Despite significant engineering challenges, technological advances are expanding the capabilities and coverage of ocean observatories around the world.

Ocean Observatories: An Engineering Challenge

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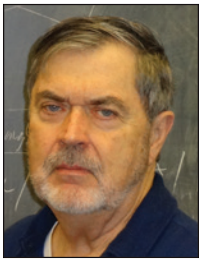

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Observatories are important components for ocean research in most developed countries with a coastline. For many decades oceanographic institutions followed what one might term "expeditionary research": ships went to places to investigate various ocean processes; observations were made and often sensors were deployed to record data for subsequent retrieval. But the observations were sparsely sampled temporally and spatially, leaving many

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processes not well understood because of the transient and regional nature of the data. As Walter Munk put it, "The key change between the century of the *Challenger* and the last 50 years is adequate sampling. The key product of the Technology Revolution is sampling" and "the requirement of the sampling theorem" (NRC 2000, p. 49). Ocean observatories will continue to meet the ever increasing requirements for adequate sampling of the oceans.

Introduction

In the early 2000s oceanographers changed their paradigm to deploy what are collectively termed "observatories." The resulting near-real-time series from ocean sensors coupled to shore with several methods of transmission enable monitoring of changes at all time scales, from daily to climatic and geodetic.

Ocean observatories enable monitoring of changes at all time scales, from daily to climatic and geodetic.

These observatories use sophisticated nodes with arrays attached for directional information for seismic, geodetic, and acoustic signals; current meters; sensors for conductivity (salinity), temperature, and depth (CTD), pH, oxygen, CO_2, and other chemicals; and biologic sensors such as fluormeters and bioacoustics. They also use autonomous underwater vehicles (AUVs) to sample the local water space. There are many opportunities for novel instrumentation.

Numerous questions remain about the role of the ocean in climate change; ways to quantify fluxes of heat, water, momentum, and gases at the air-sea interface; carbon cycling and the role of the ocean for CO_2 absorption; improved models of mixing and ocean circulation and for the crustal and deep Earth; transient biological activity such as algal blooms; ways to assess the health of the coastal ocean; monitoring of earthquakes and seismicity; and tracking of tsunami events, to name a few. Long-term time series from ocean observatories are providing answers to these questions.

Challenges for Observatories

The ocean environment presents many engineering challenges for deploying long-lasting, reliable observatories, compounded by high costs for equipment (Howe and McRae 2017). Sensors and cables must work in a corrosive environment often at the extreme pressures of the deep sea. Data transmission must choose between relatively low-bandwidth acoustic modems or higher-bandwidth cables. Currents can move or shake equipment. AUVs and their interfaces for energy and data exchange are complicated. Opportunities for repair once in place are limited. The data acquired from long-term and continuous monitoring are voluminous and require sophisticated software to disseminate to scientific, government, and industrial users. Following are major categories of challenges:

- *High pressures:* Hydrostatic pressure increases by 1 atmosphere for every 10 m of depth. The coastal ocean is nominally 100 m deep, implying nearly 150 lb/sq-ft of pressure, and the deep ocean is on average 4,000 m deep (6,000 lb/sq-ft of pressure). Housings for pressure vessels occasionally fail because of hydrostatic pressure. Penetrators into the interior of a vessel and O-rings for mating housing components are the bane of experimentalists because of failures. Their technology is expensive and requires skill to install.
- *Corrosion:* Seawater is very corrosive. Anything metal, especially stainless steel, corrodes over the long deployments expected of an observatory. Catalytic corrosion is accelerated between dissimilar metals, so identical materials must be used for metal structures, bolts, and screws. Some plastics do not fare well. Titanium, aluminum, and glass are most robust, but titanium is difficult to fabricate and expensive to acquire. Aluminum that is properly heat treated and anodized can last many years. Commercial glass balls are not reliable after several deployments and, for flotation, syntactic foam has become much more popular.
- *Fouling:* Any equipment in the upper water column can rapidly accumulate fouling as both animals and plants attach themselves. Antifouling paints have a finite lifetime, so eventually equipment accumulates large masses that interfere with moving parts and propulsion units.

- *Fishing, trawling, and vandalism:* The ocean is shared by many users. Fishing gear damages equipment and destroys moorings. Trawling rips cables off the seabed even though seafloor packages are designed to be trawl-resistant. Vandalism is common in some areas because of the perception that equipment is valuable and can be sold.
- *Electronics:* Ground loops associated with AC power supplies are notorious because of the opportunities for seawater groundings. These shorts to ground are often very difficult to find and the chances increase with the number of subsystems connected. Ground loops can be very damaging to sensitive, high-impedance electronics such as sensor preamplifiers.
- *Calibrations:* Oceanographic research relies on the ability to compare amplitudes and phases from sensor outputs to (1) detect changes over space and time or (2) combine signals to create an array for gains against noise and determine directions by spatial processing, or beamforming. Calibration errors and/or sensor drift degrade these abilities, especially for long-term climate and geodetic measurements.
- *Opportunity costs:* Oceanographic equipment is typically deployed by ships at remote locations with per-day costs of $50,000 or more. These ships also are tightly scheduled, so there is often little funding or time for academic budgets to support costly deployment delays or to return to fix a faulty installation.

Notwithstanding the challenges, ocean observatories are largely effective in gathering myriad data through both cabled and moored systems, using autonomous equipment and new technologies for sensors and communications.

Cabled Ocean Systems

Cabled ocean systems have a long history and a future rich in possibilities. Because they can be quite expensive and maintenance of the myriad instruments is challenging, the number of future national systems is likely to be limited (a system under development in China is the only one we are aware of). Multinational systems are more likely. Capability ranges from broad trans-ocean coverage with simple sensors to systems that add multiple nodes along the route (as in the Arctic, where costs are justified by societal, military, and scientific needs to better understand this rapidly changing region of the world).

History

Early forays included sound surveillance array systems (SOSUS) and occasional single-node systems, the Acoustic Thermometry of Ocean Climate (ATOC) network, and the hydroacoustic stations of the Comprehensive Test Ban Treaty Organization (CTBTO). By the end of the 1990s the essential elements of what is considered a cabled observatory were proven: substantial power and bandwidth (optical fiber), plug-and-play capability for connecting instruments, and use of human-occupied vehicles (HOVs) or remotely operated vehicles (ROVs) for service. By 2010 regional-scale multinode, high-power, and high-bandwidth systems were in operation. Sensor network infrastructure has been developed, with secondary nodes, extension cables and laying capability, and cable-connected moorings with deep and shallow water column profilers.[1]

Beginning in the 1950s

SOSUS was probably the first cabled ocean "observatory," providing the United States with acoustic surveillance of Russian submarines beginning in the 1950s. Early sites were near shore with hydrophones individually wired back to shore in large-diameter armored cables with limited bandwidth.

> *Seawater is very corrosive. Anything metal corrodes over the long deployments expected of an observatory.*

The deployment and repair of these cables led to the creation of special cable-laying ships. Subsequent systems used thinner coaxial cables with multiplexed cable telemetry and were deployed at sites much farther offshore, usually taking advantage of opportunistic bathymetry to place the arrays at the desired depths. The end of the Cold War led to the abandonment of many SOSUS nodes, but a smaller SOSUS system using fiber-optic cables continued with data telemetry from the hydrophones. Bandwidths and channel counts are no longer issues.

