# Portable Coastal Observatories

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Ocean observational science is in the midst of a paradigm shift from an expeditionary science centered on short research cruises and deployments of internally recording instruments to a sustained observational science where the ocean is monitored on a regular basis, much the way the atmosphere is monitored. While satellite remote sensing is one key way of meeting the challenge of real-time monitoring of large ocean regions, new technologies are required for in situ observations to measure conditions below the ocean surface and to measure ocean characteristics not observable from space. One method of making sustained observations in the coastal ocean is to install a fiber optic cable from shore to the area of interest. This approach has the advantage of providing power to offshore instruments and essentially unlimited bandwidth for data. The LEO-15 observatory offshore of New Jersey (von Alt et al., 1997) and the planned Katama observatory offshore of Martha's Vineyard (Edson et al., 2000) use this approach. These sites, along with other cabled sites, will play an important role in coastal ocean science in the next decade. Cabled observatories, however, have two drawbacks that limit the number of sites that are likely to be installed. First, the cable and the cable installation are expensive and the shore station needed at the cable terminus is often in an environmentally sensitive area where competing interests must be resolved. Second, cabled sites are inherently limited geographically to sites within reach of the cable, so it is difficult to cover large areas of the coastal ocean.

This paper describes a Portable Coastal Observatory (Frye et al., 1999), an alternative approach to making sustained coastal observations. In a Portable Coastal Observatory, underwater acoustic telemetry and buoy-to-shore radio telemetry replace the cables in cabled observatories (Figures 1 and 2). This wireless approach allows cost-effective monitoring of large areas in real time, is inexpensive to install and easy to relocate. It complements the cabled approach by providing broad spatial coverage using relatively low bandwidth instru-

**TABLE 1**

| Partner | Roles and Tasks | Benefit |
|---|---|---|
| U.S. Geological Survey (USGS) | Coordination, demonstration at Massachusetts Bay sites | Test feasibility of telemetering oceanographic data from sites in the coastal ocean at modest cost |
| Woods Hole Oceanographic Institution (WHOI) | Coordination, acoustic and radio-frequency telemetry, buoy design, delivery of data over the Web | Develop and test new acoustic technologies, low-cost buoys, and data delivery systems applicable to a range of projects |
| U.S. Coast Guard (USCG) | Collaborate on deployment system for navigation buoy, ship support for MWRA/USGS long-term monitoring program | Investigate use of existing navigation buoys for telemetry of oceanographic data |
| Massachusetts Water Resources Authority (MWRA) | On-going support for long-term observations | Test feasibility of telemetering data from MWRA monitoring sites in Massachusetts Bay |
| RD Instruments (RDI) | Provide ADCP, collaborate on interface of acoustic transmitter | Determine feasibility of acoustic telemetry for ADCP using low-cost acoustic technology |

