Mooring Developments for Autonomous Ocean-Sampling Networks

Daniel E. Frye, *Member, IEEE*, John Kemp, Walter Paul, and Donald Peters

***Abstract*—Two general-purpose mooring designs have been developed to support autonomous underwater vehicle (AUV) operations in autonomous ocean sampling networks (AOSNs). These moorings provide two-way communications between investigators and AUVs docked on the moorings or conducting survey operations some distance from the moorings. A deep-water design that incorporates an AUV dock and recharging station was built for use in the Labrador Sea during the winter of 1997/1998. This severe winter environment required a robust design that could operate unattended for six months while isolating the dock from surface wave motion. A much lighter, easier-to-deploy design was developed for use in coastal waters to extend the nearshore AOSN operating area by extending the communications network. This coastal design has been deployed without the dock component and has typically been configured for use in a small network of moorings maintained with a small research vessel. The deep-water mooring has been deployed successfully on two occasions, for short periods of time. The coastal moorings have been deployed a number of times and have proven to be quite effective. This paper describes the two moorings in detail and provides information on their performance so that interested investigators can utilize the technology where it meets their needs.**

***Index Terms*—Acoustic telemetry, AUV docking, satellite telemetry, telemetry moorings.**

I. Introduction

The autonomous ocean sampling network (AOSN) concept [1] is an approach to ocean measurement that is intended to significantly improve spatial and temporal sampling of the ocean's interior on a regional basis. This sampling enhancement is needed to help resolve important ocean processes that are difficult to measure, such as deep convection, coastal fronts, and hot vent plumes. An important feature of the AOSN approach is the use of autonomous underwater vehicles (AUVs) for intelligent, automated surveying. Moorings are used to provide communication gateways for AUVs and, in some instances, to provide docking and recharging facilities to extend AUV operating range and duration.

Dock moorings provide battery charging and data offload services to AUVs. The data offload service implies a need to transfer data to remote shore (or ship) facilities and for a back channel to send new mission information to the vehicles. These moorings also provide real-time links to AUVs when they are on missions away from the dock via an integrated acoustic telemetry capability [2]. Communications moorings, which do not include an AUV dock, provide acoustic and RF connectivity between network operators and AUVs and extend the AOSN operating area out to tens of kilometers. These communication capabilities are especially valuable in shallow water where precise navigation and control are needed to direct AUV survey operations.

This paper describes mooring technology that has been developed at Woods Hole Oceanographic Institution (WHOI) over a number of years to address requirements for data telemetry from subsurface instrumentation. Real-time data telemetry from *in situ* instruments has been a difficult technical challenge for ocean engineers because surface wave action places extreme demands on electromechanical mooring components, particularly where they connect to surface buoys, which are needed as platforms for radio antennas. With careful attention to detail, however, reliable moorings using electromechanical cables as the mooring strength members are realizable. Three-meter discus buoys have been moored in deep water using electromechanical cables to connect inline instruments with the surface buoy and long lengths of nylon line that are installed deep in the water column to provide compliance for waves and currents [3]. Subsurface moorings with electromechanical mooring elements have also been deployed using slack-tethered surface buoys[4], [5]. The key design issues in these approaches are the termination of the mooring cable at the surface buoy and the methods used to absorb wave energy. Two successful designs are described in the deep water and coastal designs discussed below. Because the technical methods used in successful ocean telemetry moorings have not been standardized or well documented, these AOSN moorings are described in some detail to make the design information available to the community.

II. Deep-Water Dock Mooring With Surface Telemetry Link

A deep-water AUV dock mooring with real-time data telemetry and recharging capabilities was specified to demonstrate the ability of the Odyssey AUV to investigate deep convection events in the Labrador Sea [6]. These events, which occur intermittently and on relatively small scales during winter when oceanographic vessels are rarely in the Labrador Sea, play an important role in the large-scale circulation of the Atlantic. Autonomous vehicles that are capable of sampling over modest horizontal and vertical scales may be able to observe and measure the size and frequency of these important phenomena.

Manuscript received February 21, 2001; revised June 15, 2001. This work was supported by the Office of Naval Research through the AOSN MURI under Contract ONR 322 OM/AOSN N00014-95-1-1316. T. Curtin at ONR provided funding for this work.

The authors are with the Woods Hole Oceanographic Institution, Woods Hole, MA 02543-1541 USA (e-mail: dfrye@whoi.edu; jkemp@whoi.edu; wpaul@whoi.edu; dpeters@whoi.edu).

Publisher Item Identifier S 0364-9059(01)09923-X.

TABLE I
DEEP-WATER DOCK MOORING DESIGN CRITERIA

Mooring Criteria
• support a large, heavy dock at 500m depth
• survive up to Sea State 10
• two-way RS-485 link from the dock to the surface buoy
• minimal motion of the dock due to surface waves
• current profile: 55cm/s near surface; 20cm/s near bottom
• deploy and recover in high sea-states
• minimize icing on RF antennas
RF Link Criteria
• two-way link at 56°N latitude with modest data throughput using an omni-directional antenna
• reasonable power budget
• reasonable size
• acceptable cost for hardware and data telemetry
Acoustic Link Criteria
• one-way link from AUV to mooring for status data
• omni-directional transducers for acoustic communications
• 2000m maximum depth (AUV)
• directional homing capability using a separate receive array on the AUV
• operate in the presence of LBL array at 10-12 kHz

The primary challenges in the development of this severe environment mooring were protection of the electrical conductors connecting the submerged dock and the surface buoy from failure due to wave forcing, and isolation of the dock from wave motions. Secondary challenges included maintaining the surface buoy on the surface under the anticipated current profile and keeping ice from building up on the radio antennas with subsequent loss of RF communications. In addition, the mooring and its components had to be deployable during rough sea conditions, since the deployment cruise was scheduled for January in the Labrador Sea, a location known for frequent winter storms. Design criteria for the deep-water dock mooring are summarized in Table I.

