Communications and Power Infrastructure for Cabled Seafloor Observatories

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The study of the interactive processes that comprise the dynamic earth-ocean system requires new approaches that complement the traditional ship-based expeditionary mode that has dominated the field for the past century. The physical, chemical, and biological processes that constitute the ocean-earth system vary over spatial scales of microns to hundreds of kilometers and temporal scales from seconds to decades, although these quantities have in general been poorly characterized using traditional methods. New experimental approaches involving long-term access to the seafloor are being developed to alleviate this shortcoming. As a result, ocean scientists are on the threshold of a scientific revolution enabled by rapidly emerging seafloor access technologies. In particular, oceanography is moving toward a long-term presence on, above, and below the seafloor using distributed real-time sensor networks covering large areas to address multidisciplinary scientific problems. Real-time networks also enable an education and public outreach capability that is unprecedented in oceanography, and has the potential to dramatically impact the public attitude toward ocean sciences in particular and science in general.

A seafloor observatory is fundamentally a system to facilitate ocean access for scientific purposes. It comprises two major components: an infrastructure which provides power and data communications to sensors and seafloor work systems, and a diverse network of sensors and vehicles which collect data and perform scientific tasks. Only the first of these will be considered in this paper.

There are three main approaches for providing the infrastructure: autonomous systems, systems permanently connected to surface buoys which provide power and a data link to satellites, and systems connected to shore by a submarine cable which provides the essential power and communications functions. The autonomous system is typified by the European Geostar project (http://web.ingv.it/GEOSTAR/), but usually do not provide a real-time data connection and operate on *in situ* power (i.e., batteries). While this approach is useful, it is certainly less capable and less flexible than the other two. Surface buoys are capable of yielding higher power levels than *in situ* systems (i.e., tens to hundreds of watts) and data rates of tens to hundreds of kilobits per second can be provided using current satellite technology. They are flexible since moderate size buoys can be installed where they are needed by standard oceanographic research vessels, but offer lifetimes of no more than a few years before major refurbishment or replacement is required. In contrast, seafloor cable systems offer long lifetimes (a 20 year design life is typical in commercial service), low maintenance barring catastrophic events which can largely be prevented by proper installation, substantially higher power levels than buoys (several kilowatts or more), and very high data rates (many gigabits per second using optical fiber). For all but short term applications or those in areas too remote from land to be economically served by cables, they are the preferred approach. It is interesting to note that of the existing (as of the end of 2000) fixed observatory programs in Japan, the US, and Europe constituting at least 14 separate systems, all but one are based on seafloor cable technology.

There are two types of submarine cables in scientific use, both of which were developed for telecommunications use: analog and fiber optic cables. Analog (coaxial) submarine telephone cables were installed commercially from the mid-1950's to the late 1980's, but most have now been abandoned in favor of more capable fiber optic technology. A few analog submarine telephone cables have been re-used for scientific purposes (e.g., TPC-1 in the GEOTOC project and HAW-2 for the Hawaii-2 Observatory), but such opportunities are dwindling rapidly as old systems are often physically removed from cable stations and their approaches. Future scientific cables will largely be based on the custom installation of telecommunications-standard fiber optic cables. To date, eight fiber optic systems of 100-200 km length have been installed around Japan, and two shorter fiber optic systems for coastal applications have been deployed in the US. Other systems are being planned, notably the US-Canadian NEPTUNE (http://www.neptune.washington.edu) project encompassing the Juan de Fuca plate off northwestern North America.

Submarine fiber optic cables facilitate optical communications as well as a power link utilizing a seawater return current path. Optical communications systems are rapidly evolving; the current state of the art allows up to 10 gigabits per second to be carried on a single optical channel, and 40 gigabits per second is expected in the near future. Using wavelength division multiplexing, hundreds of optical channels can be carried on a single fiber, yielding aggregate data rates that approach a terabit per second per fiber. While essential for transoceanic telecommunications, there is a serious mismatch between this capability and any reasonable scientific application, where aggregate data rates of order a few gigabits per second at most can be anticipated. Further, scientific observatories require data input and output at many seafloor sites, whereas a telecommunications system comprises a "fat" data pipe linking a small number of land-based terminuses. Finally, seafloor observatories require distributed power at the same seafloor sites, where telecommunications system require only power for seafloor optical amplifiers typically spaced 60-100 km apart. Taken together, these observations suggest that a different (i.e., non-telecommunications) approach is required for seafloor observatories, although standard off-the-shelf telecommunications fiber optic cable will certainly suffice for scientific service. In addition, the extensive capabilities to lay and service seafloor cables developed for commercial use immediately port over to scientific applications.

The seafloor observatory infrastructure should be viewed as end-to-end (i.e., shore station to seafloor node) communications and power distribution systems, with a telecommunications fiber optic cable providing a passive link between the system end members. In addition, auxiliary systems to enable unconditional control of the infrastructure and distribute accurate time information are required. Finally, a physical infrastructure that facilitates addition or removal of scientific instrumentation while being easily maintainable is also needed.

High quality optical fiber displays attenuation of about 0.2 dB/km with minimal dispersion in the band around 1550 nm that is used for optical communications. Thus, the communications system must not only provide a data link between shore and seafloor, but it must also overcome fiber attenuation. This typically requires a repeating system every 100 km or so which may or may not be an integral part of the communications system, depending on the technology which is chosen.

