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Cabled Ocean Observatory Systems

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Abstract

Future studies of episodic processes in the ocean and earth will require new tools to complement traditional, ship-based, expeditionary science. This will be enabled through the construction of innovative facilities called ocean observatories which provide unprecedented amounts of power and two-way bandwidth to access and control instrument networks in the oceans. The most capable ocean observatories are designed around a submarine fiber optic/power cable connecting one or more seafloor science nodes to the terrestrial power grid and communications backhaul. This paper defines the top level requirements that drive cabled observatory design and the system engineering environment within which a scientifically-capable infrastructure can be implemented. Commercial high reliability submarine telecommunication technologies which will be crucial in the design of long term cabled observatories are then reviewed. The top level architecture of a generic cabled observatory, describing the main subsystems comprising the whole and defining technological approaches to their engineering, is then described, along with some example design choices and tradeoff studies.

1. Introduction

Measurements and models from the exploratory, mapping and sampling, phase of oceanography that began in the nineteenth century have resulted in growing recognition of the time-dependent complexity of processes that occur within the oceans. Future studies of the dynamics of the ocean and earth require new tools to complement traditional, ship-based, expeditionary science. As a result, the ocean sciences are entering a new stage in which scientists will observe the ocean as a system using *in situ* robotic instruments and sensor webs. Routine, adaptive measurement of episodic events is vital to improved understanding of dynamic natural phenomena that span large ranges of space and time.

This emerging research paradigm will be enabled through the construction of innovative facilities called ocean observatories, which are the infrastructure that provides unprecedented amounts of power and two-way bandwidth to access and control instrument networks and platforms in the oceans. The real time information flow from ocean observatories and the ability to access archived data will lead to novel scientific insights and new discoveries. In addition, ocean observatories will create education-outreach capabilities that will significantly impact public understanding of the ocean sciences.

The important role of ocean observatories in future oceanography has received international acknowledgement, and initial projects have emerged around the world (e.g., Forrester et al., 1997; Momma et al., 1998; Beranzoli et al., 1998; Glenn et al., 2000; Delaney et al., 2000; Chave et al., 2002; Schofield et al., 2002; Hirata et al., 2002; Austin et al., 2002; Petitt et al., 2002; Beranzoli et al., 2003). Major ocean observatory infrastructure projects have been funded in Canada (NEPTUNE Canada), and are under consideration in Japan (Advanced Real-Time Earth monitoring Network in the Area or ARENA; Shirasaki et al., 2003), Europe (The European Seafloor Observatory Network or ESONET; http://www.abdn.ac.uk/ecosystem/esonet/), and the United States (Ocean Research Interactive Observatory Networks or ORION;

http://www.coreocean.org/Dev2Go.web?id=251294&rnd=3212).

2. Buoyed and Cabled Ocean Observatories

Ocean observatories may be designed around either a surface buoy containing an autonomous power source and wireless (e.g., satellite) communications link or a submarine fiber optic/power cable connecting one or more seafloor science nodes to the terrestrial power grid and communications backhaul. These infrastructure options provide significantly different capabilities and concomitant costs. Buoys can provide a limited amount of power and bandwidth. High capability buoys containing diesel generators may deliver up to 1 kW for both infrastructure and science, although more modest installations using alternate energy sources may provide only 1/10 this power. Real-time satellite connectivity at 1 Mb/s is available, but higher data rates are difficult to achieve at present. Outstanding engineering issues include buoy-based antenna stabilization and survivability of fiber optic tethers extending through the energetic water column, but neither presents overwhelming challenges.

Cable-based installations can provide much greater amounts of power and bandwidth. Tens to hundreds of kW can be delivered to cabled observatories using commercial-off-the-shelf (COTS) submarine telecommunications cables. State-of-the-art submarine telecommunications technologies can transport 1 Tb/s across transoceanic distances on a single cable (Chesnoy, 2002). The major challenge in cabled observatory design (which applies equally to buoyed installations) lies in reliability engineering. The electronic infrastructure required to implement an ocean observatory will always be more complex than that used in submarine telecommunication systems. Designing an installation which delivers the required performance and is maintainable at a reasonable cost is critical to the success of ocean observatories.

Buoys are characterized by a relatively low capital expense (CAPEX), typically of order US$1-2M per major buoy including a seafloor node, but carry an annual operating expense (OPEX) that can approach the CAPEX since ship visits to potentially remote locations will be required. Cable-based installations carry comparatively high CAPEX ranging from on order US$10M for a ~50 km long, deep water installation near a coastline or island to US$150M or more for a multi-node regional cabled observatory spanning 3000 km. Projected annual OPEX for a cabled system is under 10% of CAPEX, including maintenance of science instruments and experiments, although fixed base costs may raise this percentage for small systems. Cost comparisons are best carried out using the life cycle cost, defined as the sum of CAPEX plus aggregate OPEX over the lifetime of the system. For a set of 20 globally-distributed buoys, the 25 year life cycle cost is estimated to substantially exceed that for a 26 node regional cabled observatory, presuming that comparable reliability goals can be achieved for both approaches. Unless its location is extremely remote (e.g., amidst the Southern Ocean), the 25 year life cycle cost of a single node deep water cabled observatory will be comparable to that for a single buoy. However, life cycle cost calculations probably favor buoys in coastal installations where installation and maintenance costs are comparatively low because the water is shallow and ship transit distances for servicing are limited.

In summary, cabled installations offer a substantial margin in power and bandwidth delivery over buoyed installations. For deep water installations, cabled observatories are no more expensive than buoyed observatories when life cycle cost is considered. For these and other reasons, currently most ocean observatories and the majority of projected future international programs are based on cable technologies.

A related topic that is not treated in this paper is the re-use of submarine telecommunications systems that go out of commercial service. This can represent an opportunity to the scientific community when a cable crosses a site of interest; for example, the Hawaii-2 Observatory (H2O; Chave et al., 2002; Petitt et al., 2002) was installed halfway between California and Hawaii on the HAW-2 SD series analog cable that was abandoned in the late 1980's when virtually all analog telecommunication systems were supplanted by fiber optic ones. First generation fiber optic systems are rapidly being abandoned at the present time, and this represents the second burst of re-use opportunity. Utilizing these submarine cable systems for science may be costly because of their unique design, and there are numerous technical, permitting, and legal issues that need to be fully understood before their re-use can be deemed feasible. Unfortunately, the rate at which these cables are being turned down is more rapid than the response time of ocean scientists and their funding sources, as was also the case when analog cables went out of service, and it is not clear that extensive re-use of these systems will occur. It would behoove the scientific community to be proactive in anticipating future generations of commercial system retirements rather than only reacting when opportunities arise.

3. Science Requirements and Design Principles

The design of ocean observatories must be driven by the needs of the scientific community who will use the facilities. Extracting requirements from the science community presents a challenge to the engineering team responsible for ocean observatory design, as the typical science user cannot readily quantify present and future needs that will lead to a formal design, and may not be familiar with the relevant power, communications, control, and ocean engineering technologies.

To solve this dilemma, the engineering team has to construct a wide range of use scenarios incorporating representative suites of sensors and platforms in close collaboration with a broad group of potential science users, and derive from these a set of initial requirements for an ocean observatory system. The initial requirements are used to define an initial system architecture which is compared to additional use scenarios. The result is an iterative design process carried out by an interactive team of scientists and engineers, and comprises a major component of a formal system engineering process, as described in the next section.

The entire design process must be guided by a set of overarching principles which comprise the top-level science requirements. Unlike lower level science requirements, these can be specified a *priori* rather than being extracted from use scenarios, as they represent the overall ocean observatory design philosophy. Further, this list should be as short as possible, both to simplify the design cycle and to avoid potential conflicts. The following example set of top level science requirements has been developed for the NEPTUNE regional cabled observatory (Delaney et al., 2000), although they should be applicable to any cabled observatory. Each is preceded by a topic area and expressed using the verb "shall" in keeping with its status as a requirement. The ordering should not be construed to imply priority.

