Sensor Networks for Cabled Ocean Observatories

Bruce M. Howe* and Timothy McGinnis
Applied Physics Laboratory
University of Washington, Seattle, Washington, 98105, USA
(*phone: +1-206-543-9141; fax: +1-206-543-6785; email: howe@apl.washington.edu

***Abstract*—An infrastructure for global, regional, and coastal sub-sea observatories is being planned to support individual and networked sensors. The main emphasis has been to provide basic power and communications capability at "primary" nodes; less has been given to the sensor network infrastructure that extends the capability of the observatory into the full three-dimensional volume of interest. Secondary cables and junction boxes are needed to extend the horizontal reach by tens to hundreds of kilometers from the primary nodes; moorings up into the water column and boreholes into the sediments and crust are necessary to extend the vertical reach. The support infrastructure must include navigation and communications systems, mobile platforms such as free-swimming autonomous undersea vehicles, and bottom rovers that carry sensors and provide data and energy "tanker" service. The requirements for these various network elements and possible solutions are discussed, with an emphasis on the design of a specific mooring for the ALOHA Observatory north of Oahu. This subsurface mooring will support a full-water-column moored profiler with a docking station that transfers power and data, enabling adaptive sampling. The subsurface float at 200 m provides a ROV-serviceable platform for near surface instrumentation, such as an upward looking acoustic Doppler current profiler and a winched sensor system.**

***Index Terms*—ocean moorings, ocean observatories, ocean technology, underwater systems.**

I. INTRODUCTION

The development of sensor networks is essential to realize the full potential of cabled ocean observatories. We assume a backbone infrastructure with "primary" seafloor junction boxes or nodes that will deliver power, communications, and precise time to sensor networks consisting of the sensors and the sensor network infrastructure. The sensor networks then extend out from these nodes, filling in the three-dimensional space between the nodes. The sensor networks will account for a significant portion, if not the majority, of the lifetime costs for an ocean observatory.

Autonomous or tethered platforms and secondary cable systems will extend the network across the seafloor throughout the ocean volume. This reflects the vision of the underway NEPTUNE cabled ocean observatory in the northeast Pacific, Fig.1[1)]. In other observatories there may be only a single backbone node as, for example, beneath a "DEOS" buoy[2)] or a node at the end of a re-used telecommunications cable such as the H2O Observatory[3)] or the planned ALOHA Observatory[4)]. The NEPTUNE cabled observatory is used as a basis for much of the discussion, though, when discussing a water-column sampling mooring, the ALOHA Observatory (AO) will be used; many of the concepts are applicable to other ocean observatories.

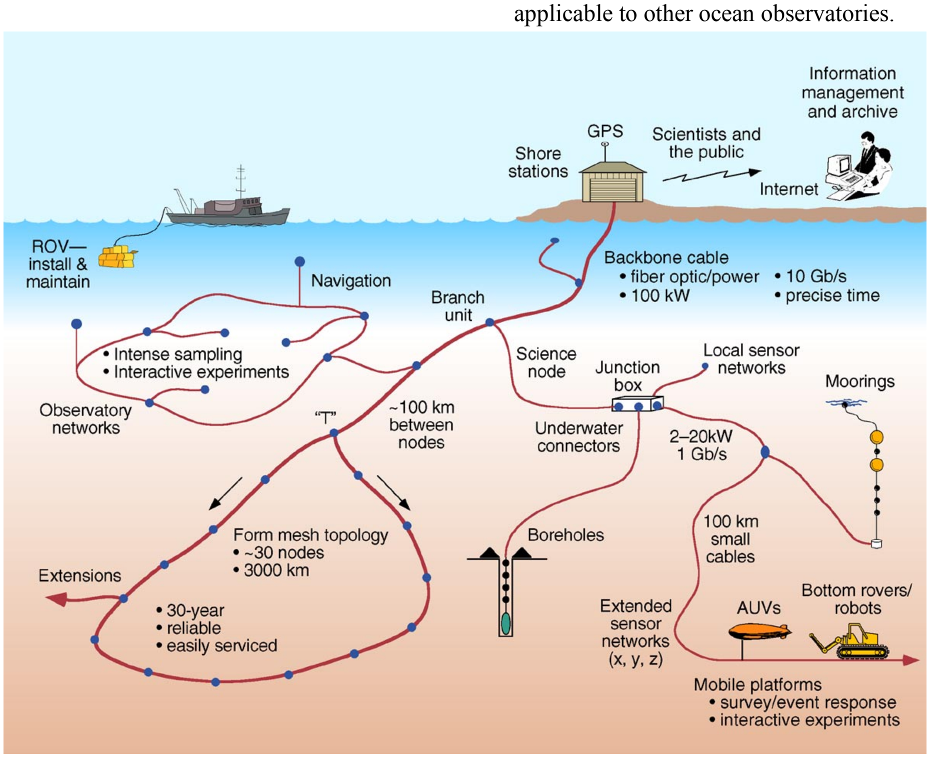

FIG. 1: Essential elements of a cabled observatory.

