

# Cabled Ocean Observatories in the Sea of Oman and Arabian Sea

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**Abstract**— As the global population grows and becomes increasingly dependent on the ocean’s resources, monitoring its physical and environmental conditions is more critical than ever: port authorities may wish to know tidal and current velocity information in order to schedule and guide shipping traffic; offshore drilling operators need real-time current velocities to determine the safety of their operations and to avoid costly delays; government ministries use knowledge of physical and biological conditions to manage and monitor the health of their fisheries resources and protect the people that use the ocean for recreation and income; coastal communities can greatly benefit from advance warning of approaching tsunamis; and coastal developers are often required to assess the impact of their developments on coastal water flow and quality. Ocean observation is clearly important to the modern world, yet many key regions of the ocean remain virtually uncharacterized and unmonitored. One such region is the northern Arabian Sea and the Sea of Oman. Since 2003, Lighthouse has worked to develop, install, and operate cutting-edge, real-time ocean observing and monitoring systems off the coast of the Sultanate of Oman.

**Keywords**- ocean observation; cabled seabed systems; tsunami warning systems; oceanographic monitoring; oil pollution; ocean engineering; ocean environmental monitoring; fisheries health; Oman; Arabian Sea; Indian Ocean

## I. IMPORTANCE OF MONITORING IN THE SEA OF OMAN

Seasonal monsoonal winds are known to drive the northeastern Arabian Sea waters and to cause intense upwelling along the southern coast of Oman [1], but less is known about the general circulation and variability of the Sea of Oman. The Sea of Oman is located in an important region separating the Persian Gulf (aka Gulf of Arabia) from the Arabian Sea at the Strait of Hormuz (Figure 1); nearly one-third of seaborne-traded oil passes through the Strait [2]. The Sea of Oman is also a rich fishing resource for the Sultanate, thus environmental data are particularly relevant for characterizing water quality parameters. Waters from this region also mix with those from the Red Sea and feed into the Indian Ocean. A general description of the current regime of the region is not fully developed, and many uncertainties regarding basic processes remain [3].

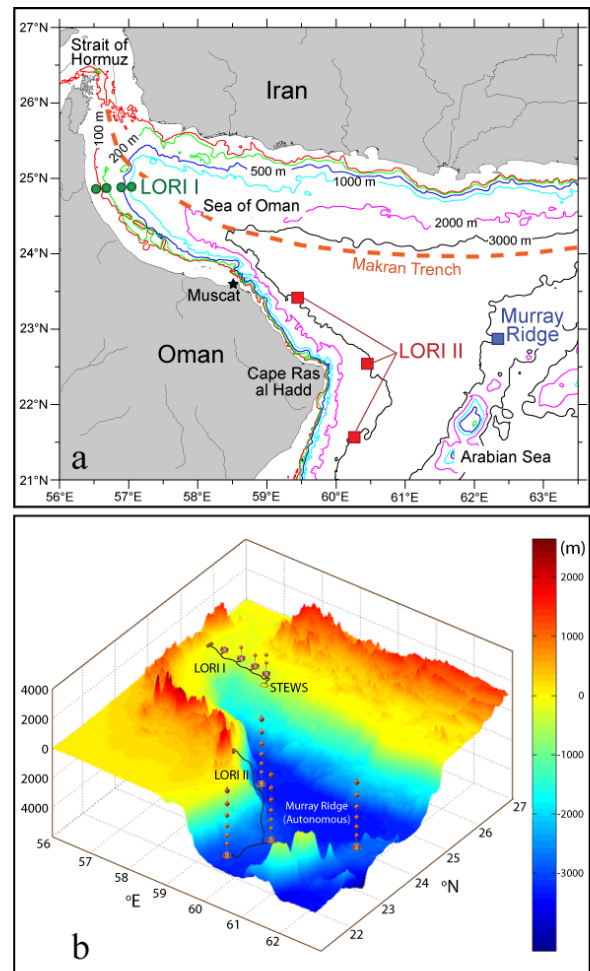


Figure 1. Location map of the moorings that comprise LORI I and LORI II and the Murray Ridge autonomous mooring. The STEWS system is located near the easternmost LORI I mooring. Seismicity along the Makran Trench (dashed orange line) has triggered tsunamis in the historical past. b. 3D location map of the arrays and moorings showing topography / bathymetry (units are in meters).

