PAPER

Deepwater Mooring Designs for Ocean Observatory Science

AUTHORS

Daniel Frye
Woods Hole Oceanographic Institution

Andrew Hamilton
Monterey Bay Aquarium Research Institute

Mark Grosenbaugh
Walter Paul
Woods Hole Oceanographic Institution

Mark Chaffey
Monterey Bay Aquarium Research Institute

ABSTRACT

Mooring systems that deliver power and data communication to sub-sea instrumentation figure prominently in future plans to build ocean observatories. Currently, this technology is immature and technological advancements need to be made before such systems are ready to be routinely implemented. This paper describes the current state of the art in mooring systems appropriate to the deepwater ocean observatory context and outlines the technological challenges that need to be addressed in order to realize moored ocean observatories as envisioned for the next generation of ocean observing systems.

INTRODUCTION

The National Science Foundation, through its Ocean Observatories Initiative (OOI) and the ORION (Ocean Research Interactive Observing Networks) program (Isern and Clark, 2003; Colwell, 2003) is planning to invest several hundred million dollars in a far reaching plan to provide the research community with long-term, continuous access to the ocean at a wide variety of locations. These ocean observatories are divided into three geographical classes; regional, coastal, and global (or open ocean), each of which requires specialized technology not currently available to make it a reality. In parallel, NOAA, working with other U.S. agencies and international partners, is embarking on an effort to monitor the oceans operationally in a sustained and global manner. These efforts are part of the Integrated Ocean Observing System (IOOS) and the Global Ocean Observing System (GOOS) programs (Ocean.US, 2002; Nowlin and Malone, 2003). They will incorporate a wide variety of technical approaches and operating scenarios including moorings, drifters, cabled sensor arrays, ships of opportunity, and satellite and shore-based remote sensing.

Reliable and cost effective mooring technology to connect seafloor sensors to surface buoys is a key technological hurdle that must be overcome before a global array of open ocean observatories can be implemented. These connections may be electro-optic or acoustic, but to be useful in the observatory context, they must operate reliably over periods of years, must be serviceable from UNOLS ships, and must be cost efficient. While surface mooring design is a mature and reliable technology and satellite data telemetry from surface buoys is routine, the connection to the bottom has been problematic because the mooring compliance needed to survive the effects of currents, waves, and wind is incompatible with the stretch behavior of copper and fiber optic conductors. The global moored buoy array will be concentrated in deepwater and high latitudes. This implies the need for high reliability and extended servicing intervals. In addition, remote locations may require the use of expensive special-purpose ships for operation and maintenance.

Single point moorings built with electro-optical-mechanical (EOM) mooring cables and using surface following buoys are the most direct approach to the design of moored buoy observatories. Large tri-moored spar buoys that respond primarily to low frequency wave motions and are based on scaled down versions of oil industry designs are a competing and somewhat complementary approach. Acoustically linked surface moorings, which do not provide power to the seafloor and do not require EOM cables, are a third approach that may prove cost effective in situations where data throughput requirements are modest and power to the seafloor is not required. Other approaches that may have utility in the global observatory context include surface moorings that collect data from sensors on the buoy and the mooring, but do not connect to the seafloor (except mechanically), and subsurface designs that provide periodic rather than continuous data connectivity. These less capable designs may play a role in severe environments, particularly at high latitudes, or in situations with severe budget constraints.

1.1 Mooring Design Requirements

The design drivers for deepwater observatory moorings include extended service and replacement intervals, data and power delivery minimums, time keeping requirements, and vessel and ROV requirements. To be practical, remote ocean observatories must be able to operate for a minimum of one year. While annual service visits to the sites may be needed to keep instrumentation calibrated and operating optimally, it is clearly advantageous to use mooring hardware that can last several years or more.

While it is almost impossible to define a general data throughput requirement for ocean observatories, the hardwired and acoustically linked mooring approaches suggest two quite different, yet complimentary, capabilities. In an acoustically linked approach, net throughput is limited by the power needed to transmit data from in situ instruments. Using the early results from experience with acoustically linked systems at WHOI as a guide, data throughputs of several hundred Kbytes per Watt-hour are possible using existing acoustic modems. In water depths of 2500 m, this has been achieved by transmitting at 5300 bps using 5 Watts of transmit power from the modem batteries.

An important consideration for implementing a sub-sea networked observatory is the selection of the communications protocol and associated media, either copper or optical. Optical fiber communications offers clear advantages in system bandwidth and energy-per-bit calculations. Unfortunately these advantages come at a 4 times higher cost for ROV mateable underwater optical connectors over their copper counterparts. These connectors are necessary for constructing and maintaining seafloor instrumentation networks. Incorporating optical fiber in mooring cables also significantly increases the cost and complexity of the cable terminations. As an alternative, copper wire communications protocols using advanced coding technologies, such as DSL, can potentially span the tens of kilometers necessary for a sub-sea observatory at communication rates of several hundred kilobits per second. Currently, a reference design optimized for moored observatories has yet to be created and tested.

In hardwired mooring systems with optical conductors, the net throughput from the buoy to the seafloor is measured in Mbytes per second on a continuous basis. In this case, the satellite link on the surface buoy frequently provides the data-to-shore throughput limitation. However, it is still desirable to develop a high bandwidth connection to the seafloor to support radio telemetry systems in some locations, as well as to ensure the ability to archive the complete data record on the buoy for periodic retrieval.

Power generated on a surface buoy by solar, wind or diesel generating equipment is delivered to the seafloor by copper conductors in the EOM cable. Typically, the seafloor power requirements are limited to a KW or less on a continuous basis, which can be handled, with proper choice of voltage, by conductors of reasonable size (DEOS Working Group, 2000). Power systems that rely on energy harvesting from solar, wind and wave sources are limited to the order of 100 Watts for buoys of typical oceanographic research size.

Proposed sub-sea experiments such as seismic data collection require a local knowledge of the absolute time to an accuracy of 10 ms across the network and acoustic experiments routinely require absolute accuracies of 1 ms. These timing requirements are not easily achieved across a moored observatory scale local-area-network using standard network time-serving applications such as Network Time Protocol (NTP). One promising new standard that can meet this requirement across Ethernet networks is IEEE 1588, although some specialized hardware is required and must be incorporated into the system design. The ability to leverage from well established communication standards factors heavily into the choice of including optical fiber into the surface to seafloor connection.

A final general constraint on observatory mooring designs, excluding cost, is serviceability using research ships and available ROVs. Like data throughput, this requirement is hard to define and there may be exceptions to any general statement. However, in order to service and repair the instrumentation at remote ocean observatories, a fleet of cost effective ships equipped with deepwater ROVs and capable of combining science and operations is required (UNOLS Working Group, 2003). It may be possible to utilize special purpose (and expensive) ships for installing long-lived moored buoy observatories (such as large spar buoys), but yearly servicing will need to be performed in a more cost effective way and will need to include scientists and engineers involved with the observatory instrumentation.

1.2 Mooring Design Challenges

The issues that drive the design problem for observatory moorings depend on the application. In an acoustically linked observatory, existing and reliable mooring designs can be configured to meet the mooring requirements. Issues pertaining to watch circle, acoustic noise generated by the interaction of waves and the surface buoy, and location of receiving transducers and how they are back-baffled and wired back to the surface buoy must be addressed with care. However, no new mooring design technology is required to be successful. In hardwired moored observatories, three design approaches have been implemented or proposed with similar design issues. These three approaches are; 1) the single point mooring with a surface following buoy and an inverse catenary mooring using synthetic EOM cable, 2) the single point mooring with surface following buoy that utilizes subsurface buoyancy to keep most of the mooring under relatively constant tension (Clark, 2000), and 3) the large tri-moored spar buoy that integrates an EOM cable with one of the three mooring legs, or runs a fourth EOM leg that does not experience any mooring loads (DEOS Working Group, 2000). The mooring design issues are:

a.) How to provide mooring compliance for waves, currents and wind without damaging the conductors or fiber optics. This may be less of an issue in the tri-moor case since the EOM cable may not experience the main mooring loads.

b.) How to provide bending strain protection for the mechanical and electro-optical components at various points along the cable where there are floats attached, where the cable stiffness changes, or where it connects to the surface buoy or the anchor.

c.) How to design the EOM cable so that normal shipboard equipment can be used for deployment and servicing.

d.) For single point moorings, how to minimize the size, weight and cost of the EOM cable so it can be used with relatively small surface buoys and in areas with strong currents. Again, this may be less critical in a tri-moor spar design where spring buoys are used to support the main mooring loads.