The robust backbone or primary infrastructure system consists of an optical-electrical telecommunications cable operating at 10 kV (~100 kW) with optical fibers for ~10-Gb/s communications and precise time distribution. The node junction boxes are connected to the backbone cable via spur cables for ease of servicing by ROV (Remotely Operated Vehicles). The primary nodes provide 400 V and 48 V (up to 10 kW per node), 100-Mb/s IP/Ethernet communications (up to 1 Gb s^{-1} per node), and microsecond timing, which will be transmitted to much of the sensor network. The entire concept depends on wet-mateable connectors and other components serviced by ROV. Interface standards will be essential, as will sophisticated data management and archiving. All active sensor network components (sensors and infrastructure such as secondary junction boxes) will have IP addresses and the interactive command and control capability, thus permitting adaptive sampling and interactive robotic control. The vision calls for open access to all data, permitting researchers around the world to mine the data for all its value.

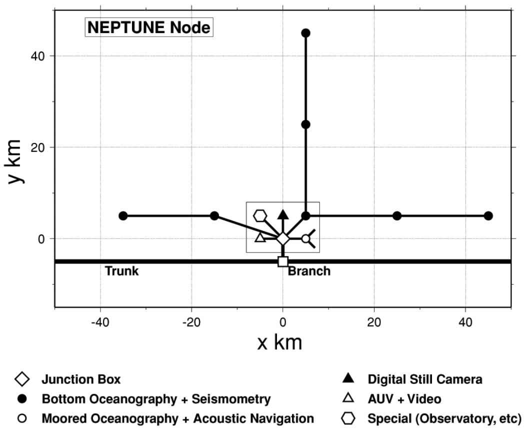

FIG 2: A possible sensor network surrounding a backbone node. Each solid dot includes a secondary junction box.

From the primary science nodes various sensor networks will radiate out in all three directions (Fig 2.). Moorings will sample up into the water column. Instrument strings in boreholes will sample the subsurface sediments and crust. Dense networks will cover small areas (Fig. 3). Various vehicle platforms carry sensors to sample between fixed sensors and to service instruments that have no direct connection to the cable system.

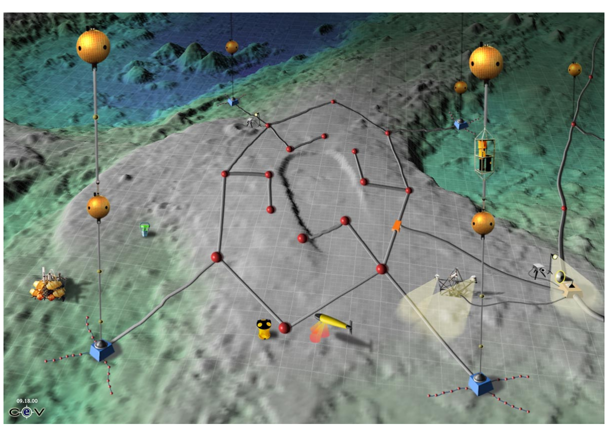

FIG 3: A possible sensor network surrounding Axial Volcano on the Juan de Fuca Ridge. The network is connected to a primary science node to the right; the red dots represent secondary junction boxes, to which many sensors would then be connected.

In the following sections we describe these various components and functions of the sensor network infrastructure. It extends the horizontal reach along the seafloor (which includes such basic components as extension cables, secondary junction boxes, converters, and interface adaptors); extends the vertical reach into the water column and the seafloor; supports autonomous undersea vehicles or AUVs; and supports services such as navigation and acoustic communication. Our primary purpose here is to stimulate discussion and the appropriate development processes. The reader is referred to the proceedings of the 4^{th} *International Workshop on Scientific Uses of Submarine Cables and Related Technologies 2003* for a recent collection of related papers[5].

II. HORIZONTAL COVERAGE

One possible simple, horizontally distributed sensor network distributes the power and communications capability of the backbone, but at a reduced capability (Fig. 4). The particular sensor suite shown here consists of robust, bottom-mounted instruments emphasizing physical oceanography, and using remote sensing for gravest mode structure (e.g., acoustics and electrometer, as noted)[6]. Secondary junction boxes, cabling, connectors, voltage and communications converters, and provision for efficient deployment, operations, maintenance, and recovery are essential elements of the sensor network infrastructure.

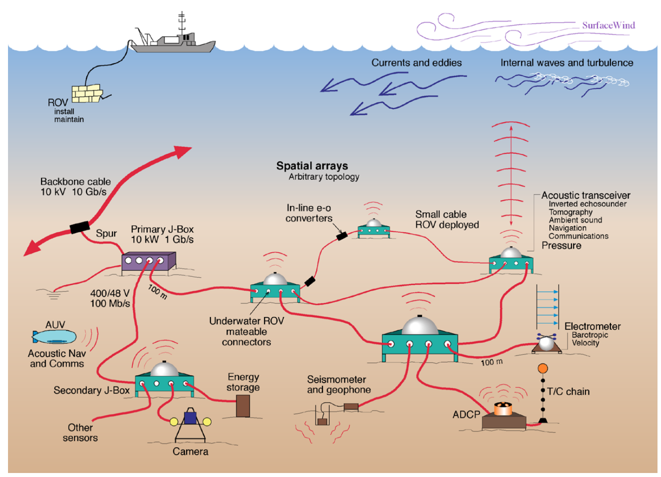

FIG 4: Possible basic sensor array emphasizing physical oceanography observations and the associated sensor network infrastructure. One secondary node and associated sensors might form the fundamental sampling unit for an observatory.