## II. OCEAN OBSERVING AND MONITORING SYSTEMS IN USE TODAY

Sustained, integrated, and operational ocean observatories are part of the long-term strategies of national and global initiatives such as the National Science Foundation's Ocean Observatories Initiative, National Oceanic and Atmospheric Administration's (NOAA) Integrated Ocean Observing System, and the World Meteorological Organization's Global Ocean Observing System. Most permanent or long-term ocean observing systems involve the use of moored instruments, which allow for placement of the instruments at fixed locations anywhere in the water column. Data are retrieved from the moored instruments in delayed mode – instruments are recovered periodically and data is downloaded – or in real time. Real-time data transmission is achieved by either acoustic modem communication between the instruments and a surface buoy, which in turn relays data via satellite to a fixed shore location, or it may occur via fiber-optic cable directly to shore, where data are then transmitted via local internet or satellite to the end user. Buoyed systems are powered by solar panels and/or batteries; power to equipment in cabled systems is usually fed by the local utility grid, diesel generators, or by solar panels (in the case of systems with limited power demands), depending on the remoteness of the site. In contrast with surface-buoyed systems, fiber-optic cabled systems offer several advantages: power can be delivered to instruments by copper casing around the cable, eliminating the need for batteries; nearly unlimited power to cabled systems permits any desired instrument configuration allowing for full characterization of the water column; cable provides virtually unlimited bandwidth for continuous data transmission whereas satellite communication is typically more limited and intermittent; completely subsurface, cabled equipment circumvents the possibility of weather damage and theft and vandalism of the near surface and surface-exposed equipment; the use of acoustic modems, which are slow and severely bandwidth limited, is eliminated; and the nearly unlimited bandwidth in cabled systems available for data acquisition and transfer ensures data are received quickly and reliably.

Most of the world's tsunami warning systems depend on a bottom pressure sensor to detect a passing tsunami wave; data are transmitted via acoustic modem to a surface buoy that relays information via satellite to a local or regional tsunami monitoring center (e.g., NOAA's Deep-ocean Assessment and Reporting of Tsunami stations [4]). The acoustic modem remains dormant or transmits data intermittently most of the time; when a tsunami wave passes overhead, the modem is triggered into event mode and begins to transmit data more frequently for a pre-specified length of time. Instrumentation consists of a sensitive bottom pressure recorder that monitors changes in wave height and is capable of detecting a passing tsunami wave even in the open ocean; an ocean bottom seismometer, buried subsurface, which records seismic activity that often precedes a tsunami, may also be part of the instrumentation. Although not commonly in use, tsunami warning systems may be cabled to the shore, thus avoiding the use of a surface buoy.

## III. LIGHTHOUSE'S CABLED OCEAN OBSERVING SYSTEMS

Since 2003 Lighthouse R & D Enterprises, Inc. has worked to develop environmental monitoring systems suited for a wide spectrum of marine environments. Lighthouse uses cutting-edge technology to provide real-time data to industry and entities with vested and multiple levels of interest in marine environments. The real-time system uses a fiber-optic cable backbone for instantaneous data transmission anywhere the customer desires via either local telecommunication lines or satellite. Lighthouse's systems are designed with full duplex capability which allows for monitoring the health of the instruments and the system from Lighthouse offices in Houston. Duplex capability also allows for modification of sampling rates, troubleshooting, or rebooting to be performed on the instruments from the Lighthouse offices.

