Partan, Peter Koski, Keenan Ball
Woods Hole Oceanographic Institution
Woods Hole, MA 02543 USA
lfreitag@whoi.edu

Abstract—The Micro-Modem is a compact, low-power, underwater acoustic communications and navigation subsystem. It has the capability to perform low-rate frequency-hopping frequency-shift keying (FH-FSK), variable rate phase-coherent keying (PSK), and two different types of long base line navigation, narrow-band and broadband. The system can be configured to transmit in four different bands from 3 to 30 kHz, with a larger board required for the lowest frequency. The user interface is based on the NMEA standard, which is a serial port specification. The modem also includes a simple built-in networking capability which supports up to 16 units in a polled or random-access mode and has an acknowledgement capability which supports guaranteed delivery transactions. The paper contains a detailed system description and results from several tests are also presented.

I. INTRODUCTION

Multi-vehicle operations in shallow water, both completely autonomous and supervised, rely on acoustics for communication and navigation. A link to a central station allows mission status to be monitored and for the vehicles to be controlled. Inter-vehicle communication allows cooperative action among vehicles, whether the same type of autonomous underwater vehicle (AUV), or different types performing diverse tasks to accomplish a common mission such as shallow-water mine countermeasures. An example of a multi-vehicle mission is a REMUS vehicle performing a side-scan survey and on-board computer-aided detection and computer aided classification (CAD/CAC), followed by an identification vehicle, which may be another REMUS or a crawling vehicle equipped with a scanning sonar.

The capability of the modem to be compatible with the REMUS transponders is important because it allows other vehicles that work with REMUS to utilize the same acoustic baseline. This puts all of the vehicles into the same navigation network and reduces localization errors that might occur with different underwater acoustic navigation systems. This is important to avoid a second similar acoustic system on a small vehicle with limited space and a fixed number of available serial ports. The modem can be configured to operate at 25 kHz, the same band as the REMUS transponders, so the hardware already had the capability, and thus the navigation functionality is simply implemented in software.

AUV mine countermeasure (MCM) operation is an example of a small communications network. Thus a simple networking capability was provided from the very beginning. The first description of the network capability was described in [1].

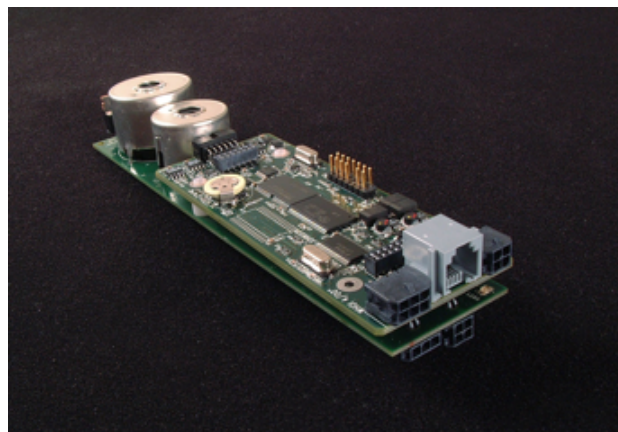


Fig. 1. Basic Micro-modem board set: power amp and main board.

That version of the system was implemented on the Utility Acoustic Modem, and used a passive navigation system with fixed nodes pinging at a rate controlled by a master node. Since then the REMUS navigation capability has been added and the networking capability made more general. It allows any vehicle to talk to another other in a random access mode if desired.

This paper will describe Micro-modem hardware and software, and present some results from recent acoustic communications demonstrations featuring our acoustic modem.

II. HARDWARE DESCRIPTION

The Micro-modem has a main electronic board which is supplemented by several different electronic modules. Each of the boards - main board, power amplifier, and floating point coprocessor is described in detail below. The section concludes with a brief description of the RF-Acoustic gateway buoy.