The mooring (Fig. 1) was designed to support the AUV dock mechanism (Fig. 2 and described in detail in [7] and [8]) and its massive battery and electronics housings and to provide a near real-time, two-way data link between AUVs and scientists on shore (or ship). It was scheduled to be deployed for six months during the winter when the full force of winter storms would impact the surface buoy. To simplify homing requirements and minimize forces on the dock and the AUV after docking, it was

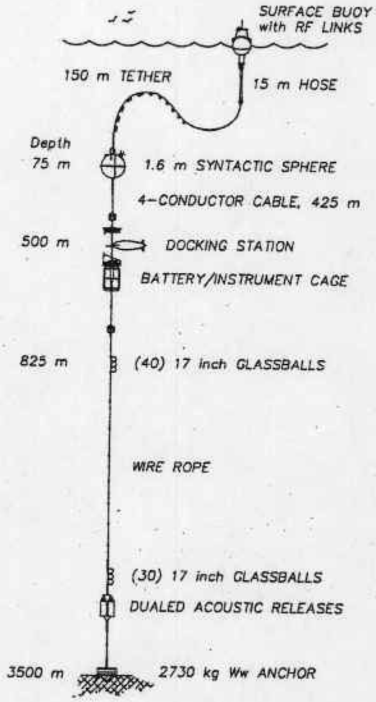


Fig. 1. Dock mooring deployed in the Labrador Sea in January 1998. The dock controller and surface buoy electronics are connected via a four-conductor cable.

important that the dock be isolated from surface wave motion. The docking process requires the AUV to acoustically navigate to the dock and latch to a pole positioned in line with the mooring. If the two-meter docking pole heaves up and down, as it would on a conventional surface mooring, then the AUV would be subjected to high dynamic loads while it was docked and would have to deal with a surging docking pole (and navigation beacon) during the docking procedure. Both of these scenarios could be fatal to system operation.

To meet the need for real-time telemetry and for a stable docking platform, a subsurface mooring was designed with a slack-tether (S-tether) connection to a small surface buoy. The surface buoy was made as small as possible to minimize the wave generated forces transmitted down the mooring line and rugged enough to survive submergence during the deployment process. The S-tether provides mooring scope needed to accommodate currents anticipated at the site, which may cause the mooring to lean over and pull the subsurface buoy deeper, and to help absorb surface wave energy. The surface buoy, a steel sphere 1.2 m in diameter equipped with an integrated instrument housing and small antenna platform (Fig. 3), has 4225 N (950 pounds) of buoyancy and is designed to stay on the surface under the operational current profile shown in Table II. During stronger current events, which had been observed near the deployment site [9], the buoy and its telemetry antennas are designed to survive excursions to 300 m depth.

The subsurface buoy (Fig. 4), a syntactic sphere with 13 344 N (3000 pounds) of buoyancy, supported 425 m of four-conductor electromechanical cable and the AUV dock with its 4960 alkaline D-cell battery pack. The docking system consists of a docking pole with a moveable clamping carriage (see Fig. 2) that positions and holds an Odyssey AUV in close contact with

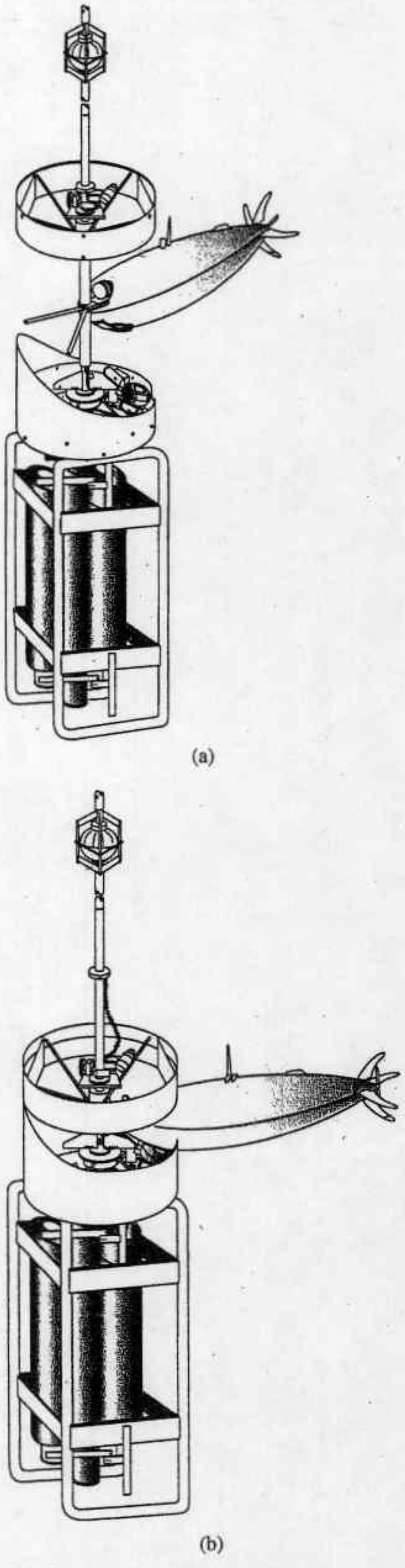
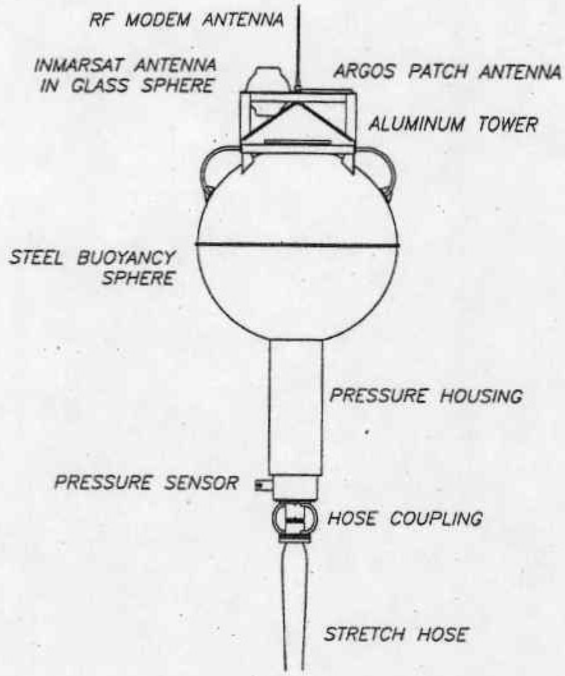


