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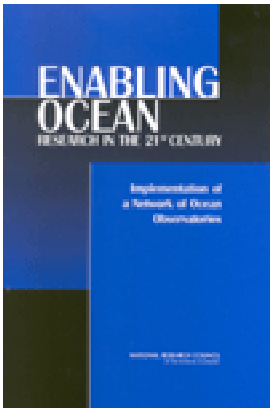

Enabling Ocean Research in the 21st Century: Implementation of a Network of Ocean Observatories

Committee on the Implementation of a Seafloor Observatory Network for Oceanographic Research, National Research Council

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ENABLING OCEAN
RESEARCH IN THE 21ST CENTURY

Implementation of a Network of Ocean Observatories

Committee on the Implementation of a
Seafloor Observatory Network for Oceanographic Research

Ocean Studies Board

Division on Earth and Life Studies

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Preface

In the ocean sciences, new technology inevitably leads to new discoveries and to fundamental advances in basic knowledge. In the years following World War II, for example, the first global-scale mapping and sampling of the seafloor by oceanographic research vessels led directly to the discovery of seafloor spreading and the development of the theory of plate tectonics which has since revolutionized ideas of earth structure and evolution. A decade later, the first exploration of mid-ocean ridges using deep-towed vehicles and manned submersibles resulted in the remarkable discovery of deep-sea hydrothermal vent communities with previously unknown forms of life and a vast, still largely unexplored microbial biosphere below the seafloor. Over the past two decades, ocean physicists, chemists, biologists, and geologists have used a variety of tools, from instrumented buoys to deep-sea drilling, to redefine their understanding of the ocean's role in controlling weather and longer-term climate change.

The ocean sciences are now on the threshold of another major technological advance as the scientific community begins to establish a global, long-term presence in the oceans in order to understand the temporal variability of ocean systems on time scales ranging from seconds to decades or longer. This opportunity arises from the confluence of a number of emerging new technological capabilities, including:

- telecommunications technology (e.g., satellites, fiber-optic submarine cables) that makes possible real-time telemetry of vast quantities of data to shore as well as real-time interactive control of instruments in even the most remote parts of the deep sea;

- telecommunication cables that enable significant levels of power to operate instruments from the sea surface to the deep seafloor;
- new sensors that make possible *in situ* measurements of physical, chemical, and biological processes;
- computational and modeling capabilities to build more realistic, multidisciplinary, and predictive models of ocean phenomena;
- data archival systems that can store, manipulate, and retrieve huge volumes of data from arrays of sensors; and
- computer networks that can bring real-time data to the desktop, which could potentially vastly increase participation of researchers, students, educators and the general public in ocean research and discovery.

The National Research Council (NRC) Committee on Implementation of a Seafloor Observatory Network for Oceanographic Research (Appendix A) was charged with addressing a number of issues related to the implementation of the National Science Foundation's (NSF) Ocean Observatories Initiative (OOI). The OOI would establish an observatory network, including coastal, regional, and global observatories, in order to facilitate basic research into physical, chemical, biological, and geological processes in the oceans. The goal of this report is to evaluate the readiness of the ocean science community, both scientifically and technically, to move ahead with the establishment of a research-driven ocean observatory network and to highlight the outstanding issues that must be addressed in order to successfully implement this observatory system. These issues include the status of scientific planning and technical development of ocean observatory systems, factors that might affect the timing of observatory construction and installation, the cost and logistical requirements for observatory maintenance and operations, observatory needs for sensor development and data management, the impact of ocean observatories on ships and deep submergence facilities available to the U.S. academic community, and the role of research-based observatories within the Integrated and Sustained Ocean Observing System (IOOS) and other international ocean-observing systems being developed and implemented primarily for operational purposes. The committee agreed that it was outside the scope of this study to evaluate the scientific merit of ocean research observatories, to carry out a detailed systems engineering design study, or to develop a comprehensive implementation plan and cost analysis.

The NRC Committee included representatives from both academia and industry with expertise in a wide range of ocean sciences, as well as in data management and commercial ship and remotely operated vehicle

(ROV) operations. This report builds on a previous NRC report titled *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science* (National Research Council, 2000), which outlined a broad range of fundamental scientific questions that would benefit from long-term, fixed ocean observatory sites. In arriving at its findings and recommendations, the NRC Committee also considered various reports on future ocean science research priorities, ocean observatory planning documents, recommendations from several recent workshops, and input from the ocean research community. At its first meeting in October 2002, the NRC Committee held an open day-long information gathering session with presentations on recent workshops and observatory planning efforts by leaders in the ocean science community. During the first day of its second meeting in December 2002, the NRC Committee again held an open meeting; as a result, various individuals with interest or expertise in ocean observatories attended and participated.

This report makes clear that many significant technical, logistical, and organizational challenges will have to be addressed in order to establish a research-driven ocean observatory network. However, the NRC Committee is optimistic that these challenges can be met and that the infrastructure provided by the Ocean Observatories Initiative will enable a new era of ocean research and discovery, facilitating major advances in basic knowledge of the oceans in the coming decades. The NRC Committee hopes this report will act as a useful first step in ensuring that the great potential of ocean research observatories is realized.

Robert S. Detrick
Chair

Acknowledgments

The committee would first like to acknowledge the contributions and support of its sponsor, the National Science Foundation.

This report was greatly enhanced by the input of those invited speakers who gave presentations at the NRC Committee's first meeting: Larry Atkinson, Old Dominion University, Norfolk, Virginia, and Ocean.US, Washington, D.C.; Peter Cornillon, University of Rhode Island, Narragansett; John Delaney, University of Washington, Seattle; Scott Glenn, Rutgers University, New Brunswick, New Jersey; Alexandra Isern, National Science Foundation, Arlington, Virginia; Richard Jahnke, Skidaway Institute of Oceanography, Savannah, Georgia; John Orcutt, Scripps Institution of Oceanography, La Jolla, California; Sarah Schoedinger, Consortium for Oceanographic Research & Education, Washington, D.C.; and Uwe Send, University of Kiel, Germany. These talks helped set the stage for fruitful discussions in the closed sessions that followed.

The committee is also grateful to a number of people who provided important discussion and/or material for this report: Anna Boyette, Alan Chave, Lawrence Clark, Tommy Dickey, William Fornes, Kim Fulton-Bennett, Bruce Howe, Carolyn Keen, Andrew Maffei, Kathleen Patterson, Nancy Penrose, Emmeiline Romana, and Todd Walsh.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. In addition, Margaret E. Sheer provided valuable copyediting assistance.

We wish to thank the following individuals for their participation in their review of this report:

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the report's conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by John E. Flipse, Distinguished Professor Emeritus, Texas A&M University, College Station, appointed by the Divison on Earth and Life Studies, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the National Research Council.

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Executive Summary

As the importance of the oceans to society grows, so does the need to understand their variation, both natural and human-induced, on many temporal and spatial scales. This need to understand change in the oceans is compelling Earth and ocean scientists to move beyond the traditional expeditionary mode of investigation to make sustained, *in situ* observations in the oceans and on the seafloor. Observing systems will enable the study of processes in the ocean basins over timescales ranging from seconds to decades and spatial scales from millimeters to thousands of kilometers, providing the scientific basis for addressing important societal concerns such as climate change, natural hazards, and the health and viability of living and non-living resources along our coasts and in the open ocean.

A recent report from the National Research Council (NRC) entitled *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science* (National Research Council, 2000) highlighted the need for long-term, fixed observatory sites in the oceans for conducting basic research to address a broad range of fundamental scientific questions. Seafloor observatories will utilize cables or moored buoys and will provide power and two-way data communication and instrument control for a wide variety of sensors located at the sea surface, in the water column, and at or below the seafloor. The *Hidden Planet* NRC report concluded that:

> . . . seafloor observatories present a promising and in some cases essential new approach for advancing basic research in the oceans… (National Research Council, 2000, p. 2).

In order to provide the U.S. ocean sciences research community with access to the basic infrastructure required to make long-term measurements in the oceans, the National Science Foundation's (NSF) Ocean Sciences Division has developed the Ocean Observatories Initiative (OOI). The OOI is an outgrowth of scientific planning efforts within both the national and international ocean research community over the past decade and is motivated in part by the rapidly expanding development of computational, robotic, communications, and sensor capabilities. The OOI, as presently envisioned, will have three primary components: (1) a global network of deep-sea moored buoys, (2) a regional-scale cabled observatory, and (3) an expanded network of coastal observatories. The OOI also includes project management, data dissemination and archiving, and education and public outreach components essential to the long-term success of ocean observatory science. The National Science Board of the NSF has approved consideration of the OOI for a Major Research Equipment and Facilities Construction (MREFC) project for a future NSF budget request.

The research-focused observatories enabled by the OOI will be networked with and become an integral part of the proposed Integrated and Sustained Ocean Observing System (IOOS) (Ocean.US, 2002a). The IOOS is an operationally-focused system, (in the same sense as the weather forecasting system) and is supported by several U.S. agencies. IOOS is a key U.S. contribution to the international Global Ocean Observing System (GOOS), which is designed to improve weather forecasts and climate predictions.

The observatory network proposed under the OOI will provide new, cutting-edge capabilities to the IOOS and to the research community. In particular, the OOI will enable the collection of time-series data at critical sites that have not previously been occupied due to the lack of systems capable of operating in severe environments. In addition, the OOI will provide previously unimagined levels of power and data bandwidth for arrays of instruments on the seafloor and in the water column. These fixed observatory sites will complement other elements of the IOOS and will expand the area of the ocean and seafloor now accessible with existing time-series sampling methods.

STUDY SCOPE

In the spring of 2002, the NSF asked the NRC to address issues related to the implementation of a seafloor observatory network for multidisciplinary oceanographic research. In particular, the NRC was asked to:

- provide advice on the design, construction, management, operation, and maintenance of the network, including the need for scientific oversight and planning, appropriately phased implementation, data management, and education and outreach activities;

- examine the effects of ocean observatories on the University-National Oceanographic Laboratory System (UNOLS) fleet and current submersible and remotely operated vehicle (ROV) and autonomous underwater vehicle (AUV) assets in the research community; and
- examine the potential role for NSF's research-based observatory network within IOOS as well as other international efforts being developed and implemented primarily for operational purposes.

The NRC Committee on the Implementation of a Seafloor Observatory Network for Oceanographic Research (Appendix A) was appointed in August of 2002 to carry out this charge. In arriving at its findings and recommendations, the NRC Committee was to consider various reports on future ocean science research priorities, ocean observatory planning documents, recommendations from several recent workshops, and input from the ocean research community.

KEY ISSUES

The establishment of ocean research observatories represents a major, long-term investment on behalf of the oceanographic research community. It is essential that this investment is made wisely and that these facilities support the highest quality scientific research and the most innovative educational and public outreach efforts. There are a number of issues that must be addressed in order to successfully implement a seafloor observatory network for ocean research (Box ES-1).

FINDINGS AND RECOMMENDATIONS

The following findings and recommendations are based on a detailed consideration of the issues listed above. These findings and recommendations are discussed in greater detail throughout this report, particularly in Chapter 7. A list of acronyms and a glossary are available for reference (Appendix B).

On the Role of Research-Driven Ocean Observatories

The NSF's OOI will facilitate research across a broad cross section of the ocean sciences and is part of a broader national and international effort to establish a global ocean-observing system. Ocean observatories will provide the infrastructure to collect long-term time-series data critical for assessing global oceanographic issues (e.g., climate change, the

BOX ES-1

Key Issues in Implementation of an Ocean Observatory Network for Research

- Evaluating the readiness of scientific planning for how to best utilize research observatories to advance basic understanding of earth and ocean processes;
- Developing and testing new observatory capabilities to enable high priority research that, to date, has not been addressed due to technical challenges;
- Coordinating planning with international research-driven ocean observatory programs, and with operational observing systems;
- Estimating the cost of observatory construction and installation;
- Assessing the national security concerns raised by advanced observatory capabilities;
- Identifying the needs for new sensors and instruments and their calibration and support;
- Establishing a management structure to oversee observatory construction, installation, and operation;
- Identifying the factors that will affect the timing of observatory construction and installation;
- Estimating the cost and logistical requirements for observatory maintenance and operation;
- Assessing the impact of observatories on the ships and deep submergence facilities available to the U.S. academic community;
- Determining the role of industry in observatory design, development, manufacture, installation, and operation;
- Establishing methods and protocols for data management, distribution, archiving, and security; and
- Determining how to utilize ocean observatories effectively to increase awareness of the importance of the oceans through education and public outreach programs.

ocean's role in the global carbon cycle, plate motions, and deep Earth structure) as well as regional issues (e.g., sediment transport, health and sustainability of fisheries, ecosystem dynamics, and interactions between organisms and their environment).

Findings

- **By exploiting rapid advances in the development of computational, robotic, communications, and sensor capabilities, the NSF's OOI will provide the infrastructure to enable a new era of ocean research in the 21st century.**

- **The network of research-driven ocean observatories envisioned by the OOI would facilitate major advances in basic knowledge of the oceans at a time when there is an increasing need to understand the oceans in order to address important societal concerns such as climate change, natural hazards, and the health and viability of the ocean's living and non-living resources.**
- **The OOI will greatly improve the ability of operational ocean-observing systems such as IOOS and GOOS to observe and predict ocean phenomena.**

Recommendations

- **The NSF should move ahead with funding for the OOI and establish the infrastructure for a network of ocean observatories for research.**
- **Coordination among the OOI, IOOS, and other national and international observatory efforts will be critical in the areas of infrastructure development, instrumentation, ship and ROV utilization, data management and technology transfer. Mechanisms should be put in place through the National Oceanographic Partnership Program (NOPP) to facilitate coordination among the different U.S. agencies supporting ocean-observing systems.**

Readiness of Scientific Planning

The OOI is the outgrowth of a number of discipline-based and interdisciplinary community-wide scientific planning efforts that have occurred over the past decade. It builds upon experience with existing observatories as well as several successful pilot projects. The three components of the OOI (global, regional, and coastal) are in different stages of scientific planning.