[1] A notable development failure is for AUV docking stations to facilitate the spatial extension of fixed cabled systems; this is being rectified, as discussed below.

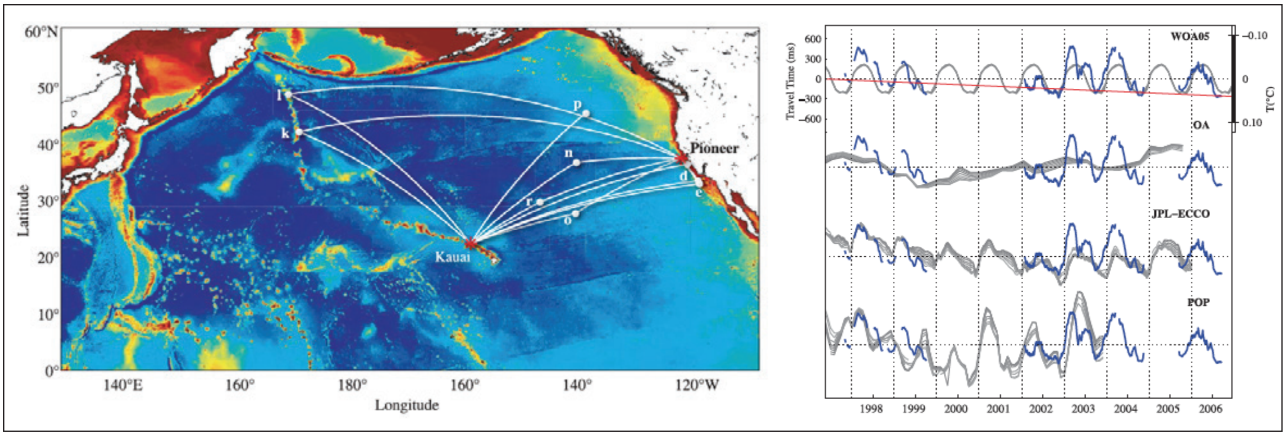

FIGURE 1 *Left:* Acoustic propagation paths from Kauai source to receivers in the Pacific for the Acoustic Thermometry of Ocean Climate (ATOC) test. *Right:* Comparison of travel times (blue) for acoustic paths with ocean climate models (grey). JPL-ECCO = Jet Propulsion Laboratory "Estimating the Circulation and Climate of the Ocean" ocean circulation model + data assimilation; OA = objective analysis; POP = Parallel Ocean Program model; WOA05 = World Ocean Atlas 2005. Reprinted with permission from Dushaw et al. (2009).

Important takeaways from SOSUS are that (1) cabled systems and their infrastructure are expensive and (2) it enabled much of the technology for cabled systems since the research community could not have afforded the technology development.

Since the 1990s

In 1993 the ATOC project cabled two acoustic sources to shore, one off Kauai (figure 1) and one off California (Pioneer Seamount). Navy SOSUS receivers and autonomous vertical line arrays were used as receivers. The intent was to determine large-scale ocean temperature changes by measuring changes in travel times (dividing known distances between sources and receivers by travel time gives sound speed, which is proportional to temperature changes) (ATOC Consortium 1998; Dushaw et al. 2009).

In 1996 the CTBTO began establishing an international monitoring system (IMS), with six cabled-to-shore hydroacoustic stations (Lawrence 1999). The installation of some of these was extremely challenging; the one at Crozet Island in the Antarctic Circumpolar Current was only finally (reliably) installed in 2017 (Haralabus et al. 2017). The IMS is the first truly international, global, real-time ocean (acoustic) observing network with (nominally) open data. As these systems near the end of their projected 25-year design life, the CTBTO is planning upgrades, with the expectation that attributes of scientific cabled systems (e.g., additional instrumentation with plug-and-play capability) will be incorporated (Zampolli et al. 2017), to better interpret local acoustic conditions and serve the ocean and Earth observing communities.

The first Scientific Uses of Submarine Cables (SSC) conference was held in 1990 in Honolulu; US-Japan collaboration in the use of out-of-service telecom cables was the focus for more than a decade.

In 1996 Fred Duennebier, a pioneer of cabled ocean observatories, installed the Hawaii Undersea Geophysical Observatory on the active Lōʻihi Seamount volcano just south of the Big Island. This was a key proof of concept for ocean observatories, with substantial power (5 kW), fiber-optic communications, and (homemade) electro-optical underwater mateable connectors; the multiport node was serviceable by HOV/ROV (Duennebier et al. 2002). The system worked for 6 months before the cable to shore failed from abrasion (this was not unexpected; an armored cable could not be afforded to run over the lava along the cable route).

In 1998 the US Hawaii-2 Observatory (H2O) was installed (Butler et al. 2000) and holds the record for the deepest observatory, at 5,000 m. The ALOHA Cabled Observatory project began in 2002, based on the work of Duennebier and colleagues (Howe et al. 2012). In 2007 a proof module was connected to a section of the optical fiber cable at Station ALOHA, 100 km north of Oahu (Duennebier et al. 2012), and in 2011 an 8-port node and instruments were attached, with several ROV service visits (Howe 2014; Howe et al. 2015). While the primary infrastructure and a core set of instruments have worked since installation, a number of other instruments have failed, likely because of cables and connectors. Given limited ROV access and time, addressing the problems is challenging. To our knowledge, this is the last reuse of a retired cable; sponsoring agencies prefer to invest in local/regional purpose-built cable systems.

In 2009 Barbara Romanowicz installed the cabled Monterey [Bay] Ocean Bottom Broadband Observatory, with an attachment to the Monterey Bay Aquarium Research Institute's Monterey Accelerated Research System (MARS) cable, funded by the National Science Foundation (NSF). The system continues to operate. Scripps installed a seafloor seismograph on the cable, as part of the Ocean Observatories Initiative (OOI), to test the new Advanced Message Queueing Protocol for transferring observatory data. The network functioned reliably (except briefly when a backhoe ashore severed the communications cable).

Seismic Studies

For some of these systems, the primary mission is seismic and tsunami early warning. A significant tsunami was recorded based on data from an open server operated by the Incorporated Research Institutions for Seismology (Thomson et al. 2011). The most comprehensive seafloor cabled observatory for early warning is the Dense Ocean Floor Network System for Earthquakes and Tsunamis (DONET) (Nakano et al. 2013), installed in 2010 offshore Japan. DONET2 was completed in 2016, and now 50 DONET stations are deployed in the Nankai trough west of Japan (Kaneda 2014; Kawaguchi et al. 2015).

DONET consists of two independent ring systems each about 400 km long with five 8-port nodes. Each node has four local observatories on 10 km extension cables with seismic and ocean sensors, can provide 500 W (using constant current power), and includes a triaxial broadband seismometer and triaxial strong-motion accelerometer. All signals are digitized at 200 Hz with 24-bit resolution. The lifetime is anticipated to be 20–30 years. Seismometers are typically buried in caissons. A special 10 km small diameter (6 mm) cable-laying capability was developed to connect local observatories to the primary nodes.

After the March 2011 Tohoku earthquake, the Japanese government commissioned the *S-net* system. An in-line system was designed in 6 months, with seismic sensors in an extended-length repeater housing laid in a continuous fashion. Six independent systems, with 200 sensor locations, have been laid off the east coast of Japan, completed in 2015 (Kanazawa et al. 2016).