2.0 Moored Buoy Observatory Designs

2.1 Conventional Mooring Designs with Telemetry

Conventional single point surface moorings can be configured to transfer data from the upper portion of the water column using inductive or hardwired techniques. The key issue in these designs is protecting the electrical cables where they pass through the air-water interface. The TAO design developed by NOAA's Pacific Marine Environmental Laboratory (PMEL) is a good example of a conventional mooring with inexpensive components that is capable of telemetering data from the upper 700 m of the water column using inductive modems (Milburn, 1996). Inductive modems have the advantage that they do not require a termination in the steel cable (unless the instrument is placed in line) and they can be used with standard, plastic jacketed wire rope. The limitation to these conventional designs is that they have no way to transfer data from sensors below the steel portion of the mooring because the nylon line cannot support the inductive telemetry. Building conductors into the nylon has not been done in traditional nylon mooring lines, though it has been done in some specialized cables used to tow gliders (Bentley, 2004). It is also possible to combine the inductive or hardwired mooring with the acoustically linked approach to cover the full water column and the area around the anchor. The inductively coupled mooring design is now a reliable and mature approach and inductive modems are available from commercial manufacturers.

2.2 Acoustically Linked Observatory Moorings

PMEL has been operating several acoustically linked surface buoys for several years using low bandwidth acoustic modems. An operational array of tsunamis warning buoys has been maintained in the Pacific for several years and has been recently transferred to NOAA's National Data Buoy Center (NDBC) for operation and maintenance (Meinig, Eble and Stalin, 2001). These

FIGEURE 1

Semi-taut, steel and nylon/polypropylene mooring design used for an acoustically linked surface mooring.

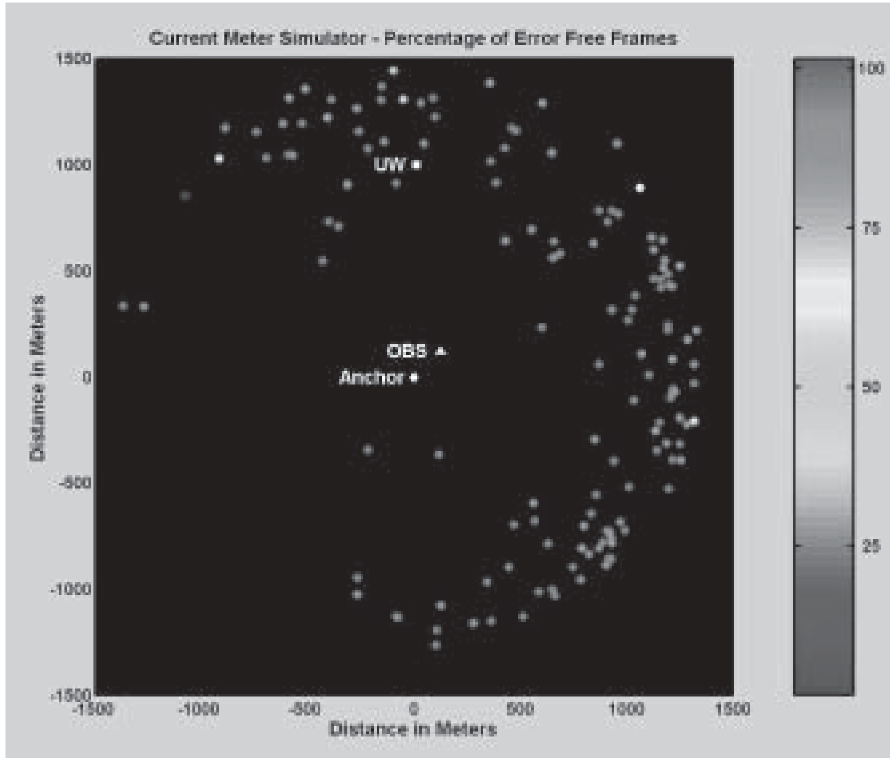
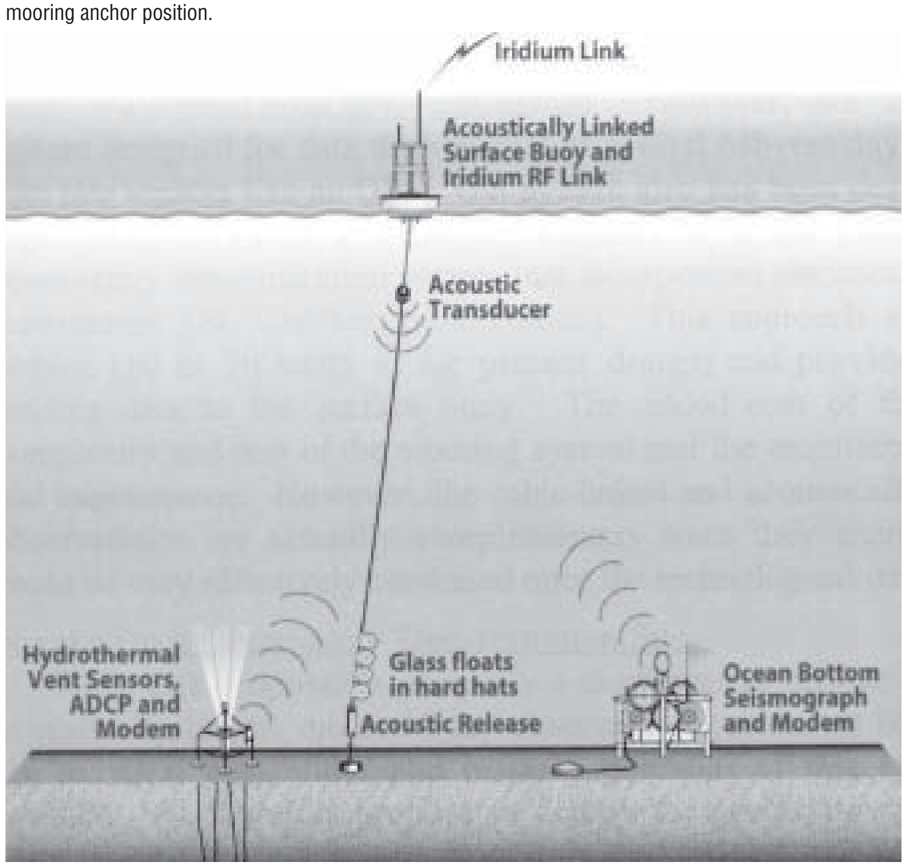


FIGURE 2

Geographical display showing a measure of the acoustic link quality as a function of location relative to the mooring anchor position.



moorings use conventional surface mooring designs and transfer small quantities of acoustic data from bottom mounted pressure sensors on a regular basis. In the event of a tsunami, they detect a small change in bottom pressure resulting from passage of the long period tsunami generated wave and forward that information to a nearby surface buoy, which then uses a satellite link to alert the system operators. PMEL also operates the NEMO observatory (Stalin, Milburn and Meinig, 2001), which is similar in design but transfers environmental and environmental data more frequently. WHOI has recently developed and tested a higher bandwidth acoustically linked observatory prototype, which is being evaluated for use in the global observatory array. It consists of a conventional surface buoy and mooring with a solar power array capable of sourcing about 10 W of power on a continuous basis in temperate regions. The surface buoy contains an acoustic modem, a controller, data storage system and dual Iridium RF links. It operates with several remote instruments by sending data requests on a schedule. The remotes, which are always listening for a data request, respond only to their specific addresses and transfer data in 2 Kbyte packets at a burst rate of 5300 bps. They use directional transducers (+/- 30 degrees pointing up) and transmit with 5 Watts of acoustic power. Missed packets are detected and re-requested. This system has been tested for a 2 month period in 2600 m of water, where it operated successfully and met its design goal of transferring about 1 Mbyte of data per day. The buoy system consumes about 5 Watts of power on average. Figure 1 shows the mooring design, which is a conventional semi-taut mooring built with wire rope, nylon, and polypropylene line. The total length of the mooring is slightly larger than the depth. It uses acoustic releases for recovery and has back-up flotation in the form of glass balls above the releases. It can be deployed and serviced from an intermediate class UNOLS ship without the use of an ROV. The system has been tested with three remote nodes, one of which is an ocean bottom seismometer, which collects large quantities of data, but the number of remotes could be much higher. The main limitation of the present prototype is the footprint on the seafloor from which data can be collected (Figure 2). Based on present directional transducers and their data rates, the acoustic footprint is limited to about the watch circle of the buoy (~ the water depth). This area could possibly be increased substantially by using a vertical array of hydrophones on the mooring coupled with a method for aiming the transducers on the remote nodes.