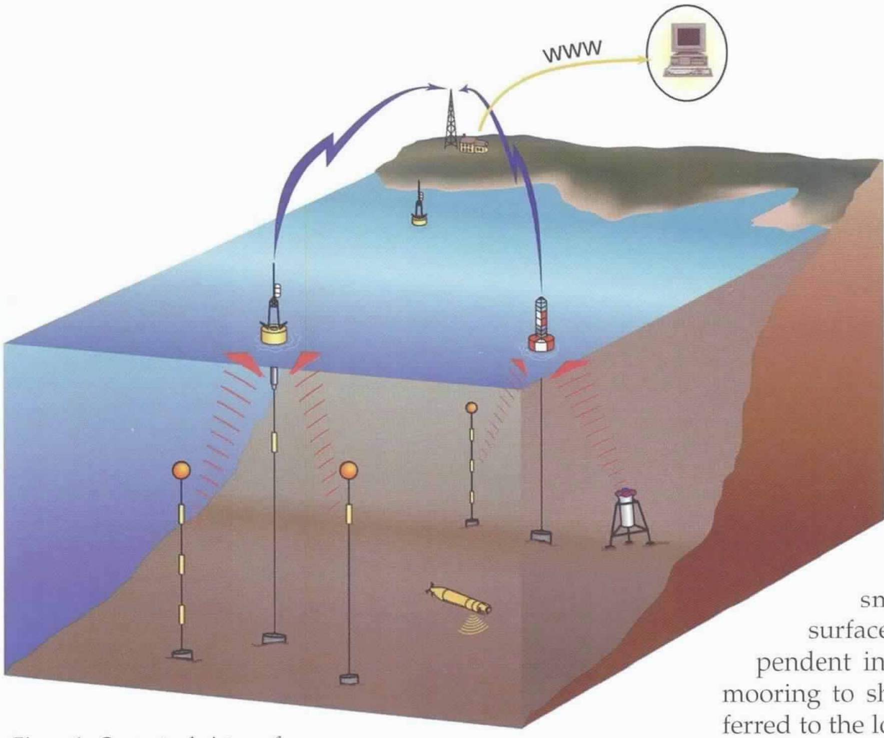


*Figure 1: Conceptual picture of the Portable Coastal Observatory. Instruments deployed near a surface buoy transmit data through an acoustic link to a receiver on the buoy. Data are immediately re-transmitted to shore and distributed over the Internet.*

ments. Key technical innovations in the Portable Coastal Observatory include compact and inexpensive acoustic links that connect subsea instruments to surface buoys, small surface moorings that support the surface electronics, and low-cost electronics that transfer the data from buoy to shore.

The Portable Coastal Observatory project has been funded by the National Oceanographic Partnership Program (NOPP) and involves partners from federal and state government, industry and academia (Table 1). The project addresses a highly relevant area of research, i.e. cost effective methods for making sustained coastal observations, and one that is of more than academic interest to all of the participants. The idea for a low-cost, real-time observing system emerged from a series of discussions of coastal observatories that were a direct result of the emphasis on collaborative research in the NOPP FY1998 request for proposals. The need for a broad consensus and a diverse group of partners brought engineers and scientists together in a way that focused the development efforts on an important and specific application in Massachusetts Bay. This focus was an important factor in design of the prototype Portable Observatory because it defined the minimum system specification and provided a realistic test case to refine the conceptual approach.

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The goals of the Portable Coastal Observatory development effort are to design, build and test the infrastructure needed for a new class of ocean observatory. This new observatory needs to be flexible, easy to install and maintain, and inexpensive. It should be compatible with most commonly used oceanographic instrumentation and it should operate with minimal need for technical oversight. To meet these goals, we are developing a new class of acoustic modem, the Low Cost Transmitter (LCT) that is small, inexpensive and able to transfer data over several km in shallow water. This device, in combination with a small, inexpensive and self-contained surface buoy mooring, can connect many independent instruments located in the vicinity of the mooring to shore. Once on shore, the data are transferred to the local phone/cable infrastructure and then, via a web interface (GeoBrowser) to the Internet. This approach is appropriate to coastal regions, but can also be configured for offshore sites by replacing the line-of-sight radio links with satellite links using Low Earth Orbit satellites.

The fundamental limitations of a distributed system such as this one are determined by the acoustic data rate and range, the number of instruments sharing the subsea channel, the spacing of the surface moorings, the power requirements of the subsea instruments and the bandwidth of the RF channel. At present, a randomly reporting protocol, where instruments transmit on their own schedules, is used to simplify the system and minimize overhead. This approach allows instruments to be installed, removed, or added without requiring any changes at the receiver (in essence, the system operates in a random access mode from the instruments to the buoys, and in a polled mode from buoy to shore). Each subsea instrument transmits its data acoustically on its own, low-duty cycle schedule. If the acoustic receiver in a nearby surface buoy receives the message, the message is forwarded to shore. If not, the message is lost unless provision has been made to transmit messages redundantly. For a typical coastal application, such as Massachusetts Bay, a dozen or so instruments, each sending a thousand bytes per hour to a surface mooring located within about 2 km could be accommodated without difficulty. A single shore station can cover several thousand square km (the present shore station in Massachusetts Bay receives data from buoys as far away as 30 km) and can act as data forwarder for a dozen or so buoys. This level of data throughput represents less than 10% usage of the system capacity. To operate the system at higher capacity would probably require use of a polled protocol for the subsea link to avoid instrument-to-instrument interference.

This paper focuses on the design of a prototype portable observatory, which will be installed in Massachusetts Bay this summer. The observatory will provide real-time current measurements from two sites. The following sections describe the design of the acoustic link, the radio link, the data handling approach, the surface buoy mooring system and the planned field trials.