A. Main Board

The Micro-modem main board is physically compact with low power consumption, allowing embedded deployments in underwater vehicles and systems. It provides analog input and output, along with high computational power, to support general underwater acoustic signal processing, primarily for communication and navigation applications. User control is via a standard RS-232 serial port, with a second serial port to allow the Micro-modem to control additional instruments.

The main board is based around a Texas Instruments fixed-point digital signal processor (DSP), the 'c5416, providing up

to 160 MIPS. The clock rate is software-configurable, allowing low-power modes, such as a matched-filter detector at about 80mW for the entire system. The system can rapidly switch to full-power (about 180mW), for instance when a packet is detected.

The analog input has a user-programmable gain stage and low-pass anti-aliasing filter, with a 12-bit A/D, typically sampling at 80 kHz. The analog output is linear via a 12-bit D/A converter and low-pass reconstruction filter.

A real-time clock provides timing, and allows the Micro-modem to program a wake-up alarm, then shut down completely in a very low-power hibernation mode. In addition to the on-board real-time clock, the user can provide a high-precision pulse-per-second signal for precision timing applications such as navigation.

Operating parameters such as network ID numbers or signal detection thresholds are stored in non-volatile memory. The system firmware is stored in flash memory, and hence can be upgraded easily by the user. Also, a standard JTAG test and debugging interface aids firmware development and testing.

The main board also has several expansion ports, allowing boards to be stacked for various applications. Among the boards developed so far are a floating-point coprocessor for PSK equalization and decoding (described below), a multi-channel analog sampling board supporting four- and eight-channel receive hydrophone arrays, and a flash memory board allowing up to 2Gbytes, for example for raw data capture.

B. Power Amplifier

The Micro-modem is outfitted with a single channel class-D power amplifier to drive the ceramic projector, to act as a single channel receiver and to act as a power conditioning system. Several mechanical form factors have been designed, including a long narrow format, shown in Fig. 2.

The power amplifier is designed to be efficient and easily modifiable for use under various vehicle power systems, signal frequency/bandwidth, and projectors. Each application may require only a minor modification to the output matching network to optimize the interface to the projector. The class-D amplifier topology was chosen due to its superior efficiency characteristics and simplicity of matching to various transducers. However, as a consequence the output power is fixed for any given application. A typical application requires 50W during acoustic transmission to achieve 190dB re 1uPa of sound pressure with an omnidirectional projector (when not transmitting, the power amp is nominally in shutdown mode).

The power amplifier also includes a single channel receiver with an onboard transmit/receive switching network and low-noise broadband preamplifier. This allows the Micro-modem to operate using just one transducer for low-rate applications. The preamplifier normally does not need to be modified for frequency or different transducers due to its broad response.

The power amp circuit board also provides the initial power conditioning circuitry for the Micro-modem system. Vehicle power to the Micro-modem system is routed through this board to protect the system from improper voltage, polarity or surges.

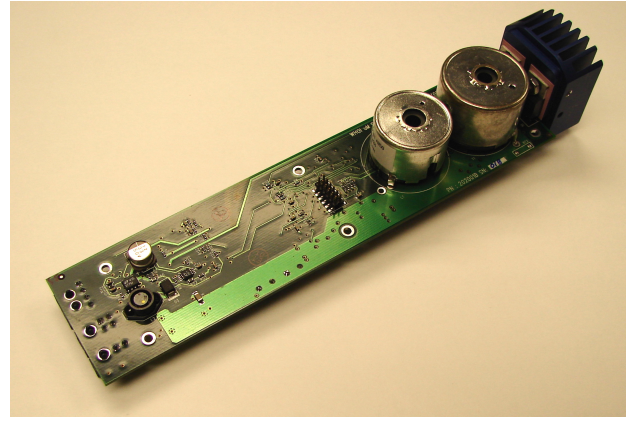


Fig. 2. Long form factor Micro-modem power amp.

Finally, as physical space is important inside a small AUV, and since power electronics tend to be large, we have multiple form-factors of this hardware to make efficient use of space.

