Bright Blue: Advanced Technologies for Marine Environmental Monitoring and Offshore Energy

R. Camilli, A. Bowen, N. Farr
Woods Hole Oceanographic Institution
Department of Applied Ocean Physics and Engineering
Woods Hole, MA 02543 USA

***Abstract*- Major programs such as the Ocean Observatories Initiative (OOI) seek to increase societal understanding of subsurface marine environments. This interest has arisen because of environmental concerns related to degradation of marine habitats, climate change, as well as the globally increasing demand for marine natural resources, particularly food and energy. These pressures now affect marine systems at scales that require active management of marine environments. Nevertheless, our ability to monitor and perform even relatively simple operations in subsurface environments remains limited and costly because of technological limitations. This paper provides an overview of advanced platform, power generation, communications, and sensing technologies that are intended to enable high-resolution environmental monitoring, real-time field surveillance, subsea infrastructure operation and maintenance, and unattended robotic intervention for event response.**

Among these technologies are new modes of subsea communication that can provide long-range and high-bandwidth data transfer for geographically dispersed instrumentation with real-time data communications on the seafloor. The WHOI Optical Modem has demonstrated high-bandwidth (>10Mb/s) wireless data transfer across ranges exceeding 100 meters. The LoRELi (Long Range Extension Link) operates on less than 0.2 Watts and is capable of medium-bandwidth (>100kb/s) data transfer across hundreds of kilometers without repeater nodes. The Nereus hybrid remotely operated vehicle (HROV) is a next generation robotic platform utilizing advanced materials and technologies that enable operation at extreme depths (to 11km) and at lateral standoff distances of several kilometers. These vehicle characteristics enable long-range reconnaissance and light intervention without dynamic ship positioning or large traction winches for the vehicle tether. TETHYS (TETHered Yearlong Spectrometer) is an *in-situ* mass spectrometer that has demonstrated operation on a variety of platforms, including tethered observatory nodes, towed ship cables, remotely operated vehicles, autonomous underwater vehicles, and human occupied submersibles. The TETHYS instrument can autonomously identify and accurately quantify dissolved gases and volatile chemicals at trace levels (to less than 1 part-per-billion) in depths throughout most of the earth's oceans and across temporal scales ranging from seconds to months. TETHYS has enabled new methods of dissolved gas analysis for scientific and ecological investigations as well as environmental cleanup operations in the aftermath of chemical spills. The Flip Wing benthic turbine is a hydrokinetic power generation system designed for operation on deep (~1km) subsurface buoys enabling low power recharge (1-10Watts) from low velocity (3-20cm/s) benthic currents. This turbine provides a mechanism for long-term operation of sub-surface sensor nodes, or periodic recharge of high-power devices such as AUVs without need for a shore power cable or large (>10kWHr) battery pack.

Individually, each of these technologies provides significant advancement within its respective area of sensing, robotics, communications, and endurance. Used in combination for observation and inspection, such as for deep offshore petroleum production or ecological monitoring located at substantial distances offshore, these technologies can provide large gains in efficiency while also reducing operation costs. The technologies presented here are particularly valuable for emerging uses, including security/defense applications, subsurface infrastructure completion for energy production, and offshore carbon capture and storage (CCS) because these operations require continuous real-time surveillance and long-term unattended operation. We present scenarios illustrating how these advanced technologies can be implemented, then compare these approaches with conventional methods and evaluate their potential advantages.

I. INTRODUCTION

There is an emerging need for active monitoring and management of subsurface marine environments. Historically subsurface operations have been conducted by divers, or with surface ships using basic tools such as trawls and dredges. In recent years more advanced technologies such as robotic vehicle platforms as well as new types of *in-situ* sensors have found increased use for industrial, military, and scientific applications. Nonetheless, these technologies have yet to fulfill the promise of long-term unattended operation. The importance of unattended systems will undoubtedly grow over the coming decades, particularly for large-scale marine environmental management and offshore energy.

