

## The NEREUS in-lake wireless/acoustic chemical data network

Harry Hemond,<sup>1\*</sup> Jimmy Cheung,<sup>1,2</sup> Amy Mueller,<sup>1</sup> Joseph Wong,<sup>1,3</sup> Michael Hemond,<sup>4</sup> Daniel Mueller,<sup>1,5</sup> Justin Eskesen<sup>1</sup>

<sup>1</sup>Department of Civil and Environmental Engineering, Sea Grant AUV Lab, Massachusetts Institute of Technology, Cambridge, MA, USA

<sup>2</sup>Current Address: Standard and Poors, New York, NY 10041

<sup>3</sup>Current Address: Mountain View, CA 94043

<sup>4</sup>Department of Biological Chemistry and Molecular Pharmacology, Harvard-MIT Division of Health Sciences and Technology, Harvard Medical School, Boston, MA, USA

<sup>5</sup>Current Address: ZipCar, Cambridge, MA 02139

### Abstract

We describe a system for the semi-autonomous in situ measurement of lake chemical properties, with high temporal resolution and the potential to map chemical properties in 3 dimensions. The system comprises both fixed sensor locations on moored buoys and one (or potentially more) autonomous underwater vehicles (AUVs) serving as mobile underwater sensor platforms. Sensors include conventional water quality multiprobes and thermistor strings and the NEREUS underwater mass spectrometer for measurement of dissolved metabolic gases such as methane as well as permanent gases. Data are delivered to a shore station via a network that includes acoustic modems for communication with the AUV and a radio network operating in the license-free ISM (industrial, scientific, and medical) band operating under the IEEE 802.11b protocol. The system is designed to use low-cost commercial hardware and open-source software wherever possible. We constructed a prototype system of 3 buoys, 1 AUV, and a shore station, and field tests have demonstrated its ability to measure and remotely display lake chemical data in real time.

### Introduction

Measuring chemical and physical properties of natural water bodies with adequate spatiotemporal coverage is a daunting problem that is often limiting to both research and monitoring programs. The current interest in underwater observatories is in part a response to this problem. Chemical and physical sensors, operated as part of a network, offer a means to advance the understanding of phenomena for which spatiotemporal variability is a key attribute (e.g., Coale et al. 1991). To be most useful, such systems need to provide real-time access to data for a large community of users. However, problems confront designers and users of environmental measuring networks on several fronts. These include the still severely limited suite of

sensors available for chemical measurement, the need for large-volume coverage with a limited number of sensors, high costs, and the challenges of communicating with and controlling underwater devices in real time. In the absence of a hardwired data link, underwater communication is usually carried out acoustically, and as a result faces challenges of low bandwidth and sometimes low reliability. The NEREUS network, named in recognition of the NEREUS mass spectrometer as a key component, is an effort to advance on each of these fronts. It employs a novel chemical sensor and an autonomous underwater vehicle (AUV) as part of an in-lake network, relying extensively on low-cost components and open-source software. The network uses acoustic communication for real-time data collection from the submerged AUV. In this article, we provide an overview of the network, with an emphasis on the pathways and control of data flow in the system.

There is currently much activity related to the use of sensors, networks, and autonomous vehicles to study marine and freshwater systems. A noncomprehensive list of systems described in recent articles includes the Ocean Observatory Initiative (National Research Council, 2003), Martha's Vineyard Coastal Observatory (Carlowicz et al. 2005), the Neptune project (Penrose and Stoermer 2003), and the Leo-15 coastal observatory

\*Corresponding author: E-mail hfhemond@mit.edu

### Acknowledgments

This work was supported by NSF EAR 0330272, a pilot grant from BP, MIT Sea Grant, the W. Leonhard Chair, and NIEHS P30 ES002109. J. Morash, V. Polidoro, and R. Damus took part in vehicle construction and field testing, T. Donoghue assisted with buoy construction, L. Freitag provided the MicroModems, H. Nepf and C. Chrysostomidis are co-PIs on EAR 0330272 and provided valuable discussions, and A. Hibbard and S. Hood facilitated lake access for our chase boat.

(Glenn et al. 2006). A brief web search reveals many other investigations (mostly marine, but some freshwater) using AUVs, instrumented buoys, or cabled observatories. Although the literature shows a very dynamic and promising field, only a modest portion of the effort addresses freshwaters or small basins, and relatively few chemical sensors are available. In particular, the real-time underwater networking of AUVs carrying chemical sensors appears to be still in the developmental stage.

To address a major need in chemical sensing, the NEREUS underwater mass spectrometer (Hemond and Camilli 2002) was developed to measure metabolically relevant dissolved gases. In situ chemical measurement will facilitate much-increased spatiotemporal coverage that is likely to be important in understanding phenomena such as inflows from discrete underwater springs or seepage areas, episodic release of gases by ebullition, formation of intrusions in stratified lakes due to boundary mixing, or short-lived inhomogeneities in oxygen or carbonate concentration as a result of patchy distribution of phytoplankton. In the case of metabolic gases, in situ measurement also obviates the need to maintain strict isolation of samples from the atmosphere, as well as the need for sample preservation by pressurization and inhibition of metabolic activities. Beyond the development of the technology, an early scientific goal of the NEREUS network is to determine the spatiotemporal distribution of methane in a lake ecosystem, providing tests of competing hypotheses regarding the fate of methane produced in the lake (e.g., diffusion to the atmosphere versus bubbling—a highly variable process, spatially and temporally—versus microbial consumption). To be most useful, however, real-time in situ underwater sensing calls for underwater data communication, which can be accomplished by a cabled observatory in the case of fixed sensors but is more problematic in the case of instruments carried by a mobile platform. Thus, a hybrid network was designed to use both radio (for overwater) and acoustic (for underwater) communication for the collection of mass spectrometric and other complementary chemical and physical data.

The NEREUS network includes fixed sensors located on buoys and mobile sensors located on an AUV to provide a relatively high density of low-cost fixed sensors as well as mobility for instrumental sensors that are too costly to deploy in large numbers. Specific objectives include provision of *a*) real-time data from all instruments and sensors, *b*) AUV tracking information, and *c*) hardware means to control the AUV, whether surfaced or underwater, in real time, in support of future development of adaptive sampling techniques. The system is intended to be adaptable to individual research or monitoring needs, and thus relies on many off-the-shelf components as well as open-source software (National Research Council 2004). Whereas systems such as this can support classical monitoring and hypothesis testing, the existence of streams of spatiotemporally diverse, real-time chemical data may also facilitate advances in research methods heretofore not traditionally applicable to studies of lake

geochemistry, such as real-time adaptive sampling and application of data fusion methodologies.