C. Floating Point Coprocessor

To support computationally complex PSK equalization algorithms, we developed a floating-point coprocessor board in collaboration with engineers from the Naval Undersea Warfare Center in Newport, RI. The coprocessor board is an expansion card which can stack onto the Micro-modem main board, as shown in Fig. 3.

The board uses a Texas Instruments 'C6713 DSP. This DSP can provide over 1 GFLOPS with well-optimized code. Due to its high-speed floating-point DSP and fast SDRAM, the coprocessor board consumes as much as 2 Watts when active. For this reason, the Micro-modem can switch the coprocessor off completely, and power it only when a received PSK packet has been detected. No analog circuitry is on this board; it is simply a coprocessor board, and receives digital data directly from the Micro-modem main board in a master-slave relationship where the main board is the master.

As with the Micro-modem main board, the system firmware is stored in flash memory, and is user-upgradable. Firmware development is again via a standard JTAG test interface.

D. Gateway Buoy

The RF-acoustic gateway buoy allows telemetry of underwater acoustic network traffic to a remote location. Gateways buoys consist of a Micro-modem and FreeWave radio in a submersible housing with foam floatation as shown in Fig. 4. The transducer and optional four channel receiver array are located on the anchor line below. The gateway buoys are mechanically based on the design of the WHOI PARADIGM buoys, originally developed to track the position of a REMUS AUV in real time by round-trip ranging.

III. SOFTWARE AND PROCESSING

As described above, the WHOI Micro-modem is a very capable signal processing platform for underwater acoustics. The modem hardware allows development of many capabilities

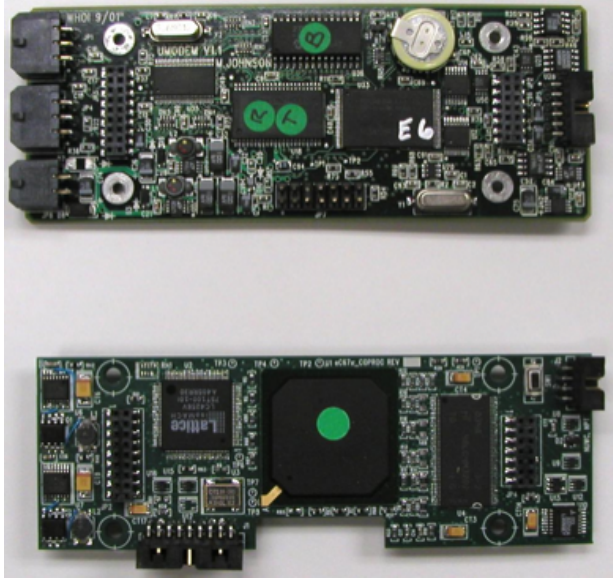


Fig. 3. Micro-modem main board (top) and TI '6713 floating-point DSP coprocessor board (bottom).



Fig. 4. Micro-modem based RF / Acoustic Gateway Buoy, with modem and Freewave serial radio

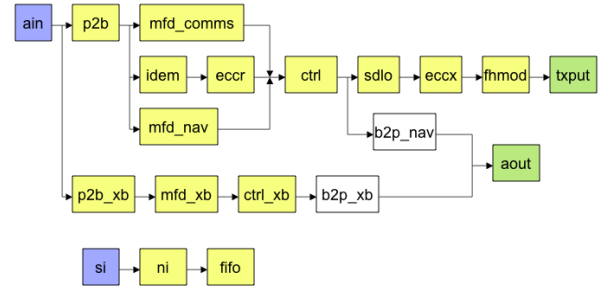


Fig. 5. Block Diagram showing Micro-modem implementation, with data driven functional blocks, using the WHOI embedded RTOS. Blue blocks are inputs and green blocks are outputs.

in software. The sections below describe many of the modem's features which have been implemented in the current firmware.