The increasing active role of marine management will be driven by a trend of growing reliance on now globally limited marine natural resources (i.e., fisheries and energy) and our need for a more comprehensive understanding of how marine systems couple with large-scale environmental dynamics such as climate forcing. These trends represent a profound shift in marine utilization, analogous to cultural shifts from once largely terrestrial hunter-gatherer to agrarian societies. Governmental regulations and policies have begun to reflect this new reality. International agreements, such as the MARPOL Convention, Evian Agreement, and London Protocol [1-3] have sought to establish global standards for sustainable management of marine environments. Most coastal nations now claim sovereignty of exclusive economic zones (EEZs). For countries with significant coastlines, such as the United States or Kiribati, their EEZ can exceed land surface area [4]. Governments including Australia, the United States, and European Union member states, have established and significantly expanded marine protected areas, and are now building large-scale ocean observation systems, while

978-1-4244-5222-4/10/$26.00 ©2010 IEEE

simultaneously opening other areas to offshore energy production.

These actions place heightened emphasis on advancing continuous, high-resolution, subsurface monitoring and intervention capabilities. The challenges of maintaining continuous subsurface presence are, however, unique and prohibitively costly if met with conventional technologies. Therefore, new subsurface technologies are required to address these needs, particularly in aspects of power generation, remote or *in-situ* sensing, robotic conveyance/mobility, and communications. While this paper provides an overview of only four modalities for subsurface sensing, mobility, power generation, and communication technologies, when used in combination they offer synergistic potential for long-term unattended operation. The following subsections provide a brief description of these technologies, and include examples of scientific and industrial use scenarios.

II. *IN-SITU* MASS SPECTROMETRY

Water column biogeochemical processes occur over a variety of space and time scales (centimeters to kilometers ranging from seconds to years). Therefore observations must correspond at appropriate scales in order to describe key aspects of these dynamics. A high resolution measurement strategy is, however, economically unrealistic if conventional ship-based sampling methods and offsite analyses are used to survey large areas or for long durations.

Mass spectrometry is, in principle, well suited for observation of subsurface dynamics because it enables concurrent detection of a wide range of dissolved chemicals, even within complex mixtures. This is advantageous for continuous monitoring and diagnosis of marine environments particularly when there is limited or no a-priori knowledge as to the chemicals that might be present. Over the past decade research efforts have appreciably advanced underwater MS to a state that instruments have been successfully deployed to great depths on a range of *in-situ* underwater platforms, including human occupied submersibles, robotic underwater vehicles, and ship-tethered systems. Despite the clear utility of *in-situ* MS, capability has generally remained restricted to short-term deployment because of technological hindrances such as power demand, operational endurance, and component fragility. These limitations are largely because *in-situ* underwater MS designs have relied on components developed for operation in controlled environmental conditions.

The TETHYS (TETHered Yearlong Spectrometer) *in-situ* mass spectrometer is an *in-situ* mass spectrometer developed for long-term *in-situ* monitoring of dissolved gases and volatile chemicals. Its ruggedized design enables operation across a wide range of marine conditions (i.e., depth, temperature, and physical shock) and its endurance characteristics permit extended deployment on moorings and cabled observatory nodes as well as mobile submersible platforms.

Deployments of the TETHYS instrument have demonstrated the capability to simultaneously track relevant gases such as dissolved methane, oxygen, carbon dioxide, and volatile organic chemicals at trace levels, with sampling frequencies of just a few seconds and endurance of months [5]. These capabilities have enabled high-resolution surveys for oil spill cleanup operations [6]. Along with conventional sensing methods a TETHYS instrument has also demonstrated the ability to act as a vehicle guidance system, enabling an autonomous underwater vehicle (AUV) to autonomously identify and classify deep ocean cold seeps [7].