A. Secondary Junction Boxes or Nodes

The essential function of the secondary junction box is to replicate the connector/port on the observatory primary junction box at remote locations. Much of the secondary junction box will mimic a primary NEPTUNE node, but with reduced capability (e.g., lower power levels and communications bandwidth) and levels of redundancy. On the secondary junction box additional ports (~4–8) will be provided. Ports can be used to link the secondary "backbone" system (400 V, 100-Mb/s Ethernet, timing) as well as for sensors. Any arbitrary network configuration can be constructed by connecting in series or using three ports to form a "T". There will likely be many different versions of secondary junction boxes tailored to specific use scenarios.

A micro-controller will be used to control the secondary junction box and to communicate with the shore Observatory Control System (OCS). It will be similar, if not identical, to the controller in a primary science node. Most of the control logic will reside on shore with the local inputs and outputs implemented by the node controller. A major function will be load monitoring and control (i.e., switching connected instruments on and off). One of its functions will be to keep the local clock synchronized with the backbone time and report differences between multiple input timing signals. This controller will look just like another instrument to the OCS and the Data Management and Archive System (DMAS). For communications, a high reliability commercial Ethernet switch will be used that takes multiple input/outputs and sends the packets to the appropriate locations, whether they are commands to instruments or data to the archive and scientist on shore. The secondary 48-V and 400-V power supplies will have similar load monitoring and control as the primary science node (i.e., switching, ground fault, and overcurrent protection).

B. Cables, Connectors, and In-line Converters

The cables and connectors linking the sensor network infrastructure are constrained by interrelated considerations including connector cost and reliability, power and data cable losses, availability of "higher" voltage DC/DC converters, desired distance, cable size and weight, and overall life cost including installation.

Underwater ROV-mateable connectors are essential to the cabled ocean observatory concept. NEPTUNE will use all electrical connectors rather than hybrid electro-optical ones because of cost considerations (approximately $4K versus $40K a pair, respectively). However, to communicate over distances greater than a hundred meters at 10 or 100 Mb/s, optical fibers are the only practical solution. Thus, the electrical signals at the connectors must be converted to optical signals for transmission over the fiber, and then back to electrical again at the next connector. This requires so-called "in-line media converters." These devices, housed in small pressure cases in-line with the cable within 100 m of a connector (or within the connector shell), convert the electrical 100baseT Ethernet signals to and from the optical domain; suitable modules a few centimeters on a side are available commercially.

For power transfer over a cable, a governing principle is that for a constant power load, the I^2R resistive losses in the cable must be less than or equal to the maximum load power, i.e., the efficiency can be no lower than 50% (at which point voltage collapse occurs). This becomes a limiting factor when using relatively low voltages and "small", high resistance cables that can be installed cost effectively by ROV. A useful way to compare cable capabilities is to calculate the power capacity: the amount of power that can be transferred for a given distance (1 km) at a particular efficiency. Table 1 shows the distance × power product (watt-kilometers) that can be delivered at four different voltages using two different wire sizes assuming a transmission efficiency of 65%—load power/(load power + I^2R cable loss).

Source Voltage	Wire Gauge	Cross Section	Wire Resistance	Power Capacity
VDC	AWG	mm^2	Ohm km^{-1}	Watt-km
2000	16	1.3	14	32500
2000	24	0.2	75	6087
1000	16	1.3	14	8125
1000	24	0.2	75	1522
400	16	1.3	14	1300
400	24	0.2	75	243
48	16	1.3	14	19
48	24	0.2	75	3

Table 1. Power delivery capacity for several scenarios.

A cable that might find widespread use has two #16 conductors and a steel tube with four fibers, all encased in polyethylene and a polyurethane jacket with outer diameter of 8 mm. Steel (or copper) is necessary to protect the optical fibers from hydrogen darkening, and polyethylene is used to prevent water diffusion, a problem with polyurethane over long duration. The cable must have enough weight to stay on the bottom and have adequate insulation and mechanical protection against fish bite and abrasion.

On several of the (eventual) longer legs, the in-line converters may need to include voltage boosting to ~1000–2000 V. Up-converters are commercially available; the down converter to 400 V can be based on the 10-kV one being developed for the primary NEPTUNE nodes (which is based on 200-W, 200-V to 50-V modules). For even higher power requirements, it will likely be necessary to use 10 kV.

If the cable is short (~100 m) it can be unreeled by an ROV in a simple operation. If longer but physically small and light weight, it can be deployed using a special ROV tool sled (already demonstrated by MBARI, JAMSTEC, and the oil industry). Other tool sleds attached to ROV garages can deploy heavier cable loads. Still larger diameter and heavier cables will likely require a surface ship for installation.

It is likely that some sensors will require adapters to interface to the system; in NEPTUNE jargon these are science instrument interface modules (SIIMs). For instance, many instruments presently use RS-232 for communications. Very small device servers exist that convert RS-232 to Ethernet; they have a small processor with memory to add metadata to the data stream. Power and timing may require a custom interface[7]. Instrument manufacturers are slowly implementing more sophisticated interfaces; by the time NEPTUNE comes on line, it is expected that many instruments will have the required interface software and hardware on-board.

III. VERTICAL COVERAGE INTO THE WATER

Observatory capabilities must be extended vertically into the water column[8,9]. An electro-optical-mechanical (EOM) cable with the necessary components to distribute power and communications throughout the water column is a possible scenario[10] (Fig. 5). Here direct plug-in capability exists at the base of the mooring and on the subsurface float. Some sensors are fixed, but the primary purpose of this particular mooring is to provide profiling capability, moving "synthetic aperture" sensor platforms that transport the power and communications capability and connect to the network via a docking station (in the case of the moored crawler/profiler). Subsurface components can potentially survive a long time and so, in this instance, permanent near surface elements subject to bio-fouling and wave stress are minimized. This particular scenario emphasizes physical oceanography and (robust) bio-optics. The expectation is that with proper tooling and jigs ROVs will be able to service the components and sensors in place while the basic mooring stays in place a long time.