A. NMEA User Interface

The Micro-modem provides a user interface on one of two available RS-232 serial ports. A command set has been developed following the NMEA 0183 Standard for interfacing marine electronics. The commands and messages conform to the sentence standard, using talker identifier "\$CA" for acoustic communications functions, and "\$SN" for acoustic navigation functions. The specification also defines standard initiator and terminator characters for message synchronization, and provides a sentence integrity check by means of an appended checksum, all of which are implemented

B. Block-based Structure

A low overhead real-time embedded operating system was created here at WHOI to manage signal processing on the Micro-modem. This operating system provides a data-driven processing capability by defining functional blocks which have a standardized semaphore protected buffer interface. A simple task scheduler ensures that blocks meet real-time requirements, by monitoring the buffer semaphores.

This allows programmers to create signal processing function blocks, and connect them in chains, to implement a DSP task. Blocks have been created to implement the Micro-modem processing chain such as a analog to digital converter driver (AIN), a matched filter detector (MFD), a basebander (P2B), and an FSK demodulator (IDEM). Figure 5 shows the current Micro-modem firmware as implemented using this block-based operating system.

C. FHFSK Standard

The physical layer modulation scheme used by the Micro-modem is based on frequency-shift keying with frequency-hopping (FH-FSK). Frequency-shift keying is a simple and relatively robust underwater acoustic communication technique, which when combined with frequency hopping, allows operation in a shallow-water environment with multi-path. The default data rate is 80 bps after the overhead from error-correction is applied. The system operates at approximately 10, 15 or 25 kHz and uses 4 kHz of bandwidth.

TABLE I
WHOI MICRO-MODEM PACKET TYPES

pkt type	num frames	frame size	total payload
1:FSK	1	32	32 bytes
2:PSK	3	32	96 bytes
3:PSK	3	64	192 bytes
4:PSK	2	256	512 bytes
5:PSK	8	256	2048 bytes

To facilitate interoperability, this modulation scheme has been published as a standard [2], at the request of ONR. Furthermore, Benthos Inc. has implemented the standard and demonstrated interoperability at AUVFest 2005.

D. Minipacket Capabilities

The modem supports communication, navigation and other functions by means of two different classes of packets: a short packet which contains only 21 bits of information which is called a mini-packet, and longer packets which may be FSK or PSK, containing significantly more data, from 32 to 2048 bytes each (see table I). Mini-packets take on a number of functions, which are described below. Additional information can be found in the Micro-modem Software Interface Guide [3].

1) *Cycle Init*: The cycle init mini-packet prefaces all data transfers. It contains the source, destination and packet type for the subsequent data transfer. In a master-slave transaction where the master is requesting data, the slave's ID is the source, and the master's ID is the destination. For a downlink transaction the order is reversed. Nodes can also address other nodes, either transmitting or receiving on command from the user.

2) *Ping*: The ping command can be used by any node to range to any other node. The modem sends a ping mini-packet to the specified node, which responds after a fixed turn-around time. The originating node subtracts the turn-around time and reports the one-way travel time to the user. The time-keeping and the bandwidth of the FM sweep used for timing provide accuracy of one base-band sample, or about 125 μ sec (less than 0.2 m).

3) *Hardware Control*: The modem has two spare digital outputs that can be toggled upon command. These can be used for hardware-based functions on an AUV such as emergency weight drop. The command can be sent by a remote unit acoustically, or over the local serial port.

4) *Data Acknowledgement*: The acknowledgement mini-packet is sent automatically when the ACK bit is set in a data packet that is received successfully by the addressed node. When the ACK packet is received by the node that originally requested the ACK when it sent data, a message is sent over the serial port to the local host. Note that automatic repeats are at the discretion of the transmitting host, but the ACK mini-packet, in combination with the ACK bit in the data packets, allows guaranteed delivery transactions to be performed efficiently.