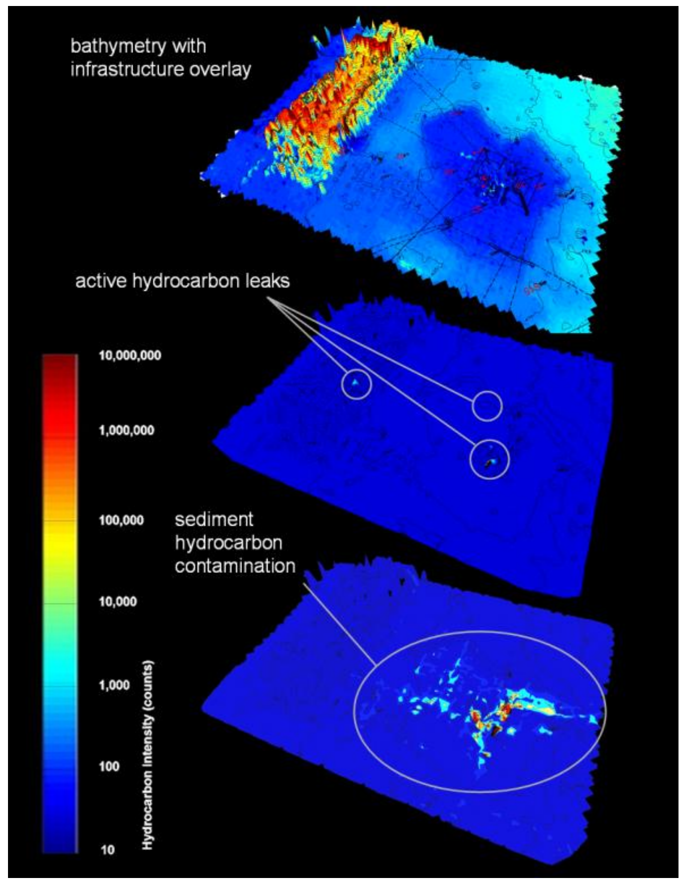

Figure 1. Pollution and infrastructure debris maps of an offshore oil production facility destroyed by a hurricane; data collected using a TETHYS equipped ROV (survey area ~ ½ km^2). Bathymetry map (top) color describes depth (red = shallow, blue = deep), active leak and sediment contamination maps (middle and lower) color describes hydrocarbon concentration. Image courtesy of Navistry Corporation.

III. SUBSURFACE POWER GENERATION

With the notable exception of cabled observatories, unattended subsurface operations are typically battery powered and their energy density limits the system's endurance. Thus, most AUVs and non-cabled subsurface moorings (SSMs) are designed to minimize power consumption and extend endurance. SSM operation costs can exceed hardware capital costs by significant margins, driven largely by the finite endurance of battery packs and the high cost of deployment/recovery operations (mainly the cost of ship time). Thus, SSM endurance is constrained by the size of the battery pack. These constraints predictably limit SSM power budgets to 5W or less. When calculated on a dollar per Watt-hour basis, SSM energy costs are typically on the order of \$10 to \$100 per Watt-hour. In comparison, electrical grid power within industrialized nations is more than a hundred thousand times less expensive.

Hydrokinetic energy provides a renewable power source that can be used to recharge unattended marine systems. Ocean surface currents are typically less than 0.5 m/s, while deep benthic currents (>500m depth) typically have velocities of less than 0.1 m/s. Thus, hydrokinetic surface ocean power is typically below $60W/m^2$, while deep benthic currents typically possess less than 1 W/m^2 of power. Although these low water velocity sources can theoretically be integrated over appropriate areas to provide large amounts of motive power, electricity generation has instead focused on developing turbine technologies for use in high energy density marine areas with water velocities >1 m/s. Although various hydrokinetic turbines capable of producing 500W-20 kW have been demonstrated for at least 30 years, there are currently no commercially available hydrokinetic turbines designed for operation in low water current environments.

To address this need, the Woods Hole Oceanographic Institution (WHOI) has partnered with Hydrovolts Inc. to develop a micro-power turbine design for generating electrical power from relatively slow water currents in benthic marine environments (Fig. 2). Unlike standard turbines which make use of lift force for propulsion, this design utilizes a displacement-type Flip Wing rotor, permitting operation in extremely low-velocity regimes. This enables operation in benthic currents that are typically below the stall speed of standard turbines which require lift for motive energy.

Figure 2. A displacement-type Flip Wing hydrokinetic turbine for electricity generation at low water velocities. Photo courtesy of Hydrovolts Inc.

IV. SUBSURFACE COMMUNICATIONS

Underwater data transfer across extended ranges (>10km) generally involves fiber optic cables. These cables, which are typically designed for commercial telecommunications, are not optimized for lower-bandwidth (<10Mb/s) operations. To maximize bandwidth and data throughput, these cables tend to operate with high-power repeaters, while requiring specialized cable-laying infrastructure and complex underwater mateable optical connections. Consequently the construction and maintenance budgets for these cabled systems are extremely high.