A mooring (Fig. 5) is now being designed to be connected to the soon-to-be-installed NSF-funded ALOHA Observatory (AO) at the Hawaii Ocean Timeseries (HOT) site 100 km north of Oahu, Hawaii[11]. A retired first generation fiber-optic telecommunications cable (HAW-4) will be cut and moved to this location and a junction box placed on the end. The mooring and other instrumentation forming a local sensor network will be connected to the AO junction box. A 100-m test mooring will be installed first on the VENUS Saanich Inlet node in spring 2005. The full-water depth mooring is scheduled to be installed at the AO in summer 2006.

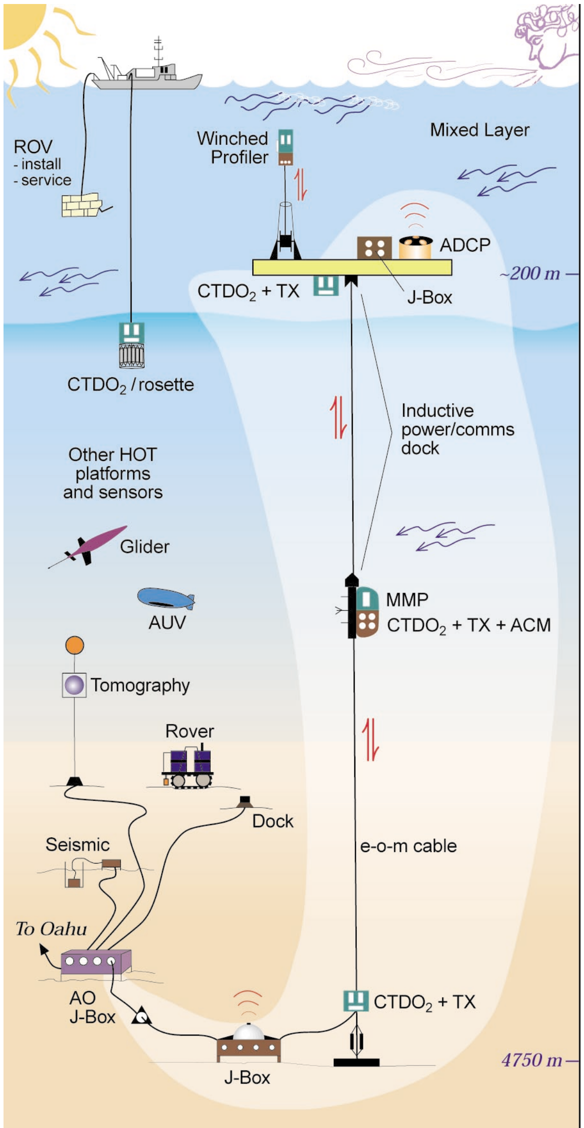

FIG 5: Mooring configuration for use with cabled ocean observatories. The primary purpose of this mooring is to provide profiling capability; other moorings will be necessary for fixed sensors as well as for surface moorings. This mooring is intended for the ALOHA Observatory (AO) at the Hawaii Ocean Time-series (HOT) site north of Oahu, Hawaii. (Highlighted portion is funded.)

The present user requirements for the mooring include:

- Provide entire water column current profiling
- Profiling from 200–4750 m with $CTDO_2$, ACM, optics
- Fixed reference measurements at 200 m and 4750 m
- Profiler vertical speed ~0.4 m s^{-1} to minimize tidal aliasing
- Profiler duty cycle should be > 95% (e.g., 4 hours of charging in 4 days of operation)
- Profiler data transfer during docking operation
- Profiler depth range must be controllable for adaptive sampling.

Within this project and if time and funds permit, it would be desirable to also:

- Provide video or still images on the sub-surface float, profiler, and at the base of the mooring for observing biology as well as for engineering purposes
- Include a real-time inductive modem between the profiler and the mooring, and thus to shore
- Make all components ROV serviceable
- Provide extra science user connectors with "standard" power and data interface

Additional design specifications are:

- Compatible with ALOHA power (400V DC, 200 W (max), ~constant power (+/- 10%) and data interfaces (10/100BaseT Ethernet)
- Provide 48-V and 400-V DC power and Ethernet communications at science connectors
- Provide connection method for standard RS-232 sensors
- ROV serviceable
- Operational life of > 2 years
- Located ~2 km from ALOHA node to allow unobstructed ROV access.

In the mooring scenario (Fig 5) the mooring cable has four #18 conductors with polyethylene insulation, four loose fibers in a 2-mm diameter steel tube, Kevlar strength member, all enclosed in a polyurethane jacket, and an overall diameter of 18 mm. The Kevlar strength member is the expensive part of the cable; it is necessary to keep elongation within the limits set by the optical fibers. A swivel EOM will be used beneath the subsurface float.