Selection of the right communications technology must be based on a set of reasonable criteria. First, it makes good economic sense to utilize commercial off the shelf (COTS) technologies rather than devise new ones. For this purpose, future projection is important to avoid buying into dead end technology which will not be available for a significant part of the observatory lifetime. Second, simplicity should be paramount, and it makes little sense to use a technology which provides complex features which are not needed. Third, upgradability is essential; no data communications technology can be expected to remain completely stable for decades. The best upgradability approach is to install "dark" fiber on the seafloor, and light it from easily maintainable electronic systems which can change over time to accommodate technological evolution. Fourth, some attention to power consumption and seafloor packaging issues is required. It makes little sense to use the bulk of the available seafloor power to energize the communications infrastructure rather than scientific experiments, and pressure cases of heroic dimensions that can accommodate large communications interfaces are very costly and hard to deploy.

With these criteria in mind, it is possible to narrow the range of possible COTS solutions. Because a seafloor observatory communications backbone is fundamentally a digital data link to instrumentation, it makes sense to consider only solutions based on the widely-used internet protocol (IP) packetized data communication technologies. There are essentially four ways to build an IP backbone over optical fiber: 1) IP over a switching technology (e.g., asynchronous transfer mode or ATM) over a time multiplexing technology (e.g., SONET/SDH), 2) IP directly over SONET/SDH (often called packet over SONET), 3) IP over fiber, and 4) stretched LAN technologies, especially the Ethernet family, of which Gigabit Ethernet (GbE) is the latest member (although 10 GbE will emerge within a year). Options 1 and 2 are telephone-company standard (but rarely used elsewhere), include numerous features to facilitate voice and video traffic of little use for seafloor observatories, require external optical repeaters for long haul applications, and typically require large, power intensive interfaces. Option 3 is emerging, but is largely aimed at high data rate applications. Option 4 offers many advantages, including intrinsic combination of the long haul repeating and data switching functions, substantially lower cost, and low power consumption and physical size, and is the most widely used and rapidly growing part of the data networking marketplace, ensuring long term availability. LAN technologies, especially GbE, is clearly the best current solution for seafloor observatories, and provides a good match between capabilities and requirements.

Submarine cables are designed to handle voltage of up to 10 kilovolts, and possess intrinsic resistances of about 1 ohm per km, which is high by power distribution standards. There are two approaches to serving power to seafloor systems over a submarine cable with seawater return: serial (constant current) and parallel (constant voltage). Both of these are DC solutions, as the use of AC is precluded due to the distributed capacitance and inductance of telecommunications cables at all save extremely low (under 1 Hz) frequencies. Serial power has long been in standard use in the submarine telecommunications industry. However, it has several significant limitations, including incompatibility with a mesh or branching topology, limited fault tolerance, and higher intrinsic losses compared to parallel power due to a higher effective impedance. Further, COTS DC to DC converters capable of operation in a constant current environment are not readily available, and custom designs are required. Parallel power is in standard use for long haul power distribution grids around the world. It offers the advantages of simple branching and higher efficiency due to a lower intrinsic effective impedance. For a seafloor system, it can be implemented using DC-DC converters at each seafloor node connected to a local sea ground and capable of operating over the 1-10 kV range, and can deliver up to 5 kW per node over a multiple thousand km distance.

In contrast, a serial power system can deliver only a small fraction of this power over such a distance. A parallel system can easily be designed to be robust to cable faults. Both serial and parallel power systems possess intrinsic stability problems (as is also the case for land based power distribution systems), and a layered control system is required for network operation with a high degree of fault tolerance.

Auxiliary systems are required for backup control of the communications and power systems and to distribute time information to seafloor instruments. The former must be simple and robust, as it provides the ultimate control of inaccessible but complex seafloor-based systems. It is the seafloor analog of a technician who can enter a router closet or power distribution room to push the reset buttons or flip circuit breakers. The required data rate is modest (tens of kilobits per second). Once the main communications backbone is functional, control functions can be transferred to standard IP protocols such as the simple network management protocol (SNMP) operating over the communications network and managed using standard network management software. Time information can be distributed over an IP network using protocols like the network time protocol (NTP). However, while this does account for latency, it is limited in accuracy to a few milliseconds. Higher accuracy time will have to be distributed using custom systems linked to some standard such as the global positioning system (GPS) satellites. It is feasible to combine the control and time distribution functions, simplifying observatory design and reducing the backbone fiber count.

The physical design of the seafloor observatory infrastructure should combine low cost maintenance with universal compability with scientific instruments and seafloor work systems. The former is best accomplished by avoiding in-line sub-system installation on the backbone which would require an expensive cable ship each time service is required. Instead, short (1-2 water depths) lateral stubs extending from branching units on the backbone cable can be terminated with the communications and power electronics, and can then be serviced using standard oceanographic research vessel assets. Finally, wide compability with instrumentation requires the specification of a standard instrument interface which is easy to incorporate into instrumentation and the use of underwater-mateable connector technology.

These concepts will be illustrated with the functional system design for NEPTUNE.