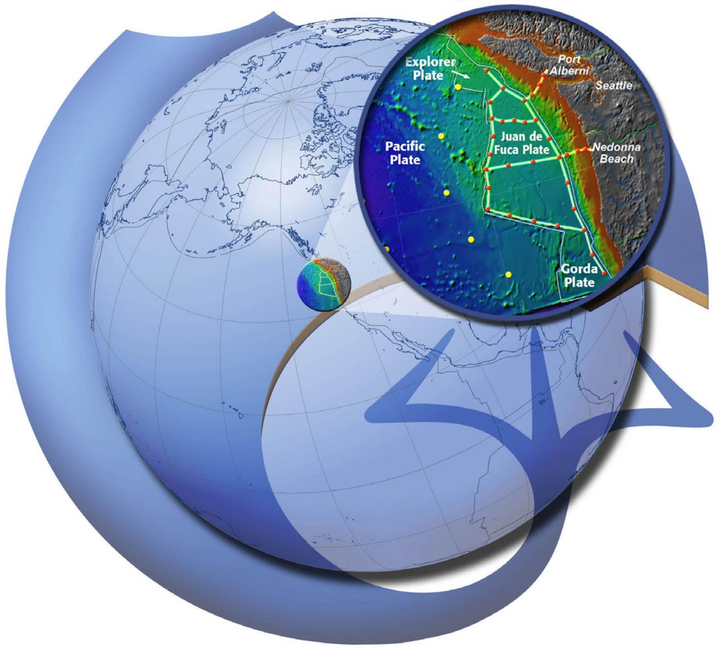
NEPTUNE



Real-Time, Long-Term Ocean & Earth Studies at the Scale of a Tectonic Plate

NEPTUNE Feasibility Study
prepared for the
National Oceanographic Partnership Program (NOPP)
June 2000

by the NEPTUNE Phase 1 Partners

University of Washington
Woods Hole Oceanographic Institution
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Foreword

This NEPTUNE Feasibility Study was partly funded by the National Oceanographic Partnership Program (NOPP) and partly supported by the NEPTUNE Phase 1 Partners: the University of Washington, the Woods Hole Oceanographic Institution, the Jet Propulsion Laboratory, and the Pacific Marine Environmental Laboratory of NOAA.

The National Oceanographic Partnership Program was established in 1997 to address the need to ensure optimal use of the oceans and coastal areas and to ensure that the U.S. maintains "its world leadership in oceanography as one key to its competitive future."

A major focus of NOPP is the implementation of "a comprehensive, integrated national ocean observations program (that) will, for the first time, bring together federal, academic, state institutions, and industry into a coordinated system for monitoring U.S. marine waters.

"A coordinated national approach, linked effectively with similar programs in other nations, is an essential prerequisite for effective use and management of the oceans. The nation cannot realize the economic, social and security benefits of the oceans in a responsible, sustainable manner without such a program."

By capitalizing on the research efforts and operational activities of various federal, academic, state, and private sector organizations it is now possible to undertake a series of actions toward implementing an ***Integrated Ocean Observing System (IOOS)****.*

The vision for IOOS is to

> *Provide a sustained national system for observations of the ocean with outputs that are easily accessible for creating forecasts and products essential to the nation's economy, the management of marine resources, public health and safety, and national security.*

The vision of NEPTUNE is to

> *Provide a new Internet-linked platform for integrated earth and ocean sciences at the scale of an entire tectonic plate using a network of submarine fiber-optic/power cables to support multiple* in situ *sensor arrays and robotic laboratories for real-time remote interaction with dynamic processes on, above, and below the seafloor.*

Abstract

How can we study the essential and interactive processes that make up the dynamic earth-ocean system, over spatial scales of microns to hundreds of kilometers, and temporal scales from seconds to decades? The NEPTUNE project will address this problem by establishing a linked array of undersea observatories on the Juan de Fuca plate located in the northeastern Pacific Ocean. Fiber-optic/power cable will connect land-based scientists, students, decision makers, and the public to distributed sensors and sensor networks above, on, and beneath the seafloor. The motivation behind NEPTUNE's scientific and educational components, technical considerations, and implementation is the topic of this feasibility study prepared for the National Oceanographic Partnership Program.

Some of the scientific topics that motivate NEPTUNE include studies of cross-margin particulate flux, seismology and geodynamics, seafloor hydrology and biogeochemistry, ridge-crest processes, subduction zone processes (fluid venting and gas hydrates), deep-sea ecology, and water column processes. Research on the deep hot biosphere is just one example of the kind of study that links together all the scientific topics. There are strong intellectual and societal drivers for implementing NEPTUNE.

The NEPTUNE infrastructure, consisting of fiber-optic/power cable and junction boxes on the seafloor, will provide large amounts of power (kilowatts) and an Internet communications link (gigabits/second) at distributed junction box nodes. Connected to these nodes will be sensors and sensor networks, some of which constitute "community experiments" while others are for individual investigators. The information management system brings together all the data to enable the linkages and connections between the various processes to be studied in detail by an extended community of scientists, students, and the public. The NEPTUNE approach also holds implications for the exploration of oceans elsewhere in our solar system. This report demonstrates that NEPTUNE is technically feasible and can be implemented at an affordable price.

The NEPTUNE concept is new to the ocean and earth science communities and will require new ways of thinking about how to do research from a technical, as well as programmatic, point of view. We must accept this challenge if we are to continue to make progress in understanding our world.

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Executive Summary

Ocean scientists are on the threshold of a scientific revolution enabled by rapidly emerging technologies. For the first time, the ability to enter, sense, and interact with the total ocean environment is within our grasp. We are expanding beyond short-term expeditions using research vessels. We are moving toward a long-term presence on, above, and below a section of seafloor as large as a tectonic plate.

The NEPTUNE project proposes to “wire” the Juan de Fuca tectonic plate with 3,000 kilometers of fiber-optic/power cable. Instrumented observatories sited along the cable will remotely interact with physical, chemical, and biological phenomena that operate across multiple scales of space and time. Data will flow in real time from instruments to shore-based scientists, educators, decision makers, and learners of all ages.

This new operational paradigm is made possible by rapid advances in computational sophistication, communication and power technologies, robotic systems, and sensor design. We will address such compelling intellectual and societal themes as the search for life beyond earth, anticipation of crippling natural hazards, informed management of marine resources, anthropogenic influences on ocean and climate systems, and the complexity of interactions of living and nonliving elements in different habitats.

The NEPTUNE observatory can provide a coherent infrastructure of high-speed communication-control links using a submarine network of fiber-optic/power cables. This capability permits interactive control over a fleet of sensor-equipped robotic vehicles and enables simultaneous, adaptive, user-designed experiments that explore the dynamics of ocean and earth processes. Scientists and society together must make long-term commitments to innovative facilities that offer new mechanisms for actively exploring the complexities of these natural systems. An enhanced understanding of volcanism, tectonics, and ocean dynamics, and the ability to examine extreme habitats remotely, will pay handsome dividends as we explore other planets.

To attract the broadest user base to this full-service oceanographic research platform and to minimize cost, we sought a study area that had a small footprint but encompassed myriad important earth and ocean processes. We also wanted the site proximal to nations with strong technological infrastructures and modern port facilities. Based on these criteria, we chose to focus NEPTUNE on the Juan de Fuca Plate region and the overlying water mass. The Plate is small and entirely submarine, and we propose treating the entire system as an ocean-earth laboratory.

By its very nature, NEPTUNE is an international program. The study area spans the territory and exclusive economic zones of the U.S. and Canada: approximately one-third of the Juan de Fuca Plate lies within Canadian waters and two-thirds within U.S. waters. Our Canadian colleagues have begun a parallel, cooperative NEPTUNE program, and we are optimistic that Canada will accept our invitation to become a partner with the U.S. in NEPTUNE. Release date of the initial Canadian report is mid 2000.

Our request for support to conduct this study was funded in equal parts by the National Oceanographic Partnership Program (NOPP) and by the four NEPTUNE Phase 1 partners (University of Washington, Woods Hole Oceanographic Institution, Jet Propulsion Laboratory, and Pacific Marine Environmental Laboratory).

The feasibility study was designed to address three questions:

- Is NEPTUNE scientifically desirable?
- Is it technically feasible?
- Is it financially reasonable?

NEPTUNE Science

The ultimate measure of success of any scientific facility is the innovative character and quality of the scientific research and public education enabled. *Ad hoc* science working groups, described below, were convened in 1999 to brainstorm the scientific viability of large, long-term group or community studies and of shorter-term individual investigator experiments and observations.

These science working groups produced white papers on the following topics:

Cross-Margin Particulate Fluxes: NEPTUNE’s capabilities will permit measuring, sampling, and experimentation during the episodic events typical of the large fluxes of sediment and associated pollutants crossing the northeast Pacific continental shelf.

Seismology and Geodynamics: The NEPTUNE study area includes all major types of oceanic plate boundaries, including the Cascadia subduction zone. NEPTUNE is very complementary to U.S. and Canadian initiatives to enhance land-based observations, and will provide a unique opportunity to address important questions related to plate boundary deformation and plate interactions.

Seafloor Hydrogeology and Biogeochemistry: Instrumented boreholes within the oceanic crust can serve as laboratories for studying the interdependence of tectonics, fluid and thermal flows, and biological activity. Early evidence indicates that these relationships are at least partially forced by tides, but the ramifications are not clear.

Ridge-Crest Processes: NEPTUNE's capabilities will help establish the specific nature of links and variations between geological, physical, chemical, and biological processes at active mid-ocean ridges. A crucial use of NEPTUNE will be rapid response to eruptions of submarine volcanoes to sample the exotic microbiological materials released there.

Subduction-Zone Processes (Fluid Venting and Gas Hydrates): The classic study site for fluid venting and gas-hydrate formation and breakdown is located within the NEPTUNE study area. Global interest in hydrates reflects their role as a vast potential energy resource and a significant source of greenhouse gases.

Deep-Sea Ecology: The deep sea represents two-thirds of our planet yet is virtually unexplored in terms of biocomplexity. The NEPTUNE network will provide the capability to develop a functional understanding of the ecology of deep-sea biota, only a small percentage of which have been sampled or identified.

Water-Column Processes: Collecting model-guided, continuous, long-term data series will improve current physical-chemical-biological models of the representative oceanic processes that occur in the NEPTUNE study area. NEPTUNE will provide the capability to conduct unique quantitative assessments of certain portions of the carbon cycle.

The overwhelming conclusion of each science working group was that NEPTUNE represents an important new approach to the earth-ocean system and that it could significantly improve the science that can be done in each field. Additional science topics for development in Phase 2 include fisheries studies, the size and behavior of marine mammal populations, carbon cycle studies, calibration and validation of satellite sensors, robotic-system test beds, studies of air/sea interactions, plate-scale submarine geodesy, and paleoceanography.

Engineering Overview and Infrastructure

Overarching technical capabilities of the NEPTUNE infrastructure include a 30-year useful life, high reliability, high-bandwidth and high-power capabilities, and real-time data and control. Conceptually, NEPTUNE has three parts: the science and educational activities; the support structure, which includes operations, maintenance, and data management; and the engineering infrastructure, which provides power and data communications to the seafloor.

The engineering infrastructure has four subsystems: power, communications, timing, and control. Each subsystem threads its way through the physical system, connecting the scientists and other users on shore to the science instruments at the seafloor. We have selected a mesh topology for both power and communications to meet the capacity requirements and to maximize reliability and flexibility.

For power, this means using a "parallel" or constant-voltage approach much like land power systems and unlike conventional submarine telecommunications systems. Parallel power on a submarine fiber-optic cable is capable of operating at, for example, 10 kV and 10 A, which would deliver 100 kW to the entire NEPTUNE system.

For communications, NEPTUNE will utilize data networking technology that is widely used to connect the Internet to laboratories, classrooms, and homes around the world. From the dual perspectives of flexibility that preserves simplicity and cost minimization, gigabit Ethernet is a very promising technology. Overall, NEPTUNE is similar to campus networks that utilize this approach and, with multiple shore connections, can benefit substantially from its automatic routing and restoration capabilities.

Accurate and precise timing is almost universally necessary for NEPTUNE science experiments whether for time-stamping data or for synchronizing actions across the system. Power and communication will be continuously monitored to ensure satisfactory performance. As conditions and observations change, the operator uses information from the monitoring system to redirect power in the network or to reallocate communication resources.

Data Management and Archiving

Data acquisition issues include management at the source, management at the shore terminal(s), and quality control and assurance throughout. During Phase 2, we will develop criteria for determining which data are fully archived. Our intent is to develop a data resource that is user friendly and flexible enough to accommodate a broad range of queries. Archiving and modeling issues include stream-oriented processing, distributed database management, content-based indexing, alerting, feature recognition, access to data, and web-centric modeling and data access.

Education

NEPTUNE's Internet technology offers great educational potential. It can provide a wide range of new opportunities to explore and investigate the dynamics of the marine world using real-time data flow to classrooms and living rooms coupled with cutting-edge visualization techniques. NEPTUNE will establish partnerships with teachers and K–12, undergraduates, and graduate students through workshops, curriculum development, and existing programs while exploring new opportunities for optimal use of the live data flow and data archives. Collaborators within the informal educational community will include museums, science centers, aquariums, media, and youth programs.

Management and Oversight

The guiding assumptions in considering options for NEPTUNE's management and oversight are as follows: 1) management and oversight must change in response to the evolving needs of the project, and 2) oversight functions should be kept separate from management functions.

Phase 2, Development (2000 – 2003), and Phase 3, Installation (2003 – 2006), will be guided by an Oversight Board composed of representatives from organizations directly involved in submarine observatories. During Phase 2, the NEPTUNE Coordinating Office will assume primary responsibility for planning and coordination activities. Early in Phase 2, both new and old partners will participate in development of the project's organizational management structure.

In Phase 4, Operations (2004 –2035), the NEPTUNE Coordinating Office will evolve into an Operations Office that will serve as the primary NEPTUNE management entity.

Environmental Considerations and Permits

Developing and maintaining high-quality communication with all potential stakeholder groups is an important responsibility of the NEPTUNE program. Several meetings were held during 1999 with groups that included fishing organizations, environmental groups, cable companies, regulatory agencies, and Native American tribes. In addition, some portions of the NEPTUNE cable may be laid on public submerged lands. To satisfy federal requirements, NEPTUNE will prepare an environmental assessment or provide an environmental impact statement under the National Environmental Policy Act.

For those parts of the system over which Canada has jurisdiction, Canadian procedures will be followed.

Realizing NEPTUNE

Phase 2, Development, is loosely defined as all activities between completion of the Feasibility Study and the initiation of activities for Phase 3, Installation. The highest priorities include establishing a solid financial base for the program, initiating the work of the technical and scientific design teams, and selecting an oversight and management framework. The engineering component includes forming an integrated engineering team, constructing the technical implementation plan, and implementing this plan within a systems engineering approach.

A major parallel effort includes establishment of long-term science working groups. Their goals will be to conceptualize the design, prototype the community experiments, and develop the strategy that will make NEPTUNE attractive and user-friendly.

Activities during Phase 3, Installation, are procurement and deployment of the NEPTUNE backbone infrastructure with the initial suites of sensors for community experiments. Phase 3 must be a smooth transition between the initial planning and design in Phase 2 and the routine operations in Phase 4. Management and oversight will be major tasks during Phase 3, as subcontractors or industry partners will handle much of the actual installation work.

Phase 4, Operations, will revolve around four functions: network operations, data management, sensor network maintenance, and node and cable maintenance. Scientific activities will be reviewed regularly, and new integration strategies and experiments will be entrained as the user base evolves. Educational curricula developed during earlier phases will be put into place in classrooms.

Cost Estimates

The estimated cost for the NEPTUNE plate-scale infrastructure is $100M; Phase 2, Development (2000 – 2003), $13M; Phase 3, Installation (2003 – 2006), $60M in 2003 – 2004 and $30M in 2005 – 2006. A rough estimate for the cost of a suite of community experiments is $100M, of which $15M is for development. Costs for experiments will be spread over the next 10 years. The largest cost uncertainty is in the community experiments. Operating costs will be about $10M/year. Costs are in year-2000 U.S. dollars.

Conclusions

1) There are strong intellectual and societal reasons for implementing a cabled plate-scale observatory for earth and ocean sciences in the Juan de Fuca region.

Intellectual drivers include gaining new understanding of all aspects of plate dynamics and applying unique new approaches to studying the deep, volcanically supported microbial biosphere. Using NEPTUNE we will gain a new and quantitative understanding of the physical-chemical dynamics and biocomplexity of a single coherent mass of the global ocean. We will explore the links between this deep-sea biosphere, the origins of life on earth, and the search for life beyond earth. Societal drivers include biotechnological spin-offs from the deep biosphere; understanding formation of metal and hydrocarbon deposits; assessment of fisheries cycles, migration patterns, and population dynamics; tsunami abatement; earthquake mitigation potential; and long-range studies of human impacts on the coastal ocean.

2) *NEPTUNE is technically feasible.*

This document establishes a technical path to the realization of NEPTUNE. The primary development effort will be in the engineering integration of available components. We will take significant advantage of established capabilities used within the telecommunications industry for the laying and protection of cable. But, as developed herein, several innovations will optimize nonstandard approaches to power and communications to meet NEPTUNE's special needs. Although significant research and development are required in the realm of robust, versatile chemical and biological sensors, a suite of existing oceanographic and geophysical instruments is available today for straightforward adaptation to the NEPTUNE infrastructure. For these reasons, excellent scientific opportunities and outreach capabilities can be realized as soon as the system is in place. With time, growing sophistication of new sensors and evolving experimental strategies will strengthen NEPTUNE's contributions to oceanography.

3) The cost is reasonable.

The rough cost of capitalizing the NEPTUNE infrastructure (shore station, cable, and junction boxes on the seafloor) is $100M. The cost of a suite of community science experiments ($100M) is likely to be distributed over a number of user communities, such as seismologists, ridge-crest researchers, gas-hydrate investigators, and sediment-transport researchers. Similar-scale projects include the construction cost of a Class 1 oceanographic ship ($60M; $5M/year), the South Pole Station Modernization ($128 million), and a typical NASA small satellite program ($100M).

Recommendations for Implementation of NEPTUNE

1) Initiate Phase 2, Development, by mid 2000.

2) *Establish a NEPTUNE Coordinating Office.*

3) *Identify institutional participants and the role of industry in the technical design and establish the project organization and management structure.*

4) Establish the long-term science working groups with financial support for the chairs.

5) Identify a variety of agency, foundation, and corporate funding sources for all aspects of the program and pursue centralized funding for Phase 2.

6) *Assemble the education and outreach team for NEPTUNE with the charge to define the major elements of the program by the end of year 1 of Phase* 2.

7) Define the international character of the program.

1. Introduction

Earth, ocean, and planetary scientists are on the threshold of a revolution enabled by rapidly emerging technologies. The future of our sciences requires an expansion beyond the intermittent expeditionary mode of identifying "what's out there" to a sustained, *in situ* experimental mode of exploring spatially well-defined natural systems by focusing on the time domain.

Historically, expeditionary science has characterized some portion of an ocean or a planet within the constraints of data collection from a research vessel or a spacecraft. Out of this exploratory work has grown a suite of models and testable hypotheses that require more than time-limited visits to evaluate.

A new operational paradigm is required, one made possible by advances in computational sophistication, communication and power technologies, robotic systems, and sensor design. New investigational strategies within this paradigm will create opportunities to address such compelling intellectual and societal themes as the search for life within and beyond earth, anticipation of crippling natural hazards, informed management of marine resources, anthropogenic influences on ocean and climate systems, and a deeper understanding of habitat complexity.

1.1 The NEPTUNE Plate-Scale Observatory Concept

A new investigative strategy is the establishment of an extensive, remote, continual, interactive "sensor-presence" within a particular system of interest, whether a fully instrumented fault system on land, a remotely wired oceanic plate, or a robotic colony on Mars. Scientists and society together must make long-term commitments to *in situ* facilities that will provide investigators, educators, decision-makers, and the general public with a new means of observing our planet. NEPTUNE is such a facility (Figure 1.1).

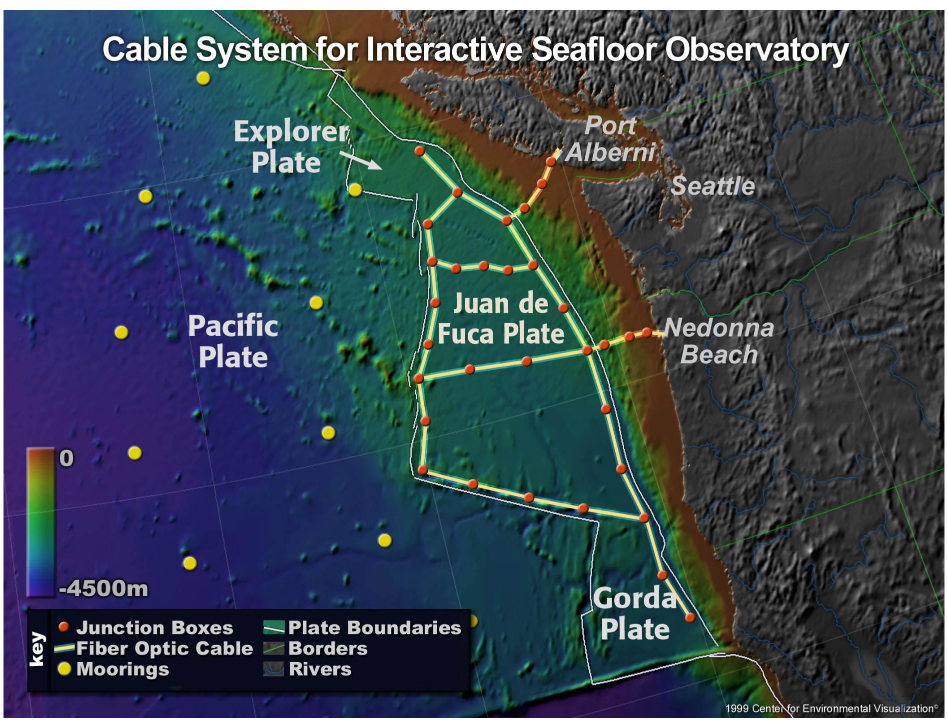


Figure 1.1. NEPTUNE will provide power and communications bandwidth via fiber-optic/power cables to junction boxes (nodes) on the Juan de Fuca Plate and surrounding areas. By connecting sensor networks to the nodes, with extensions onshore and offshore into the interior, scientists will, for the first time, have the capability to study a host of interrelated processes with high spatial and temporal resolution over long periods of time. (Graphic: CEV)

The goal of NEPTUNE is *to establish a plate-scale submarine network of remote, interactive natural laboratories for real-time, four-dimensional (3-D plus time) experiments designed to quantify the linkages among oceanographic and plate-related processes*. Although NEPTUNE's emphasis is on the ocean sciences, we expect the project to make strong and significant contributions to the earth and planetary sciences.

We have based NEPTUNE's plate-scale observatory concept on the following three premises:

- Many globally significant planetary phenomena, involving both oceanographic and solid earth processes, operate at or below the scale of a tectonic plate.
- Thorough 4-D examination of at least one plate/mesoscale system will generate major new insights into all such systems.
- Understanding the interactions among the myriad processes operative at such scales will require decadal commitment to the studies.

NEPTUNE will provide a coherent infrastructure of high-speed, submarine communication-control links using fiber-optic/power cables that will connect remote, interactive experimental sites with land-based research laboratories and classrooms (Figure 1.2). The infrastructure will provide real-time flow of data and imagery to shore-based Internet sites. It will permit interactive control over experiments and robotic vehicles on site.

1.2 Inner Space/Outer Space

The spectrum of scientific studies currently envisioned for the NEPTUNE facility covers a broad range. One major opportunity arises from recent evidence that submarine volcanoes support a substantial, unexplored high-temperature microbial biosphere sustained by volatile fluxes from the earth's interior. This insight implies that seafloor hydrothermal vent fields may be the "tips of icebergs" in total biomass supported by active submarine hydrothermal systems. A significant microbial biosphere apparently thrives within the brittle outer shell of the volcanically active submarine portions of earth.

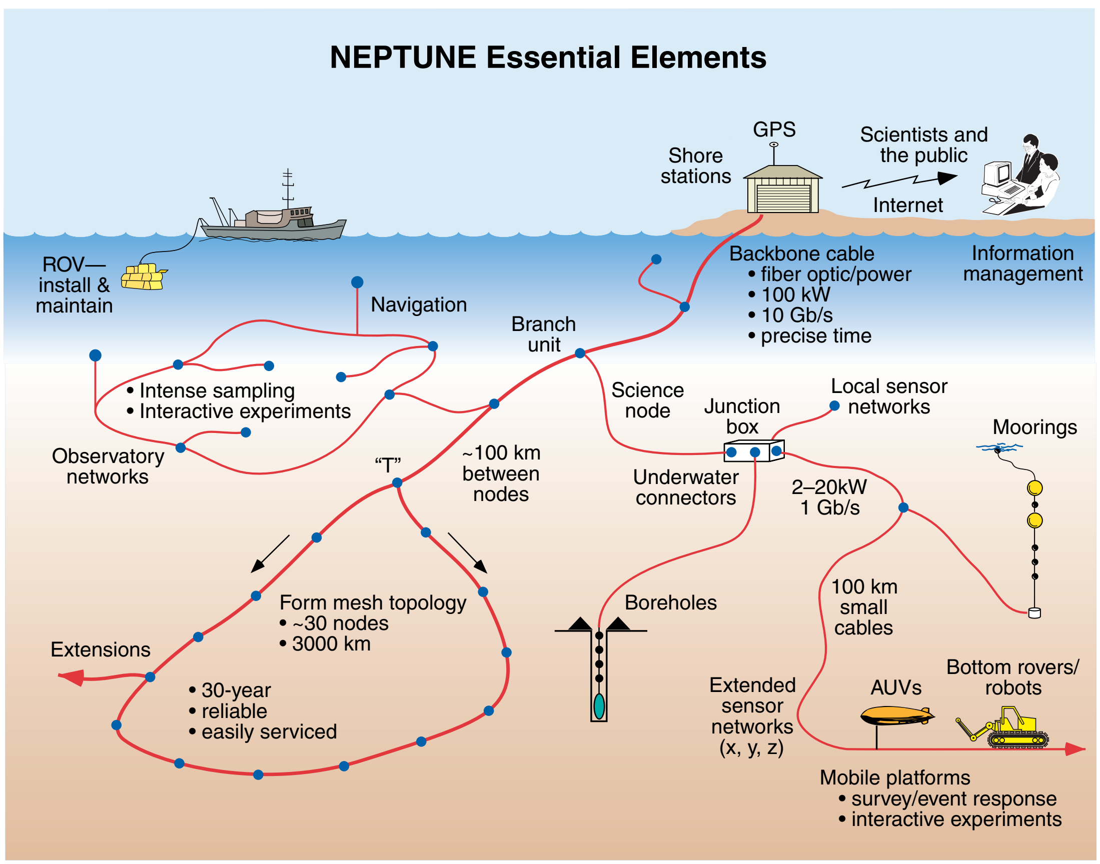


Figure 1.2. Land-based scientists and the public are linked in real time and interactively with sensors, sensor networks, and various mobile sensor platforms in, on, and above the seafloor. NEPTUNE's fiber-optic/power cable and associated technology provide the enabling network infrastructure. (Graphic: Paul Zibton)

Similar submarine volcanic systems may exist on other solar bodies, such as Europa, the second moon of Jupiter (Figure 1.3). The new field of microbial volcanic ecology is, therefore, doubly powerful. By designing innovative strategies to explore the relationships between volcanoes and the life they support here on earth, we gain not only essential knowledge about newly discovered processes and life forms on our own planet, but also critical new insights into how we might explore for signs of life on other solar bodies. NEPTUNE will allow intimate real-time access to the vigorous geophysical and geochemical processes that sustain this sub-seafloor volcanic biosphere.

NEPTUNE may also serve as a unique testbed for sensor and robotic systems designed to explore other oceans in the solar system. Indeed, we can regard NEPTUNE as an inward-looking Hubble telescope, vastly enhancing the potential for discovery by allowing unprecedented four-dimensional imagery of planetary processes not entirely restricted to earth: by looking inward, focusing on integrated, scientific experimentation in remote or hostile environments on our own planet, we will also be looking outward.

1.3 The NEPTUNE Study Area

To attract the broadest user base for this cabled laboratory network as a full-service oceanographic research platform, and to minimize the cost, we sought a site of small footprint encompassing myriad, important earth and ocean processes. We also wanted the site proximal to nations with strong technological infrastructures and modern port facilities. We selected the Juan de Fuca Plate region and its overlying water mass as the focus of NEPTUNE. The plate is small and entirely submarine, and we propose treating the whole system as a natural laboratory. Approximately one third of the Plate lies within Canadian waters and about two thirds within U.S. waters. Canadian colleagues have begun a parallel, cooperative NEPTUNE program.

NEPTUNE will allow scientists and educators to analyze and utilize real-time data bearing on the linkages and feedback mechanisms within and between key oceanographic and plate tectonic processes. Using remote intervention capabilities, coupled with real-time data flow from large numbers of instruments, we will explore many basic

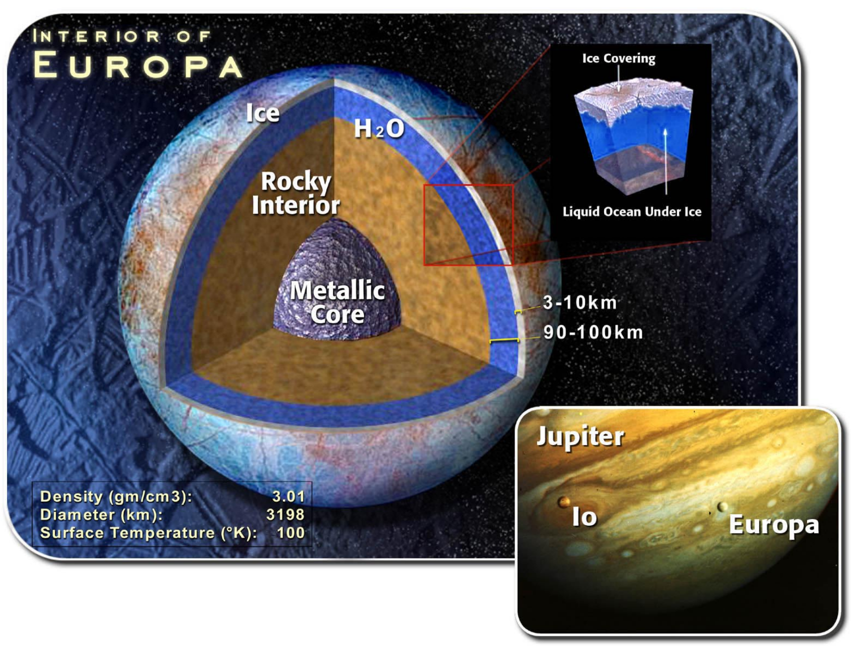


Figure 1.3. An in-depth understanding of the dynamics and life of submarine volcanoes here on earth is likely to support strategies for searching elsewhere in the solar system for similar forms of life. This figure shows Jupiter and its two inner moons Io (left) and Europa. Io is the most volcanically active body in the solar system, driven by internal heat dissipation from tidal friction. Europa is covered with water ice at surface temperatures of about 100 K and has a bulk planetary density of about 3.0 g/cm^3. Evidence indicates that Europa has a metallic core and a rock mantle underlying the outer water layer. Best estimates indicate that the outer water layer is nearly 100-km thick and that much of it is liquid water that is kept fluid by tidal heating from within. NASA is interested in searching for life on Europa, which may contain systems similar to those on earth's seafloor.

oceanographic and geophysical systems with entirely new investigative strategies.

We will be able to address a host of scientific opportunities and societal challenges, such as those listed below, with the capabilities we envision for NEPTUNE.

- For the first time, earthquake and deformation patterns associated with the creation, aging, and destruction of oceanic plates can be examined in a continuous, integrated fashion for decades. A seafloor seismic network will capture the earliest signals from great subduction zone earthquakes and can contribute critical information to tsunami and ground-shaking warning systems. (Figures 1.4, 1.5).
- Ridge-crest volcanism is intimately related to the formation of metal deposits, modulation of seawater compositions, local heating of the overlying ocean, and support of a microbial biosphere. Despite the vigor of ridge-crest activity, it constitutes less than 10% of the total global flux of heat and chemicals from the earth's interior. Ridge flanks and mid-plate portions of our planet represent the zones of major heat and chemical transfer from the earth's interior to the hydrosphere and biosphere.
- Studies of the volatile fluxes expelled along a subduction zone will allow cross-correlation with major and minor earthquake activity, thus giving crucial information about potentially major, non-steady-state carbon movements. The role of subduction gases and methane hydrates in the dynamics of the continental slope is virtually unknown.
- Migration of fish stocks along and across the continental shelf can be quantitatively tracked using innovative acoustic techniques. Tying this to small- and large-scale oceanography and the regional carbon budget will be a worthy challenge.
- A fully instrumented suite of water-column moorings will allow continuous four-dimensional real-time assessment of the physical, chemical, and biological interactions in a zone of divergence and in nearshore upwelling processes.
- Sediment transport along and across the continental shelf and into the deep ocean can be quantified as a function of the processes that drive such systems. Large fluxes of sediment laden with carbon and anthropogenic chemicals cross the continental shelf and slope in a highly episodic fashion during major storms, but the mechanisms are unknown (Figure 1.6). The more complete understanding of water-column physics, chemistry, and biology will permit addressing the links between primary productivity, fisheries, marine mammal migration, and deep-sea ecology.

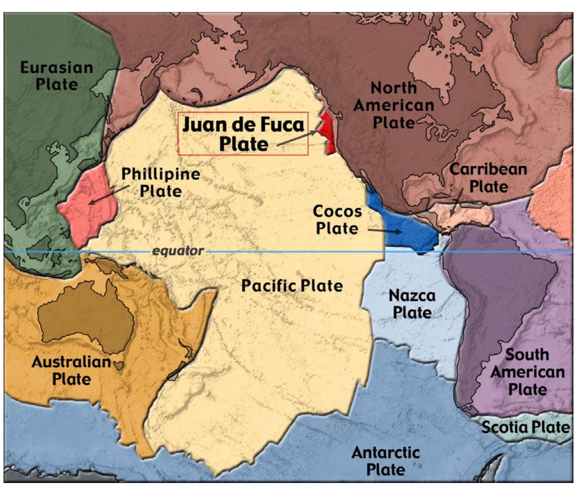


Figure 1.4. The Juan de Fuca Plate is one of a small number of tectonic plates that make up the surface of the earth and is an oceanic plate being subducted beneath the North American Plate. (Graphic: CEV)

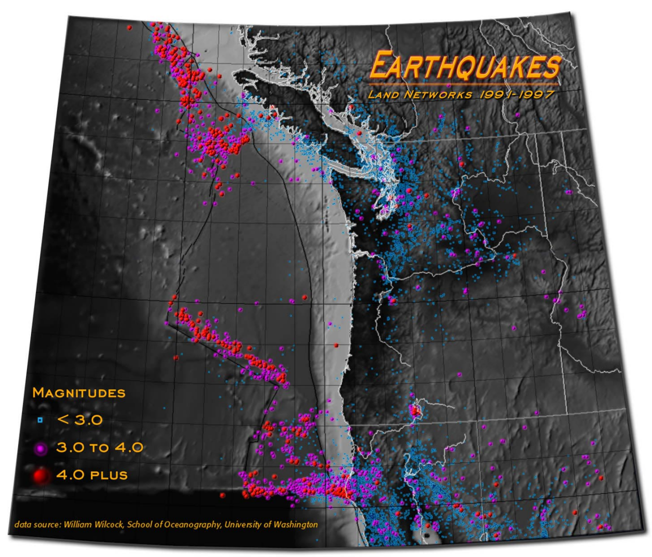


Figure 1.5. This map shows earthquake activity on land and along oceanic plate boundaries, based on data from land-based seismic networks. (Graphic: CEV)

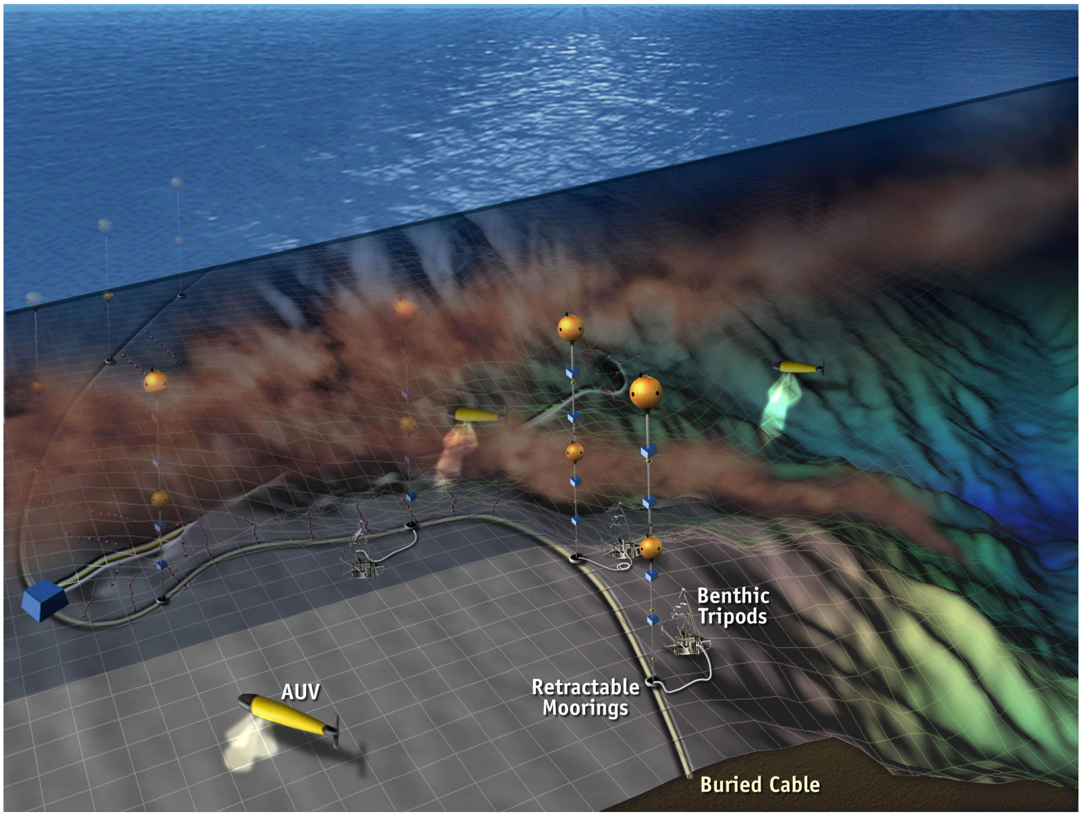


Figure 1.6. Measurement of sediment crossing the continental shelf-slope break at the head of a submarine canyon. NEPTUNE instruments and autonomous underwater vehicles (AUVs) will allow diverse observations of these episodic events. (Graphic: CEV and UW Marine Sedimentology Laboratory)

In summary, NEPTUNE's series of cabled seafloor instrument sites will provide a national and international focus for innovative earth, ocean, and planetary science investigations, engaging the imaginations of researchers and public alike. The project will drive improvements in deep-submergence technology and could provide unparalleled test beds for robotic exploration of extreme habitats, dynamic earth systems, and complex oceanographic processes. Internet access to instrument arrays and robotic systems will allow novel types of involvement by scientists, learners of all ages, and the general public. Voters and taxpayers will experience an intimate, over-the-shoulder view as scientists interact with some of the planet's most basic and dynamic processes.

1.4 Dynamics of Earth and Ocean Systems (DEOS)

During Phase 1, the NEPTUNE initiative has been aligned with a National Science Foundation (NSF)-supported planning effort designated as Dynamics of Earth and Ocean Systems (DEOS)[1]. Planning activities for DEOS have been underway for nearly three years under the auspices of the NSF Ocean Sciences Division. The objective is to simultaneously develop a nested and flexible global, regional, and local full-ocean research observing system to document the coupled behavior of the solid earth and the overlying ocean on time scales from seconds to decades.

The DEOS Planning Group (Co-Chairs: Keir Becker and Alan Chave) has prepared a summary report that was released in late 1999, and is available on the DEOS web site. The report was timed to coincide with a National Academy of Sciences Workshop held January 10–12, 2000. This workshop assessed the scientific opportunities and the technical feasibility of establishing a wide variety of observational and interactive facilities within the ocean basins. Such observatories will enable a new class of investigations with the goal of understanding the dynamic behavior of oceanographic and solid earth processes through time.

[1] http://vertigo.rsmas.miami.edu/deos.html

At present, the DEOS program includes the following three elements:

A **Global Network** of roughly 20 seafloor seismic, magnetic, and geodetic observatories designed to provide the geometrically balanced global coverage necessary to accurately image the interior of the earth and understand whole-earth processes occurring on a global scale. Planetary scale fixed ocean observatories will also serve as scientifically important long-term measurement sites for other types of oceanographic and climatic studies, such as those envisioned by the Global Eulerian Observatory (GEO) and the Acoustic Thermometry of Ocean Climate (ATOC) efforts.

A **Plate-Scale Observatory** (NEPTUNE) that will combine fiber-optic/power networks and full water-column measurements to observe processes that operate on, above and below the seafloor at the scale of a single tectonic plate. The network will provide power to instruments, high bandwidth for real-time data transmission, and two-way command-control capabilities for interaction with robotic undersea vehicles that can be operated from shore. NEPTUNE's location in the northeastern Pacific and spatial association with the Juan de Fuca Plate will involve decadal studies of a broad suite of oceanographic and plate tectonic processes.

A suite of **Relocatable Moored Buoy Observatories** that will make it feasible to carry out comparative studies of plate tectonic and oceanographic processes in areas where their expression may differ from that under study in the Plate-Scale or Global Observatories. These "portable" observatories would also allow a more flexible response to transient natural events. These observatories would provide the capability to reconfigure experiments and/or relocate to a new site as increases in knowledge are made during the course of a particular study. Examples of these types of studies might include comparison of processes at fast spreading vs. slow spreading ridges, investigation of subduction megathrusts in areas with differing sediment supply, and comparison of western boundary currents versus eastern ocean upwelling processes.

1.5 Feasibility Study Approach

Discussions of NEPTUNE-type concepts date back to the 1980s. Momentum for the present effort began to build in 1997 at the International Workshop on Scientific Use of Submarine Cables held in Okinawa, Japan, and when the DEOS effort, mentioned above, was formalized. Discussions with NSF staff convinced us that there were funding possibilities for such an endeavor, and we were encouraged to proceed.

The proposal for this NEPTUNE Phase 1, Feasibility Study, was submitted to the National Oceanographic Partnership Program (NOPP) in January 1998. The proposal was accepted, funding began in summer 1998, and the first group meeting was in November 1998. The partners are listed in Table 1.1. Many other institutions and individuals have contributed, as will become clear upon reading the report, and we are greatly indebted to them for their assistance.

We began this study with the following three questions:

- Is NEPTUNE scientifically desirable?
- Is it technically feasible?
- Is it financially reasonable?

We took a multifaceted approach to answering these questions. The science opportunities were addressed by *ad hoc* science working groups, which held brainstorming sessions to identify research opportunities that NEPTUNE could enable and to develop preliminary examples of science experiments. Infrastructure engineering was addressed by subgroups drawn from the Phase 1 partners. The subgroups researched and investigated the four major subsystems: power, communications, timing, and monitoring and control. The engineering groups methodically explored and considered a wide range of alternatives available for each subsystem. Consultants and industry were

Table 1.1 NEPTUNE Phase 1, Feasibility Study, Partners

Institution	Participants
University of Washington	John Delaney, Ross Heath, Bruce Howe, Le Olson
Woods Hole Oceanographic Institution	Alan Chave, Andrew Maffei, Robert Petitt, Dana Yoerger
Jet Propulsion Laboratory	Patricia Beauchamp, Karen Buxbaum, Harold Kirkham, David Rodgers,
NOAA Pacific Marine Environmental Laboratory	Eddie Bernard, Robert Embley, Christopher Fox, Stephen Hammond, Hugh Milburn

called upon to fill in the gaps in our knowledge. The sections on data management and archiving, environmental considerations, education, management and oversight, and cost were developed in concert with the findings of the science and engineering working groups and with input from experts in each respective field.

1.6 Navigating the Report

In Section 2 we lay the science foundation for NEPTUNE. As mentioned above, science working groups (SWGs) were organized and charged with identifying community experiments (such as a suite of oceanography and seismology sensors) and principal investigator (PI) experiments that a cabled seafloor observatory on the Juan de Fuca Plate would enable. The reports of each SWG have been summarized in this section and several crosscutting themes, such as the carbon cycle, are expanded upon. Full reports of the SWGs are available on the NEPTUNE web site.[2]

We describe a rationale for NEPTUNE node locations in Section 2.5 and continue the discussion by presenting representative scientific scenarios that address the topics covered by the SWGs. We present the rough science requirements of the system, including high-bandwidth communications for HDTV and high-frequency acoustics as well as a multitude of lower data-rate instrumentation, power for high-intensity lights, AUVs and bottom rovers, accurate timing signals, two-way communication for real-time control of instruments, and a user-friendly information management system. A generic sensor network is outlined. At the end of this section, we present the technical requirements needed to fulfill the science requirements.

In Section 3, we discuss the NEPTUNE infrastructure engineering. Our studies lead us to conclude that the basic NEPTUNE concept of a cabled system with junction boxes is technically feasible. Section 3 describes one possible path to designing this system; during actual design and development in NEPTUNE's Phase 2, these issues will be revisited in more detail to arrive at an optimal design.