Fig. 2. The AUV dock showing the carriage in the open (a) position and closed (b) position (Courtesy H. Singh).

an inductive pad used for data and power transfer [10]. In addition to the two large battery cases, dock hardware includes an electronics housing, a Long Baseline (LBL) transponder for acoustic navigation, and a Utility Acoustic Modem (UAM) for communicating with the AUV. Above the docking pole, a homing beacon provides a signal for the AUV's ultrashort baseline (USBL) homing system. Dock sensors include an Acoustic Doppler Velocimeter (Sontek ADV) to measure currents, a Seabird SBE 38 temperature sensor (temperature sensors were also located at the subsurface and surface buoys), a Paroscientific pressure sensor for monitoring total depth, as well as dock carriage position switches used to determine dock status. The complete dock system weighs 11 173 N (2512 pounds) in air and 4137 N (930 pounds) in water. A pressure sensor was also mounted on the surface buoy to measure its depth excursion during deployment. The temperature sensors were intended to provide an indication of deep convection events, which are characterized by very low temperature, unstratified conditions. Below the dock, standard mooring components (wire rope, glass balls, etc.) were used to connect the dock to the anchor in 3500 m of water. Forty 17-in glass balls on the upper section of wire rope were used to help support the mooring weight.

Key areas in the S-tether mooring design that are vulnerable to mechanical failure are the junction between the mooring and the surface buoy, the connection between the tether and the subsurface buoy and in the tether itself. Cyclic flexing deformation and axial elongation and retraction which strain copper conductors in excess of their 0.5% yield limit are the culprits in most failures that are not related to leaks and faulty connectors. To address these design issues and potential failure modes, special mechanical systems were developed to withstand the bending strains on the mooring components and the slack-to-taut transitions in the tether. At the surface buoy-to-tether connection, a compliant rubber hose is used to minimize bending strain on the mechanical connection and to protect the electrical conductors from work hardening or Z-kinking [11]. (Z-kinking is the term used to describe the way a copper conductor forms a work-hardened bulge after it has been stretched beyond its yield limit and then is forced to retract as the steel strength member in the cable shortens.) The rubber hose, which was built by Thermoid HDB Industries of Salisbury, NC, is 15 m long and 10 cm in diameter (Fig. 5). It has an ultimate strength of 44 500 N (10,000 pounds) and will stretch about 3 m at its safe working load of 19 100 N, or 4300 pounds. The hose is filled with fresh water to balance the pressure of the seawater around it. A thick hose wall and counter-helical reinforcement maintain shape stability as the hose bends. Inside the hose, a five-conductor coil cord provides a safe pathway for the electrical conductors connecting the tether cable to the surface buoy. The coil cord is designed to open its coils as the hose stretches without putting any strain on the copper conductors.[1] Aluminum pipe flanges on the ends of the hose are used for the mechanical connections to the surface buoy and to the tether cable. The hose terminations include watertight bulkheads and use underwater connectors to connect the coil cord and tether cable conductors. The ends of the hose, where bending strains are most severe, are built up with extra layers of rubber and tire cord prior to the vulcanization process to provide additional bending and axial stiffness in these critical areas.

[1]Manufactured by Whitney-Blake Corporation, Bellows Falls, VT.



(a)

(b)

Fig. 3. (a) Surface buoy schematic showing the mechanical layout. (b) Photograph of the surface buoy that supports the satellite telemetry link used with the dock mooring in the Labrador Sea.

TABLE II
OPERATIONAL AND SURVIVAL CURRENTS USED IN THE DOCK MOORING DESIGN ANALYSIS

Depth	Operational Current	Survival Current
0 m	30 cm/s	55 cm/s
760m	25 cm/s	50 cm/s
1260 m	22 cm/s	45 cm/s
1760m	20 cm /s	40 cm/s
2510m	12 cm/s	25 cm/s
3400 m	10 cm/s	20 cm/s

Between the lower end of the rubber hose and the subsurface buoy, a special S-tether cable is used to provide scope and shape compliance to absorb some of the wave energy. This tether cable is 150 m long and has a weighted section below the hose and a buoyant section above the subsurface buoy to give it an inclined S-shape under low to moderate current conditions. This shape is desirable because it allows the surface buoy to follow the seas without putting much strain on the tether or the mooring below the tether. The tether consists of a double-armored steel cable with four no. 20 copper conductors helixed around an inner core. It has a breaking strength of 35 600 N (8000 pounds) and a minimum safe bending radius of 30 cm. A thick (38-mm-diameter) foamed-polyethylene layer was extruded over the armored cable for stiffness to minimize the cable's tendency to hockle in slack conditions. The tether is terminated at the subsurface buoy (at 75 m depth) through a short molded chain section (see Fig. 4),

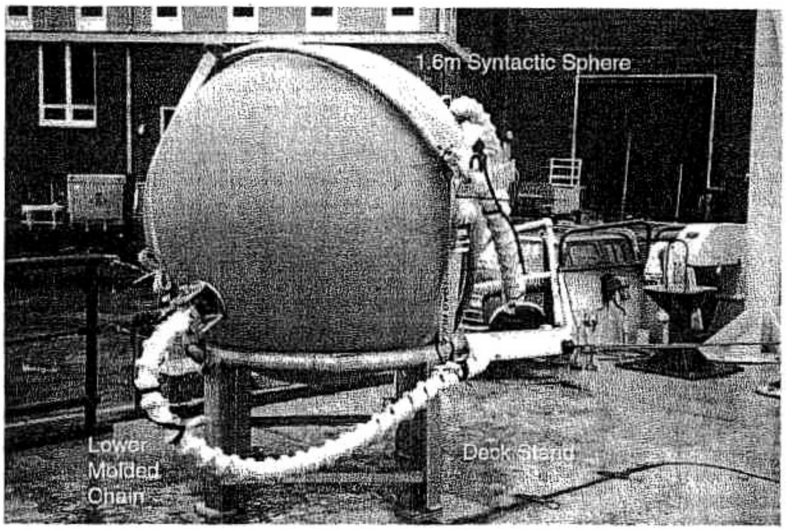


Fig. 4. Photograph of the subsurface buoy used to support the dock mooring. The molded chains are used for strain relief above and below the buoy.