The fiber-optic cable is encased in copper for electric power delivery that flows continuously to the instruments and simultaneously charges a bank of capacitors for each instrument. The capacitors accumulate charge in between sampling periods to provide an extra burst of energy that can be used during the sampling phase. With the continuous transmission of power, the need for short-lived batteries is eliminated and surface buoys are not required for hosting batteries or solar panels to feed power to the instruments. The fiber-optic cable is connected to an unmanned shore facility which uses local utility power, generators, solar panels or a combination of these energy sources (Figure 2). An uninterrupted power supply and backup diesel generators ensure continuous delivery of electricity to the system.

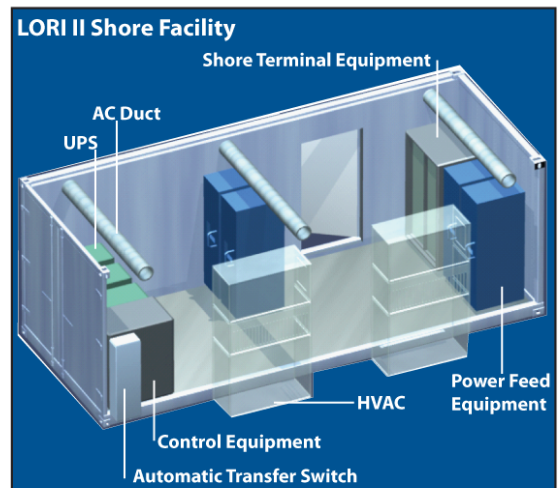


Figure 2. Design of the climate-controlled equipment container for the unmanned shore facility at LORI II. A UPS (within the container) and two diesel generators (exterior to the container) provide backup power in the event of a local power outage. The container is 20 feet in length.

## IV. LIGHTHOUSE'S ORIGINAL CABLED OBSERVATORY

Lighthouse's flagship system is a cabled ocean observatory off the northern coast of Oman that has been obtaining data hourly since mid-2005. This system, dubbed the Lighthouse Ocean Research Initiative (LORI I), records hourly current

velocities, pressure, temperature, conductivity, derived salinity, dissolved oxygen and turbidity at depths ranging from ~67 m to ~1050 m (Figure 3). Data is instantaneously transmitted via fiber optic cable to an unmanned shore facility, where it is then telemetered back to Lighthouse headquarters in Houston, TX, via satellite and dedicated telecommunication lines. The LORI I system consists of four nodes serving four moorings; on these moorings a total of eight Aanderaa Instruments recording Doppler current profilers at a frequency range of 600 Hz (RDCP600) are hosted; the profilers read current velocities above the instrument to a distance of about 50 m. Each RDCP600 is fitted with additional sensors to capture the parameters listed above. This system is rated for water depths up to 2000 m. In 2007 another 20 km of cable was added and a fifth node was installed, extending the system to 1350 m, and expanding it to incorporate a seismic tsunami early warning system (STEWS) developed in collaboration with Woods Hole Oceanographic Institution. The successful installation of the fifth node and different instrumentation demonstrated the expandability and upgradability of the system architecture (i.e., plug and play).

deepwater system was chosen for its dynamic circulation features, where water from the Arabian Sea, the Red Sea, the Persian Gulf, and the Sea of Oman all converge. The deepwater LORI II cabled moorings each consist of a 2500 m string hosting seven RDCP600s and one RD Instruments Acoustic Doppler Current Profiler Workhorse Long Ranger (hereafter ADCP). As in the LORI I array the RDCPs have additional sensors to measure other water properties. The lower six of the seven RDCPs profile current velocity above the instrument to about 50 m, the seventh profiler points downward recording current velocity with a vertical range of 50 m, and the ADCP at the top measures the upper 500 m of water above the mooring string (Figure 4). The deep water system is rated to 4000 m; a full ocean (4000 – 6000 m) system is in the planning stage.