Section 3.1, the engineering mission statement, presents the design philosophy and concepts that will guide subsequent infrastructure development. Section 3.2 addresses the major technical issues and decisions in the infrastructure definition, presents the rationale for basing the infrastructure on fiber-optic/power cable rather than buoys, compares existing technologies to NEPTUNE needs, and outlines the approaches that will meet the project requirements. The requirement for flexibility and reliability drives the decision for a mesh topology with associated ramifications for power distribution (a "parallel" configuration with sea grounds) and communications (gigabit Ethernet). A conceptual layout of a science node is presented in Section 3.2.5. Power and communication issues, as well as monitoring, control, and timing are addressed in Sections 3.3 through 3.6. We give a conceptual design in Section 3.7 and a summary in Section 3.8.

Section 4 describes the data management and archiving approach that we envision. This approach will rely on a decentralized system of multiple databases, metadata, stream-oriented processing, and web-based solutions to provide a unified archiving, querying, analysis, and modeling environment.

Education is a high priority within NEPTUNE. In Section 5, we discuss the educational potential in the areas of formal education (elementary, secondary, and undergraduate/graduate education), informal education (e.g., museums, aquariums, and marine sanctuaries), and public outreach (e.g., media, decision makers, and nongovernmental organizations). NEPTUNE's Phase 2 will include three national-level workshops that address and refine the possibilities for these groups.

The management and oversight options, discussed in Section 6, are constrained by the following two assumptions: management and oversight activities and responsibilities will change during the different phases of the project, and the oversight functions should be organizationally separate from the management functions. In Phases 2 and 3, the NEPTUNE Coordinating Office, to be housed at the University of Washington, will be responsible for project management. Oversight will come through a Board with representatives from organizations directly involved in the construction and/or use of submarine observatories. In Phase 4, the NEPTUNE Operations Office (successor to the Coordinating Office) will have primary management responsibilities. The Board will transition to a membership organization with an Executive Committee, and subcommittees will address scientific, technical, and educational issues.

For a project such as NEPTUNE, we must address environmental issues early on (Section 7). It will be essential that all stakeholders understand the project; genuine support from stakeholders will make the process of applying for the requisite permits from various government agencies a smoother and less turbulent road.

For NEPTUNE to become a reality, we must identify and prioritize the major tasks and activities to be accomplished

[2] http://www.neptune.washington.edu

in Phases 2–4. We address these issues and present a timeline in Section 8. Phase 2 begins in 2000 with the establishment of a NEPTUNE Coordinating Office. The infrastructure design and related activities will most likely begin in late 2000 and be largely completed by early 2003, though with testing of infrastructure prototypes and science sensor-network prototypes continuing. The start of Phase 3 in 2003 (overlapping with Phase 2) allows time for procurement and integration before the deployment starting in mid 2004. Phase 4, Operations, begins to ramp up in 2004. This schedule is obviously contingent on obtaining the necessary funding: system design funds in 2000 and system procurement and installation funds in 2002.

One of the first questions asked of NEPTUNE is, how much will it cost? Based on the infrastructure description and scenarios of Sections 2 and 3, as well as the level of effort implied in Sections 4–8, we present cost estimates in Section 9. These costs are divided between the three remaining project phases: design, installation, and operations. A rough estimate for community experiments is included with the understanding that the scenario upon which it is based is just a placeholder for what the science working groups will eventually design.

We close the report with Section 10 where we present our conclusions and recommendations.

Appendix A provides details of cost estimates; Appendix B lists all NEPTUNE white papers; Appendix C lists acronyms used in this report, and their associated web site addresses.

2. Science

2.1 Overview and Motivation

The NEPTUNE project has been driven by scientific opportunities and needs since it was conceived. Thus, even though the primary purpose of this report is to assess the technical feasibility of the NEPTUNE concept, we recognize that the ultimate measure of the program's success will be the innovation and quality of the scientific research it enables. Initial NEPTUNE discussions focused on the actively spreading Juan de Fuca Ridge, a locus of intense U.S. and Canadian studies for the past two decades. It quickly became apparent, however, that NEPTUNE offered great opportunities to other areas of marine science as well.

To better define the opportunities and needs of a broad range of marine scientists, we convened several *ad hoc* science working groups under the aegis of DEOS and the University of Washington. These groups considered the research opportunities that NEPTUNE would create and began to identify examples of community and individual PI experiments and observations.

The working group reports summarized here are as follows:

- Cross-Margin Particulate-Flux Studies
- Seismology and Geodynamics
- Seafloor Hydrogeology and Biogeochemistry
- Ridge-Crest Processes
- Subduction-Zone Processes (Fluid Venting and Gas Hydrates)
- Deep-Sea Ecology
- Water-Column Processes.

We briefed each group on the essential characteristics of NEPTUNE:

- Plate-scale (covering the full Juan de Fuca Plate)
- Power (order of tens of kW)
- Bandwidth (order of many Gb/s)
- Real-time data return and robotic control capability
- Robust design for high reliability
- Precision timing for all instruments
- Available for a nominal 30 years.

The primary charges to the working groups from NEPTUNE were as follows:

1. Identify "community" NEPTUNE experiments, where "community" experiments are defined as those meeting one or more of the following criteria:

    - Required by two or more independent projects
    - Of long duration (beyond the length that an individual PI could be expected to support via individual proposals)
    - Required for ongoing educational programs
    - Integrated with other programs.

2. Provide examples of PI or small-group science that could take advantage of NEPTUNE.

We emphasize that the *ad hoc* science working groups were not asked to prepare exhaustive lists of experiments or to focus on the priorities of the experiments they discussed. Such decisions, which will require more detailed assessments and will be determined by peer-review decisions in many cases, will be made during Phase 2 of the project. Rather, the meetings of the *ad hoc* groups were brainstorming sessions that allowed groups of creative scientists to explore the research possibilities that will be created by NEPTUNE's capabilities, as well as to better constrain those capabilities.

2.2 Cross-cutting Themes

Summaries of the *ad hoc* science working group reports follow this section. The full reports are available as white papers on the NEPTUNE web site.[1] These reports reveal a broad array of scientific interests. Several themes, described below, recur throughout the reports and were the subject of discussion during the meetings.

Connections

The ability to make synchronous measurements over an entire lithospheric plate and the overlying water column for periods of decades will allow hypotheses concerning numerous connections to be tested. Examples of targets for investigation by the NEPTUNE array include connections between

- tectonic, volcanic, hydrothermal, and biological phenomena along ridge crests (both within and between segments);

[1] http://www.neptune.washington.edu

- events on ridge crests, ridge flanks, fracture zones, and segments of the subduction zone;
- boundary processes and the distribution of strain within the plate;
- seismicity, mass sediment movements, gas release, and chemosynthetic biological communities along the convergent margin;
- ocean circulation, primary productivity, pelagic and benthic food webs, including fisheries, and the carbon cycle from a coastal upwelling regime to the open sea; and
- sea-surface phenomena observable by satellite sensors and processes in the underlying water column.

Temporal variations

After more than a century of expeditionary science, we have a first order understanding of the spatial relationships of crustal and oceanic phenomena. Plate tectonics and quasi-synoptic pictures of the oceanic circulation are products of this understanding. Yet we are only just beginning to study these processes in the time domain. NEPTUNE will allow synchronous measurements on time scales of seconds to decades (a range of almost 10^9). For the first time it will be possible to cross correlate water-column and seafloor processes.

Ecological studies

The NEPTUNE telepresence at a number of sites on the seafloor and in the water column will allow marine ecologists to make the same kinds of real-time adaptive observations of oceanic ecosystems that have been employed so effectively by terrestrial ecologists at Long-Term Ecological Research (LTER)[2] sites. The power, bandwidth, duration, and real-time intervention capability of the NEPTUNE system will allow researchers to carry out intervention/control experiments that have been impossible until now. The continuous telepresence that NEPTUNE will allow overcomes one of the most serious deficiencies of current expeditionary studies, where deep-sea sites can only be visited at intervals of months to years.

Education

Although the primary emphasis of the workshops was research, the value of NEPTUNE as a tool to enhance science education for K–12 students, undergraduates, and the general public was emphasized on numerous occasions. The system will have enough capacity to support student-controlled experiments without impairing the scientific mission.

2.3 Summaries of Working Group Reports

2.3.1 Cross-Margin Particulate-Flux Studies[3]

Participants

Charles Nittrouer (chair), Wilford Gardner, Barbara Hickey, Paul Hill, Richard Jahnke, Richard Keil, Brent McKee, Andrea Ogston, Richard Sternberg, Peter Traykovski

Key Issues

Rugged terrain onshore, high coastal rainfall, and a narrow continental shelf result in large fluxes of sediment across the northeast Pacific continental shelf to the adjacent deep seafloor. Yet characteristics of the cross-margin flux, most of which occurs episodically during major storms, are poorly known, as is the role of these events in controlling the architecture of the continental margin, creating the stratigraphic record of the margin, and transporting carbon and sorbed anthropogenic chemicals to the deep sea. The key to addressing all these issues is to develop a better mechanistic understanding of fine sediment accumulation.

Role of NEPTUNE

The continuous connection to the NEPTUNE array of instruments that will be able to respond to sedimentation events, either by local triggers or by remote operator intervention, will provide information about the frequency, intensity, and characteristics of these events. The availability of ample power and bandwidth will allow measurements and sampling under severe storms at spatial and temporal scales that are impossible to sample from surface vessels under such conditions.

The experiments connected to NEPTUNE will focus on fine (< 64 micron) particles and will build on past work off the Eel and Columbia Rivers (Figure 2.1). Initial emphasis will be on the sediment-water interface at the shelf break. In addition to observations and sampling, the technology possible through NEPTUNE will allow fluid and particle tracer experiments.

The availability of mobile systems (AUVs for the water column and rovers for the seafloor) will extend the array

[2] http://LTERnet.edu/

[3] *NEPTUNE Science White Paper #1: Cross-Margin Particulate-Flux Studies Associated with NEPTUNE* (http://www.neptune.washington.edu)

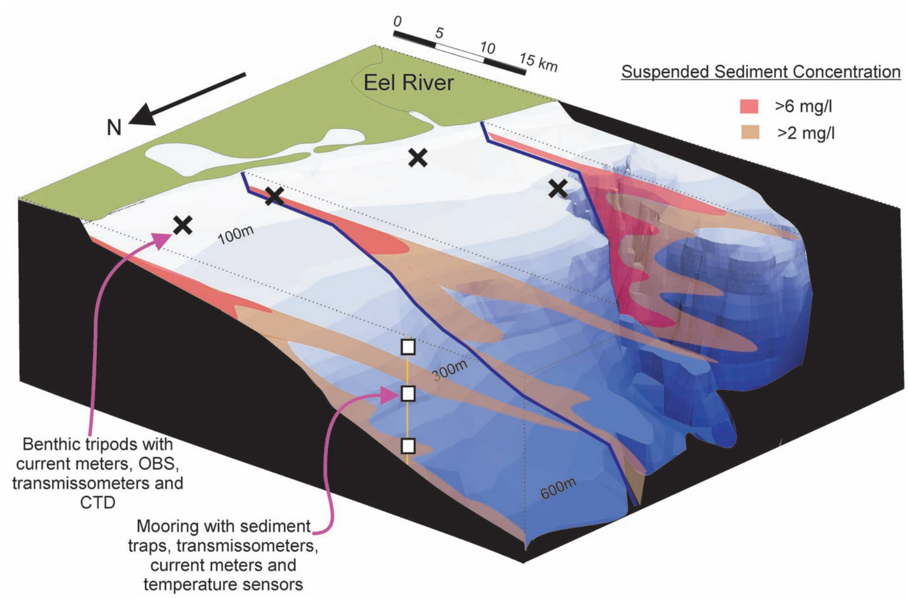


Figure 2.1. Escape mechanisms for sediment leaving the Eel shelf and reaching the continental slope. Possible instrumentation for studying these mechanisms is indicated. (Graphic: B.L. Mullenbach and C.A. Nittrouer)

and allow transects to be re-occupied and re-sampled over time. By housing both fixed and mobile instruments in "hardened" structures, damage by fishing and storms and by biofouling can be minimized.

Sensors

Existing sensors (acoustic, optic, and samplers) are already capable of characterizing particle transport. All that is required is that they be interfaced to NEPTUNE junction boxes. Substantial development is required for AUVs and bottom rovers to carry these sensors and for more sophisticated samplers and tools that will noninvasively characterize the seafloor (e.g., *in situ* X-ray and gamma-ray spectroscopes).

Community Experiments

Characterization of the flux and composition of sediment escaping across the shelf break in different morphological regions and under different forcing conditions (river discharge, shelf resuspension, currents) will be necessary as a foundation for individual and small-group experiments on the mechanisms governing cross-margin particle fluxes (Figure 2.2).

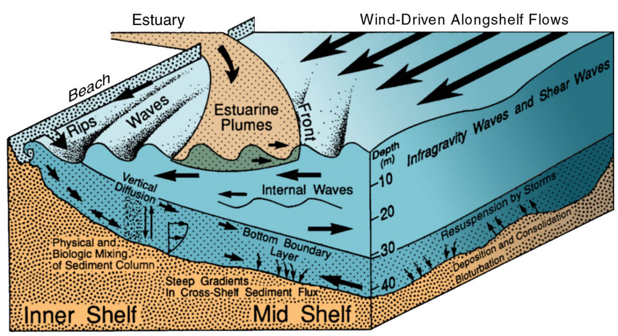


Figure 2.2. Conceptual diagram illustrating the major physical processes responsible for across-shelf particulate transport. (Graphic: adapted from Nittrouer and Wright, 1994)[4]

2.3.2 Seismology and Geodynamics[5]

Participants

William Wilcock (chair), Donna Blackman, David Chadwell, John Collins, Ken Creager, Robert Detrick, Don Forsyth, Chris Fox, Mark Hemphill-Haley, Bruce Howe, Roy Hyndman, Steve Malone, John Orcutt, Kristin Rohr, Robert Sohn, Doug Toomey, Anne Tréhu, Kelin Wang, Spahr Webb, Doug Wiens

[4]Nittrouer, C.A., and L.D. Wright, 1994: Transport of particles across continental shelves. *Rev. Geophys.*, *32,* 85–113.
[5]*NEPTUNE Science White Paper #2: Opportunities for Seismology and Geodynamics with NEPTUNE* (http://www.neptune.washington.edu)

Key Issues

The Juan de Fuca/Gorda/Explorer Plate system hosts a remarkable array of plate-tectonic features (Figure 2.3). Observations of seismicity and strain by NEPTUNE would provide an unprecedented picture of deformation along a variety of oceanic plate boundaries. Such observations will be a natural complement to the enhanced land-based networks envisioned for EarthScope, the Advanced National Seismic System, and the Canadian POLARIS program.

The last great subduction earthquake along the Cascadia Subduction Zone occurred three centuries ago and several damaging intra-slab earthquakes have occurred this century. Thus, there is strong societal benefit to be gained by improving constraints on the rupture area for great earthquakes and understanding the causes of intra-slab earthquakes (Figure 2.4). Seafloor observations will also contribute critical information to earthquake and tsunami early-warning systems developed in the future. There is considerable interest in the physics of earthquake nucleation and rupture propagation at different plate boundaries and in the relationship of mid-ocean ridge seismicity to magmatism and deformation hydrothermalism. At the plate scale, the NEPTUNE seismic and geodetic arrays would constrain the nature and causes of stress variations across the plate, the styles and causes of intra-plate earthquakes, and the styles of deformation and coupling of forces across plate boundaries. The seismic array would facilitate studies of the structure and evolution of the lithosphere-asthenosphere system to understand such processes as the nature of flow beneath plate boundaries, mantle melting, the coupling of the mantle to the lithosphere, and the pattern of return flow from trench to ridge (Figure 2.5).

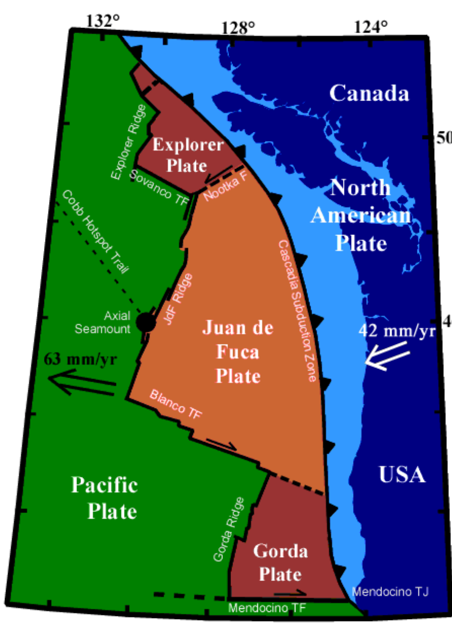


Figure 2.3. Location of plates and plate boundaries in the Pacific Northwest. The velocities of the Pacific and North American plates are shown relative to the Juan de Fuca Plate. Acronymsare as follows: JdF—Juan de Fuca; TF—transform fault; TJ—Triple Junction; and F—fault.

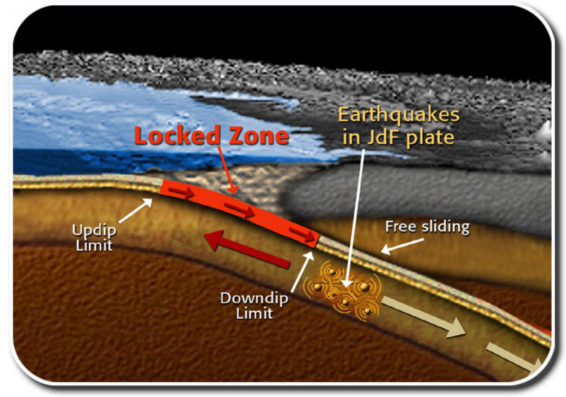


Figure 2.4. The upper and lower locked zones on the subducting plate are of critical interest to map out and examine through time. The last major earthquake in the Pacific Northwest was in January 1700, and there is considerable interest in detailed studies of how strain accumulates in both the on-land and at-sea portions of this type of system. (Graphic: CEV)

Role of NEPTUNE

The power, bandwidth, real-time data return, and accurate timing that NEPTUNE will be able to provide are ideal for supporting seismic networks. Broadband seismographs at 50–100 km intervals will provide coverage of an oceanic plate that, for the first time, will be comparable to terrestrial arrays. In addition, NEPTUNE will support dense seismic networks in areas of particular interest.

NEPTUNE will also be able to host geodetic arrays that could include acoustic strain meters, GPS-acoustic geodesy, absolute gravimeters, borehole strain meters, and tilt meters. Again for the first time, these instruments will provide long-term plate-scale measurements of the temporal and spatial changes in strain across an entire oceanic plate.

Sensors

Appropriate seismometers already exist and have been deployed in the deep ocean, and many of the geodetic techniques are also being developed. They require only interfacing to NEPTUNE junction boxes. Additional development will be needed to optimize some geodetic techniques.

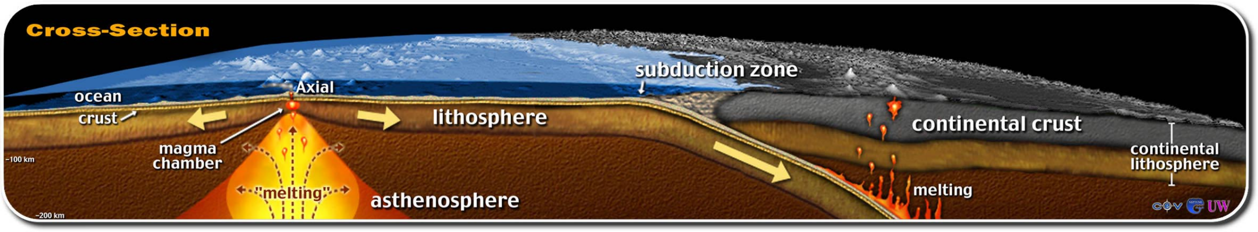


Figure 2.5. Major geological components of the Juan de Fuca Plate system are shown in this cross-section. (Graphic: CEV)

Community Experiments

The NEPTUNE seismic data will be used for a large variety of studies, many of which will also utilize data from other regional or global networks. It is essential that the real-time data from this array be processed by standard techniques and archived at the Incorporated Research Institutions for Seismology (IRIS) data center to allow access by all researchers. Similarly, the geodetic measurements should be made available as a community resource although it should be recognized that some of the geodetic data will require sophisticated processing before it is useful to the broader community.

2.3.3 Seafloor Hydrogeology and Biogeochemistry[6]

Participants

Earl Davis (chair), John Baross, Keir Becker, Bill Black, Andy Fisher, Hans Jannasch, Richard Von Herzen, Spahr Webb

Key Issues

Boreholes of the Ocean Drilling Program (ODP) and its predecessors provide unique access for experimental studies of the hydrology of the oceanic crust. In addition, boreholes are ideal sites for seismometer installations because oceanic noise near 1 Hz is substantially reduced at levels of 100 m or more below the seafloor.

A number of ODP holes in sedimented ridge crest, ridge flank (mid-plate), and subduction zone accretionary prism settings are currently available for monitoring studies (Figure 2.6). Coordinated time series observations and sampling are needed to determine the natural interrelationships among hydrologic, tectonic, thermal, chemical, and microbiological processes in the crust in each of these environments (Figure 2.7). In addition, active pressure-pulse and tracer experiments over periods of years to decades are necessary to determine fluid transport and other physical properties at a regional scale.

Drillholes in the subduction zone accretionary prism can serve as laboratories to study the behavior of clathrates in response to a range of pressure, temperature, and fluid-composition perturbations. In a hole that penetrates the primary detachment thrust fault between subducting and overriding plates, time series measurements of strain, fluid pressure, and bulk rock properties will provide insights to the dynamics of earthquake rupturing.

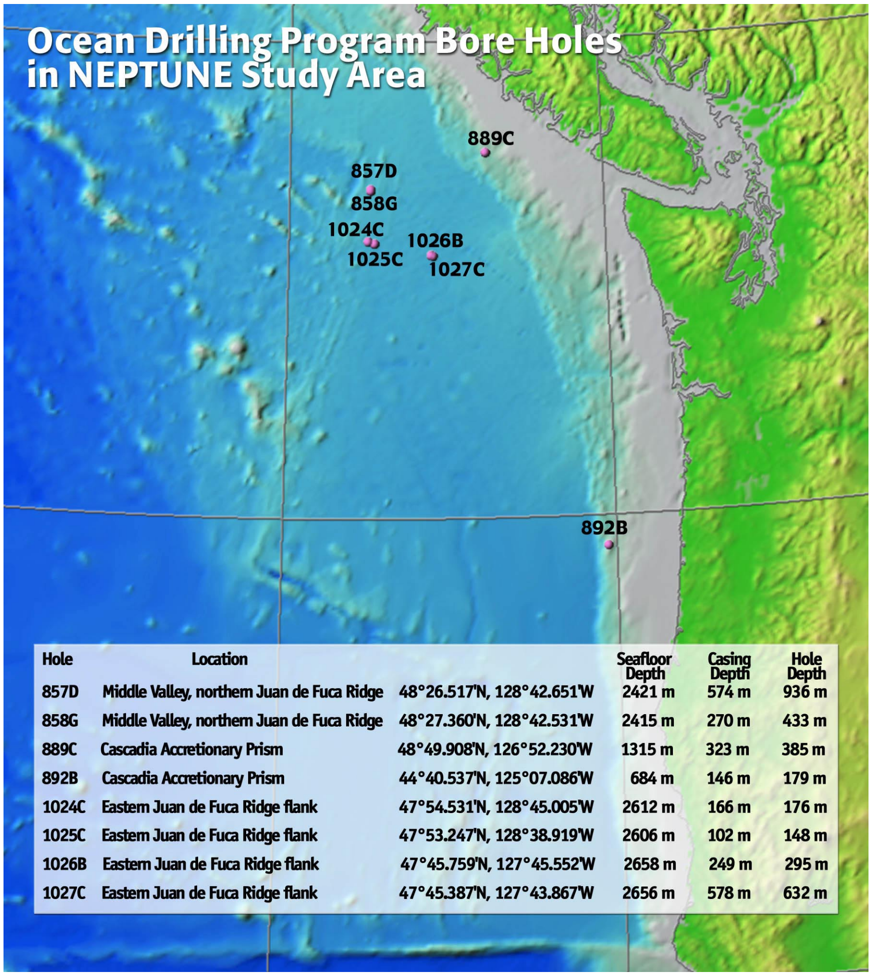
Role of NEPTUNE

The continuous availability of bandwidth and real-time control will allow experiments of much longer duration than any possible with a surface vessel, submersible, or autonomous instrumentation. The availability of power to run pumps and *in situ* samplers will allow dynamic experiments using controlled sources at an operator's convenience. The coincidence and simultaneity of a broad spectrum of observations spanning years to decades will provide clear insights into the interdependence of tectonics, fluid flow, and biological activity.

Sensors

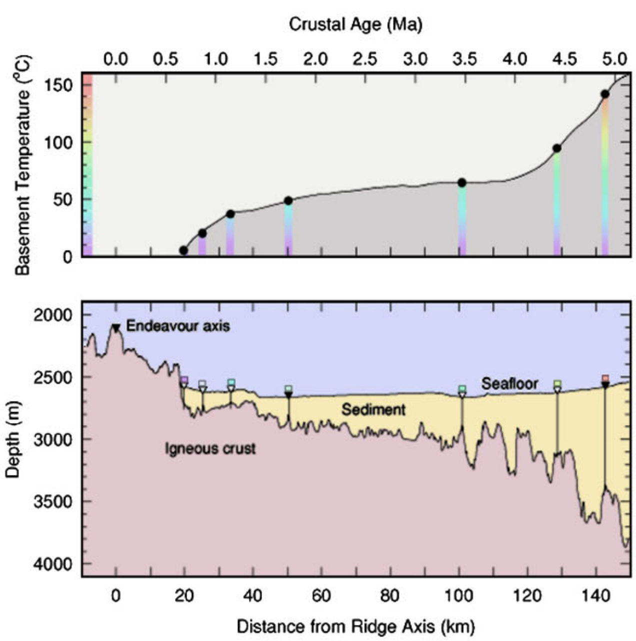
Much of the necessary technology has already been developed by the petroleum industry and ODP researchers (Figure 2.8). The initial emphasis will be on interfacing existing technology with NEPTUNE junction boxes and on designing robust, multiple-experiment packages for the boreholes. The highest data rates will be associated with seismic experiments and the highest power needs will be for pumps, resistivity measurements, and downhole heaters (for clathrate studies). Further development is required for *in situ* chemical and microbial analyzers that can be left in boreholes for periods of years or longer.

[6]*NEPTUNE Science White Paper #3: Seafloor Hydrogeology and Biogeochemistry: Opportunities for Long-Term Borehole Experiments* (http://www.neptune.washington.edu)



Hole	Location		Seafloor Depth	Casing Depth	Hole Depth
857D	Middle Valley, northern Juan de Fuca Ridge	48°26.517'N, 128°42.651'W	2421 m	574 m	936 m
858G	Middle Valley, northern Juan de Fuca Ridge	48°27.360'N, 128°42.531'W	2415 m	270 m	433 m
889C	Cascadia Accretionary Prism	48°49.908'N, 126°52.230'W	1315 m	323 m	385 m
892B	Cascadia Accretionary Prism	44°40.537'N, 125°07.086'W	684 m	146 m	179 m
1024C	Eastern Juan de Fuca Ridge flank	47°54.531'N, 128°45.005'W	2612 m	166 m	176 m
1025C	Eastern Juan de Fuca Ridge flank	47°53.247'N, 128°38.919'W	2606 m	102 m	148 m
1026B	Eastern Juan de Fuca Ridge flank	47°45.759'N, 127°45.552'W	2658 m	249 m	295 m
1027C	Eastern Juan de Fuca Ridge flank	47°45.387'N, 127°43.867'W	2656 m	578 m	632 m

(above) Figure 2.6. Several boreholes exist within the NEPTUNE study area, drilled by the Ocean Drilling Program. These and other boreholes proposed for NEPTUNE will serve as laboratories for studying the ocean crust. Borehole locations span the spectrum of geologic settings, from sedimented ridge crests to mid-plate (where most crust/ocean heat exchange occurs) to the accretionary prism of the subduction zone. (Graphic: CEV)



(right) Figure 2.7. Lithologic section and estimated temperatures at the top of permeable igneous basement across the Juan de Fuca Plate based on seismic reflection profiling, heat flow measurements, and drilling observations.

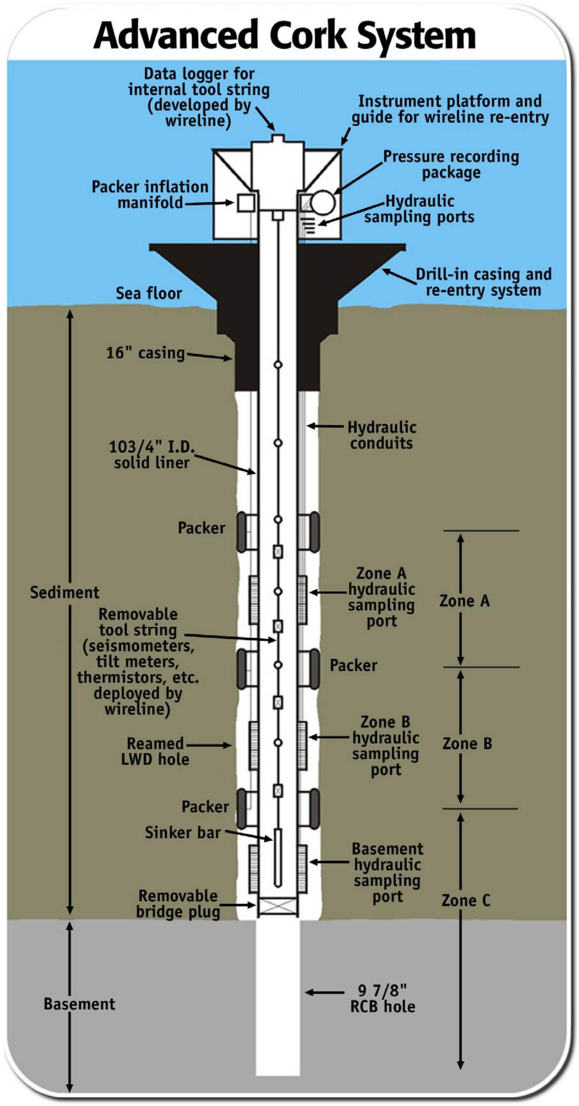


Figure 2.8. Multiple-zone borehole completion involving packer-isolated fluid sampling/monitoring ports, mobile sampler/logger, seafloor and borehole seismometers, tilt meters, and hydrologic monitoring sensors.

Community Experiments

Real-time seismic records and pressure data from packed intervals of key boreholes will be required by researchers planning manipulative experiments. Centrally managed pumps and basic control equipment at each borehole will be required to allow for multiple noninterfering PI experiments.

2.3.4 Ridge-Crest Processes[7]

Participants

Meg Tivey (chair), Suzanne Carbotte, Jim Cowen, Chris Fox, John Hildebrand, Debbie Kelley, Anna-Louise Reysenbach, Ken Rubin, Tim Shank, Rick Thomson, Karen Von Damm

Key Issues

As a result of interdisciplinary programs such as RIDGE,[8] the links between geological, physical, chemical, and biological processes at actively spreading mid-ocean ridges are well established (Figure 2.9). However, the specific nature of these links, their variation through time, the degree to which they are linked within and between ridge segments, and their relation to processes at transform and convergent plate boundaries and to processes within the plate are still topics of intense study. Current technology allows periodic visits (at intervals of months to years) to study sites and the deployment of low (battery) powered instruments to make continuous measurements for periods of months to a year or so. The deployment of continuous controllable experiments for periods of several years is currently precluded by power, communications, and data-storage limitations. Responses to remotely detected seismic and magmatic events must be mounted from shore, rather than from nearby, seafloor-based facilities because of the same limitations. Thus, critical hydrothermal and biogeochemical processes that occur at the time of an eruption have never been observed.

Role of NEPTUNE

By installing nodes at each segment high along the Juan de Fuca and Gorda Ridges, NEPTUNE will provide the power, control, bandwidth, and single clock to enable highly interactive arrays of seafloor instruments. These arrays will be capable of observing patterns and linkages in heat and fluid output and the resultant biological responses, both within and between ridge segments and transform faults. The cable will allow a larger suite of more capable instruments to assess the influence of a hot spot on ridge-segment dynamics at the New Millenium Observatory (NeMO) at Axial Seamount (Figure 2.10).[9] In addition, by providing continuous and interactive access to existing and future drillholes within the plate and on the ridge crest, NEPTUNE will allow the level of subsurface biological activity to be related to changes in the physical and chemical status of the subsurface hydrosphere. In-depth studies of the deep, hot microbial biosphere here on earth may support strategies for the search for similar forms of life elsewhere in the solar system.

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[7]*NEPTUNE Science White Paper #4: Opportunities for Investigating Ridge-Crest Processes* (http://www.neptune.washington.edu)
[8]http://ridge.oce.orst.edu/
[9]http://newport.pmel.noaa.gov/nemo/

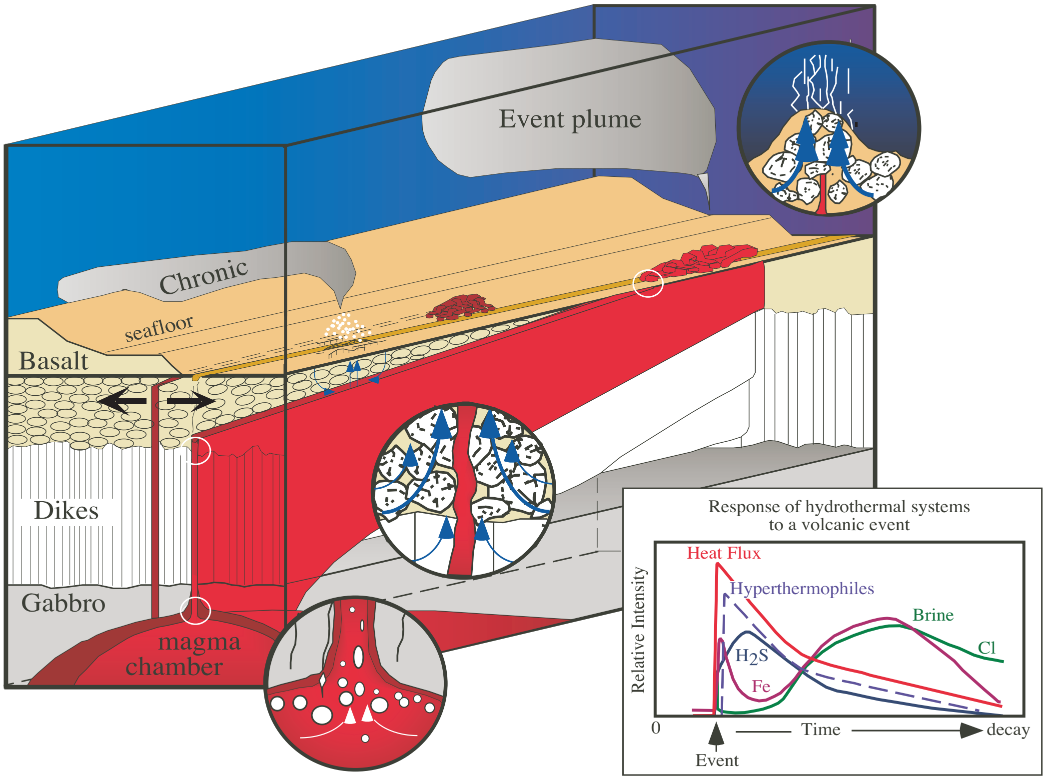

Figure 2.9. The links between tectonic, magmatic, hydrothermal, and biological processes at actively spreading mid-ocean ridges are well established. For example, cracking events, dike intrusions, and eruptions affect the chemistry and micro- and macrobiology of ridge-crest hydrothermal systems. However the specific nature of these links is still a topic of intense study: How do they vary through time? To what degree are they linked within and between ridge segments? NEPTUNE instrument arrays would help answer these and other questions. (Graphic: Delaney et al., 1998)[10]

The NEPTUNE system will also allow ocean/crust interactions to be determined as a function of space and time by supporting water-column observations from fixed moorings, from AUVs, and from Lagrangian floats launched from NEPTUNE nodes into either chronic or episodic hydrothermal plumes. The large amount of NEPTUNE-provided power will support remotely controlled seafloor vehicles (rovers) and water-column vehicles (autonomous underwater vehicles [AUVs] and remotely operated vehicles [ROVs]) that will collect data and samples either for time-series studies or in response to tectonic, magmatic, or hydrothermal events. Combinations of AUVs and water-column moorings could also be used to provide much needed information on seafloor structure, lava morphology, vent distribution, faunal distribution, and water-column structure through detailed fine-scale mapping that is currently prohibitively expensive due to the time-consuming nature of the task. The available power from NEPTUNE will also enable *in situ* manipulative experiments and analyses, as well as the storage of frozen samples for later recovery and analysis ashore.

Sensors

For many of the physical properties, sensors already exist that require only interfacing to NEPTUNE junction boxes. Meeting all the needs of ridge-crest researchers, however, requires significant development of the following: tethered and autonomous vehicles to respond to events and to generate detailed maps of the ridge crest; chemical sensors to provide drift-free analyses of key constituents of hydrothermal fluids; and biological sensors to measure *in situ* metabolic activity and to examine micro-chemical environments and species diversity in both natural and experimentally perturbed systems. High-frequency acoustic and high-definition television (HDTV) systems will also need to be adapted for use with NEPTUNE.

[10]Delaney, J.R., D.S. Kelley, M.D. Lilley, D.A. Butterfield, J.A. Baross, W.S.D. Wilcock, R.W. Embley and M. Summit, 1998: The quantum event of oceanic crustal accretion: Impacts of diking at mid-ocean ridges. Science, *281*, 222-230.

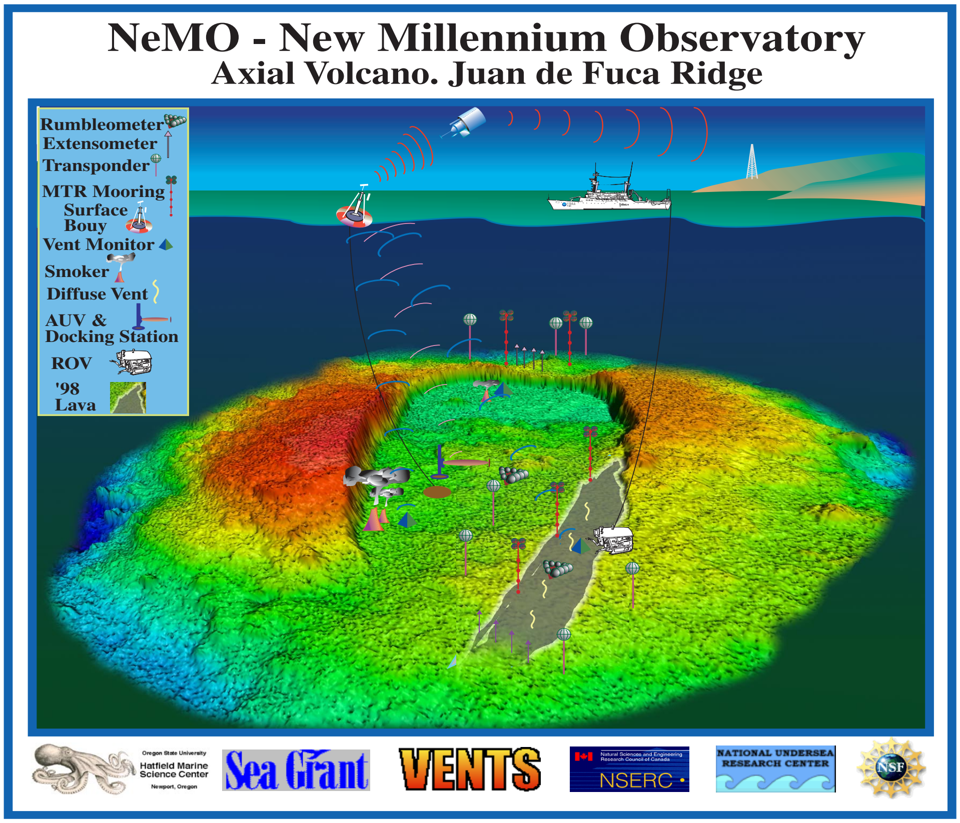

Figure 2.10. NEPTUNE will be able to support multidisciplinary ridge-crest observatories with an emphasis on co-located, synchronous experiments tied to a single clock. The New Millenium Observatory (NeMO) and the RIDGE observatories at the Cleft and Endeavour segments represent first steps toward this goal. NEPTUNE will provide the needed universal clock, power, bandwidth, and access to instruments in real time and throughout the year, unrestricted by the narrow weather window. To examine the dynamic interaction between segments, one or two nodes in addition to the node at which a large observatory is situated could be instrumented with an optimal subset of instruments (e.g., ocean bottom seismometry arrays and water-column moorings.) (Graphic: Courtesy of Robert Embley, NOAA/PMEL)

Community Experiments

The RIDGE program has identified a response capability to tectonic, magmatic, and unusual hydrothermal events as well as the establishment of a small number of "observatories" (heavily instrumented sites where coordinated measurements are relayed to shore in near-real time) as community-wide needs on which individual PI science can be built. Autonomous vehicles that can download data and samples and upload power and instructions at ridge-crest nodes are also a community-wide need. Processes associated with ridge-crest activity encompass a wide variety of questions that range from those associated with the origin and the search for life on other planets to determining how rocks that make up 60 percent of the earth's surface are formed. The ridge environment cannot be studied well without invoking truly interdisciplinary research.

[11]*NEPTUNE Science White Paper #5: Subduction-Zone Processes: Fluid Venting and Gas Hydrates at the Cascadia Convergent Margin* (http://www.neptune.washington.edu)

2.3.5 Subduction-Zone Processes (Fluid Venting and Gas Hydrates)[11]

Participants

Erwin Suess (chair), Robert Collier, Roy Hyndman, Keith Kvenvolden, Marv Lilley, Ed DeLong, Ko-ichi Nakamura, Charles Paull, Clare Reimers, Laurenz Thomsen, Michael Whiticar

Key Issues

Plate convergence is associated with great subduction earthquakes, slope instabilities, the generation of tsunamis and megaturbidites, and the release at the seafloor of carbon dioxide, methane, sulfide, and ammonia as well as trace metals and other dissolved species. Evidence of tectonically induced fluid release has been observed at the Cascadia subduction zone, the Japan trench and Nankai trough, the Peru margin, the southern Barbados accretionary complex, the Costa Rica accretionary prism, the eastern Aleutian subduction zone, the Makran margin, the central Banda arc, and the Mediterranean ridge. This process seems to be ubiquitous at convergent plate boundaries. The fluid release is attributed to tectonic overpressuring of pore fluids and the availability of escape pathways through the pervasively fractured rocks of the subduction complex (Figure 2.11). The released gases, particularly methane, create gas hydrates, support chemosynthetically based benthic ecosystems, and have been proposed as the cause of past climate warmings that are accompanied by carbon-isotope anomalies (such as the “late Pliocene thermal maximum”).

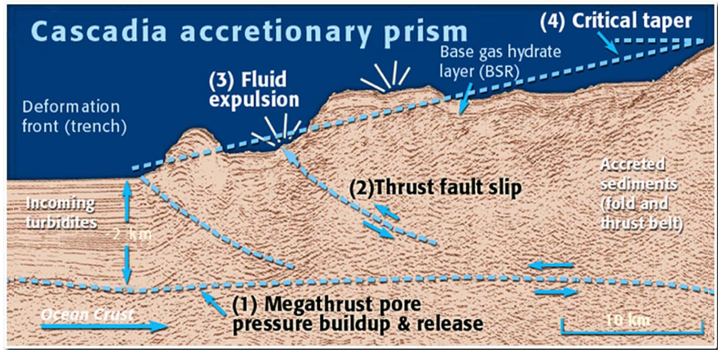

Figure 2.11. A generic seismic profile through the Cascadia accretionary prism; modes of deformation and processes of interest could be examined using a NEPTUNE-like facility. (Graphic: R. Hyndman, Geol. Survey of Canada).

Yet the magnitude of fluid escape from subduction zones, its temporal variability (in both flux and composition), the forces that drive the flow, and the biological responses are virtually unknown. Thus, simultaneous measurements of seismicity, energy, and mass fluxes from the sediments, fluid characteristics, and biological responses over an extended period are necessary if research in this area is to make substantial progress.

Role of NEPTUNE

An area off central Oregon, where compression of the Juan de Fuca Plate has created an uplifted ridge, has become a major study site for fluid venting from a subduction complex and for gas hydrate (clathrate) formation and breakdown (Figure 2.12). Researchers have already deployed a number of autonomous instruments that are providing valuable insights into the fluid venting, hydrate formation/breakdown, and associated biological activity (Figure 2.13). By connecting these instruments to the NEPTUNE array, the duration of deployments, which have detected temporal variability at all time scales up to three months, can be extended to years. Also, measurement and sampling programs can then be modified in response to actual observations and to input from other sensors, such as seismometers, along the subduction zone. Locally based AUVs and rovers will add the ability to study spatial variability through time and to respond to tectonic and hydrologic events.