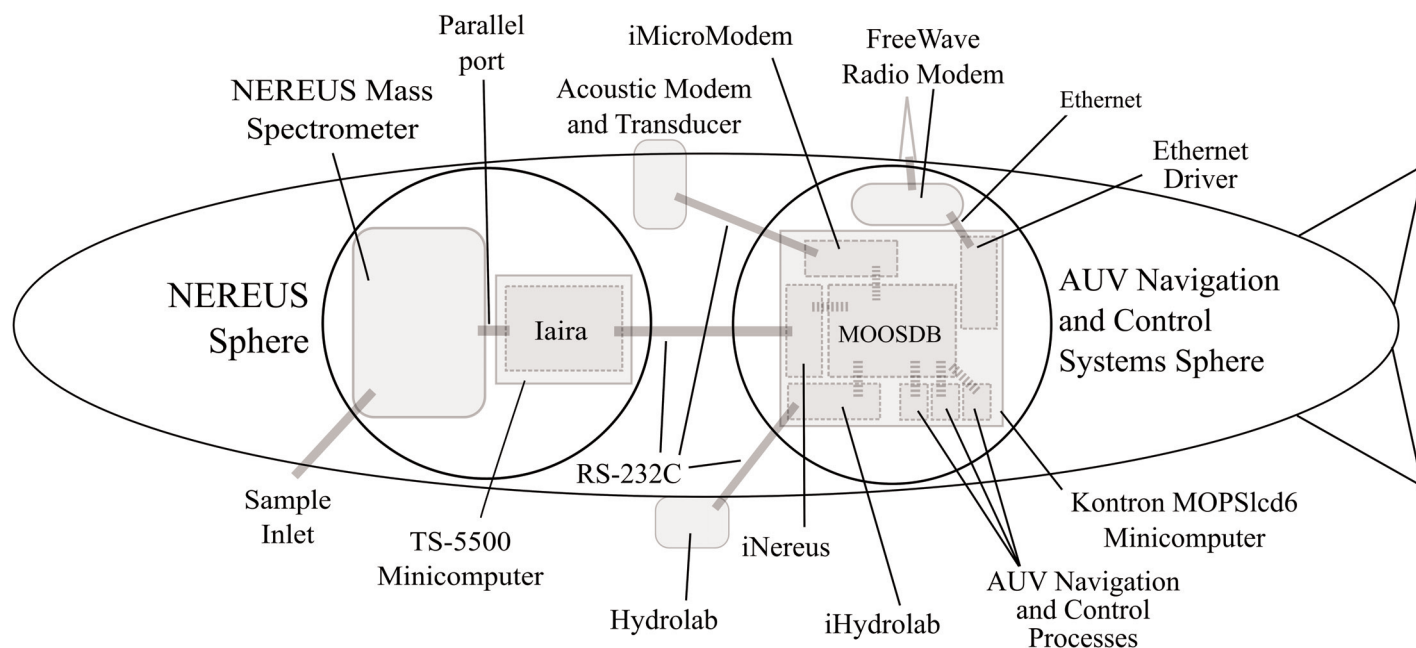
## Materials and procedures

*General*—The in-lake chemical data network comprises *a*) the NEREUS mass spectrometer and other water quality sensors, carried aboard an Odyssey-class AUV and having both underwater acoustic and overwater radio communications capability; *b*) moored buoys carrying multiple fixed sensors and having both wireless and acoustic communication capabilities; and *c*) a shore station incorporating wireless communication, logging capability, and graphical interfaces through which users may access the network. These components are shown in Fig. 1.

Chemical data measured by the sensors on the AUV can be transmitted acoustically to the buoys. These data, along with data from each buoy's own stationary sensors, are forwarded to the shore station by radio. The shore station displays and logs data and issues commands to the network. Quantities currently measured at the buoys include temperature profiles in addition to parameters measured by a typical water quality multiprobe [pH, dissolved oxygen (DO), platinum electrode potential (often called ORP or, loosely, redox potential), as well as temperature and conductivity]. The quantities measured aboard the AUV include multiple dissolved gases species such as methane, oxygen, nitrogen, and carbon dioxide, as well as the aforementioned parameters measured by a water quality multiprobe. Details of the implementation of each component of the system are described below.



**Fig. 1.** Components of the NEREUS network include an Odyssey II AUV equipped with mass spectrometer and water quality microprobe (top), several buoys that contain fixed sensors and serve as wireless and acoustic communication nodes (bottom right), and a shore station that logs data, provides real-time displays, and issues commands (bottom left).



**Fig. 2.** Network components on the Odyssey II AUV. Chemical data from the NEREUS mass spectrometer and Hydrolab water quality multiprobe are sent via standard RS-232 serial ports to the computer, where they are posted on the MOOS database (MOOSDB). When the vehicle is on the surface, data on the MOOSDB may be transmitted to the shore station by the radio modem, which serves as an Ethernet bridge. Data may also be parsed for selected quantities and compressed before underwater transmission to the buoys by the acoustic modem; the buoys in turn send data using wireless TCP/IP protocol to the shore station. The MOOS processes, iHydrolab, iNereus, and iMicroModem control data flow between the MOOSDB and the respective devices.

**AUV subsystem—Odyssey-II AUV.** Odyssey-II class AUVs are vehicles of approximately 200 kg displacement and overall length of 2.2 m (Fig. 1). The Odyssey II has a maximum speed of 3 km/h, endurance of the order of 8 h, and depth capability in excess of 2000 m, although the vehicle is currently restricted to depths in the 100-m range by the water quality multiprobe and the current mass spectrometer inlet.

An aft pressure sphere of the Odyssey vehicle houses all vehicle controls, and the NEREUS mass spectrometer is mounted in the forward pressure sphere, with the chemical-sensing membrane inlet exposed to the flow of ambient water via a penetration in the outer hull. (This layout differs in several respects from the Odyssey/Kemonaut vehicle, previously described by Camilli and Hemond 2004, which had 3 pressure spheres.)

The aft sphere contains a PC104 stack with a Kontron MOPS1cd6 166-MHz Pentium-MMX processor for vehicle control and communications. The computer communicates with all vehicle sensors, actuators, and instruments via serial ports. Other instruments in the sphere include a Crossbow AHRS400 system, which measures vehicle heading and attitude, and a FreeWave HT 900 MHz spread-spectrum radio, which serves as an Ethernet bridge to the vehicle when it is surfaced. An underwater acoustic modem (WHOI MicroModem; Freitag et al. 2005) and its transducer are mounted external to the pressure spheres, the modem being entirely within the outer hull and the transducer exposed via a penetration to the exterior.

The Hydrolab water quality multiprobe is located external to the outer hull. Antennas for a Garmin GPS and the spread-spectrum radio, as well as a strobe light, are located on the dorsal side of the outer hull, and are above water when the vehicle is surfaced. Vehicle power is supplied by a Bluefin 32-volt, 2-KWH pressure-tolerant lithium-polymer battery. A functional diagram emphasizing the pathways of chemical data flow on the vehicle is shown in Fig. 2.