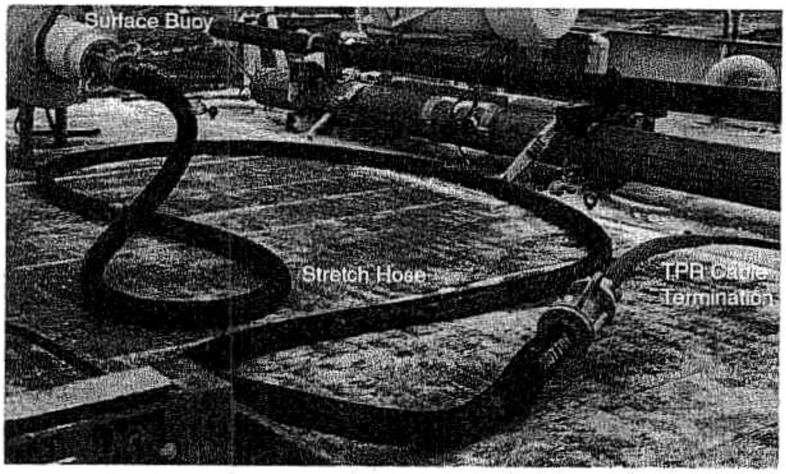


Fig. 5. Rubber hose connecting the surface buoy and the S-tether.

whose purpose is to relieve bending strain resulting from the surface buoy pulling horizontally on the subsurface buoy. The chain, which is 3 m long, is encased in a 10-cm-diameter rubber hose that is filled with polyurethane. The conductors are spiraled around the outside of the chain and hose to minimize strain on them when the chain flexes. Beneath the subsurface buoy, a second molded chain is used to minimize bending strain at that point.

The response of the mooring to wave action was investigated using WHOI Cable [12], a time-domain model of moored systems, to compute the motion at the dock under simulated sea conditions. The model was run using Sea State 6 ($H_s = 4.6$ m, $T_z = 10.5$ s) to simulate the severe operational environment expected in the Labrador Sea. Results of this simulation are shown in Fig. 6 (from [13]) where rms vertical velocities at the surface were about 91 cm/s and corresponding rms velocities at the dock were about 5 cm/s. These velocities are equivalent to rms vertical displacements of about 109 and 8 cm, respectively.

The surface buoy electronics payload consists of an Inmarsat C transceiver, an Argos PTT for back-up position data, and a short-range RF modem for transactions with the ship during postdeployment checkout. A controller in buoy communicates with the dock controller over an RS 485 link and mediates the flow of data to and from the dock controller. Inmarsat C was chosen as the primary RF telemetry link because it provides a modest data throughput (600 bit/s base data rate) and the two-way capability needed for command and control using an omnidirectional antenna. The transceiver requires about 120 W when transmitting and about 10 W when receiving and was powered down when not in use. Data transfer costs about $6.25 per kbyte. Other two-way telemetry options that have recently become available, including Orbcomm, Iridium, and Globalstar, could also provide the necessary telemetry functionality. A more detailed description of the telemetry systems on the mooring can be found in [8] and [14].

III. Labrador Sea Deployment

The deep-water dock mooring was deployed on two occasions. The initial deployment was in October 1997 at Site D (39°, 14.7′N and 69°, 59.1′W) in 2630 m of water. Its purpose