Sensors

Most of the new seafloor instrumentation, which ranges

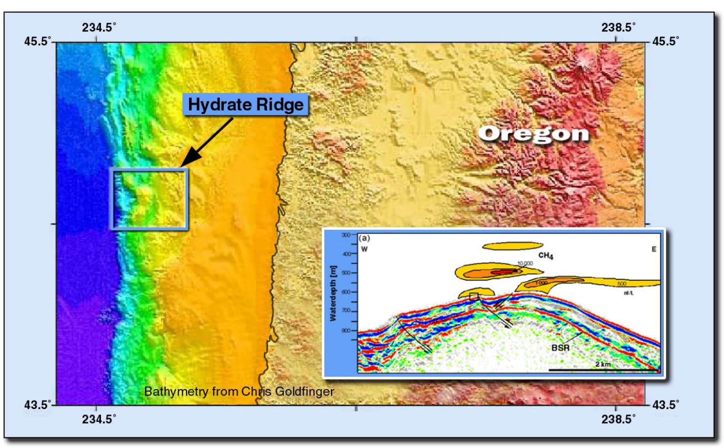

Figure 2.12. Hydrate Ridge off the coast of Oregon. A recent discovery was made of seafloor surface outcrops exposing methane hydrate deposits that are actively deforming in the accretionary prism and releasing unknown amounts of carbon into the overlying ocean and atmosphere. Further, estimates of global abundance of methane hydrate are in the range 15 Gigatons, a value that has caused government, industry, and academic groups to begin considering the resource potential of these volatile deposits (the inset shows methane plumes in the ocean overlying the deposits at Hydrate Ridge). These formations appear to be common to the continental slope in many environments around the world. The hydrate systems off the Oregon coast promise to become one of the major study areas in the world for this kind of work. (Graphic: Suess et al., 1999)[12]

[12]Suess E., M. Torres, G. Bohrmann, R. Collier, J. Greinert, P. Linke, G. Rehder, A. Trehu, K. Wallmann, G.Winckler and E. Zuleger, 1999: Gas hydrate destabilization: Enhanced dewatering, benthic material turnover and large methane plumes at the Cascadia convergent margin. *Earth Plan. Sci. Lett., 170*, 1-15.

Figure 2.13. Vent fauna community in a box corer sample. (Graphic: Suess et al., 1999)

from nutrient microprofilers, to flow meters, to time-lapse photography, to *in situ* filtration systems and sediment traps, will be readily interfaced with NEPTUNE junction boxes. Additional drift-free nutrient and trace-metal sensors that can be deployed for extended periods, as well as systems to allow *in situ* manipulation of vent characteristics and associated biota need to be developed. As with several other research groups, the availability of AUVs that can upload instructions and power and download data and samples at NEPTUNE nodes will greatly enhance the results from the fixed experiments.

Community Experiments

Ongoing real-time basic environmental data (boundary layer structure and currents, flow rate and composition of venting fluids, status of benthic communities) at a small number of well characterized sites are an essential basis for PI and small-group experiments. Repeated detailed AUV mapping of vent sites along the convergent margin is necessary to document the nature and rate of change of venting and to plan future research.

2.3.6 Deep-Sea Ecology[13]

Participants

Ken Smith (chair), Jim Barry, Stace Beaulieu, Lauren Mullineaux, Monty Priede, Bruce Robison, Tim Shank

Key Issues

Sampling and observations from periodic expeditions to the deep sea have provided insights to the magnitude and complexity of the deep-sea biota (Figure 2.14). Yet such an approach is unlikely to resolve unanswered questions about deep-sea communities, such as the following: What are the dynamics of deep-sea community structure in terms of species composition, abundance, biomass, and diversity? What processes produce/maintain diversity in deep-sea communities? What is the pattern of succession in deep-sea communities and how is it regulated? What is the influence of a spatially and temporally variable food supply on deep-sea communities? What are the vertical and lateral movements of deep-sea animals? What is the importance of vertical and lateral movements of deep-sea animals in the transport of nutrients through the water column and across the continental margin? What are the temporal and spatial influences of natural perturbations on deep-sea communities? How do anthropogenic inputs in-

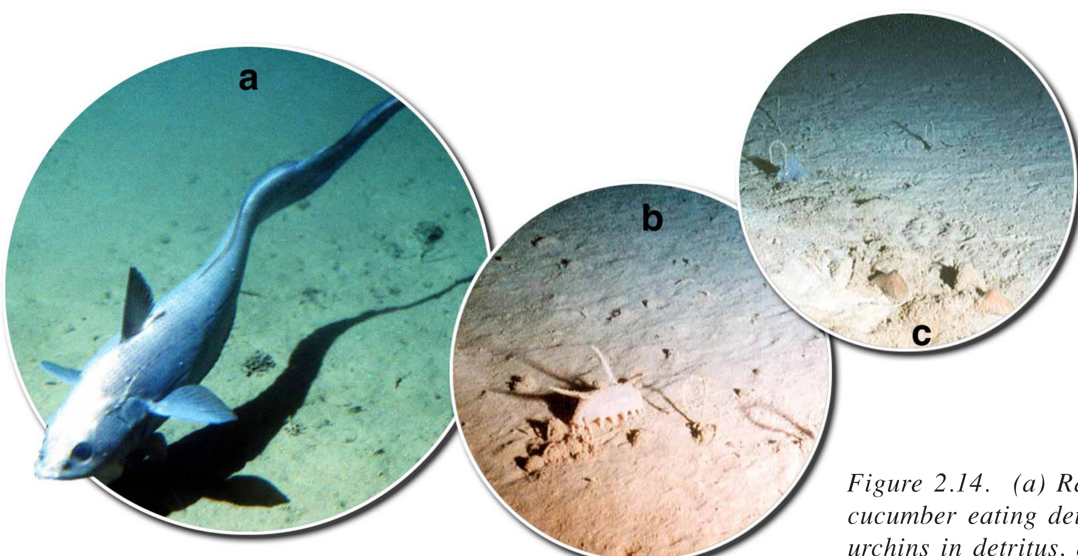

Figure 2.14. (a) Rattail, (b) sea cucumber eating detritus, and (c) urchins in detritus, all at 4100 m depth. (Graphic: Ken Smith, Scripps Institution of Oceanography)

[13]*NEPTUNE Science White Paper #6: Deep-Sea Ecology* (http://www.neptune.washington.edu)

fluence deep-sea communities? How does the productivity of chemosynthetic systems influence surrounding deep-sea communities? How do various scales of fluid release influence chemosynthetic communities? What is the structure and productivity of the sub-seafloor biosphere?

Role of NEPTUNE

The proposed array, which covers a spectrum of deep-sea habitats, will overcome many of the current constraints on biological research. These include the following: the insufficiency of battery power to operate instruments for long periods of time; the lack of real-time data transmission to shore, necessitating *in situ* data storage; the inability to modify observational and sampling strategies in response to observed processes and events; and the lack of information on instrument performance to allow corrective or compensatory changes to be made *in situ* or instruments to be replaced with minimal data loss. The current power constraint is particularly severe in its impact on the deployment of free swimming AUVs or bottom rovers (Figure 2.15) (which could be "garaged" at NEPTUNE nodes) and on the use of power-intensive analytical instruments (employing polymerase chain reactions, for example) or seafloor freezers to preserve biological material for molecular analyses ashore.

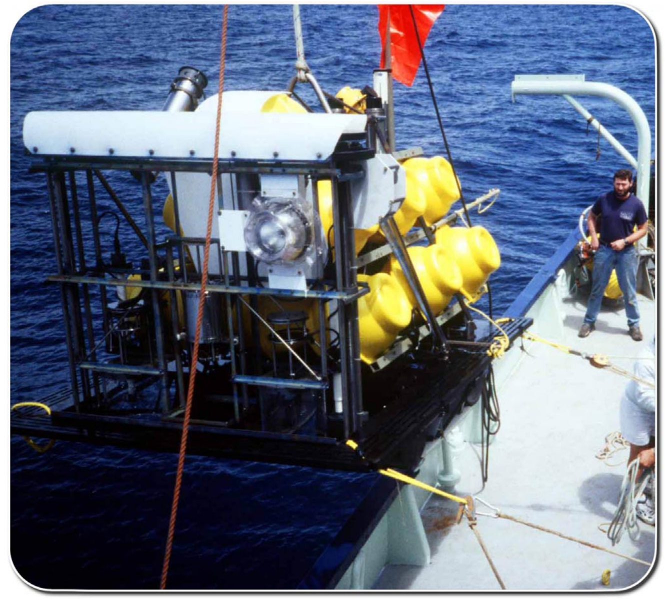

Figure 2.15. Deep-sea Rover being deployed off the R/V Atlantis II. *(Graphic: Ken Smith, Scripps Institution of Oceanography)*

Sensors

In situ biological measurements beyond respiration rates and concentration variations of a few nutrients are less advanced than measurements of the physical and chemical environment in which the organisms live. Emphasis needs to be placed on tools to identify, collect, and analyze key species (for abundance and metabolic activity) *in situ*. Tools to handle and image specimens are available (although they will require adaptation to the NEPTUNE system), but substantial work will be required to adapt laboratory molecular/genetic techniques for use on the seafloor. A combined optical-acoustic holographic-particle sensor system, supported by a high-speed data-analysis capability, could provide a continuous, real-time picture of the distribution of particles and animals in large volumes of water. Further development of AUVs and rovers is required both to achieve the high level of reliability that extended deployment from NEPTUNE nodes will require and to carry out the complex experimental and sample-collection tasks that the next generation of biological studies will demand.

Community Experiments

For NEPTUNE to be user-friendly for PIs and small groups of investigators, basic distributional and functional characteristics of a selected set of communities must be thoroughly and continuously characterized. Only then can the perturbation experiments, which will provide insights to the internal dynamics and stabilities of these communities, be implemented. Common-use facilities (ROVs, rovers, and analytical and sampling instrumentation) must be maintained at such "LTER-type" nodes to avoid the costs and risks associated with each new PI developing his or her own version of these tools.

2.3.7 Water-Column Processes[14]

Participants

Dale Haidvogel (chair), Mark Abbott, Jim Bellingham, Yi Chao, Ken Denman, Bruce Frost, Barbara Hickey, Zack Powell, Steve Riser, Rick Thomson

Key Issues

Over the past few decades, much progress has been made in understanding the global-ocean circulation and its variability through the efforts of programs such as TOGA, WOCE, JGOFS, and GLOBEC. Yet there are few examples of studies of regions of the ocean at sufficient resolution,

[14] *NEPTUNE Science White Paper #7: Water-Column Processes* (http://www.neptune.washington.edu)

with a broad selection of physical, chemical and biological sensors, and over a sufficient length of time to allow the development and use of comprehensive physical-chemical-biological models with few free parameters. Such intensive studies have the potential to provide new insights to the processes that govern biological systems in the ocean, to improve the parameterizations that are inherent in even the highest-resolution global models, and to enhance the value of satellite-based remote sensing in characterizing the state of the global ocean at a resolution and synopticity that *in situ* observations will never be able to match.

Role of NEPTUNE

Although the scale and location of the NEPTUNE array has been governed by the desire to characterize and understand the Juan de Fuca Plate, the region also has a number of interesting physical and biological characteristics. It covers the transition from highly productive coastal upwelling to relatively oligotrophic central water; it lies at the terminus of the west wind drift, where water that has flowed across the Pacific is deflected to the Gulf of Alaska and the California Current; it is an area of substantial thermal and mass fluxes from a mid-ocean ridge to bottom and intermediate waters; it lies near the end of the "grand tour" of deep and bottom waters that originated in the North Atlantic and Antarctic; and it is subject to intense winter storms that result in deep surface mixing and energy transfer from the atmosphere to the ocean (Figures 2.16, 2.17). The area is affected by temporal changes associated with both ENSO and Pacific interdecadal oscillations. Thus, an array of moorings at 50–100 km spacings (as required by seismologists, for example) that are equipped for tomographic measurements (Figure 2.18), as well as with arrays of physical, chemical and biological sensors (or with bottom-up profilers carrying these same instruments) and that provide continuous measurements for a decade or more will provide insights to these phenomena as well as to mesoscale processes captured by this 4-D network.

Sensors

Many of the physical sensors are robust and ready to be interfaced to NEPTUNE junction boxes. Optical systems will require self-cleaning capability (although bottom-up profiling would minimize the time in the euphotic zone and, therefore, biofouling). Bottom-mounted and remotely operated winches require some development. A few chemical sensors are available, but most are not yet drift-free and more are needed. Optic and acoustic biological sensors can be adapted to a NEPTUNE system, but require more development to achieve their full potential. Molecular sensors for species identification and characterization of metabolic states are in their infancy, but have enormous

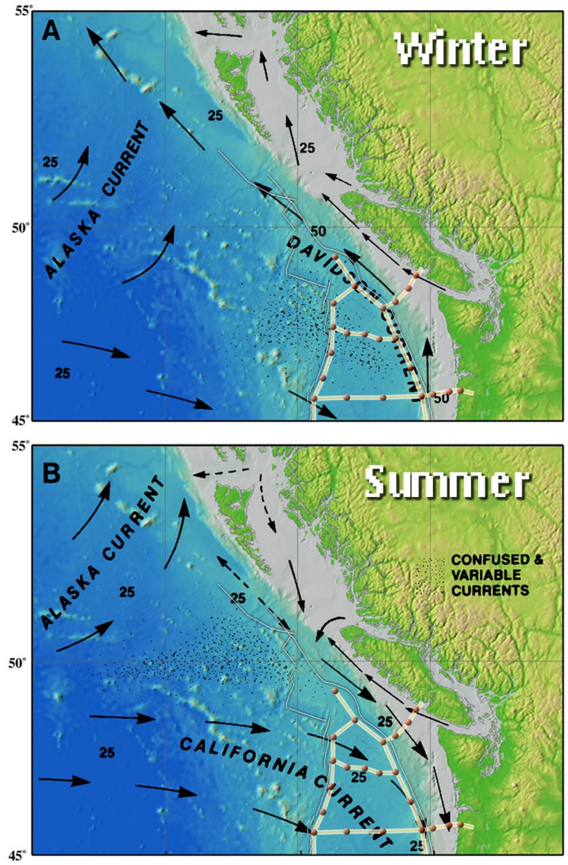

Figure 2.16. Prevailing surface circulation off the British Columbia–Washington coast in winter and summer. Broken arrows indicate uncertain currents. Numbers give speeds (cm/s). Figures adapted from "Oceanography of the British Columbia Coast," Richard E. Thompson, 1981.

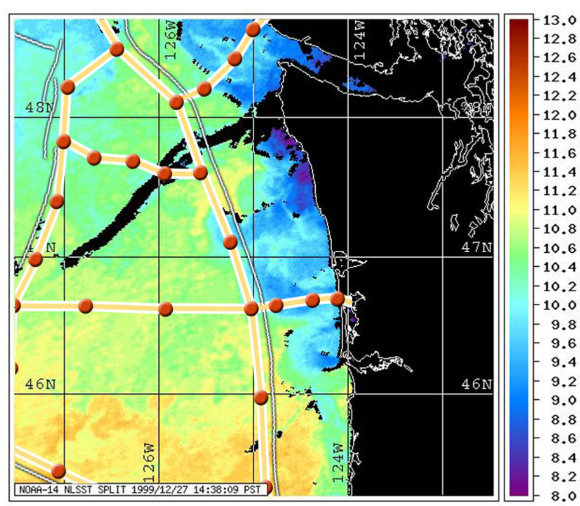

Figure 2.17. Sea surface temperatures off the Washington coast from NOAA-14 NLSST.

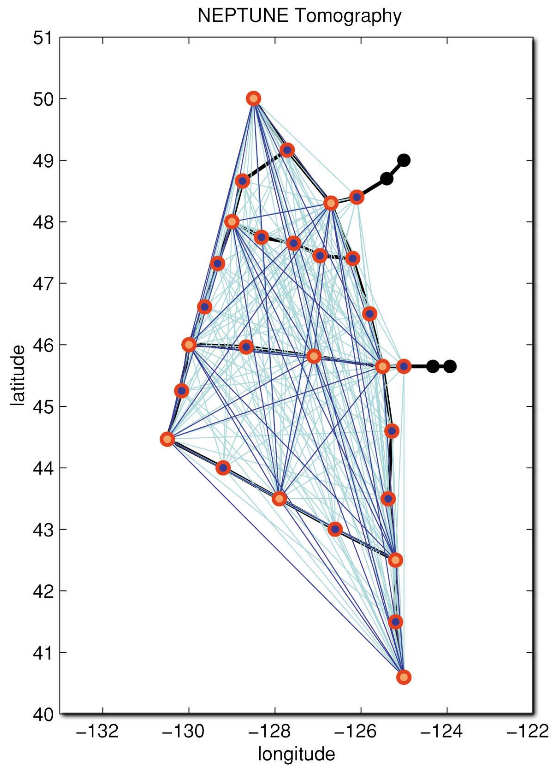

Figure 2.18. The NEPTUNE facility would provide a nexus of acoustic nodes for acoustic thermometry and tomography that would be one component of the ocean observing system within the area, as well as providing a means of directly projecting the reach of NEPTUNE to the entire basin.

potential to yield biological data with spatial and temporal resolutions comparable to physical and chemical measurements. This is an area of high priority for new sensor development.

Community Experiments

Basic physical, chemical, and biological measurements at a densely populated array of moorings or bottom-up profilers will not only support current and planned programs to define ocean weather and climate changes over a broad band of frequencies, but will also allow individual PIs, both theoreticians and experimentalists, to develop new process-oriented models and experiments. The decision on which measurements to include in the basic set should be determined by broad agreement within the oceanographic community and should be subject to critical reassessment at intervals of five to ten years.

[15]McDonald, M. A., and C. G. Fox, 1999: Passive acoustic methods applied to fin whale population density estimation, *J. Acoust. Soc. Am., 105(5)*, 2643.

2.4 Other Science Topics

In addition to the topics addressed above, NEPTUNE has potential value in the areas listed below. The development of these and, in all probability, additional research areas is an important task for Phase 2 of NEPTUNE.

- Fisheries studies, e.g., by better defining the physical environment, by tracking changes in the food chain that supports these top predators, and by direct acoustic monitoring of migrating populations of salmonids as they pass “picket fences” of sensors deployed across the inner shelf off Vancouver Island
- Monitoring size and behavior of marine-mammal populations, which are abundant in the NEPTUNE study area[15]
- Carbon-cycle studies, allowing a fully or overdetermined assessment of the fate of carbon in the region
- Calibration and verification of satellite sensors
- Serving as a test bed for robotic systems to be deployed in other hostile environments on earth and elsewhere (e.g., Mars or Europa)
- Studies of air/sea interactions and the long-term evolution of weather over the NEPTUNE study area
- Geodesy, by allowing the temporal and spatial distribution of the strain field across an entire oceanic plate to be determined for the first time
- Paleoceanography, by allowing all the processes that transform an assemblage of organisms living in surface waters to an assemblage of microfossils preserved in the sedimentary record to be evaluated and thereby improve the quality of and confidence in paleoceanographic and paleoclimatic hindcasts based on the fossil record.

2.5 Scenarios for NEPTUNE Usage

In the preceding sections, we have presented a preliminary description of NEPTUNE science opportunities. Here we continue to build upon this foundation. First, we present a rudimentary rationale for node locations to facilitate the scientific and technical discussion. Then, to further illustrate NEPTUNE’s potential, we develop four hypothetical scenarios for its use: 1) reacting to submarine volcanic eruptions; 2) quantifying processes that move carbon through the ocean; 3) capturing such geologically and societally significant events as subduction zone earthquakes; 4) conducting studies of long-term environmental change. All these phenomena involve multiple processes linked in complex ways. Understanding these systems will provide fundamentally important knowledge about basic science issues while quantifying critically lacking information on physical, chemical, and biological fluxes. None of these processes will be understood as thoroughly using conventional approaches.

2.5.1 Node Placement and Topology

We present a candidate scenario for the NEPTUNE node topology in Figure 2.19. This scenario results in what could be called "complete" coverage of the Juan de Fuca Plate. The total cable length is 3,000 km and there are 30 nodes where sensors and sensor networks can be connected via junction boxes to the backbone cable. The node placement as well as the connection topology will evolve to meet the scientific and technical requirements.

A major NEPTUNE concept arising out of the science working group deliberations is to "wire the plate." We have taken this to mean having nodes along the entire plate boundary with some in the interior and with several sections across the continental margin to shore; any point on the plate is nominally within 100 km of any particular node, which suggests a mesh network connection topology. The network covers the area between the continent and the Juan de Fuca Ridge and therefore samples the full range of processes of scientific concern described above, including seafloor spreading and ridge processes, mid-plate dynamics and hydrology, plate subduction, benthic ecology, cross-shelf transports, fisheries, methane clathrates on the slopes, and the large-scale oceanographic and seismic context. In some cases node placement is specified by physical features such as the Endeavour vents, the Axial Seamount volcano, existing boreholes in the mid-plate, and known gas-hydrate deposits.

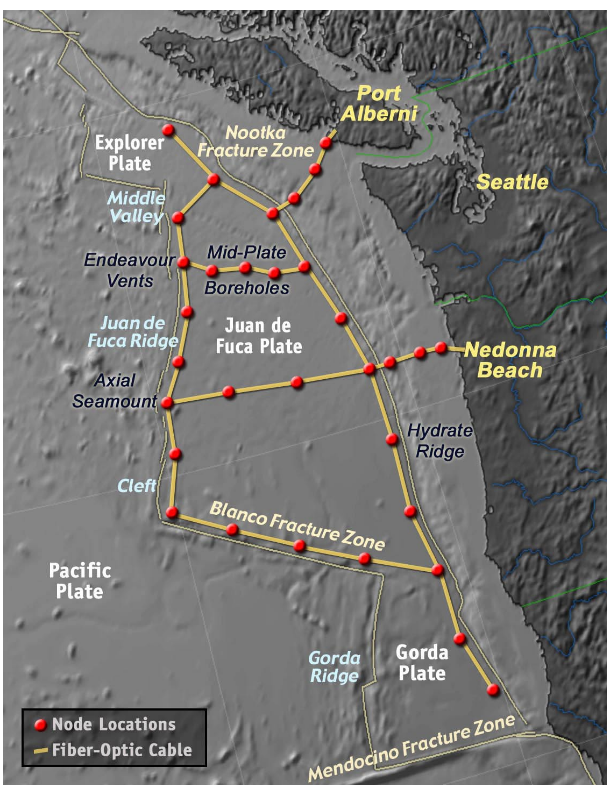

Figure 2.19. Candidate scenario for NEPTUNE node topology. (Graphic: CEV)

There are two technical considerations: multiple shore landings provide a combination of more and/or redundant power and communications capability; a nominal node/repeater spacing of 100 km is dictated by desired data rates, optical fiber properties, and laser technology. The latter spacing is consistent with basic oceanographic and seismic sampling criteria.

The section on the Juan de Fuca Ridge samples areas of well-known volcanic and hydrothermal activity: Axial Seamount, Endeavour, and Middle Valley. Two nodes are placed between Axial and Endeavour to adequately sample other features along the Ridge. The ridge from Axial Seamount south to the Cleft area and the Blanco Fracture Zone is sampled with two nodes. Continuing to the southeast, the network runs along the Blanco Fracture Zone that separates the Juan de Fuca Plate from the Pacific and Gorda Plates. To the north, the network continues along the Nootka Fracture Zone bordering the Explorer Plate. Both of these fracture zones are seismically very active, and the smaller plates are actively deforming, as compared with the relatively rigid Juan de Fuca Plate.

The subduction zone is sampled from the northern part of the Explorer Plate, south along the eastern edges of the Juan de Fuca and Gorda Plates all the way to the Mendocino Fracture Zone (along southern British Columbia, Washington, Oregon, and northern California). Along the way, two shore landings, one to Port Alberni (a retired cable station) on Vancouver Island and one to Nedonna Beach, Oregon (a relatively new cable station), just south of the Columbia River, provide nodes across the continental shelves. Additional nodes to sample the continental slope and shelf for fisheries, sediment transport, and gas hydrates can be supported by secondary cables radiating from the junction boxes on the main cable.

Existing and possible future boreholes in the mid-plate region between the ridge and the subduction zone are assigned nodes.

In many cases it will be useful to regard the main ring that circumnavigates the Juan de Fuca Plate and the sub-rings as forming the boundaries of control volumes along which boundary conditions such as fluxes are measured. The lines crossing the Plate will provide the interior state. These measurements will permit a complete control volume analyses with estimates of various budgets.

We recognize that node locations will change with the input of all science working groups. For instance, the seismology and geodynamics working group has placed high priority on a grid of instruments with 100 km spacing that extends across the Explorer and Gorda Plates. The ridge processes group has suggested positioning nodes based on segment highs, as well as along the Gorda Ridge to the south. The deep-sea ecology group has suggested a node to the southwest to provide more oligotrophic conditions. Other factors too will play a role in node placement: young turbidites at the base of the continental slope on the Gorda Plate suggest the backbone cable may be safer farther offshore. The global optimization problem implied here will itself be challenging.

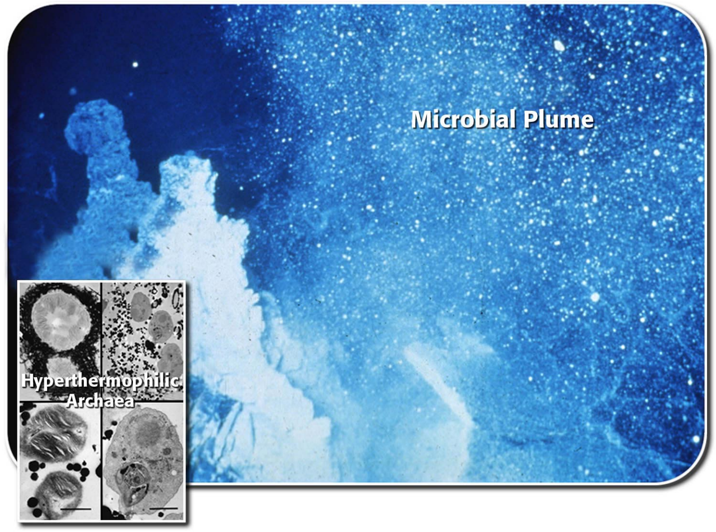

Figure 2.20. A plume of microbial material, dominantly sulfur, characteristic of activity following a seafloor volcanic eruption. (Graphic: Woods Hole Oceanographic Institution) These plumes also contain hyperthermophilic Archaea *(inset), which are closely related to some of the most ancient microbes known.* Archaea *are a major repository of living carbon, existing primarily below the seafloor, metabolizing volcanic gases. (Graphic: Jim Holden, University of Georgia)*

2.5.2 Submarine Eruption Response

The link between submarine volcanoes and microbial life is a potentially profound one, but we know little about how it functions. The origin and evolution of early life, the occurrence of life on other planets, the abundance of life deep within our planet, the formation of metal deposits, and the potential biotech uses of extreme enzymes may all be tied in some manner to underwater volcanoes. Yet volcanoes are highly episodic in character and can only be understood by studying eruptive behavior. For example, in all cases where we have sampled recent eruptions we have found massive amounts of hyperthermophilic *Archaea*, heat-loving microbes with ancient DNA signatures, issuing from the seafloor (Figure 2.20). We conclude that a vast but unexplored suite of subseafloor habitats exists in intimate association with active volcanoes. Optimal access to such systems will be during active eruptions when the hottest, deepest microbes are likely to be ejected from the seafloor.

Because of the impulsive unpredictable nature of these systems, it is virtually impossible to obtain a ship and arrive on site in a timely manner to characterize the process and to sample products of the eruption. With NEPTUNE in place, a programmed and coordinated response can be on site within hours; the essential surveying and sampling required to preserve the most exotic high-temperature microbes associated with the system will be possible using shore control and live action feedback from *in situ* sensor arrays. With the power and communication capability of NEPTUNE, AUVs could be programmed and reprogrammed to fully characterize and quantify key processes associated with these events from the onset of activity in terms of the entire physical, chemical, and biological signature of the eruptive processes. This basic capability would provide an unparalleled step forward understanding one of the most fundamental of planetary processes, volcanism, and its links with unusual and poorly understood life forms within the earth.

2.5.3 Carbon Cycling in the Ocean

Studies in the HOT and BATS programs have clearly indicated that sustained time-series studies of carbon movement through the ocean can provide unexpectedly complex results. Yet in a sense these single-point observatories demonstrate the pressing need for establishing 3-D sensor arrays that operate for years through all seasons. The NEPTUNE system can enable deployment of an observing-experimental network of unprecedented density, variety, and spatial coverage, including novel instrumentation for sensing the combined *in situ* physical-chemical-biological environments. This system could be tuned and designed to fully characterize in a single coherent volume, the movement of carbon species through real oceanographic systems.

Volatile transfer at the air–sea interface, especially during intense storms, can be quantified with vertically adjustable moorings and the correct suite of sensors. The timing and intensity of phytoplankton and zooplankton blooms can be documented continuously within the control volume, and the detailed transfer of carbon and other key nutrients into the deep ocean along with any remineralization processes can be tracked throughout the water column, including near and within the seafloor. In addition, by examining sediment character and lateral plate transfer toward and into the subduction zone, it will be possible to quantify the fate of carbon in a subduction zone. This effort could be linked to a comprehensive study of the carbon fluxes associated with methane production and gas-hydrate formation as a function of episodic movement that could trigger earthquake-pulsed volatile output from within the accretionary prism. Finally the return cycle of gas hydrate to the ocean and atmosphere could be tracked within appropriately selected control volumes. This would allow quantifiable generalizations to be made regarding the entire carbon cycle through a section of ocean ending either back in the atmosphere or in the subducted sediments.

2.5.4 Subduction Zone Earthquakes

NEPTUNE's long-term strategy is the only means to capture earthquake records in their entirety. Although NEPTUNE will record many such events, large earthquakes on the Cascadia subduction zone are of particular interest from a societal perspective. There is clear evidence of great subduction zone earthquakes in Cascadia as recently as 300 years ago. Elsewhere, these megathrust earthquakes, which occur along the boundary between the subducting and overlying plates, are responsible for the most devastating earthquakes and tsunamis. Estimates of seismic hazard in Cascadia are dependent on the landward and seaward limits of the seismogenic or locked part of the megathrust and these are poorly known (Figure 2.21). Along most of the Cascadia margin, most if not all of the seismogenic portion of the megathrust is inferred to lie well offshore under the accretionary prism. It is of particular importance to understand the seismic behavior of these sediments to determine which parts of the prism can support earthquakes.

In addition to the direct earthquake hazard, great subduction zone earthquakes are likely to have a profound effect on many geological processes in the accretionary prism (see Figure 2.11 in Section 2.3 above). Many important processes may be limited to short time intervals during and immediately following great thrust earthquakes, including 1) pore-pressure buildup and release on the megathrust, 2) thrust faulting in the overlying accretionary prism, 3) regional sediment consolidation due to fluid expulsion, and 4) slope failures that control the angle of the seafloor.

The continental margin shows scars indicative of massive slope instabilities that may have been triggered by earthquakes. There is now good evidence that megathrust earthquakes led to the most recent turbidite deposits at the base

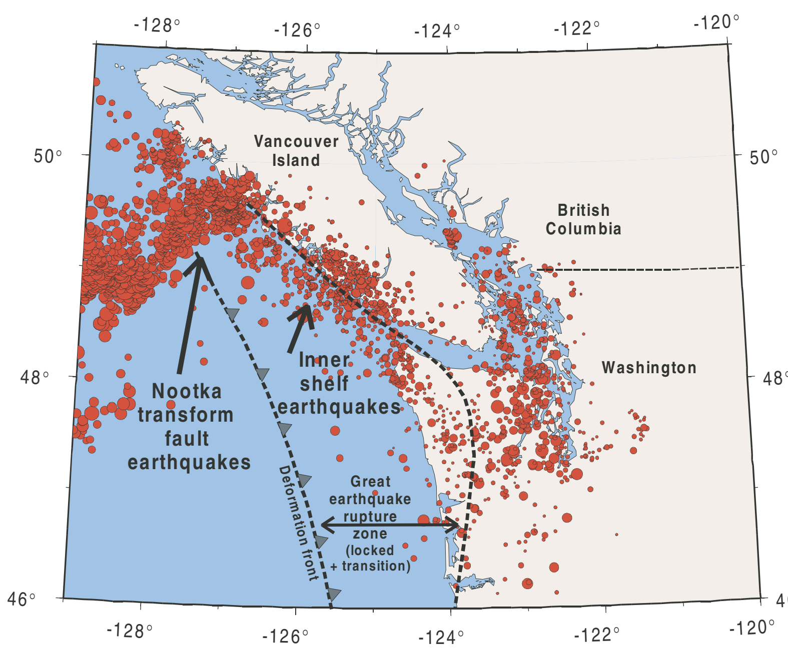

Figure 2.21. Earthquakes in the Juan de Fuca plate (1980–1998) beneath the north Cascadia margin (earthquakes in the continental crust have been excluded). The inner shelf earthquakes may mark the landward limit of the locked portion of the subduction thrust fault, but this hypothesis cannot be tested without data from seafloor seismic stations. The Nootka transform fault is a strong shaking source beneath the accretionary prism. (Graphic: R. Hyndman, Geol. Survey of Canada)

of the continental slope. Such events can trigger tsunamis, destroy offshore facilities, and release large volumes of methane into the ocean. The change in fluid pore pressures that follows a large earthquake is expected to have a substantial effect on patterns of fluid circulation and the intensity of discharge from accretionary sediments. The effect of ground shaking on gas-charged and gas hydrate-bearing accretionary complex sediments must be measured in order to develop a predictive understanding of how this hazard is linked to seismic activity.

Ideally, the processes that are initiated by great thrust earthquakes in and beneath an accretionary prism would be observed through such an earthquake. Unfortunately (or perhaps fortunately), the frequency of occurrence of such great events is too low for practical monitoring times and there is only a low probability of such an event during the design lifetime of NEPTUNE. However, there are sites at either end of the subduction zone where strong shaking is generated more frequently by other earthquake sources. The Mendocino triple junction lies at the southern terminus of the Cascadia subduction zone where it intersects the Mendocino and San Andreas transform faults. The Nootka fault zone is a region of diffuse seismicity that separates the Juan de Fuca and Explorer Plates. At both sites, magnitude 6 to 7 earthquakes occur quite frequently. Earthquake statistics suggest that shaking with accelerations of at least 10% the acceleration of gravity should occur in the accretionary prism in a recording time of a few years. Over its lifetime, NEPTUNE can expect to record a number of significant events at both sites.

NEPTUNE will provide a unique opportunity to obtain multidisciplinary observations that will allow the full characterization of the effects of a significant earthquake in the accretionary prism. The seismic network will provide strong constraints on the location and characteristics of the fault motion and the intensity and distribution of ground shaking. Complementary geodetic experiments will measure the strain changes produced by the earthquake. Arrays of instruments will be deployed on the seafloor to measure changes in chemical fluxes from the accretionary prism and to monitor sediment transport. Autonomous underwater vehicles could respond quickly to catastrophic landslides (recorded and located by the seismic network) in order to quantify the release of methane and other gases into the oceans, as well as morphological changes. Additional arrays of instruments will be deployed in deep boreholes to characterize such processes as subsurface deformation, earthquake induced changes in fluid pressures, and the resulting variations in thermal and chemical fluxes throughout the accretionary prism.

2.5.5 Long-Term Change

Few oceanographic records are more than a decade in length. Those that exist have proven extraordinarily valuable in documenting the nature and rate of change of the marine environment and its inhabitants. Prime examples are the Station P measurements in the Gulf of Alaska, the CalCOFI network of stations off California, the more recent equatorial Pacific TAO array, and moorings off Hawaii (HOT) and Bermuda (BAT). Even carefully repeated subtidal biological traverses[16] reveal subtle changes that would otherwise be undetectable. Of these examples, only the TAO (or TAO-TRITON) array[17] has a three-dimensional structure capable of unraveling long-term changes in a significant volume of ocean. NEPTUNE will have the additional capability to record changes throughout the water column, as well as within the underlying lithospheric plate. By committing at the outset to a 30-year lifetime for the network, NEPTUNE will allow scientists from a broad array of disciplines to develop strategies to study rates of environmental change that are inaccessible to normal research programs.

2.6 Science Requirements

Although the working groups did not spend much time on specific technical characteristics of the system, a number of common needs emerged. These include: bandwidth capable of supporting HDTV at many nodes; power to operate AUVs and bottom rovers with a range of capabilities (some carrying rock drills, for example); power for high intensity lights; very accurate timing signals to support dense seismometer and tomography arrays; bandwidth to support broadband seismometers at the seafloor and multi-frequency acoustic arrays in the water column; real time ability to interactively control instrumentation and actuators; reliable time series measurements; and a user friendly information management system. Several groups emphasized the importance of building in excess capacity so that the sophistication and capacity of experiments can grow through time. The science requirements are expected to more than meet the requirements for the education component.

In an attempt to begin to quantify these rather vague requirements, we have developed strawmen generic sensor networks as a prelude to estimating power and communications requirements.

[16]Barry, J.P., C.H. Baxter, R.D. Sagarin, and S.E. Gilman, 1995: Climate-related, long-term faunal changes in a California rocky intertidal community, *Science, 267*, 672.

[17]http://www.pmel.noaa.gov/toga-tao/

2.6.1 Sensor Networks

At each node there will be a scientific interface, i.e., a junction box to which science users can connect instruments for power and communications services (Figure 2.22). The generic sensor networks being considered here have somewhat arbitrarily been divided into three classes: basic, intermediate, and observatory. The divisions reflect different purposes as well as cost. The basic class consists of robust bottom mounted sensors making simple yet fundamental measurements; they are physically close to the primary junction box. The intermediate class extends the spatial coverage to sample the area between nodes, as well as up into the water column and down into the seafloor. The observatory class constructs a sub-network around a limited area to support high-resolution studies. We will conclude by taking a leap and specifying a certain number of networks from each class to define what might be regarded as a first cut at a suite of community experiments.

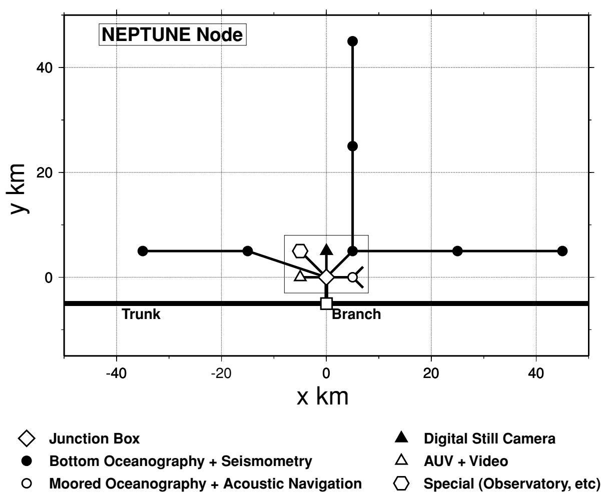

Figure 2.22. Basic and intermediate sensor networks.

We emphasize that this is only a scenario and is not intended as a solution to the science requirements identified by the science working groups to date. Rather, it is a straw man that incorporates generic sensor networks at the different spatial scales to produce rough estimates of the power and data rate requirements and installation costs and timelines for the community experiments.

Basic Sensor Network

The basic sensor network around a particular node consists of a simple star configuration, with each radial plugging directly into the primary junction box (inner box, Figure 2.22). For the present scenario, the basic sensor network consists of an ocean-bottom oceanography and seismometry package (OBOS), a digital still camera, and an AUV docking station with video camera.

We expect that one of the main sensor packages deployed in substantial numbers will be the OBOS package. The sensors will rest on (or slightly beneath) the seafloor with little vertical extent into the water column; the emphasis will be on simplicity, reliability, and robustness. The suite of oceanography sensors includes temperature, salinity, pressure, and velocity. A high-frequency, broadband acoustic transceiver will serve many uses: an inverted echo sounder (first mode baroclinic ocean structure); an ambient sound receiver (wind, rain, marine mammals); a component in a seafloor geodesy and acoustic tomography network; an acoustic modem for "wireless" communication; and a navigation transponder. The seismometry sensor suite will include broadband sensors, a geophone, and an attitude sensor. Many of these instruments are "nonpoint" in nature, providing integrated measures of the surrounding environment. Other instruments will plug into the secondary junction box associated with this package.

A panning digital still camera will observe the flora and fauna in the area around the junction box (useful during ROV work). Power usage will be low because a strobe light can be used and data rates are modest, given a reasonable cycle time, say once every 100 seconds.

Another connection will be for an autonomous undersea vehicle (AUV, free swimming or bottom roving) docking station and a video camera. These are included together because both could potentially be high power and high data rate "customers." It would be useful to have a fixed (with pan and tilt) video camera capable of seeing the AUV during docking operations. There may or may not be an AUV stationed at every node, but it makes sense to provide for one traveling from one node to the next.

Intermediate Sensor Arrays

Here we specify a collection of sensor arrays that can extend NEPTUNE's three-dimensional spatial coverage. These arrays can be used as building blocks to obtain improved resolution as well as to cover more area: horizontally distributed arrays of OBOSs, AUVs, two moorings of differing capability to sample the water column, and borehole instrumentation.

To obtain more spatial coverage for oceanographic, seismological, and the multidisciplinary studies we envision, it will be necessary to deploy instruments over a larger spatial extent than just around the primary nodes themselves (Figure 2.22). For the sake of simplicity we assume that six OBOS packages are placed at distances of 20 and

40 km from the junction box on three radial lines to obtain the additional spatial coverage. Actual spacing will depend on the particular science topic being addressed. The figure shows the three lines intersecting one OBOS, illustrating the need for secondary junction boxes or data concentrators (forming a local area network). In a similar way, one long string could be deployed up the continental slope to sample the shelf.

The AUVs[18] can carry video, digital still cameras, acoustic lenses, multi-frequency sidescan sonar, magnetometers, and conventional oceanographic instrumentation. AUVs are becoming common industry tools for seafloor mapping. We expect AUVs to play a major role in doing routine survey work of the bottom and the water column (with high-frequency sonars and video imagery) in addition to providing the capability to respond quickly to events. In addition to the conventional, free-swimming AUVs, there also will be bottom rovers that are either autonomous or tethered. Acoustic GPS-like tracking on various spatial scales will be provided, using the acoustic components in the OBOS and on moorings or dedicated systems if necessary.

Two types of oceanographic moorings extend sampling into the water column: a mooring with just the most basic oceanographic sensors (mooring A) and a more capable one (mooring B). Both will be subsurface moorings constructed for long life (5-year moorings are presently being designed) and will sit off to one side of the junction box at a distance that will not interfere with ROV work. Mooring A will have a string of temperature and salinity sensors, current meters, and nutrient and chemical samplers.

Mooring B has its top float just below the surface and the associated wave action. A variety of instruments can be put on the mooring: acoustic Doppler current meters near the top of the mooring looking up into the mixed layer and toward the surface and down into the main thermocline; an acoustic transducer and vertical hydrophone receiving array for use in acoustic navigation/GPS (AUV positioning), tomography (large-scale 3-D temperature and velocity fields), and marine mammal studies; and temperature and salinity sensors. The mooring will have several acoustic transponders around it for mooring tracking purposes. A small tethered or winched instrument package will sit on top of the subsurface float, out of the wave and euphotic zones (and associated biofouling), to periodically sample the ocean surface and the mixed layer. A variant might have a suite of profiling instruments on the main mooring line.

Lastly, boreholes will require a variety of instrumentation to sample the subsurface environment, including chemical and biological samplers, seismometers and geophones, pumps for tracer experiments, resistivity measurements, and downhole heaters (for clathrate studies).

Observatory Sites

We provide the topology for a generic observatory site in Figure 2.23. It covers an area roughly 8 by 20 km with 16 secondary sensor nodes and 4 moorings. The secondary nodes support a multitude of instrumentation. This particular layout is motivated by Axial Volcano; it will clearly be different for other possible sites such as a hot vent area, a submarine canyon, or Hydrate Ridge. Just as for the main backbone system, a ring topology improves the survivability significantly, so that if a volcanic eruption damages some of the net, the rest will continue to function. A hierarchy of junction boxes will provide power and data concentration.

Axial Volcano rises 700 meters above the mean level of the Juan de Fuca Ridge crest and is the most magmatically robust and seismically active site between the Blanco Fracture Zone and the Cobb Offset. The summit is an unusual rectangular-shaped caldera (3 by 8 km) that lies between two rift zones and is bordered on three sides by a boundary fault with up to 150 m relief. Hydrothermal vents colonized with biological communities are located along the boundary fault and rift zones. A seafloor eruption in 1998 left a new lava flow along the south rift zone and created several new vent fields (Figure 2.10).