2.3 Single Point Inverse Catenary EOM Moorings

The most direct extension of existing mooring technology to provide the complete power and data connection to the seafloor involves incorporation of electrical and optical conductors into the mooring cable. The use of EOM cables in deep ocean surface moorings is relatively new and presents significant challenges. The combination of synthetic strength members, copper electrical conductors and optical fibers in a compatible manner is a particular challenge. The traditional cable construction techniques used for seismic tow-cables, with the conductors in the center of the cable, surrounded by the strength member holds promise, but there are significant differences between the environment of a tow cable and that of a mooring. Such a system is currently being tested in Monterey Bay by the Monterey Bay Aquarium Research Institute (MBARI) to determine whether cables of this construction will survive a mooring application for the required deployment durations. A newer concept for a mooring EOM cable being developed at WHOI uses material with a relatively low elastic modulus, such as nylon or polyester, as the cable's strength member and wraps optical fibers and copper conductors around the outside in a relatively high-angle helix pattern (all of which is covered with a protective jacket). The low-modulus synthetic strength member provides compliance for handling wave dynamics while the high-angle helix pattern protects the fibers and conductors from high strain. While this approach appears promising, laboratory testing and field deployments are necessary to validate the approach. These high-modulus and low-modulus designs are described more fully in Section 4.

2.4 Combined Surface-Subsurface Mooring Designs

Another approach for acquiring real-time data from deepwater uses a subsurface buoy and S-Tether for the link between the subsurface and surface buoy. In this design, a subsurface buoy supports the mooring cable, and a slack tether is used to connect the subsurface float to a surface buoy. Most S-Tether designs use a small surface buoy so that the forces on the tether are minimized. The tether performance is key to this approach because it must contain conductors to transfer the data from the subsurface portion of the mooring, but it must also be able to accept the bending and tension fluctuations caused by wave action. The tether must be long enough to accommodate changes in the subsurface buoy depth due to currents and not get wrapped up below the subsurface buoy. A key design element in this approach is compliance in the tether. The length and buoyancy of the tether can play a role here, hence the name S-Tether, but a compliant stretchy hose positioned just below the surface buoy is a more reliable compliance provider (see Fig. 5). An S-Tether mooring was deployed in the Labrador Sea to support an AUV dock at 500 m depth and provide a satellite connection to the vehicle when it was on the dock (Frye et al., 2002). This design is reliable, though experience with it is limited, and the mechanical and electrical details are complex. The Harris Corporation has used the S-Tether approach to connect a very large surface buoy to a subsurface mooring in the Mediterranean (Clark, 2000). The Harris buoy supports a very high bandwidth satellite link (~Mbps) and is capable of generating 30 KW of power on a continuous basis. The resulting surface buoy weighs about 50 tons and carries substantial quantities of diesel fuel. A special barge is required for deployment. Whether this approach is appropriate for moorings deployed in remote and severe environments is not known. Modeling studies of the combined surface-subsurface design suggest that this configuration is less flexible and experiences higher loads and fatigue than the inverse catenary surface mooring (Han and Grosenbaugh, 2003a, b)

3.0 Design Challenges for Single Point Surface Buoy Moorings with Power and Data Connection

Most of the deepwater mooring experience in the oceanographic community is with single point surface and subsurface buoy moorings. The difficulty in modifying these proven designs to include a power and data connection to the seafloor centers around the copper and optical conductors intolerance of stretching and bending. Typically, a traditional deepwater surface mooring system is constructed of materials that have considerable compliance, stretching as much as 10% when exposed to normal working loads typically encountered. Unfortunately, copper conductors and optical fibers fail by a variety of mechanisms when stretched repeatedly beyond about 0.5%.

3.1 Compliance Approaches

A surface mooring must have sufficient compliance to deal with excursions due to ocean currents, winds, and the heave and surge motions of its surface buoy due to waves. There are two design principles that can be used to obtain the required excess length: geometric compliance and material compliance. Geometric compliance methods include the traditional all-chain catenary mooring, which is only useful in shallow water, and a method of combining copper and optical conductors with the chain segment has not been developed.

Geometric Compliance

By increasing the scope of the mooring (so that it is 10 to 25 percent longer than the water depth), one can create a catenary shape that allows for geometric changes in the shape of the mooring line in response to the buoy wave motions. Such changes in shape help to reduce stretch in the mooring line, which, in turn, help limit mooring tensions. Cable floats attached near the seafloor prevent excess mooring line from touching the sea bottom when currents are slack. Under these conditions, the mooring line forms an S-shaped or inverse catenary loop. Typically, the inverse catenary is stretched out in all but the most benign conditions.

Material Compliance

If a mooring cable has a low enough axial stiffness, then it can provide the needed mooring compliance by stretching. In shallow water, rubber moorings, some with over 100 percent elastic elongation, are used to provide the stretch to allow a surface buoy to stay at the sea surface. In deepwater moorings, cables with considerably less elastic stretch can provide sufficient compliance if the mooring line is long enough. Single point mooring designs typically utilize both geometric and material compliance to keep the tensions in the system below the working load limits of the materials. Moorings utilizing very stiff components, such as wire rope or other high-modulus materials, require more scope than moorings that consist of low modulus materials. Nylon can stretch sufficiently to provide compliance elastically, and can be used in semi-taut moorings (scope slightly greater than 1.0) with no inverse catenary. At the other extreme, for mooring lines with high elastic stiffness, geometric compliance obtained from an inverse centenary arrangement (scope equal to 1.10 to 1.25) may not be sufficient. In this case, special low modulus sections must be incorporated into the design to provide additional compliance and reduce the peak loads.

3.2 Conductor Characteristics

For fatigue reasons, copper conductors must be kept below 0.5 percent strain, as a general rule. There are techniques for making specialized conductors with more strain tolerance, but the cost/performance ratio of these conductors is not particularly attractive. Optical fibers provide a similar strain restraint but for different reasons. The most common configuration for optical fibers deployed underwater is in very small diameter welded stainless steel tubes called K-tubes. Although the optical fibers themselves can stretch quite a bit, the steel protection tube will yield plastically at around 0.6 percent strain. When the tension in the cable is removed, this excess length can result in a kink in the tube, causing the tube to fail and ultimately causing the fiber to fail. Because the strain limits for these conductors are below the strain realized in a typical cable of even the highest modulus materials, techniques for overcoming this problem typically involve arranging the conductors in a helixed configuration.

3.3 Strength Member Material Considerations

There is a wide choice of materials suitable for supporting the mooring tensions. They range from metallic (galvanized steel wires) to high modulus and lower modulus synthetic fibers to nylon tire cords embedded in rubber hoses. The elastic modulus can vary from 10^7 psi for steel armored cables to 250 psi for rubber tethers, with the synthetic fiber reinforced cables covering a range of 40,000 to 1,000,000 psi.

Galvanized Steel Wires

Counter-helically arranged layers of galvanized steel wires form the strength members of traditional EM and EOM cables. For steel armor wires, extra improved plow steel is used, which ranges in breaking stress from 270 to 330 ksi (American Iron and Steel Institute, 1975). The counter-helical wire layers in the cable have to be carefully torque balanced to avoid kink formation when the cable load is suddenly reduced. The high weight of these cables adds significant static load at the buoy termination (a 5,000 m long suspended 3x19 oceanographic wire rope has a weight load at its upper termination of 80 percent of its working load limit, assuming a 3:1 safety factor).

High Performance Synthetic Fibers

Fibers in this group are defined as having a tenacity of at least 15 gram/denier (Cordage Institute, 1999). Their strength is similar to that of steel wires, although their modulus is typically lower, with an elongation at break of about 3 to 4 percent.

Kevlar

Kevlar fiber, introduced in 1970 by Dupont, was the first high performance fiber with a strength close to steel. Its stretch at break is about 4 percent and its specific gravity is 1.44. The fiber has very low creep, but is easily damaged by self-abrasion and by kink-band formation when bent over a small radius. The kink-band formations make it a poor choice for surface moorings.

Vectran

Vectran is a Liquid Crystal Polymer fiber introduced in the mid eighties by Celanese. It has 10 to 15 percent higher strength than Kevlar and much less tendency to form kink-bands. Under sustained loads there is no creep. Vectran is well suited for strength members in cables and ropes that are used with surface moorings. Its specific gravity is 1.40.

Spectra and Dyneema

These two fibers are spun from Ultra-High Molecular Weight Poly-Ethylene with a specific gravity of 0.98. Spectra fiber was developed by Allied Chemical, now Honeywell; Dynema was introduced by DSM, the Dutch State Mines. These fibers have high strength and high resistance to abrasion. Their disadvantage is that they creep under sustained tension. These permanent length increases make these otherwise excellent fibers unsuitable for EM and EOM cables since they will eventually overstretch the conductors.