## Underwater Acoustic Communication Link

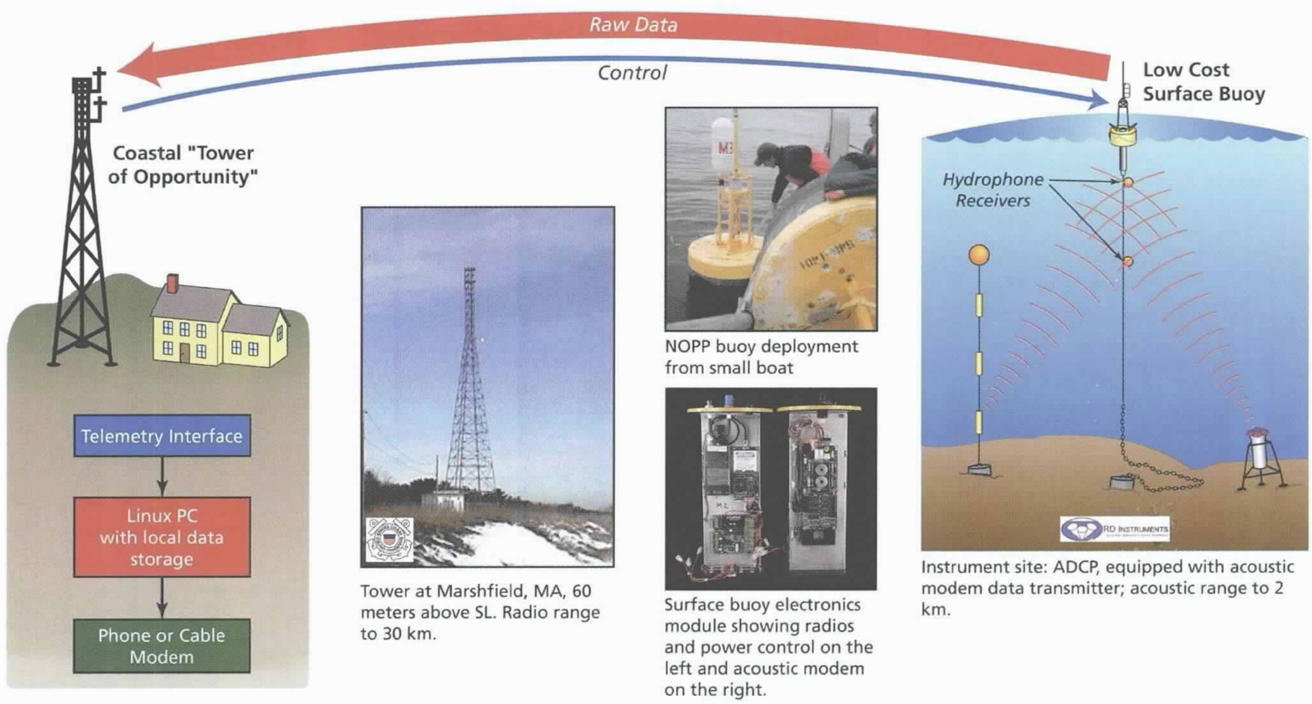
An acoustic communication link consists of an encoding circuit, a power amplifier, an underwater projector (or source) at the transmit end of the link, and a hydrophone and decoding circuit at the receiver. The encoder packetizes the incoming data, adds error-correction coding , and modulates a carrier to produce the transmit signal. Either coherent (e.g. phase-shift-keying, PSK), or incoherent (e.g. frequency-shift-keying, FSK) signaling can be used. Data rates up to 1 kbps can be achieved with incoherent signaling while rates in excess of 10 kbps have been demonstrated with coherent modulation (Stojanovic et al., 1996). However, the data rate for reliable, error-free acoustic communication is a function of the acoustic environment and can change with location and time of year. In the portable observatory application factors influencing the acoustic link are:

1. *Noise*: Coastal areas tend to have high levels of ambient noise due to human activities (shipping, pleasure boats) and biologics (e.g. snapping shrimp). These noise sources vary seasonally. Flow noise and noise related to waves, wind and air bubbles are also noise sources, as are acoustic transmissions from nearby transmitters.

2. *Refraction*: Signal attenuation due to refraction caused by sound speed variations in the water column can be particularly troublesome in summer when a strong thermocline separates the surface layers from deeper waters.