The NEPTUNE Axial Volcano observatory will support long-term time series data and enable instantaneous responses to future seismic events or eruptions. Seismometers and hydrophones located outside the caldera will be positioned to locate and characterize events yet kept distant from areas of expected lava flows. Other seafloor monitors will detect small harmonic tremors caused by magma moving in rock chambers and fissures beneath the caldera, which may predict an impending eruptive event. Acoustic ranging beacons arrayed across the rift zones will measure expansion of the summit inflation from magma intrusions. Within the water column, acoustic current profilers and vertically moored sensors will be positioned throughout the summit to measure optical and hydrographic parameters that track plume generation and advection. Chemical and biological sensors integrated into the moorings will monitor the concentration and temporal variability of important trace elements and microorganisms. Cameras and sophisticated sampling systems will be placed on the seafloor to sample fluid flow in selected vent fields. AUVs will be docked on top of the caldera

[18] *NEPTUNE Supporting Documents:* Extending our Reach Beyond NEPTUNE Nodes: AUVs and Acoustic Communications (http://www.neptune.washington.edu)

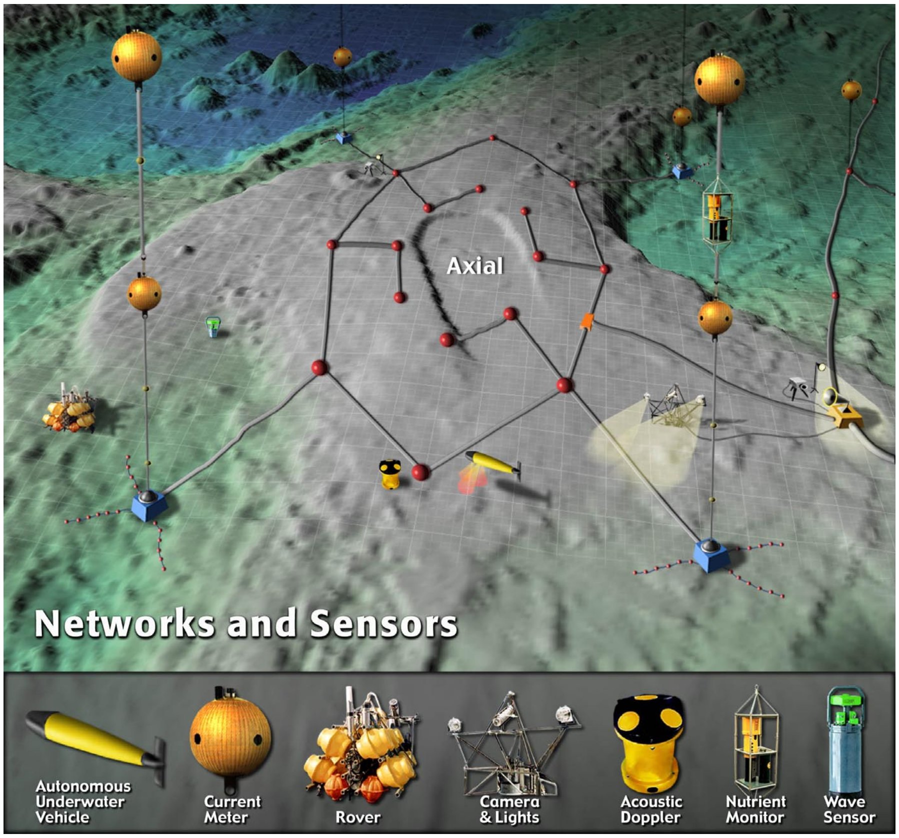

Figure 2.23. A generic NEPTUNE observatory network, draped over Axial Volcano, based on the NOAA/PMEL New Millenium Observatory. (Graphic: CEV)

wall in garage nodes that recharge batteries, receive commands, and accept data. The vehicles will make periodic excursions on programmed routes, navigating through an array of acoustic transponders, and will be commanded for specific missions in response to events. The AUVs will be instrumented with water column sensors, bottom imaging systems, and microtube pumps for continuous collection of water samples.

2.6.2 Summary—Community Experiments and Sensor Networks

Here we specify the number of each sensor network class that could represent an initial set of community experiments. This will serve the purpose of providing an overall estimate of power and communications requirements, as well as setting the stage for cost estimates. Again, specifying the makeup of the collection of sensor networks is somewhat arbitrary at this time, with definition coming in time as the science requirements evolve.

Each of the 30 nodes should be equipped with the basic sensor network consisting of an OBOS (ocean-bottom oceanography and seismometry), a digital still camera, a video camera, and an AUV docking garage or station. We will assume 15 each of the intermediate sensor network class; within this class are two types of oceanographic moorings, a spatially distributed array of OBOSs (or the moorings and other instrumentation), an AUV, and a borehole string. This is not to say all the sensors in the class are necessarily together at one node, but rather when the individual components are combined, there are effectively 15 deployed. Then we assume 4 observatory networks; sites for these might be Axial Seamount, the Endeavour hot vent field, a methane clathrate field, and a shelf-slope region with sediment flux and fisheries interest.

2.7 Technical Requirements

The scenarios outlined above and the science requirements that emerged as common needs from the meetings of the science working groups dictate the power and communication requirements of the NEPTUNE infrastructure. With time, definition of the science requirements will become more concrete as the Phase 2 science working groups continue to refine them.

In the interim, we must begin to set the engineering infrastructure requirements (e.g., amount of power and data rate) in order to begin the design process. We approach this task using the suggested suite of generic sensor networks to place conservative upper bounds on the appropriate parameters. In this subsection, we summarize the power and data communications requirements; details are in the *NEPTUNE Technical White Paper #1: Power and Communication Requirements*.[19] Section 3.1, Engineering Mission Statement, will bring in other technical requirements to provide a complete vision of the NEPTUNE infrastructure.

Major power consumers will include those instruments and devices that require the following:

- Motion (tethered, swimming, and bottom roving vehicles, active acoustics, drilling, pumping of fluids)
- Heat transfer (freezers to preserve specimens and cool electronics, heaters for chemistry experiments)
- Light (video imagery and lasers)
- Electronics (transducers, computers, communications).

A typical power requirement for any single item in the first three categories might be between 100 and 1000 W. Electronics can draw from milliwatts to order 100 W. Energy storage may be involved with any of these. At a node adjacent to an "observatory" site such as Axial Volcano where a large number of instruments are concentrated, a peak load could be as much as 20 kW. Given that most items will have duty cycles less than unity and that there will be a mix of instrumentation at the different nodes, an average load might be 2 kW at each science node.

What are the data rates required for some likely NEPTUNE instruments? A pressure gauge might require a single 16-bit sample once a second for a data rate of 16 b/s. A broadband seismometer might require three 24-bit samples at a 100 Hz rate for an overall data rate of 7200 b/s. A single high-frequency hydrophone might require 1 Mb/s, and a sidescan sonar will have a data rate many times this. A digital color video image will have a data rate approaching 1 Gb/s (similar to high-definition television). This could be reduced by a factor of 10–100 by compression and image processing techniques, and further reduced if the sample rate were lowered, as can typically be accommodated for seafloor applications.

[19] *NEPTUNE Technical White Paper #1: Power and Communication Requirements* (http://www.neptune.washington.edu)

This brief sensor data-rate survey shows that digital imagery, followed by high-frequency acoustics, dominates a bandwidth census and therefore an estimate of the number of images required per unit-time bounds the system data-rate requirement. While this is difficult to define, especially over the 30-year lifetime of NEPTUNE, an infrastructure with a capacity of a small multiple of a Gb/s should prove more than adequate. This is easily achieved using commercial technologies on a fiber-optic cable, but is beyond the capacity, or highly stresses the capacity, of any currently envisioned satellite system.

In summary, for the 30-node scenario in Figure 2.19, the overall power and communications requirements are listed below, although these very rough estimates will change as the science becomes better defined.

- Average and peak power for a particular node: 2 kW and 20 kW, respectively
- Peak power for the entire system: 100 kW
- Average and peak data rate for a particular node: of order 100s Mb/s and 1 Gb/s, respectively
- Peak data rate for the entire system: of order 10 Gb/s.

2.8 Summary

Ad hoc science working groups met to consider the research opportunities that NEPTUNE would create and began to identify examples of community experiments and observations. Their white papers (posted on the NEPTUNE web site) and the working group summaries (included in this section) give ample evidence of the broad scientific interest and the topics that can be addressed within the NEPTUNE framework. Indeed, in many cases, it is only with the capabilities of NEPTUNE that many of the science problems become tractable.

Many of the science topics cross disciplines and take advantage of the long-term approach with complementary and supporting data from each of the traditional disciplines. Dynamics of systems and changes over time due to forcing can be studied in detail, with all their intricacies and cross-dependencies.

The discussion in this section answers the question, "Is NEPTUNE scientifically desirable?" in the affirmative.

A scenario of generic sensor networks (basic – local, intermediate – spatially distributed, and observatory – high resolution) is offered as a way of illustrating the possibilities, as well as estimating the power and communications systems requirements.

3. Infrastructure Engineering

In the previous section, we summarized the broad science goals of NEPTUNE, including a description of measurement needs and the infrastructure characteristics that will satisfy the scientific requirements. In short, the NEPTUNE system must provide the power, communications, and data management services required for science within the context of a reliable, robust, flexible, and affordable infrastructure. In this section, we describe the systems within that infrastructure and the decision-making pathways we have followed to arrive at our conclusion that NEPTUNE is feasible.

Section 3.1 presents the engineering mission statement that provides the philosophical underpinnings for the NEPTUNE infrastructure. In Section 3.2, we discuss the major design issues that will begin to define NEPTUNE. Following this each of the major operational subsystems (power, communications, timing, and monitoring and control) (Figure 3.1) is presented in terms of requirements, approach and trade-offs, and concluding remarks (Sections 3.3–3.6). Although each subsystem is described separately, each must integrate seamlessly into the infrastructure. Finally, based on the conclusions of the preceding sections, a conceptual design is presented in Section 3.7. A summary is given in Section 3.8. Supporting information is provided in technical white papers available on the NEPTUNE web site.[1]

The high points of this section are as follows: we have chosen a submarine cable as the enabling technology for NEPTUNE; our rationale for this choice is presented within the context of a comparison with surface buoys. We have selected a mesh topology for both the power and communications systems to meet the capacity requirements and to maximize reliability and flexibility. For power, this means using a "parallel" or constant-voltage approach much like land power systems and unlike conventional submarine telecommunications systems. For communications, a standard data networking technology (gigabit Ethernet) is identified as a leading candidate. The decision tree in Figure 3.2 illustrates some of the decision-making process.

Our goal is for NEPTUNE to appear as an extension of the global Internet, connecting users anywhere on shore to distributed sensors on the seafloor.

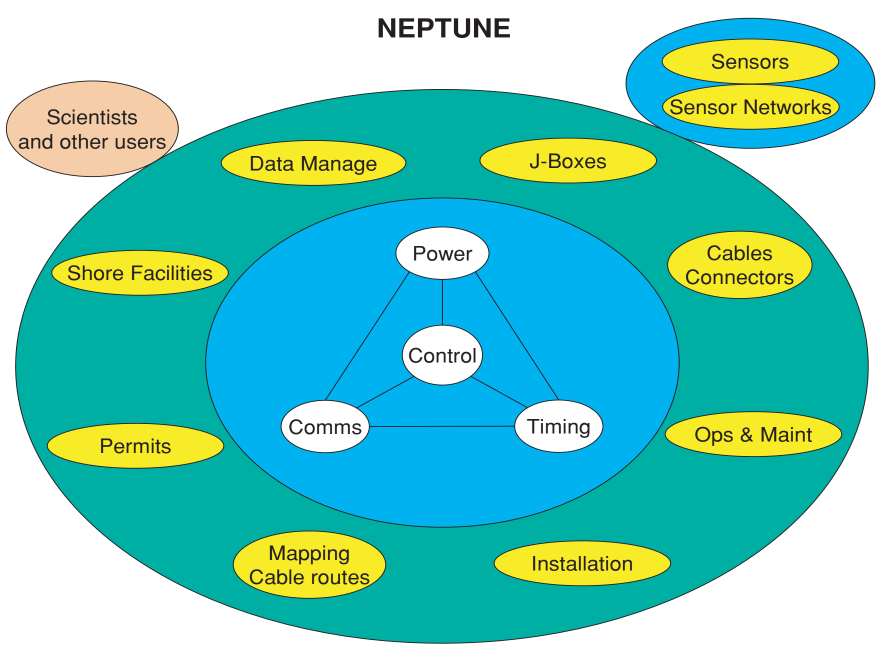

Figure 3.1. The major operational subsystems and the supporting components link the scientist/user to the sensors and data.

[1] http://www.neptune.washington.edu

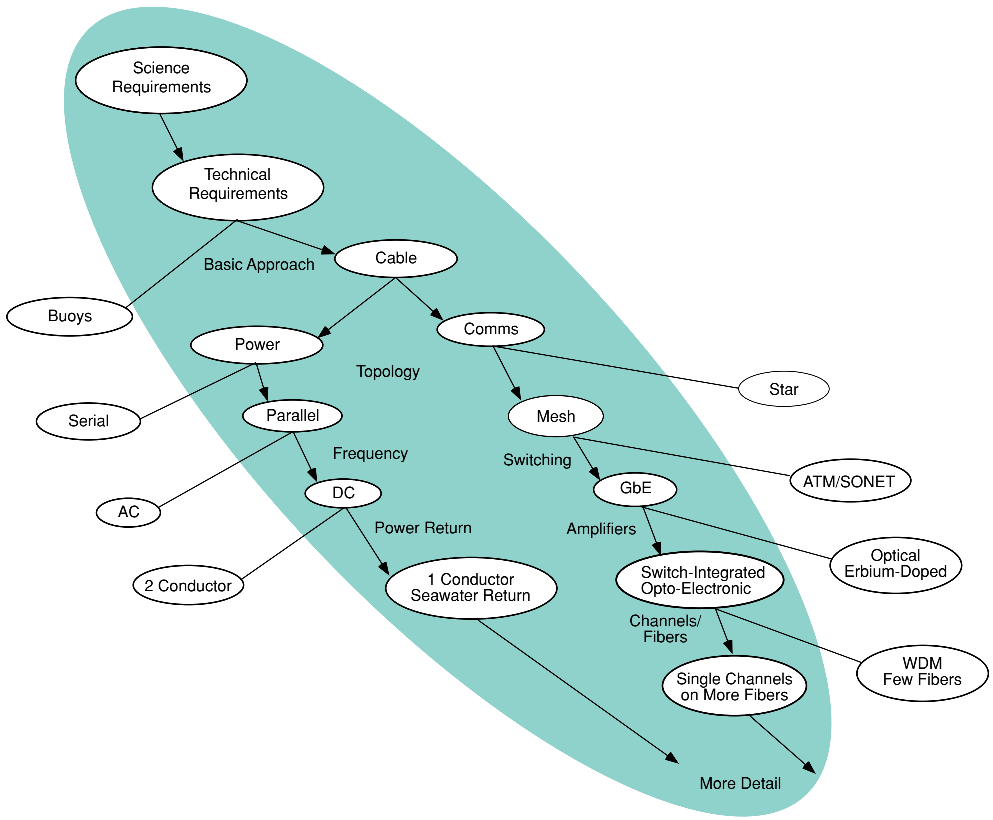

Figure 3.2. A conceptual diagram illustrating the major power and communications decisions for the NEPTUNE infrastructure. The actual decision-making process is more complex, with some decisions made in parallel or lumped together by the technologies. These decisions represent choices made for this feasibility study and provide a starting point for the Phase 2, Development, effort.

3.1 Engineering Mission Statement

The NEPTUNE infrastructure will be implemented so that the science needs and requirements are satisfied, while providing the needed degree of reliability and operability. From a management standpoint, the implementation of NEPTUNE will be dependent on the specific funding sources and the phasing of funds from those sources. The technical elements of NEPTUNE will be defined in such a way that good project management practices can be readily applied, assuring that the engineering design and implementation remain robust, irrespective of the funding process.

Conceptually, NEPTUNE has three parts:

- The science experiments
- The support structure, including operations and maintenance and data management
- The engineering infrastructure, which provides power and data communications to the seafloor.

The science experiments can be subdivided into two classes: those for long-term, community-wide science and those for principal investigator (PI) proposed and developed experiments. Well-defined interfaces will ensure that all sensor systems are fully compatible with the infrastructure. We will develop and use test beds to verify compatibility of instrumentation with the NEPTUNE infrastructure before deployment.

Overarching capabilities that influence the engineering mission statement include the following:

- The useful life of the NEPTUNE infrastructure is at least 30 years with 24-hour-per-day availability once operational.
- Reliability will be key to low operation costs. As an example, the terrestrial power system and the Internet operate at > 0.99998 level (10 min/y), while autonomous oceanographic instrumentation lies in the range 0.9 – 0.99. The precise value to be used for NEPTUNE will be derived in Phase 2 as part of

the trade-off between up-front development costs and low operation and maintenance costs. Survivability, a function of cable breaks depending on external factors, is currently estimated at > 0.99 and will be further studied in Phase 2.

- High-bandwidth and high-power capabilities are provided as a matter of policy at approximately the levels described in Section 2.7. Similarly, accurate timing and real-time two-way control capability are provided.
- Data management and archiving may be distributed, though to any user it will appear to be concentrated at a single point.
- All community experiment data are available to the public in near real time (after any necessary automatic quality control). Data from PI experiments are handled per sponsor policy.
- The engineering infrastructure is capable of reconfiguring itself automatically to suppress fault propagation and to accommodate the acquisition of science data that are event driven, e.g., a subsurface volcanic eruption.
- The engineering infrastructure, including science experiments, is designed to facilitate routine servicing of instruments using research vessels rather than commercial cable ships.

The overarching science requirement that constrains implementation is that NEPTUNE provide continuous, long-term, high-resolution four-dimensional data sets (three spatial, one temporal) that can be used to explore trends and interactions in the earth's environment. Providing high bandwidth and power maximizes the opportunity to exploit NEPTUNE's potential to generate cutting-edge science. The usefulness of a 4-D data set will be strongly affected by how straightforward it is to access the data. While a central focal point can provide "one stop shopping" and can simplify the interactions with the investigator, a distributed approach to the "central" database also offers advantages. We envision a scheme that combines these two ideas and takes advantage of the Internet.

Automatic reconfiguration is required for the data communications network and the power system to meet the availability goals. Component failures will inevitably occur within this period and, if left uncontrolled, would have a major adverse impact on availability.

To keep the interfaces to the user community simple, standard Internet protocols will be adopted for data transport and commanding. NEPTUNE is intended to be a point-and-click, plug-and-play environment. Compatibility will be ensured by complete validation of interfacing hardware and software and the designed-in fault tolerance and robustness of the NEPTUNE infrastructure.

We will design NEPTUNE so that normal operation and maintenance activities are transparent to users. In emergency conditions, such as a cable fault, users will be notified immediately of the condition. The infrastructure will be able to autonomously generate this notice and provide the information to collaborating investigators over the Internet. During an emergency, the priority will be for personnel and infrastructure safety, and all decisions will be made on this basis. The corrective action required to restore the network may not be transparent to the users and some may lose service both during the emergency and during the corrective action period.

We can significantly mitigate technical risk in the implementation phase by using proven commercial, off-the-shelf (COTS) products to the greatest extent practical. The design should be single-point failure tolerant. This ensures that the reliability of the deployed infrastructure can be assessed and used to guide implementation. Elements that are not COTS must be extensively tested and proven before deployment.

Technology changes with time, and we will design NEPTUNE to use hardware and software that will be available in 2003. The infrastructure, however, will be adaptable to evolving technologies. Systematic upgrading of NEPTUNE will be largely transparent to the individual user.

NEPTUNE's design will be accomplished within a systems engineering framework that considers the system as a whole, i.e., from the scientist to the sensor over the lifetime of the project.

3.2 Preliminary Definition of the NEPTUNE Infrastructure

NEPTUNE is an integrated system for powering and communicating in real time with large numbers of instruments distributed over a seafloor area of at least 500 by 1000 km (see Figure 2.19). In this section we discuss the rationale for basing the system on fiber-optic/power cables rather than buoys, and we describe the existing technologies and alternatives, some of the physical considerations, and the systems approach to the infrastructure.

3.2.1 Moored Buoys versus Cables

Two distinct approaches for providing power and communications to a distributed set of seafloor science nodes are 1) a distributed set of buoys, each linked to a seafloor science node, and 2) a seafloor fiber-optic telecommunications cable connecting a distributed set of science nodes to one or more shore stations. In the first case, the moored surface buoys supply power to the seafloor instruments and provide a satellite data link to land. In the second case, the seafloor fiber-optic telecommunications cable links the science nodes to one or more shore stations. Selecting the most appropriate approach depends on the amount of power needed for seafloor nodes and science instruments, on the maximum anticipated data rate over the lifetime of NEPTUNE, and on cost.

Forecasting the capabilities of moored buoys and their associated satellite data links is difficult. Present mooring technology allows surface buoys to be deployed for about one year under moderate sea conditions. Major service or replacement is required after that time. Current DEOS design efforts will extend this interval by a factor of 5 to 10. The ability to transfer power to the seafloor and data from the seafloor requires an electrical/optical link that can survive repetitive wave forces for long durations. This in turn requires significant improvements in existing mooring cable technology. Even if such improvements can be achieved, it is still difficult to envision making more than a few hundred watts available at the seafloor from a buoy using existing power technologies (e.g., diesel generators on large buoys or solar/fuel cells on smaller ones).[2]

Data transfer to satellites also poses some complex problems. At present, low data rates (under 100 kb/s) and higher data rates (up to 2 Mb/s) are both feasible using very small aperture telemetry (VSAT) with geostationary satellites. Access to geostationary satellites typically requires stabilized antennas, which in turn imposes a stability requirement on the buoy. Proposed low earth orbit (LEO) satellite systems (e.g., Teledesic, which may be in service by 2004) could provide comparable data rates with less rigorous antenna requirements and minimal delay. However, the commercial viability of LEO systems is questionable in light of the recent bankruptcy of Iridium, and hence there is risk in planning NEPTUNE around their use.

The use of buoys would place significant limitations on NEPTUNE experiments because, as outlined in Section 2.7, the power requirement for NEPTUNE exceeds the several hundred watts that could be provided by buoys. This is too little power for multiple instruments, especially if peak loads, lights, and mechanical systems are considered. When we include the power required for infrastructure electronics on the seafloor, this level proves even more limiting.

Similarly, the required data rate capacity for a NEPTUNE science node exceeds that which a satellite link can service by several orders of magnitude. Limiting the data rate to order 1 Mb/s precludes the use of key instruments such as video unless the scan rate is reduced dramatically. Thus, power and data-rate issues argue strongly against the use of buoy technology for the core portions of the NEPTUNE array. The required technological developments and commercial uncertainty surrounding available satellite systems further weakens the case for their use.

In contrast, underwater fiber-optic telecommunications cable technology is highly advanced and commercially available. It is capable of handling the higher data rates needed for NEPTUNE and providing the needed levels of power to the seafloor. Using a non-standard approach for power delivery, it is feasible to send many tens of kilowatts to the seafloor.

Optical fibers are inherently capable of extremely high data rates (many hundreds of Gb/s). Low-cost commercial technologies to transmit data at a rate of 1 Gb/s per single-mode fiber currently exist, and this rate is projected to increase by a factor of 10 within several years.[3] With multiple fibers on a seafloor cable, this approach can easily yield data rates of about 10 Gb/s for the NEPTUNE system.

These power and data-rate figures meet the NEPTUNE science requirement.

Further, the technology to lay and service seafloor cables is mature and readily available. Finally, fiber-optic systems have inherently low maintenance costs and do not require major service at frequent intervals.

This discussion argues strongly for a cabled backbone for NEPTUNE. We are not arguing against buoys for some applications; for more remote areas or for widely separated sites economics may point strongly toward buoys and away from fiber-optic cables. For NEPTUNE, buoys might be useful geographic extensions where limited suites of instruments having modest data rates and power requirements are needed.

In the end, the choice must be based on the ability of the various options to scale to the size and power and communications requirements of NEPTUNE. Some cost figures are available or can be estimated. On land, 1 W (peak power) costs about $2, scalable to any size. At a level of 100 W, a representative buoy can furnish power to the sea-

[2] http://vertigo.rsmas.miami.edu/deos/public_html/Buoy_SubGroup_Rpt.pdf
[3] Dixit, S. and A. Ylä-Jääski, 2000, March: WDM Optical Networks: A Reality Check, *IEEE Communications Magazine,* 58-60.

floor for about $10,000/W.[4] Assuming that the NEPTUNE power system delivers 3 kW to each of 30 nodes and costs $100M (total installed capital cost), the cost is $1,100/W.

The cost advantage of the cabled approach is made greater by two additional considerations. First, buoys require substantial and frequent servicing, whereas the NEPTUNE infrastructure should not. Second, the NEPTUNE cost figure used above was for the entire system, including communications to shore via optical fibers with a data rate orders of magnitude more than is possible with buoy satellite communications.

The NEPTUNE study area's proximity to land provides a strong cost-saving incentive for using fiber-optic cable rather than buoys.

3.2.2 Comparing Existing Technologies to NEPTUNE's Needs

Cable

A typical fiber-optic submarine telecommunications cable is shown in Figure 3.3. The center core contains the optical fibers, in this case in a steel tube that provides mechanical protection and a hermetic seal. Steel strength wires form a protective vault around the fiber core. Around the steel wires is a copper tube that serves as an electrical conductor and provides an additional hermetic seal to protect the fibers. Polyethylene insulation surrounds the copper.

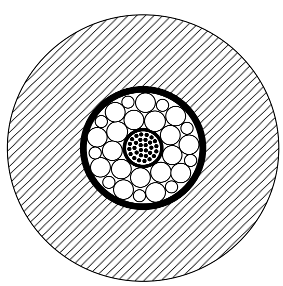

Figure 3.3. A typical fiber-optic submarine telecommunications cable. This lightweight, deep-water cable is 18.5 mm in diameter.

Voltage ratings are presently 10 kV, and 15 kV cable will soon be available. With only a single electrical conductor, a seawater return is used. Additional layers of cable protection are added as necessary, for instance, for use in shallow water. There are many different types of cable from which to choose. (See *NEPTUNE Technical White Paper #2: Cables*.)[5]

Power

Submarine fiber-optic cable always contains a single electrical conductor. Submarine telecommunications systems operate in a serial power or constant current mode in which a fixed current of about 1 A is inserted in the cable conductor at a shore station. Seawater provides the return current path. The potential along the cable drops continuously to zero at the other end apart from fixed voltage drops caused by tapping power for repeaters. The properties of the electrical insulation in the cable limit the applied voltage to about 10 kV. This limits the maximum amount of continuous power that can be distributed to the seafloor to about 10 kW. However, resistive cable losses substantially reduce the fraction of this power that could be used. In NEPTUNE's case, the required average load of 2 kW cannot be met using this technology.

Communications

Fiber-optic cable technology is widely use by the telecommunication industry for long- and short-haul, point-to-point, high-capacity voice and data transmission. Today's state-of-the-art provides a data rate of 1 Tb/s using dense wavelength division multiplexing (DWDM), in which a large number of closely spaced optical wavelengths are used to place a series of data channels on a single optical fiber. This suggests a substantial mismatch between NEPTUNE's much smaller requirements and telecommunications capabilities. Other differences create additional mismatches that extend beyond data rate. These include the following:

1. Most undersea telecommunications cables provide point-to-point links between land stations and their associated switching equipment[6]. *In contrast, NEPTUNE will include as many as 30 seafloor locations containing switching hardware where traffic is added to or removed from the communication system.*
2. Typically, the traffic on a telecommunications cable is symmetrical, with approximately equal transmission rates in either direction. *NEPTUNE traffic will consist primarily of data coming from seafloor sensors. Very little (no more than a few percent) of*

[4]For comparison, the cost of getting 1 W in orbit around Mars is $200K, and 1 W on the surface costs about $75M. (Vint Cerf, Interplanetary Internet Seminar, UCLA, February 10, 2000)
[5]*NEPTUNE Technical White Paper #2: Cables* (http://www.neptune.washington.edu)
[6]TAT-8, installed in 1988, is a rare exception. It was the first transatlantic fiber-optic cable with opto-electronic repeaters and an in-water switching branch unit connecting northern and southern Europe with the U.S. Subsequent cables branch simply by routing fibers or using passive optical add/drop modules.

the capacity will be required for commands to seafloor instruments.

3. The telephone origins of telecommunications technology lead to the requirement for minimum delay from end to end. *Most NEPTUNE users will typically not be concerned with a moderate delay in the availability of data.*

4. Once a telecommunications system is installed underwater, it is rarely modified unless it needs repair. *The NEPTUNE infrastructure is very likely to be extended after its initial deployment. It must be able to cope with major changes in topology and traffic.*

5. A user of a conventional telecommunications system is given a virtual connection from one end of the system to the other. This virtual connection, whether for voice or data, may be a slot in a time-division-multiplexed link or a channel in a scheme where the resources are allocated by frequency. *No such service is needed for NEPTUNE. The messages are expected to be packetized data containing information about the source and the destination.*

NEPTUNE's requirements are clearly different from a standard telecommunications system, although they share a dependence on fiber-optic cable for communications and power. We must find a different communications approach.

3.2.3 Examples of Existing Seafloor Observatories

A variety of cabled scientific seafloor observatories has been installed around the world in recent years. For example, more than five 100 to 200 km fiber-optic cabled systems with in-line seismic instrumentation have been installed around Japan over the past five years. A fiber-optic cabled observatory called LEO-15[7] was deployed in 15 m of water off New Jersey in 1997. A second shallow-water installation, Katama, is planned for Martha's Vineyard late in 2000.[8] A deep-ocean (5000-m) science node or junction box into which instruments can be plugged using an ROV has been installed halfway between California and Hawaii on an abandoned analog submarine telephone cable[9] (Figure 3.4).

[7]http://marine.rutgers.edu/mrs/LEO15.html and http://adcp.whoi.edu/LEO15/index.html
[8]http://adcp.whoi.edu/MV_OBSERVATORY/index.html
[9]http://www.whoi.edu/science/GG/DSO/H2O/
[10]*NEPTUNE Technical White Paper #3: Power* (http://www.neptune.washington.edu)

These systems are typically one-of-a-kind designs that are not readily scalable to a larger facility such as NEPTUNE. Nevertheless, we can certainly learn very valuable technical lessons from them. In particular, the junction box designs from LEO-15 and Hawaii-2 Observatory (H2O) may serve as prototypes for NEPTUNE science nodes.

3.2.4 Approaches to Meeting NEPTUNE Needs

Power

A parallel-power or constant-voltage power distribution method overcomes the limitations of a constant-current approach and is conceptually similar to the terrestrial power system; the power conductor is held at a constant voltage, and loads are connected between the power conductor and the return conductor (or ground). Parallel power on a submarine fiber-optic cable is capable of operating at, for example, a 10-A current level, which would deliver at least 100 kW on average to the NEPTUNE system. In fact, the electrical conductor in COTS fiber-optic cable can handle current as high as 100 A. This is actually a relatively small current for seawater return.

The average current resistive losses under parallel power are therefore lower than for serial power because current is extracted at each node, resulting in lower losses and higher efficiency. These ideas are further developed in Section 3.3 and in *NEPTUNE Technical White Paper #3: Power*.[10]

Communications

We have shown above that NEPTUNE is not analogous to a standard submarine telecommunications system. On the other hand, NEPTUNE possesses many characteristics of a distributed data network such as the combined local, metropolitan, and wide area networks (LANs, MANs, and WANs) that exist in any metropolitan area. A list of the similarities includes the following:

1. The very existence of data networks is based on the economy of resource sharing, usually the cable between nodes. *NEPTUNE, with its extensive use of fiber-optic cable, is analogous.*

2. LANs are typically dynamic during their lifetimes, with the locations and capabilities of different subnetworks changing to adapt to new requirements and rapidly changing technology. *The instrument networks around NEPTUNE science nodes are very likely to evolve after initial deployment. The sci-*

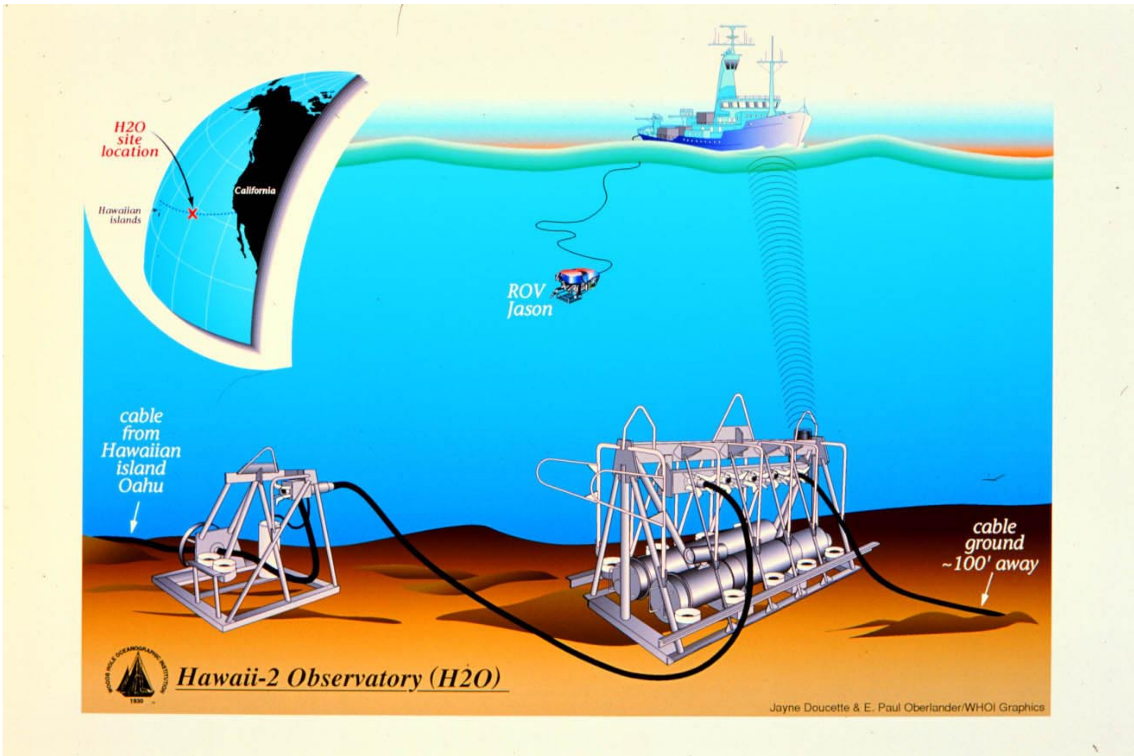

Figure 3.4. The Hawaii-2 Observatory (H2O) seafloor observatory system between Hawaii and California.

ence nodes must be able to cope with major changes in topology and traffic, and must be inherently maintainable and upgradable.

3. Data network backbone structures often change, although these changes are usually transparent to users. Topology can get complex, spreading and growing as sites are added or removed. *NEPTUNE must maintain similar flexibility to accommodate evolving science needs.*

4. The high-speed, fiber-optic based WAN backbone for a data network links a limited number of major gateways, and traffic is carried between them approximately symmetrically. *The NEPTUNE backbone connecting science nodes is conceptually analogous, though its traffic will typically be highly asymmetric.*

5. Data network backbones usually have some number of redundant routes for reliability purposes. *For NEPTUNE, the principal factor limiting backbone routing will be the number of shore links. With only one shore connection, the system will be vulnerable to faulting of the link from shore to the first node even if the remainder of the system is configured as a network. The multiple shore landings will make NEPTUNE more robust.*

Overall, NEPTUNE is quite similar to a switched data network and can benefit substantially from the automatic routing and restoration capabilities of this technology family, especially if multiple shore connections are used. This argues strongly for a data-networking architecture for the NEPTUNE communications system. We discuss this concept further in Section 3.4, and details are contained in *NEPTUNE Technical White Paper #4: Communications*.[11]

3.2.5 Conceptual Layout of a Science Node

Figure 2.19 shows a plan view of a prototype NEPTUNE infrastructure consisting of 30 seafloor science nodes distributed around the Juan de Fuca Plate, along with two shore stations located on the northwest coast of Oregon and on Vancouver Island. The physical layout for a single science node shown in Figure 3.5.

Our goal of having easily serviced junction boxes within the science nodes is underlain by several basic tenets. First, because commercial cable-ship time is very costly, the NEPTUNE science nodes should be installed and serviced

[11]*NEPTUNE Technical White Paper #4: Communications* (http://www.neptune.washington.edu)

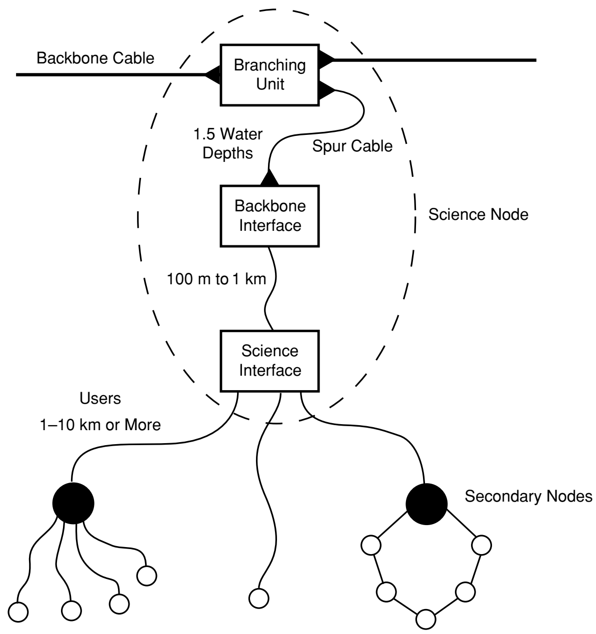

Figure 3.5. The conceptual layout of a NEPTUNE science node. A gimbaled branching unit in the backbone cable breaks out a spur cable that is about 1.5-water-depth long. The spur cable carries all of the fiber and power connections from the backbone cable to a hardwired backbone interface that contains the high-speed communications and high-voltage power components. Either individual science instruments (solid dots) or secondary nodes located some distance away plug into the science interface via appropriate cables. The backbone and science interfaces might be combined into a single unit, depending on available technology.

using scientific research vessels and ROV assets (i.e., assets that are part of the University National Oceanographic Laboratory System (UNOLS)[12]. The capabilities of the UNOLS vessels impose size and weight constraints on the geometry and on the individual components of a node. The Hawaii-2 Observatory offers a model for nodes that were specifically designed to be serviceable by UNOLS vessels.

Second, the backbone cable will be installed by the telecommunications cable-laying industry, as the technology for this purpose is mature and quite specialized. Figure 3.6 is an aerial photo of the Nedonna Beach, Oregon, cable landing, an example of an industrial cable-laying operation.

Finally, insofar as possible, the internal components of the science nodes should consist of COTS equipment to avoid costly engineering and minimize budget uncertainty.

The science node system consists of all of the components required to interface science instruments to and derive power from the backbone cable. Each science node can be divided into four main functional components: a physical connection to the backbone, an electronic backbone interface, an electronic science interface, and a series of optional secondary nodes. Science instruments plug into either the science interface or the secondary nodes.

Near the location of each science node, a commercial branching unit is inserted in the backbone and connected to a spur cable containing twice as many optical fibers and conductors as in the backbone. Alternatively, the spur could consist of a loop of backbone cable, at some cost in weight and hence ease of shipboard handling. Each of the connections to the branching unit is gimbaled to protect the cable during deployment. The branching unit contains no active components and should not need service involving a cable ship after installation.

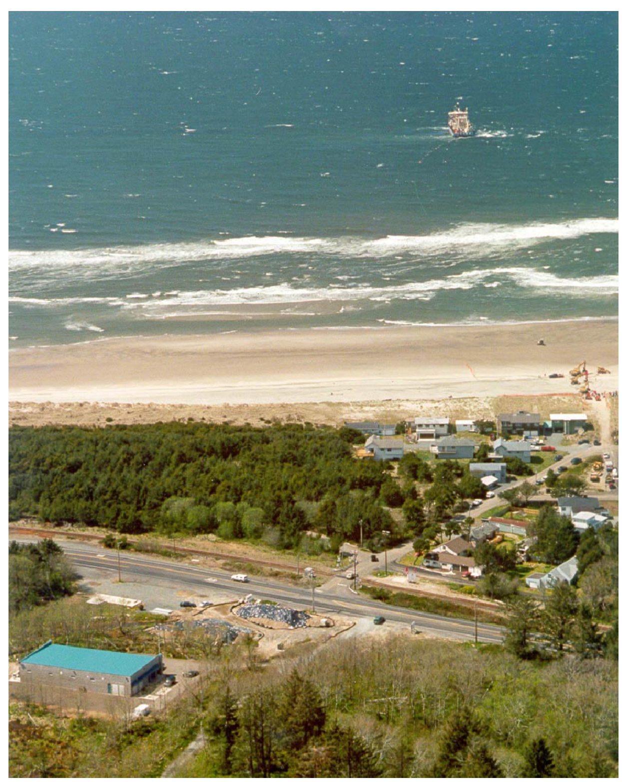

Figure 3.6. Aerial photo showing installation of the Northstar cable at the Nedonna Beach, Oregon landing site.[13]

[12]http://www.gso.uri.edu/unols/unols.html
[13]http://www.wcicable.com, http://www.southerncrosscables.com, http://www.iscpc.org

The spur cable brings all of the backbone functions to a backbone interface containing the electronic systems needed for long-haul communications and power. The backbone interface is hard wired to the branch unit through a gimbal. The 1.5-water-depth spur allows recovery by a research ship for maintenance or repair without disturbing the branching unit or backbone cable. Hard wiring the interface avoids potential single-point failures that might ensue from the use of connectors. With this approach, we eliminate the need for a commercial cable ship for all system maintenance except for breaks in the backbone cable; this latter risk can be nearly eliminated by proper cable installation and burial.

The science interface contains all the communications, power, and control systems needed to connect science instruments and sensor networks to NEPTUNE. The science interface is completely removable and recoverable, and connects to the backbone interface and science instruments by cables terminated in ROV-mateable underwater connectors. Thus, the science interface is mechanically analogous to junction boxes previously used to interface science instruments to submarine cables, such as the Hawaii-2 Observatory junction box (see Figure 3.4). The science interface can be extended over distances of many kilometers using low-cost fiber-optic links, which can be laid from an ROV and which connect to a simple data concentration node or secondary junction box. The latter device then serves as the hub for a seafloor LAN linking instruments to the science interface. There can be several LANs at each science node. Alternatively, instruments can be attached directly to the science interface if more limited geographic coverage is adequate.

3.2.6 Systems Approach

The NEPTUNE infrastructure consists of four subsystems – power, communications, timing, and control – along with supporting components (Figure 3.1). Each of these systems threads its way through the physical system, connecting the scientist and other users on shore to the science instruments. The design and integration of these subsystems, which must eventually work together at undersea nodes and on shore, is made more challenging by the likelihood of the work being the responsibility of different organizations. The systems engineering approach will be used to ensure that all the requirements of the development are properly included.

Two essential parts of the systems engineering approach are *documentation* and *reviews*. The documentation process begins with recording the requirements, concepts, and criteria for the major subsystems in some detail. These documents, which should be written at the start of the next phase of NEPTUNE, become the first of the *control documents* for the project. Documents such as these promote coordination and communication across institutions, and allow proper management of changes to the design. Through them, the final design can be traced to the requirements and criteria established for NEPTUNE.

Reviews are equally important to ensure that technical development is on track and meets performance requirements. The systems engineering process calls for peer review of the system at a number of milestones during the design and development. The critical design review, to identify just one example, takes place after the various implementation alternatives are compared in a trade-off study and a block diagram level of the proposed system can be drawn. This review estimates the ability of the proposed design to meet the system criteria.

Another major factor in the design of a long-term endeavor such as NEPTUNE must be the reliability of its components, both the hardware and the software. While repairs are possible after deployment, they are expensive. It is usually possible to reduce the need for post-deployment repairs by proper design and testing.

There are three parts to the quality assurance (QA) process. First, the appropriateness or adequacy of the overall design is evaluated. Any weaknesses or single points of failure are identified (by considering possible failure modes and their probabilities), and the system is redesigned as appropriate. Second, the components chosen for the design are evaluated. This is largely a theoretical examination. The design of the components is examined in light of the intended application: can the part work at the temperature and pressure of the likely environment? Are there susceptibilities to vibration? Third, an empirical test may be made on some components or on the complete system.

For NEPTUNE, it may be impractical (or too expensive) to test more than part of the system at a time. Deciding what tests can be considered an adequate set and the design thereof is the domain of the QA and systems engineers.

The QA process is essential to maximize the likelihood of success in a situation like NEPTUNE where repair is expensive. Surprisingly, it is not particularly costly. It is estimated that at the Jet Propulsion Laboratory a mission with a cost of around \$100M would be supported by QA at a level of around 1 full-time person during the design and build phases of a mission. The QA team would typically consist of a long-term coordinator, at a low but constant level of involvement, and a number of experts, brought in as needed as the design and building progresses. Essential to successful QA is good access to project management and clear lines of authority and communication.

As we now move to a more structured discussion of the four major infrastructure subsystems, we note that this report is the initial iteration in this systems engineering approach to NEPTUNE.

3.3 Power System

In this section, we examine options for the design of NEPTUNE's power delivery system. While the cable technology is likely to be the undersea telecommunications standard, the power system will borrow from utility practice and modern power electronics. We describe below the many choices and trade-offs that must be considered.

3.3.1 Requirements

The NEPTUNE power system can be divided into three parts: the shore station, the delivery system (essentially the cable), and the user interface. Each operates in a different regime and has distinct requirements. At the shore, for example, utility power must be converted into a form suitable for distribution via cable, and an uninterruptible power supply may be required. The power system must be operated with cable limitations in mind; the cable, though a passive component, is the backbone of the power system.

The user interface is a key component of the science nodes, and its properties reflect back into the rest of the system.

Shore Station Requirements

The shore station's primary function is to convert utility power into a form suitable for transmission by the cable. The station may also be responsible for controlling loads via a communication system and the user interface. Data on power usage by users should be available.

We note that at this stage of NEPTUNE we cannot specify fully the peak power output of the shore station. However, we can estimate this value to be between 100 kW and 200 kW by considering the total load (Section 2.7) together with the losses involved in delivering that amount of power over a lossy cable.

The shore station power system functions and interfaces are summarized in Figure 3.7.

Node System Requirements

The power from the shore is delivered via a cable to the undersea nodes. The cable will be the same as, or derived from, the design used in submarine telecommunications cables (see Figure 3.3). These have a long record of reliable operation, which NEPTUNE plans to emulate. This means the power delivery system must operate reliably, and perhaps include redundancy.

As soon as a loop can be established in the underwater network, reliability can be increased by the judicious application of alternate power feeds. We discuss below how to accomplish this.

The NEPTUNE power system consists of multiple loads and must be operated to maintain service to the maximum number of loads in the event of a fault. This task is accomplished by sectionalizing the system under the control of a relaying and protection scheme.

The functions and interfaces of the node serving the science users are shown in Figure 3.8. Local control and monitoring and, independently, protection and relaying, take place here.

We propose that the power delivered to the user be at two voltage levels: a level of 48 V DC has been chosen to satisfy the needs of most users, as it delivers moderate levels of power at low current and is a common standard; a level of 240 V DC has been selected for users requiring more power, or wishing to transport it some distance from the science node. Using only two output voltages will simplify the design of the power system and will enable us to take advantage of the economies of standardization.