5) *User Data*: The mini-packet can also be used by a user for sending very short commands if desired. This can be more efficient than full packets in certain situations.

E. Medium Access Control

An important feature of the modem is that it provides the user with information that may be used to implement a form of simple medium access control (MAC). MAC is most important in random access networks, but it is also necessary in systems where navigation and communication must coexist. For example, In the REMUS MCM application, the communication is centrally controlled by polling for data, while navigation is done on the remote units under control of the vehicle control computer.

To minimize collisions between incoming acoustic communications (or on-going communications between other users), the local application can monitor modem information. When a cycle-init packet is received it is reported to the local user so that it knows that there is an on-going cycle. The cycle is over when (1) the data corresponding to the cycle-init is received and delivered correctly, (2) the data is received but the CRC does not check, in which case the data is not delivered to the user and instead an error is reported, or (3) a time-out time has passed and no data is received, in which case a time-out message is reported.

If the user avoids initiating navigation or communication during an on-going cycle, network conflict will be reduced. While navigation pings are not disruptive to a communications packet, a communications transmission generally masks reception of navigation pings.

F. REMUS Compatible Navigation

One navigation capability on the Micro-modem is compatible with REMUS' broadband digital transponders. The transponders will reply to up to four different PSK interrogation codes. Micromodem users can interrogate these transponders, using the "\$CCPDT" command [3]. The modem will output one-way travel times to beacons, if their replies are detected.

From bench tests, Micro-modem navigation detector precision is $\pm 125\mu$ sec, which, when used to measure round-trip travel times, results in range estimate accuracy of ~ 9.4 cm. In practice, REMUS vehicles have demonstrated the ability to return to a bottom target location within ~ 1.5 meters.

G. Narrow-band LBL Navigation

In addition to polling REMUS broadband digital transponders the Micro-modem can be used to interrogate traditional narrowband transponders, by issuing the "\$CCPNT" command. The Micro-modem can be configured for various interrogate frequencies, turn-around times and reply frequencies, allowing interoperability with many commercial transponder systems.

H. High-rate PSK

A new addition to the Micro-Modem in 2005 is a multi-rate phase-shift keying (PSK) capability. All Micro-Modems can

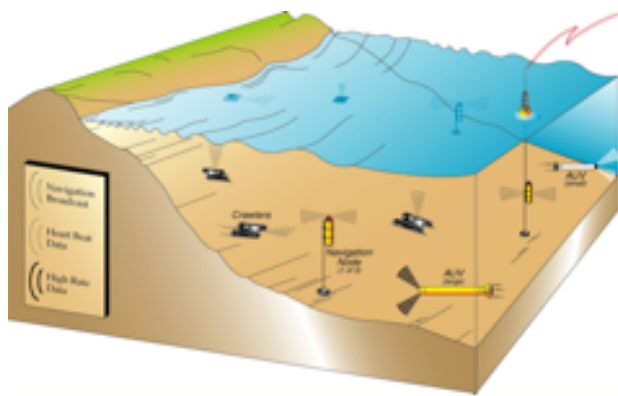


Fig. 6. Conceptual drawing showing very shallow water acoustic network for coordinated AUV MCM operations.



Fig. 7. The lightweight shallow water REMUS AUV (developed at WHOI), with Micro-modem for acoustic telemetry and remote control.

transmit PSK at data rates of 300-5000 bps (after overhead and error-correction). Modems equipped with an optional floating-point coprocessor can receive the PSK transmissions, which are processed using a decision-feedback equalizer (DFE). Multiple hydrophones can be used by the DFE, which increases reliability in horizontal shallow-water channels. In a master-slave network where most data flows from the sub-sea nodes to the surface, only the gateway buoy requires the high-rate receiver, though it is desirable for other nodes if the sensor data can be used on the other platforms. Table I lists the five packet types currently available on the Micro-modem.