A low-cost alternative to these types of long range communication architecture is the LoRELi (Long Range Extension Link) architecture developed at WHOI. This communications system utilizes a medium-bandwidth optical transceiver capable of transmitting 115kB/s across distances exceeding 100km without the need for repeater amplifiers, while requiring less than 0.2W. The LoRELi system reverts to a low power (0.002W) standby state when not actively transmitting, enabling one year of standby with a single AA alkaline battery. The LoRELi cable uses non-contact inductive transmitters that enable ad-hoc reconfigurable networking on the fly. The entire length of its lightweight armored fiber optic cable can be spooled onto a small drum for deployment by a survey class ROV or small boat. The system has successfully demonstrated continuous, error-free, data transfer across distances >50 km for several weeks at a time.

Reliable, high-bandwidth wireless communication is still challenging for underwater applications. In air and space, radio-frequency (RF) communications operate at long distances and high rates while using modest power. This is not feasible in water due to high absorption at RF frequencies. The primary tradeoff of underwater wireless communication is data rate as a function of power consumption (Table 1). Acoustic modems generally operate between about 1,200 and 5,000 bits per second (bps) over moderate ranges and potentially higher rates for some specialized, short-range systems [8]. At these speeds, large data files take a long time to transfer and real-time video transmission is not feasible. These limitations usually require an oceanographic instrument to be recovered in order to download its full data set.

Although seawater is opaque to electromagnetic radiation in most of the electromagnetic spectrum, it is modestly transparent in the visible light band. The e-folding scale of the blue-green band (400-500 nm) in clear ocean water (i.e., the distance over which light intensity decreases by 1/e ~ 0.37) is approximately 20-50 m. Along with attenuation, light scattering limits the data rate as a function of the propagation path difference between direct and scattered components. Fortunately, water clarity at depth is relatively high so that the amount of forward-scattered light is typically small. A ~10 Mbit/s data rate allows bit signaling intervals on the order of 100 ns, which are long compared with a path difference delay resulting from typical scattering 10-20° out of plane. Thus, a wireless alternative to acoustic communication is possible with optical links over ranges of ten or more e-folding scales (100-200m, and potentially longer under ideal conditions) at these data rates (10 Mbit/s or more).

TABLE I

PERFORMANCE COMPARISON OF VARIOUS MODES OF UNDERWATER ACOUSTIC AND OPTICAL TELEMETRY

Telemetry Method	**Range**	**Data Rate**	**Efficiency**
LoRELi (cabled)	>100 km	100 kbps	*600,000 bits/Joule*
Acoustic modem (wireless)	> 1 km	100 bps	*1,000 bits/Joule*
Optical modem (wireless)	100 m	1 Mbps	*40,000 bits/Joule*

This mode of underwater optical communications is particularly well suited for marine applications where low latency/high bandwidth data transfer is required, direct data line contact is impractical, acoustic channels are limited, or unrestricted near-field mobility is required [9-11]. An ongoing WHOI research program has examined trade-offs between wide-angle and aimed, collimated transmitter/receiver pairs, LED and laser diode sources, and avalanche diode and photomultiplier tube (PMT) receivers. This program has yielded prototype systems employing omni-directional links optimized for mobile as well as stationary platforms (Fig. 3).

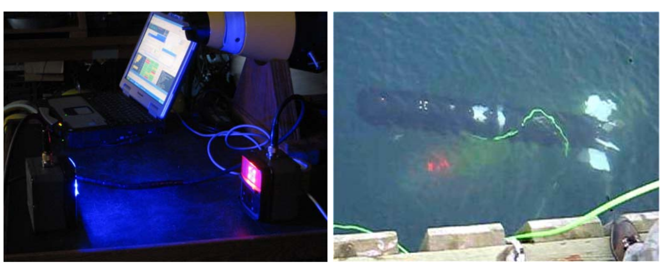

Figure 3. Bench testing (left) and in-water dock testing (right) of a compact, short-range optical modem. Photo: Woods Hole Oceanographic Institution.