The Odyssey AUV and instruments are controlled by the Mission-Oriented Operating Suite, or MOOS (Newman 2002), running under the Debian 3.0 “Woody” Linux distribution. MOOS has a star topology, with a central server process, called MOOSDB, to or from which all sensors, actuators, and instruments related to vehicle control, communications, sensing, or data logging may publish and/or subscribe to data. All information exchange among processes thus passes through this server, and individual processes are not permitted to exchange data directly. A graphical utility called MOOSScope (uMS) allows a user to view and modify the variables contained within the MOOSDB server process in real time when a TCP/IP connection is open to the vehicle. Because such a connection is not currently available when the robot is submerged, an acoustic link to the vehicle is also provided. The navigation process (pNav) interprets navigational sensor data, which come from instruments such as GPS (when surfaced), AHRS, DVL, and depth (pressure) sensors, and forms a coherent understanding of the AUV’s location using an extended Kalman filter. The



behavior-based control process, pHelm, which is programmed using text-based mission scripts, uses the navigation data that has been filtered by pNav to perform a variety of different missions. Additional custom instrument interface processes were written to provide interfaces to the mass spectrometer (iNereus) and water quality probe (iHydrolab). The WHOI MicroModem MOOS interface process (iMicroModem), originally written by M. Grund, was modified to allow the transmission of mass spectrometric and water quality data. MOOS examples, documentation, and source code (under the GNU general public license) are available at <http://www.robots.ox.ac.uk/~pnewman/TheMOOS/index.html>.

**NEREUS mass spectrometer.** NEREUS is a mass spectrometer equipped with a membrane inlet, through which it obtains a continuous flow of analyte gases from the water column by diffusion, at rates proportional to the aqueous concentration of the gas as well as to the permeability of the membrane to each gas. Within the mass spectrometer, the gases are ionized, then separated by their mass-to-charge ratio ( $m/z$ ). In the case of major metabolic gases under common ionization conditions, the most abundant ions formed are singly charged and have mass essentially equal to the mass of the original gas molecules (e.g., the principal ion seen for  $O_2$  has an  $m/z$  of 32). Measurement of ion intensity at various  $m/z$  values thus provides identity and concentration of dissolved gases. The instrument is an updated version of the instrument described by Hemond and Camilli (2002) with new inlet system, electrometer, computer system, and control software. The instrument is controlled by a Technologic Systems TS-5500 microcomputer running TSLinux 3.07a.

A new software suite, *Iaira*, was written for the TS-5500 microcomputer of the NEREUS mass spectrometer. *Iaira* accepts commands in a human-readable text format and returns data and other status information in the same format. It is thus possible to operate the instrument manually for testing purposes from a freely available terminal program such as Minicom. For  $m/z$  scanning and acquisition of ion current data, *Iaira* communicates with the mass spectrometer hardware via a 16-bit analog-to-digital converter (ADC) and a 16-bit digital-to-analog converter (DAC). The *Iaira* command set includes instructions for reading a single  $m/z$  value or a range of values, and *Iaira* handles automatic  $m/z$  calibration as well as reporting of internal battery voltage, ion pump current, and sphere pressure. All data are time-stamped and internally logged by default to allow their recovery if external communications should be interrupted.

The aforementioned MOOS instrument interface process, iNereus, was written to manage data collection and data flow from the NEREUS mass spectrometer using a modular, real-time design. The main tasks of iNereus are to harvest data from the mass spectrometer according to scheduled and real-time user requests and to parse and compress these high-priority data into minimally sized snippets for transfer to the shore station via the network. iNereus supports most of the

functionalities of the mass spectrometer, including on/off control of the emission regulator; remote shutdown; monitoring of operating parameters such as ion current, battery voltage, etc.; regularly scheduled automatic calibration; and full spectrum, partial spectrum, or single  $m/z$  scans with the desired degree of averaging. All functions can be set up statically in the configuration file to occur once or periodically throughout a mission, and real-time user requests can also be submitted through MOOS. A queue management system runs scheduled events in the order in which their timers expire. Real-time requests are added to the queue immediately after any event already in progress when they arrive. Data from *Iaira* are parsed and then passed to the MOOS database to be logged as well as transferred to the shore station by way of the buoy network. Details of the current calibration and mass spectrometer parameters are posted, as well as the most recently read values for up to 10  $m/z$  values as specified in the vehicle's configuration (.moos) file.

**Acoustic modem.** Transmission via the acoustic modem of chemical, physical, and navigational data are under the control of the MOOS process, iMicroModem. This process reads desired data from the MOOS database, compresses it into packets of 32 bytes, and directs transmission to the buoys. Specific formats are provided for both mass spectrometer data (NEREUS packets) and water quality multiprobe packets (Hydrolab packets). In each case, vehicle location is encoded along with the chemical data. For example, a Hydrolab packet comprises a byte identifying message type, as well as  $x$  position (meters),  $y$  position (meters), pH, temperature, turbidity, ORP, conductivity, depth, and DO. Encoding is based on the assignment of a number of bytes appropriate to the desired precision for each variable, then converting each decimal value to a linear integer scale within its allocated bytes. Most variables are transmitted with 24-bit precision (3 bytes each), but depth is encoded at 16-bit precision.

**Buoy subsystem—Buoy hardware.** The components for the buoys are housed in commercially watertight enclosures (Rose enclosures, 40 × 30 × 20 cm high) mounted on conventionally moored foam floats (30 cm high × 60 cm diameter) (Fig. 1). Each has a single acoustic modem and transducer for underwater communication and can accommodate several kinds of water column sensors. In the work described here, each buoy was fitted with a thermistor string of either 5 or 6 thermistors, located at 2-m depth intervals. Both sensors and the acoustic modem and transducer are fastened to a 1-cm diameter nylon support line suspended from the buoy, with nylon zip-ties located at intervals of approximately 2 m in an effort to minimize tangling. Transducer depths of 3, 6, 8, and 12 m have been used in an effort to empirically identify optimum placement. All other electronic components are mounted inside the lid of the enclosure, thus reserving the volume lower in the box for batteries. Although the enclosures are said to be watertight as purchased, it proved necessary to add PVC caps over the enclosures' latches to prevent in-seepage of water during rainstorms. Bags

containing approximately 200 g of desiccant (Drierite with indicator) are maintained in the enclosures during deployment to reduce humidity. Two magnetic reed switches are mounted on the top inside of the enclosure so that the buoys can be turned on and off with a magnet without opening the lid.