IV. RESULTS

The Micro-modem has been developed as a multi-rate and multi-user acoustic modem with acoustic networking capabilities. We have demonstrated underwater networks in a variety of ocean scenarios. Two significant demonstrations from 2005 are presented here: a very shallow water network for AUVs, and a deep water ocean bottom observatory.

A. Very Shallow Water Results

An underwater network has been developed with a focus on mine countermeasures (MCM) using autonomous underwater vehicles (AUVs), and was recently demonstrated At AUVFest 2005, in Keyport, Washington. The network relies on the

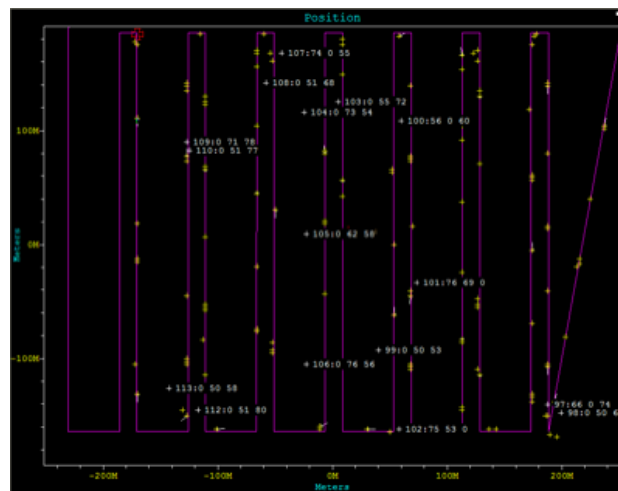


Fig. 8. REMUS real-time telemetry data showing CAD/CAC scores for bottom targets. Each target that is identified by the CAD/CAC system includes an identifier, then three scores, which are 0-100, one for each algorithm. If any of the algorithms reports a low score, then the target has a low probability of being a mine-like object [4].

Micro-modem's robust FHFSK modulation and error correction coding (ECC) scheme to communicate at long ranges (2-4 kilometers), in the very shallow water zone. In addition, the Micro-modem's multi-user networking protocol was utilized along with the broadband digital transponder capability, to supply common navigation and telemetry infrastructure for multiple AUVs working in coordinated fashion to search, classify, and map (SCM) the ocean bottom, and reacquire and identify (RI) bottom objects. A conceptual drawing of this very shallow water network is shown in Fig. 6.

As described above, the Micro-modem's network protocol supports up to 15 nodes. Additionally, up to 4 vehicles can share the acoustic navigation beacons, by using different broadband interrogation codes. These capabilities allow several REMUS AUVs, seen in Fig. 7, to coordinate their MCM missions in the same operational area, either in completely autonomous fashion, or with an acoustically networked operator issuing commands.

Figure 8 shows real-time telemetry from a REMUS. During a search-classify-map (SCM) mission, the AUV detects and classifies bottom objects by processing sidescan sonar with 3 algorithms. The object location and CAD/CAC algorithm scores are telemetered to an operator during the mission. Figure 9 shows two REMUS vehicles, configured with different sensors, re-visiting a bottom target, as directed by the operator, using an acoustic command.

B. Deep Water Results

WHOI Micro-modems were recently used to create an acoustically-linked deep water observatory. The observatory nodes use battery and solar power, relying on the low-power consumption of the Micro-modem for this long-term deployment. The system was deployed and operated for more than a year on the Nootka Fault, in the northeast Pacific [5]. A