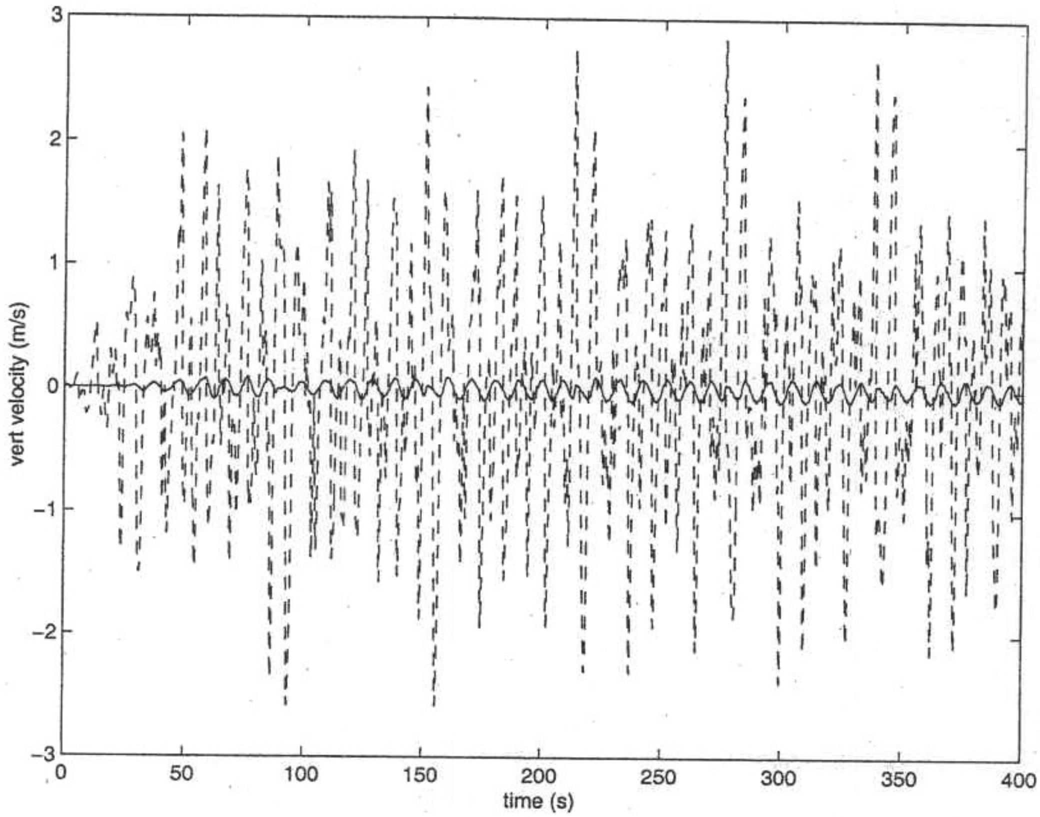


Fig. 6. Computed vertical velocities at the surface (dashed) and at the dock (solid) under Sea State 6 based on a simulation run using the WHOI cable mooring program (courtesy J. Gobat).

was to evaluate the deployment/recovery operation and the functionality of the mooring and RF telemetry systems prior to the Labrador Sea deployment. It was also meant to test the docking behavior of the Odyssey AUV and the operation of the dock and its inductive data offload system. This initial deployment was limited to a few hours by approaching bad weather and the AUV was not deployed, but the test did confirm that the mooring and telemetry systems worked as designed and that the mooring was robust enough to survive the deployment and recovery process. It also verified the stability of the dock under moderate sea conditions.

In late January 1998, the dock mooring was deployed from the R/V Knorr at 56°, 33.6′N and 52°, 39.5′W in the Labrador Sea in 3500 m of water. The deployment took 22 h during moderate sea conditions. During the anchor drop, the surface buoy was submerged to a depth of 140 m as illustrated in Fig. 7. Following the deployment, RF and acoustic communications functions on the dock and surface buoy were exercised in a variety of ways over the next 12 days and all worked as designed providing connectivity from the ship to the dock computer. The AUV was launched and, while it swam around the mooring, status data were regularly received by the acoustic modem on the dock and forwarded to the nearby ship. However, the dock carriage jammed on its initial trial under command from the ship and attempts to free it while it was deployed were unsuccessful. This mechanical failure rendered the inductive power and data transfer capability inoperative because the AUV could not be held in position. When the mooring was recovered 12 days later, the carriage moved out of its jammed state, which made it difficult to determine the cause of the failure. The two-meter docking pole was bent slightly on recovery during rough seas. It may have been bent during deployment, which could have caused the carriage to jam, but that conclusion cannot be verified. After recovery, the docking pole was straightened on the deck of the Knorr using a come-along, but a decision not to redeploy the mooring was made based on the status of the AUV power systems and considerations of time and weather.

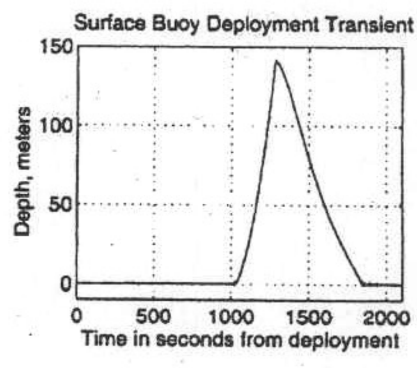


Fig. 7. Surface buoy pressure record following anchor launch in the Labrador Sea.

Since the Labrador Sea expedition, the docking system has been deployed in a shallow-water configuration in Cape Cod Bay in September 1998 and in Monterey Bay in August 1999. In both instances it performed its communications functions as designed and provided real-time connectivity between the dock controller and investigators on a nearby ship and at shore laboratories. In both of the shallow-water deployments, RF modems were used in place of the Inmarsat C telemetry link. Performance of the data and power transfer systems is described in [8], in this issue.

Recently, a new dock design has been built and tested in a prototype configuration by researchers at WHOI [15]. This new design replaces the docking pole with the mooring wire and uses the vehicle propeller to drive the vehicle along the wire until it latches on the dock frame. This simplifies the dock, reduces the potential failure modes, and allows the dock to be simultaneously configured for a variety of vehicles. The inductive data and power transfer systems have also been replaced with underwater mateable connectors and associated motorized lead screws to plug and unplug the connectors. This change has been made for simplicity and ease of use following the experience gained with the inductive approach. It is too early to tell which method will ultimately prove to be the most reliable to use at sea.

IV. Coastal Communications Mooring for Acoustic and RF Telemetry

The design challenge associated with the coastal communications mooring was to minimize the cost and complexity of the mooring system while maintaining a sophisticated acoustic and RF communications capability. A successful design would allow the moorings to be used economically in small networks to facilitate AUV surveys in coastal areas. The general specification for the coastal communications mooring was for a surface mooring designed for depths between 10 and 1000 m that could be deployed from small coastal vessels by two people. The buoy and mooring had to be lightweight to avoid the need for special handling gear and they had to be inexpensive so that a network of moorings could be installed without major program cost impacts. The telemetry requirements included a two-way acoustic link with AUVs or other underwater data sources and a line of sight RF link with nearby ships or shore stations. An ability to substitute Low Earth Orbit (LEO) satellite telemetry for the line-of-sight radio link was also desirable.

