

# Sensor Networks for Cabled Ocean Observatories

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## ABSTRACT

An infrastructure for global, regional, and coastal sub-sea observatories is being planned to support individual and networked sensors. Secondary cables and junction boxes, moorings, and downbore tools could extend the horizontal reach by tens to hundreds of km from the primary cable and nodes throughout the water column and down boreholes into the crust. The support infrastructure could include navigation and communications systems, free-swimming AUVs, and bottom rovers that could carry sensors and could provide data and energy “tanker” service.

## 1. 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 located at the science 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 and throughout the ocean volume. This reflects the vision of the proposed NEPTUNE cabled ocean observatory in the northeast Pacific (Fig.1)<sup>1</sup>. In other observatories there may be only a single backbone node as, for example, beneath a “DEOS” buoy<sup>2</sup>) or a node at the end of a re-used telecommunications cable such as the H2O Observatory<sup>3</sup>) or the planned ALOHA Observatory<sup>4</sup>). Here we consider the NEPTUNE cabled observatory scenario, but many of the concepts are applicable to other ocean observatories.

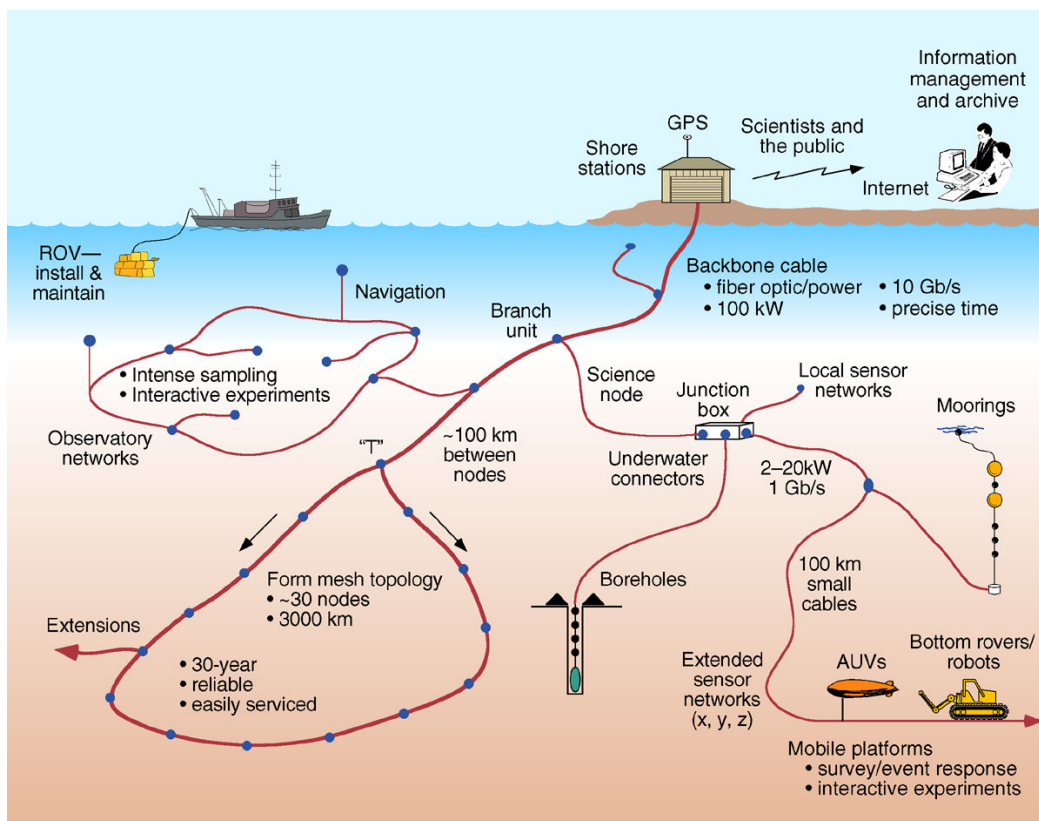
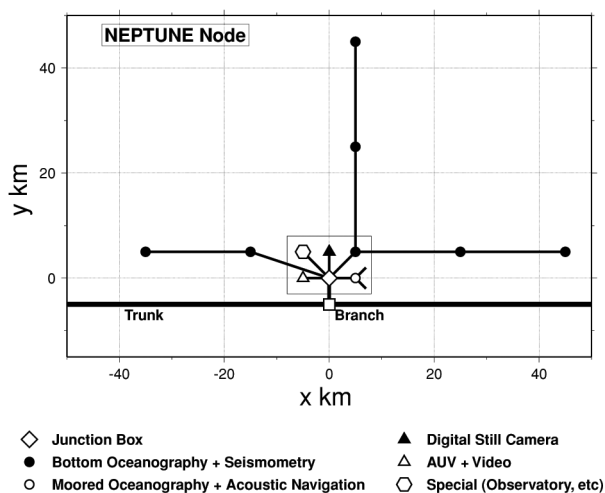