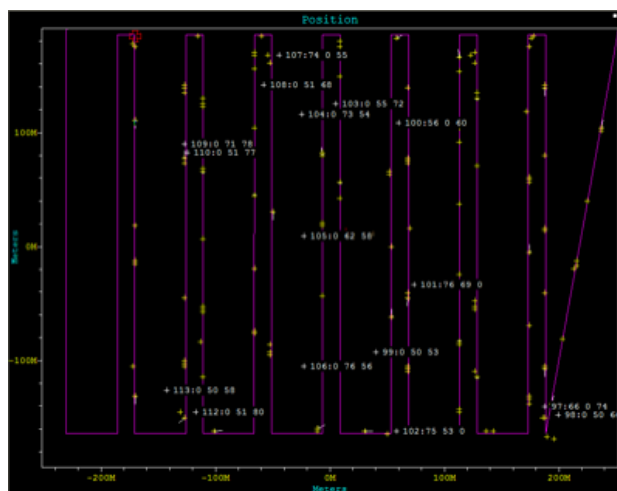


Fig. 9. REMUS real-time telemetry plot showing planned tracks of two vehicles performing a two-phase mine countermeasure mission. Blue crosses (+) show position reports from an SCM vehicle which has been re-directed for a closer look over a target, while the yellow crosses (+) are from an RI vehicle with dual frequency sonar and a low-light video camera.

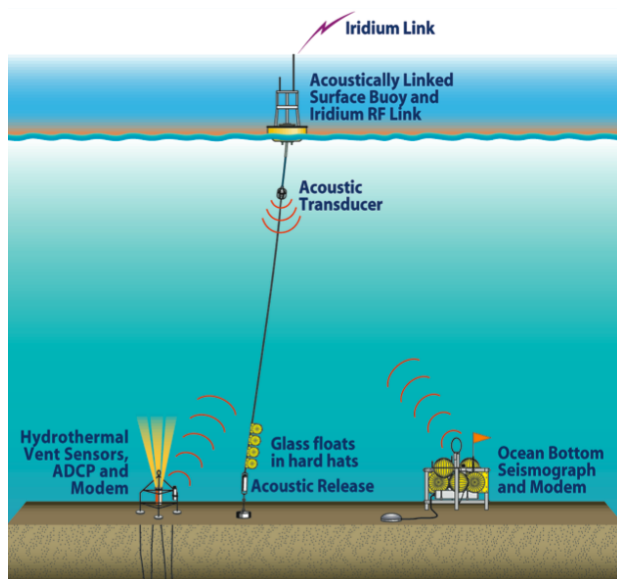


Fig. 10. Conceptual drawing showing acoustically linked deep water observatory for bottom mounted sensor telemetry.

conceptual drawing of this acoustically-linked observatory is shown in Fig. 10.

The observatory relies on a surface buoy which acts as a data aggregator: polling underwater nodes for data, collecting data from meteorological and GPS sensors mounted on the buoy hull, and relaying all data via Iridium link to a server in Woods Hole. The buoy, shown in Fig. 11 telemetered approximately 1.4MB per day.

The Iridium satellite link allows operators not only to offload observatory data, but also to update sampling schedule and sensor parameters in real-time, making the system a true ocean observatory. Figure 12 shows the location of the plates and faults in the North East Pacific. A series of



Fig. 11. The Nootka Observatory Buoy, with meteorological sensors and solar panels.

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 Fig. 13. 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 (M_w) 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.

V. CONCLUSION

The Micro-Modem was designed to be used as both a communications and navigation system. Thus it operates in different modes as commanded by the user, but retains a default behavior as an acoustic modem. The programmability of the modem has allowed the addition of features such as Ping, which are very useful in implementing useful underwater networks. The Micro-Modem has been licensed non-exclusively to Hydroid Inc. and it is now available integrated with the vehicle and on the gateway buoys. Future work includes more networking features, power control, and higher data rates.