Findings

- **The scientific motivations and benefits of research-based ocean observatories are well-defined in existing workshop reports and related documents for the three major components of the OOI: global observatories, regional observatories, and coastal observatories.**
- **Scientific planning to define the location, experiments, and instrument requirements of specific observatories varies significantly among the three OOI components, and additional planning is needed before the design of these systems can be finalized.**
- **There is currently no community consensus on the appropriate balance among relocatable observatories (Pioneer Arrays), cabled obser-**

vatories, and long-term time-series measurements needed for coastal ocean and Great Lakes research.

Recommendation

- **A process should be instituted immediately by NSF through the Dynamics of Earth and Ocean Systems (DEOS) Steering Committee, or the OOI Program Office, once it is established, to define better the scientific goals, locations, instrument, and infrastructure requirements of specific observatories. In addition, a consensus needs to be developed within the coastal research community on the appropriate balance between relocatable observatories (Pioneer Arrays), cabled observatories, and long-term moorings that best meet the largest range of specific requirements for coastal and Great Lakes research.**

Management of Observatory Construction, Installation, and Operation

The OOI is an interdisciplinary and technologically complex program that will require central program management to provide coordinated, program-wide scientific planning and oversight; provide fiscal and contract management of observatory design, installation, maintenance and operation; establish standards and protocols for data management; and coordinate program-wide education and outreach activities.

Findings

- **NSF policies and procedures for the MREFC account require that a single entity have overall financial and management accountability for the program. Thus, although the OOI encompasses a diverse group of researchers from many different disciplines working in both the coastal and open ocean, management of ocean observatory construction, installation, and operation will have to be done through a single Program Office.**
- **The maintenance and operation costs of the infrastructure associated with the OOI could run $20-30 million annually (not including ship time). With ship time included, these costs could double, approaching $50 million per year. There are concerns in parts of the community that these costs could drain resources from other areas of ocean science and monopolize assets such as ships and ROVs, or that overruns in the construction and installation costs of more technically advanced observatory systems could impact the acquisition of other observatory components.**
- **The capabilities of some proposed observatory systems raise national security issues that will need to be addressed before these systems are installed.**

Recommendations

- **A management model for the OOI based on that used successfully for many years by the Ocean Drilling Program (ODP) should be adopted, with some modifications. The program should be managed by a community-based organization, preferably with experience in managing large oceanographic research and operational programs.**
- **The OOI Program Office, once established, should conduct a thorough systems engineering design review of each of the three OOI components; develop a detailed implementation plan and risk assessment for each observatory system; produce detailed cost estimates for construction, installation, maintenance, and operations; have these plans reviewed by an independent panel of experts; and put in place oversight mechanisms and fiscal controls to ensure that implementation tasks are completed on time and within budget.**
- **The OOI Program Office should develop an operations policy that addresses allocation of research time, bandwidth, and power usage among potential users for each of the three OOI components. Prioritization of proposed experiments should be based on the quality of the proposed science as judged by a peer-review process.**
- **A successful observatory program will require sufficient funding for both the operation and maintenance of the observatory infrastructure and for the science that this infrastructure will enable. The NSF needs to take appropriate steps to ensure that sufficient resources are available to meet these needs by the time the observatory infrastructure is in place.**
- **The NSF should work with the appropriate staff from the Office of the Secretary of the Navy in cooperation with the National Ocean Research Leadership Council (NORLC) to establish, as soon as possible, policies addressing the national security issues raised by the potential capabilities of ocean observatories.**

Impact on the University–National Oceanographic Laboratory System Fleet and Deep Submergence Assets

The installation, operation, and maintenance of ocean observatories raise a number of issues, including the impact on the academic research fleet, the availability of deep submergence facilities and the role of industry in providing these assets. The primary support within the academic community for ships and ROVs is UNOLS, an organization comprised of several universities and national laboratories joined for the purpose of coordinating ship schedules and facilities for oceanographic research. Once installation has been accomplished, observatory infrastructure will require a long-term commitment of resources in order to keep it maintained and operating.

Findings

- **Ocean observatories will require substantial amounts of ship and ROV time for installation, operation, and maintenance, and will place particular demands on the scheduling of UNOLS vessels for regular servicing of observatory nodes in remote ocean locations.**
- **There are insufficient large global-class vessels and ROVs in academia to support ocean observatory installation and maintenance needs while continuing to meet on-going expeditionary research requirements. Without a commitment from NSF to augment ship and ROV capabilities to meet these needs, the scope and success of the ocean observatories program could be jeopardized and other types of ocean research requiring these assets could be negatively affected.**
- **The offshore energy and telecommunications industries have extensive experience in the design, deployment, and maintenance of submarine cables and large, moored platforms, and have assets (ROVs, cable laying vessels, heavy-lift vessels) that could be used for ocean observatory installation and maintenance.**

Recommendations

- **UNOLS and its Deep Submergence Science Committee (DESSC) should develop a strategic plan that identifies the most cost-effective options for supplying the required ship and ROV assets for observatory operation and maintenance and NSF should commit the necessary funds to acquire these assets. This plan should consider both the addition of new vessels and ROVs to the UNOLS fleet and the contracting or long-term leasing of commercial vessels or ROVs for observatory operations.**

Technical and Engineering Development Needs

The infrastructure provided to research scientists through the OOI will include the cables, buoys, moorings, and junction boxes required to provide power and two-way data communication to a wide variety of interdisciplinary sensors at the sea surface, in the water column, and at or below the seafloor. The technology and engineering needed to implement the OOI is in different stages of development for the global, regional, and coastal components.

Findings

- **The infrastructure requirements of the different OOI components (global, regional, and coastal) share many common elements, but also have important differences due to factors such as proximity to land, power and data telemetry requirements, and maintenance logistics.**

- **The technology already exists for certain types of observatories (e.g., low-bandwidth deep-sea buoys, coastal moored observatories, simple cabled observatories) and deployment of these systems can begin as soon as funding is available. Next-generation observatories (e.g., multi-loop, multi-node cabled observatories; high-bandwidth electro-optical-mechanical, cable-linked moorings; Arctic and Southern Ocean observatories, relocatable coastal observatories) require additional prototyping and testing of critical sub-systems, but should be technologically feasible within the five-year time frame of the OOI (2006-2010).**
- **The availability of retired telecommunication cables may represent a significant opportunity for ocean observatory science. Because the availability of these cables is a relatively recent development, it has not been factored into earlier planning of the OOI.**

Recommendations

- **In order for the more advanced moored buoy and cabled observatory systems to be ready for installation in the 2006-2010 time frame, the NSF will need to provide significant levels of funding over the next 2-3 years for completion of prototyping and testing of critical sub-systems, and for the establishment of testbeds where the performance of these systems and new observatory instrumentation can be evaluated.**
- **The technical feasibility, costs, and benefits of using retired telecommunication cables to provide power and bandwidth for some proposed OOI sites should be fully explored by a committee with appropriate scientific and technical expertise.**

Sensors and Instrumentation for Ocean Observatories

The development, calibration, and maintenance of new sensors and instrumentation for quantifying physical, chemical, biological, and geological processes operating in the oceans will be a critical element in achieving the true interdisciplinary promise of ocean observatories. Sensors deployed at ocean observatories will need to be able to collect accurate, long-term data with infrequent servicing and may be required to function in extreme environments such as the Southern Ocean or the Arctic. Because of the long lead-time needed for the development and production of new sensors, this effort will need to begin well in advance of the completion of observatory installation.

Findings

- **While a number of observatory-capable physical, geophysical, and bio-optical sensors are available, a very limited number of sensors**

exist for making chemical and biological measurements at ocean observatories, or for making observations in more challenging environments such as the Southern Ocean or the Arctic. Biofouling and corrosion remain major impediments to making long-term unattended measurements in the oceans.

- **The total investment in sensors and instrumentation that will eventually be made for use with the observatory systems acquired through the OOI over its first decade of operation could approach the cost of the basic infrastructure itself. The core suite of instrumentation that will be funded through the MREFC will represent only a small portion of this total.**
- **To ensure the comparability of measurements made at different OOI observatories, and to realize their full potential for research and to observing networks, observatory sensors will need to be calibrated according to international standards.**
- **The installation and maintenance of ocean observatories, and the conduct of complementary studies, will require a number of highly trained marine technical support staff that greatly exceeds existing personnel resources. In addition, observatory operation will place significant demands on instrumentation inventories and resources, including maintenance and calibration facilities.**

Recommendations

- **A core suite of instruments should be installed on every observatory node and funded as part of the basic observatory infrastructure, not only to test system functionality, but also to provide the essential scientific context for the observatory's effective use in basic research.**
- **A separate, well-funded observatory instrumentation program at the NSF, and contributions from other agencies with an interest in ocean research, will be required to obtain the full suite of sensors and instruments needed to fully exploit the scientific potential of the ocean observatory infrastructure.**
- **The NSF should augment its programs in instrumentation development, support, and calibration for observatory-capable sensors, including increasing grant duration to ensure that instrumentation groups have the capability to support the needs of the OOI. High priorities include the development of chemical and biological sensors, sensors less subject to biofouling and corrosion, sensors capable of surviving in more extreme environments, and more accurate sensors.**
- **The NSF should work with other agencies engaged in long-term ocean observations to ensure that the national resources for instrumen-**

tation, maintenance and calibration facilities, and technical staff are in place and have the necessary funding stability to support the OOI.

Data Management for Ocean Observatories

The instruments deployed on ocean observatories are expected to collect vast amounts of data, which must be transferred back to shore in an efficient, reliable, and timely manner. The effective use of ocean observatories for research, education, and public outreach will require a system for acquiring, processing, distributing, and archiving vast volumes of data from many different disciplines, much of it in real-time.

Finding

- **While archive centers exist for some data types that will be collected by ocean observatories, they do not exist for others. Without a coordinated data management and archiving system, data obtained at ocean observatories may not be generally available due to a lack of data standards, quality control, or centralized archives, and the great scientific and educational potential of ocean observatories may not be realized.**

Recommendations

- **The NSF should work with other interested agencies in the U.S. and other nations that are involved with establishing ocean-observing systems in order to ensure that centers are established and funded to process and archive data collected by ocean observatories, and to make these data readily accessible for basic research, for operational needs, and to the general public.**
- **The OOI program should have an open data policy with data from all core instrumentation and community experiments made publicly available in as near real-time as possible.**
- **Standards for data interchange, for data and metadata formats, and for archiving methods should be established for all types of ocean observatories and should be coordinated and integrated with other research-based international observatory efforts, IOOS, and GOOS.**

Education and Public Outreach for Ocean Observatories

There is a critical need to improve the science literacy of the general public and to improve the teaching of science at grade levels K-12. The multidisciplinary nature of ocean science provides a wonderful opportunity to illustrate basic science principles and their application to problems of broad societal interest, such as the ocean's role in climate change. Ocean observatories, with their advanced instrumentation and capacity for real-time data transfer, offer excellent opportunities for public outreach and innovative educational programs. They also offer the chance to foster interdisciplinary research for a new generation of students and ocean scientists.

Finding

- **Seafloor observatories will provide unique opportunities for education and public outreach (EPO) by utilizing real-time data through the interactivity of the Internet to help students, teachers, and the general public understand the relevance and excitement of ocean research to their everyday lives.**

Recommendations

- **Education and public outreach activities for observatory science should be coordinated at the program level by a professional staff supported by funding at both the program and project level. Observatory education programs should be designed to meet National Science Education Standards, and carried out as a collaborative effort with the National Sea Grant Program and with the Centers for Ocean Science Education Excellence (COSEE).**
- **The NSF or the OOI Program Office, once it is established, should solicit proposals for a workshop to address the EPO issues raised in this report and to develop a specific EPO implementation plan for ocean research observatories, including recommending a budget for EPO activities.**

1

Introduction

Historically, oceanographers have relied largely on ship-based expeditionary studies to map, observe, and sample the oceans. This mode of investigation led to the discovery of the importance of a wide range of physical, chemical, biological, and geological processes over the two-thirds of the Earth's surface that is covered by water. Oceanographers have learned that the oceans circulate vast quantities of heat that control our weather and climate. Sediments formed from organisms living in ocean surface waters are now known to contain an invaluable record of past climate change and to help regulate the concentration of atmospheric carbon dioxide. Although vast expanses of the deep ocean are still largely unexplored, the diversity of life within the oceans and below the seafloor surpasses that of any other ecosystem on the planet. Most of the active volcanoes and fault systems on Earth either lie beneath the oceans or are located along their margins. Previously unknown forms of life, possibly linked to the beginning of life on Earth, have been discovered at hydrothermal vents on the deep seafloor.

Today's society is increasingly dependent on the oceans. The oceans themselves provide a highway for most international commerce and food for our tables. The sediments along continental margins harbor most of our remaining stores of oil and gas. More than half of the population of the U.S. lives within an hour's drive of the ocean, and find it a source of both recreation and beauty, but these coastal communities are increasingly vulnerable to the storms, erosion, and sea level variations that constantly affect this dynamic boundary between the land and the sea.

As the oceans have grown more important to society, so has the need to understand their variations on many temporal and spatial scales. This need to understand change in the oceans is compelling oceanographers to move beyond the traditional expeditionary mode of investigation to make sustained, *in situ* observations in the oceans and on the seafloor. A report on the future of ocean science in the U.S., *Ocean Sciences at the New Millennium* concluded:

> The lack of extensive, more-or-less continuous time-series measurements in the oceans is probably one of the most serious impediments to understanding of long-term trends and cyclic changes in the oceans and in global climate, as well as episodic events such as major earthquakes, volcanic eruptions or submarine landslides. (National Science Foundation, 2001, p. 151)

Ocean-observing systems would enable Earth and ocean scientists to study ocean processes over timescales ranging from seconds to decades and spatial scales from millimeters to thousands of kilometers. Such systems would provide the scientific basis for addressing important societal concerns such as climate change, natural hazards, and the health and sustainability of the living and non-living resources of the world's coasts and oceans.