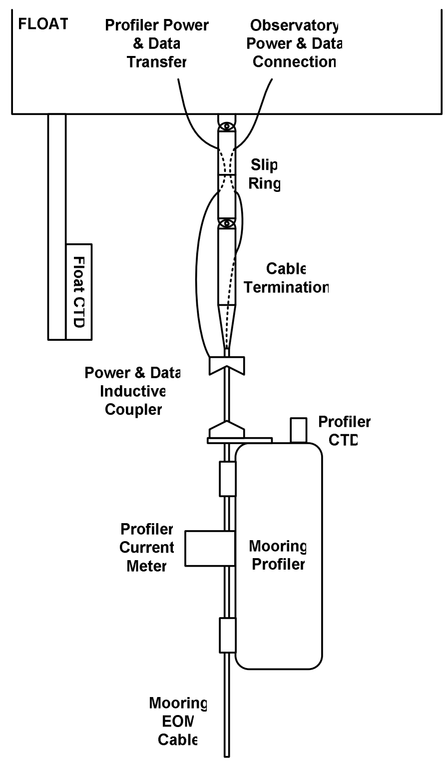

FIG 6: Schematic of the surface float, showing the junction box, ADCP, $CTDO_2$, swivel/electro-optical slip-ring connections, and the inductive coupler.

The 3-m diameter disc-shaped syntactic foam float will serve as the platform for the $CTDO_2$, transmissometer, J-box, and the 150-kHz ADCP (Fig 6). With the available power and communications, the ADCP can be run at its maximum ping rate and a winched profiler is feasible. The mounting system on the float will permit addition, removal, and servicing of sensors and the other components by ROV. This type of disc buoy provides 2000 lb of buoyancy resulting in a taut mooring to minimize horizontal and vertical motion. It has been used with success for the last 18 years for ocean acoustic tomography moorings. Vertical hydrophone arrays (VLAs, 1-inch electromechanical cable) off Point Sur, California, had typical horizontal displacements at tidal frequencies of 30 m (water depth 1800 m). Just to the south of the island of Hawaii in 5000-m water depth, a similar VLA had typical horizontal displacements of 100 m. We have modeled the effects of surface gravity waves on the mooring. The vertical float velocity for float depths of 40, 100, and 200 m is estimated to be 20, 7, and 0.05 cm s^{-1} rms, respectively. The choice of float depth will depend on many factors including the mixed layer depth, signals in the upper thermocline, wear on the moored profiler and cable, float attitude, and impact on ADCP data.

A McLane moored profiler will be modified for our use. The profiling speed will be increased from 0.25 m s^{-1} to 0.4 m s^{-1} so that the ~9000-m round trip top-to-bottom will take about 6 hours minimizing M_2 tidal signal aliasing. This will require 6 W rather than 2 W of electric power on average. The profiler will be modified to mate with a dock for inductive power and communications transfer (below). A J-box packaged in a small form factor with dry mate connectors on the profiler will serve as the interface between the MMP control system, the other sensors (e.g., the transmissometer and dissolved oxygen, as well as future ones), and the profiler docking unit and battery system. To enable the high power and energy demands, as well as fast charging, rechargeable batteries (1 MJ NiMH) will be used. Lastly, the length of the MMP will be extended and the buoyancy increased to accommodate the additional components.

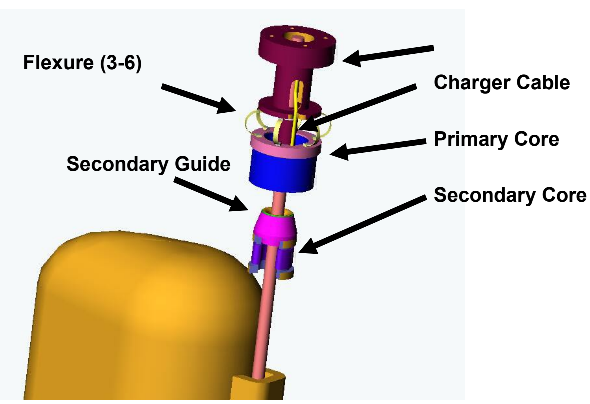

FIG 7: Schematic of the inductive coupler that provides power to the profiler as well as two-way communications when docked (courtesy of S&K Engineering).

The inductive transfer technology will be based on electric vehicle developments; they have been made rugged for military use and seawater use with 15-mm gaps for easier alignment with about 80% efficiency[12)]. The planned implementation is shown in Fig. 7. The mooring network 400 V DC is chopped to obtain 130 kHz AC, which is inductively transferred to the receiver in the profiler which rectifies the signal and outputs 250–400 V DC. About 1.5 kW can be transferred, charging the profiler battery in a short time. The profiler can go 30 km (3 roundtrips) at 0.4 m s^{-1}. The system also transfers data inductively at 10.4 kbps. The electronics in the charger and vehicle exchange some data about battery condition to control the charging but use very little of the available bandwidth. The two-way communications and power from the mooring network is crucial to enable the adaptive sampling required by the science mission.

The fixed sensors on the subsurface float and at the base of the mooring will provide calibration checks of the profiler sensors. In the future *in-situ* calibration of sensors can be done with a remotely operated vehicle (ROV) fitted with a similar sensor payload during service calls. The depth cycling between warm and cold water of the MMP should help reduce bio-fouling; all sensors as appropriate will have poison packages, copper cladding, etc.

The AO J-box is designed for ROV underwater mateable electrical connectors. An in-line converter will convert the AO electrical communications signal to/from 100-Mb/s Ethernet on fiber, necessary for the 2-km distance to the mooring. This 2-km electro-optical cable (similar e-o characteristics as the mooring cable, but only 8 mm outside diameter) will be deployed using a special ROV tool sled (as mentioned above) between the AO J-box and J-box at the base of the mooring. Short cables then connect the J-box to the connector at the base of the mooring and the local instruments.