The designs that resulted are illustrated in Fig. 8, which shows a shallow-water configuration (a) and a deeper water configuration (b). The moorings consist of small Surlyn foam surface buoys with lightweight aluminum instrument housings. The Surlyn disk provides about 2000 N of buoyancy (450 pounds) for the shallow mooring and about 5300 N of buoyancy (1200 pounds) for the deeper mooring. The instrument housing acts as the buoy strength member and mooring attachment point. A small aluminum and fiberglass tower supports a solar-powered light, a radar reflector and the RF antennas (typically a 900-MHz whip for the RF modem and 150-MHz whip for a UHF receiver that provides a remote power-on capability). Inside the instrument housing is a UAM, a spread-spectrum RF modem (Freewave Model DGR09), a UHF receiver, and a large (192 D-cell) alkaline battery supply. The electronic components are mounted on an aluminum plate bolted to the housing end cap. The acoustic hydrophones (2) and source element are mounted in an aluminum cage that is hard-wired back to the buoy. Moorings have been deployed with one or two of these cages, but a single cage suspended near the bottom

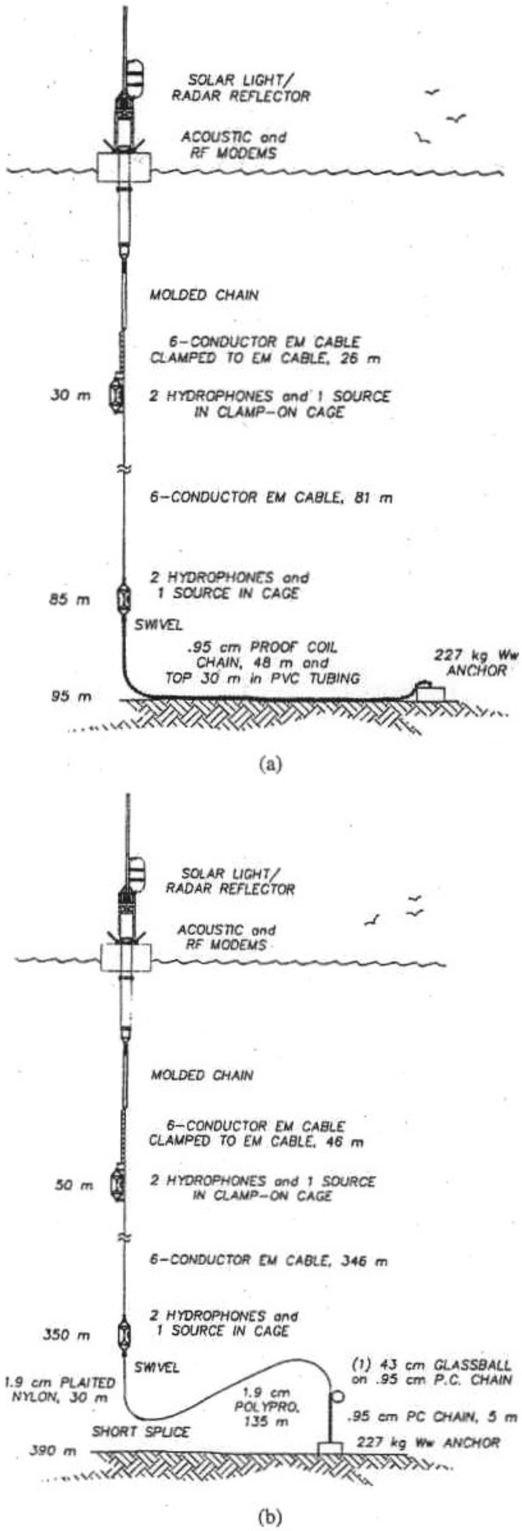


Fig. 8. (a) Shallow-water configuration of the coastal communications mooring deployed in Monterey Bay in August 1999. (b) Deep-water configuration of the coastal communications mooring used in Monterey Bay in August 1999.

usually provides optimal acoustic communications range. The mooring strength member is a double-armored, six-conductor steel cable terminated at the acoustic cage. Special cable terminations were designed to minimize failures at the ends of the cable and to protect the unarmored electrical pigtails (Fig. 9). A simple molded chain strain relief connects the buoy and the

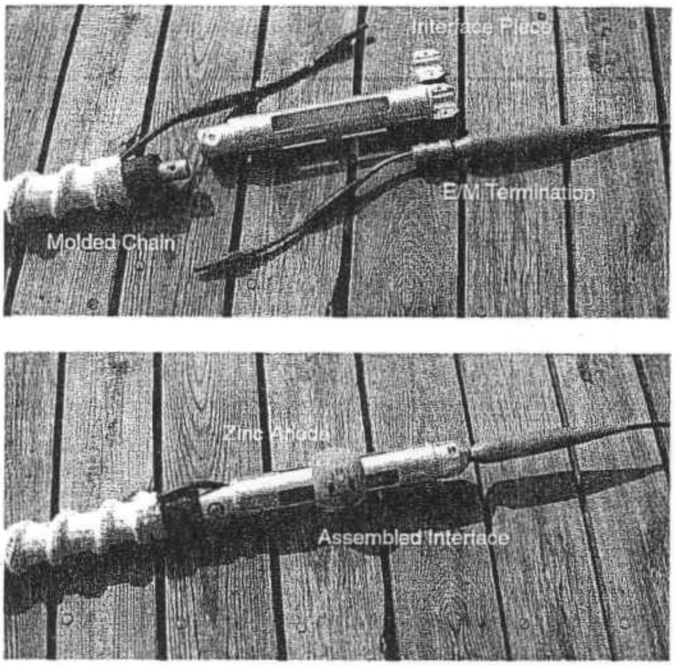


Fig. 9. E/M cable terminations developed for the coastal communications mooring.

mooring cable, as was used in the deep-water dock design (see Fig. 4). Below the acoustic cage, a 9.5-mm chain provides compliance for waves and currents and keeps the lightweight anchor from dragging. In the deep-water design [Fig. 8(b)], an inverse catenary made of nylon and polypropylene line replaces the chain to avoid the excessive weight and expense of a long length of chain. This design provided the capabilities required for the coastal communications moorings without being unduly large, heavy or expensive. The component cost of the mooring with buoy, mooring and electronics is \$12 000 to \$15 000.