FIG. 1. Essential elements of a cabled observatory.

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 that are two water depths long 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<sup>-1</sup> 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.

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.



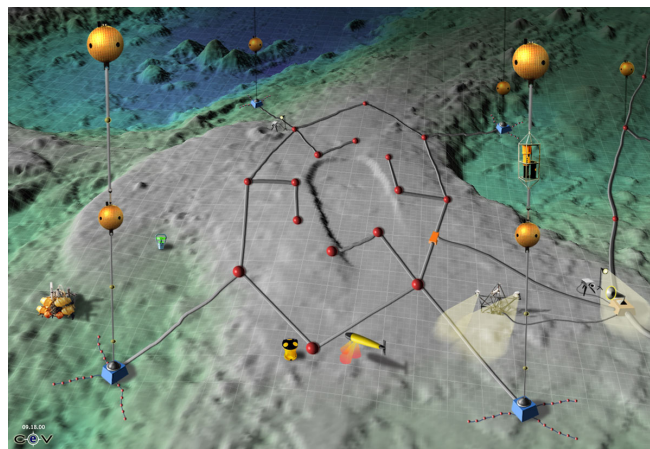
**FIG 2:** A possible sensor network surrounding a backbone node. Each solid dot includes a secondary junction box.

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 navigation and acoustic communication. Our primary purpose here is to promote discussion and to stimulate the appropriate development processes.

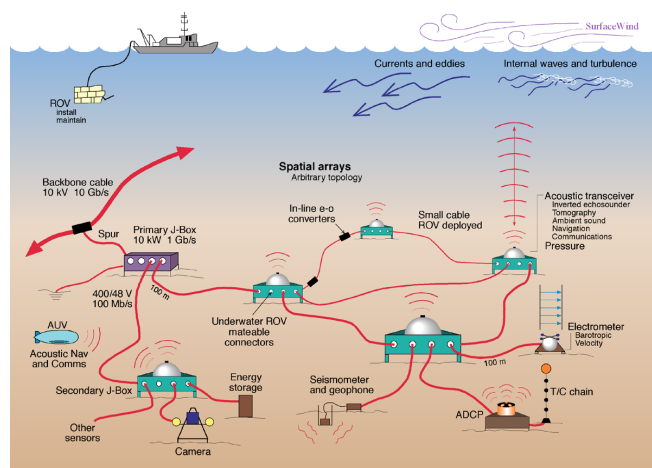
## 2. HORIZONTAL COVERAGE

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 chosen here consists of robust, bottom-mounted instruments, emphasizing physical oceanography,

using remote sensing for gravest mode structure (e.g., acoustics and electrometer, as noted<sup>5</sup>). 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 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.



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

### 2-1. 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., power levels and communications bandwidth) and levels of redundancy (see below). On the secondary junction box additional ports (~4-8) will be provided. The same ports can be used to link the secondary “backbone” system (400 V, 100 Mb/s Ethernet, timing) as well as for sensors. Then, any arbitrary network configuration can be constructed by connecting in series or using three ports to form a “T”.

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. 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 protection as the primary science node (i.e., switching, ground fault, and overcurrent).

## 2-2. 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 \$6K versus \$46K a pair, respectively). However, to communicate over long distances (greater than a few 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 are 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  $\times$  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 <sup>2</sup>	Ohm km <sup>-1</sup>	Watt-km
2000	16	1.3	14	32500
2000	24	0.2	75	6087
1000	16	1.3	14	8125
1000	14	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 generic 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 will include voltage boosting to ~1000–2000 V. Up-converters are commercially available; the down converter to 400 V will 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).