3. *Doppler Spread*: Wave-induced motion of the surface buoy (and the receiving hydrophone) can cause rapidly varying phase shifts in the received signal. This spreads the signal over frequency and reduces the ability to decode in both coherent and incoherent links.

4. *Multipath*: Delayed arrivals of the transmitted signal due to reflections from the surface and bottom are an important source of interference. In shallow water, the time extent of multipath arrivals is typically less than 30 ms, but, at the data rates of interest, this time lag may correspond to a number of bits. With incoherent signaling, frequency hopping may be necessary to overcome multipath (a coherent system will require an adaptive equalizer at the receiver to remove late arrivals).




Tower at Marshfield, MA, 60 meters above SL. Radio range to 30 km.

NOPP buoy deployment from small boat

Surface buoy electronics module showing radios and power control on the left and acoustic modem on the right.

Instrument site: ADCP, equipped with acoustic modem data transmitter; acoustic range to 2 km.

*Figure 2: Schematic showing flow of data from ocean bottom to shore.*

The goal of the acoustic link design was to develop a simple, low data rate, omni-directional link that would operate reliably in a wide variety of acoustic conditions and deployment geometries. This initial conservative strategy can be modified to incorporate higher bandwidth strategies based on field experience. An incoherent, frequency-hopping FSK modulation scheme was chosen for the initial portable observatory implementation. This scheme has limited throughput, but is relatively robust in the presence of multipath, Doppler spread and transient interference. The basic transmission rate is about 400 bps with a throughput after error-correction coding of about 300 bps. At this rate, the Acoustic Doppler Current Profiler (ADCP) data collected each hour takes about 12 seconds to transmit (450 bytes). A simple, time-division multiplexing protocol is used to accommodate multiple transmitters in a local area. The frequency band from 20 to 30 kHz was chosen to minimize the effects of ambient noise and to allow the use of small, low-cost piezo-ceramic projectors. Transmit power was set to 5 W as a compromise between power consumption and range. It is anticipated that horizontal ranges of 2 km will be achievable under most conditions. This range estimate will be verified during field trials this summer.

The key technical development in the portable observatory infrastructure is the Low Cost Transmitter, or LCT (Figure 3), which forms the subsea end of the acoustic link. It combines a low power digital signal processor with an efficient switching power amplifier to generate acoustic communications signals. It has an RS232 serial port for interfacing with subsea instruments and a real-time clock. The LCT is programmable and can be configured for a variety of modulations and protocols. Power consumption of the unit is dominated by the projector output power (about 5 W, when transmitting). To maximize battery life, the LCT uses a capacitor to store the energy required for each transmission (about 20 J) and charges the capacitor at a steady, low rate from the battery. The LCT circuit board set measures 11.4 x 4.4 x 2.5 cm.

The acoustic receiver, located in the surface buoy, is a Utility Acoustic Modem (Freitag et al., 1998), or UAM. It is a 20.3 x 8.9 x 3.8 cm board set containing a high performance digital signal processing chip and up to 4 hydrophone channels to allow reception diversity. A script-based interpreter on the UAM greatly simplifies programming the receiver algorithm and the radio interface. Like the LCT, the UAM supports a range of acoustic signaling protocols. It can also collect diagnostic information such as ambient noise spectra and channel impulse responses. This capability is useful in choosing the parameters of the acoustic link to optimize efficiency and performance.

The acoustic link implemented for the prototype wireless observatory achieves simplicity at the expense of power efficiency. Planned improvements to the link will take advantage of more power-efficient signaling protocols and hardware. A new, low power modem, the μ-modem (which is based on the LCT design), will be fully bi-directional. With μ-modems interfaced to subsea instruments, the observatory will be capable of polled operation, where each buoy requests data from each instrument and implements a re-transmission scheme for garbled data. This more sophisticated protocol will allow the use of coherent signaling to minimize power per bit in cases where efficiency is critical.