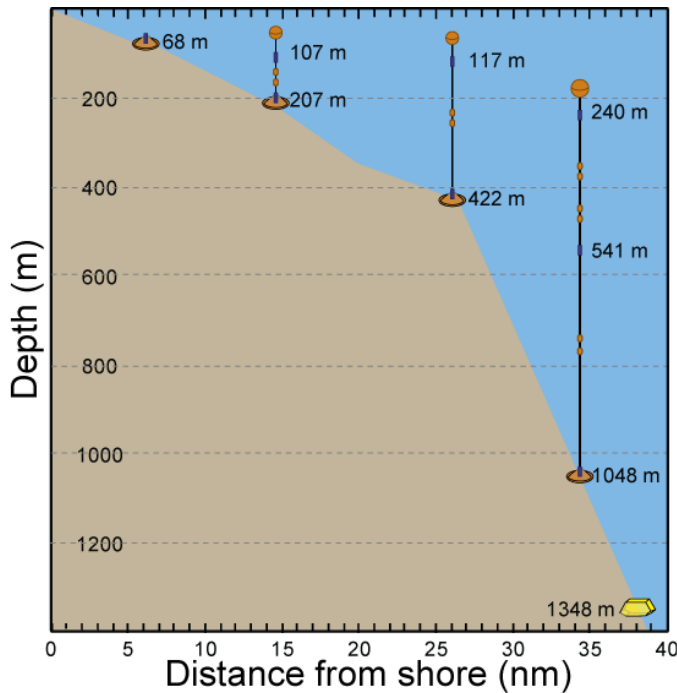


Figure 3. Distance from shore and depth of each mooring base (orange cones) and the STEWS (yellow) on the LORI I Array. Current profilers (blue rectangles) are located within the base of each mooring; additional current profiler depths are indicated adjacent to the instruments. Mooring bases, instruments, and floats are exaggerated in size and the cable and nodes not shown for clarity.

### V. LIGHTHOUSE'S DEEPWATER OBSERVING SYSTEM

In January 2010 Lighthouse cabled a second, deepwater observatory that had previously existed since 2005 as three autonomous mooring strings set along the 3000 m depth contour line off the coast of Cape Ras al Hadd, Oman. A fourth mooring – installed on the Murray Ridge, ~300 km to the east of Sur, Oman – remains autonomous. The location for the

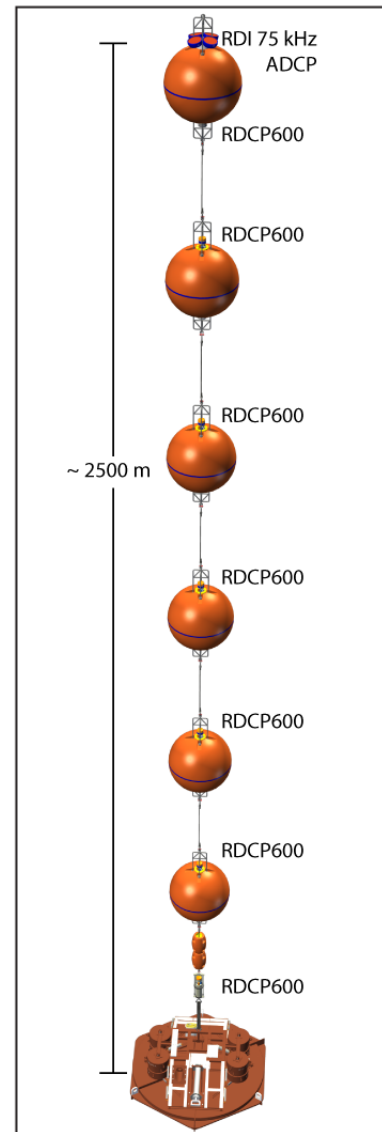


Figure 4. Design of the LORI II moorings, floatation, and instruments. The bottom six RDCP600s profile above the instruments, approximately 50 m into the water column. The top RDCP600 profiles downward. The ADCP at the

top of the string capable of profiling nearly the entire upper 500 m of the water column.