The power and data budgets are summarized in Table 2. The estimated power for the proposed instrumentation and infrastructure is about 34 W, dominated by the MMP and J-boxes. The high ADCP sample rate will allow us to temporally resolve the energy containing part of the gravity wave spectrum, as orbital velocities can be significant in the upper ocean, especially for the longer wavelengths. The Scripps Institution of Oceanography (SIO) sediment trap mooring (Ken Smith) will attach to the secondary junction box at the base of the profiler mooring. The estimated total power is well within the 200 W maximum available on a single connector from the AO. To meet high instantaneous power demands (such as the MMP battery charging) and associated I^2R losses in the long runs of small diameter cable, energy is buffered in a bank of rechargeable batteries on the subsurface float.

	Power (W)	Data rate (b/s)
ADCP (2 pings/s)	2	5,000
CTDO_2, optics (2 ea)	2	1,000
MMP profiler and dock	10	2,000
J-box (2 ea)	20	100
SIO sediment trap mooring	50	
Conversion/cable losses	40	
Totals	124	8,100

Table 2. Power and data rate budgets.

Data rates are modest and will not stress the system; future broadband acoustic devices and video imagery will likely dominate any future requirements. There is adequate margin for additional sensors and network components.

Much of the engineering, hardware, and software will directly carry over from various related projects we are involved with: the Monterey Accelerated Research System (MARS)[13)], the Victoria Experimental Undersea System (VENUS)[14)], and NEPTUNE[15)].

This is just one of the many mooring configurations that will be necessary for ocean observatories. In many cases fixed sensors along the mooring will be needed (e.g., tomography sources and receivers, large and heavy bio-chemical packages, turbulence sensors, etc.). Winched profilers, including the one shown in Fig. 5, as well as bottom mounted ones (e.g., used at LEO-15[16)]), will be needed. A challenge here is to deal with the possible snap loading as the package gets close to the surface—the continuing challenge of the air-sea interface. Long-lasting surface moorings will continue to be a challenge; the authors' view is that it will be much more effective to have several moorings that together satisfy the sampling requirements, rather than have one that tries to do too much.

IV. VERTICAL COVERAGE INTO THE SEAFLOOR

One method of extending the observatory reach into the seafloor is by using Ocean Drilling Program boreholes (the following is taken from Davis et al.[17)]). The cable connection provides multiple advantages: longer time span experiments;

coordinated, co-located experiments can be executed simultaneously; power is available for dynamic experiments using controlled sources; and experimental protocols can be changed on the fly. Significant work has already occurred for autonomous systems. An example of how a hole might be completed and instrumented is provided in Fig. 8. For new holes it will be possible to drill in casing strings that will permit access via screened ports to multiple levels in the formation.

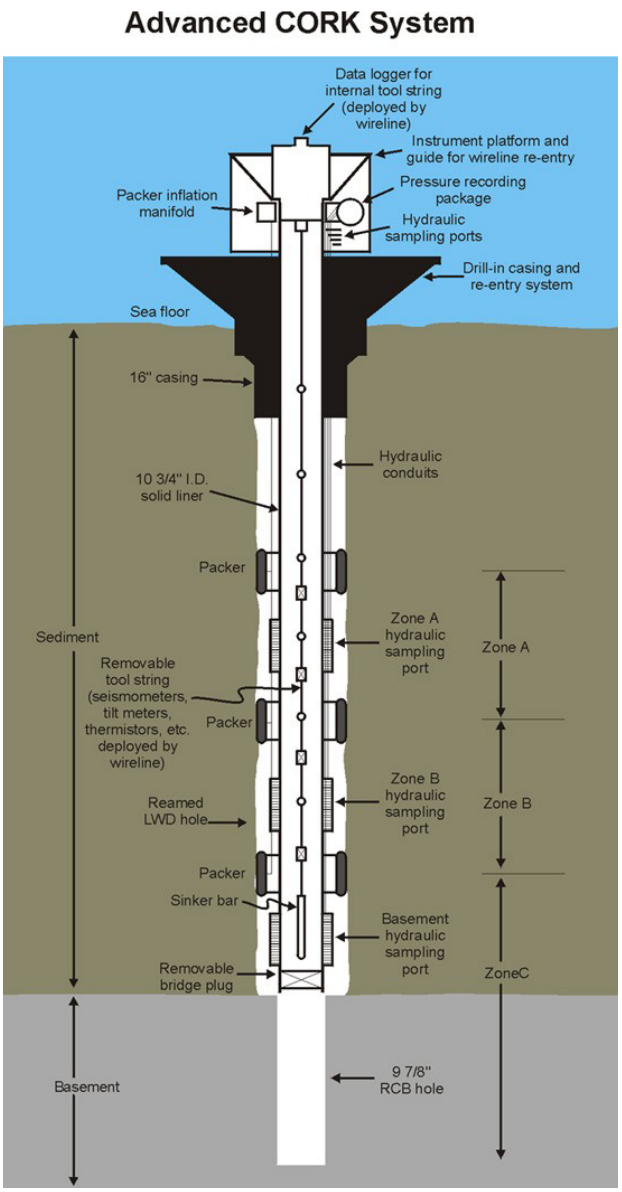

FIG 8: Advanced CORK System. Multiple-zone borehole completion involving packer-isolated fluid sampling/monitoring ports, mobile sampler/logger, seafloor and borehole seismometers, tilt meters, and hydrologic monitoring sensors (courtesy of Earl Davis).