In 1988 John Delaney began advocating a cable system on the Juan de Fuca Plate off the Washington coast to study life in the extreme environments of hot vents, volcanoes, and subduction zones (Delaney et al. 1988). The 1998 NEPTUNE project led to VENUS in the Salish Sea, MARS, NEPTUNE Canada offshore Vancouver, and the OOI Regional Cabled Array off Washington/Oregon.[2] They represent a vision of what might be accomplished with large amounts of subsea power, high bandwidth, precise timing, and essential elements of the sensor network infrastructure (e.g., extension cables, moorings, profilers, AUVs) (figure 2).

Power Systems

It was quickly realized that starting small was prudent. The first low-voltage (400 V) VENUS nodes in shallow water were installed in 2000; MARS, funded in 2002, was finally installed and operational in late 2008. It was the first node with ~10 kW, 1 Gbps, and 1 µs timing accuracy, with 8 ports at 908 m water depth. It has been used as an instrument testbed and for local science.

Cabled in situ ocean infrastructure provides undersea power and communications for year-round, real-time monitoring and data collection.

A significant technical development that differentiated these systems from previous ones was the use of a constant voltage (CV) power system (commonly used on land) vs. a constant current (CC) system (used in all other submarine cable systems); both use direct current with one conductor and seawater return. The CV system provides up to twice the power of a CC system and

[2] NEPTUNE = Northeast Pacific Time-Series Undersea Networked Experiments; VENUS = Victoria Experimental Network under the Sea.

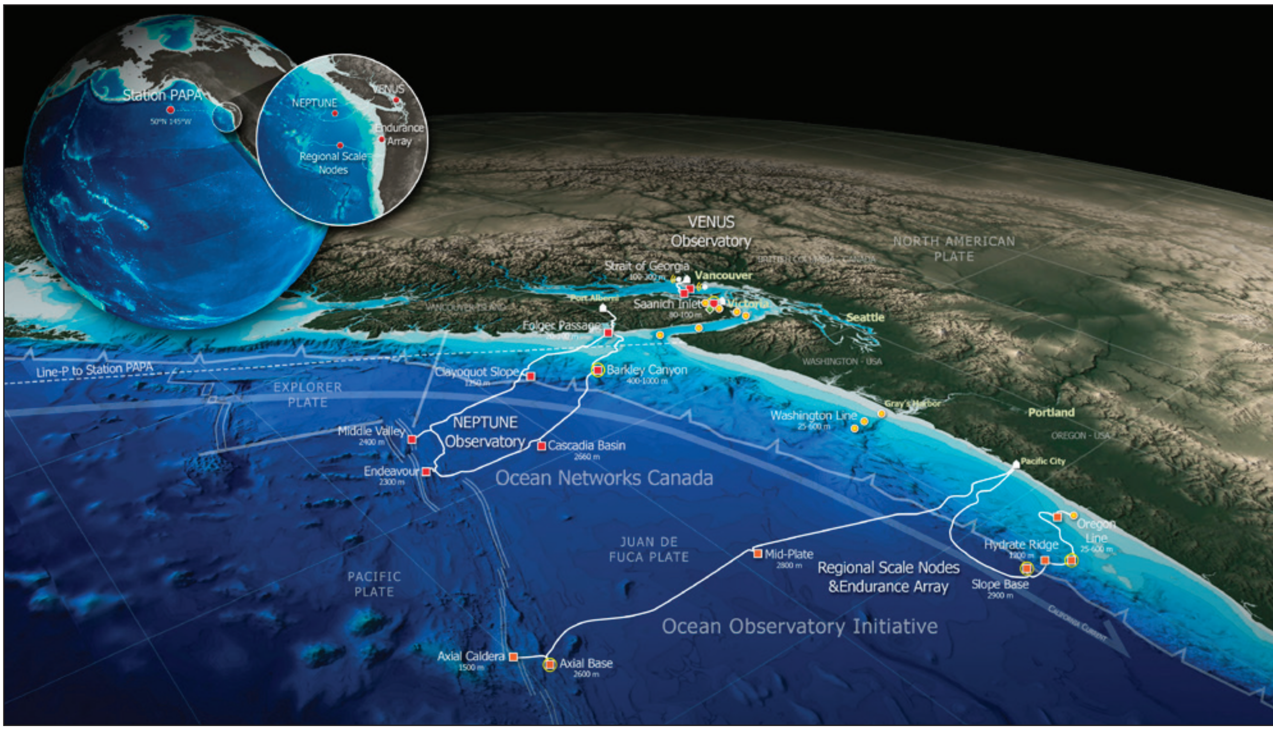

FIGURE 2 The NEPTUNE/VENUS ocean cabled observatories as part of the Ocean Observatories Initiative. Insets are local and global Pacific sitings. Image credit: Center for Environmental Visualization, University of Washington. Produced for Ocean Networks Canada (ONC) by the University of Washington Center for Environmental Visualization and reprinted with permission from ONC.

enables a mesh structure that may improve resiliency in subsea networks (Harris and Duennebier 2002). However, it will collapse with any shunt (short to ground) fault in the system, whereas the CC system can continue operation; this may be useful or even essential if the primary purpose of the system is seismic and tsunami early warning (where the high power of a CV system is less important). A new high-voltage power supply was subsequently developed (Howe et al. 2002) and used in MARS (Howe et al. 2006) and NEPTUNE Canada.

As these systems evolved, the nodes shrank in mass and volume, simplifying deployment and service. The design and servicing of the sensor network infrastructure and instrument packages is highly dependent on the ROV used and the tooling associated with it (e.g., small cable laying, through-frame heavy lift capability).

Future Cabled Systems

The integration of geophysical sensors in future commercial submarine telecommunications cable systems may provide early warning of earthquake and tsunami events and expand understanding of the ocean's role in Earth's climate. Today's cables include repeaters that amplify the signal every 50–100 km and could be a home for smart sensors for oceanographic measurements; these "smart cables" could eventually provide global coverage at a fraction of the cost of dedicated systems (Howe and Panayotou 2017; You 2010) (figure 3).

Smart Cables Joint Task Force

The Smart Cables Joint Task Force (JTF) is a partnership of three UN agencies[3] and science, telecommunications, and government stakeholders worldwide. It is working with manufacturers to develop prototype sensor suites (for bottom pressure, acceleration, and temperature) that can be included in cable repeaters without affecting the telecommunications (Barnes et al. 2016; Butler 2012; Butler et al. 2014). South Pacific island nations are particularly suited to host initial systems: they have high tsunami and earthquake risk, access to development bank funding, and significant government involvement for connecting communities.

Submarine telecommunications systems are optimized for high-capacity data transmission over long distances

[3] The International Telecommunication Union (ITU), Intergovernmental Oceanographic Commission of the UN Educational, Scientific and Cultural Organization (UNESCO/IOC), and World Meteorological Organization (WMO).