## VI. LIGHTHOUSE'S SEISMIC TSUNAMI EARLY WARNING SYSTEM

The coastal population of Oman is vulnerable to tsunamis. In 1945, a tsunami was triggered by seismic activity along the nearby Makran Trench and damaged several ports with water run up of 2-3 m [5]. The Omani coast was also impacted by the 2004 Indian Ocean tsunami that claimed more than 250,000 lives across the northern Indian Ocean. In response, UNESCO's Intergovernmental Oceanographic Commission encouraged the formation of the Indian Ocean Tsunami Warning System, and Oman participated in the development stages. Lighthouse and scientists at Woods Hole Oceanographic Institution began to develop a seismic tsunami warning system to add to their existing cabled observing system in 2006. The goal was to create a system that could deliver real-time seismic and ocean pressure data that are suitable for use by regional warning centers. The result of this effort was STEWS which consists of an ocean bottom broadband seismometer, buried subsurface, and an accelerometer, bottom pressure sensor and differential pressure gauge contained within trawl-resistant housing (Figure 5).

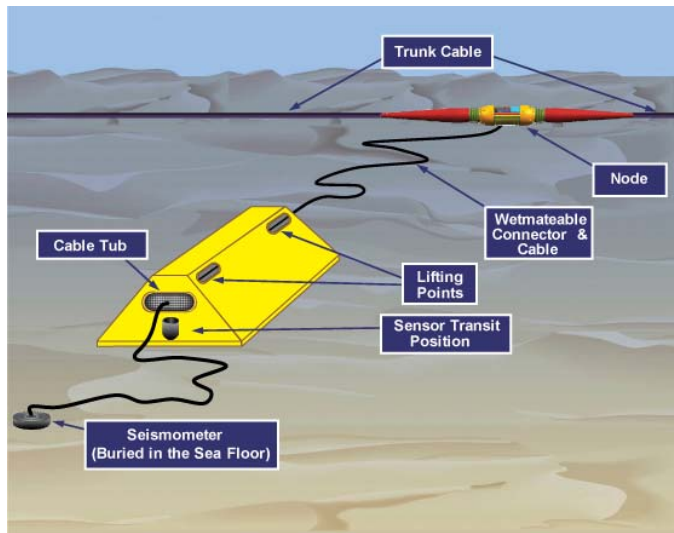


Figure 5. The general design of Lighthouse's seismic tsunami early warning system (STEWS). The trawl-resistant case (in yellow) contains the additional sensors (differential pressure gauge, accelerometer, and bottom pressure sensor).

The majority of tsunamis are triggered by large earthquakes that occur underwater and cause a large vertical displacement of the sea surface. Tsunami waves can travel great distances with little attenuation if unimpeded by land, so both near-field and far-field large earthquakes are of concern. The Guralp seismometer captures large, teleseismic events, and the Reftek accelerometer captures large, proximal earthquakes that are over the maximum threshold of the ocean bottom seismometer. The SIO differential pressure gauge serves as a backup for the accelerometer. The Paroscientific bottom pressure sensor is sensitive enough to detect very small disturbances of the sea

surface in the open ocean – for example, a 1 cm wave in 6000 m of water. Since seismic waves travel more than 35 times faster than tsunami waves through the water, the capability of identifying that a large earthquake has occurred provides the maximum time possible to issue a tsunami watch (alert) and evacuate the most vulnerable low lying areas. If a tsunami wave passes, it is detected by the pressure sensor and a tsunami warning (confirmation) can be issued. This system provides both the maximum amount of warning time possible and confirmation of a tsunami providing the public with reassurance by not issuing false positives which reduce the public's confidence in the system. The data are generated in a format compatible with standards used in regional tsunami warning centers. A further advantage of the STEWS over a typical buoy system is that, because of the continuous power and data flow to and from the system, the STEWS transmits information at all times, remaining constantly on alert.