A variety of technological approaches can be used to observe the oceans. Satellites provide global coverage of the ocean's surface, measuring sea-surface temperature, winds, and elevation; the bathymetry and bottom substrate of the coastal oceans; and, through ocean color, the phytoplankton population of the upper ocean. Acoustic thermometry can provide basin-scale measurements of ocean temperature variations. New generations of subsurface floats, gliders, and drifters will provide broad spatial coverage of ocean properties on a global scale. Measurements of air-sea interaction and ocean properties made at surface and subsurface moorings are providing an essential *in situ*, fixed reference for determining longer-term changes. Submarine, cable-based observatories could supply unprecedented levels of power, data bandwidth, and two-way communication to instruments located anywhere from the seafloor to the sea surface. These existing and emerging observing technologies, have converged with the development of new sensors for making *in situ* measurements, major advances in telecommunications technology, and vast increases in computational and modeling capabilities to offer an unprecedented opportunity to establish long-term ocean-observing systems that promise to fundamentally change the manner in which ocean science is conducted in the coming decades.

A recent report from the National Research Council (NRC) entitled *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science*

(2000) highlighted the need for long-term, fixed ocean observatory sites for conducting basic research into a broad range of scientific questions. "Seafloor observatories" are defined as "unmanned system of instruments, sensors, and command modules connected either acoustically or via a seafloor junction box to a surface buoy or a fiber optic cable to land"(National Research Council, 2000, p. 1). To quote the report:

> Seafloor observatories could offer Earth and ocean scientists unique new opportunities to study multiple, interrelated processes over time scales ranging from seconds to decades; to conduct comparative studies of regional processes and spatial characteristics; and to map whole-earth and basin-scale structures. The scientific problems driving the need for seafloor observatories are broad in scope, spanning nearly every major area of marine science. (National Research Council, 2000, p. 2)

Many of the fundamental scientific research questions that could be facilitated by ocean observatories have been identified in the National Science Foundation (NSF) Ocean Sciences Division's long-range "Futures" reports (Baker and McNutt, 1996; Royer and Young, 1998; Jumars and Hay, 1999; Mayer and Druffel, 1999), in the report *Ocean Sciences at the New Millennium* (National Science Foundation, 2001), in *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science* (National Research Council, 2000), and in a number of community planning documents (Appendix C). These scientific problems include:

- determining the role of the ocean in climate change;
- quantifying the exchange of heat, water, momentum and gases between the ocean and atmosphere;
- determining the cycling of carbon in the oceans and the role of the oceans in moderating the increase in atmospheric carbon dioxide;
- improving models of ocean mixing and large-scale ocean circulation;
- understanding the patterns and controls on biological diversity in the oceans;
- determining the origin, development and impact of episodic coastal events such as harmful algal blooms;
- assessing the health of the coastal ocean;
- determining the nature and extent of microbial life in the deep crustal biosphere;
- studying subduction zone thrust faults that may result in large, tsunami-generating earthquakes; and
- improving models of global earth structure and core-mantle dynamics.

THE NATIONAL SCIENCE FOUNDATION'S OCEAN OBSERVATORIES INITIATIVE

In order to provide the ocean sciences research community in the U.S. with access to the basic infrastructure required to make long-term measurements in the oceans, the NSF's Ocean Sciences Division has developed the Ocean Observatories Initiative (OOI). The OOI is an outgrowth of community-wide scientific planning efforts, both national and international, and builds upon recent technological advances, experience with existing observatories, and several successful pilot projects. As they mature, the research-focused observatories enabled by the OOI would be networked into and become an integral part of the proposed Integrated and Sustained Ocean Observing System (IOOS) (Ocean.US, 2002b). This operationally-focused system, which receives support from several agencies, is a key U.S. contribution to the international Global Ocean Observing System (GOOS).

The observatory network proposed under the OOI will provide cutting-edge capabilities to the IOOS and the research community. These observatory sites will complement other elements of the IOOS, such as the *Argo* profiling floats, and will expand the area of the ocean and seafloor beyond that now accessible through existing time-series sampling methods, such as the moorings used in the National Oceanic and Atmospheric Administration (NOAA)-funded Tropical-Atmosphere-Ocean (TAO) array (Appendix D). Much of the data from OOI sites will be available in near-real-time and will feed into ongoing ocean data assimilation and prediction efforts such as the Global Ocean Data Assimilation Experiment (GODAE) as well as driving new scientific research.

The infrastructure provided to research scientists through the OOI will include the cables, buoys, deployment platforms, moorings, and junction boxes required for power and two-way data communication to a wide variety of sensors at the sea surface, in the water column, and at or below the seafloor. The initiative also includes project management, data dissemination and archiving, and education and outreach components essential to the long-term success of ocean observatory science. A fully operational research observatory system would be expected to meet most of the following goals:

- continuous observations at time scales of seconds to decades,
- spatial measurements from millimeters to kilometers,
- sustained operations during storms and other severe conditions,
- real-time or near-real-time data as appropriate,
- two-way transmission of data and remote instrument control,
- power delivery to sensors between the sea surface and the seafloor,
- standard Plug-n-Play sensor interface protocols,

- autonomous underwater vehicle (AUV) docks for data download and battery recharge,
- access to deployment and maintenance vehicles that satisfy the needs of specific observatories,
- facilities for instrument maintenance and calibration,
- a data management system that makes data publicly available, and
- an effective education and outreach program.

The OOI, as presently envisioned, will have three primary components: (1) a global network of deep-sea moored buoys, (2) a regional-scale cabled observatory, and (3) an expanded network of coastal observatories.

Global Observatories

The global observatory component of the OOI design includes a network of 15-20 moored buoys, linked to shore via satellite. These buoys support sensors for measurement of air-sea fluxes; physical, biological, and chemical water column properties; and geophysical observations on the seafloor. Such moorings, designed to make interdisciplinary measurements at a common site, are a unique aspect of this component of the OOI program (Plate 1). Some moored systems may occupy sites indefinitely; others will be relocatable in order to study processes in different parts of the world's oceans or for rapid deployment of power and bandwidth resources in response to transient events. Many of the buoys will be specifically designed for operation at high latitudes, especially those in the Southern Ocean. This network of fixed ocean observatories is designed to contribute to studies of the ocean's role in climate change by providing a four-dimensional view of variations in oceanographic properties and air-sea interactions on a global scale. This network also seeks to improve understanding of the structure and dynamics of the Earth's interior by expanding the international Global Seismic Network (GSN) into those areas of the oceans lacking island stations, and could become a component of the Comprehensive Test Ban Treaty Hydroacoustic data collection system. Relocatable moorings will be used to study Earth and ocean processes where they are most active, such as across major ocean current systems, in regions of high biological productivity, or along volcanically and seismically active geological plate boundaries.

Regional-Scale Cabled Observatory

The second element of the OOI is a cabled observatory that will provide the first comprehensive set of long-term measurements of geological and oceanographic processes on a regional scale. For example, a regional-scale observatory could observe a tectonic plate encompassing all of the major types of plate boundaries-spreading center, transform fault, and subduction zone. This observatory system would use electrical/fiber-optic cables to provide unprecedented levels of electrical power and real-time two-way communication between a shore station and instrumented seafloor nodes, allowing for real-time and interactive investigation of physical, chemical, and biological processes occurring over many scales of space and time (Figure 1-1). A variety of measurement systems have been proposed for the seafloor nodes, including: (1) bottom-fixed sensor packages for geophysical measurements or geological observations; (2) instruments for *in situ* biological and chemical measurements on the seafloor and in the water column; (3) cameras and real-time video; (4) instrumented bot-

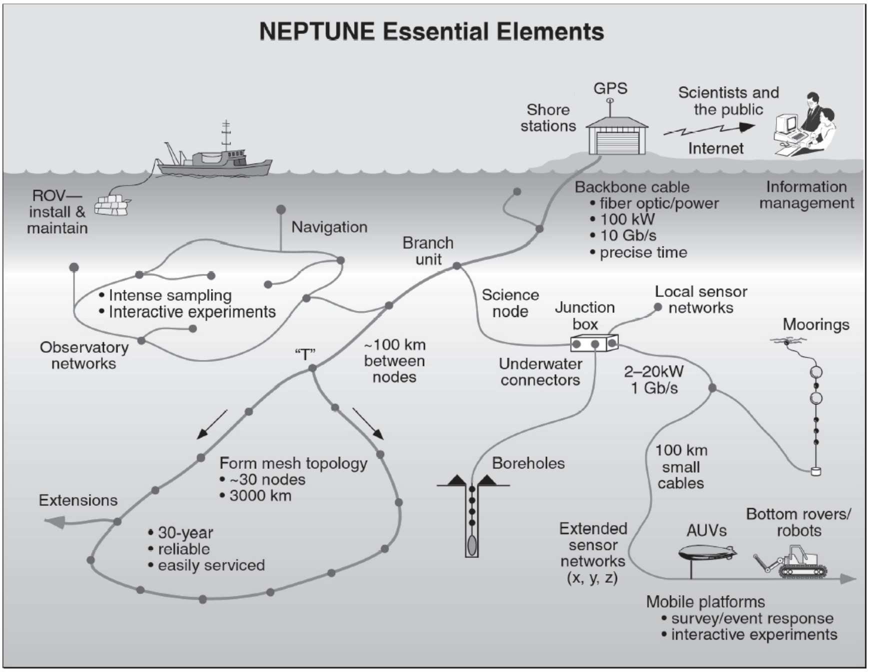

FIGURE 1-1 Concept of a regional cabled observatory being developed for the OOI. Land-based scientists, educators, decision-makers, and the general public are interactively linked in real-time with sensors on or below the seafloor or in the overlying ocean via a fiber-optic/electrical cable that provides two-way data communication (Gb/s) and power (kW) between a shore station and an array of seafloor nodes over a regional area. Image provided courtesy of the NEPTUNE Project (*www.neptune.washington.edu*) and produced by Paul Zibton.

tom tripods; (5) winched, buoyancy-controlled or wire-crawling profilers, and subsurface and surface moorings for vertical measurements throughout the water column; (6) instruments for deployment within boreholes below the seafloor; and (7) AUV docking ports and acoustic communication and navigation networks for enhancing spatial sampling (Plate 2) (NEPTUNE Phase 1 Partners, 2000; Dickey and Glenn, 2003). A regional observatory would have close links to other major geoscience programs such as Ridge 2000, MARGINS, and EarthScope (Appendix B).

Coastal Observatories

The OOI will enhance and expand existing and planned networks of coastal observatories in the U.S., providing an important research component of the Coastal Global Ocean Observing System (C-GOOS) whose primary mission is to serve operational oceanographic needs (see Chapter 6 for a detailed discussion of the relationship between OOI and IOOS/GOOS and the differences between operational and research-driven observatories). The coastal component of the OOI would provide new opportunities for research in areas such as the variability of large-scale coastal ocean circulation, material mass balances (e.g., nutrient and carbon budgets), ecosystem studies, and coastal morphology and beach erosion. These observatories are particularly important because they will facilitate basic research on episodic and extreme events in the coastal ocean. Such research will improve predictions of harmful algal blooms or storm-related coastal erosion, improve the accuracy of regional coastal models and forecasts, and assess the magnitude and quality of anthropogenic effects on the coastal ocean. A variety of methods will be employed to gather data in the coastal region, including moored buoys, cables, surface radars, AUVs, airborne sensors, and ships (Plate 3).

Funding of the Ocean Observatories Initiative

Funding for the OOI is being sought through the NSF's Major Research Equipment and Facilities Construction (MREFC) account. This agency-wide capital assets account was established to provide funding for major science and engineering infrastructure with costs that range from tens to hundreds of millions of dollars. Over five years, approximately $200 million is expected to be available through the OOI for construction and installation of coastal, regional, and global ocean observatories and critical shore-based facilities (e.g., data distribution and archiving centers).

According to the NSF Fiscal Year (FY) 2004 budget request, released in February 2003, funding for the OOI is slated to begin in FY 2006 and runs through FY 2010 (Figure 1-2). In its budget request, the NSF stated that it expects to spend approximately $14.2 million in concept and engineering development activities through FY2003 and will spend an additional $1.3 million on these activities through FY 2005. The total five-year construction costs for the OOI are budgeted at $208 million, beginning in FY2006. Maintenance and operation of the observatory infrastructure acquired through the OOI MREFC will be supported by the NSF's Ocean Sciences Division Research & Related Activities account. In its FY 2004 budget request, the NSF projected that these costs would ramp up to $10 million per year by FY 2011. Science programs utilizing the observatory infrastructure are expected to be funded by the NSF and a variety of other agencies that support basic research in the oceans (e.g., NOAA, the Office of Naval Research [ONR], and the National Aeronautics and Space Administration [NASA]).