Zylon

This fiber was developed by Dow Chemical in 1990 under the trade name PBO and is now manufactured and marketed as Zylon by a Japanese company. It is about 50 percent stronger than Kevlar and Vectran and it is the strongest fiber known. Its specific gravity is 1.53. Due to its high price, its use has so far been limited to very small cables for aerospace applications. This fiber is also very sensitive to ultraviolet radiation. Although this is not a fundamental problem for mooring systems, it does add a handling complication.

Industrial Fibers

Industrial fibers have 40 to 50 percent lower strength and higher elongation compared to high tenacity synthetic fibers. They are considerably cheaper than the high-performance synthetics and are widely used in many applications.

Nylon

Nylon was the first synthetic fiber developed in the thirties by Dupont. It is the highest stretching fiber with an elongation at break between 15 and 28 percent depending on processing. The high elongation makes it a prime candidate for semi-taut mooring cables. Due to its high stretch, the incorporation of conductors is a special challenge. Its specific gravity is 1.14, which is beneficial for moorings in deep water because it minimizes the static load due to mooring cable weight in seawater.

Polyester

Polyester, introduced in the fifties, has a similar strength as nylon, but stretches 12 to 18 percent at break depending on processing. Its stretch at maximum work load is only 3 to 5 percent after initial stretch has been removed by load cycling. Its specific gravity is 1.38, the heaviest of all industrial synthetic fibers.

Polypropylene

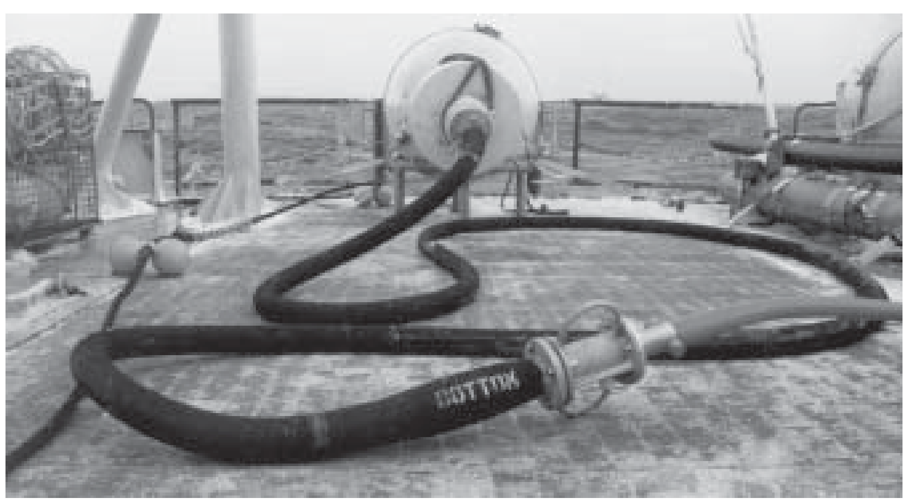
Polypropylene was introduced in the fifties and has become widely used in marine applications. It floats in seawater (specific gravity = 0.91) but has a slight tendency to creep. Its stretch behavior is similar to polyester. Due to its creep, polypropylene is less suitable than nylon or polyester for EOM cables. However, polypropylene ropes without conductors are frequently used in surface moorings to provide a combination of geometric and elastic compliance.

Nylon Cord Reinforced Rubber Hose

An alternative class of compliant mooring elements has been developed by one of the authors using reinforced rubber stretch hoses with embedded conductors (Paul, 1995). Hoses of this type (called snubbers) are connected to the bottom of the surface buoy to lower dynamic tensions. Figure 3 shows a photograph of a typical rubber hose assembly. These low modulus elements are excellent candidates for increasing the compliance of a mooring made of axially stiff mooring lines. A short length of these elements provides considerable compliance and reduces the dynamic loads in a high-modulus mooring dramatically. The ideal length of such elements is a trade-off between their weight in water and their ability to reduce dynamic loads. Modeling results indicate that snubber lengths should be less than 70 m (Han and Grosenbaugh 2003a). For conductor linkage in these elastic elements, either an internal coil cord (similar to a phone cord geometry) is used, or conductors are spiraled at a stretch neutral wrap angle inside the hose wall during fabrication.

FIGURE 3

Snubber hose (black) used with Vectran EOM mooring cable to increase the compliance of the mooring and decrease dynamic tensions in waves. Bend relief boot (orange) covers top of EOM cable and its diameter eventually tapers down to the EOM cable diameter.



The rubber hoses with molded-in couplings are a rugged and flexible design. Their main load carrying support is through two or more counter-helical layers of nylon sandwiched in the hose wall between a rubber inner liner and an outer rubber cover. A Kevlar cord layer is sometimes added as fish bite protection. The load elongation behavior is modified within a given hose size through changes of the nylon cord's wrap angle and the rubber hose's wall thickness. Stretch levels at maximum working load can be varied between 30 and 150 percent compared to at most 10 percent for low-modulus EOM cables. Stretch hose sections with conductors are currently manufactured in lengths up to 15 m, though several elements may be used together to provide the desired total length.

3.4 Cable Design Options

There are two main options for EOM cable design. The traditional technique is to locate the conductors in the core of the cable, surrounded by the strength member. A newer design consists of conductors wrapped around the outside of a center strength member. Each design has advantageous and disadvantages as discussed below.

Center Conductor Core (CCC)

The traditional method used to build steel wire armored cables is to place the conductors at the cable core and then spiral layers of the strength member around the core in a counter helical pattern. An outer extruded jacket protects the cable strength member from abrasion and corrosion. With synthetic EOM cables, all of the strength member fibers undergo stretch that is considerably more than that of the 0.5 percent limit of the copper conductors. In order to use synthetic strength members in CCC designs, excess amounts of the strength member material must be used so that its stretch under load stays below 0.5 percent. Only high modulus fibers come close to keeping the conductor and cable stretch at around 0.5 percent at maximum working load, and to do this they require safety factors of 10 or more, where a considerably smaller safety factor (3 to 5) would be sufficient for long term survivability. Lower modulus strength members (nylon and polyester) will always overstretch the electrical and optical conductors in a CCC design. The advantages of the CCC design are the large experience base that the cable manufactures have with this construction, the protection of the conductors that comes from placing them at the core. A disadvantage of an axially stiff cable is that it must be used in conjunction with a snubber hose in order to limit the mooring line tensions.

Center Strength Member (CSM)

In this design, a torque balanced braided and spliceable strength member is selected as the cable core and the conductors are spiraled around the outside of the center strength member. The proper wrap angle for the conductor layer can be calculated from the experimentally determined Poisson ratio (Paul, 1995). The conductors are embedded in a plastic layer to keep them from rubbing or slipping during cable handling. A plastic outer jacket or a textile braid cover is applied over the conductor layer to complete the cable design and protect the conductors from external abrasion. This design allows for the combination of a high-stretch strength member with low-stretch conductor elements. While a very attractive concept, experience with these designs is limited. However, work is ongoing at WHOI to develop this design further, and laboratory testing and field deployments are planned for later this year.

3.5 Bending Relief

One significant disadvantage of the inverse catenary mooring is that, in benign conditions, low tensions allow the cable freedom to bend where there is a mismatch in bending stiffness, such as at connectors and at attached underwater floats. Sharp bends at low tension appear to be capable of damaging all synthetic strength members to varying degrees.

Low Tension Bend Relief

The most dangerous periods of low mooring line tension occur when currents and winds are low and the waves are large. The light weight in water of the cable along with fluid drag associated with downward movement of the mooring line in waves allows the cable to form bends. The sharpest bends have been found to be destructive in particular for center conductor cable (CCC) designs with a Kevlar strength member. The strength member on the inside of the cable bend is compressed and forms a series of small folds or kink-bands which weaken the Kevlar strength member by up to 70% (Riewald et al., 1986).

High Tension Bend Relief

Bending of the cable can occur at the surface-float attachment point at high tensions due to sea state interaction. Cable bends can also occur in the cable section immediately above the anchor depending on how the cable is terminated. Molded plastic boots, serving as bend stiffeners and arranged over the cable next to its termination, are one method of minimizing bending of the cable at these points. A molded chain section above and below the ends of the EOM cable can also help reduce the effects of bending (Paul et al., 1994; Hamilton et al., 2003; Kemp, 2004).

3.6 Other Issues

Flotation Attachment

All of the current cable designs are denser than water and require that flotation be installed along the cable to induce the catenary shape and keep the cable clear of the bottom in calm conditions. Flotation attached to the cable introduces a point at which significant lateral loading can occur due to drag forces and the buoyancy of the flotation itself. This loading must be carefully managed to avoid fatigue damage to the cable. Dynamic modeling indicates that flotation arranged in a single sub-sea arch spanning tens of meters of the cable length results in a more stable system than "football" type floats distributed over a longer length of the cable (Hamilton, 2004). A bend-restrictor configuration insures a minimum bend radius within the flotation section. Bending strain relief boots are used to manage the transition at the ends of the floating section. This arrangement is currently being tested on the MBARI MOOS mooring in Monterey Bay and is discussed in Section 4.0.