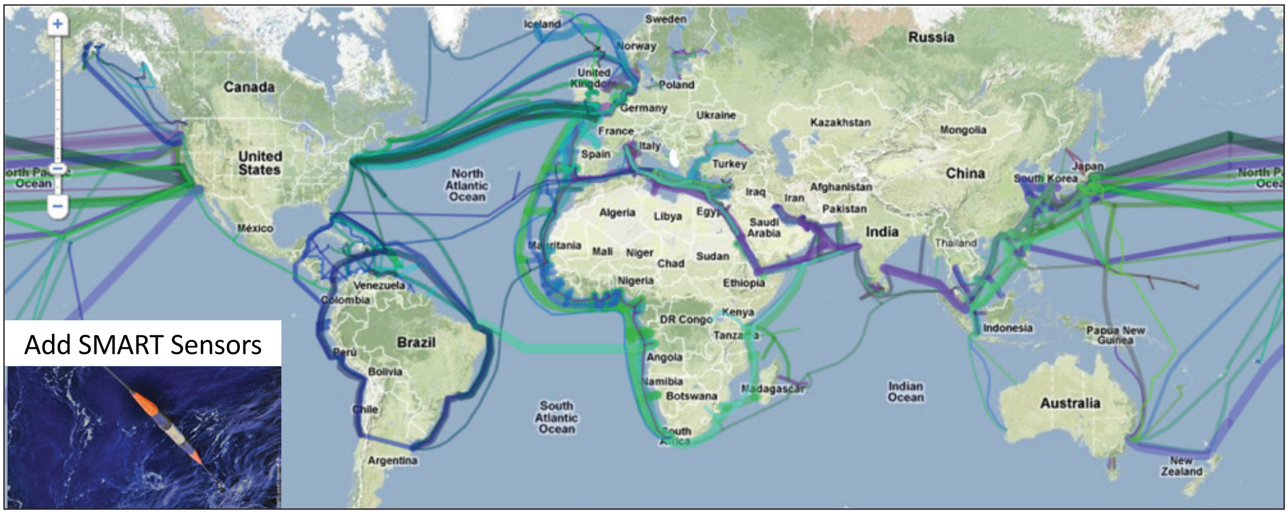

FIGURE 3 The Global Reach of Undersea Cables. Undersea telecommunications cable network for oceanographic measurements: 1,000,000 km, 10–20 year refresh cycle. Repeater stations needed for amplification would be modified to include sensors *(inset)* for oceanographic measurements on a not-to-interfere basis. Image by Greg Mahlknecht, available at https://www.cablemap.info/.

and routinely achieve operating lives of 15–25 years without internal faults or failures. These systems comprise pressure housings (incorporated in the cable at intervals of 60–150 km), optical fiber amplifiers, simple power supply circuits, and little else. Modification—to incorporate temperature, pressure, and acceleration sensors and deliver communications and power to them with negligible impact on the repeaters' primary telecommunications functions—presents certain engineering challenges.

To guarantee complete separation of telecom and science systems, a separate (less expensive) fiber pair with ethernet regenerators could be used for science communications, and power transferred to the (necessarily) external pressure and temperature sensors via a short optical fiber with laser and photocell at respective ends (with no galvanic electrical penetration of the pressure case), providing the necessary 15 kV isolation (Lentz and Howe 2018).

Arctic Cabled Observatory

The Arctic Ocean is both uniquely important and suited for in situ cabled ocean observing systems. Although the Arctic is rapidly progressing toward ice-free conditions in the summer, it will continue to be ice covered in the winter, making satellite coverage and surfacing for GPS and communications very difficult if not impossible. Cabled in situ ocean infrastructure provides undersea power and communications for year-round, real-time monitoring and data collection from instrumented moorings and underwater vehicles. It also supports the implementation of multipurpose acoustic networks for passive monitoring of ambient sound (ice, seismic, biologic, anthropogenic), active remote sensing (thermometry, tomography), underwater communications, and navigation for autonomous vehicles and floats (Mikhalevsky et al. 2015). This is in direct analogy with the use of the Global Navigation System of Systems for many similar purposes beyond navigation.

The reduction of ice cover makes the Arctic Ocean more accessible for shipping, tourism, oil and gas exploration, mineral extraction, fishing, and search and rescue, all of which raise complex geopolitical and economic issues and will affect the environment in ways that are impossible to predict. In situ ocean, terrestrial, and atmospheric observations will be needed to show these changes, identify impacts, and inform strategies among nations to protect and manage the uses and resources of this vulnerable environment.

Trans-Arctic acoustic thermometry was among the first measurements of the influx of warm salty Atlantic water (AW) in the Arctic Ocean in 1994 (Dushaw et al. 2001; Mikhalevsky et al. 1999). It showed an increase in the average AW maximum of ~0.4°C relative to Arctic Ocean climatology (EWG 1997), confirmed by submarine and icebreaker transects, demonstrating the feasibility and value of this method of active acoustic remote sensing. The experiment was repeated in 1998–99 (Mikhalevsky and Gavrilov 2001;

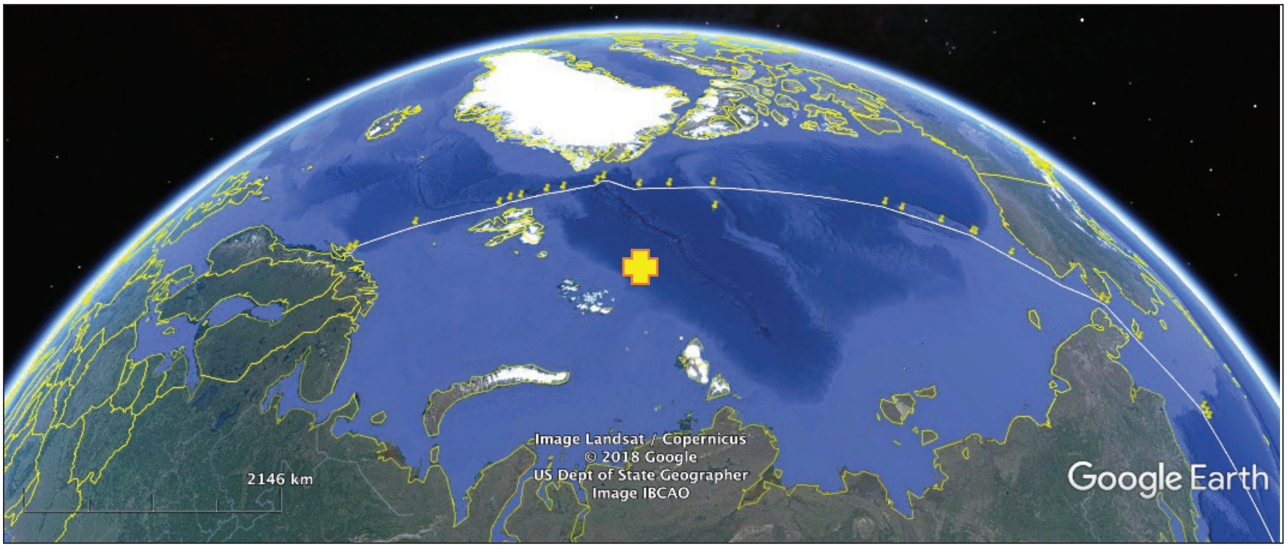

FIGURE 4 Proposed Arctic Ocean observatory system, utilizing a trans-Arctic ocean cable from Norway to Alaska with suggested location for science modules for ocean sampling.

Mikhalevsky et al. 2001) and an additional ~0.5°C was measured as well as evidence of a warm pulse of AW entering the Arctic from Fram Strait (Gavrilov and Mikhalevsky 2002).

The Coordinated Arctic Acoustic Thermometry Experiment will be conducted with an acoustic source deployed on the ice as part of the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAIC) cluster next to the research vessel (RV) *Polarstern*, which will be frozen in the ice and drift across the Nansen Basin in the Arctic Ocean to Fram Strait. A moored source will be deployed in the Canadian Basin along the acoustic section, where fixed receiver moorings will receive signals from both the fixed and drifting sources and provide year-long time series of a large swath of the Arctic Ocean and along the trans-Arctic section for 25 years after the first measurements (Sagen et al. 2018).