Management and Oversight of the Ocean Observatories Initiative

The NSF has proposed a management structure for the acquisition and implementation phase of the OOI based on the structure that has been used successfully by the Ocean Drilling Program (ODP) for many years. Following that model, management, coordination, and oversight of the OOI will be the responsibility of the Executive Director of a centralized OOI Program Office, to be established through a cooperative agree-

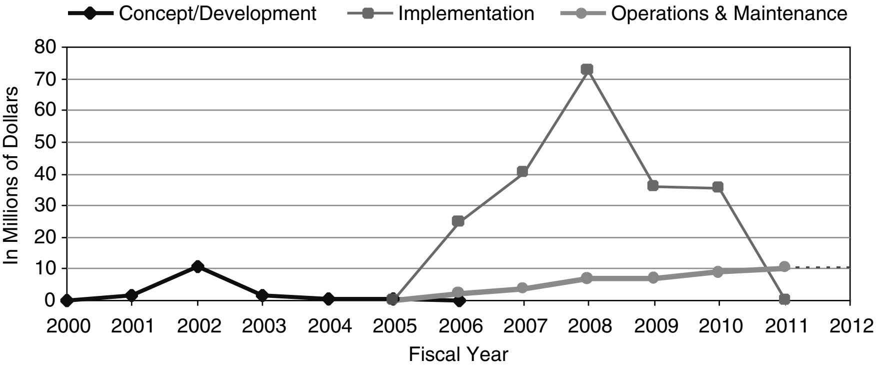

FIGURE 1-2 OOI funding profile from the FY 2004 NSF Budget Request. Figure reprinted from the National Science Foundation's *Major Research Equipment and Facilities Construction FY 2004 Budget Request* (2002).

ment with the NSF. This Director will be accountable to an Executive Committee, which in turn will be advised by various scientific and technical advisory committees whose membership will be comprised of individuals with expertise in ocean-observing science and engineering. Experiments utilizing the OOI infrastructure will be selected on a peer-review basis. The OOI Program Office also will be responsible for coordination with the U.S. IOOS as well as other international ocean-observing programs.

COMMUNITY INPUT TO OCEAN OBSERVATORIES INITIATIVE PLANNING

A number of recent and on-going community-wide scientific planning workshops provide the foundation for the development of the OOI (Appendix C). The workshops most directly tasked with providing input to the OOI are described below and include the Dynamics of Earth and Ocean Systems (DEOS), the NorthEast Pacific Time-series Undersea Networked Experiments (NEPTUNE), and the Global Eulerian Observatory (GEO) Time-series Program as well as two recent workshops, one tasked to focus on cabled observatories (the Scientific Cabled Observatories for Time-series [SCOTS] Workshop) and the other tasked to address coastal observatories (the Coastal Ocean Processes [CoOP] Observatory Science Workshop).

Dynamics of Earth and Ocean Systems

The DEOS Steering Committee was established in 1997 under the auspices of the Consortium for Oceanographic Research and Education (CORE), with funding from NSF. The DEOS mission is to provide a focus for coordinated scientific planning for the establishment of a network of research-based ocean observatories, to advise the NSF on technical specifications and management issues, and to explore the new opportunities for education and public outreach activities offered by ocean-observatory systems.

DEOS arose out of the marine geosciences community's need to make long-term observations in conjunction with major marine geosciences research programs such as the ODP, Ridge InterDisciplinary Global Experiment (RIDGE) and MARGINS (See Appendix B). The planning effort was subsequently broadened to include physical oceanographers, chemists, and biologists to reflect the interdisciplinary nature of any ocean observatory program. DEOS has developed a strategy to implement a research-based seafloor observatory system emphasizing the pursuit of two technologically distinct approaches:

(1) *Seafloor observatories linked with submarine cables to land and the Internet.* These are of two types: (a) those using retired telecommunications cables that may become available in regions of current scientific interest, possible only on an opportunistic basis; and (b) those specifically deployed as scientific cables in a few selected locations where critical Earth and oceanographic processes are most active and proximal to land. An example of the latter is NEPTUNE, a proposed cabled observatory crossing the Cascadian margin and subduction zone and spanning the entire Juan de Fuca tectonic plate (NEPTUNE Phase 1 Partners, 2000). The NEPTUNE concept has stimulated an extensive scientific and technical planning effort that has laid the groundwork for the establishment of regional, cabled observatories in a variety of settings (e.g., Dickey and Glenn, 2003).

(2) *Moored-buoy observatories providing power to seafloor instruments and a satellite communication link to land and the Internet.* These moorings will require annual servicing and could be deployed either: (a) permanently, to complete the distribution of a global observatory network, or (b) for periods of up to a few years in locations where process-oriented problems can be addressed without a permanent installation. Examples of the latter might include earthquake studies in subduction zone settings, investigations of cross-shelf and along-shelf sediment transport in different coastal settings, or studies of the interannual variability of major ocean current systems.

DEOS has overseen a number of community scientific and engineering planning activities. In December 1999, DEOS published a working group report on the scientific rationale for a global network of moored buoys (DEOS Global Working Group, 1999). The *DEOS Moored Buoy Observatory Design Study*, published in August 2000, examined the scientific requirements, technical feasibility, and potential costs associated with specific mooring designs. These designs include (1) a low-bandwidth discus buoy system that uses acoustic modems to transfer data from instruments on the mooring or the seafloor to the buoy and that is linked to shore via satellite and (2) a high-bandwidth design utilizing a large spar or discus buoy equipped with a 64 kb/s C-band satellite system, power generators on the buoy, and an electro-optical-mechanical cable to deliver power and two-way data communication to a junction box on the seafloor.

DEOS has coordinated its planning efforts with the Time-series Science Team of the Ocean Observing Panel for Climate (OOPC) and the NEPTUNE group, the latter has proposed a plate-scale cabled observatory in the Northeast Pacific on the Juan de Fuca plate. DEOS has also coordinated with GOOS, which is developing plans for the deployment of a global network of moored buoy systems for multi-disciplinary science.

During 2002 DEOS facilitated NSF-sponsored workshops on research at coastal observatories run by the CoOP Program (Jahnke et al., 2002) and on the scientific applications of regional cabled observatories (Dickey and Glenn, 2003).

These planning activities and workshops have provided essential information for this report and they are briefly summarized below (see also Appendix C).

North-East Pacific Time-series Undersea Networked Experiments

A centerpiece of the DEOS planning effort is NEPTUNE, a joint U.S.-Canadian, multi-institutional project, whose goal is to install approximately 30 instrumented nodes, linked by a 3,700-km network of fiber-optic/power cables, over an area roughly 500 km by 1,000 km on the Juan de Fuca tectonic plate in the northeast Pacific Ocean (NEPTUNE Phase 1 Partners, 2000). The NEPTUNE infrastructure is being designed to provide large amounts of power (kW level) and data bandwidth (Gb/s) to each observatory node, with a working lifetime of more than 30 years. The NEPTUNE construction partners are the University of Washington, the University of Victoria (in Canada), the Woods Hole Oceanographic Institution (WHOI), Canada's Institute for Pacific Ocean Science and Technology, NASA's Jet Propulsion Laboratory (JPL), and the Monterey Bay Aquarium Research Institute (MBARI).

An extensive scientific and engineering planning effort centered around NEPTUNE has been carried out over the past several years, providing information on the scientific rationale and technical requirements for a regional-scale cabled observatory. The National Ocean Partnership Program (NOPP) funded a NEPTUNE Feasibility Study published in June 2000 (NEPTUNE Phase 1 Partners, 2000). The NSF independently funded design studies of power and communications systems for a regional cabled observatory. Two testbeds, the Canadian Victoria Experimental Network Under the Sea (VENUS), and the Monterey Accelerated Research System (MARS), have been funded by the Canadian Foundation for Innovation (CFI) and the NSF, respectively, to validate these designs (see Chapter 3). The CFI has promised funding, subject to certain conditions, for the development and installation of the northern portion of NEPTUNE.

Global Eulerian Observatory Time-series Program

Another element of DEOS is an international planning effort for the establishment of fixed, moored observatories at key geographic sites in the world's oceans, which has been under way for some time as part of the international GOOS. The GEO program proposes to make time-series measurements with high vertical and temporal resolution from the ocean-atmosphere boundary layer down through the ocean mixed layer and into the deep sea, on time scales ranging from minutes to years. Time-series stations at select sites are seen as a key element of *in situ* observations of the global ocean, providing continuous data at select sites to complement the *Argo* floats, remote satellite sensing of sea surface properties, and essential reference information on the relatively slowly changing properties of the deeper ocean. The GEO time-series program is an essential component of both the international Climate Variability and Predictability Programme (CLIVAR) and the Carbon Cycle program. GEO will also be an important element of the GODAE, an international program to combine *in situ* and satellite ocean observations with profiling float data from the *Argo* program and numerical circulation models to determine ocean dynamics and variability over time.

Scientific Cabled Observatories for Time-series Workshop

In August 2002, the NSF sponsored a workshop to define the scientific problems that would require or be most effectively addressed by cabled observatory networks (Dickey and Glenn, 2003). Workshop participants also reviewed the status of cabled observatory and related technologies in order to provide context for this activity. The workshop report concluded that cabled observatories would enable new classes of scientific questions to be addressed because of their ability to (1) supply power sufficient for energy demanding sensors and systems, (2) sample at high data rates for long periods, (3) collect a large number of virtually continuous and diverse measurements over different spatial scales for unprecedented interdisciplinary coherence analyses, and (4) communicate the full datasets to shore in real-time. The final report makes several recommendations including:

- encouraging cabled observatory development in all three domains (global, regional, and coastal);
- pursuing means to relocate retired telecommunication cables to fill in gaps in a global, deep-earth imaging observatory network;
- pursuing technologies for deploying coastal scientific nodes along cables running to deep-water observatories;
- testing and development of a variety of sensors and technologies (e.g., sensor suites, AUV docking stations, communication systems, etc.);
- establishing standards for instrument interfacing, data distribution, and management policies;

- accelerating development of new autonomous sensors and systems;
- assessing the availability and capability of remotely operated vehicles (ROVs);
- integrating cabled observatories with other observational programs;
- modeling components;
- balancing funding expenditures between infrastructure and experimental assets; and
- implementing a governance structure with clear lines of responsibility, authority and accountability, and scientific involvement (Dickey and Glenn, 2003).

Coastal Ocean Processes and Observatory Science Workshop

The CoOP Observatory Science Workshop was convened in May 2002 to provide focus and direction for the development of the coastal observatory component of the OOI. In particular, the more than 60 participants were charged with identifying research topics that can best be studied using coastal observing systems, current capabilities critical to those research topics, and areas for coastal observatory development that would provide the greatest benefit to coastal research.

The resulting report concluded that coastal observatories will provide fundamental new opportunities for research in a variety of areas, including:

- integrated, synoptic, large-scale measurements of coastal ocean processes;
- interactions between physical and biological systems;
- material mass balances such as nutrient and carbon budgets;
- coastal biogeochemistry;
- beach erosion and cross-shelf sediment transport;
- impacts of episodic and extreme events (e.g., storms, toxic algal blooms); and
- the human impact on ecosystems (Jahnke et al., 2002).

The coastal observatory system envisioned will be comprised of three basic observing components: (1) fixed, region-specific observatories; (2) a widely-spaced distributed set of moorings that will span and link different coastal regions; and (3) relocatable or "Pioneer" arrays that would be targeted for specific, process-oriented research studies. Given the budgetary constraints provided at the workshop, the report recommended that

Pioneer research arrays constitute the principal OOI contribution to the coastal observatory infrastructure, complementing and enhancing the operational backbone of coastal observatory infrastructure as envisioned by IOOS. Each Pioneer Array would be comprised of 30-40 sensor moorings, and would be dedicated to a particular process-oriented study and deployed for periods of three to five years, after which they would be relocated to a different area.

PURPOSE OF THIS STUDY

There has been significant progress in the scientific planning and technical development of ocean observatories since the report *Illuminating the Hidden Planet* (National Research Council, 2000) recommended that the NSF move forward with the planning and implementation of a seafloor observatory program. As a result, in the fall of 2002, the NSF asked the NRC to conduct a follow-up study to develop an implementation plan for the establishment of a network of seafloor observatories to be used for multidisciplinary ocean research. This network will include both cabled seafloor nodes and moored buoys, located in both coastal and open-ocean areas. The study will describe the strategies needed to carry out the priority science identified in existing reports. In particular, the NRC was charged to:

- provide advice on the design, construction, management, operation, and maintenance of the network, including the need for scientific oversight and planning, appropriately phased implementation, data management, and education and outreach activities;
- examine the impact of ocean observatories on the University-National Oceanographic Laboratory System (UNOLS) fleet and current submersibles and ROV/AUV assets in the research community; and
- examine the potential role of NSF's research-based observatory network within the IOOS and other international efforts being developed and implemented primarily for operational purposes.

In arriving at its findings and recommendations the study committee was to consider recent reports that outline ocean science research priorities, existing observatory strategies and implementation plans, and input from the ocean research community.

REPORT STRUCTURE

This report contains seven chapters and five appendixes. **Chapter 2** outlines the lessons learned from existing ocean observatories that can serve as valuable experience in planning for current and future efforts. **Chapter 3** discusses the status of planning for proposed research-oriented global, regional, and coastal observatories, based on recent reports and workshops listed in **Appendix C**. **Chapter 4** addresses a variety of issues related to the implementation of a research-based ocean observatory network, including program management, infrastructure, sensor needs, construction and installation (including phasing scenarios), operations and maintenance, data management, and education and outreach. **Chapter 5** discusses related facility needs for an ocean observatory network such as ships and deep-submergence assets, as well as the role of industry in providing facilities or services for the observatory program. **Chapter 6** explores the relationship of NSF's OOI to the IOOS and other national and international ocean-observing systems. **Chapter 7** summarizes the major findings and recommendations of the report.

Appendix A contains biographical information on the Implementation of a Seafloor Observatory Network for Oceanographic Research Committee members. **Appendix B** contains a list of acronyms and a glossary of technical terms used in this report. A list of workshops and workshop reports consulted for this report is contained in **Appendix C**. **Appendix D** contains information on the ocean-observation programs mentioned in this report. **Appendix E** provides a table of sites chosen for global time-series measurements.