Fishbite Protection

Damage to cables due to fishbite may be encountered in the upper 1,000 to 2,000 meters of water in the warmer portions of the world's oceans (Berteaux and Prindle, 1987; Prindle and Walden, 1975). In these regions and down to these depths, a steel armored cable or synthetic cable with an outer stainless-steel wire braid is typically used. Recently, Kevlar braids have been designed and implemented as an alternative, lighter, protection against fishbite damage. If the fishbite protection does not extend the entire length of the cable, the transition region needs to be managed carefully to avoid an abrupt change in cable stiffness. The cable dynamics at such a transition are not well understood, but there is evidence that severe bending forces may result (Hamilton et al., 2003).

Termination and In-Line Instrumentation

The termination of EOM cables must ensure integrity of the strength member and the conductors through millions of load cycles. The presence of the copper conductors and optical fibers complicates this procedure. For center conductor cable designs, there is a wealth of experience in the oil and seismic exploration industries with socketed terminations. The center strength member cables present new challenges and there is considerable work to be done to develop terminations for these cables. The desire for instrumentation in-line with the riser cable introduces many more potential termination points. Cost effective and reliable in-line terminations that allow data and power signals to be broken out of the cable currently do not exist. The center strength member cables may provide a significant advantage in this regard as the strength member itself may not have to be interrupted. Rotary slip-ring junctions for fiber-optics are expensive and the rotation characteristics of the deep-water moorings are a subject of current research with the hope that rotary junctions in these systems can be avoided.

Connection to Seafloor Networks

Because the purpose of developing these moorings is to connect to a sub-sea network of instrumentation, methods for making that connection at the seafloor using existing ROV capabilities must be addressed. MBARI ROVs have dove on the base of the prototype moorings several times in the past year and experience is being gained in working near the mooring cable with ROVs. In August 2004, MBARI intends to make the connection between a single instrument node and the MOOS test mooring with the ROV Ventana.

Deployment Handling

The usual handling techniques that are employed with wire rope and nylon rope moorings are not always directly transferable to EOM cables. These cables are much more sensitive to damage than wire rope. Issues must be carefully managed regarding spooling of the cable under tension, spooling of the cable in the correct direction relative to its construction, and adhering to the minimum bend radius of the cable. These issues do not preclude deploying these systems from UNOLS-class vessels, but training, new techniques, and perhaps specialized tools may be required. The traditional "anchor-last" deployment scenario remains attractive and early results indicate that this technique can be retained for deploying these systems, alleviating the need to have equipment and lines capable of lowering the anchor in very deep waters (Hamilton et al., 2003).

4.0 Design and Implementation of Two Single-Point EOM Mooring Prototypes

Currently, two single-point oceanographic EOM mooring design prototypes are being pursued by WHOI and MBARI. These systems differ in approach, with the WHOI system testing a low-modulus center strength member (CSM) design and the MBARI system testing a more conventional high-modulus center-conductor (CCC) design. The MBARI system was deployed in April, 2004 in Monterey Bay. The WHOI system incorporating a low-modulus CSM cable will also be deployed in Monterey Bay in December, 2004. This section presents the designs of the two EOM cables and the characteristics of the prototype moorings including the expected performance of each system based upon numerical modeling.

4.1 Cable Designs

The high-modulus cable used in the MBARI system is a Vectran EOM cable that uses a center conductor construction (CCC). This cable consists of a small interior plastic core around which six electrical conductors and four single-mode optical fibers are wrapped (two pairs each encased in stainless-steel tubes).

FIGURE 4

Cross-section of the high-modulus EOM mooring cable.

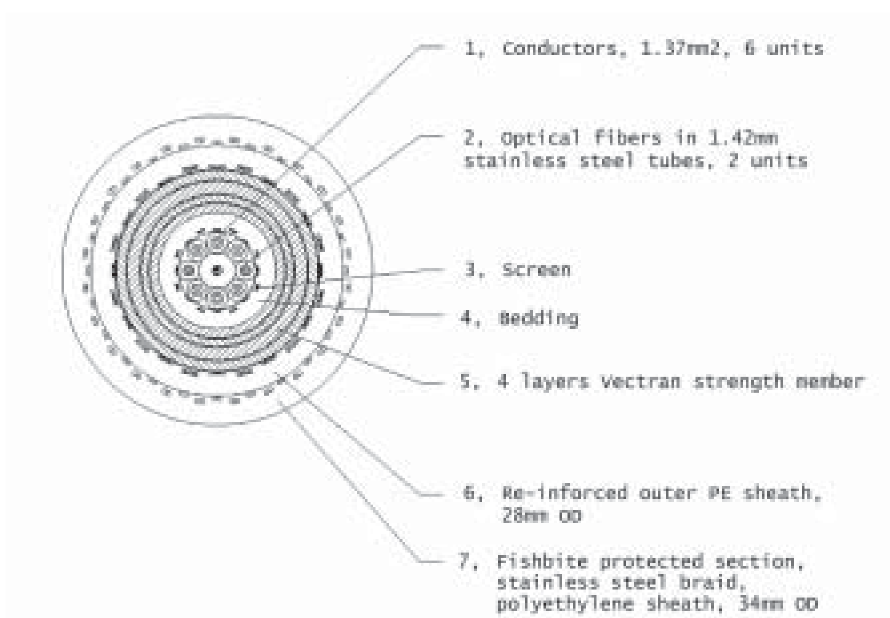
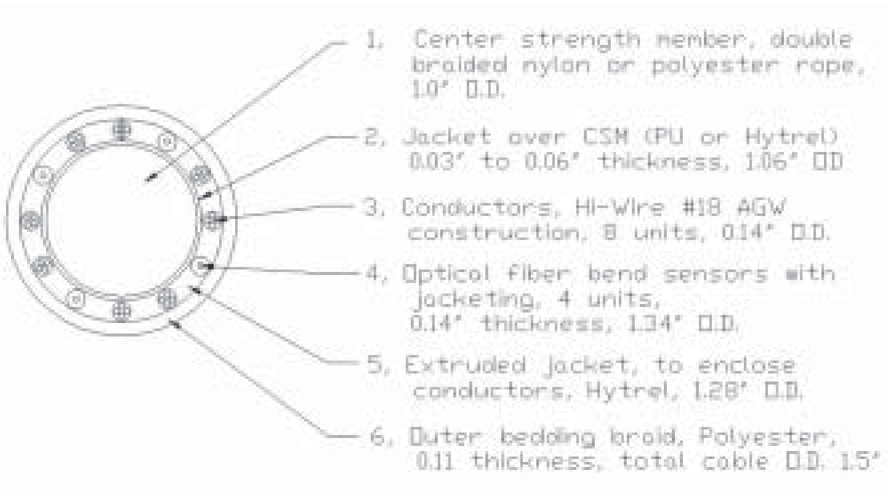


FIGURE 5

Cross-section of the center-strength-member low-modulus EOM mooring cable.



This conductor package is covered with an extruded polyethylene jacket. Four layers of Vectran fibers are helixed around the outside and serve as the strength member. The layers are laid in alternate directions for torque balancing. A second extruded polyethylene jacket covers the outside. The resulting cable (Figure 4) has a diameter of 28 mm and a breaking strength of 55,000 lbs. The section of cable that is located in the upper 700 m of the mooring has an additional outer layer made from an extruded polyethylene sheath with an embedded stainless steel braid for fishbite protection, which increases the diameter to 34.5 mm. This cable is a second generation cable, the design of which is based upon experience with a Kevlar cable of similar construction that failed in an initial deployment of this system in 2002. The failure of the first cable was found to be due to low-tension bending where flotation was attached to the cable system. Testing has shown this second generation cable to have superior characteristics in this failure mode. The mooring system itself was also re-designed as discussed below to minimize these bending effects in the system.

The design for the low-modulus EOM cable used in the system being developed by WHOI is based on a center strength member (CSM) construction with the core composed of 25-mm diameter double-braided nylon rope. A cross-section of the low-modulus EOM cable currently under test is shown in Figure 5. Numerical models of cable mechanics (Paul, 1995) show that a CSM design with conductors spiraled around it provides long-term conductor durability by keeping the conductor stretch near zero and thereby providing "conductor comfort" for long service life. The double-braided construction has the favorable property of a fairly high contraction of the diameter with increased stretch and tension. This helps to lesson the point pressure on the optical fibers, which can lead to signal attenuation and reduces the conductor wrap angle required to achieve conductor "comfort". Eight electrical conductors and four Kevlar-reinforced, single-mode optical fibers (encasing the fibers in stainless-steel tubes is still an option) are wrapped around the outside of the rope. An extruded polyurethane covering and an outer jacket of braided polyester is used to cover the conductors and fibers and increase the ease of handling. The resulting cable has a diameter of 39 mm and a breaking strength of 30,000 pounds. The upper 700 m will have fishbite protection in the form of stainless steel wires braided over the outer polyester covering, which will gradually be removed at the bottom end to minimize any bending strain concentration.