1. Lifetime: the cabled observatory shall meet all science requirements, with appropriate maintenance, for a design life of at least 25 years.
2. Cost: the cabled observatory shall be designed to minimize the 25 year life cycle cost.
3. Controllability: the cabled observatory shall allow resources to be dynamically-directed where science needs and priorities dictate.
4. Flexibility: the cabled observatory shall be expandable, so that additional science nodes which meet the observatory reliability goals can be placed near or at locations of interest that may develop in the future.
5. Upgradeability: the cabled observatory shall be upgradeable to accommodate future technology improvements.
6. Reliability: the primary measure of cabled observatory reliability shall be the probability of being able to send data to/from any science instrument from/to shore and/or from/to other science nodes, exclusive of instrument functionality.
7. Futurecasting: the cabled observatory shall have functionality and performance significantly beyond that required to support current use scenarios so that experiments and instruments that may reasonably be anticipated to develop over the expected life of the facility can be accommodated.

The first two of these are self-explanatory. The third requirement dictates a design which is inherently dynamic, and static implementations would not be appropriate. The fourth requirement states that designs which inherently limit either the number of science nodes or their locations would be unsuitable. The fifth requirement states that designs which either utilize technologies which can reasonably be expected to acquire legacy status during the observatory lifetime or which preclude technological change should be avoided. The sixth requirement states that the aggregate probability of getting data to/from a sensor from/to the end user (whether on shore or on the seafloor) should drive the design. This means that the reliability of all infrastructure elements spanning the path between a seafloor science instrument and a shore- or seafloor-based user will affect the overall observatory reliability, which will inevitability be dominated by the lowest reliability components. Finally, the last requirement is at the same time perhaps the most important and the hardest to quantify of the list. However, failure to consider it can lead to a system which is obsolete shortly after installation, or which seriously limits the scope of the science which can be accomplished.

4. Science Requirements and the System Engineering Process

A system is a collection of functional elements which work as a whole to perform some set of functions. It consists of a hierarchy of sub-systems which, taken together, comprise the system. System engineering is a management and engineering process which brings a system into existence. Its evolution into an engineering sub-discipline grew from management and integration challenges in increasingly complex technological projects, especially in the defense and aerospace industries. Neither the system engineering process nor its procedures are uniquely defined, although it has a set of common elements in any implementation. A common version is Military Standard 499B (1991), and recent reviews are given by Eisner (1997), Blanchard (1998), and Stevens et al. (1998).

Figure 1 is a top-level view of the Mil Std 499B system engineering process. It consists of three main stages:

1. Requirements Analysis
2. Functional Analysis/Allocation
3. Synthesis

along with a continuous, cross-cutting, System Analysis and Control phase.

Requirements Analysis centers on two areas: user and performance requirements. The goal is to identify and define the set of functions that the system must do to meet the user requirements, and to place bounds on how well these functions must be carried out. These are usually called functional and performance requirements, respectively. In the context of ocean observatories, the functional and performance requirements, together with the top level requirements given in Section 3, constitute the science requirements.

The second system engineering stage is Functional Analysis/Allocation, in which the objectives defined by the science requirements are decomposed into a set of lower-level functions, and performance allocations are applied to each of them. The functional interfaces and architecture flow from this process, which is iterative with the Requirements Analysis stage to ensure that the science requirements are being satisfied. The third system engineering stage is Synthesis, in which all elements of the functional design are transformed into a physical design. Synthesis begins at a concept design level, then passes on to a preliminary design level where high risk elements of the hardware and software are tested, and then passes to a detailed design level where full prototypes are constructed. This stage is also iterative with the preceding two stages to make sure that the required functionality is being provided and that the science requirements are being met.

The cross-cutting phase of the system engineering process is System Analysis and Control. This consists of a set of tradeoff studies comparing the feasibility, performance, and cost of alternative technical approaches along with a set of over-arching tasks to manage risk, configuration, interfaces, and documentation.

A major theme of this paper is that ocean observatories are quite different from submarine telecommunication systems, but that many of the high reliability technologies and practices developed in that industry are essential to the implementation of the emerging ocean observatory paradigm. In the next two sections, the core technologies required to implement a cabled ocean observatory are described. The first set of technologies encompasses the design and installation of wet plant hardware for submarine telecommunication systems based on state-of-the-art commercial practices. The second are derived from the use scenario/system engineering process described here, primarily for the NEPTUNE regional cabled observatory (Delaney et al., 2000; Rodgers et al., 2001; Massion et al., 2003). The authors believe that the issues and tradeoffs analyzed for NEPTUNE, and the system architecture derived from that formal design process, are generic, and apply to understanding the implementation of any cabled ocean observatory.

5. Submarine Cable Technologies

Over a hundred years of development of submarine cables for the telecommunications industry has resulted in highly reliable COTS products which are readily applicable to ocean observatories. The key considerations in submarine cable design include stability under load and pressure, protection from environmental effects such as hydrogen, choice of optical fiber type, and selection of structural form and armor package best suited for a specific installation route (Waterworth, 2003).

With the exception of high voltage and umbilical cables, the submarine cable industry's main customers have traditionally been the major telecommunication operators. Many of the standard principles used for the design of all modern submarine cables are based on early work reviewed by Libert and Waterworth (2002). Submarine fiber optic cable that can be deployed and recovered in over 8000 m of water was developed in the 1980's, with the first transoceanic system commissioned in 1988. During the 1990's, approximately 20 submarine telecommunications systems were installed per year. Deregulation of the telecommunications market worldwide, the advent of the Internet, and high initial realized profits factored into an explosion of interest in submarine telecommunication systems between 1997 and 2001. During the peak of this bubble market in 2000, four Transpacific and three Transatlantic systems were commissioned, where previously the average had been less than one per year. These market factors were exacerbated by the disruptive effect of dense wavelength division multiplexing (DWDM) technology, which dramatically increased the capacity of individual submarine telecommunication systems. The bubble market imploded in 2001, leaving the global manufacturing capacity largely intact and hence in an oversupply situation.

The design requirements for an ocean observatory cable, where data and power are to be delivered and distributed about a submerged network, are very compatible with the standard capabilities of telecommunications cable. As is normal industry practice, all of these cables have proven and qualified couplings and penetrators for connection to underwater equipment based on designs with more than ten thousand cumulative operating years without a failure. These can be readily adapted to interface with a wide range of scientific equipment.

A submarine telecommunications cable has to provide a service life of 25 years or more with stable optical and electrical performance. It must be easy to joint and maintain at sea. It must survive both the rigors of installation and the environmental conditions on the seabed. Installation in either shallow or deep water imparts tension and torsion on the cable structure which houses the optical fibers and electrical conductor. Longevity of the installed cable depends on minimizing the strain induced on the fibers. Environmental influences such as hydrostatic pressure, abrasion, mechanical crush, and hydrogen intrusion must be accounted for. The cost of developing and qualifying a submarine telecommunications cable to meet these requirements with a very low failure rate is extremely high and is normally amortized over many thousands of kilometers of cable. However, the extensive development costs for telecommunications cables are historic and therefore non-recurring.

The cost of a submarine cable repair at sea is substantial. Virtually all reported submarine cable failures are due to external aggression, notably from fishing activity in water shallower than 500 m, although anchor damage in shallower water and natural chafing and abrasion in the deep ocean also occur. It is standard industry practice to separate the cable from potential hazards during route engineering and installation. Careful route planning is essential, and burial is used where circumstances require it. All of the technologies for these activities are highly evolved. Submarine cable is always manufactured to order for compatibility with a specific route, and hence the cable mechanical characteristics are an integral component of the overall system design. All of these issues are reviewed by Horne (2002).