2

Lessons from Existing Ocean Observatories

Over the past 30 years oceanographers have gained valuable experience with a few pioneering ocean observatories (Appendix D). Some of these have been "observatories of opportunity," in which systems built for other purposes have been leveraged for research. One such program was the network of ship-based Ocean Weather Stations (OWS), established after World War II for the primary purpose of guiding ocean-crossing aircraft, which ended in 1981. While on station, ships collected oceanographic data that played an important role in early efforts to understand how the ocean has changed over time. In particular, data from this program helped define the relationship between the ocean and the atmosphere.

Another example of an "opportunistic" observatory is the Sound Surveillance System (SOSUS), a classified system developed by the U.S. Navy in the late 1950s to detect, track, and classify Russian submarines using arrays of underwater hydrophones. SOSUS is a network of acoustic arrays in which hydrophones are connected to a shore station by a submarine cable. Since the end of the Cold War, oceanographers have been provided limited access to the SOSUS network. Researchers with security clearances have used the system for productive studies of mid-ocean ridge volcanic-hydrothermal systems, marine mammals, and acoustic thermometry. SOSUS has also provided the research community with engineering know-how that will be relevant to any cabled network of ocean observatories. However, SOSUS has also highlighted the national security concerns that will be raised by observatories with similar capabilities.

More recently, a small number of long-term measurement sites have been established in both coastal settings and the open ocean using arrays of moored buoys. One of the most successful deep-sea sites has been the TAO array in the equatorial Pacific. Developed as part of the 10-year international Tropical Ocean Global Atmosphere (TOGA) program (1985-94), the TAO array enabled improved detection, understanding, and prediction of El Niño events and provided essential data to further understanding of the El Niño Southern Oscillation. Other upper-ocean and air-sea interaction observatory sites that have been established and maintained in recent years include the Bermuda Atlantic Time-series Station (BATS), the Hawaii Ocean Time-series (HOT) program, and the European Station for Time-series in the Canary Islands (ESTOC) (Appendix D).

A small number of cabled observatories have also been established in coastal settings. One of the oldest is the Field Research Facility (FRF) off Duck, North Carolina, established by the U.S. Army Corps of Engineers (USACE) in 1977. The FRF provided a unique infrastructure of cabled observatory sensors, measurement platforms, and deployment vehicles to support a wide variety of basic research studies of near-shore fluid and sediment processes at an open-coast beach. The 1996 installation of the Long-Term Ecological Underwater Observatory (LEO-15) in 15 m of water off the New Jersey coast pioneered the use of cabled observatory systems for multidisciplinary, integrated studies of meteorological, physical, and biological processes on the continental shelf. In 2000, another cabled, near-shore observatory was established off the south shore of Martha's Vineyard. The Martha's Vineyard Coastal Observatory (MVCO) is being used as a natural laboratory to study how winds, waves, and currents affect the coastline and to monitor oceanic and atmospheric conditions. The Hawaii Undersea Geo-Observatory (HUGO), the first submarine volcano observatory, was installed at Loihi Volcano off Hawaii in 1997, using a 47 km electro-optical cable donated by AT&T. The Hawaii-2 Observatory (H2O), a permanent deep-water geophysical research observatory, was installed in 5000 m of water about halfway between Hawaii and California in September 1998 on the retired Hawaii-2 telecommunications cable (HAW-2).

These observatories have not only demonstrated the significant potential of observatory science but also have provided valuable lessons on the installation, management, and operation of ocean observatories. These lessons should be considered as plans are developed for the new generation of ocean observatories envisioned in the OOI. In this chapter some of the 'lessons learned' for each of the implementation issues addressed in Chapter 4 are briefly summarized.

PROGRAM MANAGEMENT

- Experience from existing observatories (e.g., LEO-15, FRF) indicates that observatories must be under the control of their users, the research scientists, to provide maximum innovation and flexibility. Experiment prioritization should be controlled by scientific requirements and resource availability.
- A successful observatory program—including well-balanced science priorities, development goals, and operational needs—requires constant communication among scientists, engineers, and managers (e.g., TAO, BATS, HOT, FRF).
- Existing observatories (e.g., FRF and LEO-15) have proven the value of a broad-based, interdisciplinary approach to observatory research and the need for early and continued involvement of the modeling community to ensure that data collected are of sufficient quality and quantity to be of value to modeling efforts.
- Experience from almost every existing ocean observatory has shown the difficulty of sustaining funding for the maintenance and operation of long-term observations in a funding environment dominated by short-term, two- to three-year grants.

SENSORS

- Sensors appropriate for observatory use must maintain their calibration and sensitivity characteristics for long periods of time—at least six months to a year (so-called ‘observatory-capable’ sensors).
- Years of deploying open ocean (e.g., TAO, BATS, HOT) and coastal moorings (e.g., FRF) have shown that degradation of sensors on surface buoys (due to exposure, vandalism, or sea birds), and damage to sensors in the upper ocean and shallow, coastal waters (due to biofouling, fish bite, corrosion, ship collision, or fishing gear) are major problems that must be addressed to reduce maintenance costs and improve the reliability of observatory measurements (Figure 2-1).
- Observatories such as LEO-15 and MVCO clearly indicate that basic suites of observations, too expensive for individual investigators to gather, provide the essential scientific context for an observatory’s effective use in research and need to be provided as part of the observatory infrastructure.
- Results have shown that one of the greatest benefits of ocean observatories (e.g., FRF, HUGO, H2O) is high-frequency, long-duration sampling that can delineate transient events such as frontal passage, harmful algal blooms, volcanic eruptions, or severe storms.
- Experience demonstrates that the development of new *in situ* instrumentation for observatory use is a lengthy process requiring multiple

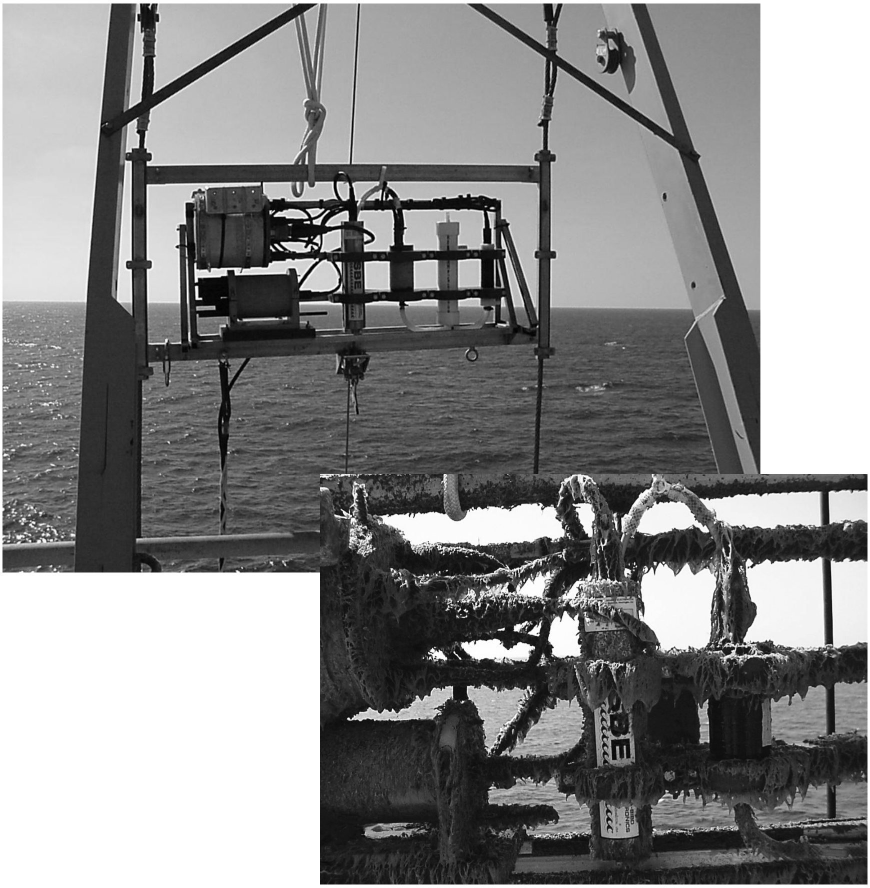

FIGURE 2-1 This before-and-after picture shows the tremendous problem that biofouling presents to the long-term deployment of instruments in the upper ocean, especially in coastal regions. Figure courtesy of Richard Jahnke, Skidaway Institute of Oceanography.

cycles of design, field-testing, troubleshooting, and redesign before the instruments become seaworthy enough to be used routinely.

- Moorings (e.g., the Bermuda Test Mooring-BTM) or cabled sea-floor junction boxes (e.g., LEO-15 or FRF) should be easily accessible (close to shore) for testing new technology and instrumentation. Such access can greatly accelerate the pace of developing and proving new technology and instrumentation, as well as providing a platform for establishing the comparability of a new technique with older methods that are being phased out.

CONSTRUCTION, INSTALLATION, AND TESTING

- Experience from the telecommunications industry and at research observatories such as HUGO, LEO-15, and MVCO shows that securing landing rights for a cable shore station, conducting various environmental assessments, and securing the necessary regulatory approvals from local, state, and federal authorities, is extremely time consuming—requiring lead-times as long as two years. Using retired, in-place telecommunications cables and existing cable stations eliminates the need to go through a lengthy permitting process.
- H2O and HUGO demonstrated that reuse of retired telecommunication cables for ocean research observatories is feasible. The principal limitation is power, not bandwidth.
- Experience with HUGO and H2O has indicated that engineering instrumentation should be installed on observatory nodes to provide key feedback on infrastructure performance and design and to evaluate instrument performance.
- Experience at HUGO, H2O, and FRF emphasizes the importance of knowing seafloor properties and, in some settings of armoring or burying of cables. HUGO failed six months after it was emplaced because of mechanical wear to unarmored cable lying on the rough volcanic terrain of Loihi submarine volcano. Experiences at FRF demonstrated that strong wave and current action on a cable lying on the seafloor can cause abrasion of the cable as well as strain on junction boxes, cable splices, and sensor connectors (Figure 2-2). A cable buried even several meters can become exposed following sediment movement.
- Several commercial firms are available for cable installation and ocean hardware design and maintenance. The considerable experience of these firms represents a valuable resource for observatory design and installation (e.g., HUGO, H2O) that the academic community should utilize.

OPERATION AND MAINTENANCE

- The OWS, BATS, and HOT time-series sites showed that the value of time-series data depends on the continuity and length of the record. Ocean observatory systems and their instrumentation must be designed for reliable, continuous operation and maintenance costs must be minimized if these systems are to be operated for decades or longer.
- Observatory operations and maintenance (whether for moorings or seafloor nodes) requires the availability of skilled and experienced personnel. Availability of trained personnel to go to sea is an occasional problem at present and will pose an even greater challenge for the expanded observatory network envisioned by the OOI (e.g., FRF, TAO).

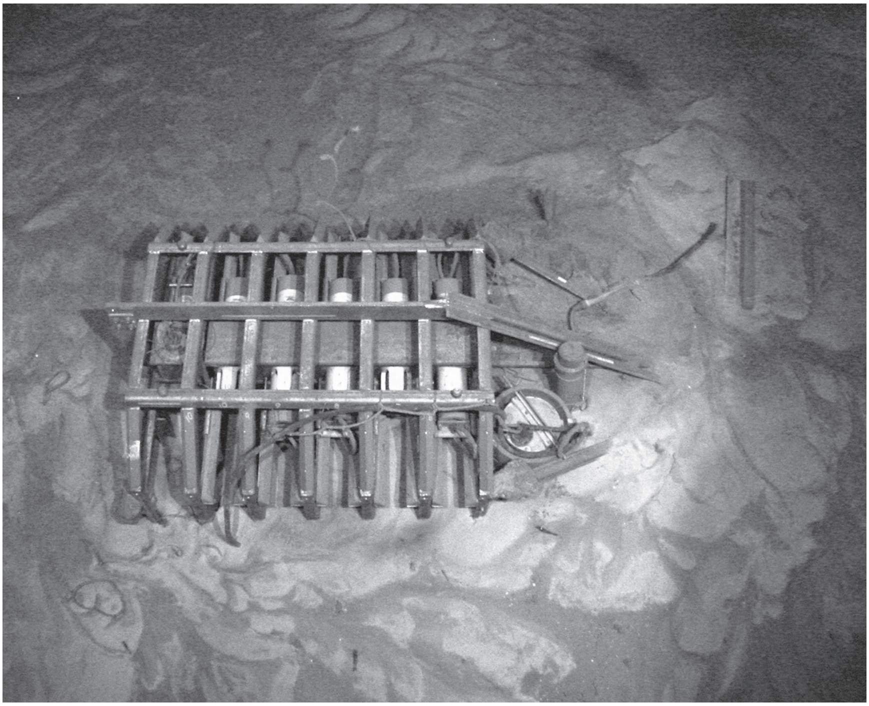

FIGURE 2-2 Seafloor junction box at HUGO, atop Loihi Volcano off Hawaii, after five years on the ocean floor. The partially buried package, recovered in October of 2002, is still in excellent condition. Use of titanium and plastics has virtually eliminated corrosion problems. Figure courtesy of Fred Duennebier, University of Hawaii.

- Coastal observatories are most beneficial when an inventory of community coastal vehicles (e.g., skiffs, surf zone working platforms, etc.), are available on site for deployment and retrieval of sensors (e.g., FRF) (Figure 2-3).
- Surface observatory nodes require regular routine servicing to replace or repair system components and instrumentation and to maintain data quality and continuity. Experience shows that these maintenance costs are often initially significantly underestimated (e.g., LEO-15, FRF).
- Even with the few open-ocean observatories currently in operation, the limited availability of ships and ROVs has hampered their operation and maintenance (HUGO and H2O). These assets are in high demand and scheduled well in advance, making it extremely difficult to respond quickly to observatory failures. The future need for ROV assets

FIGURE 2-3 The USACE FRF's Coastal Research Amphibious Buggy (*CRAB*). This deployment and retrieval platform is a tower on three wheels, hydraulically driven by a diesel engine located on the operations platform, 11 m above the seabed. The *CRAB* can operate in 2 m high breaking waves in 10 m depth of water, with Global Positioning System (GPS)-positioning accuracy to deploy fluid- and sediment-boundary layer sensors. The *CRAB* has also been used to measure monthly bathymetric changes at the Duck, NC site over the past 25 years. Figure courtesy of Joan Oltman-Shay, NorthWest Research Associates, Inc.

will likely increase significantly as more ocean observatories are established.