VI. ACKNOWLEDGEMENTS

The shallow water acoustic networking work described here was supported by the U.S. Office of Naval Research,

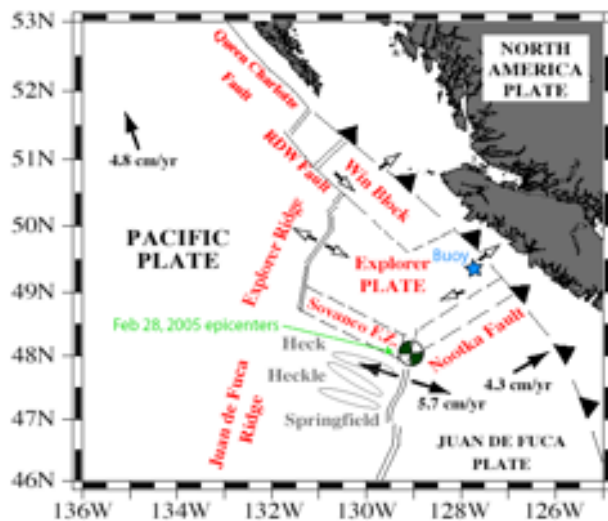


Fig. 12. Tectonic framework of North East Pacific showing locations of the buoy and Nootka Fault and the epicentral locations of the three earthquakes shown in 13

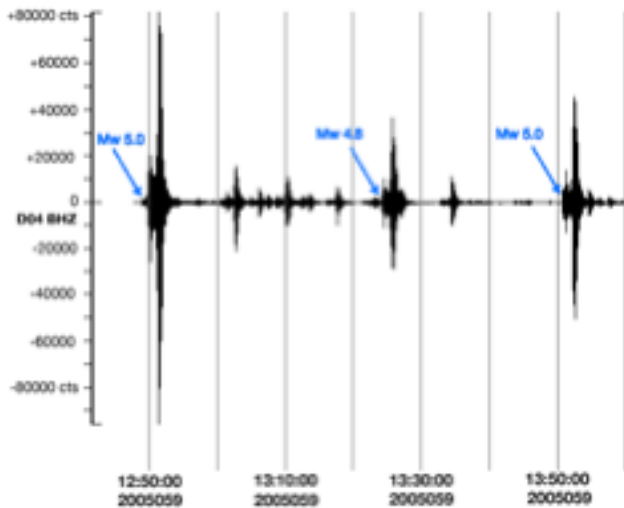


Fig. 13. Seismograms recorded on February 28, 2005 by the WHOI OBS deployed in the immediate vicinity of the buoy anchor.

REFERENCES

- [1] L. Freitag, M. Johnson, and M. Grund, "Integrated Acoustic Communication and Navigation for Multiple UUVs," in *IEEE Proceedings of Oceans, Honolulu*, October 2001, pp. 2065–2070.
- [2] L. Freitag and S. Singh, "Multi-User Frequency Hopping Underwater Acoustic Communication Protocol," Woods Hole Oceanographic Institution, Technical Report, 2000.
- [3] L. Freitag and M. Grund. Micromodem Software Interface Guide. [Online]. Available: <http://acomms.whoi.edu/micromodem/>
- [4] C. Ciany, W. Zurawski, and G. Dobeck, "Real-time performance of fusion algorithms for computer aided detection and classification of bottom mines in very shallow water environment," in *Proceedings IEEE Oceans Conference*, 2003.
- [5] D.Frye, J. Ware, M. Grund, J. Partan, P. Koski, S. Singh, L. Freitag, J. Collins, and R. Detrick, "An Acoustically-Linked Deep Ocean Observatory," *Proceedings of IEEE Oceans Europe, Brest France*, June 2005.

Code 321OE (Dr. Thomas Swain) under grants N00014-99-1-0280 (REMUS development), and N00014-99-1-0287 (acoustic communications).

The deep water ocean observatory work described here was funded through an NSF Collaborative Research MRI (OCE 0215670) managed by S. Shor and A. Isern. Satellite telemetry service was provided by the Ocean.US Iridium project.

The authors would like to thank R. Johnson, M. Lilley, W. Willcock, D. Kelley, A. LaBonte and J. Delaney of the University of Washington School of Oceanography and K. Brown of the Scripps Institution of Oceanography for coordinating placement and operation of their vent monitoring instrument near the Nootka buoy in September 2004.