Submarine telecommunication cables can be equipped with virtually any fiber type and any reasonable number of fibers. However, the life of the system will be limited if the fiber is not suitable for the submarine environment. The fiber types used for submarine transmission are optimized for minimum attenuation over the full C-band (1530-1570 nm) with dispersion characteristics that depend on the application. Higher dispersion fibers are required for un-repeatered DWDM transmission over long distances because the penalty from non-linear effects is minimized. Lower dispersion fibers are necessary for repeatered DWDM transmission. Ultra low attenuation fibers, which normally have a pure silica core, are used on long unrepeatered systems (up to 500 km). Dispersion compensation fibers may be employed for long haul, high data rate systems. The cable optical properties are an integral part of the optical communications system.

Submarine fiber properties are further discussed by Bickham and Cain (2002).

It is well known that silica-based optical fiber is sensitive to the presence of hydrogen. Hydrogen can enter interstitially into a fiber, straining the crystalline structure, or it can form hydroxyl groups and defect centers. All of these increase the optical attenuation and can require cable replacement. Galvanic corrosion of external armoring, polymer degradation, metallic out-gassing of the internal structure, and biological activity can all play a part in generating this adverse condition in a submarine cable. Power systems that require sea returns can also generate hydrogen at the ground. Fibers intended for submarine application can be manufactured with tight controls on contaminants and halogen content, reducing the effect hydrogen has on optical loss. This is not sufficient for full protection, and all submarine telecommunications cable designs employ methods to protect the fiber from up to several atmospheres of hydrogen partial pressure. The main technique used in all successful implementations is provision of a hermetic barrier fabricated by forming and welding a metallic tape into a tube surrounding the fiber bundle (Figure 2). Another cable design issue is limiting the internal axial ingress of seawater through effective water blocking when a cable is damaged by external aggression. High hydrostatic pressure can force water many km along an unblocked cable, requiring replacement of long sections of cable at sea.

Another key consideration in submarine cable design is ensuring ready repairability at sea. A fast, reliable and widely available jointing process is often preferred to a cable supplier's proprietary technique. Five industrial concerns have formed the Universal Jointing (UJ) Consortium, which offers qualified and proven jointing techniques for a wide range of cable types. Repair vessels around the world are equipped and trained for the Universal Joint.

There are many types of submarine telecommunication cables available. The design varies depending on manufacturer, fiber count, powering requirements, and the external protection package. Figure 3 shows a typical range of cables qualified to supply 200 kW of power and up to 24 optical fibers whose installation depth capability increases from left to right. Double armor heavy (DAH) cable has two layers of large steel wires to protect the insulation, both of which are laid in the same left hand sense. This cable has very high tensile strength and weight per unit length, and is used in shallow water where the greatest level of protection is required. This is typically where the cable cannot be buried at all due to seabed geology, pipe, or cable crossings, in very shallow water (<80 m) where the risk of anchor damage is high, or for shore ends. A variant called rock armor with a shorter outer armor layer pitch is sometimes used where a higher level of crush resistance is required. Double armor light (DAL) is a lighter version of DAH used in less difficult shallow water situations. Single armor heavy (SAH) has a single layer of ~5 mm wires to protect the insulation, and is normally used up to 1500 m water depth where full burial protection cannot be guaranteed. Single armor light (SAL) has a single layer of smaller (<4mm) diameter wires, and is normally used where a cable can be successfully protected by burial. SAL cable is preferred for plow burial. Due to the twisting limitation on most armored cables, installation depth of SAL is confined to 2000 m or less. Lightweight protected (LWP) cable incorporates a metallic tape to provide a lesser degree of abrasion protection for the insulation than SAL. It can be deployed down to 7000 m and is often used in deep areas of abrasion risk, such as slopes and high current environments. It is sometimes used in shallow water where conditions allow for sound burial. Finally, lightweight (LW) cable has a low weight per unit length and does not twist excessively under load. It is used in deep water (over 2500 m) installations where the seabed is flat and ambient currents are weak.

The interface between a cable and the submerged plant is complex. Not only must the connection provide load transfer through a mechanical discontinuity in the cable, but it must also maintain electrical insulation while supporting the safe connectivity of both optical fibers and electrical conductors. At any submerged plant element such as a repeater, connection to the cable is undertaken within an extremity box (EB), effectively representing one half of a cable-to-cable joint.,with the other EB at the distal end of the submerged equipment. The internal components of the EB (Figure 4) are comprised of a stainless steel hydrostatic pressure and tensile load bearing housing having cable vault anchorages at either end for termination of the cable strand wire and inner fiber tube. A splicing box is located between the anchorages where fiber interconnections between the wet plant and cable are stored. The integrity of electrical insulation is maintained by over-molding the entire assembly. Once over-molded, the EB housing is placed within a glass-filament-wound sleeve which provides protection for the insulation, an anchorage for armor wires, and a means of load transfer between the cable and the articulated coupling attached to the submerged equipment. In this instance, armor wires are splayed inside a conical seating within the sleeve, and are prevented from extraction under tension by filling the cavity with an encapsulating epoxy resin.

The load chain is maintained between the EB glass-reinforced sleeve and the main housing of the submerged plant by a flexible coupling called an armadillo (Figure 5), which is a long-established, successful, and versatile design. The unit is comprised of a series of angular faced plates linked by spherically-seated high strength bolts. Such an arrangement allows up to 90 degrees of articulation, depending on the number of plates selected, and can support loads of over

60 tons in straight tension and 20 tons articulated. Anchorage of the unit is by direct coupling to the sea case via a threaded base plate, while the sleeve of the termination is accommodated within the nose cone of the coupling. Such a robust coupling design is essential, as during the deployment and recovery of submerged equipment from a cableship, the weight of the cable and submerged plant in suspension passes through the repeater and couplings. In addition, the housing length can magnify the inboard cable tension as it passes over cable drums or sheaves.

Optical and electrical interconnection between the EB and the main equipment housing is provided by a unique penetrator design called the composite gland. The composite gland is a combined electrical and optical feed which provides the only means of access in or out of an electronics housing. The gland not only has to provide insulation against system line voltages, as the housing and bulkhead into which it is located are at sea potential, but must also prevent water and hydrogen gas penetration while supporting a benign optical fiber environment. As the gland is located inside of the cable coupling, its physical geometry must also provide for the extension, compression and flexural movement of the coupling while exposed to hydrostatic pressure at depths of up to 8 km.

The single penetration composite gland is mounted within the main bulkhead at each end of the equipment sea case. Both units are hydraulically sealed using o-rings and hermetically sealed using a pressure activated lead shear seal. The gland is comprised of a long water-blocked tube which acts as both the electrical conductor and fiber carrier. Over voltage insulation of up to 36 kV is provided by a ceramic sleeve that is bonded to the conductor using a ceramic-to-metal seal. A polyethylene sheath on the tube and further over-molding on the gland housing provide continuity of the cable and EB insulation. The fibers themselves are sealed within the assembly using a cocktail of resins, and the carrier tube is filled with a blocking material which has low permeability to hydrogen. As the gas leakage performance of the gland is proportional to the bore diameter of the tube and inversely proportional to its length, the gland is not only coiled for compliance within the coupling, but is tuned to meet the hermeticity requirement for the submerged plant.

This discussion only begins to outline the numerous engineering issues associated with fabricating long-life, high reliability underwater systems. Further details may be found in Hazell and Little (2002). The experience base of the submarine telecommunications industry is directly applicable to ocean observatory needs. As an example of an adaptation for ocean observatories, Figure 6 shows a serviceable science module designed around qualified submarine telecommunication components for the MARS testbed system to be installed off California in 2005 in ~900 m of water (Waterworth et al., 2004). To facilitate connectivity of science experiments and sensors, science instrument ports are housed and protected within a trawl-resistant frame. A door is provided to allow access by an ROV to connect science experiments to a port. The serviceable science module is designed so that the communication and power pressure cases can be recovered to the surface for repair or replacement. This is achieved by mounting the serviceable units within an integrated, detachable and nearly neutrally buoyant module. A repair operation would be carried out by disconnecting the wet-mateable optical and electrical connectors that link the cable terminating assembly to the science module with an ROV, docking with the module, and recovering it to the surface, leaving the trawl-resistant frame, cable and cable terminating assembly in place on the sea floor.