The estimated properties of the proposed Vectran CCC and Nylon CSM cables (with and without fishbite protection) are listed in Table 1. Also included are the material properties of the snubber hose that is used with the high-modulus Vectran CCC cable.

4.2 Mooring Prototype Design Specifics

MBARI MOOS Mooring with High-Modulus Center Conductor Cable

The high-modulus EOM cable mooring was deployed in a water depth of 1500 m. It incorporates a 24-meter snubber section below the buoy, a single 28 meter long floatation section, and has an overall scope of 1.25. In order to accommodate the optical and electrical conductors in the snubber section, a "coil-cord" arrangement similar in geometry to a telephone cord is used inside the hose sections of the snubber. The flotation section is made of interlocking syntactic foam elements that act as a bend restrictor with a lock-up radius of approximately 1.3 m. These floats are secured to the cable with one central clamp and the ends of the flotation section are fitted with bending strain relief boots to prevent

TABLE 1

Material properties of the different EOM mooring cables and the snubber hose, which is used in combination with the Vectran EOM cable. Weights and breaking strength are given in Newtons (1 N = 0.225 lbs.)

Cable Properties	Nylon CSM Cable	Nylon CSM Cable w/ Fishbite	Vectran CCC Cable	Vectran CCC Cable w/ Fishbite	Snubber Hose
Elastic Stiffness EA (N)	3.7 ´ 10^5	3.7 ´ 10^5	7.6 ´ 10^6	7.6 ´ 10^6	~3 ´ 10^4
Mass/length (kg/m)	0.97	1.33	0.70	1.15	17.00
Wet-weight/length (N/m)	0.95	3.28	0.64	2.06	21.96
Diameter (m)	0.039	0.039	0.028	0.034	0.1334
Normal Drag Coef.	1.5	1.5	1.5	1.5	1.5
Tang. Drag Coef.	0.01	0.01	0.01	0.01	0.01
Breaking Strength (N)	133,500	133,500	244,000	244,000	85,000

violating the minimum bend radius of the cable at this point. This mooring supports a connection to a sub-sea network of instrumentation through an ROV mateable electrical and fiber-optic connector.

WHOI Mooring with Low-Modulus Center Strength Member Cable

The low-modulus EOM cable mooring being developed by WHOI will be deployed in a water depth of about 3000 m and have a scope of 1.2. Beneath the surface buoy a universal joint will be installed through which electrical and optical cables are passed to a 6 m molded chain assembly (made with 19-mm chain with an inner rubber hose that acts as a mandrel for the conductors and an outer rubber hose that protects the assembly). The bottom of the molded chain is connected directly to the top of the EOM cable with the electrical connections protected within the molded chain assembly. Syntactic floats are attached to the cable about 300 m above the bottom end to reduce the chance that the cable will interact with the bottom. These floats will provide about 220 lbs. of buoyancy. Their shape and the specifics of how they will be tied to the cable are not completely defined at this time. At the bottom of the EOM cable, the conductors are connected to a molded chain similar to the one at the top of the mooring. The lower molded chain will have a syntactic float with about 110 lbs. of net buoyancy at the upper end to keep the chain from interacting with the bottom in slack currents.

4.3 Mooring Simulations

For the numerical simulations, we used a water-depth of 3000 m and a scope of 1.2 for both moorings. For the MBARI mooring, this was achieved by increasing the length of the EOM cable above the long floatation section, which was located in-line about 400 m above the sea bottom. Figures 6 and 7 and Table 2 show the results of static and dynamic analysis of the high-modulus Vectran EOM cable mooring and the low-modulus nylon EOM cable mooring. The static and dynamic response of the mooring configurations was obtained using WHOI Cable, a general-purpose numerical code for calculating the static and dynamic response of moored and towed oceanographic systems (Gobat and Grosenbaugh, 2000). For this application the code was used in two dimensions to analyze the statics due to wind and currents and the dynamics due to the passage of ocean waves. The wave calculations assume that the vertical displacement of the surface buoy follows the wave elevation, which is described by the Modified Pierson-Moskowitz spectrum. For the analysis, a hypothetical mooring site in the North Pacific Ocean near the Juan de Fuca mid-oceanic ridge was chosen. A 25-year return period storm was chosen with wind speed of 26 m/s , a significant wave height of 14.0 m, and a peak wave period of 21 s. The current profile decreases from 1 m/s at the surface to 0.5 m/s at 200 m and then decreases further to 0.1 m/s at 3000m.

The static results indicate that the horizontal offset (Figure 6) depends on the elastic stiffness, EA, of the EOM cable. The elastic stiffness determines how much the mooring scope will increase due to stretch of the mooring line. The largest horizontal offset corresponds to the low-modulus EOM cable while the smallest offset corresponds to the mooring with the Vectran EOM cable. This is because the nylon mooring line stretches 184 m under these forcing conditions, while the Vectran/snubber system only stretches 22 m. Over half of the stretch in the Vectran/snubber mooring is taken up by the snubber, which itself stretches over 50% of its length (12.7 m of stretch). The mean tensions (Table 2), which depend on wind, current, and waves, are a function of the wet-weight, elastic stiffness, and the diameter of the mooring cable. The mean tensions of the high-modulus Vectran/snubber mooring are slightly higher than the mean tensions of the low-modulus nylon mooring, principally due to the strain hardening of the snubber hose at large tensions.

The dynamic response in a severe sea state shows the low pass filter characteristics of moorings constructed with nylon EOM cable compared to a mooring constructed with Vectran EOM cable and a snubber hose (Figure 7). The dynamic tension at the anchor of the nylon mooring is significantly reduced from that at the surface buoy (Table 2). The dynamic tension at the anchor of the Vectran mooring is actually increased compared to the dynamic tension at the surface buoy. While the snubber accommodates the wave motion and helps lower dynamic tension at the buoy, it is not successful as a low pass filter because of its short length.

FIGURE 6

Static configuration of moorings using different types of EOM cable.