Demands of in-hole instrumentation for communications should be modest. The highest data rates will be required by seafloor and sub-seafloor seismic installations, which may involve multi-level seismic (displacement, velocity, and/or acceleration) and hydrologic (pressure transducer and/or hydrophone) sensors. Greatest powers will be needed by such things as active hydrologic testing (for pumps), resistivity experiments (for EM signal generation; resistivity is proportional to porosity, which is a measure of density), and hydrate dissociation experiments (for heating), although the higher dissipation tests will probably be intermittent with a low duty cycle. High peak demands can be handled by local power buffers.

Efforts must be made to piggy-back as many experiments in a single hole as possible, and to make removable as much of the in-hole instrumentation as possible, so that holes can serve multiple purposes throughout the lifetime of the observatory array. Given the anticipated capabilities of the multi-level casing strings, it should be possible to meet these requirements. Remote access can be gained to the formation for pressure monitoring, fluid sampling, and hydrologic testing via lines run on the outside of the casing liner. This will leave the inside of the solid liner available for strings of sensors that do not require direct exposure to the formation (e.g., for seismic, electrical, and thermal monitoring). If cooling of formation fluid during its ascent to the seafloor for sampling cannot be tolerated or accounted for (e.g., for chemical and biological purposes), experiments can be performed on fluids at *in-situ* conditions via through-liner ports that can be coupled to, opened, and closed at will.

One type of device that can benefit from the power and real time control offered by cabled observatories are those that would drill or push probes into the seafloor installing sensors, making downhole measurements, injecting tracers, collecting/analyzing pore water, etc. Seafloor robotic drills have been built[18)] (Fig. 9) that would drill 25–50-mm holes 3–5-m deep in hard rock with the power available at NEPTUNE nodes. Similarly, there are existing systems that can push a 12-mm probe 10–20 m into unconsolidated sediment. Real time feedback is important for these systems to allow the coring/probing parameters, such as bit weight, rotation rate or flushing water, to be changed in response to changing geological conditions.

FIG 9: Remotely operated bottom rock drill.

V. OTHER SENSOR NETWORK COMPONENTS

While cabled instrumentation will provide much of the long term sampling, it is clear that mobile platforms that fill in the sampling between fixed instruments will be essential. Further, mobile platforms with cabled docking stations can serve as “tankers” for power and data transfer between non-cabled instruments and the cable system. For many biological and geomorphology/geodesy studies precision repeat surveys of the bottom over large areas will be needed. For extended ranges, vehicles like the Autonomous Benthic Explorer (ABE)[19] or the Dorado[20] might be used (once a docking station is proven). For strictly bottom studies near a junction box, a bottom rover, tethered or untethered, may be appropriate (Fig 10). Clearly many new and different forms of undersea robots need to be developed. A hot vent field might be explored and documented by a robotic, sensor-laden crab. Undersea robots (possibly AUV/ROV hybrids) may be used for installation (e.g., cable laying and connector mating) and maintenance (repairing cable faults) of the sensor network infrastructure. In these robotic systems the tradeoffs between closed loop, low latency communications to shore and local intelligence with less demanding communications requirements must be evaluated.

FIG 10: Bottom rover under development by Ken Smith (SIO) for deep sea ecology studies.

For many of the moving platforms, acoustic navigation and communications will be necessary. There are very distinct synergies with the science that uses acoustics, e.g., float and animal tracking, tomography, and ambient sound including wind, rain, mammals, seismics, and shipping. An important part of this work will be to develop the concept of "underwater GPS". A few strategically placed acoustic sources and receivers on many of the fixed observatory platforms as well as profiling and other floats will go a long way to satisfying many infrastructure and science applications. In an effort to promote unity in this area, the lead author has established a committee, Integrated Acoustic Systems for Ocean Observatories (IASOO)[21], sponsored by the Acoustical Oceanography Technical Committee of the Acoustical Society of America (ASA)

Electric cables on the seafloor can be used to determine the depth-averaged or barotropic transports across the cable (conductive sea water moving through the earth's magnetic field produces a voltage in the cable electrical conductor)[22]. In an ocean observatory setting, one can consider laying very small cables with a very fine conductor on the seafloor, or possibly use parts of the sensor network cabling.

In the original sensor network scenario described in the NEPTUNE Feasibility Study[1], there were basic sensor suites (Fig. 3) at each primary node, fifteen "intermediate" networks with horizontal extent with basic sensor suites, moorings, and boreholes, and four "observatories" (Fig. 4). This requires 170 secondary junction boxes, 1500 connector pairs, and 1500 km of secondary cable. These likely cover only the first 5–10 years. Clearly a significant effort must be made to develop, construct, and commercialize these aspects of ocean observatories. Many research, development, and manufacturing groups are already involved in this work, but as the above example shows, order of magnitude increases in sensor network components, as well as human resources, will be required. Further, with the planned long lifetimes of ocean observatories, reliability will very important to build in from the beginning. These development efforts can be facilitated with test bed facilities such as MARS [11] VENUS[12].