6. A Generic Cabled Ocean Observatory

Figure 7 is a functional block diagram showing the main subsystems of a cabled ocean observatory science node, such as is shown in Figure 6. Copies of these elements appear both in other science nodes (if present) and in the shore station, either of which is a logical peer. Design specifics and performance requirements for each of the subsystems flow from the system engineering process described in Sections 3 and 4. Some candidate implementations are described below, although these may be observatory specific.

The main subsystems in a cabled ocean observatory science node handle power, data communications, observatory management (including instrument interface and data archiving functions), and time distribution. Each of these may be subdivided into a hierarchy of sub-subsystems or beyond; the first sub-level is depicted for some elements in Figure 7.

The linking technology for any new cabled ocean observatory will be COTS submarine telecommunications cable, as described in Section 5. The design of COTS submarine fiber optic cable is a strong constraint on the design of an ocean observatory power subsystem because the presence of a single conductor requires the use of a seawater current return, the resistance per unit length of the conductor restrains the ability to extract power from the cable, and the insulation thickness requires the applied voltage to be under 10-15 kV. These limitations can be removed only by incurring significant non-recurring engineering (NRE) costs for re-design and re-tooling, and will be strongly restricted by a rapidly increasing weight per unit length as the size and/or number of conductors is increased which will inevitably preclude installation in deep water. These constraints may be overcome for short coastal installations where COTS underwater power or ROV cable (both of which typically include some optical fibers) may be applicable. For example, the LEO-15 cabled coastal observatory (Forrester et al., 1997) uses 3 phase AC power carried by multiple conductors over distances of a few km in an ROV cable. This approach would not work over substantially longer distances.

The key engineering tradeoffs that guide decisions about ocean observatory power are reviewed by Howe et al. (2002). They describe the technical difficulties that an underwater AC power system present, and show that DC power provides a significant cost advantage. They also present the tradeoffs between placing the sources and loads in series or in parallel. The former is typically used in submarine telecommunications systems where the underwater repeater loads are fixed and inherently lie in series, with the seawater return electrode located at the distal end of the string for a single end fed system. Parallel power requires a separate sea ground at each load (i.e., science node). Parallel power is simpler to implement with a branched network topology. More importantly, it has an inherent higher power delivery capability compared to series power. Finally, Howe et al. (2002) show that maximum power transmission for an undersea system using COTS telecommunications cable will be limited by line properties and load distributions rather than source properties. In aggregate, these mitigate in favor of a DC parallel power approach which is analogous to terrestrial utility practice. Such a system can deliver 5 kW continuously to each of 26 nodes on a 3000 km regional cabled observatory.

The node power subsystem (Figure 7) transforms the high voltage carried by the submarine fiber optic cable conductor to lower levels usable by both internal node systems and science users. This may be performed in two stages using DC/DC converters, with the backbone power step converting the line voltage to a mid-level bus value (e.g., 400 V) and the user power stage providing isolated standard voltages (e.g., 48 V) to user loads. For a single node coastal observatory, a power system of this sort with simple monitoring and telemetry will probably suffice. As the number of nodes grows on a multi-node system (such as NEPTUNE), issues of power monitoring, protective relaying, fault isolation and location, and power management increase in complexity, as described by Kirkham et al. (2003). This is particularly true with the intrinsically high resistance of COTS submarine telecommunications cable on a large multinode system which results in substantial voltage fluctuations across the network as the loads vary. The challenges of state estimation and power management in a large multi-node observatory are described by Schneider et al. (2002) and Liu et al. (2003). In addition, the NEPTUNE power design includes novel autonomous backbone breakers at each node which serve to isolate faulted sections of cable independent of node functionality, although the entire observatory power system must be turned down to accomplish this.

The data communications subsystem serves two key purposes: aggregation of variable rate data streams from many sensors around a science node, and routing/repeating on the high speed backbone optical network. These two functions are represented respectively by the access communications and the backbone communications/optical transport sub-subsystems in Figure 7. Anticipating that future ocean observatory instrument data will consist primarily of Internet protocol (IP) packets, the access communications block can be implemented using a layer 2 (i.e., data link layer) Ethernet switch which aggregates instrument data and transfers them to the backbone communications sub-subsystem. Ethernet is available at standard data rates of 10 and 100 Mbit/s and 1 and 10 Gb/s, and these are expected to increase over time. At present, it is difficult to identify candidate seafloor instruments which produce data at rates above 100 Mbit/s, and hence limiting the access communications system input data rate to 10/100 Mbit/s appears not to be restrictive. This may change in the future as sensor technologies evolve, and especially as high density television (HDTV) proliferates.

For a single node coastal installation, the backbone communications/optical transport sub-subsystems can be relatively simple; a high speed (1 or 10 Gb/s) Ethernet switch with a non-DWDM optical physical layer will be the simplest and lowest cost solution. This approach has been taken for the Martha’s Vineyard Coastal Observatory (Austin et al., 2002), which has a Gigabit Ethernet backbone.

For multi-node ocean observatories, the backbone communications functions can be implemented in one of several ways, depending on the optical transport protocol and network physical topology. For a mesh network, which constitutes the most efficient way to increase network reliability for a given number of nodes (Ramaswami and Sivarajan, 2002), the simplest approach would utilize a high speed version of Ethernet using multiple independent optical transport channels, with the number depending on the desired total data rate. The optical transport can be implemented using either multiple optical fiber pairs, with one pair supporting full duplex transmission at the design data rate (1 or 10 Gb/s), or using dense wavelength division multiplexing on a small number of fibers. A Gigabit Ethernet/DWDM backbone supporting an aggregate data rate of at least 8 Gb/s has been selected for the NEPTUNE baseline design, as described by Maffei et al. (2003). For a mesh network at points where a given node may connect with more than two others, the node-resident backbone communications sub-subsystem typically operates at layer 3 (i.e., network layer) as a router. An alternate approach would be point-to-point Ethernet over Synchoronous Optical Network (SONET), although COTS interfaces for this technology typically are relatively costly and have a larger form factor with comparable to lower reliability compared to straight Ethernet products. These issues are further discussed by Maffei et al. (2001).

An alternate data communications architecture has been considered for NEPTUNE, consisting of a home-run or star logical topology, where each science node communicates directly only with one or more shore stations. As a result, all node-to-node communication occurs via a shore station, raising overall latency. The home-run topology is implemented by selecting individual wavelengths at each node from a DWDM comb using distributed optical add/drop multiplexers (OADMs). The principal reason to consider this architecture is that extremely reliable (albeit expensive) submarine telecommunications-standard optical amplifiers can be used in the backbone, so that failure of a given node (where much lower reliability communications interfaces are housed) cannot influence any other node. As a result, it was initially believed that this approach would be more reliable than the Ethernet baseline. Because long chains of optical amplifiers exist between a given science node and shore, SONET framing of Ethernet must be employed on the backbone. However, since sophisticated submarine-quality transponders with associated optical management, SONET-clocking, and forward-error-correcting (FEC) features cannot be employed in the nodes due to their size and cost, the alternate system may have difficulty meeting the bit-error-rate requirements to transport high speed Ethernet and provide the optical tuning capabilities required for optically-repeated systems. Differentiating between the baseline and alternate architecture will be further discussed in section 7 as a case example of the science and engineering tradeoffs involved in designing a cabled ocean observatory.