The Arctic Watch program envisions a trans-Arctic cable that will instrument a large portion of the Arctic Ocean and provide for continuous real-time in situ observations, including support for multipurpose acoustic networks. It will be useful to consider a system that combines telecommunications, distributed simple robust sensors, and a small number of science observatory nodes. Such a system spanning the Arctic from Norway to Japan is being proposed (figure 4). The science component is a significant cost (because of the nodes and the scale), but commensurate with the scientific need to observe the Arctic Ocean given its climatic importance (Moritz et al. 1990; Polyakov et al. 2017). (A significant portion of the system is in the North Pacific, with equally relevant climate and tsunami warning drivers.) Such a system can provide a fiber pair (15 Tb) dedicated to scientific research, “science telecom” both between land points and from the ocean floor, a handful of branch units supporting “science observatories/nodes” (to add/drop wavelengths), and simple sensors (pressure, temperature, and acceleration) deployed along the cable every 60–100 km on the 10,000 km route (a quarter of Earth’s circumference). Telecom branches to landing sites can also support science and may facilitate more nodes/power and spatial diversity off the trunk cable route.

To support the additional power requirements and ensure separation of telecom and science, a dual conductor cable will likely be required. The nodes will support vertical water column profilers, AUV docking stations, and long-range acoustic tomography/navigation/communications equipment; all of these will extend the sampling footprint of the entire network throughout the basin and under the ice. The incremental cost for the science portion of such a system will be on the order of a “small” OOI, but with several countries involved the cost can be bearable, especially in this region of extreme science interest and need.

Moored Observatories

For moored observatories, suspended above the seabed on cables and buoyed by floats, the design of the cable and buoys is an engineering challenge. A very taut, stiff cable requires a lot of flotation and can be prone to vibration/strumming; but a loose, compliant cable leads to a large "watch" circle as the surface module is pushed by tidal currents. The high-stress environment from high surface waves requires isolation systems that can withstand large forces (e.g., from "snap" loading, whereby a taut line is suddenly stressed). The continuous wave action causes fatigue. Finally, cathodic currents as the result of dissimilar metals and biofouling of equipment near the surface are often failure points.

TOGA

The decade-long Tropical Ocean Global Atmosphere (TOGA) construction program (1985–94) focused on El Niño/Southern Oscillation (ENSO) in the equatorial Pacific (McPhaden et al. 2010). El Niño and La Niña are major climate signals, and TOGA supported research for forecasting the ENSO warm water (El Niño) and cold water (La Niña) mass oscillations with nearly 70 autonomous temperature line system (ATLAS) moorings arranged on north/south lines crossing the equator from Indonesia to South America. The moorings have temperature and depth sensors down to 700 m and meteorological sensors mounted on a toroidal buoy. The data were transmitted to users by the Argos satellite system and supplemented with data from drifting buoys, near-shore tide gauges, and TOPEX/Poseidon, the European Space Agency Remote Sensing Satellite (ERS-1), and US Department of Defense satellites, plus ships of opportunity. TOGA (now known as the TAO array) demonstrated the value of long time-series data for oceanography and climate. Arrays in the Indian Ocean (RAMA) and the Atlantic (PIRATA) are also providing ongoing data for climate studies.

Ocean Observatory Initiative

The OOI was a major NSF effort supporting the concept of ocean observatories (Delaney and Kelley 2015; Smith et al. 2018). The regional cabled array components, NEPTUNE and VENUS, are described above. The moored components were systems of coastal and deepwater global arrays, with several moorings primarily to obtain directional information. OOI goals were sustained measurements over 25 years with (1) real-time (or near-real-time) availability; (2) two-way communications links for control; (3) ports, power, and bandwidth for expandable instrumentation; and (4) adaptive sampling for episodic events such as earthquakes, eruptions, and phytoplankton blooms.

Coastal Arrays: Endurance and Pioneer

The Endurance Array comprises two lines off the coasts of Washington and Oregon, deployed by the University of Oregon and moored in shore (~30 m), shelf (~100 m), and offshore (600 m) water. Each array has a surface buoy, one of several profiler moorings, and a "multifunction" mooring anchor. The surface buoys have a complete set of meteorological instruments for monitoring solar radiation, near-surface water temperature and salinity, surface wave directionality, near-surface currents, and momentum and buoyancy. They also have profilers that sample the water column by traveling up and down the mooring cable, with thermometers and chemical sensors for dissolved O_2, pH, and optical properties. An acoustic Doppler current profiler (ADCP), which measures currents by backscattering from suspended particulates, is located above the maximum profiler excursion depth. These are supplemented by a fleet of buoyancy-driven gliders and on-station Wave Gliders (by Liquid Robotics/Boeing). Sampling rates cover the range appropriate for the processes studied, and the data are transmitted inductively on the mooring cable by satellite to shore or by a fiber link to the cabled array. Wind turbines and solar panels charge batteries to provide power.

The reduction of Arctic ice cover will affect the environment in ways that are impossible to predict. In situ observations will be needed to show these changes.

The Endurance Array works with the NEPTUNE/VENUS cabled observatory to measure coastal anomalies from ENSO, the Pacific Decadal Oscillation, the wind-driven up-/downwelling caused by the Columbia River, hypoxic and anoxic events, algal blooms, and ocean acidification.

The Pioneer Array, on the shelf break off New England, has an instrumentation suite similar to the Endurance Array, with ten mooring locations over a 9 km × 47 km area from 95 to 450 m deep. These fixed moorings are supplemented by six coastal and two profiling gliders that run a preset track to interpolate the mooring observations and sample eddies of the Gulf Stream.

Global Arrays: Irminger Sea, Station Papa

Four deepwater global arrays were planned for OOI. The Irminger Sea Station is southeast of Greenland and Station Papa is west of Canada. Two others—in the Southern Ocean (planned west of southernmost Chile) and the Argentine Basin (southeast of Rio de Janeiro)—were deployed and recovered, but programmatically terminated because of budgetary issues.

Global arrays need to be able to operate in very high winds and waves, so the engineering challenges for long-term survivability are great.

The global arrays need to be able to operate in very high winds and waves, so the engineering challenges for long-term survivability are great. Each array has a triangle of global/surface moorings separated by approximately 10 water depths (nominally 40 km). Each triangle has redundant meteorological systems, a covariance flux system, and sensors for wave spectra, irradiance, air-sea pCO_2, dissolved O_2, nitrate, fluorescence, salinity, and temperature. Each array has a CTD profiler that samples the water column. Additionally, CTDs and ADCPs are deployed in the upper water column down to 1,500 m. Inductive coupling on the mooring cable provides communications (by internet linked by Iridium) from the profilers and instruments. Energy is provided by wind turbines and solar panels charging lead acid batteries.

There are three goals for these arrays: (1) observations of the full water column and sea surface; (2) sampling of physical, biological, and biogeochemical variables; and (3) sampling of eddy scale variability. The triangular geometry enables directional analysis of mesoscale variability.