V. Experience With the Coastal Communications Mooring

Two of the coastal communications moorings were deployed in Cape Cod Bay during September 1998 as part of the Site 98 AOSN demonstration. They were equipped with RF modems for line-of-sight telemetry to the R/V Oceanus, which was on site throughout the experiment. They were deployed in 25 and 40 m of water at sites separated by about 10 km and were used for both acoustic communications testing and as relay links for ship-to-AUV communications while the AUV was submerged. In the acoustic communications test mode they successfully demonstrated acoustic communications out to 10-km ranges in 40 m of water. In the data relay mode, they forwarded status data from the AUV while it was underway and within about 5 km of the mooring to personnel on the Oceanus.

Three coastal communications moorings were deployed in Monterey Bay during the AOSN SITE 99 demonstration from August 21 through September 16, 1999. These moorings were similar to the Cape Cod Bay systems in design, but were modified to increase their acoustic communications capabilities and to handle the increased water depth and current forces in Monterey Bay. Each of the three moorings was outfitted with two acoustic cages, each with a source and two hydrophones. One cage was suspended at 50-m depth using a separate six-conductor cable clamped to the main mooring wire. The second cage with source and hydrophones was positioned at the bottom of the six-conductor mooring cable about 50 m above the bottom (except at the shallowest site where the cage was 20 m off the bottom). The moorings were deployed in water depths of 95, 240, and 390 m to provide AUV connectivity while the vehicle was deep in Monterey Canyon and when it was in the shallow water on either side of the canyon. A shallow-water dock mooring was also installed using the surface elements of the coastal communications mooring system. After some initial problems with the UAM power amplifier boards, which failed due to over voltage, the communications moorings operated as designed and provided the Odyssey AUV with real-time connectivity within the mooring network. The moorings communications capabilities were exercised on a regular basis during the deployment period from the MBARI shore station and were also used regularly for collecting data on the acoustic communications channel. On several occasions, an Odyssey class AUV used the moorings as a real-time link to investigators on board ship during survey runs. The moorings were also used to demonstrate the capability of forwarding control information to an AUV while it was submerged and underway. These capabilities were dramatically demonstrated during a period when an Odyssey vehicle was incapacitated on the Canyon floor and could not free itself. The acoustic moorings provided a real-time data link between operators on the research vessel and the incapacitated AUV until its batteries were depleted. The vehicle was eventually recovered with an ROV.

A third coastal AOSN demonstration was conducted in Monterey Bay in August and September 2000 as part of the Muse Field Experiment [16]. Four coastal communications moorings were deployed in this experiment in an array offshore of Santa Cruz. Two of the moorings, which were each equipped with a single acoustics cage containing two hydrophones and one source, were deployed in 40 m of water and two similarly equipped systems were deployed in 85 m of water. As in the previous deployment, they were designed to support acoustic communications testing and AUV operations within the network. In addition, researchers from the Naval Postgraduate School deployed a bottom-mounted ADCP equipped with an acoustic modem near one of the 85-m moorings. The acoustic modem transmitted hourly current profiles to the nearby mooring and the mooring then forwarded the data to the shore station in Santa Cruz. The shore station was linked by Internet to MBARI so that the current data were available to all of the experiment participants in near real time [17]. While the acoustic data from the ADCP was intended to be linked by the nearest communications buoy (deployed within a few hundred meters), the mooring farthest from the ADCP (one of the 40 m sites) also reliably received and forwarded the data. This 40-m mooring was about 8 km from the ADCP.

VI. Conclusion

The deep-water dock mooring provided a stable and reliable platform for the dock and its related equipment. It was deployable in the difficult Labrador Sea environment and operated under a range of sea conditions. However, because the dock carriage jammed, tests of the data and power transfer systems were not performed. As a consequence of this problem and problems with the AUV systems, the deployment was limited to only 12 days and the long-term reliability of the design could not be fully verified. Mooring motion at the dock was measured and was within acceptable limits as predicted by the mooring simulation analysis. The surface buoy remained on the surface during the deployment interval and only suffered from minimal icing of its antennas. It was dragged down to a depth of 140 m during the deployment process, but operated without any problem after it resurfaced. The basic dock mooring has been used a number of times in shallow water over several years and continues to perform well. A revised dock design is presently being tested that retains the omnidirectional design of the original prototype, but eliminates its moving carriage and inductive data and power transfer subsystems. This new prototype may prove to be simpler to operate and more reliable in the field than the original system, but field tests have just begun.

The low-cost communications mooring design has proven to be quite flexible and easy to use. The design is being applied to several other projects with similar requirements, for example as the key infrastructure in a design for a Portable Coastal Observatory [18] and for a real-time current monitoring program in the Gulf of Mexico [19]. In particular, the moorings are easy for two people to deploy from small to medium size vessels. Careful attention to details such as E/M cable terminations, electrical connections, and corrosion protection make these systems highly reliable without excessive size or weight. One of the moorings in Massachusetts Bay has been on station for over a year without any mechanical problems. Designs for shallow and intermediate water depths provide the flexibility needed to use these systems in a wide range of environments. The RF modem has suitable range for many coastal applications and is easy to use and quite robust in terms of both the hardware and the data throughput. Substitution of LEO satellite links for the RF modem give these coastal systems unlimited range from shore. The moorings and their payloads are inexpensive to build and maintain and they are becoming a standard part of the toolkit for shallow water moored systems at WHOI.

ACKNOWLEDGMENT

T. Curtin at ONR provided valuable leadership in the AOSN concept design. The authors appreciated the excellent support of the Captain and crew of the R/V Knorr during the Labrador Sea expedition, the R/V Oceanus during the Cape Cod Bay and Site D cruises, and the R/V Shana Rae during the Monterey Bay deployments. The authors would also like to thank the numerous engineers and technicians at WHOI who contributed to the success of this work.

REFERENCES

[1] T. B. Curtin, J. G. Bellingham, J. Catipovic, and D. Webb, "Autonomous oceanographic sampling networks," *Oceanography*, vol. 6, no. 3, pp. 86–94, 1993.

[2] L. Freitag, M. Johnson, and J. Preisig, "Acoustic communications for UUVS," *Sea Technol.*, vol. 39, no. 6, pp. 65–71, 1998.