Time distribution can be provided by Network Time Protocol (NTP), which is a widely used IP application layer protocol that can serve time at an accuracy of a few to ten milliseconds corrected for latency across an IP network whose traffic flow is managed by a single authority. NTP has the advantage that implementing software is available for most platforms and operating systems, enabling general low-cost use. It can serve as a primary time standard suitable for most instruments and users on a cabled ocean observatory. Higher accuracy (e.g., order 1 μs) synoptic time can be served to science users using a separate system as shown in Figure 7. This can be implemented using precision quartz clocks in each node which are synchronized to standard time at regular intervals over a dedicated non-IP channel that eliminates error from router jitter. The reset signal can be be returned to the shore-based master clock upon receipt so that the two-way travel time (and hence latency) can be measured on a node-by-node basis and corrected for in each node, including accounting for possible seasonal temperature effects and aging.

The remaining science node subsystems in Figure 7 provide specialized functions that are unique to ocean observatories, and are actually elements of a comprehensive observatory management system (OMS) made up of the data management and archive, node control, and instrument interface subsystems (henceforth abbreviated as DMAS, NCS, and IIS, respectively) that span the observatory from seafloor instrument to distributed shore-based data archives. Figure 8 shows the key functional elements required to implement the OMS, emphasizing interfaces and its distributed nature.

The NCS, with components in each science node and on shore (Figure 7), is the central element in the OMS. A partial list of its functions includes: monitoring and control of the node power busses and power consumption by internal node hardware; node ground fault detection; monitoring and control of the node access and backbone data communications hardware; collection and transmission of node engineering data to shore; and monitoring and control of node time keeping systems. It may communicate using a combination of in-band and high reliability out-of-band channels. The NCS may be distributed among the node power and communications subsystems or could be highly centralized, depending on the implementation.

The IIS provides power, communications, and time services to instruments and sensors, and may be physically distributed between the science nodes, individual instruments, and even the shore when operating in proxy mode. A partial list of its functions would include: monitoring and control of power to the instruments; instrument ground fault detection; bi-directional transmission of data to/from instruments; storage and forwarding of instrument metadata to users or data repositories as required; acquisition and processing of accurate, synoptic time from the infrastructure for use in an instrument; provision to receive instrument reset or parameter change commands from shore; receipt and handling of broadcast notification of observatory state changes (e.g., outages); provision for instrument access control; and provision for instrument oversight for national security. The IIS could incorporate a standard science instrument interface that is included in instruments plugged into the observatory analogous to the puck concept introduced by O'Reilly et al. (2001). This would simplify interfacing of diverse sensors by providing a range of standard voltages (e.g., 5, 12, 24, and 48 V), both serial (RS232/RS422) and Ethernet instrument communications, and high accuracy time distribution. The standard interface could also support metadata functions and protection of the infrastructure from a range of instrument failure modes.

The dominantly shore-based elements of OMS perform operations and data flow management functions as the shore-based counterparts of NCS, IIS, and DMAS. A partial list of the control functions includes: monitoring and control of system-wide power usage and availability;

monitoring and control of system-wide data bandwidth usage and availability; monitoring and control of a master GPS-synchronized observatory clock; ensuring that instrument data and power usage lies within prescribed limits; creation of data paths between instruments or nodes and other processes; elimination of data paths between instruments or nodes and other processes; setting bandwidth limits between data paths; and setting quality-of-service parameters to control the latency and jitter characteristics of a data path. The power and communications control processes on shore interact with the NCS in either of two ways. The first class includes long duration interactions which provide critical telemetry and control functions; an example is power management in which voltage and current information throughout a multi-node cabled observatory must be telemetered to the shore power control process many times per second whenever the observatory is functioning. The second type is ephemeral, and is created in response to a specific intra-observatory event; an example is the communications control response to a request from a specific instrument for allocation of a high quality-of-service, high data rate link to shore.

The remaining pair of shore-based functions depicted in Figure 8 are the data buffering and data archive processes which are part of DMAS. The former gathers real-time data (and instrument metadata) from all instruments, as well as engineering data from the nodes, and stores it temporarily. This function will always be located at each shore station, and serves to provide a short term buffer in the event that connectivity to the Internet and distributed data repositories is interrupted for any reason. In ordinary operation, it simply serves a pass-through function.

The data archive subsystem gathers and receives data and/or metadata from specified instruments. Different repositories may receive and process data from different types of instruments. A partial list of data archive functions includes: extraction of instrument metadata from instruments as required; acquisition and post-processing of data streams from instruments; provision for national security control of data access; hierarchical archival of data in different states of quality control; provision of standard formats for use in assimilation modeling; and archival of model results. Recursive operation may also be envisioned; for example, numerical models could interact with the OMS processes to modify the data collection protocols.

This description outlines the potential intricacy of the OMS services needed to operate an ocean observatory. Complexity will increase with the size of the installation, and is certainly greater for a multi-node observatory than for a single node because of the requirement to coordinate services across the entire facility. While many of the required functions could be implemented in hardware, a key characteristic they share is the need for frequently repetitive and autonomous inter-service communication and exchange of data or commands. In addition, the services required to operate an ocean observatory will evolve over time as new modes of operation emerge and experience is gained by both users and operators. This argues strongly for a design which specifies hardware interfaces at primitive levels in the subsystems comprising OMS and constructing inter-process control and communications connections in software which can be modified as required. This is especially true for a remote seafloor installation where changes of hardware are extremely expensive. Finally, as ocean observatories proliferate, the need for interoperability will become paramount. This is especially true at the sensor and user interfaces where standardization will be essential to broad use of instruments and data from diverse installations. However, interoperability at the OMS level will lead to a substantial reduction in operating costs as the community-wide experience base grows.

St. Arnaud et al. (this issue) discuss these issues in greater detail, and suggest the use of web services as a unifying protocol to handle them. Web services can wrap diverse hardware and software processes and provide a simple, scalable, and extensible means for OMS functions to communicate within and between ocean observatories. They would also enable the dynamic establishment of multiple virtual ocean observatories within or across installations comprised of the same instruments, and devolve the majority of observatory control functions to the science user for the life of the project.

7. Discussion

The generic observatory design of Section 6 contains numerous constraints derived from the iterative use scenario/engineering design loop described in Section 4. Three examples are:

1. Estimating the maximum individual instrument data rate
2. Estimating the backbone data transmission capacity
3. Constraining the maximum power required at each node

The first of these can be approached by surveying the capabilities of currently available sensors and instrumentation, and attempting to project this into the future according to top level requirement 7 in Section 3. It quickly becomes apparent that HDTV bandwidth requirements substantially exceed that of any other postulated instrument; HDTV requires >1 Gb/s uncompressed and as little as 20 Mbit/s compressed (depending on the algorithm employed), with compression resulting in some loss of scene resolution. The vast majority of oceanographic instruments can be accommodated at slow Ethernet (10 Mbit/s) speed. In fact, HDTV so dominates the data transmission budget that the required backbone data capacity for a specific system can be estimated by simply counting the number of HDTV cameras that will be deployed. For the NEPTUNE regional cabled observatory, these observations led to the science interface design requirement of most instrument data connections at slow or fast Ethernet rates, while leaving the option open for the Gigabit Ethernet connection of a very limited number of instruments at each node. Further, reasonable projections of the number of HDTV cameras and the infrequency with which they will need to operate in uncompressed mode leads to an aggregate backbone data rate of order 10 Gbit/s. Neither of these choices requires any technology push, as much higher bandwidth data communications is routinely available. Further, the NEPTUNE baseline design allows for relatively low cost expansion of both the backbone capacity and the number of high data rate instruments that can be accommodated, either by increasing the number of DWDM channels in the optical transport or by upgrading the access and backbone communications systems to a faster technology in the Ethernet family. Such flexibility is possible with this design because the optical fibers linking the nodes are dark and contain no components which would limit upgrade paths other than their inherent attenuation and dispersion characteristics.