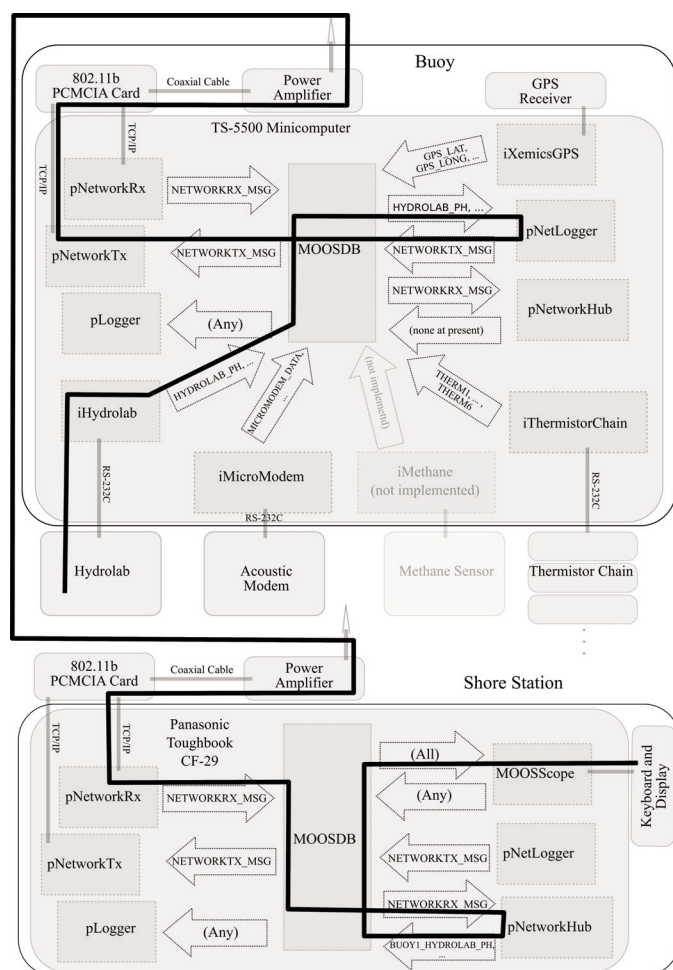
Each buoy is controlled with a Technologic Systems TS-5500 microcomputer, which uses an AMD Elan 520 processor and has a compact flash card slot, a PCMCIA slot (for a standard laptop wireless card), and 3 serial ports (Fig. 3). The TS-5500 is augmented by a TS-SER4 expansion board to provide an additional 4 serial ports. The TS-5500 is also equipped with the factory-optional on-board 12-bit analog-to-digital converter (ADC) to monitor power supply and battery voltages.

The acoustic modem is a WHOI MicroModem identical to that used on the AUV and is interfaced to the microcomputer via serial port. The modem is suspended in the water column beneath the buoy, in its pressure case, both for convenience and because we surmise that such mounting may provide useful electrical isolation between the pulse-producing modem and any noise-sensitive electronics on the buoy.

Wireless communication for the buoy, using 802.11b protocol, is provided by an Orinoco Gold wireless card using the `orinoco_cs` driver for Linux. RF output from this card is available at an external jack and is routed to a 2.5-GHz power amplifier/preamp module (Hyperlink Technologies HA2401G-1000). An external antenna (Hyperlink Technologies HGV-2406U) is mounted on the lid of the box. Additional details concerning card setup are provided in Wong (2004).

Each buoy is equipped with a global positioning system (GPS) receiver (Xemics RGPSM002), entirely contained within the enclosure and interfaced to the computer via a driver chip (needed because the GPS is a 3.3-volt device) and an RS-232 serial port. The GPS streams data in the NMEA format using the \$GPGGA message, which contains latitude and longitude information as well as information on the quality of the positional fix.

The buoys can accommodate an arbitrary number of sensors, in practice restricted by the number of serial or other ports available and the set of waterproof connectors provided on the box for sensor connection. Current configuration includes a water quality microprobe (Hydrolab Model 4a Mini-sonde) and a thermistor string. A serial port and waterproof connector is also provided for a METS methane sensor. The water quality multiprobe is interfaced to the microcomputer via an RS-232 serial port, using a TTY mode that is accessible via the Setup menu and which allows streaming of data without a console. The thermistor strings contain 5 or 6 thermistors, each of 10 kOhm nominal resistance, molded at intervals of 2 m onto a rubber-jacketed cable. We reused units originally manufactured by Coastal Leasing, Inc., for a different project, but owing to the standardization that has occurred in the thermistor market we believe that any similar 10k thermistor string would be serviceable. An interface for the thermistor string was constructed using a Maxim 6682 thermistor-to-digital integrated



**Fig. 3.** Functional diagram of a buoy and the shore station, showing major hardware components and pathways of data flow. Large arrows represent data values communicated among MOOS processes via the MOOSDB; the name of the MOOS variable under which each value is published in the MOOSDB is shown within the arrow. Data shown going from the database to pNetLogger (HYDROLAB\_PH) are exemplary, as indicated by the ellipsis (...); data from all other sensors as well as the acoustic modem also are posted to the database as MOOS messages, and are processed for transmission by pNetLogger. As an example, the heavy line traces the flow of data from a Hydrolab pH sensor attached to a buoy. Data are read from the instrument by the iHydrolab MOOS process and written to the MOOSDB in the variable HYDROLAB\_PH. The pNetLogger process is configured to read HYDROLAB\_PH and prepare it for transmission by encoding it as a string in the variable NETWORKTX\_MSG. This variable is read by pNetworkTx, which transmits it to the pNetworkRx process running on the shore station via TCP/IP over the wireless link. The pNetworkRx process publishes the encoded data to the shore station MOOSDB under the name NETWORKRX\_MSG. Finally, the pNetworkHub process recognizes the encoded data within that variable and extracts the pH value, writing it to the MOOSDB as BUOY1\_HYDROLAB\_PH. Chemical data from the NEREUS mass spectrometer are conveyed to a buoy by acoustic modems and written to the MOOSDB of a buoy by iMicroModem. Transmission to the shore station then proceeds via a process similar to that described above for Hydrolab pH data. pLogger can be configured to make a permanent record of variables of interest for later analysis, while MOOSScope allows data to be read directly from the MOOSDB in real time.

circuit (IC) chip and a Maxim 4638 multiplexer IC, interfaced to a general-purpose digital I/O port on the microcomputer. The interface is described in detail by Wong (2004).

Power is provided from two 6-volt 30 amp-hour sealed lead-acid batteries. The microcomputer, which represents the largest load on average, is supplied with 5.0 volts from 1 battery via a MIC29502BT low-dropout (low-overhead) linear regulator. The choice of a linear regulator is based on simplicity and low cost together with the fact that in this application power loss is small, due to the small voltage difference between battery and computer supply voltage. However, it is critical to use a low-dropout regulator, as many linear regulators have excessive voltage drop for this application, and the TS-5500 is fairly strict in its requirement of a 5-volt supply; even an extremely brief voltage sag will cause it to reboot. The acoustic modem and Hydrolab Mini-sonde are provided with raw 6-volt power. In the case of the acoustic modem, a 12-volt supply was initially used; however, it was found that the lower transmit power when using a 6-volt supply actually seemed to improve acoustic communication reliability in the Upper Mystic Lake. (Only acoustic power output was affected by the lower supply voltage, as, except for the power amplifier, the modem operates internally at <6 volts. The reduced voltage is not an important factor in the buoy power budget due to the low transmit duty cycle). The GPS and thermistor sensors require 3.3 volts at sufficiently low power that linear regulators can be used with negligible penalty. The 2.5-GHz amplifier module is provided with raw 12-volt power from the 2 batteries in series. Because the upper battery has much less load than the lower battery that handles the 6-volt devices, it can be swapped with the lower battery at the appropriate time for a near-doubling of battery life. Currently this must be done manually, although we plan to eliminate the need for this task and slightly increase total battery capacity by paralleling the two 30-amp-hour, 6-volt batteries and adding a small upper battery to meet the modest 12-volt power needs.