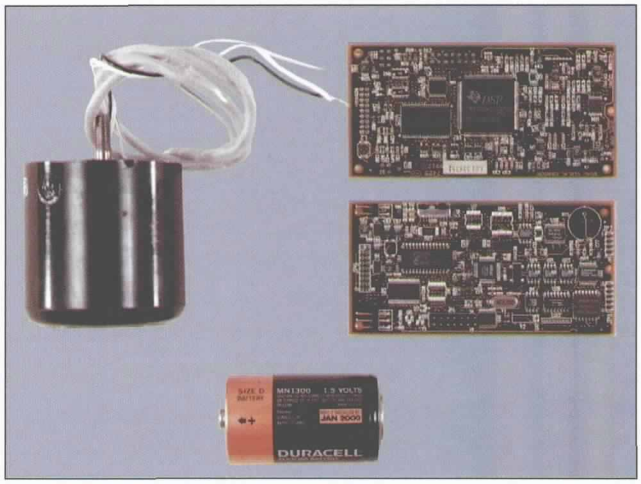



*Figure 3: The key to the sensor acoustic link is the Low Cost Transmitter, or LCT, which provides a cost effective, easy to use acoustic link for existing oceanographic instruments (battery shown for scale).*

## Radio Communication Link

Spread spectrum radio modems are long distance replacements for wired connections between computers. These off-the-shelf systems, designed to operate in the unlicensed Industrial, Scientific and Medical bands (915 MHz, 2.4 and 5.7 GHz), are effectively transparent to the user, with error-free data transfer rates up to about 100 kbps. A degraded link margin results in lower throughput rather than poor quality data. In the coastal observatory application, the radio link operates at 19,200 bps to ease the response time required of low power controllers used at the buoy end of the link. The modems are typically capable of error-free data rates of 50-70% of the selected bit rate. Complete board level radio modems such as the Freewave DGR09 are available for about $1000 and can be integrated easily into PC-based control systems.

FCC regulations require radios in these bands to have transmitter power less than 30 dBm (1 Watt) and EIRP (effective isotropic radiated power) no greater than 4 W, which includes the "on beam" gain of the antenna. The intent for these unlicensed systems is that they have sufficient power to be useful over modest line-of-sight ranges (4-36 km), while allowing multiple systems to operate in the same band and area without disabling interference. High antenna gain maximizes range and can minimize interference to others by concentrating

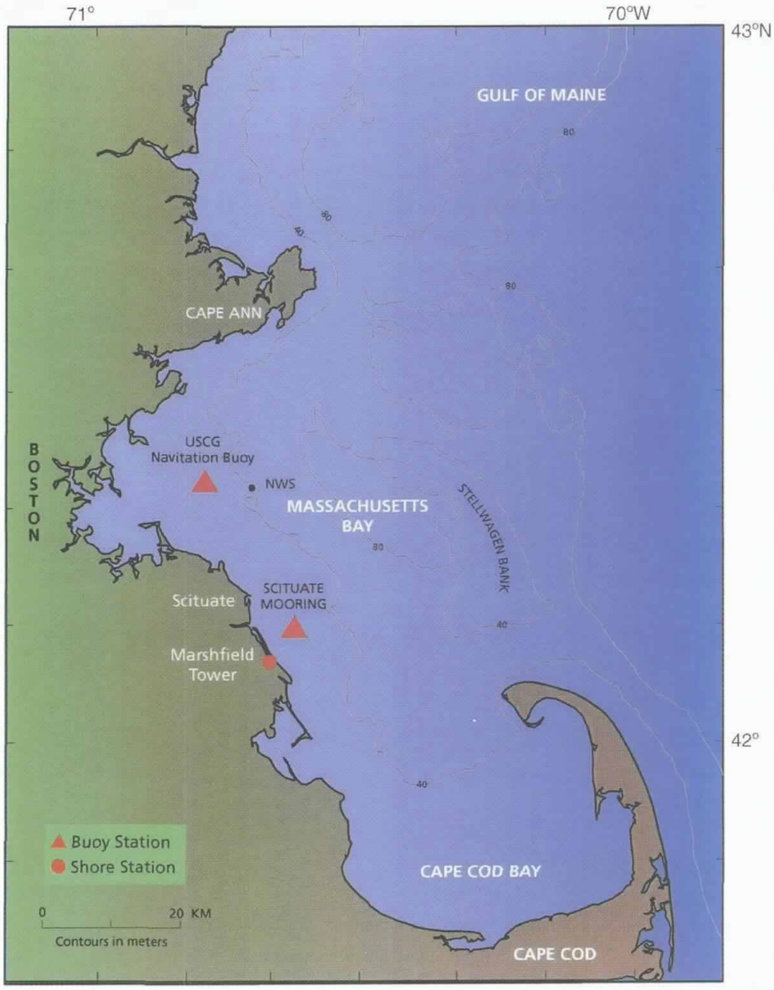



*Figure 4: Mooring sites instrumented as part of the Portable Coastal Observatory in Massachusetts Bay.*

the radiated signal in a directional beam. Interference rejection is increased outside the beam. A technique for increasing the operational range of these low-power systems in point-to-point applications employs maximum legal gain on the transmitters while using arbitrarily higher gain antennas at the receiver.