Estimating the total power that is required, and reconciling it with that which can be delivered, represents a very different situation. The required power includes both the hotel load for the node electronic systems and that needed for science experiments. The former can readily be constrained to a few hundred watts, while the latter will be dominated by the drain required for lights and electric motors. Power loss in DC/DC converters must also be accounted for; with efficiencies of ~90%, this can amount to 500-1000 W per node. Use scenarios where 10 kW per node are required can easily be constructed. However, Howe et al. (2002) showed that the power which can be delivered over a COTS submarine telecommunications cable network will be limited by the electrical characteristics of the cable. For the NEPTUNE regional cabled observatory, simulations showed that 5 kW could be delivered to each of 26 nodes using two shore connections, but 10 kW could be delivered to only a few at a time with reduced power available for the rest. Thus, delivered power is limited by physical constraints to a level below what users might desire.

Another critical step in the design of an ocean observatory is differentiating between different design approaches through tradeoff studies. This can be done at many levels under varying criteria, but the top level science requirements given in Section 3 serve as the most fundamental. As an example, the baseline and alternate backbone communication designs for NEPTUNE outlined in Section 6 will be compared using these six requirements in turn. These are by no means the only means of differentiating these two designs; some technical challenges for the alternate approach were outlined in Section 6.

Both designs can reasonably be expected to meet the lifetime requirement (1).

The CAPEX differential between the approaches can be estimated either by examining the design differences or by constructing complete system budgets for each. In either case, it is apparent that the alternate design costs will exceed the baseline costs approximately by the NRE required for specialized and qualified OADMs and other backbone components, and the capital cost for ~60 submarine optical amplifiers. The OPEX differential will depend on the relative reliability of the communication electronics in the nodes. With current products suitable for seafloor packaging, more electronic failures can be expected for the alternate as compared to the baseline. The life cycle cost (requirement 2) of the alternate will be higher, with the increment depending critically on the state of the submarine telecommunications marketplace and the reliability differential between suitable DWDM optical transport systems at the time of system build. Whether this cost differential is acceptable or not will depend on other factors.

Both designs will meet the controllability requirement (3), although the baseline offers more flexibility in bandwidth allocation because the entire aggregate backbone capacity can in principle be supplied from a single node. The alternate has a fixed capacity per node that is sufficiently large that this is probably not a major issue.

The baseline design fully meets the flexibility requirement (4), as it utilizes a partially connected mesh network approach with COTS Ethernet hardware which is inherently capable of expansion at any point. The alternate design is substantially less flexible in at least two ways. First, because individual wavelengths are dropped at each node using an OADM, expandability of the network will be limited by the number of DWDM wavelengths per fiber pair that can be accommodated at system build. This could be increased by raising the number of backbone fiber pairs to provide spare capacity, but that also requires increasing the fiber capacity of the optical amplifiers, which raises their costs. Second, the backbone optical amplifiers incorporate optical bandpass filters which restrict the available bandwidth, while the baseline design uses dark fiber between nodes which inherently yields more usable bandwidth.

Both designs can reasonably be expected to accommodate upgrades of the communications technology in the future subject to physical attenuation and dispersion constraints from the backbone optical fibers and (if used) optical amplifiers. These will be more restrictive for the alternate than for the baseline because of optical amplifier spacing and characteristics.

Comparing the reliability of the two designs requires specific electronic system reliability numbers for all components which are vendor and product specific. Once these are available, estimating the reliability of the alternate is straightforward. However, for the mesh network design of the baseline, the analysis is not simple, and a Monte Carlo simulation approach is required. Such an analysis reveals that the reliability of the two designs using current COTS products under requirement 6 is nearly identical, and data will reach shore with equal probability. This may seem surprising given the high reliability of the backbone in the alternate design, and shows the power of meshing to raise network reliability that also characterizes the Internet. It also reflects the fact that high and low reliability systems placed in series between a sensor and shore in the alternate design yield an overall reliability controlled by the least reliable components. It should be recognized that it is possible for multiple, simultaneous node failures to isolate one or more working nodes in a partially connected mesh network such as the baseline. However, Monte Carlo simulation shows this to be a very rare occurrence, and hence of limited concern.

Finally, the futurecasting requirement reveals a potential difference between the two communications designs. If use scenarios require that data transmission be highly asymmetric, with transport dominantly occurring between seafloor instruments and shore, then there is little distinction between the two designs. However, the alternate cannot accommodate low latency communications between instruments at different nodes, as all inter-node data have to be routed through a shore station. An emerging paradigm in wireless data networking is sensor webs, which are interoperable, intelligent, dynamic, flexible, scalable networks of interconnected sensors that fuse together to form a distributed, coherent whole (e.g., Delin, 2002; Teillet et al., 2002; Gibbons et al., 2003; see also http://sensorwebs.jpl.nasa.gov and http://intel.com/research/exploratory/wireless-sensor.htm). This paradigm will work over any data network, and it is reasonable to expect it to be ported to ocean observatories in the future. Use scenarios can readily be constructed with sensor webs that operate across a regional cabled observatory like NEPTUNE. Whether or not these can function in a high latency inter-node communications environment needs to be fully understood before the alternate communications design is pursued, or else important future classes of research may be precluded.

In the end the decision in a tradeoff study such as this will be made by weighing the pros and cons from the top level science requirements described here, as well as lower level functional and performance issues. The choice is sometimes obvious and at other times presents difficult sets of pros and cons. Further, this represents one among many such trade studies in the design of a cabled ocean observatory, all of which need to be tracked and documented so that a coherent , defensible overall ocean observatory design can in the end emerge.

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Figure Captions

Figure 1. Flow chart showing the major stages of the system engineering process defined in Military Standard 499B (1991).

Figure 2. Typical deep water cable cross section showing internal hydrogen barrier and steel vault.

Figure 3. Deep water submarine telecommunications cable intended for increasingly deep installation from left to right. The cable types starting at the left are rock double armor heavy (RAH DAH), double armor heavy light (DAH DAL), single armor heavy (SAH), single armor light (SAL), lightweight protected (LWP), and lightweight (LW). See text for discsussion.