**Buoy software.** The buoys each implement a MOOS community, running under TSLinux. MOOS is used to provide a measure of commonality between the buoy and AUV systems. However, the buoy MOOS communities do not use any of the vehicle control processes; instead, the MOOS processes on the buoys are all related to communications, logging, and instrument control, and many were written de novo.

Each buoy and the shore station are assigned a unique static IP address (192.168.x.y, assigned in accordance with RFC 1918) for communication over the 802.11b network, which is run in ad-hoc mode. Name resolution uses a hosts file (/etc/hosts) on each machine. The use of TCP/IP can facilitate relaying of packets from buoys that are out of range of the shore station, if this should prove necessary in a scaled-up implementation of the network.

The upper panel of Fig. 3 illustrates the relationship among the various processes that govern data flow at a buoy. Individual MOOS processes control acoustic communication

(iMicroModem), wireless communication via 802.11b (pNetworkTx and pNetworkRx), the packaging of data for transmission and the parsing of received messages (pNetLogger and pNetworkHub), local data logging (pLogger), and interfaces to a water quality multiprobe (iHydrolab), thermistor string (iThermistor), methane sensor (iMets), GPS (iGPS), and battery voltage (iBattery). Additional instruments can be added as desired by writing additional MOOS processes. All data, whether received from the AUV via acoustic modem or from sensors attached to the buoy, are posted to the buoy's MOOS database, and are both logged locally and transmitted to the shore station, as specified by the buoy's configuration file. Descriptions of the key processes are given below, and additional details can be found in Cheung (2005) and Wong (2004).

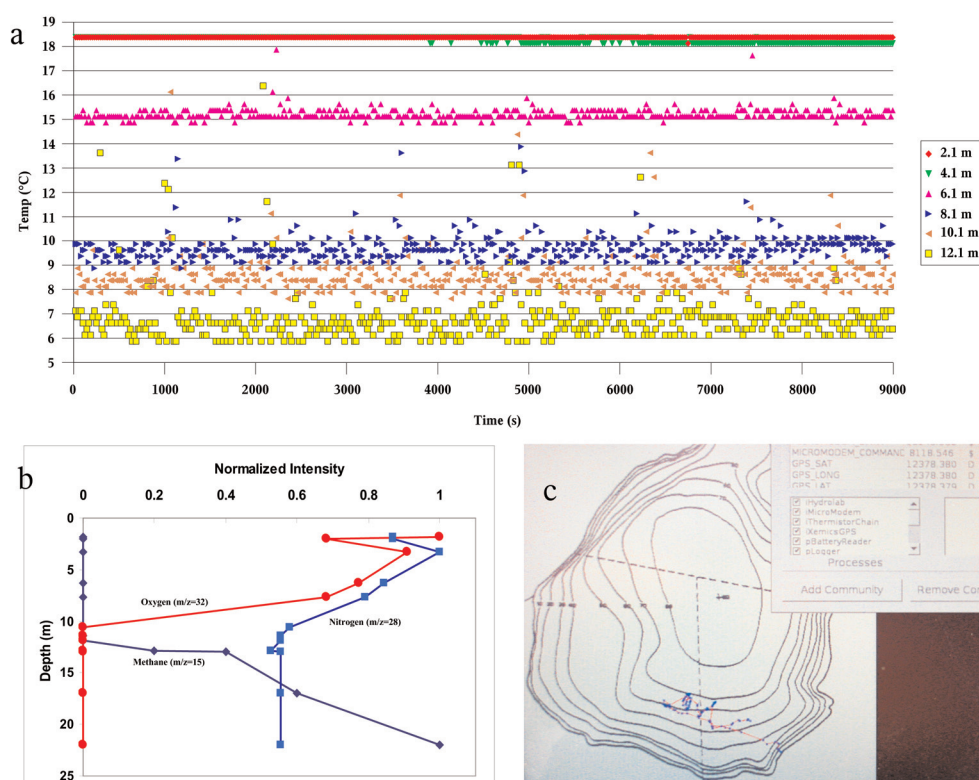
pNetLogger packages data for transmission to the shore station by subscribing to MOOS variables specified in the configuration file, adding a prefix such as "BUOY1\_" to identify the transmitting buoy, and posting the result as a NETWORKTX\_MSG message for transport to the shore station. pNetworkTx reads messages published in the NETWORKTX\_MSG variable and delivers the message to the indicated destination system (normally the shore station) via a TCP connection on port 5000. pNetworkRx and pNetworkHub handle incoming messages; these processes are discussed in more detail as part of the section below on shore station software. pLogger is a process that logs data locally on the buoy. Variables can be selected for logging by specifying them in the configuration file.

iMicroModem, a process that runs on the AUV and is discussed earlier, also runs on the buoys. The process accepts packets of binary data from the acoustic modem, extracts the data into the format of a text string, and posts the data to the MOOS database. On the buoys, iMicroModem also accepts, via the buoy database, commands transmitted from the shore station. One useful example is the command to send an acoustic ping to any other acoustic modem. A successful ping results in iMicroModem posting a string of data to the database that includes information on signal quality and round-trip travel time. The former provides a measure of probable communication success, and the latter is potentially useful for navigational purposes.

**Shore station subsystem—Shore station hardware.** The shore station is a ruggedized Panasonic CF-29 laptop computer, equipped with an Orinoco Gold wireless card, Hyperlink amplifier, and omnidirectional antenna essentially identical to the corresponding hardware used on each buoy. The amplifier is mounted in a splashproof portable metal box together with a 7-amp-hour sealed lead-acid battery, and the antenna is mounted on the box lid. Because the external antenna jacks on the wireless cards are fragile, the wireless card is normally unplugged from the computer, without disconnecting the RF cable from the card, when the shore station needs to be partially disassembled for easier transport.