On the surface buoy end of the link, a 3 dB whip antenna is used to accommodate buoy motions. The radiation pattern of this whip is omni-directional in the horizontal with an approximately 35-degree beam pattern in the vertical, which in the majority of sea conditions is optimal. Higher gain leads to reduced vertical beam width and may result in reduced link quality in rough seas due to pointing error. Each of the surface buoys in the Portable Coastal Observatory contains an RF modem operating at 915 MHz, a UHF radio operating at 465 MHz, which is used to reset the system remotely, and a UAM for receiving acoustic transmissions from the subsea instruments. The UAM controls power to the radio, turning it on only when acoustic data have been received to conserve battery power. The UHF link draws about 10 mW on average while monitoring the 465 MHz channel for the reset command. The UHF link uses a unique ID to determine if the command channel message is for a particular buoy before it causes a reset. In this way a number of surface buoys can share a single UHF frequency band. The RF modem consumes about 6 W when transmitting and about 2 W when receiving. The buoy battery (an alkaline D-cell pack) is sized for 6-months operation at an average drain of about 600 mW.

The shore station in the Portable Coastal Observatory acts as a buffer and a relay between the offshore buoys and a data distribution server at WHOI. Depending on its height and seaward view, a shore station can receive data from a dozen or more buoys, each asynchronously attempting connection and data transfers. The present configuration of the shore station equipment in the Massachusetts Bay field demonstration includes a PC with Linux operating system, an interface module with an RS422 line driver to the radio modem on the tower (60 m above sea level), a DTMF converter for the 465 MHz link, and a telephone modem connection to the Internet. Because of the particular geometry of the sites in Massachusetts Bay, where one site is about 30 km from the shore site and the other is only about 8 km, but in a somewhat different direction, a 10 dB Yagi antenna is used at the shore site for the RF modem antenna. A site survey conducted prior to shore station installation confirmed that this level of gain was capable of achieving error-free data transfers at the far site and that the off-beam signal level was high enough to maintain a solid link with the nearer site. The shore station configuration is illustrated in Figure 2. During normal operations, a buoy in the observatory establishes a link to the shore site, which is always listening for a message, and transfers its data file. The data is stored on the local hard disk and emailed to the web-based server at WHOI via a dial-up connection. Associated with each data transmission is information on the data source, its location, and a time stamp. This information forms the basic tracking system used by the GeoBrowser software.

## Internet Connectivity and Web Interface

A web-based data access system, based on a software package developed at WHOI called the 4DGeoBrowser, is used to provide Internet access and data display of the observatory data. The system has several methods for importing data automatically. For the Portable Coastal Observatory, an email mechanism is used when the shore stations asynchronously send data to the Geobrowser server. Once an email message is received, the data are automatically logged, indexed and made available on the web (with access restrictions, if needed). The Geobrowser system provides temporal, spatial and keyword searching capabilities and includes the ability to generate interactive geographical and time-series plots. The system handles metadata and data seamlessly and takes advantage of web technology including supporting multi-media for sensors or observatories that may need image, video or audio capability.

An essential feature of the Portable Coastal Observatory is a web-based data access system for handling the geographically spaced, multi-disciplinary data. Since coastal observatories typically contain multi-disciplinary data, it is important that the data be stored in a web-based database system for scientists in addition to a public website. Using the Geobrowser system, scientists can easily access the raw data collected geographically, temporally or by sensor type and use either built-in tools for plotting and analysis or they can export the data to external computers. This infrastructure is designed to be a standards-based plug-and-play system that need not change as new sensors are added or new observatories come on-line. The web infrastructure can support cabled observatories as well as wireless observatories.