Ice-Tethered Profilers

While there is the hope for an Arctic Ocean cabled system, there is now no long-term observatory capability in this critical ocean. The semipermanent Ice-Tethered Profiler (ITP) from the Woods Hole Oceanographic Institution (WHOI) measures ice drift and samples the upper water column using profiler buoys installed by operations of opportunity (Toole et al. 2006). Nearly 100 ITPs have been deployed by drifting ice stations, icebreakers, aircraft, and other means such as submarines; locations vary since they are dependent on the field programs. Most ITPs start out drifting in the Beaufort Gyre of the western Arctic or in the Transpolar Drift of the eastern Arctic; almost all either exit the Arctic into the north Atlantic or are destroyed by ice activity.

Each ITP has a GPS and a profiler. Every 4 hours the profiler measures CTD and O_2 on the upward excursion from a depth of 750 m. The data are transmitted to WHOI through the Iridium satellite system and, after being edited for quality, posted on the internet. Recent measurements of the horizontal velocity of the profiler as it ascends the mooring line have provided the first synoptic data of Arctic Ocean processes such as ice rheology, currents, eddies, halocline formation, and water mass intrusions. Combined with satellite observations they have yielded new insights about Arctic oceanography.

Sensors

To make reliable measurements over long periods, ocean sensors must be free of drift over time and the clocks used to record data must be highly accurate. We illustrate selected sensor challenges and solutions.

The Wendy Schmidt Ocean Health XPRIZE competition offered $2 million in prizes to inspire accurate, durable, and affordable pH sensors for the study of ocean acidification. Two prizes were awarded, for accuracy and affordability.

Global ocean acidification is increasing, but spatial and temporal measurements are challenging given the relatively small yearly changes. The same problems arise with other ocean observables such as temperature and salinity. The ARGO program deals with the stability problem over the >5-year deployment of each float by using sensors uniformly manufactured to detailed specifications, often from a single provider. (The use of sensors that differed from the specifications has led to anomalies in measurements.)

Timing is difficult in the deep ocean beyond the reach of GPS, especially the measurement of travel times between widely separated acoustic sources and ATOC receivers. If the time is known accurately, the travel time of signals over hundreds and thousands of kilometers can be determined over decades to provide an accurate measure of ocean warming. But over large distances, say 1,000 km, 1 m°C results in a 2 millisecond change in travel time. Temperature changes can be inferred by travel time changes only if clocks are stable and accurate.

Acoustic thermometry measurements require an error of less than 1 ms during a year, or $1{:}3.2 \times 10^{10}$. A solution did seem to be in hand with new relatively low power Chip Scale Atomic Clock (CSAC) technology. The manufacturer had claimed an error of ±3E-10 s per month, but over longer periods of time the accuracy degenerated to unacceptable levels. While this is an improvement over previous clocks, it is still necessary to use a rubidium oscillator (using significant power) that checks the clock frequency at prescribed intervals (Worcester et al. 1985). This combination—the rubidium oscillator turned on and off with a very low duty cycle and the CSAC running continuously—can provide times accurate to a ms over the course of a year. As frequencies of interest decrease, the accuracy required also decreases; for example, the Global Seismic Network (GSN) requires an accuracy of 10 ms over a 2-year period (1.59E-10) using GPS. But seafloor GSN stations (or other instruments) do not have the advantage of connecting to GPS to determine time. Thus, the use of atomic clocks is critical in the oceans.

An ocean geodetic measurement that requires in situ correction involves seafloor pressure. The goal is to use accurate pressure measurements at the seafloor to measure ocean thickness that could be attributed to sea level rise due to melting land ice, or the depression of the seafloor due to plate tectonic movement.

Realizing that commercial quartz pressure gauges drift slowly over time with either sign, Sasagawa and colleagues (2016) designed an instrument that calibrates pressure gauges at the seafloor using deadweight testers, precision weights on a piston-cylinder assembly, to measure drift over time. Commercial quartz pressure gauges drift slowly over time with typical rates of 20–30 cm/yr. For more than a year, calibration sessions on the Juan de Fuca Ridge were repeated 22 times. Each session required approximately 20 min, with 12 repetitions to improve the statistics of the estimate. The pressure drift corrections provided a consistent record of uplift for both instruments. In another recent technical development, to measure the drift (offset vs. time) the pressure sensor is switched occasionally between the external water to internal air in the instrument case, with the latter pressure measured by a barometer. Initial results show drifts of ~1 mm/yr that can be compared with ~3.2 mm/year for globally averaged sea level rise (Wilcock et al. 2017).

If time is known accurately, the travel time of signals over thousands of kilometers can provide an accurate measure of ocean warming.

Seafloor geodetic measurements associated with plate tectonics can be measured without drift through GPS-A (A for "acoustic"; Chadwell and Spiess 2008). Accurate measurements of ship position can be transferred to a geodetic/acoustic monument on the seafloor. The initial result in measuring the velocity of the Juan de Fuca Plate with respect to North America is 63.6 ± 3.6 mm/a to the southeast (67.2° ± 7.9°). Chadwell and Spiess (2008) substituted a Wave Glider autonomous surface vehicle (ASV) for the ship, launched from the shoreline to the monument to make the necessary measurements. The technique has been adopted in Japan to augment DONET's seismic measurements.

Accurate seismic measurements on the seafloor can be made over a very broad spectral band. Triaxial broadband seismic measurement extends from 10^{-4} to 50 Hz with a 360 s natural period mass; 24-bit digitizers have been used to measure displacements as small as 1 nm, the size of the C^{60} Buckyball molecule. A new seismometer measures mass displacements in seismometers using laser interferometry with an accuracy of a femtometer (10^{-15} m), the size of a proton (Zumberge et al. 2018).

There are no electronics involved in the measurement, unlike the very broadband systems discussed above. Nevertheless, considerable computing power is required to track the interferometric fringes as the masses move. The Laser Interferometer Gravitational-Wave Observatory (LIGO) similarly detects gravity waves in space-time; eventually it will be possible to make such high-bandwidth measurements on the seafloor. Pressure measurements using differential pressure gauges extend from the tides (10^{-5} Hz) to at least 50 Hz.

Observatories at the seafloor need to communicate with "offboard" sensors and AUVs that are not connected by either electrical or fiber-optical cables.

Communications

Communications for observatories were a challenge until the availability of satellites such as the Argos and Iridium systems. Even now links to deep-sea observatories can be problematic. We divide systems into three categories: cabled, moored, and drifting.

- *Fixed systems connected to shore by cables:* The most notable of these systems are DONET, OOI, and Ocean Networks Canada, whose system design includes wide-bandwidth, multichannel communications.
- *Moored systems on an anchored tether:* These can have two forms: (1) a vertical line array of sensors sharing a cable to a central module that periodically surfaces for a data dump to a satellite system or (2) a module that has only a surface expression and is designed for wave stresses. In some installations, a surface extension (e.g., Wave Glider) may maintain station above a seafloor observatory, forming a "virtual" tethered system with satellite communications.
- *Drifting systems:* These are floats deployed either to set depths in the ocean (e.g., 2,000 m) or on the ocean or ice surface. They drift with the currents and periodically surface to report their data usually by a satellite link. They have been robust and provided sparse but widespread sampling of the CTD and dissolved oxygen levels of the ocean interior. They are expendable and originally lasted 4 years; plans exist to extend their lifetime to 6 years and their use to the deep ocean. By far the most successful and important are Argo floats (see Fu and Roemmich 2018 in this issue).

In the Arctic Ocean the ITP is a hybrid of all three categories (Toole et al. 2006).