**Shore station software.** The shore station runs under Ubuntu Linux 6.06 LTS (*Dapper Drake*) and, like each buoy and the AUV, implements a MOOS community. Several MOOS





**Fig. 4.** Mystic lake data reported by 802.11b/acoustic communication network, fall 2006. (A) Temperature record, Sept. 25, 2006, as recorded from thermistor string on a buoy located in Upper Mystic Lake near the Aberjona River inflow. (B) Dissolved gas profiles measured by NEREUS mass spectrometer (see text). (C) Photograph of shore station laptop screen showing AUV track (displayed as red line on bathymetric map), and part of MOOSScope display showing current updates to the shore station's MOOS database. Full daylight exposure limits effective contrast of the display, although it remains readable (the CF-29 laptop is designed to be readable in daylight). A shade over the screen would improve visibility under these conditions.

processes on the shore station are essentially the same as on the buoys, whereas others are unique to the shore station's larger display and command roles. The various processes that run on the shore station are shown in the bottom panel of Fig. 3.

pNetworkRx manages all incoming connections on port 5000 and posts received messages to NETWORKRX\_MSG. These received messages mainly comprise data sent from the buoys. pNetworkHub parses the received messages that have been placed into NETWORKRX\_MSG by pNetworkRx. It extracts the MOOS variable name, data type, value, and timestamps, and then posts the data to the MOOSDB. As an example, the HYDROLAB\_PH data from Buoy1 is posted in the variable BUOY1\_HYDROLAB\_PH. pLogger serves the same role on the shore station that it does on the buoys, except that its location in the network makes it possible to archive data from all buoys, including data transmitted from an AUV and relayed via the buoys.

uSubTracker is a MOOS process that graphically displays the most recent known position of the AUV on a map of the operating area. The coordinates of the vehicle are parsed from the acoustically transmitted NEREUS and Hydrolab data packets and are plotted on a background map as they are received. The map is displayed from an .xbm (X bitmap) file that is

specified in the configuration file; the map must be calibrated by specifying 2 pairs of points at which  $x$  and  $y$  values of the vehicle's coordinate system map onto known pixels of the .xbm file. A map file can be created, for example, by scanning a paper chart and then converting the resulting image to .xbm format using standard Linux software.

The MOOS utility program MOOSScope displays the current contents of MOOS databases. An operator of the network can read the most recently posted value of any variable on the shore station database (e.g., data received from buoys, as well as any locally issued commands), and can also watch individual buoy databases by specifying the IP addresses of the buoys of interest. MOOSScope also allows the manual insertion of variables into a database, providing a means of issuing commands to the network. A photograph of a shore station screen display, taken during operation in the field and containing both a uSubTracker plot and a portion of the MOOSScope display, is shown in Fig. 4.

**System operation**—Although a particular sequence is not obligatory, the network is typically activated by first booting to Linux and starting MOOS on the shore station. The command, pAntler, automatically starts all MOOS processes specified by the user-provided configuration (.moos) file. The

buoys, which are configured to boot to Linux and start MOOS on power-up, are turned on by placing a magnet in its holder on each buoy's enclosure lid (proper shutdown requires first halting Linux, typically via ssh from the shore station, before removing the magnet). Connection from buoys to shore station is automatic; if all is working properly, data from the buoy sensors become visible on the shore station screen, using the MOOS utility, MOOSScope, shortly after buoy power-up.

The AUV is powered up before launch by turning a waterproof external switch, and MOOS is started manually via the radio link using an ssh terminal. This enables a shore test of the AUV's actuators, thruster, attitude and heading reference system, and radio. Power is applied to the mass spectrometer with a second switch accessible outside the AUV. During the field tests described here, *Iaira* was started and configured manually through the AUV computer using a terminal program (Minicom); it has since been modified to start automatically on power-up.

After launch, the AUV is either towed using a small boat or manually piloted over the network as an ROV using the MOOS utility iRemote to a suitable starting location. When a mission has been started, the vehicle executes a path with track, speed, and depth as specified by a mission or hoof (.hoof) file. The mission file can be edited or replaced via the vehicle's radio link. Currently, surface missions can be terminated at any time, but underwater missions must run until complete or until they are terminated by an abnormal condition such as insufficient height over the bottom. Upon mission completion, the vehicle surfaces and can then receive further instructions by radio. Code has been written, but not yet tested, to command mission alteration by acoustic modem while the AUV is submerged.

Typically the vehicle is configured (using the configuration file for the MOOS process, pScheduler) to automatically transmit 32-byte acoustic packets every 8 s. Packets containing Hydrolab data are typically alternated with packets containing mass spectrometer data; all packets contain vehicle position data. Data are read by and posted to the databases of all buoys, thus providing redundant data paths. Because the 802.11b link from the buoys to the shore station is orders of magnitude faster than the acoustic links, there is no need to prioritize in sending buoy and AUV data to the shore station.

## Assessment

The several components of this system, such as the Odyssey II AUV, the NEREUS mass spectrometer, the 802.11b network, and the buoy sensors, each have widely different figures of merit (e.g., detection limit, response time, precision, and accuracy in the case of sensors; speed, endurance, navigational accuracy in the case of an AUV; range, data rate, percentage of missed packets in the case of a data link). Thus the purpose of the data presented here is not to exhaustively document these numerous individual component characteristics, but rather to

confirm the operation of the integrated network and assess its utility as a scientific tool.

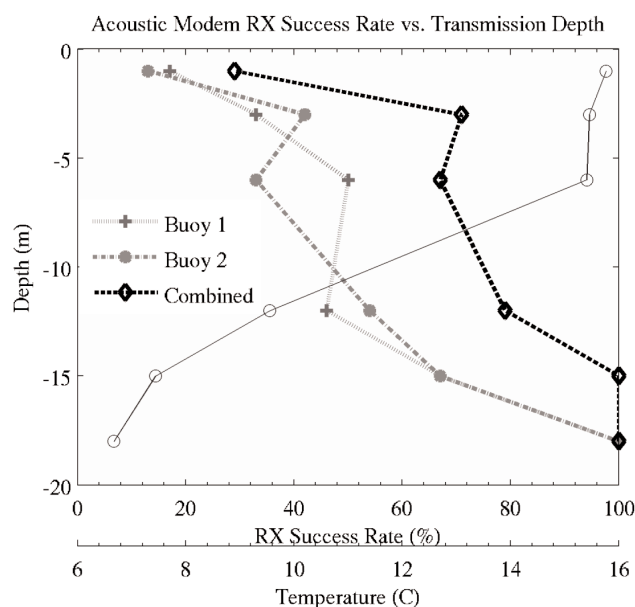
The in-lake network was operated as a whole during the summer and fall of 2006. Representative buoy sensor data are shown in Fig. 4. Panel A represents 3 h of temperature profile data near the north end of Upper Mystic Lake. Although independent controls were not run for any of the data shown here, the minimal variance in the temperature data from 2.1 m, within the generally near-isothermal and well-mixed epilimnion, suggest that there is minimal noise introduced by the sensors or network. This is supported by the low channel-to-channel variance among thermistors when the thermistor string is coiled up and the thermistor sensors are operated in close proximity to one another (data not shown). The cause of the temporal variance in the deeper temperature signals has not yet been further investigated, but seems likely to result from hydrodynamic phenomena within the lake (e.g. internal seiching or influence of river inflow).