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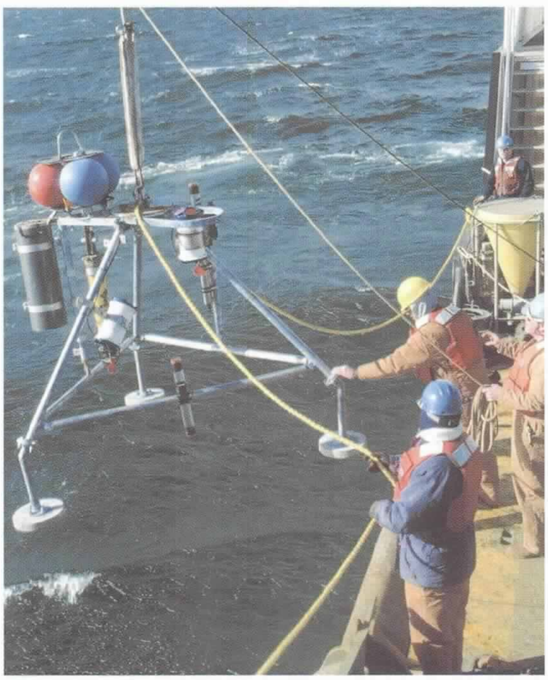

*Figure 5: Tripod frame being deployed in Massachusetts Bay. An ADCP mounted on the tripod transfers current profiles to an LCT on an hourly basis. The LCT then forwards the data to the surface buoy for transmission to shore.*

## Surface Buoy Telemetry Moorings

Surface buoy moorings used to support the acoustic receiver and the RF link have been designed to be small and easy to deploy, but capable of operating reliably for many months in the coastal ocean. Their small size allows them to be deployed from small vessels normally used in coastal research and also helps to make them inexpensive. The buoy and mooring design are illustrated in Figure 2. Each component of the mooring has been designed to minimize the potential for failure and to make deployment simple. Surface electronics are packaged in an aluminum tube that acts as the buoy strength member and provides a means to attach the Surlyn foam flotation collar, which has 180 kg of buoyancy. The upper end cap of the tube has penetrators for RF antennas and the hydrophone, which is located externally. Below the buoy, a 2 m length of chain is used to deal with the mechanical stresses associated with buoy pitch and roll. The electrical conductors that connect to the hydrophone, which is positioned at mid-depth to optimize the acoustic path, are spiraled around the chain section, which has been encapsulated in polyurethane. This detail is critical to survival of the electrical conductors over extended deployments. A multi-conductor electromechanical cable connects the chain section to the hydrophone cage. Special aluminum termination fittings connect the ends of the E/M cable to the chain and hydrophone cage. These terminations provide space to make the electrical connections and also transfer the mechanical loads. Below the cage, a length of 9.5 mm chain terminates at a small anchor, typically weighing about 115 kg. The RF antennas are mounted on a 3 m fiberglass mast along with a solar-powered light and a radar reflector. The entire mooring system, including buoy and anchor, weighs less than 200 kg in air and can be deployed by hand from a small vessel without any heavy lifting gear. Retrieval of the anchor does require some lifting capability, such as a winch and davit, or a boom and capstan. The surface buoy with mooring can be fabricated for about $7500 and the system electronics cost about $5000, including an alkaline D-cell battery pack capable of powering the system for 6-months. A week or two of technician time is needed to install and test the electronic systems prior to deployment.

In addition to the low-cost stand-alone surface buoys, hardware is being developed to take advantage of existing navigation and weather buoys. Use of these and other buoys-of-opportunity for coastal observatory installations is an inexpensive and convenient way to increase the number of platforms available throughout U.S. coastal waters. A Coast Guard navigation buoy in Massachusetts Bay near the Boston ocean outfall is being equipped with an acoustic receiver and RF modem to demonstrate this capability under the NOPP funding. It would be difficult to maintain one of the small telemetry buoys at this site due to heavy vessel traffic, but this is an important site to monitor in real time, since the outfall is nearby. Hardware on the buoy consists of instrument housings for the electronics and batteries and a hydrophone suspended over the side of the buoy. The radio modem is mounted with its antenna on the buoy tower to minimize RF losses in the antenna cable.