## VII. DESIGN, INSTALLATION AND MAINTENANCE

Operating in a dynamic deepwater environment, such as that off the coast of Oman, presented several challenges to designing, constructing, operating, and maintaining the system. The real-time cabled system's architecture had not been previously attempted and the regional currents and seasonal variations were unknown. Additional challenges encountered include selection of robust instrumentation with the capability of being fitted with additional sensors as required, an array design that could maintain the vertical orientation of the profilers even in strong currents, and both typical and unexpected corrosion and biofouling issues.

Strong currents are a concern when measuring current velocities; Doppler profilers are designed to rotate in the water column to some extent, but need to remain within 20° of vertical to provide the most robust data. To keep the instruments near vertical, it was important to design a larger cable; the heavier cable required larger supporting floatation and increased weight of the mooring base to keep it well anchored. As the framework of the system grew heavier, costs increased; a delicate balance had to be achieved to ensure the heartiest design while maintaining control on costs.

Installation preparation and procedures also had to be developed from the ground up. An international industry-standard survey of the seafloor in the region is performed prior to installation; this allows for identification of the ideal cable-lay route (Figure 6). The cable and nodes are laid prior to placing the moorings and connecting them to the nodes. Each mooring string is installed prior to connecting the cable and turning the power on; efficient energy and data transfer requires the mooring to be emplaced within 10 meters of the node's location. The mooring bases are left on the seafloor during maintenance of the instruments – a pin is removed by an ROV and the top of the mooring base and mooring string can be brought to the vessel for cleaning, repair or replacement. The nodes, through which the cable trunk line passes, have an ROV-friendly wet mate connector (Figure 7). This allows for the ability to connect new or different types of instrumentation should technology change or should other types of sensors be desired, i.e., plug-and-play capability. Since the wet mate

connection is often the most likely place for problems to occur, a single wet mate serves the node for the entire mooring string; for example, at LORI II the 2500-meter-long mooring strings are entirely dry-mated. Once the moorings are in place, the mooring strings are plugged into the node by an ROV.

with buoys prior to final emplacement. b. Same as (a) but taken from the vessel towards the shore. c. The emplaced cable (black line) on the seafloor.

Initially, the required service intervals were unknown as were some of the problems encountered early on; thus, the arrays were visited more frequently until adjustments in things like cathodic and biofouling protection could be improved. The goal was to lengthen the life of the system while working to reduce costs by minimizing the need for maintenance. Maintenance costs, especially vessel costs, are reduced significantly by the completely subsea architecture which obviates most types of damage to the system. The arrays are serviced at least once every 48 months, but generally more frequently for shallower systems. An ROV inspects each mooring string; the strings may be brought up to the ship where instruments can be cleaned, serviced, upgraded or replaced as needed. At this time, additional sensors or instruments can be added. Based on the level of biofouling or corrosion present, preemptive measures may be taken such as adding additional cathodes.