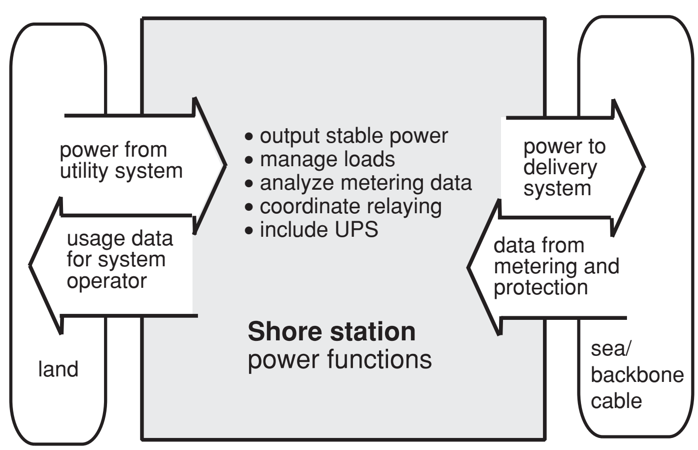

Figure 3.7. Functions and interfaces for the shore station power system.

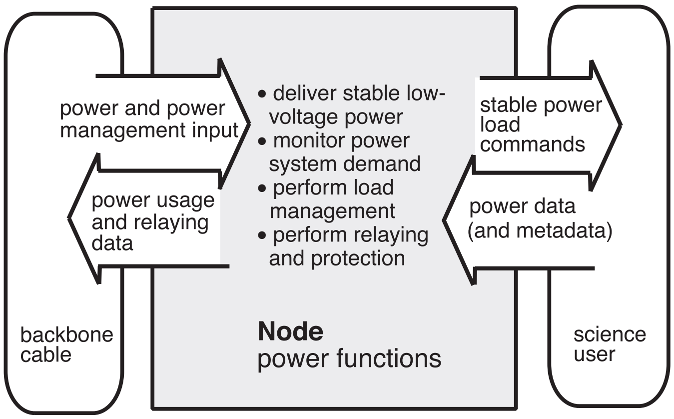

Figure 3.8. Functions and interfaces for the node power system.

3.3.2 Approach and Trade-Offs

The NEPTUNE link from shore is analogous to a utility power transmission system in that large distances are covered. However, unlike an ordinary transmission system, the NEPTUNE backbone system is not part of an interconnected network, at least not until enough cable is laid to form a loop, with an alternative supply point. Another difference is that power is fed to the science nodes via a single conductor because we consider it too costly to provide a metallic return conductor. We propose a seawater return instead.

The historical reasons behind how a conventional power system is ordinarily put together, for example, the choice of voltage levels and frequency, do not apply to NEPTUNE. Likewise, the reasons for choosing a series connection with a constant 1 A current for a telecommunications cable do not apply to our situation. We are therefore free to optimize our choices based on engineering considerations alone.

AC or DC?

Efficient DC/DC and DC/AC converters are readily available at power levels of a few watts and a few megawatts. Indeed, the technology of high-voltage direct-current (HVDC) transmission is widely applied in utility power delivery systems. Because HVDC is a relatively arcane area even within power engineering, we will briefly demonstrate the maturity of the technology.

HVDC technology began as a delivery approach with the installation of an offshore link to Gotland, an island off the coast of Sweden, in 1954. Today, worldwide, HVDC systems handle about 60 GW. Seawater returns are often used. The Kontek HVDC system between Germany and Denmark passes 1500 A into the ocean; the Baltic link (Sweden to Germany) has a current of 1330 A; and a seawater return is planned for the high-voltage DC link between Italy and Greece, to be completed this year. The current there will be 1250 A.[14] The electrode design for such large currents has been described.[15]

In North America, there are twelve back-to-back (zero line length) converters connecting the four major regions of the power system that are not interconnected by AC (Figure 3.9). There are also seven HVDC lines that transmit power mainly from remote sources to major load centers. The biggest of these are the Nelson River system in Manitoba, Canada, and the Pacific Intertie between Oregon and California, both operating at ±500 kV (Figure 3.10).

Clearly, HVDC is a mature technology. DC delivery at a relatively low voltage (around 10 kV) is therefore a viable candidate for NEPTUNE, with the shore stations delivering high-voltage power and voltage-reducing converters in the science nodes supplying the loads.

However, DC systems have insulation problems that AC does not. For example, long-term DC excitation tends to cause breakdown (“treeing”) of solid insulation, and there are problems with charge trapping and charge migration. This may mean that the cable insulation voltage limit has

Figure 3.9. Twelve back-to-back HVDC converters interconnect the four separate networks of the North American electric power system.

[14]George, G., 2000: Interconnecting the Globe. *Transmission and Distribution World*, 18-32.

[15]Tykeson, K., A. Nyman, H. Carlsson, 1996: Environmental and geographical aspects in HVDC electrode design, *IEEE Transactions on Power Delivery, (11) 4,* 1948-1954.

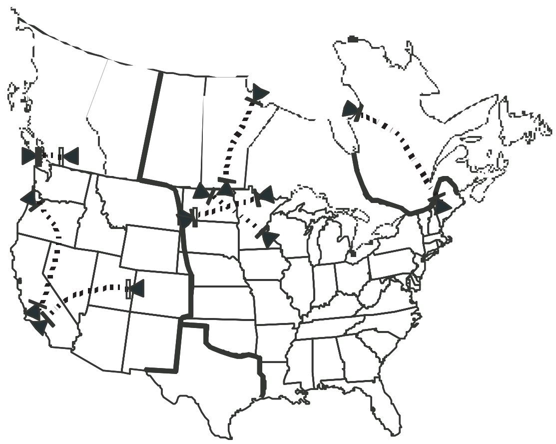

Figure 3.10. There are HVDC lines operating in all electrical regions of the U.S. except Texas.

to be derated. Thus, while DC is conventionally used on undersea telecommunications cables, we might consider an AC alternative. The cable's electrical properties, i.e., its distributed shunt capacitance and series inductance, allow the use of only very low-frequency AC, perhaps on the order of 0.1 Hz, without compensation. (See *NEPTUNE Technical White Paper #3: Power* for details.) We show below that a satisfactory DC solution exists.

Voltage and current levels

The maximum voltage that can be applied to a cable is set by the likelihood of insulation breakdown. This in turn is set by the electric field gradient at the surface of the inner conductor. It is shown in *NEPTUNE Technical White Paper #3: Power* that the electric field for a coaxial cylinder geometry varies reciprocally with distance from the center conductor. If realistic values for the cable dimensions are used and if the fields inside the cable are considered, then a level of 10 kV (typical rating) could readily be used with DC, and it could be even higher with AC.

The electrical specifications of the submarine cable do not include its current-carrying capability (ampacity). Most likely this is because there has never been a need to approach this limit in the usual telecommunications applications. Nevertheless, if we are to design a flexible power system for NEPTUNE, we must have an upper bound on this parameter. *NEPTUNE Technical White Paper #3: Power* shows that the center conductor of the typical underwater cable should be capable of handling 100 A without difficulty. The resistance of the cable is high (typically 1 Ω/km) so that the I^2R voltage drop will be the factor that limits the current.

Series or parallel?

Underwater telecommunications systems use a series connection of the sources and loads. A constant current is inserted by a shore station into the cable conductor. The potential along the cable drops continuously from a maximum at the supply point to zero at the other end. The current is the same everywhere.

In a parallel system, the shore station applies a fixed voltage between the cable and ground, and the voltage everywhere along the cable is about the same. The current is different in different parts of the system. Given that the resistance of the cable is the same for either configuration, a scheme in which the current is lower, even in only some parts of the network, must be more efficient.

A parallel system constrains all the loads to have the same voltage, whereas a series system requires the loads to have the same current. The latter requires that a varying load must somehow accommodate a constant current, a much stronger constraint. Because of this lack of flexibility, all utility power systems are parallel.

We view parallel power as a logical approach for NEPTUNE power distribution on the basis of efficiency, reliability, and flexibility.

Converter

Because the current in the cable will cause a voltage drop that affects the voltage to other nodes, the input voltage at a science node might be as high as 10 kV or as low as 1 kV. We must therefore use a converter that can handle this variability.

A typical converter is shown in Figure 3.11 The switch (consisting of a number of field-effect transistors (FET)

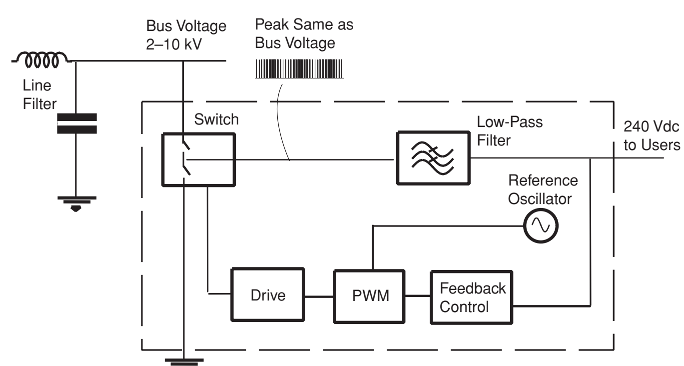

Figure 3.11. Block diagram of a converter to supply 240 V DC output from 1 – 10 kV DC input.

in series) alternately connects the input of a low-pass filter to the incoming high voltage or to ground. A pulse width modulator (PWM) driven by a reference oscillator at about 50 kHz determines the time at each level. The frequency of the PWM switching is high to simplify filtering of the output signal. The output of the filter is a DC level whose highest value is set by the incoming voltage and whose lowest level is set by the switching speed of the transistors. Preliminary design considerations indicate that a level of 240 V DC can be obtained for an input between about 1 kV and 10 kV.

Protection

In power system terms, protection means the automatic and rapid disconnection of faulted components of a power system. The word "protection" is really a misnomer, as the system acts only *after* a fault has occurred, rather than before. Protection has been described as the ambulance at the bottom of the cliff, rather than the fence at the top.

The purpose of the protection system is, of course, to disconnect as much of the system as is needed to allow rapid and safe restoration of service to the remainder. In a terrestrial AC power system, it is possible for disconnection to occur within one cycle (16 ms) if the fault can be detected rapidly and if the protection scheme and the circuit breakers are fast enough. Typically, however, the equipment is much slower than this, and disconnection takes many cycles. Restoration may take as long as a few seconds. A big DC system (such as the Pacific Intertie) is typically shut down following a fault for about a quarter of a second, to allow time for the complete line to discharge before reapplying power.

From the system engineering viewpoint, the post-fault system can be viewed as partially meeting the success criteria for the system mission: delivering power to all the loads all the time. Under most circumstances for such a partial success, system engineering would require a trade-off between the cost of increasing the likelihood of mission success (decreasing either the fraction of the system that remains disconnected or the chance of faults) and the cost of not doing so.

For NEPTUNE the cost of having anything less than maximum success is large in terms of the science not done. The best that can be done is to build the system using conservative design (to minimize the chance of a fault), and then when a fault occurs to disconnect only the faulted part of the system, and restore power to the rest. The system described below is aimed at disconnecting only the faulted part of the NEPTUNE power system, even if it is the protection system itself that experiences the fault. The cost of designing and building such a protection scheme will not be small, adding perhaps 5 percent to the cost of the power system. However, it is our opinion that a higher degree of mission success will result if the money is spent on protection rather than on repairs to the underwater components.

Protection schemes work by comparing measured values of system values with expected values. For example, if we suppose that a cable fault occurs somewhere in the NEPTUNE system, then the current into the fault is momentarily uncontrolled and may be quite high for a little while as the cable capacitance is discharged. Eventually, the power delivery control system acts to limit the current. Of course, the power system is in an abnormal state since the voltage at the fault is greatly lower than before the fault and may be zero.

If an *overcurrent* relay decision could be made rapidly enough, the relay might be able to clear the fault while the current was still above its normal value. However, because the current will be limited by the control action of the shore-based supply, the overcurrent setting is critical so that no more than a minimum of the system may thus be disconnected.

To solve this, we can use a *distance* relay. This device uses a computation based on the measurement of both voltage and current to determine if the fault is close or not. By arranging for faults that are close by to trip breakers faster than faults that are distant, this approach can cope with overlapping zones of protection and therefore tolerate relay failure.

We suggest a better protection scheme that could be used in NEPTUNE: the *differential* approach. In this instance, the current at one end of a section of the cable is compared with the current at the other end. If there is a difference, there must be a fault between the two points of measurement. This kind of protection relies on the existence of a fairly fast communication connection between the two ends. In NEPTUNE, we can assume this connection exists, even if the route for such communication involves the shore-based Internet, so that a differential protection scheme can be used.

However, because a fault might prevent communications, we should be prudent and adopt the utility practice of having *layers* of protection. NEPTUNE's protection scheme could include differential, distance, and overcurrent relaying. This way, the first (and best) line of defense would be the differential scheme; if the fault causes loss of communication, the distance relaying would operate; if the distance relaying failed, the overcurrent system could save the day. Because the loads are expected to be far more deterministic than those of a typical utility, overcurrent protection levels can be set quite close to the normal load values.

Insulation Coordination

On any electrical network, transients will happen, and they will propagate along the wires. If a short circuit occurs at a point on the cable between the NEPTUNE nodes, the instantaneous voltage on the cable could be 0 or $2V$ (twice the nominal voltage) or anywhere in between. To deal with the possible overvoltage, a device called a "surge arrester" is used. This is designed to dissipate the energy of the transient and thereby limit the voltage. Surge arresters are routinely used on most power lines. We have several types to choose from, the choice being based on the energy dissipation requirements and the degree of limiting needed.

In power systems, because of the possibility of lightning strikes, the basic insulation level is high relative to the expected voltage at the low-voltage end of the system. Because NEPTUNE's underwater cable will not be struck by lightning, insulation coordination (see Figure 3.12) can be based on the maximum overvoltage of $2V$. In fact, if the power components are designed to withstand a surge of, for example, three times the normal maximum voltage and if the surge arresters will allow 2.5 times the normal voltage, then the components will never come close to their breakdown stress values and the arresters will never operate, thereby lasting indefinitely.

In terms of the current, or energy dissipation, we can limit the available energy in the design of the control system.

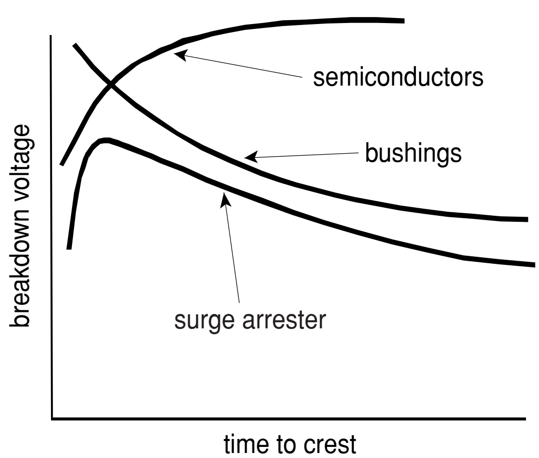

Figure 3.12. Insulation coordination consists of making sure that the arresters act to absorb the surge energy before system components, such as semiconductors and bushings (e.g., bulkhead connectors), fail.

Compared to a power system subject to lightning, with a high rate of rise of voltage and a high current capability, the NEPTUNE insulation coordination problem is very straightforward.

3.3.3 Build or Buy?

The technology of HVDC is commercial and mature, but standard power levels are very much higher than required for NEPTUNE. Even "HVDC-light" (voltage-sourced converters) operates at power levels of 30 MW. Much smaller switching converters are abundant; they are used by the millions in personal computers. Between the sizes of a few hundred watts and a few megawatts there seems to be much less that is COTS. Nevertheless, the design of a converter to meet NEPTUNE requirements should not prove difficult as components such as solid state PWM switches with the appropriate ratings are COTS.

The technology of very low-frequency AC is little used. Some cable tests are being done at sub-hertz frequencies, but the hardware tends to be more or less custom built, as with intermediate power DC.

We believe that ultimately the power system can be built commercially, but at this time there is no COTS system. We will consider building a proof-of-concept breadboard before making final decisions.

3.3.4 Concluding Remarks

- Power at a nominal 240 V can be delivered to science users at a number of remote locations by a submarine telecommunications cable operated at about 10 kV DC. Voltage-sourced converter design should allow the point of connection to the backbone system to be anywhere from about 1 kV to 10 kV.
- The 240 V supply voltage can be reduced for most users by means of additional DC/DC converters.
- A backbone voltage higher than 10 kV (capable of delivering more power) may be possible if very low-frequency AC is used, without compromising the insulation lifetime.
- A parallel connection of the science node loads has the advantage of a higher maximum power compared to a series connection.
- An autonomous system aimed at protection against faults and voltage surges will complicate the design, but is feasible.

- A power level of 200 kW on shore would probably translate to 100 kW delivered to the science nodes. This level of delivered power is required to meet NEPTUNE needs.

3.4 Data Communication System

Data communication systems are usually defined in terms of a series of protocol layers, each of which performs a particular function and communicates only with the layers immediately above and below it. (See *NEPTUNE Technical White Paper #4: Communications* for details.) The group of layers chosen for a particular application is called a protocol stack. The choice of communications medium (fiber-optic cable) is a physical layer decision, specifying a relatively minor part of the overall design, and determining little about the other layers in the stack. Here we address some of the remaining issues and layers.

In the design of a communication system, details such as the protocols that will operate on the network, the bandwidth needed, and the way the nodes are interconnected are usually fixed by considering the overall requirements, including factors such as the number and location of users, the nature of the traffic (bursty or otherwise), and the allowable latency. A first cut at the requirements was given in Section 2.7. Some of the available protocols and technologies that meet these and other needs are discussed below.

Figure 3.13 illustrates the major components of the NEPTUNE data communication system. The backbone cable is connected to the shore station, from which traffic associated with commands originates and to which the scientific data are returned. Because of attenuation on optical fiber over the distances involved, optical repeaters are usually required along the cable. At frequent intervals, there are branching units that are usually attached to science nodes where communications traffic is added to or dropped from the backbone cable. The science nodes include junction boxes where science instruments or sensor networks are connected (Figure 3.5). Some of the branching units correspond to major divisions in the backbone cable. Others connect to observatories, which include additional branching, and perhaps subnetworks.

3.4.1 Requirements

Each of the several different parts of the NEPTUNE communication system could follow different practice. We have so far discussed only the underwater section. Consideration of the communication system begins at the shore station and extends all the way to the most remote instrument on the seafloor. In between is a cable system that is only superficially like a telephone system.

Shore Station Requirements

Beginning at the shore station, we can examine the interfaces and functions of the various parts of the system. Figure 3.14 illustrates the requirements.

The shore station requirements of multiple interfaces and multiple users are similar to a server site on the Internet, and indeed the shore station must operate in this capacity. This view fits well with the fact that the data communication requirements are not quite real time.

Node System Requirements

The fiber-optic backbone system must connect the shore station to the science instruments with high reliability. With multiple paths to each science node, we can construct a

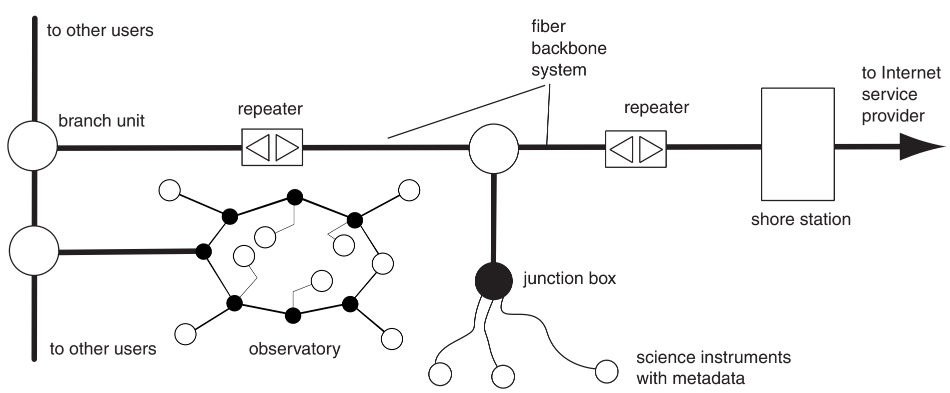

Figure 3.13. The NEPTUNE data communication system: shore station, fiber-optic backbone, repeaters, branching units, science nodes, and many science instruments.

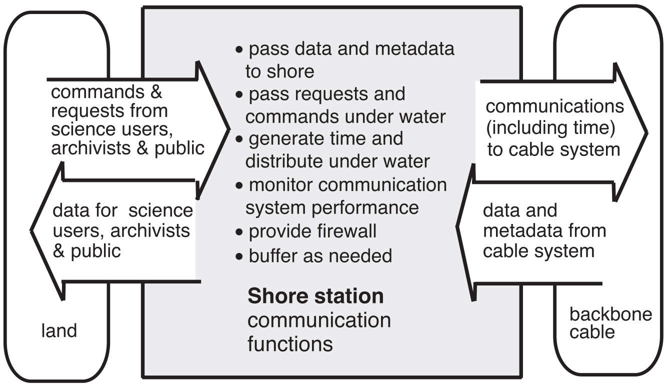

Figure 3.14. Shore station communication functions and interfaces. (Timing is considered in Section 3.5.)

system that is usually immune to loss of connectivity to nodes or to a cable break.

Nodes in the network can store tables of adjacent nodes or tables of routes to distant nodes, or they can periodically explore the network to discover working nodes. These tables become out of date if the network topology changes, either intentionally or unintentionally because of failures. The Internet solution is to periodically explore the connectivity. Given the possibility of faults in the network and the need for reliable communications, an Internet-like approach to routing is justified for NEPTUNE.

The functions and interfaces of the node are shown in Figure 3.15.

The user interface is the remote end of the seafloor communication system. While the shore station has to be designed to meet the standards of the Internet, NEPTUNE can establish its own internal standards for interfacing to the data archive and the backbone system. Further, while the fiber-optic backbone system can be independent in most operational aspects, it must establish a standard interface to science instruments. This interface must be adequate for all present and future requirements.

For NEPTUNE, the science user interface should be as standardized as possible. Such standardization will allow developers to use the laboratory for testing of sensor suites. Other important interface-selection criteria include simplicity, flexibility, extendibility, and cost. It may be prudent for NEPTUNE to furnish instrument developers with test-bed implementations as well as interface specifications.

Individual science instruments must have unique addresses. It is important that communications be able to use the rich and familiar transmission-control protocol/Internet protocol (TCP/IP) family of protocols. Also required is a standard user interface that links a general instrument to NEPTUNE.

Some of the likely NEPTUNE instruments produce data at very low rates and will require a minimum of user interaction to, for example, alter sample rates. These instruments impose no stringent requirements on the connection to the network, and their needs could be met with simple serial protocols. Others, such as tethered bottom rovers with HDTV video cameras and manipulators, may create up to 20 Mb/s of data on a continuous basis and will require extensive user interaction involving closed loop control. Between these extremes, there lies a range of instrument types with disparate data rate requirements.

An additional complication is that some instruments may be located close to the junction box, while others may be located many kilometers away.

We recognize that no single interface may be appropriate to accommodate all of the speed and distance requirements.

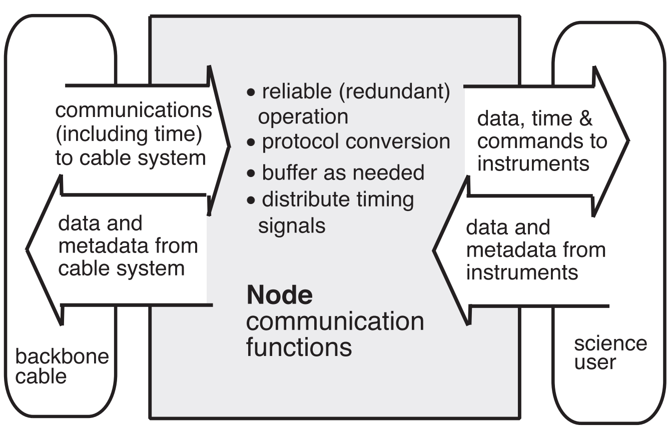

Figure 3.15. Node communication functions and interfaces.

Further, we must maintain flexibility in communications rate, range, and degree of two-way interaction to allow for expansion and for as-yet-unimagined instruments. To be prudent, we should to extend these upper limits to accommodate future needs.

Metadata, such as a calibration factor, data units, or the sample rate, are often not stored with the raw data and can be lost when an investigator departs a project. We will ensure that such losses do not occur with any NEPTUNE instrumentation. Storing metadata in the instrument or its interface is straightforward and costs little in the way of power or computer resources. Such information can then be accessed as part of the data stream and archived with the data as appropriate. As instruments are added and replaced during the lifetime of the project, a continuously available record of the state of the instruments is available. It should also be possible to automatically adjust the structure of the database that holds the NEPTUNE results as the instrumentation changes.

3.4.2 Approach and Trade-Offs

In this section, we consider several possibilities for the backbone network configuration, discuss the pros and cons of several backbone protocols, address quality of service issues, and describe science user protocols considered for NEPTUNE.

Backbone Network Configuration

We offer several possibilities for network configuration. In one the nodes would be arranged in a serial daisy-chain configuration. Such a system would be capable of delivering enormous amounts of data. However, a break anywhere in the system would isolate all nodes further down the chain. An alternative is a star network (Figure 3.16), where each node has its own optical fiber (or wavelength in the case of WDM) linked directly to the shore station. This configuration offers some advantages: there is less chance of network congestion, the latency of communications from a given location is constant, which simplifies the distribution of timing signals, and failure of one node affects no other. A star topology, however, leads to a more expensive fiber-optic backbone system because of the large number of fibers and repeaters (and optical add/drop multiplexers in the case of WDM) required.

The third, preferred, alternative is a mesh topology. Sharing resources via interconnection can lead to a network with greater reliability, which is achieved through redundancy and cross connection. Clearly the science nodes must handle the issue of addressing in the network: they must perform at least some of the functions of a switch or router in a wide area network. In fact, science nodes might as well be switch routers of the kind used routinely in land-based Internet service. If faults are limited to single cable breaks or failure of a router somewhere in the network, the other routers can use alternate paths to maintain the reliability of the overall system at a high level.

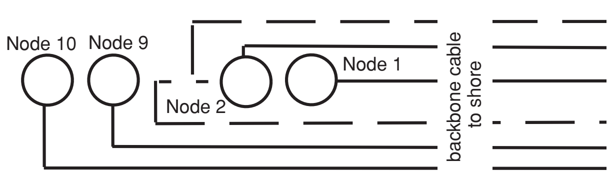

Figure 3.16. Although the NEPTUNE layout in Figure 2.19 suggests a daisy-chain of nodes, separate connections to each node result in a star network of greater reliability and data throughput.

A simple illustration of redundancy is shown in Figure 3.17. In this example, the backbone cable consists of six fibers. At the first science node, two of the fibers go through a repeater and four go through a router. At the next science node, two of the four that went to the previous router bypass this router, while two go through it. Both of the fibers that bypassed the first router connect to the second. We are not suggesting that this is necessarily the best way of interconnecting the units, or even that this approach could be easily implemented. However, even though this approach poses problems for the local science node, it is immediately clear that the failure of either router does not become a block to the entire network. Further, after the routers have acted, the failure of a repeater has the effect of removing only one fiber from effective service.

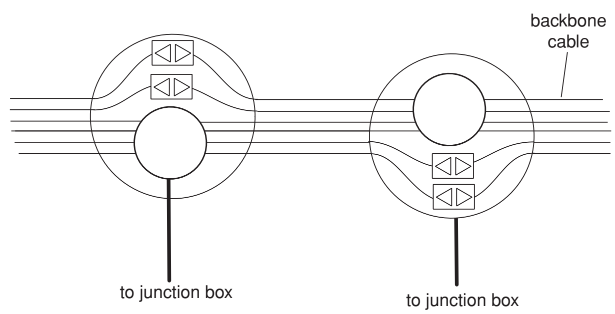

Figure 3.17. By not passing all fibers through all routers, the reliability of a communications system can be increased.

A Cautionary Tale

A single-mode optical fiber can be operated at 1550 nm over 100-km distances with a bit rate of about 2 Gb/s. If WDM were added, the effective rate is this number multiplied by the number of wavelengths utilized. Suppose 16 wavelengths were used; the bit rate would then be over 30 Gb/s on each fiber. The six-fiber network described above could collect data at a rate of 192 Gb/s.

This seems to be unjustifiably large given the requirements defined in Section 2. Further, it seems likely that such a scheme would not have the reliability of a more conservatively designed fiber network and would be more expensive to construct. Although the communication system will be accessible for repair and maintenance, such operations are expensive and time consuming. For a long-term observatory such as NEPTUNE, we much prefer a conservative design that meets the considered requirements of the science.

The story of NASA's *Galileo* spacecraft, launched in 1989, supports our conservative approach to design. The data rate requirement on *Galileo* was imposed by the various remote sensors on board. This rate was so high that, in order to maintain the signal-to-noise ratio, a bigger antenna was needed than could normally be accommodated by the launch vehicle. A folding design was developed.

After a delayed launch, it was discovered that a metallurgical problem with the antenna during the delay prevented the antenna from unfolding. Unable to support the design data rate, the still-functioning low-gain antenna reduced the spacecraft communications rate by three orders of magnitude.

We discuss this here not because the problem crippled the mission, but because it did not. The protocols and data compression on *Galileo* were reprogrammed. As a result, the information returned to earth is estimated to be only one order of magnitude less than the original plan. Perhaps the original "requirements" had not been sufficiently considered.

While a single high-quality image might account for 30 Mb of data, it is not necessary to have 60 such images per second to produce good video. We should consciously avoid getting many, many bits simply "because it's possible." The lesson for NEPTUNE is to consider these requirements carefully.

Backbone Protocols and Technologies

There are a number of ways to connect the NEPTUNE server to the Internet at a shore station via an internet service provider (ISP). Connection can be made via cables operated at speeds as low as T3 (45 Mb/s) or as high as OC48 (2.488 Gb/s) or more. While it may seem odd that a slow link might connect the shore station to the Internet, this may be appropriate if some level of data reduction, rejection, or compression were first carried out. The ISP connection would, of course, support standard TCP/IP and web applications. We consider a firewall essential at this point in the system. Details of this connection will likely be specified by the commercial supplier of the service.

The backbone communications system for NEPTUNE lies somewhere between a metropolitan and wide area network (MAN and WAN) in scale. There are several communications technologies that might serve the NEPTUNE purpose. Choosing between them is not a simple decision, as further discussed in *NEPTUNE Technical White Paper #4: Communications*. We list below at least three practical considerations:

- NEPTUNE should utilize COTS components wherever possible to minimize development and acquisition costs and to maximize component reliability. Component choices must include an element of forecasting to avoid buying into technology that is not expected to endure.
- Different MAN/WAN technologies offer different capabilities and limitations. We must choose a technology that meets NEPTUNE needs but avoids additional complexity from features that are not required; simplicity is a distinct virtue in a remote and extreme environment such as the deep seafloor.
- Some specific requirements for the NEPTUNE science nodes include packaging to fit into pressure cases of reasonable size, moderate power consumption (i.e., there are limitations on the power and heat that can be dissipated), high reliability and fault tolerance, ease and effectiveness of management, and the ability to sustain upgrades as the technology evolves.

The science user interface and shore station Internet interface will utilize the Internet protocols that have emerged as the dominant internetworking protocol. Accordingly, it makes sense to use IPs on the backbone. There are four logical ways to build an IP backbone for NEPTUNE:

- IP over some switched technology such as asynchronous transfer mode (ATM) riding in turn over a multiplexing technology like synchronous optical network (SONET)
- IP running directly over SONET
- IP over glass, eliminating SONET multiplexing entirely
- Stretched-LAN technologies, e.g., gigabit Ethernet

We discuss these briefly below, and compare and contrast them in more detail in *NEPTUNE Technical White Paper #4: Communications*.

SONET and ATM are technologies designed to handle primarily voice communications, while also accommodating IP data. Although this protocol family offers strong features in the area of quality of service (parameterized latency, jitter, and peak bandwidth), these features increase complexity, size, and cost. SONET is a virtual circuit, time domain multiplex approach to implementing a physical layer. An associated header overhead makes SONET comparatively bandwidth inefficient. SONET is designed to operate on optical networks such as those provided by telephone companies, and hence requires external repeaters on long (order 100 km) fiber runs, which again raises costs. Further, both ATM and IP over SONET COTS switches are large (a rack 19-in. wide by 19-in. high) and consume a fair amount of power (> 600 W). Finally, fault tolerance and reliability issues strongly suggest that at least part of the interface in each science node would have to be duplicated, requiring even more space and power.

The last two solutions we list above are converging solutions, although IP over glass[16] is an emerging technology; COTS availability of the latter is limited at present and is aimed at high data rate applications. The key stretched-LAN technology is gigabit Ethernet (GbE) and is the present high-speed version of Ethernet, the most widely used data networking technology in the world. Ethernet also has 10 and 100 Mb/s versions that are widely used on LANs.

GbE routing and switching hardware is readily available from many vendors, and several are also marketing integrated gigabit interface converters (GBIC) with the ability to directly drive up to 100 km of single-mode optical fiber. This functionality permits GbE hardware to serve the dual functions of a data concentrator/router and an optical-fiber repeater, which results in large cost savings. This functionality also yields long-haul 1-Gb/s full-duplex communications using a pair of optical fibers; higher aggregate data rates are feasible using multiple fiber pairs. Further, GbE hardware is small (typically, a six-port router fits on a 12- by 14-in. card) and consumes about 100 W.

While Ethernet has traditionally been viewed as a LAN technology, the emergence of GbE has extended its use into the MAN and WAN arenas.[17] Two GbE WANs covering hundreds of kilometers apiece exist in Alberta and Quebec.[18] The anticipated entrance of 10 Gb/s Ethernet into the marketplace in 2001 may provide another option for NEPTUNE.

On the basis of the discussion above, GbE has clear advantages over the alternatives. A large competitive market exists for GbE, assuring low cost and widespread future use. GbE takes advantage of flexible network management features developed over many years for Ethernet systems. Finally, this technology is compatible with seafloor packaging and power constraints. The combination of all these attributes makes GbE the most attractive candidate for the NEPTUNE communications system.

[16]http:// www.cis.ohio-state.edu/~jain/cis788-99/ip_dwdm/
[17]http://www.nwfusion.com/netresources/ge.html
and http://www.cookreport.com/08.13.shtml
[18]http://www.canarie.ca/frames/workshop.html

Quality of Service

Given the real-time nature of the NEPTUNE data, we must carefully assess whether the chosen backbone protocol stack can provide the required data delivery characteristics. This can be done by defining "classes of service" that guarantee parameters such as peak bandwidth, throughput latency, and jitter. For example, video data will be competing with real-time seismic data and a limited amount of closed-loop control data. We should be able to assign backbone bandwidth to instruments to create a non-blocking environment. However, switch routers must also be capable of creating separate queues for high- and low-priority data streams in the event of bandwidth oversubscription.

Features providing this sort of functionality are referred to as "quality of service," and are further discussed in *NEPTUNE Technical White Paper #4: Communications*.

Science User Interface

The preceding sections have dealt primarily with the backbone portions of the communications system. We will design these portions to be largely transparent to the user. We now address the communications system more from the user's perspective.

There are many candidate protocol specifications. If we could specify a small number (or just one) as being the preferred NEPTUNE interface, then the designers and users of the system would find their jobs simplified.

The problem we must solve is defining a standard user interface for a wide range of proprietary instruments. The interface should not limit the instrument performance parameters, nor should any given instrument dictate the network interconnection properties. One approach to solving this problem is to define a standard interface protocol and require its use by all instruments. A method to implement this approach is to interpose a "black box" between the sensor and the network (Figure 3.18). The black box speaks to the sensor and the network, performs any necessary translations, and might perform other functions such as storing metadata.

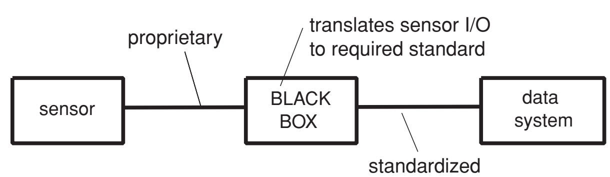

Figure 3.18. The usual approach to interfacing a variety of instruments to a standard data system is to interpose a black box to translate the information.

In Table 3.1, we have drawn up a partial list of existing protocol standards. None of these protocols meets all of the NEPTUNE needs, and we are unlikely to find a single one that does. Of the protocols considered in Table 3.1, 10/100 Mb/s Ethernet covers all of the data rate, range, and most timing needs. Interface cards that convert most of the above protocols to and from Ethernet are readily available, as are low-cost interfaces to the backbone for use in the NEPTUNE science interface hardware. Ethernet implicitly provides many familiar application protocols to the user; for example, web interfaces to instruments can easily be utilized.

Existing IEEE 1451 products accommodate all but the highest data rate needs and include Ethernet as a communications protocol, covering the same physical range. Unlike Ethernet, IEEE 1451 also includes metadata in the standard. Some products include precise timing features. All these factors make IEEE 1451 a good candidate for an interface to be incorporated into individual science instruments. Further details may be found in *NEPTUNE Technical White Paper #4: Communications*.

3.4.3 Build or Buy?

While the routing function in the nodes could be performed by hardware specially developed for NEPTUNE, commercial routers are available to handle this function, which makes their use an attractive choice. The undersea backbone could be considered a part of the Internet and designed accordingly. The rest of the system could then be assembled around the undersea portion. This approach would likely keep costs down and result in few integration problems.

However, meeting all the requirements of the overall communications system may require adding custom hardware or software. The requirements on control and time signal distribution, discussed in subsequent sections, may fall into this category.

Table 3.1 Protocol Standards Considered for NEPTUNE

Protocol Standard	Comments
RS-232	- from the 1960s - serial physical-layer specification for connections up to 19 kb/s - limited range capability - no solution to the distribution of time or the storage of metadata
IEEE 488	- parallel protocol - enough speed for many applications (8 Mb/s) - short distances - parallel interface with many connections complicates underwater connectors
Field bus standards	- relatively fast serial protocols - power and data on the same conductors - not internationally accepted
IEEE 1394 or Firewire	- originally to interface peripherals of any kind to the personal computer - peer-to-peer protocol - 400 Mb/s - very short range - no time distribution - newer Universal Serial Bus (USB) may supplant it
Universal Serial Bus (USB)	- serial master-slave protocol - for personal computers - 12 Mb/s (soon to go to 480 Mb/s) - cannot meet NEPTUNE's range or timing requirements
Ethernet	- packetized communications protocol - widely used - data rates of 10, 100, and 1000 Mb/s - interfaces cover ranges to many kilometers - carries many upper layer protocols (TCP/IP) - timing accuracy of 1 ms.
IEEE 1451	- specification for black box interface specifically for sensors - covers NEPTUNE situation: multiple sensors of unknown provenance - connected to a single standardized infrastructure - includes electronic data sheet for metadata - has both serial and Ethernet (10 Mb/s) interfaces - can precisely synchronize local time

3.4.4 Concluding Remarks

- An Internet-like packetized data communication scheme will serve most of the needs of the NEPTUNE project in terms of network configuration, data rate, and reliability.
- Commercially available components are adequate to support this part of the system; gigabit Ethernet is an attractive candidate for NEPTUNE.
- Packaging issues such as heat dissipation will have to be addressed.
- Ethernet is a leading candidate for the science user communications interface, provided metadata can be accommodated.
- IEEE 1451 is a candidate science user communications interface for individual science instruments with low data rate (<10 Mb/s) requirements.

3.5 Timing

In the NEPTUNE context, accurate and precise time information will be almost universally necessary for science experiments, whether for timestamping data or for synchronizing actions across the system. This will require a reference standard and the distribution of a time signal.[19]

In the U.S. the reference function is performed by the National Institute for Standards (NIST), with an atomic clock generating the signal that is distributed by a number of NIST radio stations and the global positioning system (GPS) system. NEPTUNE could access the time signals on shore and distribute them (taking into account delays) to the science nodes. At each node the signals can be used either directly for timestamping data or to synchronize local clocks to the master clock at NIST.

3.5.1 Requirements

Some measurements (such as seafloor geodesy and acoustic tomography) require that time be known more finely than is directly provided by the NIST time signal itself. This is a question of resolution. The solution is to subdivide the basic clock interval.

[19]Allan, D.W., 1987: Time and frequency (time-domain) estimation and prediction of precision clocks and oscillators. *IEEE Trans Ultrasound, Ferroelectrics and Frequency Control, (34) 6*, 647-654.

[20]Mills, D.L., 1994: Unix kernel modifications for precision time synchronization. Electrical Engineering Department Report 94-10-1, University of Delaware, and http://www.eecis.udel.edu/~mills/bib.htr

Other measurements require that the relative or absolute time be known across large distances to some specified accuracy. This can be viewed as a question of synchronization.[20] The solution is to periodically correct a local clock according to an external master. The accumulated error is amortized, often slowly enough to produce a relatively smooth variation.

Several of these "clock discipline" schemes are available. In the first instance, without a local clock, the incoming reference signal is simply subdivided. In either case, if the reference signal has come over an IP network, the signal is subject to a jitter due to latency variations and must be smoothed.

The timing system, unlike the other systems that have been described in this report, is essentially a one-way scheme. The time is set at the shore station, and distributed to the users. The flow is shown in Figure 3.19.

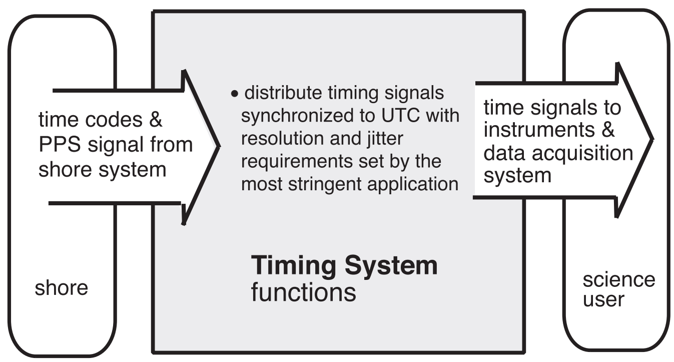

Figure 3.19. Timing system functionality.

Requirements on resolution

Accuracy of even a minute would be adequate for timestamping data from some sensors. Other parameters require much greater precision than this; short-scale seafloor geodesy or acoustic tomography could require knowledge of the sample instant better than several microseconds between sensor sites.

Conventional practice in metrology requires margin of a factor of ten to control uncertainty. If we adopt this principle for time, we need a resolution of about 200 ns.

Requirements on relative accuracy

If we visualize the NEPTUNE system as a branched network from the time distribution point of view, then the question of relative accuracy is this: What error is tolerable between the time at locations on opposite sides of the network? On opposite sides of observatory sites?

The answer can be given only if the processing is specified. For example, if it is necessary to coherently process data from an array of hydrophones 10 km across at a sample rate of 50 kHz (for acoustic tomography), then timing with a resolution of 2 µs (1/10th the sample interval) is required. If similar analyses are expected from anywhere within the NEPTUNE system, the size of the area at this accuracy includes the whole system. If, on the other hand, data from one part of NEPTUNE are considered to be totally uncorrelated with data from another, there is no requirement on the relative accuracy of their time.

It would be prudent to assume the more stringent case.

3.5.2 Approach and Trade-Offs

The problem of clock synchronization over computer networks has been addressed extensively. The time at a computer, relative to a master clock, can be written

$$T(t) = T(t_0) + R \cdot (t - t_0) + {}^1\!/\!_2 D(t - t_0),$$

where t is the current time, T is the time offset at the last update t_0, R is the frequency (rate) offset, and D is the (long-term) drift. T is reduced to zero by resetting the clock. The rate error R is reduced by adjusting the oscillator frequency. The drift error D is usually corrected by whatever means are used to correct the other two errors.

Several correction schemes are available. We briefly review below network time protocol (NTP), digital time synchronization service (DTSS), pulse per second (PPS)[21], and time codes.

NTP

NTP is a widely used clock discipline that operates over an IP network, such as the Internet. In normal situations, NTP can correct the time to a few milliseconds. In operation, NTP[22] amortizes the time offset T and adjusts the clock to minimize the rate error R. An assumption of symmetrical latency in the network is made when estimating the time, which may not be valid with the asymmetrical traffic expected in NEPTUNE. More sophisticated NTP algorithms have been developed.

DTSS

DTSS is similar to NTP in that it zeros the time error. However, it does not adjust the clock, so that "sawtooth" errors occur in the time, as the term $(t - t_0)$ is periodically set to zero. If the local clock is good, these will not be important. The advantage of DTSS over NTP is that it is simpler and is considered to be more robust, but at an apparent sacrifice in performance.

PPS

In order for time to be available with resolution and synchronization better than the millisecond offered by the clock disciplines discussed so far, an additional level of control is required. This could be provided by a separate signal at 1 pulse per second, delivered via a separate communication network. The PPS signal could be used either to synchronize the NTP or DTSS processes in the science nodes or be distributed directly to the science users.

In the first case, the PPS signal interrupts the NTP or DTSS process in the computer in question, which would require a modified kernel. In the second case, individual users use the PPS as best suits their needs.

Time codes

With the addition of separate PPS hardware, a time code could be distributed along with the PPS signal, and the lower quality NTP would not be needed at all. There may be some merit in retaining it as a backup for the applications that do not have stringent timing needs. Most COTS timing equipment is built around a time code called IRIG- B, distributed on a 1000-Hz carrier. This can be used for timing in the millisecond to microsecond range. IRIG- G, based on a 100-kHz carrier, is used in JPL's Deep Space Network (DSN) to achieve 50 ns setability and 2 ns jitter over distances of a few tens of kilometers. Over the larger distances needed in NEPTUNE, this level of performance would likely be sufficient.

Since JPL is presently involved in a study to expand their DSN system using COTS equipment, it seems prudent for NEPTUNE to follow their efforts closely.