Observatories at the seafloor need to communicate with "offboard" sensors and AUVs that are not connected by either electrical or fiber-optical cables. The two modalities are acoustics ("acomms") or more recently optics. Acomms operate at 1–15 kHz depending on the range desired and power available; bit rates typically range from 100 bps (bits per second) for very long range links to 10 kbps for near-line-of-sight ones. Modern communication modulations and coding have led to low error probabilities, but there are often outages due to propagation variability. The WHOI Micromodem (Freitag et al. 2005) uses frequency-hopped (Hedy Lamarr, US Patent 2292387A, 1941), frequency shift keying modulation, but other methods (orthogonal frequency division modulation, turbo coded) are being tested. In most applications these systems have not been bidirectional. For the Scripps seafloor seismic system in deep water, the modem efficiency is highly reliable (Berger et al. 2016).

Optical links have been tested (Farr et al. 2016), and ranges up to 100 m and bit rates of 10–20 Mbps in clear dark water have been claimed. These systems use hemispherical LED sources, photomultiplier receivers, and time-division-multiplexed bidirectional links. Another approach involves a narrow beam laser and sensitive single photon detectors based on transmissions from the Moon. Rates close to 1 Gbps at 150 m have been tested (Hamilton et al. 2017). The technology challenge is to keep the laser pointed amid sensor platform motion and ocean turbulence.

Once data are at the surface there are several methods for transmission to users and for users to command observatory operations. We classify these as satellite or radio frequency systems. The former include Argos, Iridium, and FleetBroadband (Inmarsat). An Argos platform transmitter sends a message (up to 256 bits) to a satellite in near-polar, sun-synchronized orbit; the message is downlinked to a receiver site and sent to processing centers in either the United States or France, from which it is made available on the internet.

The Iridium low Earth orbit (LEO) constellation of about 66 satellites is a very popular means for transmitting data. The system operates in the L-band (1616–1626.5 MHz) and has 240 channels, each providing 2.4 kbps with a 5 W uplink power. The low power and approximately 10 cm form factor of the transmitter make these satellites very convenient for many oceanographic applications. Importantly, Iridium enables connectivity in polar latitudes.

FleetBroadband uses three geosynchronous satellites and can provide up to 432 kbps (depending on the size of the antenna). The fastest rates, using 50 W for uplink power, are appropriate for large buoys. The geostationary orbits limit their use in polar latitudes.

If an observatory is close to shore, several noncommercial technologies are available, including cell phones. These ad hoc systems use both the high-frequency spectrum, with ground-based propagation, and very high frequency, with sonobuoy technology developed by the US Navy. Scripps Institution of Oceanography pioneered the provision of internet to the Academic Research Fleet with support from ONR. Ships, which are often used to install, maintain, and retrieve observation systems, themselves now serve as mobile observatories, continuously returning data of interest to shore in near real time.

The HiSeasNet project, launched in 2002, provides internet access to ships at sea in the University-National Oceanographic Laboratory System (UNOLS) fleet over satellite, at 21.5 Mbps speeds from shore to ship and 1.5 Mbps ship to shore. With the growth and expansion of research and communications technologies it is mission critical that HiSeasNet provide uninterrupted internet access with sufficient bandwidth for scientific teams at sea to support research and communications with shore-based scientists and educators. Initially implemented on global C- and Ku-band channels, these systems use geosynchronous satellites such as the Intelsat network. After nearly 16 years of service, for the early adopter ships of HiSeasNet the lifecycle replacement of key systems has begun, with new equipment to promote effective system maintenance and management and simplify operations for both shipboard and shore-side technicians. Scientific parties will experience more uniform, higher-bandwidth network access across all UNOLS vessels.

The installation on NSF's ice-strengthened RV *Sikuliaq* has maintained communications as far north as 75°N, where the geostationary satellite is very close to the horizon. The *Sikuliaq* must move around ice coverage to reach targets near the pole, and satellite imagery access is essential for daily cruise planning.

The bandwidths cited above are much smaller than normally available through university or home connections (e.g., >100 Mbps), making data rates painfully slow for shipboard users. Scripps is planning experiments with small satellites ("CubeSats") to significantly increase bandwidth and decrease costs. The shipboard antennas for LEO and MEO (medium Earth orbit) satellite systems are compact, flat synthetic aperture systems that do not require a large, expensive steerable antenna on board. Gbps bandwidths are already available and will continue to grow. In addition, the miniaturization of antennae will soon support communications with ASVs.

Uninterrupted internet access with sufficient bandwidth is critical for scientific teams at sea to support research and communications with shore-based scientists and educators.

AUVs and ASVs

Oceanographic research has traditionally relied on the use of ships at sea for sampling as well as instrument deployment and recovery. Many scientific problems will continue to require the use of ships, but to contain costs, continuing research will require the use of battery-dependent AUVs and ASVs that draw on wave or wind energy for propulsion and solar power for instrumentation. The costs for construction and operation of autonomous vehicles are substantially less than for surface ships or submarines.

Acoustic modems enable the transfer of data to and from deep seafloor sensor packages to an ASV (Berger et al. 2016), which connects to the Iridium satellite constellation for transmittal to laboratories ashore and thence to an open repository for scientific community access. Future systems may take advantage of small

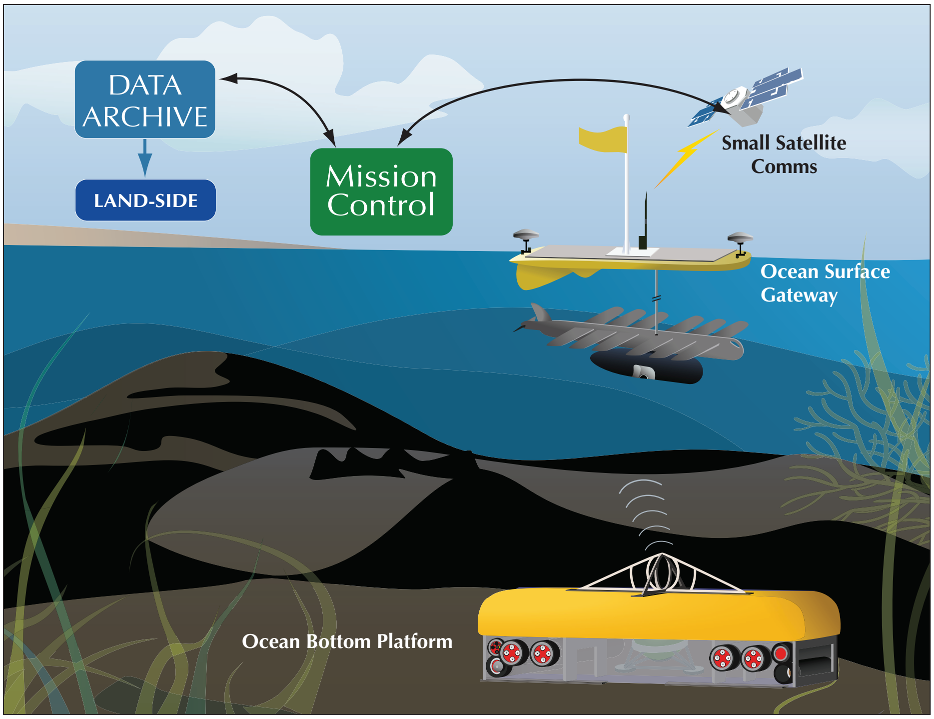

FIGURE 5 Low-latency autonomous seafloor observatory using acoustic modem in the water column connected through ASV to shore.

satellites to enhance data rates and reduce costs. Blue-green light can be used for transferring data much more rapidly, but the range between such modems is very limited, necessitating additional vehicles for data transfer (Farr et al. 2016) (figure 5).