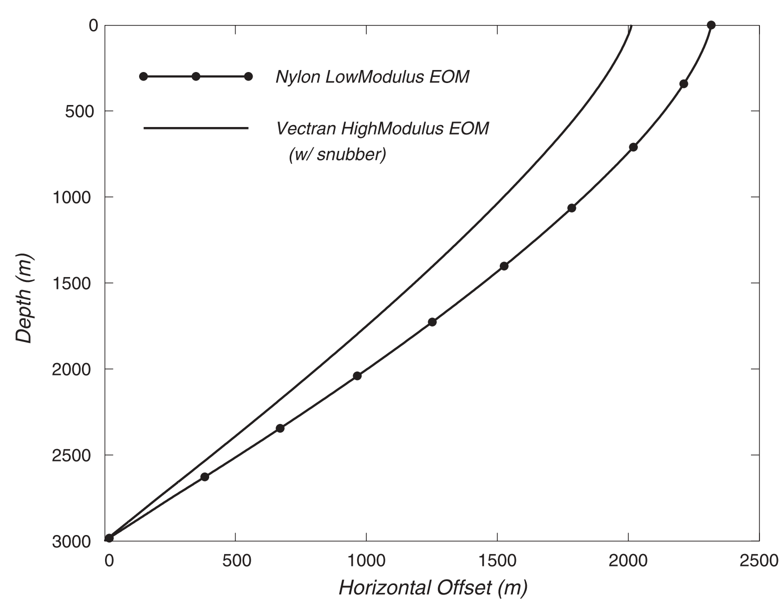
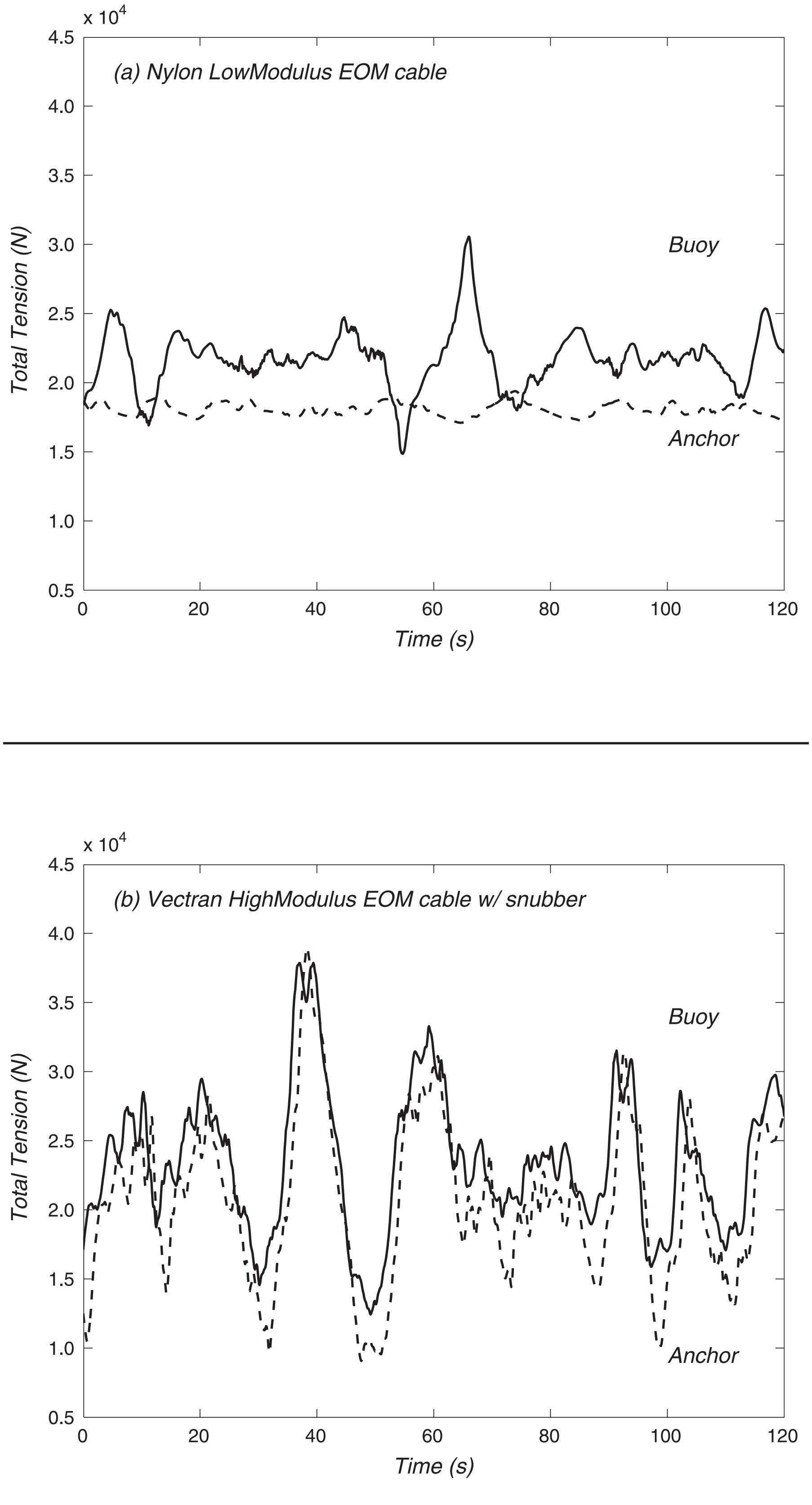


FIGURE 7

Total tensions at surface buoy and anchor of a cabled observatory mooring made up of a nylon EOM cable (top) and a Vectran EOM cable plus snubber hose (bottom). The input is a random sea with significant wave height of 14 m and peak period of 21 s.



The nylon mooring has the lowest dynamic and total tensions (Table 2) at both the anchor and the surface buoy. Again, much of the dynamic tension in the high-modulus Vectran mooring under these extreme conditions comes from the hardening of the snubber hose, which has a maximum stretch of just over 60%. Still, the maximum stretch of the Vectran EOM cable under these conditions is 0.6%. In contrast, the maximum stretch in the nylon EOM cable is 9.1%.

5.0 Other Conceptual Designs for Moored Observatories

Several additional mooring concepts have been proposed for deepwater ocean observatories. These concepts range from large tri-moored spar buoys to small subsurface moorings equipped with data capsules for periodic data delivery. The utility of each approach depends on the requirements for data delivery, power delivery, and the environment that is anticipated at the deployment site. The British DEOS planning group has proposed the deployment of large spars in the Southern Ocean using oil industry construction and deployment methodologies (Boyle and McCarthy, 2001). A group in the U.S. led by Scripps Institution of Oceanography has proposed a similar design to support high bandwidth C-Band satellite communications (DEOS Working Group, 2000). The advantage of the spar design is two-fold. First, the spar provides a stable platform in heave and rotation, typically reducing the heave by 50% or more depending on its size, and reducing rotation to a few degrees. The rotational stability may be important for the satellite communications system because it minimizes the dynamic pointing requirements of the large dish antenna. This may be of less importance with newer Ka band satellite equipment that is sized more appropriately for surface buoys. Second, the tri-moor design uses large synthetic mooring lines that are designed for a ten-year lifetime. While this approach may require the deployment of these systems from special purpose ships, they could be maintained with UNOLS vessels. The presumption, based on experi-

TABLE 2

Summary of the predicted response of moorings made with Nylon and Vectran EOM cables in 25-year storm conditions. The maximum dynamic tension is defined as 4 times the standard deviation of the tension response. The maximum total tension is the sum of the mean tension and the maximum dynamic tension.

	Nylon EOM Cable	Vectran EOM Cable w/ Snubber
MEAN TENSION		
Surface Buoy	21,600 N	23,200 N
Anchor	18,100 N	20,400 N
MAXIMUM DYNAMIC TENSION		
Surface Buoy	8,400 N	20,500 N
Anchor	1,900 N	23,100 N
MAXIMUM TOTAL TENSION		
Surface Buoy	30,000 N	43,700 N
Anchor	20,000 N	43,500 N
MAXIMUM CABLE STRAIN		
Top (below surface buoy	0.091	0.006
Bottom (above anchor)	0.067	0.006

ence with much larger spars used as oil storage facilities, is that they would survive the severe weather in the high latitudes better than a large single point mooring. The trimoor design is substantially more expensive than a single point mooring, it requires the use of large surface buoys to withstand current forces, and the EOM cable path is an open issue. However, if the spar design were to perform reliably for ten years, then the cost comparison with single point moorings is favorable.

Large surface buoys moored with single point moorings were investigated as an alternative to the large spar buoys for supporting C-Band satellite dishes and large diesel generators (DEOS Working Group, 2000). From the mooring perspective, 5 m buoys, scaled directly from the 3 m design currently in use, do not present a serious design problem. The mooring loads are only slightly higher than conventional surface moorings since the displacement of the surface buoy has only a small effect on the mooring line tension. The primary source of added tension arises from the additional windage on the buoy. The logistical issues are more problematic. UNOLS ships cannot carry more than one or two 5 m discus type buoys and they would need to have additional lifting capability to launch them. Deck load issues may also be important.

At the opposite end of the performance and size spectrum is the subsurface mooring with periodic data delivery. This approach is aimed at reducing the cost of data collection and allowing measurements to be made at locations where the conditions may be too severe for surface moorings. The subsurface telemetry scheme has limited data throughput and the system cannot provide surface meteorological data, but it can provide data from the water column and the seafloor and it can be used even in locations with seasonal ice cover or extreme currents. A prototype system of this type has been built and tested by one of the authors (Frye, Hogg and Wunsch, 2002). It is a subsurface mooring with instruments deployed along the mooring line. Acoustic modems are used to collect the data at a central point where the data are loaded into ten expendable data capsules. The capsules contain memory, an Iridium transceiver, and 4 lithium batteries. The mooring is designed for a 5-year service life and capsules are released at 6-month intervals over the 5 year period. The initial test of this system was conducted offshore Bermuda from Nov, 2001 to Feb, 2004 and it performed very well. A 5-year deployment is scheduled for July, 2004 offshore of Greenland. Data throughput of the system is of the order of 10 Kbytes per day over the 5 year period. However, much higher throughputs are possible using similar technology. In fact, we are working on a data capsule system using Iridium, which will have a throughput capacity of about 100 Mbytes per capsule with capsule costs of about $5,000.

6.0 Discussion

Mooring designs for ocean observatory science range from small subsurface designs that send limited quantities of data to shore on a periodic basis to large tri-moored spars buoys that are capable of supporting high bandwidth satellite links. The scientific issues that can be addressed by each of these approaches and the cost, complexity and reliability of the designs are still very much in the evaluation stage. The key distinction between these real-time systems and the more conventional approaches that have been employed by the oceanographic community over the last 40 years is that they provide connectivity and power delivery to/from *in situ* seafloor instrumentation. The question that the oceanographic community needs to answer is which approaches can be engineered to meet the reliability requirements while remaining cost effective.