3.5.3 Build or Buy?

Clock synchronizing over the NEPTUNE IP communications system cannot be accomplished with the resolution required by at least some of the applications envisioned without using PPS. There is an excellent chance that the underwater network components chosen for NEPTUNE

[21]http://www.cabletron.com/support/internet/Internet-Drafts/draft-mogul-pps-api-02.txt and http://search.ietf.org/internet-drafts/draft-mogul-pps-api-06.txt

[22]Mills, D.L., 1991: Internet time synchronization: the Network Time Protocol. *IEEE Trans. Communication, (39) 10*, 1482-1493.

will not handle PPS and that separate systems will be required. However, we may not need to custom make these, as interest in high-precision time is growing. As the project moves forward and the build-or-buy decision cannot be further delayed, we should examine the possibility of obtaining a COTS system to run over separate fibers in the NEPTUNE cable.

3.5.4 Concluding Remarks

- Distributing time with an uncertainty of about 1 ms is very practical using IP protocols and should be possible. For many applications, this is adequate.
- Distributing time with higher resolution, on the order of a few hundred nanoseconds, is more difficult and will require non-Internet-like communications, such as IRIG-G. It may be possible to buy COTS equipment for the purpose.
- The science community must define the NEPTUNE timing requirements more precisely.

3.6 Monitoring and Control

The power and communication systems on NEPTUNE must be continuously monitored (and occasionally adjusted) to ensure satisfactory performance. As conditions and observations change, information from the monitoring system will likely be used to redirect power in the network or to reallocate communication resources. We discuss below how this might be accomplished.

3.6.1 Requirements

Ideally, the power part of the monitoring and control system must have supervisory access to switches and circuit breakers from the backbone system down to the loads, and must monitor the sequences of events that lead the protection system to disconnect faulted parts of NEPTUNE. The system must allow the operator to reconfigure the power network via remote control, including the disconnection of users if necessary. Changing relay settings (e.g., the current and voltage values at which a relay is supposed to operate) must be possible without affecting normal operation.

The communications part of the monitoring and control system must have similar properties. If some part of the network becomes congested or loses connectivity and if automatic rerouting fails, then operator intervention must be possible. The system must be able to detect inappropriate use of the communication resources and to correct the problem.

These various functions are summarized in Figure 3.20.

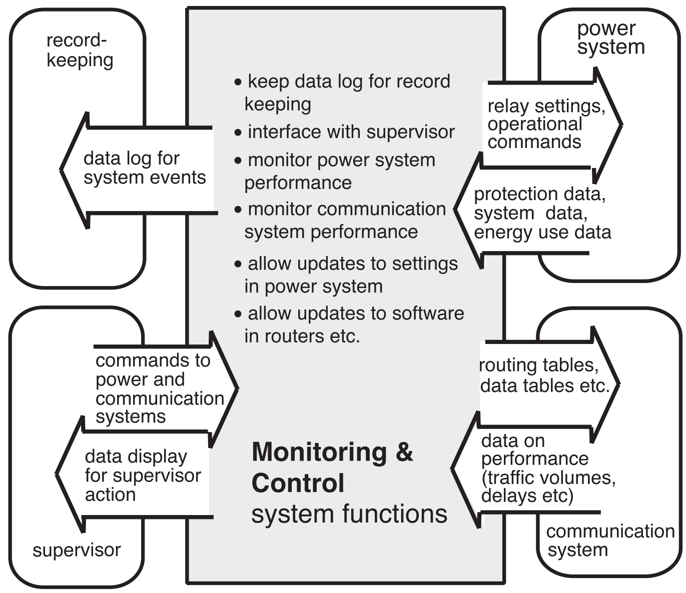

Figure 3.20. Functions and interfaces of the monitoring and control system for power and communications.

Record-Keeping Requirements

For continuous monitoring to be useful, a record of the monitored parameters must be available in the short term and stored for the long term. Immediately following some event, enough information must be kept to facilitate a reconstruction of the problem. For the longer term, a summary history of the system's performance could be useful in determining the reliability of components or the benefits of changes made to the operating procedures. Therefore, we envision a two-part log as part of the monitoring system. Detailed recordings could be updated automatically as events occur. Long-term summaries could be generated at regular intervals, also automatically.

Access Requirements

The power monitoring and control system is similar to a utility supervisory control and data acquisition (SCADA) system: it monitors the performance of the system and the loads on the system; it allows operator control of all the major functions, including switch and breaker operation, voltage control, and load management; and it monitors energy use. While the power monitoring and control system allows the settings of the protection system to be changed on-line, it will be prudent to store a previously satisfactory set of such values at each location for backup use.

The communications monitoring and control system is functionally similar to its power counterpart and is a standard part of every data network, usually using the simple network monitoring protocol (SNMP) running in a network management station. The system must monitor communications system performance in terms of such parameters as routes taken by packets, delays in communication, and error rates, as well as provide access to the inner workings of the routers to update software or route tables as needed. As with the power system, it will be prudent to store a previously satisfactory set of such parameters at each location for backup use.

3.6.2 Approach and Trade-Offs

Little can be said at this time about how the requirements on the monitoring and control systems for power and communication can be met. The details will inevitably depend on the way the monitored systems are implemented.

For power, which will almost certainly not be a COTS system, the monitoring and control system may be an adaptation of a commercial scheme or it may be custom designed. We will make decisions as the power system design advances.

For communications, the likely use of COTS switch routers to create the network will implicitly specify a control and monitoring system. We will consider the suitability of the approach for NEPTUNE as part of the source selection process.

3.6.3 Concluding Remarks

- Because the requirements for monitoring the power equipment are different from those for monitoring the communications network, the monitoring systems for power and communications will inevitably be separate.
- COTS systems for each function are likely to be separately tailored to the NEPTUNE requirements.

3.7 Conceptual Design

In the previous subsections, we presented the basic arguments favoring a technical approach for NEPTUNE based on a combination of parallel (constant voltage) power and data networking packetized communications. A parallel power distribution approach is justified by the substantially higher level of power that can usefully be delivered to the science nodes and instruments. A COTS data networking approach is warranted by the substantial cost savings over other technologies, the ready availability of hardware and software, upgradability and backward compatibility as the technology evolves, and a high degree of inherent fault tolerance.

In this subsection, a block-diagram level system architecture for NEPTUNE is constructed on this foundation. We specifically assume the following:

- Power: parallel architecture with seawater return, operating at nominal 10 kV DC, 10 A, 100 kW
- Communications: gigabit Ethernet for the backbone, and 100/10BaseT Ethernet for the science interface
- Timing: millisecond timing service provided using NTP on the main communications system, supplemented with PPS on dedicated fibers
- Monitoring and control: a simple, low-level, fiber-based serial communications system.

We must note that the solution presented here is not unique and variants are possible (Figure 3.2). The detailed trade-offs and eventual selection of a single design must be part of the NEPTUNE Phase 2 development that follows from this report.

3.7.1 Shore Station and Backbone Cable

Figure 3.21 presents a block diagram of a NEPTUNE shore station. The basic functions of the NEPTUNE shore stations are the provision of power to and the serving of data to and from the science nodes distributed around the system. A functional division of the shore station separates power, network, and science instrument management tasks. There are associated timing, control, data archiving, and system security tasks as well.

Some of the functions shown in Figure 3.21 must be performed at the shore terminuses, while some might be controlled remotely. For example, power must be supplied at the shore stations, although it can be managed from anywhere with Internet access. Many aspects of network and science management can easily be carried out at remote sites.

In this conceptual design, the NEPTUNE backbone cable will be assumed to have nine pairs of optical fibers and a single electrical conductor, typical of cable produced by

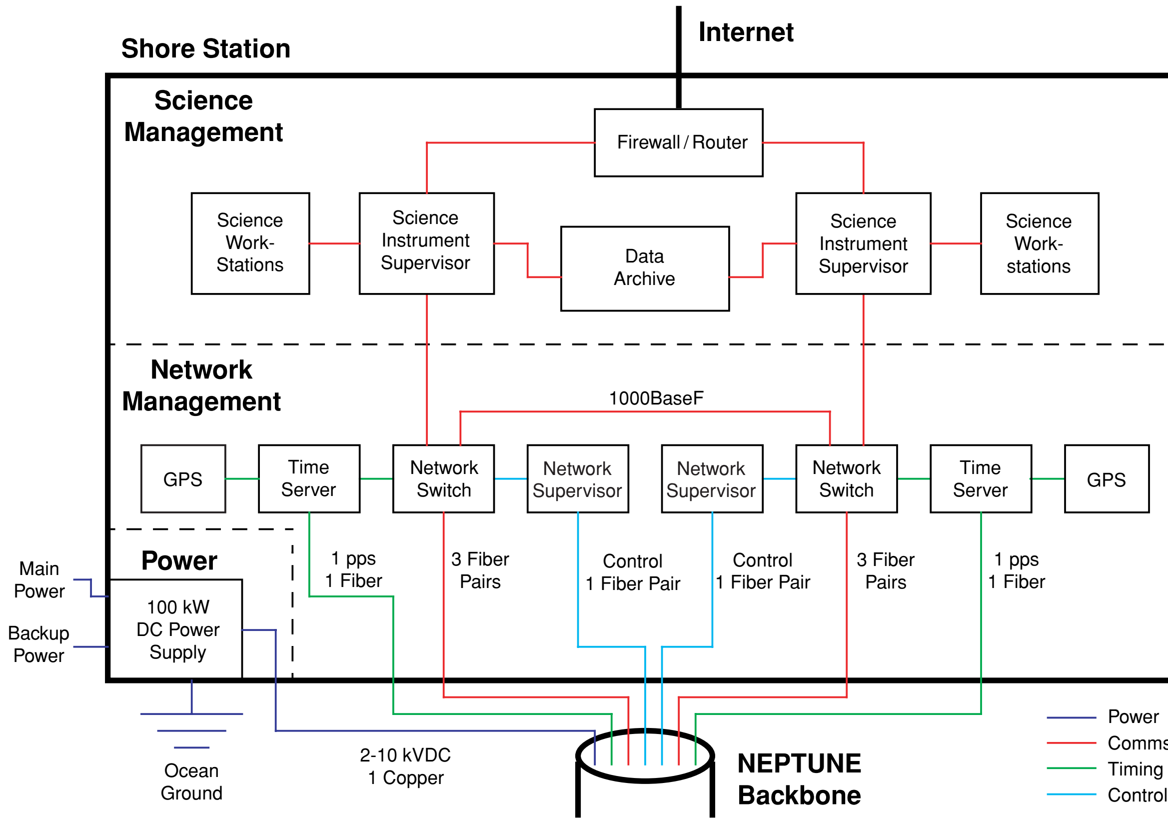

Figure 3.21. Block diagram of a conceptual NEPTUNE shore station separated into power, network, and science instrument management components. The major links are color coded into power (blue), timing (green), communications (red), and monitoring and control (cyan) components.

many commercial vendors. The solution we pose here is based on the capabilities of current (year 2000) COTS technology, and could change as new developments enter the marketplace.

Power System

Each shore station power system will operate at about 100 kW and provide a variable voltage (nominally 2–10 kV DC, depending on the load) at a current of up to 10 A. The voltage is controlled to be the minimum level that will meet the load, as this will prolong the cable insulation life.

We use an uninterruptible power supply (UPS) consisting of a combination of an ultracapacitor and a “no-break” diesel generator. The ultracapacitor provides backup for 5 seconds of full power while the “no-break” generator is operated off the commercial mains with rapid diesel generator clutch-in if the mains fail. Such power sources are COTS.

In this scenario, NEPTUNE will operate as a DC single-conductor system with seawater return. This mode of operation requires a reliable, low-resistance ocean-ground system at each shore station. This system consists of a network of deep-ground rods near the shore edge.

Network Management System

The network management portion of the shore station combines the management functions associated with the communications, timing, and monitoring and control systems. For reliability and fault tolerance, the appropriate parts of these systems are duplicated and cross-linked both at the shore station and on the backbone.

The heart of the NEPTUNE shore station data networking system consists of a pair of cross-linked GbE network switches. The network switches dynamically handle the incoming data streams from the science nodes and connect them to the science management system. These are COTS fault-tolerant devices coupled with gigabit Ethernet converters (GBICs, i.e., fiber-optic transceivers) capable of driving 100 km of optical fiber. Based on current technology, we propose switches able to handle at least three fiber pairs apiece. This provides an aggregate data rate of 12 Gb/s, which substantially exceeds that derived from science requirements.

The brain of the NEPTUNE network management system is a pair of network supervisors. These computers run COTS network management software that controls the network switches and communications aspects of the seafloor science nodes. Normal control of the science node systems is accomplished using SNMP, which is a widely used protocol for controlling network hardware, is interfaced to a number of higher-level languages like java or c++, and is standardized on most COTS equipment extending to the user level. The NEPTUNE collaboration will develop client software for non-standard components such as the science node power systems and control computers, as well as management software for communications over the low-speed serial control channels.

The primary NEPTUNE time service will be NTP carried directly on the data communications backbone. Operating as multicast clients in the science instruments, NTP daemons automatically detect all shore station NTP servers and synchronize internal clocks to an accuracy of about 1 ms. For users requiring higher accuracy, a dedicated time server that couples the 1 pps output of a GPS receiver onto an optical fiber will also be provided. This signal is repeated at subsequent science nodes. With correction for propagation delays along the optical fiber, the signal can be used in instruments to derive time to a fraction of a microsecond or better.

Monitoring and control functions are accomplished using dedicated optical fibers that carry system commands and telemetry. The control system and communications system must both be highly reliable with independent failure modes. The control system must be kept as simple as possible, as it serves as the ultimate means to enable and manage the science node functions. An approach might be based on a serial communications bus with drops at each science node, carrying status information to shore and control commands to the seafloor systems.

Science Management System

The NEPTUNE science management system consists of a pair of science instrument supervisors, a data archive, and one or more connections to the Internet. Science instrument control and data flow functions are carried out by these components.

The science instrument supervisors take the raw data streams from the backbone via the network switches and route the streams either to the data archive, a remote user, or both. All instrument control commands, whether they originate directly from the science management system or from a remote user, pass through the science instrument supervisors. Manipulation and display of a minimal set of key instrument functions (power-on, power-off, instrument-port on, instrument-port off, current limits, maximum bandwidth allocated, etc.) are facilitated and automated via SNMP commands. These commands are issued by the network administrator. Additional embedded *http* servers or higher-level interfaces can provide secondary access to other, less important (from the network viewpoint) instrument functions.

The data archive preserves both the raw data originating from seafloor instruments and the metadata describing these data. Some of the raw data may be processed before being archived. We use hardware capable of storage and rapid access to terabytes of data, i.e., tape and disk "farms." A significant concern will be specifying standard data formats or "wrappers" capable of accommodating a diversity of instrument and data types. The physical components of the data archive will most likely be distributed.

The final component of the NEPTUNE science management system is the connection to the worldwide Internet via one or more ISPs.

3.7.2 Science Node System

The science node system consists of all of the components required to interface science instruments to and derive power from the backbone cable, i.e., a physical connection to the backbone, an electronic backbone interface, and an electronic science interface. The physical layout has already been described in Section 3.2.5 (see Figure 3.5).

Backbone Interface

Figure 3.22 contains a block diagram of the backbone interface. There are four major components in this unit: the GbE routers, the high-voltage DC/DC converters, the time interface/repeater, and elements of the control system. Each of these is fully redundant and, insofar as possible, cross-linked to maximize fault tolerance and reliability.

The backbone communications interface consists of a pair of GbE switches with GBICs capable of driving multiple optical fibers over 100-km distances. Each of these switches is connected to six backbone optical fibers in pairs (three fibers in and three fibers out), and serves the dual

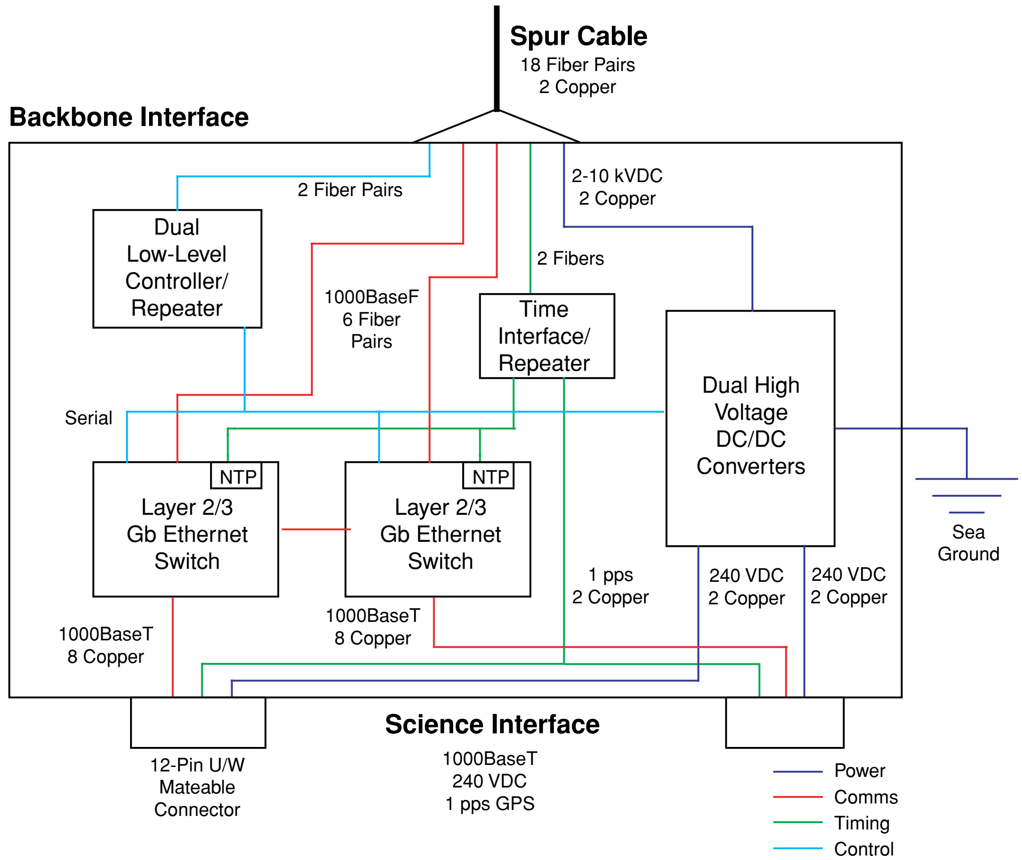

Figure 3.22 Block diagram showing the backbone interface components, consisting of a pair of gigabit Ethernet layer 2/3 switches, high-voltage DC/DC converters, control system elements, and a time interface.

roles of an active optical repeater and of a data networking router to switch traffic onto an appropriate path. The two GbE switches are cross-connected for redundancy and fault tolerance. For control and monitoring purposes, each switch runs an SNMP client, which is linked to network supervisors at the shore stations. Each switch is separately linked to a wet-mateable electrical connector to which the science interface is attached. These switches are of a size and have a power consumption appropriate for use in underwater pressure cases.

A pair of DC/DC converters (1–10 kV input, 240 V output, up to 20 kW) is the second major backbone interface system and serves to power both internal components and the science interface and instruments. These converters are designed to operate in a parallel power mode using a local sea ground. Further, because both sides of the backbone power conductor are brought into the backbone interface, a backbone cable fault can be isolated. Designs for a DC/DC converter and for protection relays for the backbone are Phase 2 engineering issues; commercial units operating at these voltages and power levels are not available.

The time interface/repeater system is a simple unit that has the dual functions of buffering the 1-pps GPS clock signal to the science interface connectors and repeating it to the next science node. High-accuracy calibration of the 1-pps system can be accomplished during installation by comparing the signal at a node with a GPS 1-pps signal routed through an ROV attached via umbilical to the mother ship.

The final backbone interface system to be discussed is the monitoring and control system, which interfaces to the network supervisors located at the shore stations. This system has to repeat the control signals to and from adjacent science nodes and provide an interface to control and monitor other backbone interface systems.

Science Interface

The major functions of the science interface are shown in Figure 3.23, and include all science instrument communications, power, and timing functions. As with all of the NEPTUNE infrastructure, we have incorporated redundancy for fault tolerance.

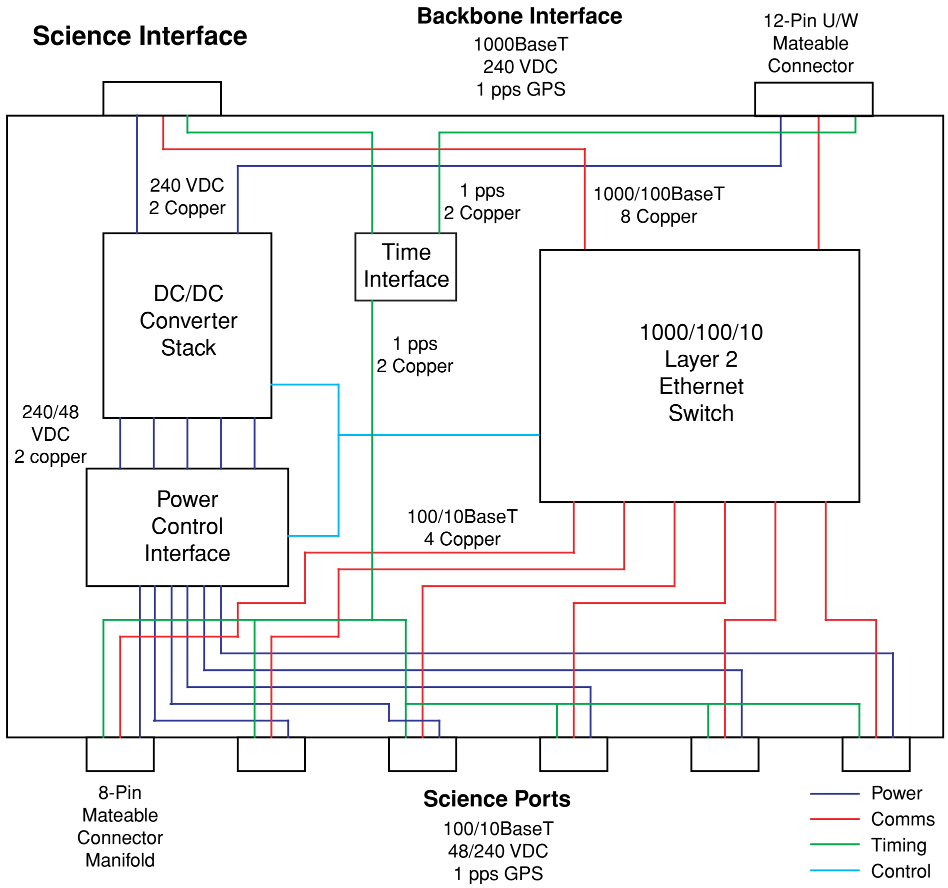

Figure 3.23. Block diagram showing the science interface, consisting of a layer-2 Ethernet switch, a power interface, and a time interface.

The communications system consists of Ethernet switches that connect to each backbone interface connector using GbE and to a set of science user ports using 100/10 Mb/s Ethernet through a crossbar switch. SNMP clients in the switches are linked to the network supervisors for monitoring and control.

A standard NEPTUNE science network interface will be specified for instruments that connect to the user ports. This interface defines the minimal IP suite that will be supported and provides a "toolbox" that users can choose to implement to meet the specification. An SNMP client can run in the instrument communications and power interface to facilitate automatic monitoring and control by the science instrument interface on shore. Other user functions without the potential to interfere with NEPTUNE are handled through alternate protocols. As already noted, IEEE 1451 fulfills many of these requirements.

The science interface power system consists of a redundant stack of DC/DC converters that take the 240 V DC output from the backbone interface and produce 48 V output power for user instruments. The converters' output is connected to a power control interface capable of switching the output of each DC/DC converter to each science port and providing circuit breaker disconnect and voltage/current monitoring capability. Provision of protected 240 V power to user instruments is also accommodated. SNMP clients in the power system facilitate control and monitoring from the science instrument supervisors. The time interface provides a very simple buffer between the 1-pps GPS signal from the backbone interface and the science ports.

3.8 Summary

This section has presented the major technical issues associated with NEPTUNE, the requirements and approaches for each of the major subsystems, and a preliminary view of what the system might look like. We draw the following conclusions:

- NEPTUNE is technically feasible. The technology base for NEPTUNE exists. The system design will consist primarily of integrating COTS components.
- A "parallel" power architecture similar to the terrestrial power system will meet the power requirements. The system will operate nominally at 10 kV DC and be able to deliver 100 kW. While very "doable," a significant effort at integrated design is needed.
- A data networking approach based on the Internet protocol (IP) is warranted for NEPTUNE. Gigabit Ethernet is an attractive candidate technology for the backbone communications system; it is largely COTS "plug and play."
- The provision of precise and accurate timing is possible; the science community needs to define specific requirements.
- A monitoring and control system will be necessary, with implementation depending on the specifics of the other subsystems.
- The decision to base NEPTUNE on fiber-optic/power cable rather than buoys ultimately comes down to cost. For the NEPTUNE requirements, combined with the geographical setting, a cabled system is less expensive.

4. Data Management and Archiving

4.1 Overview

Data archiving is a mature field. However, the technologies associated with the sensing and archiving of data are evolving quite rapidly. A system built today to a design that was developed over the last year or so will be hard to maintain in a few years' time. The result is that the actual archive part of the archiving system has to be updated periodically, at intervals of around 3 or 4 years.

Archiving architectures have evolved to allow the changes to be made without loss of capacity. An example, based on an approach used by NASA, is shown in Figure 4.1.

In Figure 4.1, the archive can be seen at the center. The incoming data (and the metadata) reach the archive by way of an *ingester* that uses the metadata to decide the appropriate archiving method. Access to the archive for output to the PI or the public may be via electronic means or human. One of the goals of the architecture shown is to allow the archive to be migrated from one technology to another (for example, from magnetic tape to optical disk) without interrupting the archiving process.

Coordination of the whole is done by a data management system that not only interfaces to the ingest and distribute functions but also works with the *user services* function. These services are the primary (human) interface for the PI. In an archiving system such as that discussed here for NEPTUNE, 5 full-time staff may be required.

The actual raw data are rarely supplied (or wanted): instead *data products* are supplied, generated with consideration for data quality and the application. Data products exist at several levels, and different users may require different products from the same raw data.

It should not be understood from Figure 4.1 that we have a particular archiving design in mind. Rather, we will establish the architecture, policies, and protocols for data management and archiving during Phase 2 of NEPTUNE. The design approach will be determined by the following:

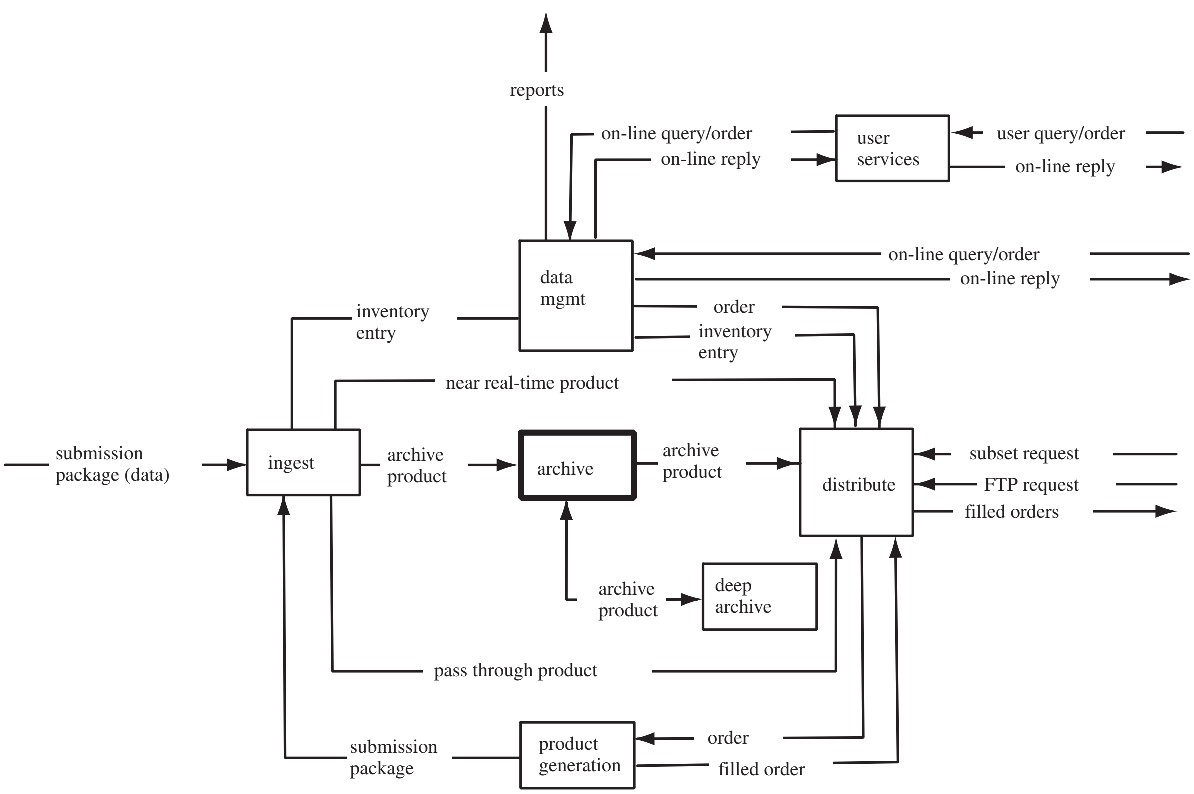

Figure 4.1. An example of archiving architecture, based on an approach used by NASA.

- Funding agency regulations and requirements
- Needs and expectations of research users
- Needs and expectations of educational users
- Developments in database design and "mining" techniques (currently an area of active research)
- Properties of the NEPTUNE data stream
- Costs.

Phase 2 plans will draw on emerging technologies in information management and on the experience of organizations such as NASA, NOAA, and IRIS, all of which manage large and heavily used databases. Scientific researchers are coming to expect user-friendly, web-based access to large data sets (e.g., the SeaWiFS products) and NEPTUNE is likely to follow this course.

In the subsections that follow, we treat data management and archiving in two phases: data acquisition (4.2) and archiving and modeling (4.3). We will address detailed design of these requirements during Phase 2.

4.2 Data Acquisition

4.2.1 Data Management at the Source

Protocols for packaging and transmitting data from sensors to shore stations via lower-tier junction boxes and nodes will be specified as part of the basic infrastructure. Standard protocols will be used, but will have to be documented. We will fully specify these protocols and all interface requirements for experiment designers in Phase 2.

The issue of a general need for *in situ* processing to optimize available bandwidth and to provide data buffering in the event of system failure will be addressed during Phase 2, as will the issue of providing *in situ* data processing that is remotely programmable (most likely in individual instruments). In general, *in situ* processing should be minimized to enhance the reliability of the system.

The detailed design will also need to address decisions on the magnitude of package buffering at the junction box or node level. The ring topology planned for the NEPTUNE backbone makes it resistant to major failures. Nevertheless, a system as complex as NEPTUNE will require system-failure safeguards. Trade-off studies to assess the value of *in situ* buffers will require an assessment of the impact of data gaps versus the cost of a more complex system.

4.2.2 Data Management at the Shore Terminal(s)

If significant subsetting/sampling of data is acceptable to end users, processing at shore terminals is an option. This is a likely option for video data, but it is not clear at this point how important this will be for lower bandwidth data streams.

The availability and cost of backhaul bandwidth from terminals to NEPTUNE data centers will significantly influence the role of the shore terminal or terminals in data management. Also, user needs for full real-time data sets will be a factor. If backhaul costs are unacceptably high or if user requirements are satisfied by real-time access to compressed data or data subsets from the incoming data stream, significant data processing and archiving at the shore terminal may be required or be desirable. If there is more than one shore terminal, the non-overlapping responsibilities of each will have to be negotiated. If data are archived at shore terminals it will be necessary, periodically, to move these data to more secure repositories. This will create a latency period between data collection and full user access.

Even if little or no data processing occurs at shore terminals, the shore terminals will need some buffer capacity to avoid data loss if a landline is damaged or if their Internet connection is interrupted. We will specify this capacity during Phase 2.

4.2.3 Quality Control and Quality Assurance

There is a clear requirement to record all metadata at the time of acquisition to help with Quality control and quality assurance (QC/QA). QA plans will need to be fully specified prior to installation of experiments. In general, we can expect that data quality questions will become increasingly coupled with archiving and analysis.

The Phase 2 task will specify QC/QA procedures for the community experiments and observations. To the maximum extent possible, these procedures will be automated and tested thoroughly on synthetic and real data streams prior to NEPTUNE coming on line and as new sensors are installed over time. The NEPTUNE operator and cognizant science working group will share responsibility for auditing and, if necessary, upgrading the QC/QA procedures for each experiment. With respect to QC/QA, we will design all components of NEPTUNE to record all relevant metadata associated with each data stream.

The Phase 2 task will also specify requirements for QC/QA procedures for PI-initiated experiments. QC/QA procedures, particularly to the extent that they impact NEPTUNE operations, will be negotiated with the NEPTUNE operator during the experiment design phase and fully specified prior to installation of an experiment. If current trends continue, most funding agencies will require QC/QA and archiving plans as part of the NEPTUNE experiments that they support.

4.3 Archiving and Modeling

When fully deployed, NEPTUNE will be capable of transmitting data at a rate in the many Gb/s range. Such a data stream has the potential to stress any processing and QC/QA system. It also has the potential to generate archives that are massive, expensive, and difficult to exploit and maintain. Thus, during Phase 2, we will develop critical and robust criteria to determine which data are archived and will develop an archive structure that is user friendly and flexible enough to accommodate queries that cannot now be anticipated.

To address the needs of a modeling and analysis community over a decadal time scale, an important issue will be the development of a stream-oriented processing perspective, emphasizing the movement and distribution of data. This approach is a departure from the historical emphasis on file-oriented systems and the storage of data. A related issue is the importance of developing unified modeling and archiving environments in which scientific models can be generated, validated against data, and distributed between collaborating teams in much the same way that we currently think of data alone.

4.3.1 Archive Requirements

Historically, most oceanographic data have been archived in total, regardless of the information content. Because most of these data sets are of modest size, this has been a cost-effective approach. For NEPTUNE, whatever archive requirements are adopted will affect the approach to data-subsampling and data-compression schemes. Just as for the data-acquisition component, cost and capability trade-off analyses will shape these requirements.

For NEPTUNE, where many of the experiments will be focused on slowly varying or intermittent processes, it will be technically possible to collect orders of magnitude more data than are needed to address any conceivable question. An example might be HDTV images of the growth of a mid-ocean ridge hydrothermal stack. Interframe differences will generally be small. Thus, an appropriate strategy might be to archive full frames infrequently (every hour or day, for example) with intermediate frames captured only when features change from the preceding frame by more than a specified amount. Such a strategy would allow the full video to be reconstructed, but could reduce mass storage requirements by many orders of magnitude. By archiving only significant image-to-image differences with lossless compression, even more archival space could be saved. Such approaches are simple in concept but require dedicated effort to develop a theoretically sound subsampling strategy and tools to accomplish that strategy. We will budget for the effort to adapt or create such tools as part of Phase 2.

For PI experiments, funding agencies will generally require compliance with their own institutional archive policies. Compliance with such policies will have to be negotiated with the NEPTUNE operator during the design and construction of the experiments.

4.3.2 Distributed Database Management System Architecture

An alternative to the centralized approach shown in Figure 4.1 would be a decentralized system of multiple databases with different formats, different vendors, etc. The key would be to provide a coordinating loosely controlled layer that could transparently translate between distributed archives. These archives would appear to users as a single querying and analysis environment. Considerable development would be required to make such a scheme practicable, especially in light of the anticipated 30-year lifetime of NEPTUNE. However, we can expect advances in the development of relational and object-oriented databases, as well as new developments in federated database design.

Our design goal for NEPTUNE is to provide datasets that can be easily linked and visualized in both the time and space domains to address cutting-edge problems and to allow completely new questions to be posed and answered. Database design and "mining" techniques are subjects of active research. NEPTUNE should take full advantage of existing databases while remaining flexible enough to take advantage of new developments prior to activation of the array. Existing databases can be used as models, such as the Monterey Bay Aquarium Research Institute (MBARI)[1] video information management system (VIMS) for video annotation and archiving. The IRIS data center for seismometer data is an example of a data repository. IRIS holds

[1]http://www.mbari.org

12 Tbytes of seismic data, receives 1Mb/s of new data, responds to 50,000 requests/yr with a 1-day turn around, and costs about $1.8 M/yr with a total staff of 12 to operate.

4.3.3 Content-Based Indexing, Alerting, and Feature Recognition

Early estimates suggest that the eventual information streams can be separated into the following three components:

- Video data characterized by huge volumes and great stress on all parts of the archiving and data management pathway
- All other electronic data, which can most likely be stored in their entirety and place many fewer demands on the processing stream
- Physical samples, which will likely be incorporated into existing institutional collections.

Video streams will require the development of real-time scientific alerters that can flag particularly important events and patterns for labeling and storage at high resolution and that can perhaps redirect data acquisition via *in situ* data processing strategies. These alerters must clearly operate in real time. Less obvious is the need for a similar capability even in the case of non-video data. Furthermore, post-processing querying systems will increasingly rely on metadata indexes that label important scientific features and patterns for modeling and analysis, in order to support querying between multiple datasets and multiple models. In this case also, the most efficient and realistic strategy is to perform the labeling and indexing in real time.

A related issue is the question of whether to archive data according to content-based indexing schemes, an area of active research. At this state of NEPTUNE, it is unclear whether such a scheme is necessary. However, even if archiving is ultimately performed within a standard relational scheme, content-based metadata indexes will remain essential as an aid to analysis. Fortunately, several of the major database vendors are developing products to support such metadata generation.

4.3.4 Access to Data

We will make data from the community experiments available to the full community of researchers and educators in near real time (subject only to network latency and the minimal delays associated with automated quality control). This will encourage the use of these data for innovative science as well as for the development of new visualization techniques and educational products. It could be argued that such "level playing field" access will discourage researchers from investing the effort to work on these data sets because of the possibility of being "scooped" by competing research groups. However, experience with rapidly accessible NASA data sets (such as SeaWiFS, altimeter, and radiometer outputs) suggests that this is not a serious problem; creative people have great confidence in their ability to do innovative science with "shared" data.

Access to data from PI experiments will be enabled after an established proprietary period (or sooner if authorized by the PI). Funding agencies will generally have data-access policies associated with their archive policies. These institutional approaches will influence our approach for release of NEPTUNE data. Two very different models exist for the management of PI-generated oceanographic data: 1) Under the UNOLS vessel model, PIs walk off the ship with their data, which are not shared with the broader community until digested and published. Funding agencies do have policies for the release and archiving of such data, but these policies are weakly enforced. Even when data are submitted to a national archive or an archive that is maintained by a professional society or publisher of a scientific journal, these data are often difficult to link to other data sets and frequently do not carry all the relevant metadata: 2) The alternative model, used by the Ocean Drilling Program and MBARI, involves institutional archiving of community data sets, but provides protection for PIs by specifying an embargo period during which the data are not accessible to other researchers.

In the broader scientific community, there are still other models. The issues of data access and proprietary periods will have to be addressed by funding agencies and by NEPTUNE advisory groups during Phase 2. The Phase 1 NEPTUNE participants favor the "central archive/embargo period" model because it facilitates development of an integrated data-access system, encourages maximum future use of NEPTUNE research results, and allows educators to develop products with confidence in the future predictability and stability of the data-management system. We will identify and define options and a recommended approach to data archiving and data access for PI experiments during Phase 2.

4.3.5 Web-Centric Modeling and Data Access

Web-based solutions will be crucial to successful implementation of NEPTUNE, as they provide convenient access to data by all users, both new and established. In addition, the prevalence of open standards in the web community allows significant leverage to be obtained from standards developed for a large developer community, and significantly decreases the risk of technological obsolescence of NEPTUNE implementations.

The need for simple web-based access to both data and models strongly suggests the use of web-centric standards such as extensible markup language (XML) for labeling and structuring information. This will enable easy and convenient transfer of data between researchers, and will provide important benefits in the form of straightforward mechanisms for fusing disparate datasets, for discussing and comparing parameterized models, and for validating those models against data. Increased emphasis on the web as an analysis as well as a data interchange environment will require that we consider metadata issues associated with the analysis of data as an integral part of any data management and archiving approach.

4.4 Summary

We will define NEPTUNE data management and archiving in Phase 2 with input from the science community and a working group established for this purpose.

Data acquisition issues related to data management and archiving activities include *in situ* processing, compressing and buffering of data at the source, metadata, and subsampling/processing/archiving at the shore station. The community experiment data must pass through quality control and assurance in near real time before being released.

The data archive may be centralized, distributed, or some combination of the two, although this will be transparent to the user. For instance, some data types, such as biological and video data, may fit most appropriately in a central NEPTUNE archive; other types may most logically reside elsewhere, such as seismic data in IRIS.

Many advances in database organization and management, with related improvements in data "mining," are occurring at a rapid pace. The NEPTUNE system will accommodate these advances, and thereby provide the level of support expected by the user community.

5. Education Elements

5.1 Overview

The oceans hold answers to compelling scientific questions and are also central to societal issues, such as global change and environmental protection. Coupling these facts with the inherent fascination the marine world holds for students and the general public alike reveals NEPTUNE's great educational potential.

We recognize that NEPTUNE's educational strengths closely parallel its scientific motivations: the same Internet technology that will offer scientists continuous, long-term access to the study area will also allow learners of all ages to explore worlds on, above, and below the seafloor, and to even pursue lines of investigation. Our ability to provide real-time output from some of the most dynamic of earth and ocean systems makes this project ideally suited for use in the classrooms, laboratories, and even living rooms of interested learners and viewers.

Two technological possibilities have particular appeal: development of a suite of virtual caves that would allow immersion activities for both scientific and educational purposes, and establishment of a dedicated educational experimental node on the seafloor. The potential for using stereo high-definition television (HDTV) to create a dynamic high-resolution rendering of the seafloor environment would captivate many educators and, in a ten-year time frame, is realistic especially with industry support. The dedicated experimental node is important to enfranchising a community of education-outreach oriented users in new and innovative methods.

Electronic access to the oceans, as made possible by NEPTUNE, can become a paradigm for public access to the *process* of scientific inquiry, with the ability to kindle an ongoing interest in this process, a significant step beyond just making finished scientific results available (Figure 5.1).

The public's imagination is also bound to be captured by the common goals between the search for life elsewhere in the solar system and the investigation of the mechanisms that support life without sunlight on the seafloor. Indeed, we must look inward to guide our search as we look outward.

We have identified the following education and outreach targets as central elements of NEPTUNE's long-term approach:

- Elementary and secondary schools
- Undergraduates (projects, classes)

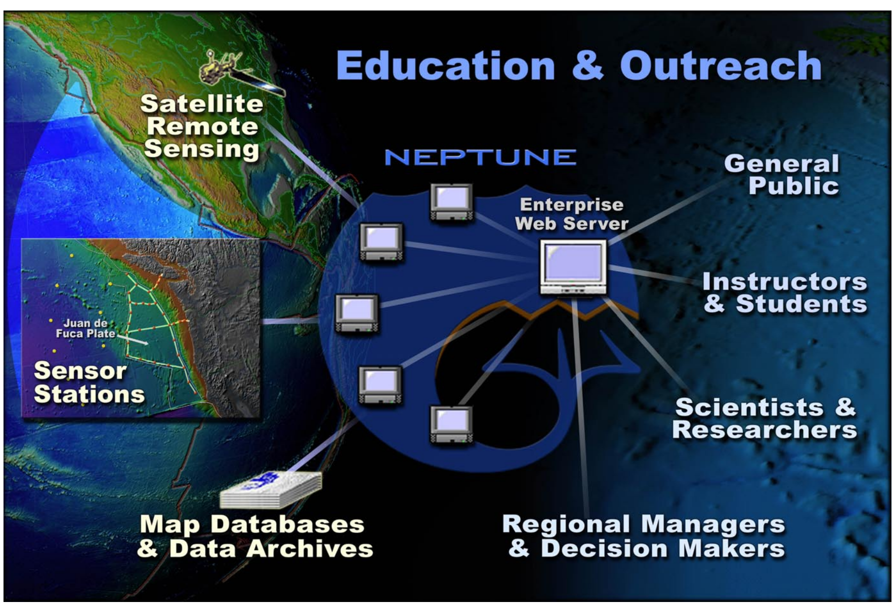

Figure 5.1. NEPTUNE's education and outreach components will reach a wide audience of students, scientists, general public, and decision makers. (Graphic: CEV)

- Graduates (including non-majors)
- Science and engineering communities
- Related industries
- Public - structured (e.g., aquariums)
- Public - unstructured (e.g., media, WWW)
- Decision-makers
- National legislature
- Government agencies
- State/provincial entities
- Nongovernmental organizations.

5.2 Phase 2 Activities

During Phase 2, NEPTUNE will proceed from the conceptual to the specific, and will begin the detailed design work for the education plan with a series of national workshops. We will design these workshops to attract the best educators, scientists, technologists, archivists, and skilled innovators in the world of science-content presentation to guide the establishment of a broad national education and outreach strategy.

Three workshops are planned to address three major aspects of education and outreach: K–12, undergraduate/graduate, and public education. While these workshops will explore the many options for outreach through traditional formal and informal educational channels, we will also explore and create detailed plans for outreach and application development relevant to private companies and the broader scientific community. This follow-up thrust will include forming a small number of working groups to define the specifics of how the real-time excitement of NEPTUNE and its ever-more powerful archiving capabilities can best be used to create a new type of educational outreach medium.

In anticipation of Phase 2, we discuss possible approaches below. Some of our proposals take advantage of existing programs, while others represent new work.