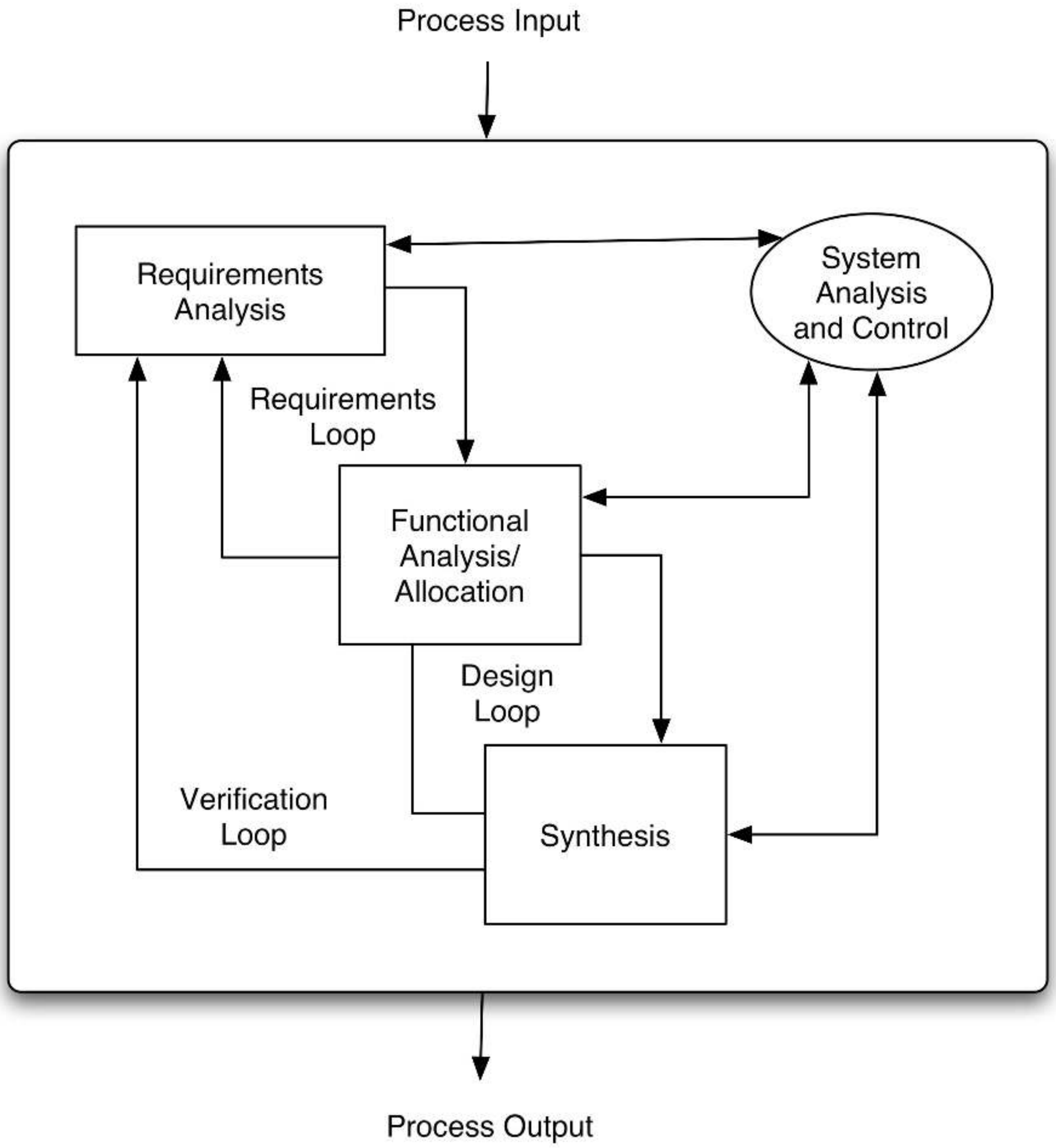
Figure 4. Typical extremity box with wire anchorage. See text for discussion.

Figure 5. Submerged equipment coupling and gland interface.

Figure 6. Cabled observatory science node for use in shallow (<2000 m) water consisting of a cable terminating assembly, trawler resistant frame, and serviceable science module. The latter can be disconnected by an ROV and returned to the surface for repair. The closed doors on the trawler resistant frame protect a set of wet-mateable connector ports to which science experiments are attached.

Figure 7. Block diagram showing the main seafloor science node subsystems. See text for discussion.

Figure 8. Block diagram defining the distributed processes required to implement a comprehensive Observatory Management System. See text for discussion.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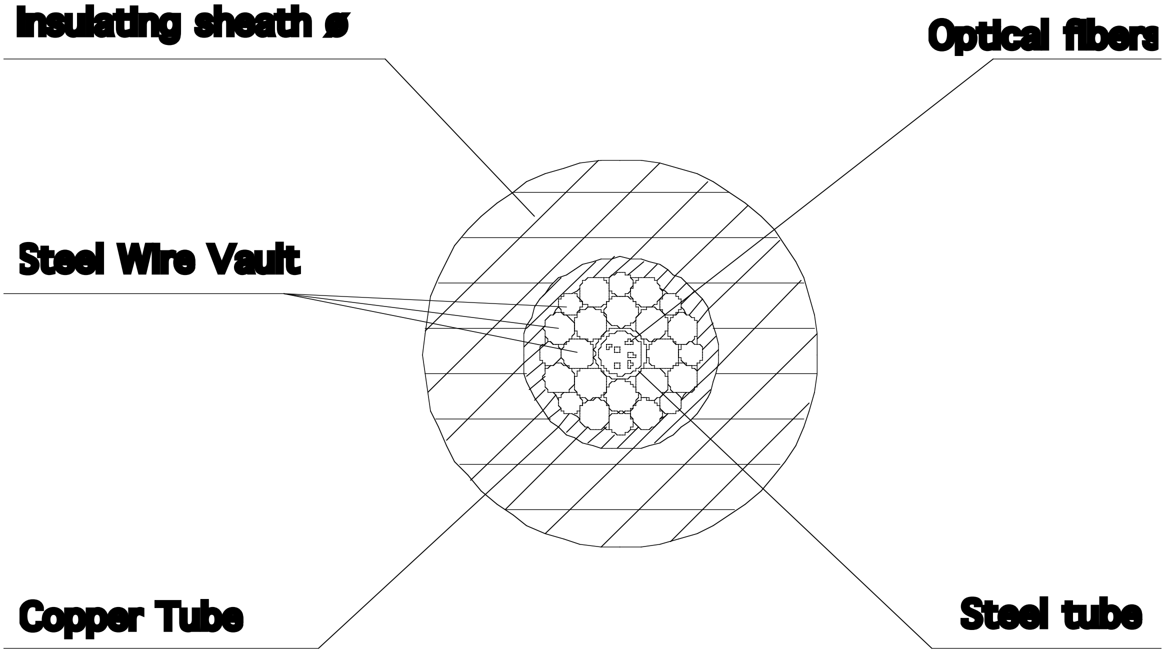
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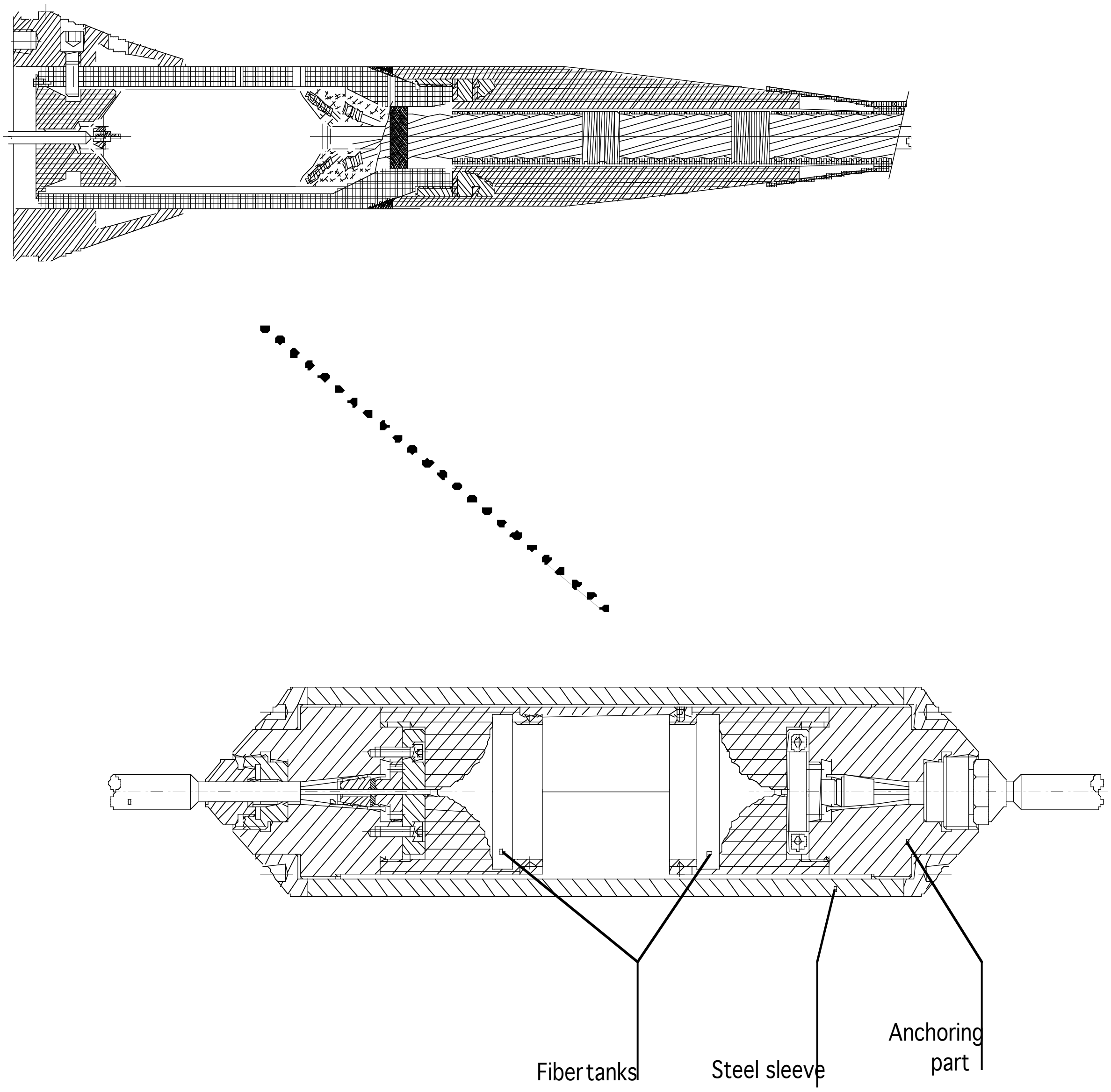
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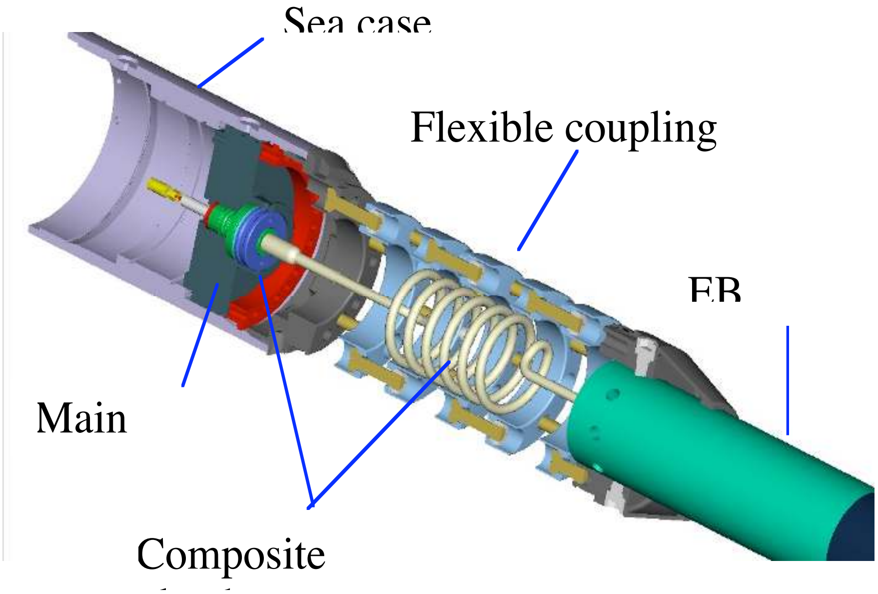
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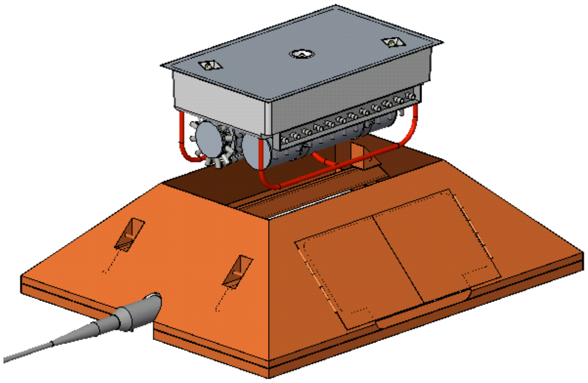