V. ROBOTIC PLATFORMS

Remotely operated vehicles (ROVs) have extended humans' reach into the oceans. Still, deep-water operations with heavy power and telemetry cable tethers result in high operating costs, including ships with specialized positioning systems, large A-frames and winch systems; special command-and-control vans and a large number of dedicated personnel.

Robotic platforms have evolved significantly since their first emergence in the late 1970's. Unlike the vehicle platforms, tethering techniques have changed little over the years. Even though the development of multiplexing systems and the eventual application of fiber optic technology to tethers have had important impacts on design, the fundamental concept has retained a physical tether. Modern conventional ROV tethers remain comprised of copper for power, optics for data and sufficient strength to ensure the elements stay within accepted stresses as loads change.

As applications have pushed ROVs into deeper water, the tethering subsystem has become a major limiting factor to the overall vehicle system capabilities. Associated infrastructure relating to vehicle tethers increasingly is becoming a limiting factor, driving overall performance and cost. Examples of these limitations relate to reliability, overall system size/complexity and associated support infrastructure such as surface support vessels.

While ROV development over the past 30 years has been incremental, the development of autonomous vehicles during this period has provided an influential step change in capability. The accompanying evolution of power storage, control and through-water communications has resulted in a valuable new class of undersea vehicle, able to accomplish an increasing range of tasks historically undertaken with ROVs or other similarly tethered systems. Although AUVs are now routinely used for functions broadly characterized as survey, they remain limited in their ability to carry out more sophisticated tasks such as detailed inspection or interactive intervention. While laboratory experimentation and development programs are actively pursuing extended autonomy, it is clear that variable degrees of human supervision will be required for such systems to successfully interact in highly unstructured environments in the near term.

The Nereus hybrid remotely operated vehicle (HROV) has effectively demonstrated the capability of a vehicle to operate as both an AUV and ROV through the use of a novel tethering approach (Fig. 4). By integrating the power system to the vehicle, as is required for AUV operation, Nereus is able to employ a radical variation on a tether, comprised solely of a slender glass fiber having a diameter of only 0.01 inch, up to 40 kilometers in length. While development of this tethering system was the result of a desire to design a cost-effective vehicle capable of effectively working at depths up to 11,000 meters, its successful demonstration points to new opportunities for vehicles with less extreme depth capabilities.

While Nereus' capabilities are only a small subset of a fully founded work class ROV, the vehicle has demonstrated an important capability to perform work at extreme depths while requiring minimal support infrastructure. For example, Nereus is mobilized from a single 20 foot shipping container and can be deployed from non-dynamically positioned ships, utilizing existing handling systems. Indeed, Nereus performed a range of both AUV and ROV functions from the *R/V Cape Hatteras*, a 41 meter vessel with twin screws, in water depths up to 5,000 meters in the Cayman Trough [12]. On a single dive in ROV mode, the vehicle covered approximately 7 kilometers on the seafloor, requiring little maneuvering of the vessel.

The opportunity now exists to combine the Nereus HROV with current developments in underwater control and communications to produce a new class of vehicle, capable of blurring the distinction between AUV and ROV. Whether utilizing acoustics, newly available optical communications, or the small diameter fiber as pioneered by Nereus, the opportunity for a "virtual tether" is upon us. By coupling rapid developments in energy storage systems with advances in tethering techniques, it is possible to imagine a range of new capabilities that will radically change the way in which underwater vehicles are conceived and utilized.

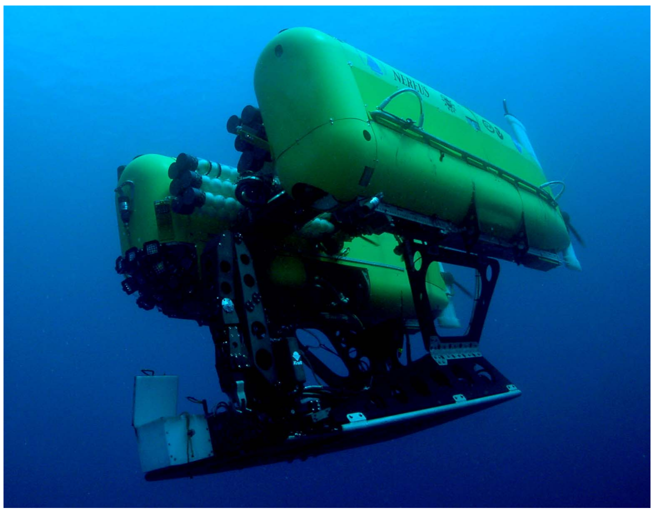

Figure 4. The Nereus HROV, capable of diving to 11,000 meters is leading to a redefinition of a tethered vehicle.
Photo: Woods Hole Oceanographic Institution.