- Experience from years of operating oceanographic moorings shows that inter-comparison and inter-calibration procedures are essential. These procedures ensure data are of uniform quality even though they are collected from diverse sites using different instruments. Ship and/or ROV time must be dedicated to *in situ* sensor performance checks just before and just after deployment, as well as on recovery; a requirement which is often overlooked.

NATIONAL SECURITY

- One lesson from the U.S. Navy's SOSUS array is that the acquisition and public distribution of acoustic and other geophysical data in some regions along the U.S. coastline poses a significant national security risk. Deploying sensitive arrays in some areas could lead to the need to restrict data access, prevent data acquisition at random intervals, or restrict publication of results.

DATA MANAGEMENT

- Other major ocean science programs such as RIDGE, the World Ocean Circulation Experiment (WOCE), and the Joint Global Ocean Flux Study (JGOFS) show that the ocean observatory program cannot rely on individual investigators to manage, archive, or disseminate observatory data. Instead, data must be professionally managed and distributed through established data centers according to a policy that guarantees data is made available to the science community.
- Experience has demonstrated the value of establishing data formats and metadata content among participating data centers during the design phase of an observatory before data collection begins. For example, H2O data is distributed in the Standard for the Exchange of Earthquake Data (SEED) format, making it particularly valuable to seismologists around the world.
- Major ocean science programs like RIDGE, WOCE, and JGOFS indicate that strong interaction between science teams and data management groups is essential for a data management system. Without this interaction, requirements are often not implemented as intended.
- Instrument interfaces and data formats should be compatible amongst various instruments to simplify their integration. A standardized interface that would automatically associate an instrument's metadata with its data stream would facilitate such integration.

- Considering the large data acquisition rates (e.g., Gb/s to Tb/s), and the complexity of data products that an ocean observatory network could produce, levels of data products need to be defined and standardized for sharing data. For instance, both satellite missions and *Argo* define multiple levels of data products.
- Data archive centers require sustained funding to support data archival and distribution, even after the life of a program. For example, the Incorporated Research Institutes for Seismology's (IRIS) Data Management System archives approximately 3.5 Tb per year of seismic waveform data and is funded at about $3.5 million annually. In addition, NASA maintains three major archive centers and one long-term backup center at a cost of close to $100 million a year.

EDUCATION AND PUBLIC OUTREACH

- Experience has shown that education and outreach efforts will be more successful and more cost-effective if they are part of the initial observatory design rather than an afterthought.
- As illustrated by experience with H2O, outreach is best if handled at a central facility (in this case, IRIS) than by individual investigators.
- NASA has shown that a successful education and outreach program requires a professional staff with expertise in education and outreach. These activities need to be coordinated at the program level, not at the individual investigator level. In addition, a mandatory percentage of every project budget should be earmarked to support education and outreach activities.

3

Status of Planning for Proposed Research-Oriented Ocean Observatories

This chapter offers an assessment of the readiness of scientific planning and technical development for construction and installation of each the three main infrastructure components of the OOI. A summary of the scientific and technical readiness for each component is presented after each section (Box 3-2, Box 3-4, and, Box 3-6).

GLOBAL OBSERVATORY PLANNING

Global observatory science can be loosely divided into two categories, according to whether the data are obtained from the seafloor or the water column and sea surface. Data from the seafloor include geophysical information about earthquakes and the structure of the Earth, investigations of volcanic and tectonic activity, and studies of life on or below the seafloor. The data collected in the water column and at the sea surface are used for research on weather and climate, interactions between the atmosphere and ocean, and ocean physics, chemistry, and biology.

Global geophysicists are particularly interested in sites far from island-based or other land-based observatories in order to provide more uniform sampling of the Earth's interior. Oceanographers are more interested in measuring air-sea fluxes, investigating water mass formation, measuring transport and variability of major current systems, and studying the variability of the ocean's interior. While the sites of greatest interest to these various disciplines often do not coincide, the cost and limited availability of observatories in the more remote parts of the world's oceans argue strongly in favor of locating global observatories where many research goals can be concurrently and productively pursued. Studies that cannot be supported by fixed observatories will likely find support in Lagrangian and satellite observing systems.

The global observatory component of the OOI will provide important long-term, interdisciplinary measurements at 15-20 widely separated sites in all of the world's major oceans. A high priority is occupying sites in the remote Southern Oceans that are currently not sampled. This network will complement and enhance other international global observatory efforts (see Chapter 6). The following discussion summarizes the status of scientific planning and technical development for the OOI global observatory network.

Status of Scientific Planning

The scientific rationale for a global network of ocean observatories is well defined and planning for this network is well advanced, including the identification of specific sites for these observatories (Table 3-1). The primary drivers behind this planning effort are international scientist communities involved in climate, global carbon cycle, biological and biogeochemical, and solid earth geophysical research. Major research programs such as WOCE, JGOFS, CLIVAR, RIDGE, ODP, GSN, the Global Ocean Ecosystem Dynamics Program (GLOBEC), the Carbon Cycle Science Program (CCSP), and the Surface Ocean Lower Atmosphere Study (SOLAS), have all pointed to the establishment of long time-series sites as critical elements of their research strategy. International groups providing guidance on the development of a global observatory network include the Ocean-Observing System Development Panel (OOSDP), the Ocean Observations Panel for Climate (OOPC), the CLIVAR Ocean Observations Panel (COOP), the DEOS steering committee, and the International Ocean Network (ION). Each has laid foundations for developing global arrays.

These groups recognize the unique attributes of fixed observatories, which include high temporal and vertical resolution, the ability to observe from the sea surface to the seafloor, and their presence on site through episodic events and in conditions difficult for ships. Such groups have indicated that fixed observatories would be an essential element of the observational approach needed to address their science foci (see Box 3-1). In each case, strong arguments have been made to justify the cost of establishing long-term observatories, using a global reference frame that applies modeling, remote sensing, and other, already-available sampling methods to complement the observatory network (National Research Council, 2000). It is particularly important to test the success of models at replicating the variability observed in long time-series collected around the globe in different characteristic regimes. For example, satellite remote sensing helps numerical weather prediction models predict the global pattern of weather systems with greater accuracy, but such models have biases and error in sea-level meteorology and air-sea fluxes. With only one OWS (a ship) now operating and few open ocean time-series of surface meteorology available from buoys, there is no way to systematically address the size of the errors, why the models fail, and how to improve the model physics and performance in different regimes (such as in stratus cloud deck regions, in the trade winds, in the tropics, in the Southern Ocean, etc.). Global observatories would make available time-series crucial to developing better air-sea flux fields and improving atmospheric general circulation models.

An international Time-series Science Team (TSST) now coordinates the planning efforts of many of the groups interested in these scientific questions. Formed by CLIVAR and GOOS (through the COOP and the GOOS OOPC), and endorsed by the Partnership for Observation of the Global Ocean (POGO), the TSST represents the ocean community's diverse scientific interests and is developing consensus on the desired locations for time-series stations. In addition, it is charged with beginning the implementation of different components of an integrated global ocean-observing system. The TSST has identified a number of potential sites located at the intersection of regions of interest for multiple disciplines, giving priority to those sites where a shared interdisciplinary infrastructure will provide cost-effective observing systems that should be affordable and functional for decades to come.

The DEOS Steering Committee has used the work of the TSST to identify preliminary locations for 20 moored-buoy observatories that could comprise the global network component of the OOI (Figure 3-1, Table 3-1). The criteria for selecting these sites are outlined in the DEOS Global Network Implementation Plan (DEOS Moored Buoy Observatory Working Group, 2003). These 20 sites are a subset of a longer list identified to date by the TSST (Appendix E). Some of the sites on that longer list are already funded; the OOI contribution of an additional 20 sites would represent a dramatic increase in capability as well as a major step toward a global array of ocean observatories.

Status of Technical/Engineering Development and Planning

There are two distinct technological approaches for providing power and two-way communication to instruments at ocean observatories (1) moored observatories linked to shore via satellite and (2) observatories linked to shore by cables. Moored systems presently in use include both

TABLE 3-1 Potential Global Network Sites Proposed by the DEOS Global Working Group

Latitude/ Longitude	Remarks
Atlantic Ocean Sites	
36N 70W	Gulf Stream extension; flux reference at critical site for air-sea coupling; exchanges of heat; CO_2; freshwater; water column instrumented for water mass-variability and modification studies.
32N 65W	BATS/Station S/BTM; historical time-series record and testbed site; physical, meteorological, biogeochemical.
30N 42W	North Atlantic multi-disciplinary site; instrumented for DEOS; geophysics, meteorology, physical, biogeochemical.
0N 20W	Multidisciplinary mooring; site now occupied by the Pilot Research Moored Array in the Tropical Atlantic (PIRATA) surface mooring, getting surface meteorology and upper-ocean data; upgrade to more capable full water column and seafloor.
10S 10W	Flux reference site; for Atlantic climate modes; as above, upgrade existing PIRATA mooring.
35S 15W	South Atlantic multidisciplinary site; instrumented for DEOS; geophysics, meteorology, physical, biogeochemical.
Pacific Ocean Sites	
50N 145W	Former Ocean Weather Station P (“PAPA”), known today as Site P; meteorology; physical, biogeochemical.
40N 150E	Kuroshio Extension; meteorology and air-sea fluxes, water mass variability.
48 30N 176 30W	Endeavor segment of Juan de Fuca Ridge; RIDGE Integrated Study Site (ISS); seafloor biology, hydrothermal vents, geophysics.
9 50N 04 20W	East Pacific Rise RIDGE ISS site; tropical air-sea coupling, surface meteorology, water column, seafloor biology, hydrothermal vents, geophysics.
0 145W	Eq. Pacific multidisciplinary site; upgrade Tropical Atmosphere Ocean Project (TAO) site for flux; biogeochemistry, water column.
40S 115W	South Pacific multidisciplinary site; instrumented for DEOS; geophysics, meteorology, physical, biogeochemical.
35S 150W	South Pacific multidisciplinary site; instrumented for DEOS; geophysics, meteorology, physical, biogeochemical.
Indian Ocean Sites	
15N 65E	Arabian Sea; meteorology, physical, biogeochemical.
12N 88E	Bay of Bengal; meteorology, physical, biogeochemical.
10S 90E	90E ridge multidisciplinary site; surface meteorology, water column, seafloor.

continued

TABLE 3-1 Continued

Latitude/ Longitude	Remarks
25S 97E	Indian Ocean DEOS; geophysics, physical, meteorology, biogeochemistry.
47.7S 60E	Kerguelen Fixed Station (KERFIX), part of the Kerguelen Islands Time-series Measurement Programme follow-on; physical, meteorological, biogeochemical.
Initial Southern Ocean Sites	
42S 9E	SW of Cape Town; meteorology, water column instrumentation, geophysics.
55S 90W	Antarctic Intermediate Water (AAIW) water-mass formation region; meteorological, physical, CO_2, geophysical.
47 S 142E	South of Tasmania; meteorology, physical, biogeochemical, geophysics.

SOURCES: Modified from Figure 1, DEOS Moored Buoy Observatory Working Group, 2003 and data from R. Weller, Woods Hole Oceanographic Institution, personal communication, 2003.

BOX 3-1

Interdisciplinary Science Addressable With a Global Ocean Observatory Network

- Quantifying the exchange of heat, freshwater, and momentum between the ocean and the atmosphere;
- Obtaining a better understanding of upper-ocean mixing and the formation of the ocean's surface mixed layer;
- Determining interannual-to-decadal changes in ocean salinity and water mass formation;
- Making direct observations of ocean currents and transport and their variability;
- Detecting basin-wide and global-scale changes in upper-ocean temperature through acoustic thermometry;
- Investigating the variability of the ocean's interior;
- Quantifying the ocean's role in the global carbon cycle;
- Improving imaging of the structure of the Earth's interior by completing a network of global seismic and geomagnetic stations in the oceans that cannot be composed of island stations alone;
- Monitoring global plate motions and determining lithospheric deformation through establishment of seafloor geodetic stations;
- Studying volcanic, tectonic, and hydrothermal processes along active plate boundaries; and
- Exploring deep-sea and sub-seafloor ecosystems and their biodiversity.