VI. CONCLUDING REMARKS

The sensor networks (sensors and sensor network infrastructure) will supplement the observatory backbone infrastructure that is part of the NSF Ocean Observatories Initiative (OOI)[23] within the overarching ORION (Ocean Research Interactive Observing Networks) program[24], as well as other initiatives around the world. This OOI plans to provide junction box nodes on the seafloor that furnish power and communications, and distribute timing signals. There are three elements of the OOI: a regional-scale cabled observatory in the northeast Pacific (e.g., NEPTUNE) with dozens of nodes, a sparse global array of buoys with seafloor nodes, and an expanded system of coastal observatories. Each of these observatories will depend on suites of sensors from a number of communities and individual investigators, and it is likely that once the observatory infrastructure itself has been installed and commissioned, most of the physical interaction with an observatory will be for installing, operating, servicing, and recovering sensor networks. These activities will be supported by the proposed infrastructure, enabling the full potential of the observatory to be reached.

ACKNOWLEDGMENTS

Support from the National Ocean Partnership Program (Grant N00014-99-10129), the National Science Foundation (Grants OCE 0116750 and OCE 033082), and the authors' institution is gratefully acknowledged.

REFERENCES

[1] NEPTUNE Phase 1 Partners (University of Washington, Woods Hole Oceanographic Institution, Jet Propulsion Laboratory, Pacific Marine Environmental Laboratory), *Real-time, Long-term Ocean and Earth Studies at the Scale of a Tectonic Plate. NEPTUNE Feasibility Study* (prepared for the National Oceanographic Partnership Program), University of Washington, Seattle, 2000. http://www.neptune.washington.edu.

[2] DEOS: http://www.coreocean.org/DEOS

[3] Butler, R., et al.: "The Hawaii-2 Observatory (H2O)," *Trans. AGU Eos*, 2001.

[4] ALOHA Observatory: http://hahana.soest.hawaii.edu/hot/hot.html

[5] *Proceedings of the 3rd International Workshop on Scientific Use of Undersea Cables and Related Technologies*, IEEE, Tokyo, Japan, June 2003.

[6] Sanford, T., et al., *Basic Sensors*, 2002. Proposal submitted to the National Science Foundation. http://www.neptune.washington.edu/pub/documents/Sensor_Prop.pdf,

[7] O'Reilly, T.C., et al., "'Smart Network' infrastructure for the MBARI Ocean Observing System," *Proceedings of the Oceans 2001 MTS/IEEE Conf., Honolulu, Hawaii, November 5–8, 2001*.

[8] Howe, B.M., A.M. Baptista, J A. Barth, E.E. Davis, J.K. Horne, S.K. Juniper, R.M. Letelier, S.E. Moore, J.D. Parsons, D.R. Toomey, A.M. Tréhu, M.E. Torres, and N.L. Penrose, *Science Planning for the NEPTUNE Regional Cabled Observatory in the Northeast Pacific Ocean: Report of the NEPTUNE Pacific Northwest Workshop*, Portland State University, Portland, Oregon, 2003, 72 pp. http://www.neptune.washington.edu/documents

[9] Purdy, M., and D. Karl, *Regional Cabled Ocean Observatory Network (of Networks), Report of the Cabled Regional Observatory Workshop*, San Francisco, California, October 2003.

[10] Howe, B.M., et al., *SENSORS: ALOHA Observatory Mooring and Adaptive Sampling*, National Science Foundation funded grant, 2003. http://kela.soest.hawaii.edu/ALOHA/NSF_Mooring_Fastlane_20030306_Text.pdf,.

[11] Hawaii Ocean Time-series: http://www.soest.hawaii.edu/HOT_WOCE.
[12] Henze, C.P., *Inductive Coupler Concepts for Coupling 1500W Across a Gap up to 15 mm Operating in Air or Seawater*, White Paper, Analog Power Design, Inc., Lakeville, MN, 2002.
[13] Monterey Accelerated Research System (MARS): http://www.mbari.org/mars/
[14] Victoria Experimental Undersea System (VENUS): http://www.venus.uvic.ca.
[15] Massion, G., P. Beauchamp, A. Chave, T. McGinnis, P. Phibbs, and D. Rodgers, "System engineering for a regional scale cabled observatory, process and progress," *Proceedings of the 3rd International Workshop on Scientific Use of Undersea Cables and Related Technologies*, IEEE, Tokyo, Japan, 234–239, June 2003.
[16] LEO-15: http://marine.rutgers.edu/nurp/factech.html
[17] Davis, E., et al., *Seafloor Hydrogeology and Biogeochemistry: Opportunities for Long-term Borehole Experiments*, NEPTUNE White Paper #3, Working Group Meeting, Pacific Geoscience Centre, May 24–25, 1999.
[18] McGinnis, T., Advances in deep ocean seafloor coring, *Sea Technology Magazine*, June 2000.
[19] Autonomous Benthic Explorer (ABE): http://www.marine.whoi.edu/ships/auvs/abe_description.htm
[20] Dorado AUV: http://www.mbari.org/rd/projects/2000/moos/dorado.html
[21] Integrated Acoustics Systems for Ocean Observations (IASOO): http://www.oce.uri.edu/ao/AOWEBPAGE
[22] Baringer, M.O., and J.C. Larsen, "Sixteen years of Florida Current transport at 27 N," *Geophys. Res. Lett.*, 28, 3179–3182, 2001.
[23] Clark, H.L., New sea floor observatory networks in support of ocean science research. *Proceedings of the Oceans 2001 MTS/IEEE Conf., Honolulu, Hawaii, November 5–8, 2001*.
[24] Ocean Research Interactive Observing Networks (ORION): http://www.orionprogram.org.