The progression to develop a detailed implementation plan will be from possibilities (ideas), to feasibility (technology, funding, phasing), to plans for implementation (the action plan). Implied is a budget for education and outreach explicitly specified in the detailed design of NEPTUNE. (As an example, we note that NASA's benchmark for many of its projects is at least 1% of project budget.) We will certainly need to augment this basic budget to go beyond just a highest-priority, highest-leverage set of plans for NEPTUNE education and outreach.

5.3 NEPTUNE Formal Education

The NEPTUNE project will be a real-world experience that will excite and inspire students to learn more about the oceans and the world around them. Real-time access to information from the ocean floor and the water column above it will provide teachers and students at all levels with their own underwater laboratory in which to study ocean and geologic processes. By connecting with existing education programs, NEPTUNE will leverage its ability to reach teachers and students across the United States and in other countries. Within the broad category of education, we will explore partnerships that address three audiences: teachers, K–12 students, and undergraduate students.

Teacher Training

Our goal is to develop companion materials that address how NEPTUNE resources may be used in the classroom to augment standards-based curricula. We also plan to work with teachers so that they are comfortable enough to incorporate NEPTUNE resources into their classroom learning on a basic level. Ideally, teachers would be able to develop new and innovative uses for the resources.

K–12 Students

In the K–12 workshop, we will work with educators to identify an appropriate curricula developer who is familiar with national science, math, and geography standards. This curricula developer will understand how to incorporate a virtual seafloor laboratory, oceanography, and geology into the classroom at various levels. These activities may vary from understanding how to use a map at the K–4 level to explaining the natural hazards in the Pacific Rim region at the 9–12 level (both benchmarks from the National Geography Standards).

We will also seek to work with the Ocean Envoy program developed by the TOPEX/POSEIDON project at the Jet Propulsion Laboratory to increase the knowledge and familiarity of teachers with regard to NEPTUNE resources. The Ocean Envoy program will select and train educators and informal educators for NEPTUNE as "master teachers" who will in turn educate teachers in their region. Areas of focus will include an overview of the science goals of the NEPTUNE program, the data available through NEPTUNE, use of online resources (both from NEPTUNE directly and from educational resources), and the integration of real-time information into the classroom.

To promote student participation, we will investigate partnerships with the Global Learning and Observations to Benefit the Environment (GLOBE) program. GLOBE is a worldwide network of students, teachers, and scientists working together to study and understand the global environment. Students and teachers from over 7,000 schools in more than 80 countries are working with research scientists to learn more about our planet. GLOBE students make environmental observations at or near their schools and report their data through the Internet. Scientists use GLOBE data in their research and provide feedback to the students to enrich their science education. Global images based on GLOBE student data are displayed on the World Wide Web, enabling students and other visitors to visualize the student environmental observations. NEPTUNE's component would be to expand measurements to the ocean and seafloor and allow students to compare life underwater to life on the surface. NEPTUNE will also investigate possible teaming with NOAA's Sustainable Seas program and will explore partnering with the Consortium for Oceanographic Research and Education (CORE), which sponsors the National Ocean Science Bowl and a number of education programs both nationally and regionally.

Undergraduate and graduate education

To advance undergraduate education, we will seek to work with CORE's Intern Program. This program is designed to further two complementary goals: professional development of scientists and marine policy experts, and assistance to the CORE full-time staff. The program will provide interns with an opportunity to work on projects relevant to their research, area of concentration, or degree. Interns will have an active role in the entire spectrum of CORE activities, including involvement in the legislative process, projects with various Federal oceanographic agencies, and a variety of educational initiatives. We will also look at partnering with existing undergraduate programs that strive to improve undergraduate curricula. These partners will be identified through the NEPTUNE workshop in 2000 that focuses on undergraduate/graduate formal education.

The NEPTUNE project offers a remarkable opportunity for incorporation of cutting-edge real-time data into undergraduate and graduate coursework and research. We will work with our design-team partner, the National Oceanic and Atmospheric Administration/Pacific Marine Environmental Laboratory (NOAA/PMEL), to make research data available to undergraduate and graduate laboratories, drawing on PMEL's successful experience with data distribution from the Tropical Atmosphere Ocean (TAO) array. In the workshop, we will also identify high-leverage approaches to undergraduate research opportunities in NEPTUNE. Washington NASA Space Grant has a very successful summer undergraduate research program, and the oceanographic research could be modeled on this approach. Undergraduate participation in NEPTUNE could also include equipment development.

Student participation can be extended to graduate students in engineering and science through creation of opportunities to develop equipment, collect data, and work with the results. We will explore successful innovations in graduate education that have involved students in just this way, such as that developed around the Bermuda Testbed Mooring (BTM) program at University of California, Santa Barbara and the California Space Initiative (CalSpace) operated under the California Space Grant Consortia.

As another part of its attention to post-secondary education, NEPTUNE will seek partnership with the Marine Advanced Technology Education (MATE) Center in Monterey, California. The MATE Center is one of ten *Centers of Excellence* funded by NSF. As a national collaboration of educational institutions and organizations, MATE seeks to improve the education of people interested in ocean occupations and to meet the needs of the U.S. ocean-related work force and employers. A partnership with MATE would be inspired by the goal of incorporating NEPTUNE into the Center's programming, making NEPTUNE a training site for marine technologists.

5.4 NEPTUNE Informal Education

Informal education is most generously defined as learning outside of the formal school classroom. This definition provides room for creativity and opportunity in an outreach plan for a program such as NEPTUNE. The width of the program's elements suggests the use of several venues for a sustained informal education program that can include a scheduled series of topics interpreted in a meaningful way. Each institution will interpret and manage the knowledge in its own way, which will add strength to the national outreach program by serving numerous local communities, utilizing local strengths and traditions.

A short list of potential informal education collaborations includes natural history museums, science centers, aquariums, nature centers, national parks, youth organizations, marine sanctuaries, ocean ecology organizations, and international partnerships with Pacific Rim nations in particular, but not exclusively.

Identifying institutions and organizations already involved in ocean interpretation will be key to this outreach plan's strategy. The insertion of NEPTUNE's information into these institutions will be a win-win-win situation for the public, the institution itself, and the NEPTUNE partner agencies. This information can be produced in a format that is easily digested and can be replicated to numerous informal institutions across the country, much of the data in real or near-real time. The informal institutions will also need some local control over selection of the voluminous data around which they can build their story.

Larger themes can be addressed with static and interactive exhibits developed in collaborations between the NEPTUNE partners and the informal-education community. These efforts should also be replicable to other institutions of various sizes across the nation. Most of these thematic displays would be developed by the larger institutions with matching budgets but they must be designed with elements that can be fully utilized by the smaller and middle-sized informal-education community.

There will also need to be ongoing and consistent educator training regarding the specifics of what NEPTUNE is producing, how the data interrelate, and how they can best be interpreted. We suggest that the Ocean Envoy Program, which is similar to a blending of the Ambassador and Fellows programs of NASA's Space Science, be utilized for this function. The Envoys would be given materials and informal training regarding NEPTUNE and the remote sensing of the earth and would be tasked with presenting live programs to interested groups gathered at informal education sites within their region.

This Ocean Envoy program also encourages local scientists to participate in the program or the process to produce the program, thereby leaving behind a local resource after the presentation has been completed. Because not all areas have local scientists, the Envoy will need to build a working relationship with a regional scientist who can support the efforts. NASA has demonstrated success with this approach to educational outreach and advocates it as a high leverage use of its outreach dollars.

Many of the designed programs will be using cutting-edge communications tools that will facilitate rapid dissemination of information. These same communication tools can be used for training purposes, both the initial training and "refresher courses."

We will also invite the media to participate in the outreach efforts of the NEPTUNE team. For example, radio "articles" are usually only one to two minutes long yet have great impact on their listening audience. The NEPTUNE information can be written by an invited journalist who submits it to the editor for final copy and to the producer for broadcast dates. There are several radio programs already in existence, e.g., National Public Radio's (NPR) *Science Friday* and *Living on Earth,* and National Geographic/NPR's *Radio Expeditions*. These programs draw a nationally syndicated audience and will be given the opportunity to use NEPTUNE in their broadcasts.

Youth programs, particularly those that serve underrepresented groups, will have programs collaboratively designed and built to meet these youths' educational needs. The museum community's *Youth Alive*, the National Park Service's *Junior Ranger*, or NOAA's *Sustainable Seas* would provide a framework upon which we can put the NEPTUNE data.

5.5 Public and Commercial Outreach

We must extend public outreach to the general public, government, the broader science community, and the commercial sector, i.e., beyond the classroom. Experience has shown that routine production of high-quality information pertinent to areas of commercial operation leads to that information being incorporated into operational products. Examples here are the incorporation of sea-surface temperatures into fisheries products and the current incorporation of altimeter data into a very wide variety of products that include hurricane forecasts. For this to happen, we must routinely generate and make easily accessible derived information products, in addition to the scientific raw data products specified by the research community.

Reaching a broader scientific community is also important. With good information products, we can extend science findings beyond NEPTUNE specialists, and scientists in related disciplines will be able to benefit from NEPTUNE science in an interdisciplinary environment. In its education and outreach workshops during Phase 2, we will explore ways to identify derived products of greatest potential value. Methods and means would be explored, predicated on the idea that these derived data products would be made freely available though the web, together with a suite of pages on applications as they develop. We recognize that the suite of products will evolve as applications develop.

The NEPTUNE project also provides the opportunity for government agencies and industry to test equipment in a test-bed environment. Equipment to be tested would include both communications and environmental sensors and robots. A possible approach is to view this aspect of NEPTUNE as a world-class facility for testing and development of underwater technology.

5.6 Summary

In recent years, public attention has been drawn to the universe around us. We have been actual or armchair explorers of space, both in sensational science missions and science fiction. But it is equally important for us to draw public attention to the realm of "inner space" in the depths of earth's oceans and the dynamic seafloor beneath.

NEPTUNE's Internet technology will create remarkable opportunities for outreach to a broad public audience through formal and informal education initiatives. The project can provide a wide range of new opportunities to explore and investigate the dynamics of the marine world using real-time data flow to classrooms and living rooms coupled with cutting-edge visualization techniques. NEPTUNE will establish partnerships with teachers and K–12, undergraduates, and graduate students through workshops, curriculum development, and existing programs while exploring new opportunities for optimal use of the live data flow and the growing archive. Collaborators within the informal educational community will include museums, science centers, aquariums, media, and youth programs.

From conception to conclusion, this observatory can be a source of inspiration and insight as we use ingenuity and technology to study the complex interactions of processes on, above, and below the seafloor. Perhaps most exciting is the opportunity to compare and contrast our own world with other watery worlds in outer space. In the years of NEPTUNE operation, as we thoughtfully explore a volume of earth's ocean, space scientists will explore the once-wet planet Mars and the water-encased Jovian moon Europa. As scientists probe the origins of life on earth and in space, it is especially important that outreach to the broadest possible public be engineered into the design and operation of NEPTUNE.

6. Management and Oversight

6.1 Overview

The management and oversight options presented below are constrained by the following two assumptions:

1. The activities and responsibilities during the four phases of NEPTUNE (feasibility study, development, installation, and operations) are sufficiently different that the management and oversight of the project will have to change over time in response to evolving needs. Challenges will be to maximize corporate memory and minimize disruption to the project during phase transitions.
2. To the maximum extent possible, oversight functions should be organizationally separate from management functions. This model, which is used by JOIDES/ODP, UCAR/NCAR, and IRIS, minimizes the possibility of real or perceived conflicts of interest and allows the two functions to evolve independently in response to the needs of the project and the interests of constituencies.

6.2 Phase 1—Feasibility Study

6.2.1 Oversight

There was no formal oversight structure in place for Phase 1. However, more than 60 individual scientists (see Section 2) generously served on *ad hoc* science working groups to define potential research goals. The Canadian NEPTUNE program, coordinated by the Institute for Pacific Ocean Science and Technology (IPOST), worked closely with the U.S. feasibility study team to ensure plan compatibility. In addition, MBARI and representatives of the LEO-15 project at Rutgers University freely shared their experiences and plans with NEPTUNE investigators.

6.2.2 Management

The feasibility study, funded by NOPP and the four partner institutions (University of Washington's School of Oceanography, Woods Hole Oceanographic Institution, Caltech's Jet Propulsion Laboratory, and NOAA's Pacific Marine Environmental Laboratory) was managed informally by the partners. The UW took the lead in compiling and editing the report, organizing *ad hoc* science working groups, and developing a NEPTUNE web page. WHOI, in collaboration with JPL, focused on technology.

6.3 Phase 2—Development, and Phase 3—Installation

Phases 2 and 3 of NEPTUNE involve the detailed planning and installation of the NEPTUNE backbone cable, all user interfaces, and a full spectrum of community experiments.

6.3.1 Oversight

For Phases 2 and 3, the advisory structure must be broad enough to represent the community with direct interests and skills in the design and construction of NEPTUNE and to address the full range of community experiments. The structure must be compact enough to respond quickly and decisively when important issues arise.

Phase 1 participants propose establishment of an Oversight Board of representatives from institutions directly involved in the construction and/or use of submarine observatories. The institutions will be members of the Oversight Board; individual representatives will be appointed by the institutional director in consultation with NEPTUNE staff to ensure balance of expertise. The Board will meet about twice a year and will carry out most duties by e-mail and through *ad hoc* committees and working groups. The Oversight Board will advise on the creation of the Phases 2 and 3 management structure, will maintain a continuing review of NEPTUNE's progress, and will make recommendations.

The two principal committees, approved by the Oversight Board, will act as liaison with international collaborators and funding agencies, and will deal with the transition to oversight during Phase 4, Operations.

The working groups will address science, technology, data management and archiving, and education and outreach. Development of community experiments will be a key responsibility of the science working groups. All working groups will draw their members from the interested scientific community, with the goal of providing balance and appropriately comprehensive expertise, rather than institutional representation.

6.3.2 Management

Phase 2, Development, and Phase 3, Installation, are likely to be the most management-intensive portions of the entire project. Planning, design, and coordination activities for which the primary management entity, the NEPTUNE Coordinating Office, will be responsible will include the following:

- System design, integration, prototyping, and testing
- Preparation of bid packages for cable laying, repair and maintenance, construction and installation of junction boxes and community experiments, ROV, AUV, and Rover development and operations, and data management
- Supervision of installation subcontractors (Phase 3)
- Interaction with permitting authorities, stakeholders, and interested nongovernmental organizations (NGOs)
- Negotiation of cable-crossing agreements
- Mapping of cable routes and community-experiment sites
- Liaison with the science and technical working groups developing and testing community experiments
- Facilitation of PI proposal development
- Definition and monitoring of safety and pollution issues
- Liaison with agency, industry, and international collaborators
- Facilitation of education and outreach activities
- Coordination of fund-raising activities among government agencies, foundations, and the private sector.

Although not all of these activities will be performed within the NEPTUNE Coordinating Office, the Office will be responsible for developing timelines, for identifying deliverables, and for implementing optimal coordination to ensure that tasks are completed to specifications, within budget, and on time.

Issues Regarding Management

We can envision multiple organizational approaches to implement all of these tasks in a timely and integrated manner. However, at the conclusion of this feasibility study, the level of funding in hand does not permit us to proceed in this manner, nor do we currently have sufficient funding to conduct all of Phase 2. We recognize that the NEPTUNE management approach will be influenced by the timing, by the specific sources of support, and by the paths of funding within NEPTUNE. For this reason, the team that prepared this document did not address in detail the organizational structure that will eventually operate NEPTUNE activities. Those deliberations logically fall into an early Phase 2 time frame when additional participants are identified and the Oversight Board is in place to endorse a management structure.

Issues of importance that bear on organizational decisions include the following questions:

- What are the prospects for funding of Phase 2/Phase 3? What sources are likely and what are probable timelines for funding?
- What level of management/business plan is necessary to attract funding in the amounts that NEPTUNE will require?
- Which institutions are to be involved in Phase 2 and in what capacities?
- The Canadians will be full partners in design and construction. How do international participants interact with the design teams?
- Will Phase 2 be funded from a single source at a specific time or will support arrive in small packets for subtasks within the overall NEPTUNE structure? How should money flow through the structure?
- Will industrial groups be early partners or simply subcontractors late in the process? Should the ultimate builders be involved in the designs?
- Can management foster creativity in the early design phase and ensure dependable deliverables at the construction stage?

NEPTUNE Tasks

Regardless of the details of the management structure, the following tasks must be accomplished for there to be a smooth and successful transition from Phase 2 to Phase 3:

- Provide overall strategic project leadership, with ultimate authority over all aspects of the project. Additional responsibilities include interacting with the Oversight Board, fund raising, interaction with sponsors, and arrangement of national and international collaborations.
- Provide operational project leadership. One person or group must take responsibility for overall coordination of the project as a system, including scheduling, budgets, contracts, bid packages, permits, and conflict resolution.

- Provide technical oversight and coordination, integration of technical design, construction and installation of the entire system (Phase 3), and management of a smooth transition to Phase 4, Operations. Components of these efforts will be distributed among institutions and industry. This activity requires considerable mobility and broad technical skills.
- Develop intellectual and practical interfaces among the science working groups, including data management and archiving. Management of links between the science groups and the rest of the project must foster effective communication and assist the working groups in coordinating activities.
- Establish strong links between NEPTUNE and education and outreach activities. Develop innovative uses of NEPTUNE capabilities while obtaining support for enhancing formal and informal education.
- Provide support functions (administrative, fiscal, travel, graphics, etc.) for all project personnel. Coordinate permits, media relations, and all other office activities.
- House the NEPTUNE Coordinating Office during Phases 2 and 3. The School of Oceanography at the University of Washington, with substantial institutional support, has volunteered for this task.

6.4 Phase 4—Operations

6.4.1 Oversight

The Oversight Board of Phases 2 and 3 is expected to transition to a membership organization for Phase 4. Membership in this organization (analogous to UCAR or IRIS) will be open to any interested institution for a nominal fee. The members will meet annually to elect an Executive Committee with ongoing responsibility for liaison with the NEPTUNE Operations Office (the successor to the NEPTUNE Coordinating Office) and funding agencies. The Executive Committee will carry out many of its duties via scientific, technical, and educational subcommittees that will take over (preferably with substantial membership overlap during the transition) from the committees and working groups of Phases 2 and 3. Figure 6.1 shows one concept of the subcommittee structure and its relation to the activities and responsibilities of the NEPTUNE Operations Office.

The Executive Committee, in collaboration with the funding agencies, will periodically establish *ad hoc* panels to review the community experiments for the quality and accessibility of their results and their continuing programmatic relevance.

6.4.2 Management

After installation of the submarine network and community experiments, the primary responsibilities of the NEPTUNE Operations Office will be as follows:

- Continuing operation (power and communications) of the network
- Maintenance and repair subcontracts with cable repair vessel(s) and ROVs
- Installation, maintenance, and recovery of scientific experiments (including ROV subcontracts)
- AUV and Rover subcontracts
- Community experiment subcontracts
- Liaison with funding agencies
- Liaison with international collaborators (in the case of substantial Canadian involvement in the construction of NEPTUNE, a joint Office, perhaps alternating between the two countries, may be appropriate)
- Liaison with NEPTUNE Executive Committee
- Liaison with scientific and technical advisory subcommittees
- Liaison with education and outreach programs
- Advising PIs developing experiments to be attached to NEPTUNE and reviewing experiments for compatibility with NEPTUNE
- Data management and archiving
- Proactive and reactive public information, with special emphasis on interested non-technical communities and organizations
- Liaison with related scientific programs.

The contract for the NEPTUNE Operations Office will be competed at 7–10 year intervals to allow interested, qualified institutions to compete for this activity. An *ad hoc* panel will review the performance of the Office at 3–5 year intervals.

The size of the Operations Office staff will be determined by the extent to which ongoing NEPTUNE activities are subcontracted versus being carried out directly by the Office. The NEPTUNE members, funding agencies, and NEPTUNE Coordinating Office will resolve this issue prior to Phase 4.

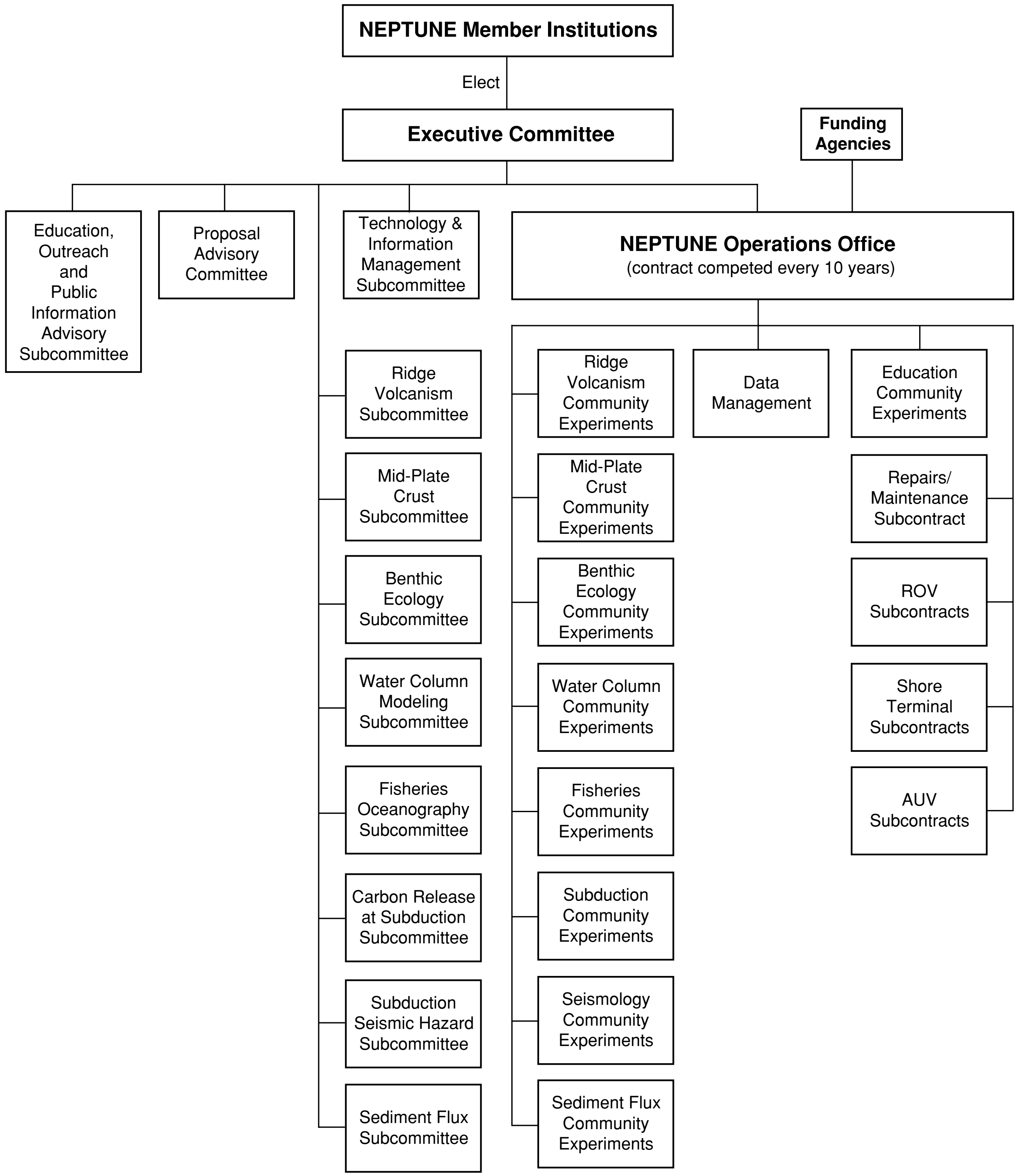

Figure 6.1. NEPTUNE Phase 4, Operations, management and oversight structure.

6.5 Summary

NEPTUNE's management and oversight structure is guided by two assumptions: 1) management and oversight must change in response to the evolving needs of the project, and 2) oversight functions should be kept separate from management functions.

In Phase 1, Feasibility Study, there was no formal oversight structure in place, and management was handled informally by the partners.

Phase 2, Development, and Phase 3, Installation, will involve the detailed planning and installation of the NEPTUNE backbone cable, user interfaces, and community experiments. The proposed advisory structure is an Oversight Board whose members are appointed representatives from institutions directly involved in the construction and/or use of submarine observatories. Principal committees, approved by the Oversight Board, will act as liaison with international collaborators and funding agencies, and will deal with the transition to oversight during Phase 4, Operations. Working groups will address science, technology, data management and archiving, and education and outreach. The NEPTUNE Coordinating Office will be the primary management entity during these phases and will be responsible for developing timelines, for identifying deliverables, and for implementing optimal coordination so that tasks are completed to specifications, within budget, and on time.

We recognize that the NEPTUNE management approach will be influenced by the timing, by the specific sources of support, and by the flow of funding within NEPTUNE. For this reason, the Feasibility Study does not address in detail a finalized organizational structure. Those deliberations logically fall into an early Phase 2 time frame when additional participants are identified and the Oversight Board is in place to endorse a management structure.

For Phase 4, Operations, the Oversight Board of Phases 2 and 3 is expected to transition to a membership organization. Membership in this organization (analogous to UCAR or IRIS) will be open to any interested institution for a nominal fee. The members will meet annually to elect an Executive Committee with ongoing responsibility for liaison with the NEPTUNE Operations Office (the successor to the NEPTUNE Coordinating Office) and funding agencies. The contract for the NEPTUNE Operations Office, the primary management entity, will be competed at 7–10 year intervals.

7. Environmental Considerations and Permits

7.1 Overview

Although NEPTUNE is years away from laying cable on the seafloor, it is important that we identify groups with interests in or concerns about the project and address these issues proactively. The regulatory requirements for this project are numerous and rigorous at both the state and federal levels. The permit process, particularly the National Environmental Policy Act (NEPA)-driven environmental impact statement if required, will take a year or more to complete. NEPTUNE will also likely interact with other government entities that do not hold regulatory authority over the project but that may still have an interest or concern, such as the U.S. Navy and Native American tribes. On the private sector side, we will have to negotiate agreements with fishing groups and cable companies with regard to cable siting, liability, maintenance, and crossings, among other issues. Several individuals with experience in cable-landing issues in Oregon, who work for the state government, the cable industry, or the fishing industry, have recommended that NEPTUNE become a member of the Oregon Fishermen's Cable Committee (OFCC).

All of the interest groups contacted for this study showed great interest in NEPTUNE and generally did not view the project as a threat to their livelihoods or to the environment. Stronger opinions or concerns about the project may arise as details of the project are worked out and the permitting process commences. Because NEPTUNE was still in its planning stage, some questions from interest groups could not be answered with certainty, such as the exact location of the cable or instruments. The primary concern that arose involved the fishing community's desire to avoid gear conflicts with the cable system. We will likely be required to work out this issue in an agreement with fishing groups prior to laying cable. When negotiating this agreement, NEPTUNE should obtain maps and charts of fishing areas to identify the best possible cable-laying routes. Fishing groups had several research ideas that they would like to see implemented within NEPTUNE, and suggested opportunities for NEPTUNE-related studies to combine with or complement current fisheries research.

For the most part, environmental groups expressed excitement about the project, because of its implications for improving fisheries science, for example, rather than concern about any potential impacts. They were supportive of the project, viewing it more as a research endeavor than a cable project.

NEPTUNE is cognizant of the need to work closely with the U.S. Navy regarding oceanographic acoustic systems.

Several outreach and education groups were eager to assist NEPTUNE in spreading its message and increasing public awareness of the project. There will also be many opportunities for NEPTUNE representatives to attend conferences and offer information displays, while the media and the Internet will be important resources for updating the public on NEPTUNE's progress. Thus far, the project seems to enjoy support from the stakeholder community. Maintaining this support will likely entail upholding good and regular relations with these interest groups.

7.2 Historical Context

Academic oceanographic research in the post World War II era has proceeded with remarkably little interaction between anyone other than the scientists involved and the research-funding agencies. Following ratification of the 1982 Convention on the Law of the Sea, prior approval and reporting requirements for work within the 200-nautical-mile exclusive economic zones (EEZ) of most nations became more stringent; U.S. researchers working in the U.S. EEZ, however, are not affected by such requirements.

Since the first National Marine Sanctuary was established in 1972, and with growing public interest in the health of the marine environment (fostered in part by more frequent, and more frequently reported, anoxia events and toxic algal blooms), oceanographers have come under more official and unofficial scrutiny than ever before. Researchers must be prepared to explain and even defend their science in forums that can be difficult to identify ahead of time and that can change over time. The power of individuals and groups outside the field and outside formal regulatory agencies to affect oceanographic research was illustrated by the experience of the Acoustic Thermometry of Ocean Climate (ATOC) program. The ATOC goal was to use acoustic tomography to detect changes in ocean temperature over large areas. An Internet-based campaign opposed ATOC because of the program's perceived impact on whales, delaying the program for three years at a cost of more than $5 million. The fact that the original concern was based on incorrect physics did little to affect the strength of the opposition or its impact on ATOC.

Consequently, even though NEPTUNE is years away from installation, we have begun the process of identifying agencies that may have regulatory interests in the project, as well as other groups, both governmental and private, that may have interests in, or concerns about, the NEPTUNE cable and the kinds of experiments it may support. Because many questions on NEPTUNE's extent, exact location, and experiments have yet to be answered, we have made no formal requests to potential regulatory agencies. Rather, the focus of this assessment is to identify the principal entities with possible regulatory or nonregulatory interests in NEPTUNE (see Table 7.1), to interview representatives of a subset of these entities, and to collate expressed interests and concerns so as to better plan permitting and public information activities during later stages of the project. We primarily emphasize U.S. entities, although comparable Canadian groups were identified but not contacted. We anticipate that the parallel Canadian NEPTUNE program will identify more groups and will work directly with them. Close liaison between the two programs should be maintained; concerns and misapprehensions do not respect national boundaries. For those parts of the system over which Canada has jurisdiction, Canadian procedures will be followed.

Issues that emerged during conversations with interest-group representatives and a summary of the key points are reported in *NEPTUNE Technical White Paper #5: Environmental Considerations and Permits*.[1]

Table 7.1. Entities with regulatory or nonregulatory interest in NEPTUNE.

Agencies	
Federal	
Coast Guard	National Marine Fisheries Service
Department of Defense	National Marine Sanctuary Program
Department of Interior	National Park Service
Department of Transportation	Olympic Coast National Marine Sanctuary
Environmental Protection Agency	Olympic National Park
Federal Communications Commission	U.S. Army Corps of Engineers
Federal Emergency Management Agency	U.S. Fish and Wildlife Service
Federal Maritime Commission	U.S. Geological Survey
National Oceanic and Atmospheric Administration	U.S. Navy
State	
Oregon Coastal Zone Management Association	Northwest Straits Commission
Oregon Department of Fish and Wildlife	Washington Department of Ecology
Oregon Department of Land Conservation and Development	Washington Department of Fish and Wildlife
Oregon Department of Transportation	Washington Department of Natural Resources
Oregon Division of State Lands	Washington Department of Transportation
Oregon State Parks	Washington Environmental Education Association
Puget Sound Action Team	Washington Governor's Council on Environmental Education
Canada	
British Columbia Ministry of Fisheries	Department of Fisheries and Oceans
Tribes	
Hoh Tribe	Quileute Tribe
Makah Tribe	Quinault Tribe
North West Indian Fisheries Commission	

[1]*NEPTUNE Technical White Paper #5: Environmental Considerations and Permits* (http://www.neptune.washington.edu)

Table 7.1., Cont'd.

Fishing Organizations	
At-Sea Processors Association	Pacific Fishing Vessel Owners Association
Coalition of Washington Ocean Fishermen	Pacific Seafood Processors Association
Groundfish Forum	Pacific States Marine Fisheries Commission
Habitat Steering Committee Pacific Fishery Management Council	Purse Seine Vessel Owners Association
Institute for Fisheries Resources	Sea State
Midwater Trawlers	Washington Dungeness Crab Association
Oregon Fisherman's Cable Committee	United Catcher Boats
Oregon Trawl Commission	Washington Trollers Association
Pacific Coast Federation of Fisherman's Association, Inc	Western Fishboat Association
Pacific Fishery Management Council	
Environmental Organizations / NGOs	
Center for Marine Conservation	Oregon Shores Conservation Coalition
Ecotrust	Pacific Marine Conservation Council
Environmental Defense Fund	Pacific Ocean Conservation Network
International Marine Association Protecting Aquatic Life	People for Puget Sound
Marine Conservation Biology Institute	Puget Soundkeeper Alliance
Marine Life Sanctuaries Society of BC	Seaview Coastal Conservation Coalition
National Wildlife Federation	States/BC Task Force
Natural Resource Defense Council	Surfrider Foundation
Olympic Natural Resouces Center	
Cable Companies and Associations	
Alcatel	Pirelli
AT&T	SAIC MariPro
General Dynamics	Simplex
International Cable Protection Committee	Tyco International
Margus	Tyco Submarine
Pacific Telecom Cable	WCI Cable, Inc.
Outreach Partners / Consultants	
Coastal Ecosystems Research (Canada)	Natural Resources Consultants, Inc.
Hatfield Marine Science Center	Oregon Sea Grant
Woods Hole Oceanographic Institution	Pacific Fishing Magazine
National Marine Educators Association	Washington Sea Grant
National Undersea Research Program	

7.3 Summary

It will be necessary to keep all stakeholders proactively involved. Of the groups and people already contacted, many expressed support for NEPTUNE.

An environmental impact statement most likely will be required. At this time, we see no obstacles to obtaining the necessary permits for installing and operating NEPTUNE.

8. Realizing NEPTUNE

We divide the remaining parts of the project, after this Phase 1 feasibility study, into the following three phases:

- Phase 2, Development: plan and set in motion the science and engineering design, obtain funding, and define technical requirements/prototypes/specifications/bid packages.
- Phase 3, Installation: procure and deploy the NEPTUNE backbone infrastructure and initial suites of sensors.
- Phase 4, Operations: operate and manage the system, install and service sensors, manage data, and coordinate and manage overall project.

The timeline for the project is shown in Figure 8.1. Phase 2 begins in 2000 with the establishment of a NEPTUNE Coordinating Office. The infrastructure design and related activities will most likely begin in late 2000 and be largely complete by early 2003, though with testing of infrastructure prototypes and science sensor network prototypes continuing. The start of Phase 3 in 2003 (overlapping with Phase 2) allows time for procurement and integration before the deployment starting in mid 2004. Phase 4, Operations, begins to ramp up in 2004. This schedule is obviously contingent on obtaining the necessary funding: system design funds in 2000 and system procurement and installation funds in 2002.

In this section we describe some of the major tasks and activities during these phases of the project.

8.1 Phase 2—Development

We show the components of Phase 2 in Figure 8.2. The project management centered in the NEPTUNE Coordinating Office will have overall responsibility for the execution of the program.

8.1.1 Science

Three broad areas of scientific activity are of high priority during Phase 2:

Establishment of science working groups (SWGs). The principal roles of the SWGs will be to define community experiments and information management requirements for the major scientific opportunities enabled by NEPTUNE. SWGs must also pursue the development of experiments and focus attention on needed new technologies.

Design and prototype testing of community experiments on a schedule that will ensure readiness for deployment, as the NEPTUNE infrastructure becomes operational. In some cases, all that will be required is the interfacing of existing sensors to NEPTUNE junction boxes (e.g., standard oceanographic sensors and seismometers). In other cases, substantial development will be required (e.g., drift-free chemical sensors, AUVs, and rovers that can operate from NEPTUNE nodes for periods of a year or more without servicing). This activity will require the collaboration of SWGs, NEPTUNE, and funding agency representatives.

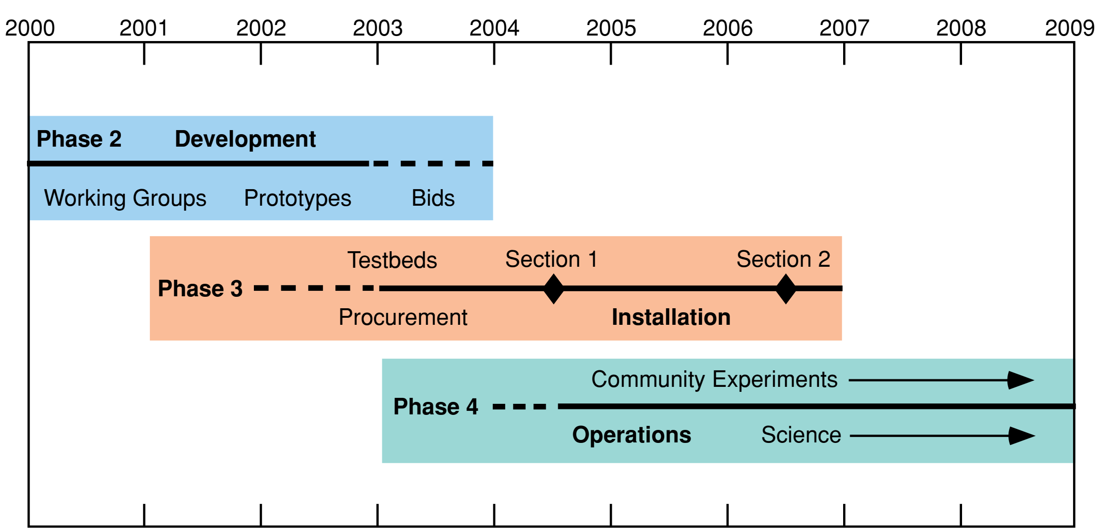

Figure 8.1. NEPTUNE project timeline.

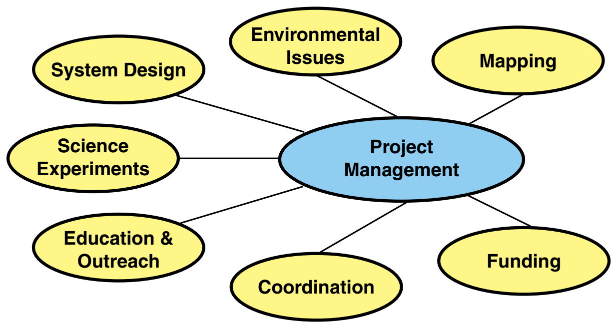

Figure 8.2. Components of NEPTUNE Phase 2, Development.

Development of a strategy to make the NEPTUNE system attractive and user-friendly for individual PIs. This activity, which will involve the SWGs and the NEPTUNE Coordinating Office, is essential for the long-term health of the program.

8.1.2 International Interest

From project inception, international participation has been encouraged. During Phase 2, we will seek additional users from international, as well as national, communities. Below we show two examples of specific international interest in NEPTUNE. We will work with these groups during Phase 2 to encourage their full participation.

Canada

Statement of Support from John C. Madden, Institute for Pacific Ocean Science and Technology, Project Manager, NEPTUNE Canada.

"The first major event of the study was the Science Workshop, held in Victoria on March 3–4, 2000. Over sixty people attended, drawn from across Canada, and including three representatives from the University of Washington, led by Dr. Delaney. Canada's Minister of the Environment, the Hon. David Anderson, attended part of the wrap-up session on March 4, and expressed strong enthusiasm and support in principle.

"The output of the workshop exceeded expectations. Three major scientific issues were identified for which there is significant interest and leadership capability within the Canadian scientific community, where the resulting knowledge would have significant practical benefits for Canadians, and where NEPTUNE's capabilities would permit significant advances which would be difficult to achieve in any other way.

"These scientific issues are:

- *Plate Tectonics and Earthquakes*
- *Climate Change*
- *Biodiversity and Earth's Major Ecosystems*

"It was also clear that there is strong support for NEPTUNE from a number of leading Canadian scientists. The overall scientific questions closely resemble those developed by the U.S. NEPTUNE science working groups, for the good reason that this is the leading edge of earth science.

"However, a number of new ideas surfaced:

- *extending the network to the northwest (and southwest) to improve its ability to monitor ocean climate change in areas representative of major gyres*
- *extending the network to include Explorer plate*
- *using the network to monitor the behaviour of the California undercurrent as it transports nutrients northward*
- *taking advantage of the NEPTUNE site surveys to collect samples for maps of seafloor ecosystems and to determine the distribution of gas hydrates in the accretionary prism along the continental margins."*

Germany

Statement of support from Erwin Suess, Chair, Department of Marine Environmental Geology, GEOMAR Research Center for Marine Geosciences

"The Department of Marine Environmental Geology deals with global material budgets and process studies of element cycling in the ocean and its sediments and exchange between the major reservoirs. The focus of research is process-oriented and is aimed towards predictive modeling of variability, composition, and biogeochemical reactions in the oceanic water column and at the sea floor. Fundamental questions in this context are currently being studied at convergent plate margins, where crustal components, ocean water, and sediments exchange material and energy and thereby exert an influence on the composition of the hydrosphere, biosphere, and atmosphere. These objectives closely coincide with those of NEPTUNE.

"Consequently, the group in environmental geology at GEOMAR has contributed towards formulating selected objectives of the NEPTUNE program and is actively engaged to help implement the program in the future through national participation. As part of GEOMAR's contribution, I chaired the working group on

"Subduction Zone Processes" with particular focus on gas hydrate dynamics at active continental margins.

"The group at GEOMAR has extensive experience in studies on fluid flow from vents and since 1997 has been involved in the US/German TECFLUX program on the Cascadia margin, a prime area within the NEPTUNE framework.

"…simultaneous measurements of seismicity, energy and mass fluxes from the sediments, fluid characteristics, and biological response over an extended period are paramount to make substantial progress. GEOMAR has deployed in the past a number of autonomous instruments that provide insight into the dynamics of venting, hydrate formation and breakdown, and associated biological activity. Connecting these and other instruments to the NEPTUNE array over the next decade along the convergence zone would yield extraordinary data on material fluxes.

"Therefore, GEOMAR is looking forward to a successful implementation of the NEPTUNE program for an on-line connection to the deep sea and pledges its long-term participation and support through a number of pending proposals and those under consideration for the future."

8.1.3 Education and Outreach

Important themes that must be addressed early in Phase 2 are designing an overall strategy for education and outreach, raising the funding necessary to implement that strategy, and ensuring that the design components of the overall system are compatible with the goals of reaching the public.

Developing a strategy will require that a series of national workshops be conducted to explore the specific challenges and opportunities involved in preparing NEPTUNE output for optimal use within different sectors of the general public. Individual workshops will address issues for K–12, undergraduates, the general public, news media, entertainment groups, and the public that can be reached through established educational groups such as aquariums, museums, and science centers. Reports from each of these meetings will be integrated into a national strategy with the intent of engaging financial support from appropriate sources. The goal is to complete the workshops and integrate the results in 2001.

A fund-raising effort will be launched as the outlines of NEPTUNE approaches to education and outreach become clear. Representatives of selected foundations will be entrained when possible in the deliberations from the outset. We anticipate strong support from NSF and NASA for some aspects of this effort and will consider approaching selected portions of the information-entertainment industry for participation in some of the higher profile event-related NEPTUNE products. Whether any of these aspects contain the potential of a funding stream for the life-time of the project is unclear.

Two technological tools hold particular appeal for NEPTUNE's education and outreach programs: a suite of virtual caves that would allow immersion activities for both scientific and educational purposes, and an experimental seafloor node dedicated to educational purposes. This node could support high-definition television (HDTV) that would provide educators access to a dynamic, high-resolution rendering of the seafloor environment.

8.1.4 Engineering

The technical system design consists of all activities culminating in all the plans, technical requirements, specifications, and bid packages necessary to accomplish the procurement, construction, and operation of the NEPTUNE infrastructure.

- Build an integrated engineering team. The recruitment of a project/systems engineer is a crucial first step. The roles of academia, government laboratories, and industry will be defined in the process of building the team. We recognize the clear advantage to bringing in partners earlier rather than later to maximize interaction and minimize possible problems later.
- Construct the technical implementation plan. Specifically, how will the system be designed, built, installed, and operated? This report is a first pass at answering the question, but is clearly just the beginning of such a plan. We must define the work plan, including tasks, resources, schedule, and cost.
- Implement the plan within a systems engineering approach:

1. *Conceptual phase*. We will review and extend the work represented by this report, beginning by formally identifying and documenting the overall system requirements, concepts, and criteria. This will be a top-level effort and will involve all participants, requiring interaction between scientists and technical design staff. This effort will lead to the specification of the major subsystem requirements, concepts, and criteria. These specifications will

be documented in detail and published as control documents. For each major subsystem, functional requirements and criteria will be specified and analyzed with interface requirements included (the "big-arrow" diagrams in Section 3 are a beginning). A design review will conclude this phase.

2. *Definition or preliminary design.* We will determine the technical requirements of the system based on the foregoing results. Trade-off studies, taking into account the system performance, reliability, and life-cycle cost, will be made based on these technical requirements. For example, the decision tree (Figure 3.2) will be reviewed, and various system configurations will be simulated to identify the best one. The operational and supporting systems will be evaluated via models to assure compliance with the requirements and criteria. After a design review of the complete system, preliminary specifications can be prepared, and a draft design, including some level of detail, will be prepared and published. This design will be reviewed and approved by the entire team.

3. *Detailed design and development.* This will be the major engineering development effort for NEPTUNE and includes detailed simulations, breadboarding, and prototypes of critical components. Design reviews will be conducted throughout.

4. *System integration.* This step will close the loop on the development work. We will ensure that the final design meets the requirements and criteria laid down earlier; we will consider the various subsystems as part of the whole system, and thereby ensure compatibility and satisfactory operation. Prototypes will be tested and reliability assessed. This step will include checking the validity of any assumptions that have been made along the way, and it is the last opportunity to check a number of items before changes become costly. A critical design review will conclude the process.

- Prepare requests for proposals, bid packages, and detailed plans for Phase 3.