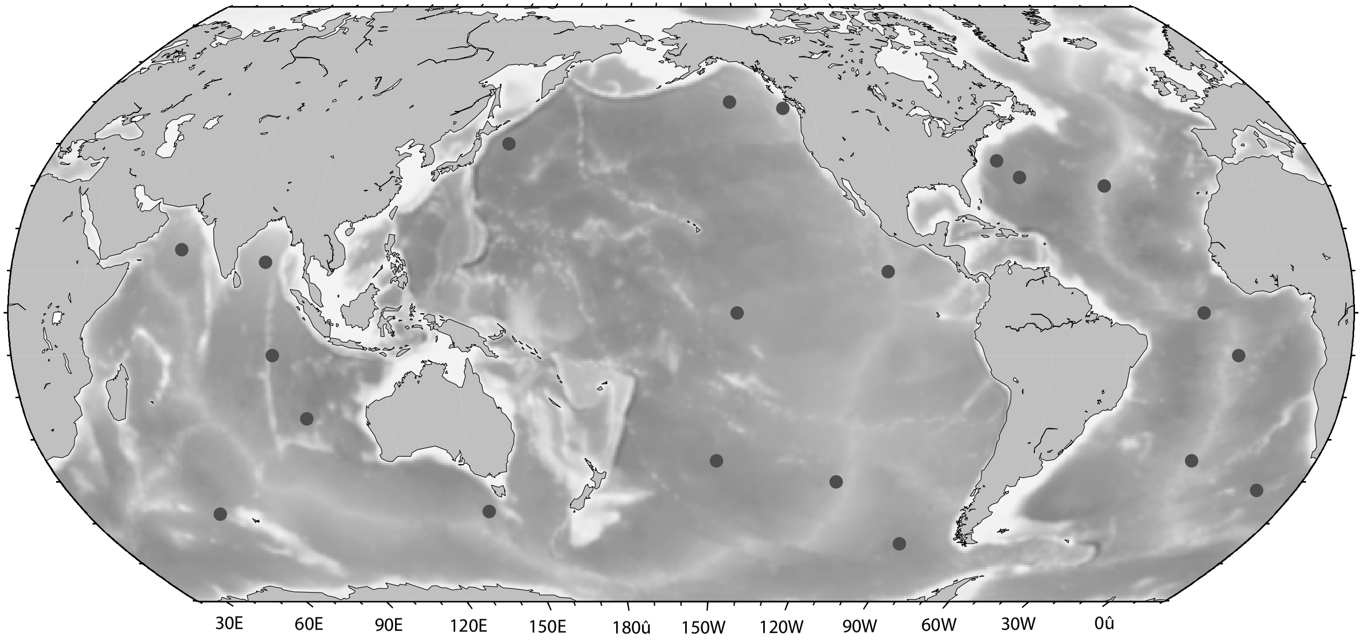

FIGURE 3-1 Location of proposed OOI global observatory network sites.

subsurface and surface moorings, but neither type has a hard-wired power or data connection to the ocean floor and thus cannot power or control instruments on the mooring or on the seafloor.

Cabled observatories can be further subdivided into those utilizing new cables and those re-using cables retired by the telecommunications industry. Global observatories based on new-cable infrastructure are probably beyond the scope of the OOI given the high cost of the cables needed to reach remote observatory sites. Re-using retired telecommunications cables for observatories is feasible in some circumstances, and is already occurring with the retired TPC-1 cable. Other cables are being used by the Earthquake Research Institute in Japan, the H2O, and A Long-Term Oligotrophic Habitat Assessment (ALOHA) Observatory (Appendix D).

Planning for the OOI global observatory network has thus far focused primarily on moored buoy systems. The opportunity to re-use retired telecommunication cables for some of these sites should be thoroughly investigated, however, as it might offer a cost-effective alternative to moored buoy systems in some locations.

Moored Buoys

At present, well-instrumented moored observatories using surface buoys are operational at tropical and mid-latitude sites (e.g., TAO, BATS, and the Pilot Research Moored Array in the Tropical Atlantic [PIRATA]). Surface meteorological sensors are mounted on the buoy and suites of oceanographic sensors are mounted on the mooring line, spaced as little as 5 m apart throughout the upper ocean, and extending into the interior of the ocean at wider spatial intervals (Plate 4). Those surface moorings designed to survive strong currents and high seas, as in the Arabian Sea, have used a scope (the ratio of mooring line length to water depth) close to 1.4 and have included synthetic rope (often nylon), which stretches and prevents the anchor from dragging and the surface buoy from submerging. The basic 3 m discus buoy hull developed at WHOI, used at many sites for research, has also been used by the National Data Buoy Center (NDBC) for collecting weather observations at many sites around the U.S. Exclusive Economic Zone (EEZ).

Many aspects of surface and subsurface mooring technology are very well developed for surface and water column measurements. Servicing intervals are dictated primarily by the need to maintain sensor quality in the face of biofouling and corrosive marine air. While some subsurface moorings can be installed and left unattended for up to five years, servicing intervals for surface expression moorings are typically six to twelve months for current generation moorings. Increasingly sophisticated instrumentation is also being developed for moorings, including multidisciplinary instruments, water samplers, *in situ* analyzers, and profiling instruments that move up and down the mooring line.

Current oceanographic moorings, however, have important limitations that the OOI should address. These moorings have a very limited capability for telemetering data to shore (samples per minute), since they rely on very low-bandwidth satellite systems. The buoy systems in use today also possess very limited power generation capabilities, as they rely generally on batteries or solar panels. Present-day moored observatories have no capacity to power or communicate at high data rates with instrumentation on the mooring or the seafloor. Inductive coupling of instruments to steel mooring cable and acoustic telemetry have been used to communicate with underwater instruments, but data rates are low. Surface-to-bottom electro-mechanical (EM) or electro-optical-mechanical (EOM) cables are as yet unproven and their reliability in this application is unknown.

Strong ocean currents, high sea states, freezing spray, and floating ice all challenge the survival of even the most robust surface moorings and cables available today. The large drag of strong currents can cause anchor dragging or buoy submersion. High waves lead to large cyclic tensions and mechanical fatigue, and may affect the performance of directional satellite antennas unless the surface buoy is large and designed to minimize pitch and roll. To sustain the quality of meteorological and air-sea flux observations in high sea states, buoy motion and mean tilts will need to be measured, or meteorological sensors will need to be mounted in gimbals. In addition, meteorological sensors more resistant to hostile environments must be developed. Mitigating the effects of freezing spray requires heated meteorological sensors and, by extension, buoys with significant power generation capabilities.

Subsurface moorings can survive longer in such hostile environments as they are not exposed to surface wave motion, can be deployed underneath ice cover, and are less likely to be vandalized. However, subsurface moorings are sometimes damaged by fishing activity. Furthermore, the lack of surface expression limits data return to using pop-up capsules that communicate via satellite at relatively low data rates, absent a direct connection to a seafloor cable (e.g., ALOHA observatory).

The DEOS Committee investigated new, more capable moored buoy systems, and found two particular concepts to be most promising for further development (Table 3-2) (DEOS Moored Buoy Observatory Working Group, 2000). The first option is a cable-linked, high-bandwidth spar or discus buoy that uses an EOM cable to connect seafloor and moored instruments to the surface (Figure 3-2). This system is designed to deliver approximately 500 W of power to the seafloor and would telemeter data

TABLE 3-2 Technical Specifications of Moored Buoy Systems Under Development

	Low-Bandwidth, Acoustically-Linked	Low-Bandwidth EOM Cable-Linked	High-Bandwidth, EOM Cable-Linked
Buoy type	Discus buoy	Discus buoy	Spar buoy
Mooring design	Taut mooring	S-tether mooring	Tri-moored
EOM cable	No	Yes	Yes
Data throughput	2.4 kb/s	9.6 kb/s	64 kb/s
Power to sensors	None	20W	500W
Junction box	No (acoustically-linked)	Yes	Yes

NOTE: Data volume delivered to shore will depend on commercial telemetry charges rather than bandwidth of telemetry link (e.g., Iridium telemetry costs are currently $1/minute).
SOURCE: Data from DEOS Moored Buoy Observatory Working Group, 2003.

to shore using a 64 kb/s C-Band satellite telemetry system with a stabilized, directional antenna.

The second concept is a low-bandwidth, discus buoy system that could be implemented using either of two different approaches (Figure 3-2). One option uses acoustic modems to transfer data intermittently from instruments on either the seafloor or the mooring to the buoy at rates of up to 5 kb/s and a low power, omni-directional satellite system to telemeter data from the buoy to shore at rates of 2.4 kb/s. A second approach uses an EOM cable to deliver approximately 20 W of power to instruments on the seafloor and to provide two-way data communication between the buoy and a benthic node. A low power satellite telemetry system would then deliver data from the buoy to shore at rates of up to 9.6 kb/s. See Table 3-2 for a summary of the technical specifications of the systems discussed above.

The following discussion offers an assessment of the technical readiness of each of these systems based on the recent DEOS Global Network Implementation Plan (DEOS Moored Buoy Observatory Working Group, 2003).

Low-bandwidth, acoustically-linked system

This design builds upon previous successful discus buoy deployments of up to one year in a variety of locations in the world's oceans. An acoustically-linked moored observatory has been used successfully by the NOAA Deep-Ocean Assessment and Reporting of Tsunamis program (DART) (*www.pmel.noaa.gov/tsunami/Dart/*). While there are no high-risk

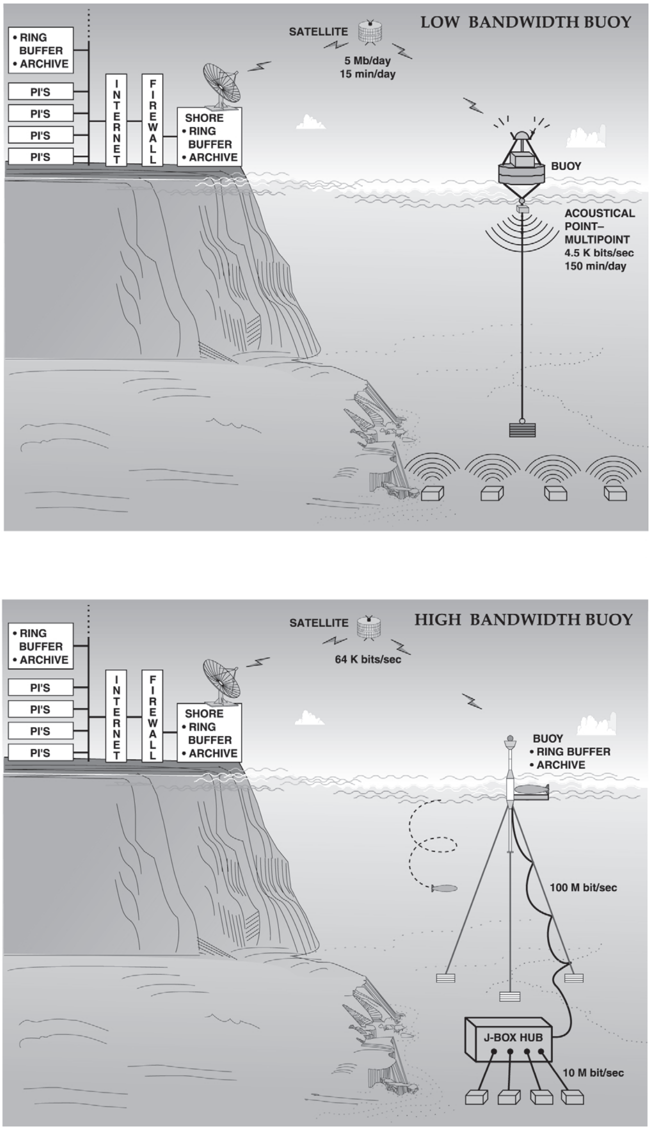

FIGURE 3-2 Two moored-buoy design concepts being examined for the OOI. Top: A low-bandwidth discus buoy system uses acoustic modems to transfer data intermittently from instruments on the seafloor or mooring to a surface buoy and from surface to shore via a low-power, omni-directional satellite system. Bottom: a high-bandwidth moored observatory that uses an electro-optical cable to deliver power and two-way data communication to a seafloor junction box and is linked to shore via a 64 kb/s C-Band satellite telemetry system. Figure courtesy of John Orcutt, Scripps Institution of Oceanography.

technologies associated with this system, there are questions associated with the performance of the acoustic modems under various environmental conditions. The primary issues that need to be resolved are (1) the reliability of the acoustic communication link; (2) the average data rates possible, both for instruments directly below the buoy on the mooring and for instruments placed some distance away on the seafloor or in the water column on a near-by subsurface mooring; and (3) the maximum horizontal distance from the surface buoy at which a useful acoustic communication link can be maintained.

Low-bandwidth, EOM-cable-linked system

The primary difference between this design and the other low-bandwidth system is that an EOM cable, rather than an acoustic-link, is used both to provide two-way communication to a seafloor junction box, and to provide small amounts of power (20 W) to the seafloor. In this design, the EOM cable moors the buoy. The lack of experience with using an EOM cable in this way makes the mooring the highest-risk sub-system in this approach. Conventional mooring designs with a wave-following buoy use the large scope of the mooring line to accommodate both the hydrodynamic forces associated with the mean currents that would otherwise either submerge the buoy or cause the anchor to drag, and the flexural fatigue problems associated with surface wave motion. Further, on conventional designs, plastic-jacketed wire rope extends down to about 1500 m in depth and then transitions to synthetic line. As the buoy heaves with surface waves and swell, many cycles of flexing occur, and there is motion of the stiff steel cable relative to the synthetic line below, which must have its uppermost section supplemented with a strain relief boot to reduce fatigue from bending and wear from chafing. With an EOM mooring cable, however, scopes of close to one times the water depth are planned in order to avoid slack line that might loop, flex, and bend as currents and sea state vary, thus causing failure of the optic fibers or strain hardening of the copper conductors in the EOM cable. In that case, however, in-line tensions could be high and cyclic variation in load significant enough to risk fatigue-related failure of the cable. The expected operational lifetime of EOM cables in this application, and the way in which factors such as sea state and currents affect their reliability, is not well known. Outstanding issues regarding EOM cable include (1) cable design and selection, (2) EOM termination design (including bending relief), and (3) design of the junction between the discus buoy and EOM cable.

High-bandwidth, EOM-cable-linked spar buoy system

This design is the most challenging of the proposed new systems and includes several new or high-risk sub-systems. Unlike the discus buoy design, the spar buoy system design does not require that the EOM cable be load-bearing. Nonetheless, there is little or no experience with EOM cables used to connect seafloor and moored instruments to the surface. The expected operational lifetime of the EOM cables, or the way in which factors such as sea state and currents affect their reliability is unknown. In addition to the EOM cable, two other sub-systems requiring further development and testing include (1) the high-bandwidth C-band satellite telemetry system and (2) the diesel power generation system on the buoy. A key issue is determining if these systems are capable of reliable, unattended operation for 12-month periods.