VI. ENVIRONMENTAL MONITORING

Ocean observation systems are now being built that range in size from local to global in scope. These systems typically utilize seafloor cable nodes or surface buoys for power and data transfer. Laying cable is a costly operation and can be difficult due to legal permitting requirements, crossings with existing infrastructure, or high-energy near-shore environments. Therefore, programs such as the United States OOI have developed surface moorings, which generate power via photovoltaic panels, fuel cells, and wind turbines, and transfer data via satellite. These moorings can be periodically repositioned because they lack a shore cable, but are prone to damage from high sea states, as well as entanglement with fishing gear, and vandalism.

An alternative approach to long-term fixed-position environmental monitoring can be to utilize SSMs equipped with low-speed hydrokinetic turbines, optical modems, and *in-situ* chemical sensors such as mass spectrometers. This avoids the cost and potential physical damage associated with a surface expression, while still enabling adequate power generation for *in-situ* sensing and high-bandwidth offloading of data.

This SSM architecture enables AUVs or ROVs to be used for non-contact data offload from the SSM, while operating as data 'mules' transporting large quantities of data to the sea surface (Fig. 5). The SSM can be used as a docking and recharge station for long-term unattended operation of an AUV or virtually tethered ROV. In this scenario the vehicle would be operated as a locally roaming sensor node for use in periodic survey or event response type environmental applications.

An experimental benthic mooring now under development at WHOI uses the previously mentioned low-velocity turbine design to provide periodic recharge to a 900 meter deep sensor array that is used for long-term observation of gas hydrate dynamics at the Gulf of Mexico Mississippi Canyon Block 118. This power generation and storage architecture provide up to 50 days of operation between recharge, permitting operation during extended lulls in the benthic water currents, and full recharge during episodic passage of ring currents and other high energy benthic water mass movements (>10cm/s) within that 50-day window. This mooring design also uses an optical modem to permit periodic (bi-annual) high-speed data upload to a surface ship via an ROV or AUV data mule.

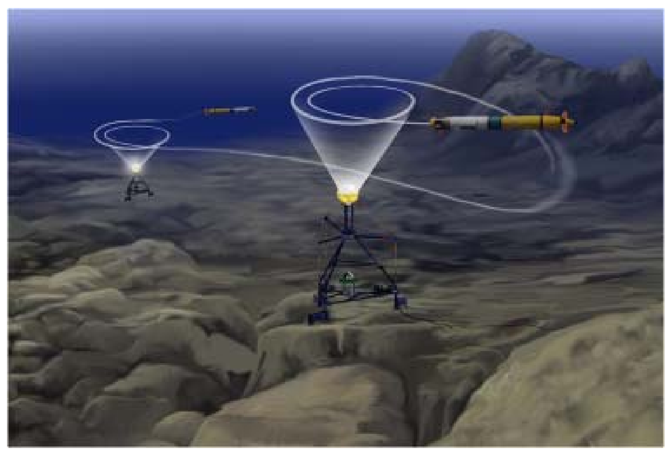

Figure 5. Data mule concept for an optical modem where an AUV finds, then loiters and offloads data from a subsea data collection station.

VII. OFFSHORE ENERGY

Offshore energy faces substantial technical challenges as petroleum production facilities migrate into deeper waters and necessarily evolve toward fully subsurface completions. This trend will intensify an already growing need for subsurface field surveillance and intervention on a timely basis. Conventional subsurface intervention practices use infrastructure (i.e., dynamic position (DP) ships and work-class ROVs) that require scheduling days-to-weeks in advance for mobilization to the operations site. The associated cost and scarcity of these systems generally preclude their exclusive use at a single operations site. Thus, as the offshore energy industry transitions toward subsurface infrastructure, unattended modes of continuous field surveillance will be required.