Operational Paradigms

Ocean monitoring and observation systems can be significantly enhanced by autonomous mobile platforms attached to the cabled observatory infrastructure. AUVs and ASVs can be launched by operators in response to episodic events detected by other sensing modalities. The persistence and sensing capabilities of such small platforms have improved dramatically, and AUVs and ASVs are now widely used in oceanographic research. Autonomous undersea sensing systems are also valuable for the detection and tracking of marine mammals and man-made sources of sound in the presence of ambient noise.

Limitations of Human-Operated Platforms

AUVs and, to a lesser extent, ASVs are almost entirely operated from staffed surface platforms, where operators program the vehicles for a specific sensing mission (e.g., measuring salinity, temperature, or bathymetry in a "lawnmower" survey pattern). This approach is of limited utility for AUVs responding to episodic events.

Because such events are often of limited extent in both time and space, traditional sampling strategies would spend most of their time in areas of quiescence with little useful information collected relative to events. This comes back to the fact that the ocean is undersampled both temporally and spatially.

Effective use of resources requires that platforms be redirected during a mission (e.g., to closely follow a plume or frontal boundary). But the ability of human operators to redirect autonomous assets in real time is severely constrained—even impossible—because of the band-limited and intermittent communications connectivity. Even with today's advanced acoustic communications technology, the propagation physics of the ocean waveguide allows for the transmission of only a few hundred bytes per minute, with typical intermittency of tens of minutes over distances beyond a few kilometers, effectively prohibiting the human operator from redirecting an AUV mission in less than hours—the duration of a typical AUV mission anyway.

Behavior-Based Platform

For a powered AUV to be an effective part of an ocean observatory, the operational paradigm must rely on artificial intelligence (AI), to allow the AUV to respond to its sensors, and have a high level of onboard situational awareness. Without the possibility of transmitting large amounts of data back to the operators, the onboard autonomous function must be capable of completing the mission objective (i.e., sampling and characterizing an event) and of adapting to the environment in a manner that is optimal for the tactical situation and mission stage, without any human intervention or assistance. To achieve this, the AUV must be controlled by a *behavior-based* autonomy system that does not require reprogramming or reconfiguration between missions or even mission phases to ensure optimal data collection. Such a system can autonomously respond to both predictable and unpredictable sensor events, requiring operator intervention only via simple, high-level status messages and commands for switching between mission modes.

"Nested autonomy" is such an operational paradigm, centered around a multiobjective optimization helm that makes constant decisions on speed, heading, and depth based on onboard situational awareness, sensor processing, and modeling and forecasting (Schmidt et al. 2016). The AUV can thus adapt its navigation and sensor modalities for completely autonomous detection, classification, localization, and tracking of episodic—usually unpredictable—events.

In addition, individual nodes may actually collaborate with others without a human operator in the loop (Schneider and Schmidt 2010). Network nodes within (at least occasional) acoustic communication range of each other may fuse their data with those obtained and broadcast by others in the vicinity. For example, two AUVs with acoustic arrays may track a marine mammal and collaboratively create an accurate localization by triangulation.

A typical acoustic or optical sensing system generates data at a rate of megabytes per second, which the acoustic communication capacity of the undersea environment is totally inadequate to transmit to operators. Therefore, in contrast to air- and land-based equivalents, data processing cannot be performed centrally but must be largely distributed to individual nodes. Similarly, real-time "tethered" control of underwater assets is impossible because of the latencies imposed by the use of occasionally surfacing gateway nodes. Consequently, real-time command and control decisions must be made locally on the nodes, in turn requiring that not only the data processing but also the analysis and interpretation, traditionally performed by human operators, be done on the nodes. This requires fully integrated sensing, modeling, and control equivalent to what is available on crewed submersibles in terms of intelligence and resources. In effect, the autonomy system must have "cloned" versions of all the domain experts required for achieving the mission objectives—an onboard "oceanographer," "acoustician," "communications engineer," and, most importantly, "captain" who makes the final decision for any action based on input from the domain experts weighed against the objective of maintaining operational safety. This AI-based design is at the core of the nested autonomy paradigm (Benjamin et al. 2010).

AI-based autonomy also enables adaptive control of mobile nodes to take optimal advantage of an environmental and tactical situation through modeling and forecasting. For example, a mission to map internal waves on the continental shelf requires the AUV to focus its sensors on the main thermocline (Petillo and Schmidt 2014), which is not optimal for communication with a gateway buoy because of the strong downward refraction of the shallow water waveguide. For the vehicle to communicate its status and event reports to the operator, the helm must change depth while communicating, with minimal time away from the thermocline. To do this, the helm asks the onboard "acoustician," through a high-fidelity embedded acoustic model, to provide a robust estimate for the optimal acoustic communication depth.

An AUV's onboard function must be able to adapt to the environment in a manner that is optimal for the tactical situation and mission, without any human intervention.

Docking Stations and AUVs

An AUV downloads data from an ocean bottom seismometer (OBS) and uploads them to a Wave Glider surface gateway via the Iridium satellites. This can work well if the system operates within the radius of the so-called reliable acoustic path (near-vertical ray paths).

A central node and possibly several AUVs would provide local reconnaissance of the seafloor, physical oceanography data (e.g., CTD), and chemical and biological samples. This has been called "bits for joules": an AUV would gather data and return to the observatory node where the data "bits" would be transferred and the AUV batteries recharged with "joules" from the node. The technology is considered well within reach but, aside from some tests with the LEO-15 observatory, docking stations remain a future possibility, largely because of concerns about a very expensive AUV being at risk and the need for a costly recovery operation.

For the docking process the AUV is guided to a cone by high-frequency acoustics, typically around 20 kHz, and/or optics (if the water is clear). The final homing uses directionality similar to split beams whereby up/down and port/starboard steering corrections align the vehicle with the cone axis, which has been aligned “upwind” of the current to provide control. Then either a waterproof mechanical connection or an inductive coupling transfers energy to recharge the AUV batteries. Data are downloaded either by a waterproof electrical connection or by optics. Other modalities have been suggested such as linking with a cable that is either moored or deployed from a surface buoy. Development of practical docking stations is under way—a 2 m AUV repeatedly docked at 100 m water depth in the South China Sea (Y. Chen, personal communication; Lin et al. 2018). It is expected that in the near future docking stations will be connected to cabled observatories, enabling both routine surveys and event response. This will finally force the severing of the bond between AUVs and their direct human operator (i.e., on a nearby ship).

Summary Comments

We have reviewed the engineering challenges for staging observatories to sample the oceans and their depths (on average 4, but sometimes 12, km deep). The need for data from these observatories is critical. The oceans are the greatest driver of the Earth’s climate since they store nearly 95 percent of its heat content. Virtually all commerce rides on them and the world’s data networks run beneath them. US national defense depends on control of the seas.

The technologies of observatories must often work at extreme pressures in a very corrosive and challenging environment and they push the state of practice. Observatories are complicated systems that draw on many disciplines of engineering and science—from hydrodynamics to digital communications, from metallurgy and corrosion to biological processes, from acoustics to optics, and more. Interdisciplinary capabilities are imperative.

Observatories for long-term observations complement the traditional expeditionary approach of ocean science to enhance understanding of the dynamics of planet Earth.

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