## Massachusetts Bay Prototype Trials

As part of the NOPP-funded development effort, field trials of two prototype surface moorings and associated subsea sensors are being conducted in Massachusetts Bay (Figure 4). This array constitutes a nascent Portable Coastal Observatory. One of these surface moorings is to be deployed in 25 m of water about 8 km offshore Scituate, MA and the other will be deployed on the Coast Guard buoy near the Boston outfall located about 13 km offshore of Boston in about 30 m of water. Both of the sites will be equipped with an ADCP integrated to an LCT (Figure 5). Every hour, about 450 bytes of current data will be transferred to a shore station located in Marshfield, MA. Preliminary system tests conducted at the Scituate site with a UAM interfaced to an ADCP mounted on a tripod moored on the ocean bottom have demonstrated the feasibility of the system design. In these preliminary tests the acoustic link was sensitive to wave conditions and error rates increased substantially when the weather was stormy. The hydrophone used in the initial test has been replaced with a unit with better filtering at low frequencies and improved performance is anticipated on the next trial. Present plans are to continue testing with the UAM as the transmitter until the LCT hardware is completed this summer. An operational system with two surface links and two acoustically linked ADCPs is planned for fall 2000.

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## Vision of the Future of Portable Coastal Observatories

The Portable Coastal Observatory technology developed under NOPP funding is a prototype of an infrastructure that will ultimately become an important means for making sustained ocean observations. As the acoustic link technology matures, it is anticipated that very low cost acoustic modems will become available that will support high rate, two-way communications. The LCTs developed on this program will eventually have this capability using coherent signaling strategies. They will cost about $1000 exclusive of the projector. They will incorporate data compression capabilities and will be fully integrated with ocean sensors to form low cost, low power, real-time monitoring modules. In deep water LCTs will operate at lower frequency and at rates up to 10,000 bps and will be even more energy efficient. Recent experiments conducted by one of the authors (Freitag et al., 2000) indicate that a data rate of 10 kbps is possible in 6000 m of water using a 10 W source. This capability will make deep-water, moored buoy observatories a practical reality.

The acoustically linked Portable Observatory is a broad and flexible concept that has important applications in scientific research, coastal and deep water monitoring efforts and military operations. Several specific applications that are presently being investigated are described below as examples of how the concept might be applied.

1. Autonomous Oceanographic Sampling Networks (AOSN) (Curtin et al., 1993). These networks of passive and active sensor systems are meant to provide real time, 3-dimensional descriptions of regional ocean volumes. They combine fixed and moored sensor data with data from Autonomous Underwater Vehicles (AUVs), gliders, and drifters and data from remote sensing systems. Two-way acoustic communication links are being used to connect AUVs and moored sensors to surface buoys equipped with RF modems and from there to investigators on shore (or ships) for real-time control of AUV sampling strategies.
2. An open ocean observatory concept has been developed based on high speed, two way acoustic links between water column and seafloor instruments and large surface buoys equipped with high speed satellite telemetry links. This approach eliminates the need for fiber optic cables (from shore or from the bottom) and greatly simplifies the logistics of maintaining long-term deep ocean observational outposts.
3. Regional monitoring efforts on the U. S. Gulf Coast require real-time current data for input into numerical models. Acoustically-linked ADCPs and nearby surface buoys equipped with Orbcomm transceivers are being considered for a prototype real-time system. Additional sites and sensor arrays may be added to the prototype system to expand coverage to a broad area of the Gulf Coast.

Radio telemetry to support the buoy-to-shore link is available now and is improving rapidly. In addition to the short-range RF modems used for the field trials described above, long-range satellite links are available with worldwide coverage. Presently available (or nearly available) links include Orbcomm, Globalstar and Argos. For near shore sites cellular telephone is another option. Eventually, broadband data links with low power omni-directional antennas will provide even more capacity to meet the needs of the community, though the timing of these improvements appears uncertain at the moment.

In the near term, given successful field-testing of the portable observatory prototype this summer, the USGS and WHOI, with continued collaboration with MWRA, RDI, and the USCG, are planning on operating the observatory continuously for the next year. Telemetry of ADCP observations from two sites in Massachusetts Bay will be part of an ongoing monitoring program carried out by the USGS in cooperation with the MWRA. This trial will exercise the acoustic technology in an operational mode and provide the opportunity for the science and management community, as well as the public, to utilize the near real-time measurements. The observatory will be operational during the start-up of the new Boston ocean outfall, scheduled to begin discharge of treated effluent into western Massachusetts Bay in 2001. It is anticipated that real-time data from the observatory will be available beginning in Fall 2000 at http://woodshole.er.usgs.gov/.

## Acknowledgements

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NOPP

National Oceanographic Partnership Program