An emerging aspect of the offshore energy industry is carbon capture and storage (CCS) for mitigation of green house gas emissions through long-term sequestration of carbon dioxide. CCS technologies are intended to provide a mid-term emissions mitigation solution, enabling a 50-year transition away from fossil fuels [13]. Seepage liability makes offshore geologic formations more attractive than onshore sites because of the limited risk to humans and insignificance of submarine groundwater contamination [14]. Several CCS emission mitigation facilities are now either under construction or in operation throughout the world. Statoil's Sleipner offshore platform became the first operational CCS facility in 1996. Over the past 13 years this facility has sequestered approximately 8 Mt of CO_2 from produced natural gas/condensate and re-injected into a sandstone formation 1km below the seafloor. Larger CCS facilities, such as Chevron's Gorgon platform near Barrow Island, Australia (designed to sequester 3.5Mt CO_2/yr into an offshore sub-seafloor saline aquifer), are scheduled to begin operation in 2011.

At present these CCS methods utilizing geologic formations are under review by the United Nations Framework Convention on Climate for approval as a clean development mechanism (CDM). Although geologic formations can be highly impermeable, long-term CO_2 migration and evolution following injection into a geologic formation is not well understood. Various processes are thought to be possible, including leakage of migrating supercritical CO_2 through seismic faults and damaged well casings, or formation of meta-stable hydrate strata. Thus, offshore CCS facilities are likely to require a careful site selection process with detailed environmental impact study prior to development, followed by comprehensive surveillance and intervention throughout the lifetime of the CCS facility operations, and periodic environmental assessment decades thereafter.

Future scenarios for offshore energy and CCS operations will undoubtedly require high-resolution observation and efficient intervention capabilities to survey potentially complex seafloor sites and regulate or repair infrastructure components. Although subsurface field surveillance is a specialized type of unattended environmental monitoring, the modularity of the technologies described in this paper enables adaptable use. An example of this flexibility is the long-term hydrocarbon monitoring node that was recently installed at Panama's Coiba National Park, a UNESCO World Heritage Site. This subsurface sensing node relies on a TETHYS mass spectrometer and LoRELi cable for real-time unattended measurement of biochemical productivity and respiration in an ecologically sensitive coral reef habitat while simultaneously monitoring for petroleum spills and other types of chemical pollution.

Within the coming decade sophisticated marine subsurface surveillance networks are likely to be realized for offshore energy production and CCS sites. In this scenario distributed *in-situ* sensors powered by integrated benthic turbines will act as unattended sentinels. When an anomalous situation is detected, these sensors relay their information to shore via a high-speed/low-power LoRELi type network. The information is then used to task a hybrid AUV/ROV, that responds by swimming (in AUV mode) from its underwater docking/recharge station to the area of interest. Upon arrival at the target area it makes contact with sentinel nodes using its optical modem and switches into ROV mode using this 'virtual' tether (i.e., optical modem in combination with the long-range extension link network). Detailed assessment and light intervention operations are then carried out under human control. The horizon appears bright for coordinated use of these new robotic systems and other 'blue' technologies.

ACKNOWLEDGMENT

TETHYS development was supported by grant OCE-0537173 from the National Ocean Partnership Program and carried out in joint partnership with Monitor Instruments Company. Embedded intelligence research for extended autonomy is carried out through grant NNX09AB76G from the National Aeronautics and Space Administration's ASTEP program. We thank the Navistry Corporation for contribution of its hydrocarbon map. Benthic turbine research is conducted in partnership with Hydrovolts Inc., experimental deployment and operations testing are through the kind support of the Gulf of Mexico Hydrates Research Consortium and National Oceanic and Atmospheric Administration grant NA07OAR4300494. LoRELi development was made possible through the Woods Hole Oceanographic Institution's Green Technology Innovation Award and volunteer genius of Dr. Al Bradley; deployment was carried out with support from the Woods Hole Oceanographic Institution's Ocean Life Institute. For the development of the Optical Modem we gratefully acknowledge the support of the National Science Foundation under grants OCE-0428552, OCE-0737958, OCE-0942835. We also acknowledge the optical modem team, Jon Ware, Cliff Pontbriand, Hugh Popenoe, Jason Kapit and Terry Hammar. We gratefully acknowledge support of Nereus HROV development by the National Science Foundation under grants OCE-0334411, OCE-0453105, OCE-0452262, the Office of Naval Research under work order N0001409WX20051, the National Oceanic and Atmospheric Administration under grants NA04OAR4300168, the Woods Hole Oceanographic Institution, and the Russell Family Foundation. Finally we thank Judith Fenwick for her indispensable editorial assistance.