[3] H. O. Berteaux, D. E. Frye, P. R. Clay, and E. C. Mellinger, "Surface telemetry engineering mooring (STEM)," *Sea Technol.*, vol. 30, no. 7, pp. 10–13, 1989.

[4] J. Lynch, D. Frye, K. Peal, S. Liberatore, S. Kery, E. Hobart, A. Newhall, and S. Smith, "Real Time Tomography Mooring," Woods Hole Oceanographic Institution, Woods Hole, MA, WHOI Tech. Rep., WHOI 92-29, June 1992.

[5] D. E. Frye and H. O. Berteaux, "Telemetry concepts for deep sea moorings," *Sea Technol.*, vol. 33, no. 5, pp. 30–34, 1992.

[6] J. S. Wilcox, Y. Zhang, J. G. Bellingham, and J. Marshall, "Atmospheric and Planetary Sciences AUV Survey Design Applied to Oceanic Deep Convection," Massachusetts Inst. Technol., Cambridge, MA, MIT Sea Grant Pub. no. 97-9J, 1997.

[7] M. F. Bowen and D. B. Peters, "A Deep Sea Docking Station for Odyssey Class Autonomous Underwater Vehicles," Woods Hole Oceanographic Institution, Woods Hole, MA, WHOI Tech. Rep., WHOI-98-11, June 1998.

[8] H. Singh, D. Yoerger, F. Hover, J. Bellingham, B. Moran, S. Lerner, and K. von der Heydt, "Docking for AOSN—omnidirectional homing and autonomous operations," IEEE J. Oceanic Eng., to be published.

[9] M. Visbeck, Personal Communication, Lamont Doherty Geological Observatory.

[10] A. Bradley, M. Freezor, H. Singh, and F. Yates Sorrell, "Power systems for autonomous underwater vehicles," IEEE J. Oceanic Eng., to be published.

[11] W. Paul and A. Bocconcelli, "Drifting buoy systems using rubber stretch hose," *Sea Technol.*, vol. 35, no. 11, pp. 37–43, 1994.

[12] J. I. Gobat, M. A. Grosenbaugh, and M. S. Triantafyllou, "WHOI Cable: Time Domain Numerical Simulation of Moored and Towed Oceanographic Systems," Woods Hole Oceanographic Institution, Woods Hole, MA, WHOI Tech. Rep., WHOI-97-15, Nov. 1997.

[13] J. I. Gobat and M. A. Grosenbaugh, "WHOI cable: Time domain numerical modeling of moored and towed oceanographic systems," in *Proc. Oceans'98*, Sept. 1998, pp. 1681–1685.

[14] K. von der Heydt, M. Johnson, and D. Frye, "A moored system for data telemetry and control of autonomous underwater vehicles," in *Proc. MTS Ocean Community Conf.*, Nov. 1998.

[15] H. Singh, Personal Communication, Woods Hole Oceanographic Institution.

[16] MBARI Monterey Bay Aquarium Research Institute. MBARI-MOOS Upper Water Column Science Experiment. MBARI, Moss Landing, CA. [Online]. Available: http://www.mbari.org/muse/

[17] J. Paduan, S. Ramp, F. Bahr, D. Frye, P. Koski, F. Chavez, J. Reid, and B. Bluth, *Atmospheric Forcing and Oceanic Response During Late Summer Upwelling and Relaxation Events in Monterey Bay*, Poster presented at OI Americas, Miami, FL, Apr. 2001.

[18] D. Frye, B. Butman, M. Johnson, K. von der Heydt, and S. Lerner, "Portable coastal observatories," *Oceanography*, vol. 13, no. 2, pp. 24–31, 2000.

[19] Naval Oceanographic Office U.S. Nay Website.. [Online]. Available: http://www.navo.navy.mil/NGLI/

Daniel E. Frye (M'90) received the M.S. degree in physical oceanography from Oregon State University, Corvallis, in 1971.

He was a Staff Scientist at Argonne National Laboratory from 1971 to 1974 and at EG&G Environmental Consultants from 1974 to 1983. He was a Division Manager at Ferranti ORE from 1983 to 1987. He is presently at Woods Hole Oceanographic Institution where he is a Senior Research Specialist in the Applied Ocean Physics and Engineering Department where he manages the Advanced Engineering Laboratory. His research interests include ocean moorings, satellite telemetry, and ocean instrumentation.

John Kemp has been with the Woods Hole Oceanographic Institution since 1978. He provides technical support for acoustic and oceanographic mooring operations both at WHOI and at other institutions around the world. He performs design, fabrication, testing, and deployment of complex surface and subsurface mooring systems. He has participated in over 120 oceanographic cruises, totaling over 1549 sea days, primarily associated with mooring deployments and recoveries.

Walter Paul received the Ph.D. in mechanical engineering from the University of Hannover, Germany, with thesis work performed in the area of fiber rope mechanics.

After working as an Application Engineer for two fiber rope companies, he was employed for 19 years in Maryland in the mechanical design of fibrous strength members and tow cables for US Navy high-performance towed arrays. At the Woods Hole Oceanographic Institution, Woods Hole, MA, his research tasks include innovative approaches to the development of compliant shock absorbing strength members and electro-mechanical cables to moor buoys and aquaculture structures. He currently chairs the Buoy Committee of the Marine Technology Society.

Donald Peters received the B.S. degree in civil engineering from Pratt Institute in 1988 and the M.S. degree in ocean engineering from the Massachusetts Institute of Technology, Cambridge, in 1992.

He has been at the Woods Hole Oceanographic Institution, Woods Hole, MA, since 1994. He supervises a mechanical engineering group, which supports a wide range of research projects at WHOI. This support includes design of mooring components and buoys, mechanical design for oceanographic instrument development, mechanical and electromechanical cable terminations, and molded systems. He has an interest in the design of surface buoys and seafloor instrumentation packages as well as the development of lightweight, low-cost, coastal mooring systems.