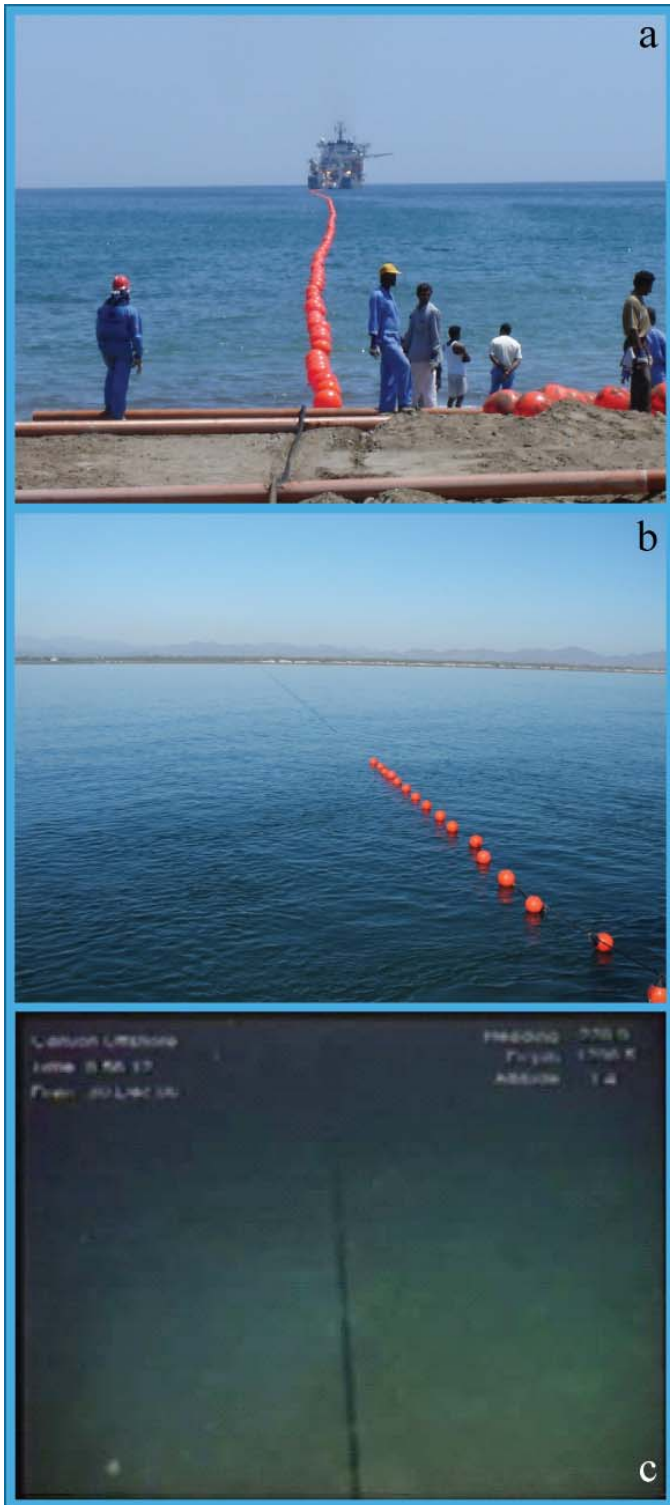


Figure 6. Photos depicting the cable-laying process. a. Cable is guided from shore to ship along the pre-determined path by suspending it at the surface



Figure 7. a. Node (left) showing ROV-friendly wet-mate connector (yellow). ROV arm is in the upper right of the picture. b. Animated view of the ROV (left) plugging in the mooring cable to the node's wet mate.

### VIII. SCIENTIFIC QUALITY AND IMPLICATIONS

Performing quality control and quality assurance (QA/QC) of the data are major tasks since data are reported every hour of every day. Beginning in 2007, Lighthouse has partnered with oceanographers and engineers at Texas A&M University to develop and apply QA/QC procedures and to interpret observations and perform quantitative analyses of the data. Theoretical research – modeling of the water bodies in the region of the LORI I and LORI II systems and tsunami inundation of the coastal region – also began concurrently with the observational research. Numerical models of the ocean in this region help to fill in the gaps between where observations are made and to predict the timing and impact of major events such as offshore oil spills or tsunamis. Likewise, the observational data can be used to test the model results and to fine tune the model's predictive capabilities so that they can be used in a forecast mode with high rates of accuracy. Results from observations made with the LORI arrays, coupled with numerical modeling, will also allow for significant advancements in our knowledge of the behavior of the region's water bodies. The implications of observations and modeling in

the region range from planning evacuation routes for potential tsunamis, to water quality monitoring to ensure safe fish to target and consume, to knowledge of current velocities throughout the water column to predict where spilled oil may travel. Ocean environmental monitoring can lead to improved public policies ensuring the long-term health of the oceans and the lives and ecosystems that depend on it.

To learn more about Lighthouse R & D technologies, projects and capabilities, go to [www.lighthousehouston.com](http://www.lighthousehouston.com).

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