Dissolved gas data from the NEREUS mass spectrometer are shown in panel B of Fig. 4, which features unprocessed ion current intensity data, normalized for convenient display on a single axis, as a function of vehicle depth. The data show *a*) the strong clinograde oxygen profile of the lake and *b*) the sharp rise in methane concentration beginning just below the depth at which oxygen approaches nondetectable levels. Oxygen data by mass spectrometry track the corresponding oxygen concentration data from the water quality multiprobe as expected (data not shown). Methane is measured at  $m/z$  15 to avoid interference from doubly charged  $^{16}\text{O}_2$ . The chief purpose of this figure is to validate that the network can provide autonomous control of the mass spectrometer and accurate real-time data transmission to the shore. It is also possible to infer from these data the need for a temperature-dependent calibration routine to convert ion intensity data to concentration data; while nitrogen concentration likely increases with depth, the data show lower ion intensity at depth, evidently due to the strong thermal stratification of the lake (see panel A) and the temperature dependence of the membrane inlet.

A real-time map display created by SubTracker, using acoustic data, is shown in panel C. This particular complex vehicle track is the result of the AUV being manipulated during trim tests. AUV location shown by SubTracker coincided with observed location of the chase boat. Accuracy and precision of the navigational data are primarily determined by the characteristics of the Doppler velocimeter log (DVL) and the vehicle's attitude and heading reference system (AHRS). In these tests, error in the latter appeared to be the factor most strongly limiting accuracy of vehicle navigation. A newer AHRS unit having the ability to automatically determine the required corrections for magnetic deviation has recently been installed, providing accuracy of >5% of distance traveled in both  $x$  and  $y$  directions over a course 320 m in length.

The acoustic/wireless network was shown to successfully transmit data acoustically from the AUV to the buoys, and





**Fig. 5.** Rate of successful reception (RX), via each of 2 data buoys, of acoustic data transmissions from a transducer at the depths indicated on the vertical axis. Data at 1, 3, 6, and 12 m depth are calculated from a population of transmissions that includes 3 replicates at each depth, at each of 8 stations along a simulated AUV mission track. At 1 location, 6 transmissions were made from 15 m, and another 6 were made from 18 m. Combined success rate is based on successful receipt of data transmissions at either or both of the buoys. Stratification condition of the lake on this date is shown by the plot connecting open circles; the lake is well-mixed above 6 m depth.

from there to the shore station for display via the wireless network. Under no circumstances was evidence seen of corrupted or erroneous data arriving at the shore station. However, the acoustic network sometimes either failed to detect acoustically transmitted data from the AUV or detected but then rejected received acoustic data on the basis of a failed cyclic redundancy check (CRC). Adverse effects of refraction and reverberation on acoustic communication were not unexpected in this dimictic lake, but the exact physical mechanisms responsible for transmission success or failure remain conjectural at the moment.

Fig. 5 summarizes results of field experiments in which we explicitly obtained statistics on the frequency of successful and unsuccessful acoustic data transmissions to each of 2 buoys. Because orientation of the AUV was found to affect the success rate of acoustic communications (success rate was lower when the receiving buoy was located to the rear of the AUV, requiring transmission through the propeller wake), we removed AUV orientation as a variable from these experiments by instead lowering a transducer, identical to the one on the AUV, from a boat and then transmitting data from this transducer. Depth and position of transmission was varied systematically to simulate communication during an AUV mission around a triangular closed course of approximately 500 m length. A total of 108 data transmissions were made, 3 each from depths of 1, 3, 6, and 12 m at 8 locations on the course,

plus 6 transmissions from 15 m and 6 transmissions from 18 m near the center of the lake. Average success rate for a single transmission was 42% to buoy 1 and 41% to buoy 2. The success rate increased systematically with depth of transmission, from <20% at a depth of 1 m to slightly >50% when transmission originated at 12 m depth. Even higher success rates were observed for the transmissions from 15 and 18 m. Interestingly, average results were nearly identical for both buoys, despite the buoy 1 transducer being located in the epilimnion at 3.1 m depth and the buoy 2 transducer in the hypolimnion at 11.6 m depth. Importantly, transmission failures to one buoy appeared to be essentially independent of failures to the other, and the overall success rate for any single message arriving at either one of the two buoys, or both, was 66%.

In a separate experiment, acoustic travel times from one buoy to another were measured, to assess the reliability of using travel time data from the acoustic modems as a future means of calculating navigational fixes for a submerged AUV. With fixed transducer depths of 4.7 and 6.0 m, and using the pinging mode of the MicroModems, 18 pings were manually commanded during a half-hour time interval between 2 buoys separated by approximately 530 m. Mean travel time was 0.357 seconds, with a standard deviation of 0.0012 seconds, the latter corresponding to about 1.8 m of sound travel. This error figure includes effects of propagation variance, modem error, and the possible movement of buoys during testing, so it is conservative as a measure of ranging error that may be expected when using the MicroModems as AUV navigational aids in the future.

## Discussion

The demonstration of this network shows the feasibility of constructing a moored wireless network and associated fixed sensor platforms capable of delivering lake chemical data in real time using low-cost hardware and open-source software. It also demonstrates the means to incorporate AUV-based sensors, including a mass spectrometer, into such a network, and it demonstrates the ability of acoustic communication to provide real-time data from an AUV in a thermally stratified lake.

Tests of this network illustrate the potential that an AUV-based mass spectrometer, combined with other chemical sensors and coupled to a network, can have for expanding chemical knowledge of a water body. Multiple chemical data were available within seconds after the AUV occupied a water mass in Upper Mystic Lake, in contrast to the hours to days of delay entailed by classical sampling and laboratory analysis. Moreover, each datum was automatically recorded along with the relevant time,  $x$  and  $y$  coordinates, and depth of measurement. Although corrections for variations in membrane inlet permeability with changes in water temperature will be needed for best analytical accuracy, it is clear that real-time availability of chemical data from an AUV can help test hypotheses that require data of high spatial or temporal resolution. In addition, the use of in situ instrumentation aboard an AUV may facilitate

long-term ecological studies as well as have practical applications for the detection and localization of pollution activities.

The results also demonstrate the value of acoustic communication in closed, stratified freshwater basins, as well as the need for improvement in this area. The probability of an individual data transmission successfully reaching a buoy was high enough to be very useful; and, furthermore, the use of multiple buoys substantially increases overall success probability. Success rate in the stratified lake also improved as the depth of the transmitting unit increased. However, the specific reasons for the observed acoustic behavior are not yet known. One factor that may create more problematic acoustic conditions in stratified lakes than in open ocean is the presence of steeper thermal gradients, and hence stronger gradients in sound speed, leading to more refraction. Another factor may be a larger role of bottom reflections, due to relative shallowness of the water column and perhaps to high bottom reflectance associated with sediment gas content. The resulting possible corruption of signals by multipath propagation and reverberation may be the reason that lower transmit power seemed in general to improve results. There is reason to anticipate that performance can be further improved. Much of the vast body of existing knowledge of ocean acoustics can likely be applied to study the acoustics of lakes, and many variables affecting communication success are open for optimization, including depths of the fixed transducers, and choices of transducer radiation patterns, power levels, modulation techniques, and transmission speeds.