If the cable is short (~100 m) it can be unreeled by an ROV in a sample 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; ROV *Jason-2* will be laying cable at H2O in summer 2004). 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 (SIIM). 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<sup>6</sup>. Instrument manufacturers are slowly implementing more sophisticated interfaces; by the time NEPTUNE comes on line, it is expected that instruments will have the required interface software and hardware on-board.

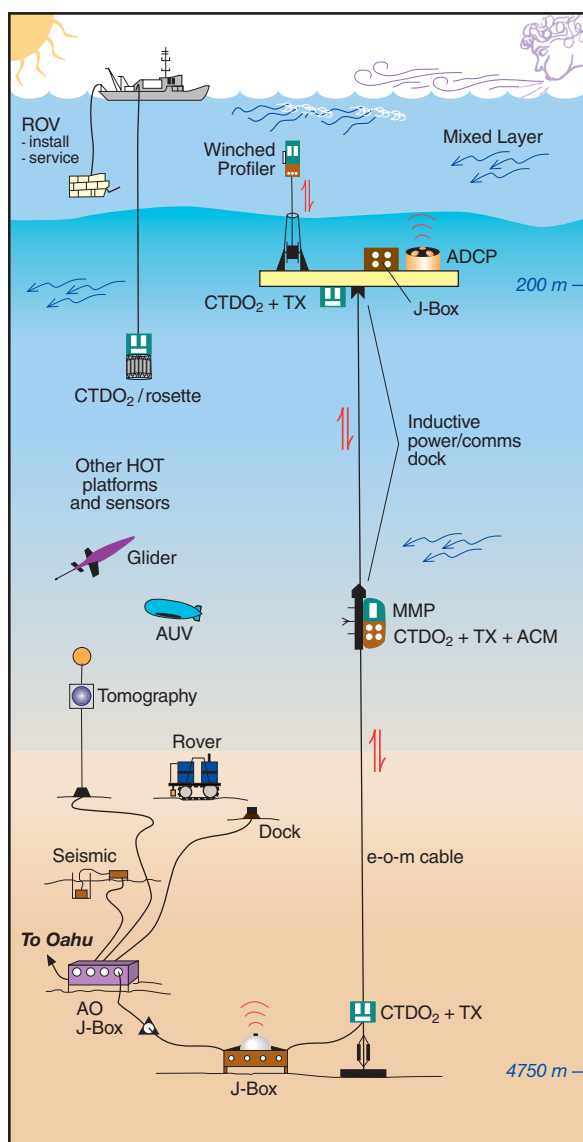
## 3. VERTICAL COVERAGE INTO THE WATER

Observatory capabilities must be extended vertically into the water column. An electro-optical-mechanical (EOM) cable with the necessary components to distribute power and communications throughout the water column is a possible scenario<sup>7</sup> (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, 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.

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, large and heavy bio-chemical packages, turbulence sensors, etc.). 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.

For the mooring scenario shown in 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, armor wires (above 1500-m water depth for fish bite

protection) enclosed in a polyurethane jacket, and an overall diameter of 25 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. Swivels (e-o-m) will be used at the base of the mooring and at the top beneath the subsurface float.



**FIG 5:** A possible 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<sup>8)</sup>.

The 3-m diameter disc-shaped syntactic foam float will serve as the platform for the CTDO<sub>2</sub>, transmissometer, J-box, and the ADCP. 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<sup>-1</sup> 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 (e.g., a McLane Moored Profiler—MMP) and cable, float attitude, and impact on ADCP data.

The inductive transfer technology could 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<sup>8)</sup>. 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 125 km (14 full-depth roundtrips) at 0.25 m s<sup>-1</sup> and 30 km (3 roundtrips) at 0.4 m s<sup>-1</sup>, which is perfect grist for the development of adaptive sampling optimization techniques. The system also transfers data using the SAE J1850 standard 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.

Winched profilers, including the one shown in Fig. 5, as well as bottom mounted ones (e.g., used at LEO-15<sup>9)</sup>), 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.