8.1.5 Data Management and Archiving

Data management and archiving were not explored in depth during Phase 1 of NEPTUNE. Thus, early in Phase 2, a data management and archiving working group will be established under the Oversight Board to undertake activities that include the following:

- Define the data management and archiving philosophy and system for NEPTUNE.
- Research existing high-bandwidth information management systems (those of NASA and IRIS, for example) to assess the merits and economics of various data management and archiving approaches.
- Interact with infrastructure developers and SWGs to optimize components of the data management and archiving system.
- Develop specifications for the operational data management and archiving system to allow the activities to be partitioned into those that can be subcontracted to existing data management and archiving organizations (such as IRIS and the National Oceanographic Data Center [NODC]) and those that will have to be created and overseen by NEPTUNE.
- Evaluate the merits of contracted versus in-house operation of NEPTUNE-specific data management and archiving activities.

8.1.6 Environmental Considerations and Permits

Throughout Phase 2, NEPTUNE will consult on an ongoing basis with the various interested constituencies contacted during Phase 1 and will seek out and solicit input from additional groups. As the routing and installation strategies of the backbone cable and nodes become better defined, the NEPTUNE Coordinating Office will apply for necessary permits and consult with cognizant agencies and organizations to ensure that the technical progress of the project is not interrupted by unexpected socio-political issues.

8.1.7 Mapping and Cable Route Survey

We expect EM-300 swath bathymetry mapping of the entire Juan de Fuca Plate may be accomplished in the next several years quasi-independently, yet coordinated, with NEPTUNE, as part of the Global Ocean Mapping Project (GOMaP).[1] These data will by and large be adequate for establishing node locations and much of the cable route. A preliminary route must be specified and risk assessments (e.g., fishing hazards) must be made—this is included in what is called a "desktop study." It will still be necessary to perform high-resolution side scan surveys in Phase 3 of some of the node sites and route.

[1] *NEPTUNE Supporting Documents: The Juan de Fuca Plate as a GOMaP Pilot Project, 2000:* (http://www.neptune.washington.edu)

8.1.8 Funding

Present plans call for Phase 1 participants to be joined by the Monterey Bay Aquarium Research Institute (MBARI) to form the early nucleus of the Phase 2, Development, team. The Canadians will be involved in development, and they anticipate providing funding to cover costs of implementing NEPTUNE within their own waters. The Canadians have launched their own parallel NEPTUNE effort and had a successful initial meeting in March 2000.

The core Phase 2, Development, team will raise support for designing and building NEPTUNE. A suite of potential contributors includes interested agencies, private and public foundations, and private industry in both the U.S. and Canada.

As we enter Phase 2, we will expand institutional participation and must consider involving private industry in the development and installation phases. If industry partners are entrained, they may share some of the program costs. If industry involvement is largely as subcontractors, they will not participate in program management. We will explore potential mechanisms for attracting corporate interest in sponsorship of and/or active financial participation in NEPTUNE.

The group of institutions and individuals that will be NEPTUNE users will include members of the core development team and a wide array of possible contributors to the program. These participants will be organized into science working groups (SWGs) with the responsibility to define, design, purchase, and deploy suites of instrument arrays for NEPTUNE experiments and educational activities. The SWGs and individual PIs will seek funding from a variety of sources over the coming four years to allow timely deployment of a beginning set of instruments and experiments when the development phase nears completion.

Our most pressing issue is obtaining support for Phase 2, which we estimate will cost $13M. Early support of the feasibility study came from NOPP. We will submit proposals to the NSF Ocean Sciences Division within the Geosciences Directorate for a significant portion of the funding necessary to complete Phase 2, Development, and Phase 3, Installation. Building upon early involvement of NASA through JPL's participation in Phase 1, we will continue to work toward finding elements of common interest between NEPTUNE and NASA Codes Y and S.

A project of NEPTUNE's scope and magnitude is considered large within the field of oceanography. Except for ship construction, there are few comparable capital expenditures for research platforms in our field. Building a ship usually involves a single source of funding with a designated community of ship users specifying design parameters. It is unlikely that any single source of support will provide all the funding requirements for design, testing, construction, instrumentation and operation of NEPTUNE over its nominal thirty-year life span. With this in mind, early Phase 2 activities must be aggressively focused on identifying and entraining in-kind contributors and specific financial supporters.

8.1.9 Oversight and Management

Together with building a strong financial base, the most urgent Phase 2 item for NEPTUNE will be the establishment of an oversight and management structure to oversee the development of the program. Priorities in this area, in rough chronological order, are listed below:

- Formalize affiliations of Phase 2 institutions with NEPTUNE
- Institution directors appoint Oversight Board members
- Oversight Board meets to establish its operating procedures, elect officers, and work with the NEPTUNE Coordinating Office to formalize the NEPTUNE management structure
- Begin to staff NEPTUNE Coordinating Office to meet its Phase 2 responsibilities
- Oversight Board appoint members of its key committees and working groups
- Committees and working groups establish electronic communications and set agendas and timetables
- Oversight Board and its committees and working groups establish a schedule of regular interactions (some electronic, some in-person) with the NEPTUNE Coordinating Office to oversee all Phase 2 activities.

8.2 Phase 3—System Installation

For the science and education components of NEPTUNE, Phase 3 is a smooth transition between the initial planning and design in Phase 2 and the implementation in Phase 4. However, for the NEPTUNE infrastructure, Phase 3 is the culmination of effort and is addressed here.

8.2.1 Oversight and Management

A significant part of the Phase 3 work will be done by industry, and thus within NEPTUNE the major task will be management and oversight, as listed below.

- Issue requests for proposals for the required work, based on the work of Phase 2, ideally in 2002. Awards could then be made by late 2002 for the long lead items, especially the cable and science nodes.
- Provide the technical contract management for the individual industry contracts.
- Coordinate all efforts to assure a seamless integration.

8.2.2 Infrastructure

Some of the specific tasks that constitute the technical part of Phase 3 are as follows:

- Cable-route surveys and planning. Cable route surveys will be performed as necessary, with initial routes based on the plate-wide EM300 mapping. The nearshore, buried segments out to a water depth of 2000 m will be surveyed.
- Continue prototype testing. Existing prototypes will continue to be subjected to strenuous testing using appropriate test beds.
- Inspection and testing of cables, connectors, nodes, and shore equipment. During manufacturing and after acquisition, components must be inspected and tested. For instance, as nodes (junction boxes) are manufactured, NEPTUNE must conduct independent inspecting and testing.
- Physical (hardware and software) system integration and testing before deployment. All the nodes and cable must be prepared for deployment, cables joined to branch units and backbone interface junction boxes, etc. A suitable staging area near the operations area will be selected for this.
- Preparation of shore facilities and installation equipment. Two candidate shore stations are described in *NEPTUNE Technical White Paper #6: Shore Stations*.[2] All shore-side facilities, both at the shore station and at the remote network operations and control center, must be ready when the cable is first deployed. The data management and archiving system will begin to ramp up operations.
- Installation of the first backbone section. The marine installation of the backbone cable will follow generally accepted industry practice. Cable ships, cable ships-of-opportunity, and UNOLS vessels will be used as appropriate. Cable will be buried 1 m deep to the base of the continental slope, which in this region is at approximately 2000 m water depth. The buried cable sections will be inspected. The backbone interfaces will be installed at each node.
- Installation of science nodes. The installation of the science interface junction boxes will be done from a separate vessel with an ROV following the backbone cable lay.
- System commissioning. There will be a period of months before the system can be declared fully operational. During that time, some of the science experiments can be installed.
- Installation of community science experiments. This task overlaps with Phase 4, Operations. The installation of the science sensor systems will require ROVs with the capability to lay cable from cable packs, drums, or sleds. The Navy has developed the capability to lay and bury small-diameter cable using an ROV, and this capability will be required for work on the continental shelf and slope. Tracked ROVs that can pull sleds with reels are also becoming more common. In some cases, cable-laying equipment that could be installed on an academic ship may be appropriate. The installation of the "basic" sensor networks can occur along with the installation of the science interface junction boxes; other community experiments would be installed later.
- Installation of PI science experiments. Some of these could be installed in parallel with the community experiments, though most likely would wait for the completion of system commissioning.
- Repeat for the second backbone section in 2005 (procurement) and 2006 (installation).
- During the installation and commissioning, system documentation will be completed and the operators will be trained.

8.3. Phase 4—Operations

The operational phase of NEPTUNE will begin in earnest when the first sensor systems are installed, in 2004. Components of Phase 4 are shown in Figure 8.3.

8.3.1 Oversight and Management

Once the NEPTUNE backbone is installed and comes on line, the oversight of the program will transition from the focused Oversight Board of the development phases to a broadly based organization analogous to IRIS, NCAR, or CORE (it could even be a subsidiary of an existing such body). Any interested institution will be able to join the NEPTUNE oversight organization for a nominal fee. Mem-

[2]*NEPTUNE Technical White Paper #6: Shore Stations* (http://www.neptune.washington.edu)

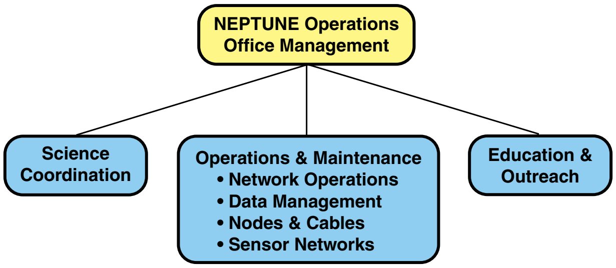

Figure 8.3. Components of NEPTUNE Phase 4, Operations.

ber institutions will meet annually to elect officers and an executive committee, which will be responsible for appointing advisory committees and working groups that will work on a day-to-day basis with the NEPTUNE Operations Office (itself the successor to the NEPTUNE Coordinating Office). This well proven organizational structure will provide continuing, independent, user-community oversight of NEPTUNE and will provide a structure for periodic critical peer reviews of the core operations and community experiments of the program.

8.3.2 Science Coordination

Responsibilities of the SWGs, which will be reduced once NEPTUNE becomes operational, will include the following:

- Focus on ensuring that community experiments are carried out effectively via periodic in-depth reviews to assess the continuing relevance and technical currency of these experiments.
- Recommend and oversee development of new community experiments.
- Track data management and archive systems to ensure user needs are met.
- Respond to requests for advice on the feasibility and priority of new experiments, particularly if NEPTUNE-network power, bandwidth, or both become limiting.

8.3.3 Education

With the beginning of NEPTUNE operations in Phase 4, data will begin to flow to education and outreach programs. K–12 curricula developed and tested during Phases 2 and 3 will be put into the classroom. Master teachers will be taught how to train fellow teachers in the use of NEPTUNE resources. NEPTUNE information will be integrated into institutions and organizations involved in ocean interpretation.

8.3.4 Operations and Maintenance

Technical operations will revolve around four functions: network operations, data management, sensor network maintenance, and node and cable maintenance. These functions will reside under one management umbrella within the NEPTUNE Operations Office, probably with subcontracts to one or more groups.

- *Network operations*. In the ideal situation, the network operations associated with the backbone infrastructure run automatically; this should indeed be the case for a steady state system. However, with sensors coming and going, and with varying power and communication requirements, the network will require monitoring. We expect that monitoring by NEPTUNE personnel 8 hours per day, 7 days per week will be adequate; shore station contract personnel, shared with other cable systems, can monitor the system for the balance of the time.
- *Data management and archiving* The form of the data management and archiving is not yet clear, but we assume there will be at least a small, central group that works to manage and archive the data. This will include QC/QA of community experiment data, caring for NEPTUNE-specific data, routing particular kinds of data to other data centers (such as IRIS for seismic data), and assisting scientists performing data "mining."
- *Sensor network maintenance*. The continual support and maintenance of the community and PI experiments will require the use of a Class 1 oceanographic vessel during the "fair weather season" of May – October, with ROV support. A dedicated support group will be required to maintain the sensor networks, install community experiments, and assist on PI experiments.
- *Seafloor node and cable maintenance*. We assume that each node will be serviced once every 5 years, with unscheduled service calls on 2 of the 30 nodes per year. This will require 1 month of ship and ROV time. Personnel can be shared with the sensor network maintenance. If the backbone cable breaks for some reason, a plan must be in place for making a timely repair. At this time, we assume that a contractor will maintain the necessary pre-positioned equipment and supplies and a list of possible repair vessels—either cable ships or cable ships-of-opportunity. UNOLS ships may possibly be used for some repairs if appropriate.

8.4 Summary

The project timeline has been given in Figure 8.1.

In Phase 2, Development (2000–2003), the following will be accomplished:

- Begin long-term planning necessary for sustained science; define, plan, obtain funding for, and develop community experiments.
- Accomplish infrastructure engineering design, form integrated engineering team, define role of industry.
- Plan data management and archive system; solicit community feedback via a working group.
- Map the Juan de Fuca Plate to establish node sites and cable routes and as a prerequisite to conducting useful science. Mapping will most likely be undertaken in close cooperation with GOMaP.
- Obtain environmental permits and interact with stakeholders.
- Define and plan the NEPTUNE education and outreach program.
- Pursue public, corporate, foundation, and private funding.
- Establish Oversight Board and define project organization and management. Establish NEPTUNE Coordinating Office.

In Phase 3, Installation (2003–2006), the management function will transition to technical oversight of the procurement and installation activities. Steps in system installation include the following:

- Procure hardware, software, and services.
- Plan cable route, based on mapping in Phase 2.
- Prepare for deployment. Integrate and test system before deployment. Prepare shore facilities (including network management) and installation equipment. Ramp up data management and archive system and the education/outreach program, in synchrony with the expected data flow.
- Install backbone cable.
- Install community and PI experiments, starting in 2004.
- Document system and train operators.

During Phase 4, Operations (2004–…), education and outreach activities will be fully implemented. Oversight and management structure will likely change to an organization analogous to IRIS, NCAR, or CORE.

The NEPTUNE Operations Office will oversee the following:

- Network operations
- Data management and archiving
- Sensor network maintenance
- Seafloor node and cable maintenance

The responsibilities of the science working groups will include the following:

- Oversee continuing and new community experiments.
- Assure the data management and archive activity well serves the community.
- Advise on feasibility and priority of new experiments and resolve conflicts that arise.

9. Cost Estimates

The preceding sections of the report provide the information needed to estimate the cost of NEPTUNE. We give a summary here; details of costs are provided in Appendix A. Costs are given in year-2000 U.S. dollars. Inflation over the NEPTUNE timeline is a significant factor and must be taken into account. The consumer price index (CPI) averaged over the last 5, 10, and 20 years is 2.0, 3.3, and 4.7%, respectively. For reference, over a 5-year period these values correspond to 10, 18, and 26%; when presenting inflated costs we will use 4.7% to be conservative.

9.1 Phase 2—Development (2000–2003)

The main elements of Phase 2 are shown in Figure 8.2. Phase 2, with a duration of approximately 3 years, runs nominally from the end of this feasibility study to the point when bids are issued and the infrastructure system design is complete. The costs are given in Table 9.1. The total estimated cost of $12.9M includes $5.7M for infrastructure system design, $2.8M to organize the science effort, and $3.0M for the NEPTUNE Coordinating Office. Table A.1 in Appendix A provides details of these costs.

Table 9.1. Development costs (year-2000 U.S.$)

	Cost $M
NEPTUNE Coordinating Office	3.0
Infrastructure System Design	5.7
Cable Route Planning	0.2
Environmental Considerations and Permits	0.7
Community Experiment Planning	2.8
Education and Outreach	0.6
Totals	**12.9**
Community Experiment Development	*15.0*

We have held separate the estimated cost of community experiment sensor network development because of the high uncertainty associated with this cost. Our rough estimate of $15M assumes that sensor network development for the initial community experiments will consist primarily of integrating existing sensor systems and that major efforts, such as AUV development, will be funded from other sources. The basis for this estimate is described in Section 2.6.1, where we present scenarios that represent a first cut at a collection of community experiments. We emphasize again that these scenarios are intended only as generic placeholders for what the science community will design, build, and deploy.

9.2 Phase 3—Installation (2003–2006)

The summary of the estimated costs for NEPTUNE installation is given in Table 9.2. (Detailed costing information is given in Table A.2, Appendix A.) We believe these cost estimates are conservative. Part of the Phase 2 effort will be to determine the appropriate level of reserve after assessing risk, reliability, and maintenance issues. The shore facility includes the physical plant at each shore site as well as the network operations center and data management and archive. The node cost is based on experience with the Hawaii-2 Observatory junction box. Budgetary proposals for the installation were obtained from two marine installers, Global Marine and Pirelli-Jacobson; these were merged with our experience and the experience of our consultants to arrive at the costs given.

The cable length includes spare as well as slack necessary in laying (each 5%). Estimated freight costs ($0.9M) are included in the cable cost. A total of 93 days of cable-ship laying time is required. Two spare nodes are included. The cost of the basic cable is the single largest cost. The average cost per kilometer is $30K; average cost per node is

Table 9.2. Summary of NEPTUNE installation elements and costs (year-2000 U.S.$)

km	Cable $M	Nodes	Nodes $M	Install $M	Shore $M	Total $M	UNOLS Ship $M	UNOLS Ship days
3321	**34.4**	**32**	**19.8**	**16.9**	**12.8**	**83.9**	**4.6**	**237**

$3M. Costs for ship time associated with the post-lay inspection and burial (PLIB) and for the science-node installation are separate, under the assumption that these services can be provided by UNOLS. We assume that installation is accomplished in two sections, with the first section installed in 2004, at a cost of $54M, and the second in 2006, at a cost of $29M ($65M and $39M, respectively at 4.7% annual inflation).

The estimated costs for the procurement and installation of the community science sensor networks are given in Table 9.3. Again, these estimates are based on the scenarios of Section 2.6.1. Unit costs for the sensor network are shown in Table A.3, Appendix A. We do not attempt to cost any additional experiments, but the costs provided indicate what other similar sensor networks might cost. The basic network will probably be installed with the science nodes, thereby eliminating much of the associated installation ship time.

If we assume the procurement and installation is over 6 years starting in 2004, as shown in the time line, then the annual cost during installation is $11.2M/year (in year-2000 U.S.$). If we assume 4.7% inflation, then the first year costs $13.5M/year and the sixth year costs $17.7M/year.

9.3 Phase 4—Operations (2004–…)

Annual operating costs are broken into seven sections and are summarized in Table 9.4. Costs within each section are described in Appendix A, Section A.3.

9.4 Summary

NEPTUNE costs are summarized in Table 9.5.

The estimated cost for the NEPTUNE plate-scale infrastructure is $102M; Phase 2, Development (2000–2003), $13M; Phase 3, Installation (2003–2006), $60M in 2003–2004 and $30M in 2005–2006. A rough estimate for the cost of a suite of community experiments is $98M, of which $15M is for development. Costs for experiments will be spread over the next 10 years. Operating costs will be about $10M/year. Costs are in year-2000 U.S. dollars.

Table 9.3. Costs of sensor networks (year-2000 U.S.$)

Sensor Networks	Number	Unit cost $M	Total $M	UNOLS Ship+ROV	
				$M	Days
Basic	30	0.2	6.2	4.5	150
Intermediate	15	2.2	32.3	5.0	165
Observatory	4	7.1	28.5	6.0	200
Total			**67.0**	**15.5**	**515**

Table 9.4. NEPTUNE annual operating costs (year-2000 U.S.$)

Phase 4	Cost $M	UNOLS Ship+ROV	
		$K	Days
Neptune Coordinating Office	0.8		
Network Operations	1.4		
Data Management and Archive	1.2		
Education and Outreach	0.3		
Sensor Network Maintenance	1.3	2.7	90
Seafloor Node Maintenance	1.0	0.9	30
Cable Maintenance	0.4		
Totals	**6.4**	**3.6**	**120**

Table 9.5. NEPTUNE summary costs (year-2000 U.S.$)

Infrastructure	Total $M	UNOLS $M	UNOLS Days
Phase 1 Feasibility Study	1		
Phase 2 Development	12		
Phase 3 Installation	84	5	237
Phase 4 Operations	6/y	4/y	120/y
Community Science			
Phase 2 Development	15		
Phase 2 Build & Install	67	16	515
Infrastructure	**$102M**		
Science	**$98M**		
Annual Cost	**$10M/y**		

The major cost uncertainty for all phases lies in the Community Science category. In Phase 2, we have explicitly accounted for costs of science planning, with the expectation that the science working groups will better define the budget requirements and then organize the funding. Because the experiments are not yet defined, we have presented what we hope is a plausible scenario, with the understanding that eventual implementation will be most certainly different but within the same cost envelope. Furthermore the community science scenarios given here will continue to evolve, with associated costs, over the life span of the system.

In Phase 3, costs directly associated with the installation of the infrastructure are believed sound and somewhat conservative. One of our major assumptions throughout is that it is valid to separate the post-lay inspection and burial ship time and the science-node- and network-installation ship time as UNOLS ship time.

Because data management and archive specifications are still in a rudimentary stage, costs in all phases are less certain.

10. Conclusions and Recommendations

10.1 Conclusions

NEPTUNE will deliver high-bandwidth two-way communications and substantial electrical power to a four-dimensional array of large numbers of instruments and sensors. It will foster a new, more integrated era of research and education in the ocean and earth sciences. Experimental nodes for the system will be distributed over a volume that will extend from the air–sea interface to the bottom of the oceanic crust covering an area that includes the entire Juan de Fuca Plate, its margins, and beyond.

In framing our study, we asked three questions about the NEPTUNE concept:

1. Is NEPTUNE scientifically desirable?
2. Is it technically feasible?
3. Is it financially reasonable?

The answer to all three questions is “yes.”

First, there are strong intellectual and societal drivers for implementing NEPTUNE.

- New Approaches - NEPTUNE represents a new, technologically innovative, four-dimensional approach to the study of earth and ocean systems. The history of science shows that new technologies, like telescopes and microscopes, commonly result in discoveries that are difficult to predict.
- Origin and Limits of Life - Some of the most primitive habitats on earth exist in submarine volcanoes. Establishing a continual instrumental and robotic presence within such dynamic systems will allow totally new forms of research into the conditions under which ancient life evolved, the upper limits to life, and exotic deep-crust life forms released only during eruptions.
- Understanding Plate Dynamics - A comprehensive decadal-scale examination of all processes operating in a single active plate system has never been attempted. Intriguing new data suggest that plate activities may be more interconnected than previously suspected.
- Education and Public Outreach - A completely new approach to both formal and informal education can be developed around the capability to provide real-time data and interactive opportunities with dedicated submarine laboratories accessible via the Internet. Such systems will become much more common.
- Ocean Productivity Studies - Establishing selected, and nested, control volumes for detailed, continuous long-term assessment and quantification of all physical, chemical, and biological interactions involved in primary and secondary productivity will fundamentally re-orient biological approaches to ocean science.
- Marine Mammal and Fish Stock Assessment - A NEPTUNE facility will allow real-time tracking of the health and behavior of marine mammals and the abundance and migration patterns of open ocean fish stocks.
- Resource Formation - Documentation of the formation and accumulation of metal deposits and of hydrocarbon accumulation processes and rates will provide new insights into the search for scarce resources.
- Hazard Mitigation - Recognizing and anticipating earthquake patterns, landslide activity, and tsunamis are areas where the NEPTUNE capability will provide important new insights. Tracking pollution and tracking toxic blooms are other potential uses.
- Greenhouse Gas Cycling in the Ocean - A broad spectrum of processes involved in movement of carbon gases through the ocean is accessible for quantification using specifically designed experiments enabled by the NEPTUNE cabled facility and instrumental arrays .
- Biotechnological Use of Extremophiles - Enzymes extracted from diverse microbial communities supported by extreme conditions within the ocean and underlying crust are and will be sources of bioactive materials for powerful industrial applications. The ability to track and sample otherwise undetected events will give us new access to such compounds.
- Perturbations - With NEPTUNE the scientific community will be able to actively perturb the natural system and track the actual results to establish whether these results unfold as predicted by existing models. Examples include iron fertilization experiments, modification of a black smoker, and triggering of turbidite flows.

Second, NEPTUNE is feasible from a technological point of view. This report demonstrates that the needed electrical power can be delivered to as many as 30 experimental nodes distributed across the plate environment and its overlying mass of ocean. The approach to power recommended herein is not standard for submarine cable systems currently in use by the submarine telecommunication industry, but it is common for land-based power systems. By extending the well-established protocols and technology developed for the Internet to the seafloor, we can use commercial-off-the-shelf (COTS) components that contribute to the dependability of the system and will make the program affordable. Requirements for accurate and precise timing can be met.

Third, within the context of what NEPTUNE brings to the earth, ocean, and planetary sciences, the system is quite affordable. The cost estimate for the basic infrastructure, without instruments attached, is about $100M. In addition, depending on the effort and commitment of the scientific and educational participants, the cost estimate for a plausible set of sensor networks is about $100M. Post construction, routine operations will average about $10 M/yr. These numbers are not substantially different from numbers for an ice-capable research vessel, yet NEPTUNE is an entirely new approach to conducting science at sea.

As with ships, telescopes, and other common facilities in use within the scientific community, it is unlikely that any single scientific group would be able to argue cogently for a NEPTUNE facility strictly on the basis of their own science. But by designing the system with the geographic scale of an entire plate and with the temporal scope of seconds to decades, NEPTUNE offers much broader appeal to a wide spectrum of scientists and educators to pursue the next advances in their fields. Indeed because it will encompass such breadth, the potential for making new cross-cutting discoveries is much enhanced by casting all the activities within a common area along the same timebase.

10.2 Recommendations

1) *Initiate Phase 2, Development, by mid 2000.*

2) *Establish a NEPTUNE Coordinating Office.*

3) *Identify institutional participants and the role of industry in the technical design and establish the project organization and management structure.*

4) *Establish the long-term science working groups with financial support for the chairs.*

5) *Identify a variety of agency, foundation, and corporate funding sources for all aspects of the program and pursue centralized funding for Phase 2.*

6) *Assemble the education and outreach team for NEPTUNE with the charge to define the major elements of the program by the end of year 1 of Phase 2.*

7) *Define the international character of the program.*

The time to initiate NEPTUNE is now. Despite the fact that communications, networking technologies, sensor development, robotic research, and miniaturization are changing rapidly, the existence of a major cabled facility will focus research on the integration of these systems into critically needed applications for NEPTUNE-like systems.

We recommend that the focus of NEPTUNE remain at the overall mesoscale plate-scale observatory. At these scales we can encompass many of the basic processes operative on the planet. As a community, we are not yet ready to build a planetary scale observatory with NEPTUNE capability, and the next scale down is that of a plate. We have demonstrated that it is both feasible and affordable.

It is crucial that the scientific working groups be identified and enfranchised as soon as possible. They will have the primary responsibility for definition of the essential intellectual and practical elements of the program from the point of view of the science and the measurements to be made. These teams will be responsible for designing major high-profile experiments and for delivering the appropriate types and numbers of instruments to the program when ready for installation.

We recommend that the program be international in character. The Juan de Fuca plate is shared by Canada and the U.S. We will work closely with our Canadian colleagues to implement the program in a timely manner and invite scientific and educational participation in the use of the facility from personnel in the U.S., Canada, Germany, and other countries.

10.3 Final Comments

The NEPTUNE program offers exciting opportunities to move ahead in three broad areas.

First, as envisioned, NEPTUNE will enable the deployment of an observing-experimental network of unprecedented density, variety, spatial coverage, and flexibility. It will include novel instrumentation for sensing the combined *in situ* biological, chemical, and physical environment on, above, and below the seafloor.

Second, a cornerstone of the natural sciences is the recognition of the need to create models that describe in simplified form the world in which we live. NEPTUNE observations will support a modeling effort that will distill the essence of the observations and permit detailed assessment of model fidelity, followed by further testing and stressing under different circumstances. Within NEPTUNE, as the models acquire skill, they can be used to adaptively redirect deployment of mobile observational platforms in anticipation of, or in response to, episodic and other events.

Third, the availability of a unified observing system for the NEPTUNE region will allow scientists to address issues of process-coupling across multiple spatial and temporal scales. Properly configured and executed, NEPTUNE may become the equivalent of a large ship designed to sail through time rather than space. In this sense, NEPTUNE represents a major step toward conducting oceanographic research and education in the 21st century.

The level of excitement that NEPTUNE and its capabilities has engendered among members of the broad marine science community leaves no doubt that the time to move ahead is now. For the first time, the supply of substantial amounts of continuous power and two-way communications to a diverse set of sensors and interactive experiments will allow science at sea to become as rich and unfettered as science on land. We can forecast with confidence that NEPTUNE will lead to quantum leaps in our understanding of processes in the ocean and underlying lithosphere. These leaps in turn will translate into a greatly improved ability to model and predict the behaviors of these dynamic parts of our environment and their impact on our social and economic well being.

Appendices

Appendix A—Cost Estimate Details

A.1 Phase 2—Development (2000–2003)

Phase 2 includes all tasks from the end of this feasibility study to the point when bids are issued and the system design is complete. As the timeline in Figure 8.1 indicates, its duration is 3 years. Phase 2 is divided here into 6 categories, Table A.1.

Coordinating Office. This office will provide the overall coordination and direction required for a project of this scope. The project director and project manager will be supported by an administrative staff and by publications/graphics personnel. Office equipment, travel, services, and supplies are included. The NEPTUNE Coordinating Office will be responsible for coordination with the scientific community, including one general workshop each year. The Office will assist the science working groups in coordinating workshops and planning community experiments.

Infrastructure System Design. The infrastructure system design task deliverable is a set of bid packages (or equivalent) that contain all the relevant information for NEPTUNE to be built and installed; implicit in this are working prototypes of critical components of the system. The task begins with a revisit of all the issues raised in this report to define the system, followed by preliminary and detailed design phases that include science-node engineering and prototyping, shore-station engineering, and data management and archiving. One of the tasks early in Phase 2 will be to determine the appropriate role of industry. For the engineering effort, the following is assumed on average per year: 5 man years divided between a project/systems engineer, a scientist, a manager, and 4 senior engineers (hardware and software), 3 man years for technical and administrative support staff, and travel, equipment, supplies, and services.

Cable Route Planning. While a mapping effort for the complete Juan de Fuca Plate may be sponsored by the Office of Naval Research (ONR) and NSF (and paid for separately), the cost of such an effort is estimated to be $5M. The results of this large-scale survey will provide a good first estimate for the cable route planning, thereby reducing the costs of the subsequent (Phase 3) high-resolution surveys. In Table A.1, costs are included only for the coordination with the main mapping effort and the "desktop survey" that uses existing data.

Environmental Considerations and Permits. While the NEPTUNE Coordinating Office will take a lead in this task (with direct personnel costs covered in the NEPTUNE Coordinating Office task), there will be additional costs for consultants, conducting public meetings with stakeholders, and satisfying NEPA and permitting requirements. We assume here that an Environmental Assessment or an Environmental Impact Statement will be required ($250K).

Table A.1. NEPTUNE Phase 2 costs (year-2000 U.S.$).

	Year 1 $M	Year 2 $M	Year 3 $M	Totals $M
NEPTUNE Coordinating Office	0.8	1.1	1.1	3.0
Infrastructure System Design	1.7	1.9	2.0	5.7
Cable Route Planning	0.1	0.1	0.1	0.2
Environmental Considerations and Permits	0.1	0.3	0.3	0.7
Community Experiments	1.0	1.0	1.0	2.8
Education and Outreach	0.2	0.2	0.2	0.6
Totals	**3.7**	**4.4**	**4.7**	**12.9**
Community Experiment Development				*~15.0*

Community Experiments. During Phase 2, overall system requirements (including such things as node locations) and sensor systems must be developed by the science community. Sensor systems must be ready for deployment when the NEPTUNE infrastructure becomes operational. NEPTUNE will jump-start this effort through the science working groups, enlisting the leadership of distinguished senior scientists to spearhead the development. The figures given here reflect 3 months of support for 10 senior scientists, with travel and meeting costs ($40K per year), to organize this effort. At this stage, we expect the required technical development to be incremental, primarily the integration of existing sensors, rather than the development of new sensors (which will be essential in the long term). We take a representative development cost to be $15M. This is somewhat more than the estimated total cost of each of the three sensor network classes (a total of $11.5M, see Section A.2), or about 17% of the total NEPTUNE community science capital cost estimate.

Education and Outreach. One staff member will be supported for this task, ramping up from half to full time. Workshops for each target group (K–12, undergraduate, and public) will be held.

A.2 Phase 3—Installation (2003–2006)

This section is divided in two parts: one for the NEPTUNE infrastructure, and the second for the community experiments based on the scenario of Section 2.6.

A.2.1 NEPTUNE Infrastructure

A summary of the unit costs for the major cost drivers and other relevant parameters used for estimating costs is given in Table A.2.

A.2.2 Community Experiments

In the scenario section, basic, intermediate, and observatory sensor networks are described. We emphasize again that these scenarios are intended only as generic placeholders for what the science community will design, build, and deploy.

The estimated cost for each class of sensor network is given in Table A.3. These costs do not include development or labor. We assume here that the UNOLS cost now includes both $20K/day ship costs and $10K/day for an ROV.

Per the discussion in Section 2.6, a reasonable mix of community experiments is represented by 30 basic sensor networks (1 at each node), 15 intermediate sensor networks, and 4 observatory sensor networks. We do not attempt to cost any additional experiments, but these costs give an indication what other similar sensor networks might cost. The basic network probably will be installed with the science nodes, thereby eliminating much of the associated installation ship time.

A.3 Phase 4—Operations

Described below are the seven categories of annual operating costs (Table 9.4).

NEPTUNE Operations Office. Two senior personnel, 3 full-time support staff (includes 1 student), travel and meetings.

Network Operations. Six full-time technical staff with support and $30K/yr in equipment upgrades. This level of staffing will permit manning 8 hours per day, 7 days a week.

Data Management and Archiving. Four and a half full-time technical staff with support and $200K/yr in equipment upgrades. If the data management and archiving (DMA) and the Network Operations Center are co-located, there would be resource sharing that would lower the cost. For comparison, the IRIS data management operation costs $1.8M/ year, which includes $300K/y for equipment.

Education and Outreach. One full-time person with support for 1 workshop per year.

Sensor Network Maintenance. Four full-time technical people, travel, equipment ($200K), and supplies ($150K).

Seafloor Node Maintenance. Three full-time technical people, travel, equipment ($200K) and supplies ($150K) are used. The sensor network maintenance task and the seafloor node maintenance task will probably share resources.

Cable Maintenance. There are several possibilities for backbone cable maintenance; the cost shown here assumes a maintenance contract that uses vessels of opportunity. The cost reflects one repair every four years, which is conservative.

If we assume these costs start in year 2004, then the inflated cost (4.7% per year) in 2004 is $7.7M/year, increasing to $19.3M/year 20 years in the future.

Table A.2. Costing parameters for Phase 3 (year-2000 U.S.$)

Item		Units		Item		Units
Cable*	9.86	$/m		Slack	5	%
				Spare cable	5	%
Shore Facility				Science nodes		
Engineering and Management	2000	$K		Standard	556	$K
Power System	1000	$K		Branching Node	633	$K
Communication System	1000	$K		Shelf Node	721	$K
Data Management and Archive	600	$K				
Sea/Shore Interface	300	$K				
Installation						
Management and Engineering	1000	$K				
Freighter Transit Cost	8	$K/day		Freighter Speed	28	km/hr
				Freight Distance	10,000	n. mi.
Cable Ship with Plow	70	$K/day		Cable Lay Speed	6	km/hr
UNOLS Ship	20	$K/day		Cable Burial Speed	0.6	km/hr
ROV—Cable	15	$K/day		Pre-Lay Grapnel Run (PLGR) Speed	1.0	km/hr
ROV—Science	10	$K/day		Post-Lay Inspection and Burial (PLIB) Speed	0.3	km/hr
Mob/Demob Cost	300	$K/lay				
Cable Route Surveys	600	$K				

*This cable cost is the list price for one particular external strength member cable with 15 fiber pairs. The actual cost may be less because of discounts and/or by using center strength member cable and fewer fibers, or some mix thereof.

Table A.3. Sensor network unit costs (year-2000 U.S.$)

Sensor Network	Sensors	Sensors	Cable+ Connectors	Total	UNOLS Ship+ROV	
		$K	$K	$K	$K	Days
Basic	OBOS, Video, Digital Still, AUV Dock	150	58	208	150	5
Intermediate	6 OBOS on 3 40-km Legs	300	520	820	180	6
	Mooring A	110	30	150	30	1
	Mooring B	400	30	430	30	1
	AUV	250		250		
	Borehole	400	30	430	90	3
	Total	1460	610	2080	330	11
Observatory	68 Sensor Suites 130-km Cable	5290	1844	7134	1500	50

*OBOS—Ocean bottom oceanography and seismometry

Appendix B—NEPTUNE White Papers

All white papers and supporting documents are posted at http://www.neptune.washington.edu

Science White Papers

NEPTUNE Science White Paper #1: Cross-Margin Particulate-Flux Studies Associated with NEPTUNE

NEPTUNE Science White Paper #2: Opportunities for Seismology and Geodynamics with NEPTUNE

NEPTUNE Science White Paper #3: Seafloor Hydrogeology and Biogeochemistry: Opportunities for Long-Term Borehole Experiments

NEPTUNE Science White Paper #4: Opportunities for Investigating Ridge-Crest Processes

NEPTUNE Science White Paper #5: Subduction-Zone Processes :Fluid Venting and Gas Hydrates at the Cascadia Convergent Margin

NEPTUNE Science White Paper #6: Deep-Sea Ecology

NEPTUNE Science White Paper #7: Water-Column Processes

Technical White Papers

NEPTUNE Technical White Paper #1: Power and Communication Requirements

NEPTUNE Technical White Paper #2: Cables

NEPTUNE Technical White Paper #3: Power

NEPTUNE Technical White Paper #4: Communications

NEPTUNE Technical White Paper #5: Environmental Considerations and Permits

NEPTUNE Technical White Paper #6: Shore Stations

Supporting Documents

The Juan de Fuca Plate as a GOMap Project

Extending our Reach Beyond NEPTUNE Nodes: Autonomous Underwater Vehicles and Acoustic Communications

Appendix C—Acronyms and URLs

AGU	American Geophysical Union http://www.agu.org/
ATOC	Acoustic Thermometry of Ocean Climate http://atoc.ucsd.edu/
BATS	Bermuda Atlantic Time-series Study http://www.bbsr.edu/cintoo/bats/bats.html
CANARIE	Canada's advanced Internet development organization http://www.canarie.ca/frames/workshop.html
Cal COFI	California Cooperative Oceanic Fisheries Investigations http://www-mlrg.ucsd.edu/calcofi.html
CEV	Center for Environmental Visualization http://www.cev.washington.edu
Cook Report on Internet	Gigabit Ethernet Rides Economy of Scale http://www.cookreport.com/08.13.shtml
CORE	Consortium for Oceanographic Research and Education http://core.cast.msstate.edu/members.html
DEOS	Dynamics of Earth and Ocean Systems http://vertigo.rsmas.miami.edu/deos.html
DFO	Department of Fisheries & Oceans (Canada) http://www.ncr.dfo.ca/
GEO	Global Eulerian Observatory
GEOMAR	Research Center for Marine Geosciences http://www.geomar.de/
GEOSTAR	GEOphysical and Oceanographic Station for Abyssal Research http://giove.ingrm.it/GEOSTAR/
GLOBE	Global Learning and Observations to Benefit the Environment http://www.globe.gov/
GLOBEC	GLObal Ocean ECosystems http://www.usglobec.org/
H2O	Hawaii-2 Observatory http://www.whoi.edu/science/GG/DSO/H2O/
HOT	Hawaii Ocean Time-series Program http://hahana.soest.hawaii.edu/hot/hot_jgofs.html
HUGO	The Hawaii Undersea Geo-Observatory http://www.soest.hawaii.edu/HUGO/hugo.html
IP over DWDM	Abstract by Raj Jain http://www.cis.ohio-state.edu/~jain/cis788-99/ip_dwdm/
IPOST	Institute for Pacific Ocean Science and Technology http://ipost.org
IRIS	Incorporated Research Institutions for Seismology http://www.iris.edu/
JGOFS	Joint Global Ocean Flux Study http://ads.smr.uib.no/jgofs/jgofs.htm
JOI	Joint Oceanographic Institutions http://www.joi-odp.org/

JOIDES	Joint Oceanographic Institutions for Deep Earth Sampling http://www.joides.geomar.de/
JPL	Jet Propulsion Laboratory http://www.jpl.nasa.gov/
Katama	Martha's Vineyard Coastal Observatory http://adcp.whoi.edu/MV_OBSERVATORY/index.html
LEO-15	Long-term Ecosystem Underwater Observatory http://marine.rutgers.edu:80/mrs/LEO15.html
LOE	Living on Earth: NPR's Environmental News Show http://www.loe.org/
LOT-PPG	JOIDES Long-Term Observatories Program Planning Group http://vertigo.rsmas.miami.edu/ltoppg.html
LTER	Long Term Ecological Research Network http://LTERnet.edu/
MATE	Marine Advanced Technology Education http://www.marinetech.org/
MBARI	Monterey Bay Aquarium Research Institute http://www.mbari.org
NASA	National Aeronautics and Space Administration http://www.nasa.gov/
NCAR	National Center for Atmospheric Research http://www.ncar.ucar.edu/
NEIC	National Earthquake Information Center http://wwwneic.cr.usgs.gov/
NeMO	The New Millennium Observatory http://newport.pmel.noaa.gov/nemo_cruise98/
NEPTUNE	http://www.neptune.washington.edu/
NEPTUNE Canada	Canadian NEPTUNE project http://www.neptunecanada.com/
Network World Fusion	Research on Gigabit Ethernet http://www.nwfusion.com/netresources/ge.html
NIST	National Institute of Standards and Technology http://www.nist.gov/
NOAA	National Oceanic and Atmospheric Administration http://www.noaa.gov/
NODC	National Oceanographic Data Center http://www.nodc.noaa.gov/
NOPP	National Oceanographic Partnership Program http://core.cast.msstate.edu/NOPPpg1.html
NOPP Observation Plan	http://core.cast.msstate.edu/NOPPobsplan.html
NPR, RE	National Public Radio, Radio Expeditions http://www.npr.org/programs/RE/
ODP	Ocean Drilling Program http://www.oceandrilling.org/
OFCC	Oregon Fishermen's Cable Committee http://ofcc.org/

ONR	Office of Naval Research http://www.onr.navy.mil/
PGC/NRC	Pacific Geoscience Centre/National Resources Canada http://www.pgc.nrcan.gc.ca/
PMEL	Pacific Marine Environmental Laboratory http://www.pmel.noaa.gov/pmelhome.html
PMEL-VENTS	NOAA/PMEL VENTS Program http://newport.pmel.noaa.gov/
POLARIS	Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity http://www.cg.NRCan.gc.ca/polaris/
PPS	Pulse per second, Internet-Drafts http://www.cabletron.com/support/internet/Internet-Drafts/draft-mogul-pps-api-02.txt and http://search.ietf.org/internet-drafts/draft-mogul-pps-api-06.txt
REVEL	Research and Education: Volcanoes, Exploration, and Life http://www.ocean.washington.edu/outreach/revel/
RIDGE	Ridge Inter-Disciplinary Global Experiments http://ridge.oce.orst.edu/
ROV.net	Commercial ROV site http://www.rov.net/
Science Friday	Weekly science talk radio show http://www.sciencefriday.com/
SeaWiFS	Sea-viewing Wide Field-of-view Sensor http://seawifs.gsfc.nasa.gov/SEAWIFS.html
SIO	Scripps Institution of Oceanography http://www.sio.ucsd.edu/
TAO	Tropical Atmosphere Ocean Project http://www.pmel.noaa.gov/toga-tao/home.html
TOGA COARE	Tropical Ocean Global Atmosphere/Coupled Ocean Atmosphere Response Experiment http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/TOGA/nasa_coare.html
TOPEX/ POSEIDON	Understanding Our Oceans and Climate from Space http://topex-www.jpl.nasa.gov/
UCAR	University Corporation for Atmospheric Research http://www.ucar.edu/
UNOLS	University-National Oceanographic Laboratory System http://www.gso.uri.edu/unols/unols.html
USGS	U.S. Geological Survey http://www.usgs.gov/
UW	University of Washington http://www.washington.edu/
Washington NASA Space Grant Consortium	http://www.waspacegrant.org/
WHOI	Woods Hole Oceanographic Institution http://www.whoi.edu/
WOCE	World Ocean Circulation Experiment http://www-ocean.tamu.edu/WOCE/uswoce.html

Inside back cover

A scenario for NEPTUNE node placement. (Graphic: CEV)

Back cover

NEPTUNE's linked array of undersea observatories will allow ocean scientists to study essential and interactive processes in the dynamic earth–ocean system off the coasts of Washington, Oregon, and British Columbia. Fiber-optic cable (white) will carry electricity and the communication power of the Internet to the seafloor. Red nodes indicate locations where suites of instruments will be attached. Sea surface and water column colors are proportional to satellite-derived and direct measurement of temperatures. NEPTUNE will permit studies of a single coherent volume of ocean and its underlying seafloor for periods up to three decades; data will flow in real time to land-based scientists, students, and decision makers.

Right inset shows the overall geometry of the NEPTUNE network on the Juan de Fuca tectonic plate. *Center inset* is a portable moored buoy observatory that may extend the NEPTUNE footprint. *Left inset* is an example of one of the NEPTUNE nodes, an observatory network draped over Axial Volcano and based on the NOAA/PMEL New Millenium Observatory. This node will provide crucial new insights into volcanic and seismic activity on the seafloor. (Graphic: CEV)

Data Sources:
Smith, W. H. F. and D.T. Sandwell, Global Seafloor Topography from Satellite Altimetry and Ship Depth Soundings; Multibeam bathymetry for Axial Seamount from RIDGE Multibeam Synthesis Project; GTOPO30 Topography; CIA World Databank for rivers and coastlines; and NOAA Coastwatch Satellite Data for sea surface temperature; Dynamics of Earth and Ocean Systems (DEOS) program.