### **Comments and recommendations**

Several potential improvements have been identified relative to the NEREUS network. One issue relates to underwater data rate, which in our testing has been limited to about 4 bytes/s. By prioritizing and compressing data, the current system avoids being severely limited by this factor; the response time of the mass spectrometer is of the order of 10 s, so there is enough bandwidth to convey essential mass spectral peak heights along with the spatial coordinates of the vehicle and associated data from the water quality probe. However, the ability to communicate diagnostic and debugging data in real time when the vehicle is submerged, and to accommodate larger and faster instrument suites, will require more bandwidth. Studies based on the fundamentals of acoustic propagation in stratified lakes may lead to improvement of communication reliability as well as higher bandwidth. Characterization of lake basins using both ray-tracing models and field experiments should help guide selection of parameters such as transducer depths as well as modulation and signal-processing techniques.

Other than in the acoustic links, the system is not bandwidth-limited for chemical data. The 802.11b protocol used for data transfer between the shore and the buoys supports nominal data rates from 1 to 11 Mbit/s, which vastly exceed the average data rate in the network even when accounting for the substantial overhead of TCP/IP connections. Although

802.11b devices share bandwidth with other nearby devices operating in the ISM band, we saw no indication of interference problems despite the fact that much of the shoreline of Upper Mystic Lake is developed. Odyssey II class AUVs themselves have successfully supported the relatively high bandwidth of an optical camera and side-scan sonar; however, owing to the current limitations of underwater communication bandwidth, such imagery has not been returned to shore in real time. However, by adding additional serial ports, numerous additional chemical sensors having data rates at least in the tens of Hz range could be accommodated on the AUV and on the buoys, limited in practice only by weight, volume, and power considerations.

It would be very desirable to have the ability to deliver updated mission programs to the AUV while it is underwater, inasmuch as waiting for a mission to expire and the AUV to surface before being able to effect a new mission is clearly a drawback. The current acoustic modems provide the hardware necessary to send new mission data to the AUV while it is submerged, and we have written but not yet tested software to provide this capability. Extended underwater missions, in turn, will create a need for periodic underwater navigational fixes, as GPS navigational data are not available underwater. Inasmuch as the MicroModems can measure acoustic times of travel among themselves with acceptable accuracy for this purpose, such navigational capability can be provided using existing hardware by writing additional MOOS processes.

Attention should also be given to the best means of extending buoy battery life, which somewhat exceeds 24 h (twice that with battery rotation as described earlier) but could be extended greatly by use of more exotic battery chemistries, aggressive energy management, lower-power processors, or the addition of solar panels. The architecture of the present buoys seems to be both flexible and reliable, so there is not otherwise a great inducement to change processors, but in future generations of buoys this might be reconsidered. Most of the software described above should be readily adaptable to any processor capable of running Linux, although modification would be required of certain low-level drivers that manipulate hardware specific to the TS-5500.

Although not the primary focus of the experiments described here, results also point toward certain desirable improvements in both the AUV and the mass spectrometer. Because it now relies on dynamic forces for depth control, the vehicle could benefit from active buoyancy control, allowing it to travel more slowly and thus provide higher spatial resolution of the chemical measurements when needed. As previously noted, the desirability of means of correcting for temperature-induced changes in mass spectrometer membrane inlet permeability was also suggested in these tests.

The costs associated with the AUV and mass spectrometer, and secondarily with the acoustic modems, represent by far the largest portion of the total cost of the NEREUS in-lake chemical data network. The stationary components are a

small portion of the total cost, as the software used in the system is open-sourced and available at no cost, and straightforward and relatively inexpensive off-the-shelf components are used to build the shore-based and buoy-based components of the system. We note that various subsets of the system (such as instrumented buoys with a shore station and wireless network) can function independently with no modification of the hardware or software described here, and may be useful by themselves in some studies, while providing a basis for future addition of new instruments and platforms.

## References

- Camilli, R., and H. F. Hemond. 2004. NEREUS/Kemonaut, a mobile autonomous underwater mass spectrometer. *Trends Anal. Chem.* 23:307-313.
- Carlowicz, M., J. Trowbridge, J. Edson, and H. Sosik. 2005. The new wave of coastal ocean observing: shore stations and seafloor nodes provide connections for long-term studies of coastal processes. *Oceanus* online, January 6. <http://www.whoi.edu/oceanus/viewArticle.do?id=2489> (Accessed June 19, 2008).
- Cheung, J. 2005. Design and development of a network architecture for a chemical sensor network. M. Engineering Thesis, Massachusetts Institute of Technology. This document may be ordered from MIT Document Services: online directions are provided at <http://libraries.mit.edu/docs/theses.html>, and the catalog record link is <http://library.mit.edu/item/001340920>.
- Coale, K. H., C. S. Chin, G. J. Massoth, K. S. Johnson, and E. T. Baker. 1991. In situ chemical mapping of dissolved iron and manganese in hydrothermal plumes. *Nature* 352: 325-328.
- Freitag, L., Grund, M., Singh, S., Partan, J., Koski, P., Ball, K. 2005. The WHOI Micro-Modem: an acoustic communications and navigation system for multiple platforms. In: IEEE Oceans Conference, Washington, DC, 2005.
- Glenn, S. M., O. M. Schofield, R. Chant, J. Kohut, and J. McDonnell. 2006. The Leo-15 coastal cabled observatory: phase II for the next evolutionary decade of oceanography. *SSC06 Scientific Submarine Cable 2006*.
- Hemond, H. F., and R. Camilli. 2002. NEREUS: engineering concept for an underwater mass spectrometer. *Trends Anal. Chem.* 21:526-533.
- Newman, P. 2002. MOOS: a mission-oriented operating suite. Massachusetts Institute of Technology, Dept. of Ocean Engineering, Technical Report. This document is archived and available online at <http://ora.ouls.ox.ac.uk:8081/10030/1773>.
- National Research Council. 2003. Enabling research in the 21st century: implementation of a network of ocean observatories. Ocean Studies Board, National Academy Press, Washington, DC, 220 pp.
- . 2004. Future needs in deep submergence science: occupied and unoccupied vehicles in basic ocean research. National Academies Press, 144 pp.
- Penrose, N., and M. Stoermer. 2003. The Neptune Project. *Current* 18:39-44.
- Wong, J. Y. 2004. Design of a real-time chemical sensor network. M. Engineering Thesis, Massachusetts Institute of Technology. This document may be ordered from MIT Document Services: online directions are provided at <http://libraries.mit.edu/docs/theses.html>; it is also available via DSpace at <http://hdl.handle.net/1721.1/18003>.

Submitted 5 May 2007

Revised 5 March 2008

Accepted 8 May 2008