Projects whose goals are to develop special EOM cable and mooring techniques that are compatible with traditional mooring designs for single point surface moorings are underway at MBARI and WHOI. The rationale for maintaining backward compatibility is to take advantage of the experience the community has installing and maintaining these kinds of systems. This approach reduces the number of unknowns in the cost estimates and means that a variety of research ships can be used to maintain the observatory arrays. If these projects are successful at developing fully capable systems that are reliable over deployment periods of 3 to 5 years in a range of environments, then a major technical hurdle standing in the way of deepwater observatories will have been cleared. It is anticipated that these systems would have the capabilities needed for a majority of the locations and science plans envisioned for the global moored array. To accomplish this goal, we need to do more than build and test mooring and cable designs. We also need cable termination techniques, testing and acceptance protocols, methods for connecting and disconnecting seafloor arrays from surface moorings, and methods for recovering and re-deploying surface moorings with seafloor arrays developed in parallel with the mooring design work.

Systems capable of operating at high latitude and in other severe environments, such as ice-covered seas and areas with extreme currents, have yet to be developed. The roles of acoustically linked observatories and subsurface moorings with periodic data return in these applications will depend on issues of capability, reliability, and cost effectiveness. For all of these fixed systems, installation, maintenance and repair methodologies need to be determined. This will require continuing effort from the vessel operators, ROV operating groups, and mooring designers. High bandwidth moorings—such as large spar buoys, capable of surviving and operating in high sea states and providing large amounts of power—need further evaluation from the perspectives of life cycle costs, service and maintenance requirements, and science utility.

7.0 Acknowledgements

The authors gratefully acknowledge funding from the David and Lucille Packard Foundation, the National Science Foundation under awards OCE-0337888 and OCE-0215670, and from the Woods Hole Oceanographic Institution. The development of WHOI Cable was funded by the Office of Naval Research (Ocean Engineering and Marine Systems).

References

American Iron and Steel Institute, Steel Products Manual. 1975. Wire and Rods, Carbon Steel, Washington DC, p. 70.

Bentley, D. 2004. Designing Cables for Survivability in the Dynamic Marine Environment, Concept and Case Studies. Presented at the ONR/MTS Buoy Workshop, St. Petersburg, FL, March 8-10, 2004.

Berteaux, H. O. and B. Prindle. 1987. Deep Sea Moorings Fishbite Handbook, WHOI Technical Report WHOI-87-8, pp. 93-117.

Boyle, E. and S. McCarthy. 2001. Dynamics of Earth and Ocean Systems (DEOS) Moored Buoy Ocean Observatories Design Study, Kvaerner E&C Australia Pty Ltd., 57 pp.

Chaffey, M., E. Mellinger and W. Paul. 2001. Communications and Power to the Seafloor: MBARI's Ocean Observing System Mooring Concept. Proc. MTS/IEEE Oceans '91.

Chaffey, M., J. Erickson, M. Kelley, G. Massion, L. McBride, E. Mellinger, W. Radichonski, J. Ryan, and K. Raybould. 2002. MBARI Ocean Observing System Update, MOOS Mooring System, Presented at the ONR/MTS Buoy Workshop 2002, Seattle, WA, Apr. 9-12, 2002.

Clark, A. M. 2000. Deep Sea Observatories. MTS J. 33(4).

Colwell, R. R. 2003. Ocean Research Interactive Observatories Network (ORION): Planning for the Future of Ocean Science at the National Science Foundation. MTS J. 37(3):15-17.

Cordage Institute, CI Guideline 2003, October 1999, Fibers for Cable, Cordage, Rope and Twine, Wayne, PA. [**are dates correct? – October 1999?**]

DEOS Moored Buoy Observatory Working Group. 2000. Moored Buoy Observatory Design Study. August 2000. 102 pp.

Detrick, R. S., J. A. Collins, L. Freitag and D. E. Frye. 2002. Development and Testing of a Deep-Water, Acoustically-Linked, Moored-Buoy Seafloor Observatory. Proposal submitted to the National Science Foundation by Woods Hole Oceanographic Institution, WHOI Prop. No. GG1122.00, January 24, 2002.

Frye, D. E., J. Kemp, W. Paul and D. Peters. 2001. Mooring Developments for Autonomous Ocean-Sampling Networks. IEEE J Oceanic Eng. 26(4):477-486.

Frye, D., N. Hogg and C. Wunsch. 2002. New-generation Mooring System Allows Longer Deployment. EOS, Transactions, AGU. 83(34):370-371.

Gobat, J. and M. Grosenbaugh, 2000. WHOI Cable v2.0: Time Domain Numerical Simulation of Moored and Towed Oceanographic Systems. Technical Report, WHOI-00-08. Woods Hole, MA: Woods Hole Oceanographic Institution.

Hamilton, J. A., M. Chaffey, E. Mellinger, J. Erickson and L. McBride 2003. Dynamic Modeling and Actual Performance of the MOOS Test Mooring. Proc. Oceans 2003, pp. 2574-2581.

Hamilton, J. A. 2004. The MOOS EOM Mooring: In-situ Instrumentation and Shore-Side Cable Testing. Presentation at the ONR/MTS Buoy Workshop 2004, St. Petersburg, Florida.

Han, S. and M.A. Grosenbaugh. 2003a. Comparison of Two Seafloor Observatory Mooring Designs, Proc. IUTAM Symposium on Integrated Modeling of Fully Coupled Fluid-Structure Interactions Using Analysis, Computations, and Experiments, Piscataway, NJ.

Han, S. and M.A. Grosenbaugh. 2003b. Bending Fatigue Analysis of Seafloor Observatory Moorings, ASME Proc. Offshore Mechanics and Arctic Engineering Conference, Cancun, Mexico.

Heinmiller, R. H. 1973. Details of Woods Hole Moorings. WHOI Tech. Rpt. 73-71, Oct. 1973.

Isern, A. R. and H. L. Clark. 2003. The Ocean Observatories Initiative: A Continued Presence for Interactive Ocean Research. MTS J. 37(3):26-41.

Kemp, J. 2004. WHOI Experience with Electromechanical Chains on Surface Moorings. Presentation at the ONR/MTS Buoy Workshop 2004, St. Petersburg, Florida

Meinig, C., M.C. Eble and S.E. Stalin. 2001. System development and performance of the Deep-ocean Assessment and Reporting of Tsunamis (DART) system from 1997–2001. Proc. International Tsunami Symposium 2001, pp. 235-242, Seattle, WA, 7–10 August 2001.

Milburn, H. B., P. D. McLain and C. Meinig. 1996. ATLAS Buoy- Reengineered for the next decade. Proc. Oceans'96, pp. 698-702, 23-26 Sept. 1996.

Nowlin, W. D. and T. C. Malone. 2003. Research and GOOS. MTS J. 37(3):42-46.

Ocean.US. 2002. An Integrated and Sustained Ocean Observing System (IOOS) for the United States: Design and Implementation. Ocean.US, Arlington, VA, 21 pp.

Paul, W., A. Bocconcelli, M. Grosenbaugh. 1994. Drifting Buoy Systems Using Elastic Rubber Stretch Hoses. Proc. BOSS'94 Behavior of Offshore Structures, Vol. 2, pp. 213-225.

Paul, W. 1995. Design Considerations for Stretch Conductors in Oceanographic Moorings. Technical Report, WHOI-95-15. Woods Hole, MA: Woods Hole Oceanographic Institution.

Paul, W., D. Bentley, M. Chaffey and D. Frye. 2003. Electrical and Electro-Optical Mooring Links for Buoy Based Ocean Observatories. Proc. 3rd International Workshop on Scientific Use of Submarine Cables and Related Technologies, pp. 201-206, 25-27 June 2003, Tokyo, Japan.

Prindle, B. and Robert G. Walden. 1975. Deep-Sea Lines Fishbite Manual. Stennis Space Center, MS: NOAA National Data Buoy Center.

Riewald P. G., R. G. Walden, A. S. Whitehill and A.S. Koralek. 1986. Design and Deployment Parameters Affecting the Survivability of Stranded Aramid Fiber Ropes in the Marine Environment. Proc. Oceans'86, pp. 284-293.

Stalin, S.E., H.B. Milburn and C. Meinig. 2001. NeMONet: A near real-time deep ocean observatory. Proc. 2000 MTS/IEEE Conf., pp. 583-587, Providence, RI, 11–14 September 2000.

UNOLS Working Group on Ocean Observatory Facility Needs. 2003. Ocean Observatories Initiative Facilities Needs from UNOLS. Dec. 2003. 53 pp.

Walz, M. A., R. L. Boy and D. R. May. 1989. NDBC Mooring Design Manual. U. S. Dept. of Commerce, NOAA, National Weather Services, NDBC, Dec. 1989, 53 pp.