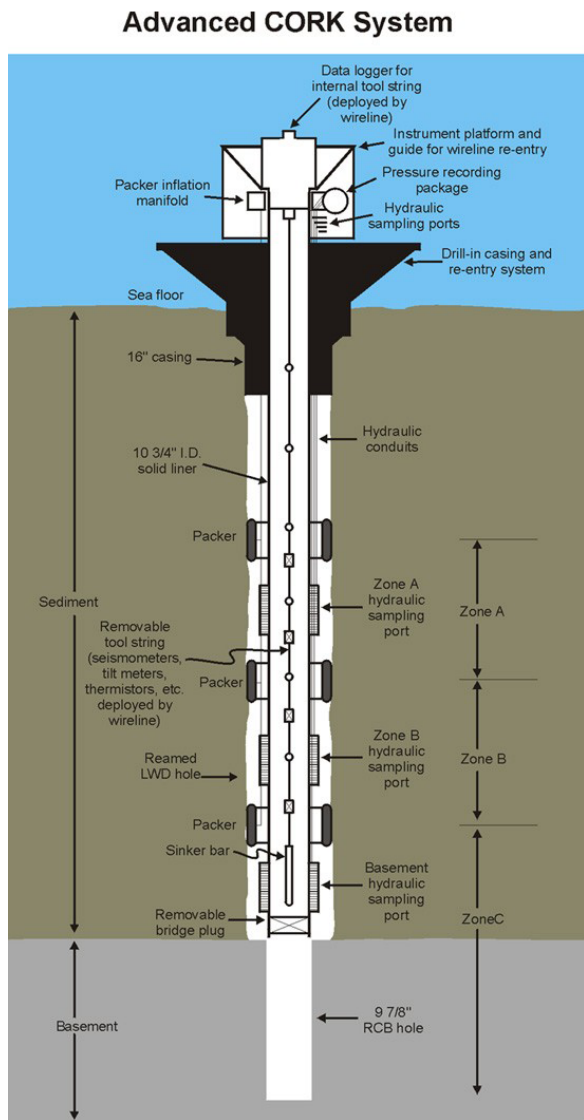
#### 4. VERTICAL COVERAGE INTO THE SEAFLOOR

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.<sup>10)</sup>). 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. 6. 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.

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 easily 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

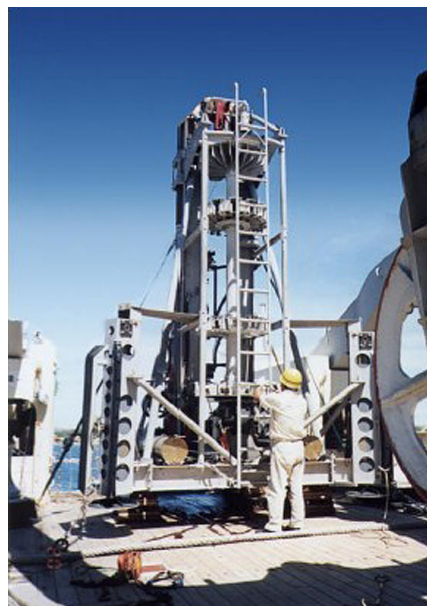
via lines run on the outside of the casing liner. This will leave the inside of the solid liner available for strings of sensors that do not require direct exposure to the formation (e.g., for seismic, electrical, and thermal monitoring). If cooling of formation fluid during its ascent to the seafloor 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.



**FIG 6:** 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).

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<sup>(11)</sup> (Fig. 7) that would be able to 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 7:** Remotely operated bottom rock drill.

## 5. 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)<sup>(12)</sup> or the Dorado<sup>(13)</sup> 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 8). 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., 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 8:** 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 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)<sup>14</sup>, 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 (a moving conductor, the seawater, produces a voltage in the cable electrical conductor as it moves through the earth’s magnetic field)<sup>15</sup>. 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<sup>1</sup>, 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). At least 170 secondary junction boxes and 1500 connector pairs are required. There were 1500 km of secondary cable planned. These likely cover just 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

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in sensor network components will be required. Further, with the planned long-life times 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 VENUS<sup>16</sup> and MARS<sup>17</sup>.

## 6. 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)<sup>18</sup> and 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 (such as 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 sensors. These activities will be supported by the proposed infrastructure, enabling the full potential of the observatory to be reached.

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