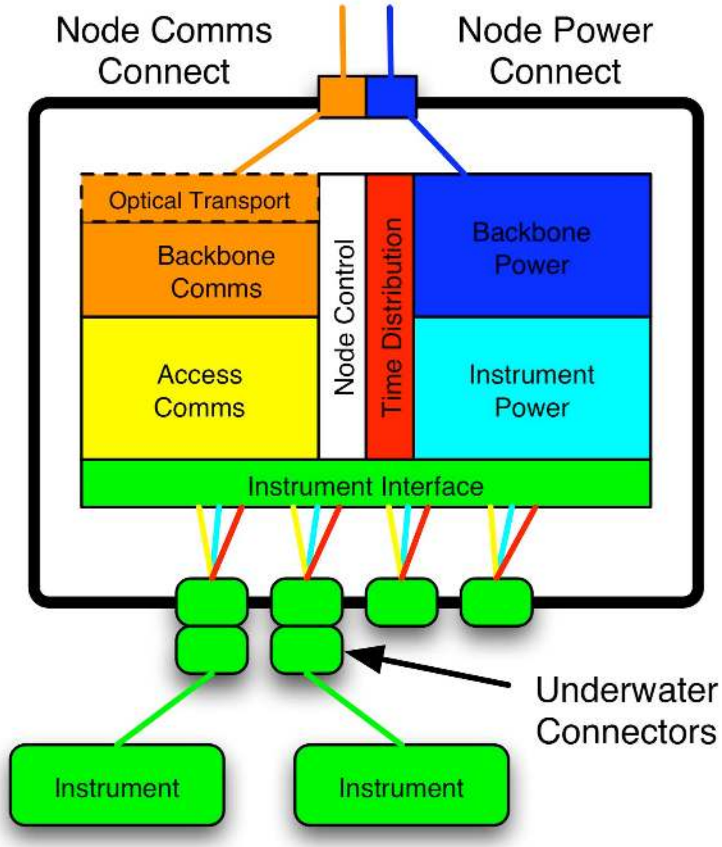
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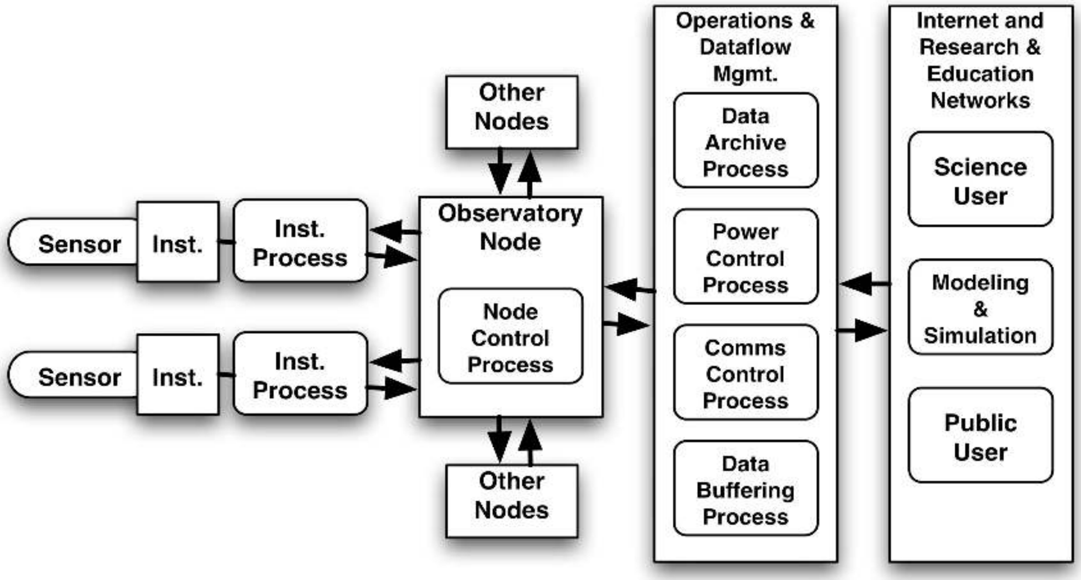
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Data Buffering Process
Internet and Research & Education Networks
Science User
Modeling & Simulation
Public User