REFERENCES

[1] "International Convention for the Prevention of Marine Pollution from Ships, 1973 as modified by the Protocol of 1978 relating thereto (MARPOL 73/78)," 1978.

[2] G8 Action Plan, "Marine Environment and Tanker Safety," in *Evian Summit*, Evian-les-Bains, France, 2003.

[3] International Maritime Organization, "1996 Protocol to the London Convention 1972: Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter." 36 ILM 1 (1997), 1996.

[4] J. Fenwick, *International Profiles on Marine Scientific Research: National Maritime Claims, MSR Jurisdiction, and U.S. Research Clearance Histories for the World's Coastal States*. Woods Hole, MA: Woods Hole Oceanographic Institution, 1992.

[5] R. Camilli and A. N. Duryea, "Characterizing Spatial and Temporal Variability of Dissolved Gases in Aquatic Environments with in situ Mass Spectrometry," *Environmental Science & Technology,* vol. 43, pp. 5014-5021, 2009.

[6] R. Camilli, B. Bingham, C. M. Reddy, R. K. Nelson, and A. N. Duryea, "Method for rapid localization of seafloor petroleum contamination using concurrent mass spectrometry and acoustic positioning," *Marine Pollution Bulletin,* vol. 58, pp. 1505-1513, 2009.

[7] R. Camilli, D. Yoerger, M. Jakuba, O. Pizarro, S. Williams, and D. Valentine., "Extending autonomy for exploration, discovery, and characterization of deep sea extreme environments," in *Eos Trans. AGU, 91(26), Ocean Sci. Meet. Suppl., Abstract MT15A-15*, 2010.

[8] D. Frye, J. Ware, M. Grund, J. Partan, P. Koski, S. Singh, L. Freitag, J. Collins, and R. Detrick, "An acoustically-linked deep-ocean observatory," in *Oceans 2005 - Europe*, 2005, pp. 969-974 Vol. 2.

[9] N. Farr, A. D. Chave, L. Freitag, J. Preisig, S. White, D. Yoerger, P. Titterton, J. Bolstad, and D. Leonard, "Optical modem technology for seafloor observatories," in SSC06 *Scientific Submarine Cable Workshop*, Dublin, Ireland, 2006, pp. 1-6.

[10] N. Farr, A. D. Chave, L. Freitag, J. Preisig, S. N. White, D. Yoerger, and F. Sonnichsen, "Optical Modem Technology for Seafloor Observatories," in *OCEANS 2006*, 2006, pp. 1-6.

[11] N. Farr, A. Chave, L. Freitag, J. Preisig, S. White, D. Yoerger, and P. Titterton, "Optical modem technology for seafloor observatories," in *OCEANS, 2005. Proceedings of MTS/IEEE*, 2005, pp. 928-934 Vol. 1.

[12] A. D. Bowen, D. R. Yoerger, C. Taylor, R. McCabe, J. Howland, D. Gomez-Ibanez, J. C. Kinsey, M. Heintz, G. McDonald, D. B. Peters, B. Fletcher, C. Young, J. Buescher, L. L. Whitcomb, S. C. Martin, S. E. Webster, and M. V. Jakuba, "The Nereus hybrid underwater robotic vehicle," *Underwater Technology,* vol. 28, pp. 79–89, 2009.

[13] R. S. Haszeldine, "Carbon Capture and Storage: How Green Can Black Be?," *Science,* vol. 325, pp. 1647-1652, Sep 2009.

[14] D. P. Schrag, "Storage of Carbon Dioxide in Offshore Sediments," *Science,* vol. 325, pp. 1658-1659, Sep 2009.