While prototypes of the two low-bandwidth systems will be built and tested at sea during the next two years (see discussion below), a detailed system engineering study of the high-bandwidth spar design must be completed and a prototype built and tested before this system will be ready for installation as part of the OOI. The design should consider issues associated with the use of a spar buoy as a measurement platform and any possible way in which it might interfere with meteorological measurements. Similarly, the approach to making those near-surface measurements in the ocean that are important to studies of upper-ocean physics, biology, optics, and air-sea fluxes needs to be thought through carefully as the hull of the spar will disturb the flow of the critical near-surface layer of the ocean and complicate instrumentation.

The seafloor junction box

Both the low- and high-bandwidth EOM-cable-linked systems require a seafloor junction box between the various instrument systems and the EOM cable to the surface. The moored-buoy junction box should be designed to appear to the user as identical to the cabled observatory junction box. The only difference would be the amount of power and bandwidth that will be available. Engineers developing the cabled and moored-buoy observatories will need to coordinate closely to ensure a common seafloor junction-box interface protocol.

Operation of these systems in severe environments

One of the most challenging goals of a global ocean observatory program is to establish observatories at high-latitude sites where high winds, high seas, and strong surface currents often prevail. Challenges range from the operational efficiency of the satellite telemetry system to the survivability of the mooring itself. The large tri-moored, spar buoy design seems like a promising approach for these harsh environmental conditions. The British DEOS (B-DEOS) has also developed an alternative design for a large, high-latitude buoy on a single-point S-tether mooring that behaves like a spar buoy at lower sea states and a wave-following buoy at high sea states. Before the OOI will be ready for deployment at high-latitude sites, the system design requirements for deployments in severe environmental conditions will need to be defined, and engineering and testing of various sub-systems will need to be completed.

Testbeds

Several efforts are under way to test various systems and sub-systems associated with the next-generation moored ocean observatories discussed above.

Acoustically-linked ocean observing system

A group of investigators from WHOI and the University of Washington have received funding from the NSF to develop and test a prototype deep-water, acoustically-linked moored-buoy observatory called the Acoustically-Linked Ocean-Observing System. The purpose of this project is to demonstrate the technical capabilities and scientific potential of an acoustically-linked moored-buoy system for ocean observatory studies. In late 2003, the prototype system will be deployed for three months off the U.S. East Coast, and in late 2004 for 15 months in the Northeast Pacific, in order to test the reliability of acoustic communication and the buoy-to-shore satellite link, in a variety of seasonal conditions.

Monterey Bay Aquarium Research Institute Ocean-Observing System (MOOS)

MBARI is testing several high-risk technologies associated with an EOM-cable-linked moored buoy observatory at the MOOS test mooring site in 1,860 m of water in Monterey Bay, California. These tests include (1) deployment of a mooring to verify dynamic modeling of the mooring and to verify the survivability of an EOM cable that delivers power and communications to benthic and water column networked instruments, (2) use of an ROV to lay EOM cable between benthic nodes, and (3) evaluation of smart network technologies to provide automated device discovery, configuration, and operation when an instrument is plugged into a node. Testing of these prototype efforts will continue through 2003, leading to an integrated system deployment in 2004 or 2005 in Monterey Canyon. This system will include:

- a surface buoy generating 50 W DC power;
- bi-directional Globalstar communication to shore;
- an EOM cable delivering power and communications to a benthic network;
- two or three benthic nodes connected to the EOM cable;
- Plug-n-Play instrumentation providing automatic dynamic mooring configuration; and
- a shore-side data system that receives data automatically associated with its metadata.

Real-time Observatories, Applications, and Data Management Network (ROADNet) Project

Scripps Institution of Oceanography is currently testing the performance of a commercial C-Band antenna system, one of the key design features of the high-bandwidth buoy system. For these tests, a 2.4 m C-Band satellite antenna from Seatel, Inc., of Concord, California has been installed on the *R/V Roger Revelle*, and service leased from a commercial teleport to provide a 64 kb/s full-period connectivity between the ship and the public Internet (a cost of about $100/day for 64 kb/s). A prototype shore-side teleport is located at the San Diego Supercomputer Center (SDSC) on the University of California San Diego main campus. The SDSC is a major node on the Internet, providing a convenient wide-band gateway. This prototype network provides for real-time delivery of large quantities of shipboard data to shore for quality control, archiving, and real-time data availability. During the first year of tests, throughput has been about 82 to 85 percent of capacity. The performance of the system to date suggests that the motion requirements specified in the DEOS Buoy Design Study (DEOS Moored Buoy Observatory Working Group, 2000) of less than 10 degrees per second may be unnecessarily stringent because of the rapid response of the antenna servo (90 degrees per second). However, the reliability of the system will need to be improved in order for one year of unattended operation to be possible.

Cabled Systems

Planning for cabled observatories in the remote oceans began with meetings in Honolulu, Hawaii in 1990 to discuss the use of retired telecommunications cables (Chave et al., 1990), and in La Jolla, California in 1995 to plan for permanent ocean observatories (Purdy and Orcutt, 1995).

The IRIS took the lead by forming the Cable Steering Committee, and the Ocean Seismic Network (OSN) planning effort (Dickey and Glenn, 2003). Until very recently it seemed that only older co-axial cables would be retired in the next decade, given the rapid growth of the telecommunications industry. However, the lag in increase in demand for bandwidth and the huge increase in available bandwidth in new optical cable systems has led to the imminent retirement of the older optical cable systems well before their design lifetimes. For example, the Hawaii-4 cable, which will be retired in 2003, was installed in 1989. Since this development is very recent, little planning has been accomplished for the possible use of these cables for ocean observatories. In fact, the high cost of new cable and cable ships was believed to limit the use of cables for observatories to near shore observatories; the development of the OOI reflects this history.

Using submarine optical cable systems at global observatory sites is advantageous, given:

- their high data bandwidth available for data transmission (250 Mb/s or more);
- their ability to transmit large volumes of data to users in real-time;
- their relative immunity to weather problems;
- their ability to function without routine maintenance;
- their ability to provide large amounts of continuous electrical power (kW) to the ocean floor;
- the costly shore connections already in place for many applications; and
- the high reliability of the technology provided by commercial research and development.

On the other hand, new submarine cables are relatively costly (about $10,000/km depending on cable characteristics and market conditions), although this is not an issue for cable re-use. In addition, installation of long cables is expensive, often requiring cable burial near shore and the use of cable laying ships. Furthermore, new shore stations, required to provide power and data links to users when a new shore connection is required, are also expensive.

More than 35,000 km of electro-optical telecommunications cables on the ocean floor, representing more than $500 million in cable assets, will be retired in-place by the industry within the next few years, and more during ensuing years. These cables come to shore at existing cable stations, and the shore hardware systems and the cable stations could be available for observatory use at little cost. These cables present a one-time opportunity to the oceanographic community for re-use in observatory support. The newest fiber cable systems, which use optical amplifiers rather than optical signal regenerators, will likely not be retired for decades, since they have extremely high bandwidths and can be upgraded in place. A few of the oldest optical amplifier systems, installed in the mid 1990s, have relatively low bandwidth compared to the newest systems, and could be retired within a decade. Such systems use less current than the repeatered systems, and thus would supply less power to observatories. The near-shore end of these cables often represents a liability to the telecommunications industry due to fishing concerns and anchoring. As a result, the retired cables are often removed from the continental shelf after retirement, rendering them useless for in-place observatories. When these older cables are gone, the opportunity for cable re-use for observatories will likely end for decades.

There are a number of technical, logistical, and financial issues that need to be evaluated in order to determine the suitability of using retired cables for any particular global observatory site. However, in those cases where cables can be used in-place or moved only a short distance while still utilizing the original shore station, submarine cables potentially offer many advantages over the use of buoys or laying new cable. In this case, installation cost is very low, as it requires only the recovery and termination of the cable. If sampling of the upper ocean and measurements of air-sea interaction are required, the installation of a surface or subsurface mooring may be necessary. Installation of the H2O on the retired Hawaii-2 coaxial cable between Hawaii and California was accomplished in 1998 with a UNOLS vessel (Petitt et al., 2002) (Figure 3-3). It is technically feasible to relocate cables to a new, distant location, but doing so requires recovering and relaying the cable, establishing a new shore connection, obtaining permitting for the landing site, constructing a shore facility, and acquiring access to power and data distribution infrastructure on shore. In such a case, the cost and feasibility of moving and installing a re-used cabled system needs to be carefully assessed and compared to the cost, reliability, and assets of buoy observatories. Initial estimates suggest that from four to eight observatory nodes could be attached to a single optical cable, supplying up to a kilowatt of power and 100 Mb/s bandwidth to each node. The NSF should appoint a committee with the appropriate expertise to thoroughly evaluate the issues regarding cable reuse and recommend how best to utilize this potentially valuable resource for observatory science. Some key technical, logistical, and financial issues this cable re-use committee should address include:

Technical

- the feasibility of recovering these existing fiber-optic cables from the deep sea without damaging the cable and repeaters; and

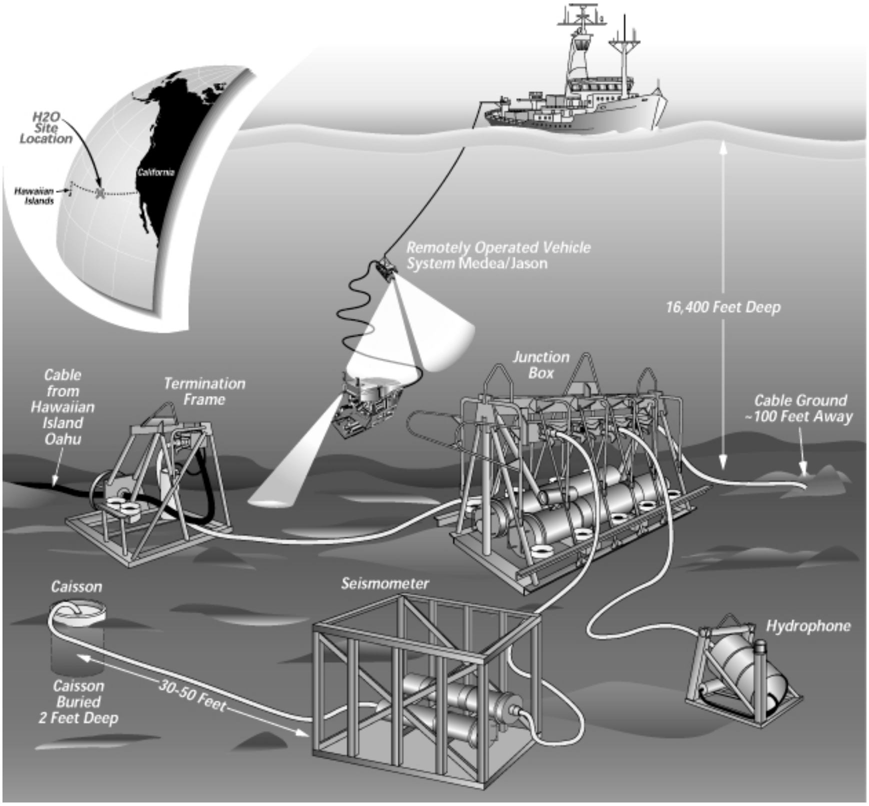

FIGURE 3-3 The H2O, the first deep-sea cabled research observatory, was established in 1998 using the retired Hawaii-2 coaxial telecommunications cable. A seafloor junction box in 5,000 m of water provides power and data communication for up to six instruments including a broad-band seismometer. More than 35,000 km of electro-optical telecommunications cable will be retired in place by industry within the next few years, providing a potentially significant resource for ocean observatory science. Figure courtesy of Jayne Doucette, ©Woods Hole Oceanographic Institution.

- the ability to produce appropriate hardware and software for use of these systems for observatories;

Logistical

- the problems surrounding the cooperation of foreign countries with established power and communications infrastructure, required to establish cabled observatories in remote areas;

Financial

- moving long sections of cable will require a commercial cable ship and experts to handle and terminate the recovered cable. The adequacy of the benefits of making high-bandwidth and power available to observatories in remote areas in offsetting the costs of the commercial cable ship and experts to handle and terminate the recovered cable in order to move long sections;
- the affordability of shoring these cables, which will require armored cable and cable burial in many cases; and
- the possibility of using spare cable equipment and cable that will also be discarded by the telecommunications industry for future observatories, and any attendant liabilities.

BOX 3-2

Summary of Global Observatory Scientific and Technical Readiness

- The general scientific rationales for global-scale observatories are well established and planning for the location and scientific focus of individual nodes is well-advanced.
- The low-bandwidth, acoustically-linked buoy systems are technologically feasible now, although acoustic-link performance under realistic environmental conditions needs to be assessed through at-sea prototype testing.
- The EOM-cable-linked, low-bandwidth and high-bandwidth buoy systems face significant engineering development issues. The highest-risk sub-system is the EOM cable, as the expected operational lifetime of EOM cables in this application, and the way in which factors such as sea state and currents affect their reliability is unknown. The performance and reliability of the C-Band antenna systems and of power generation on unattended buoys will require additional testing and evaluation.
- Re-use of retired telecommunications cables may offer a highly cost-effective alternative to moored buoys at some global, regional, and coastal network sites. The NSF should establish a committee with the appropriate technical and scientific expertise to thoroughly evaluate the potential of this option.
- Capitalizing on improved data communication and power availability will require further development of meteorological sensors for use in more severe environments.
- Two already funded prototype systems will begin to address some of these issues over the next two years. However, additional funding will be required for engineering design studies, sub-system testing, and prototype construction and deployment of the high-bandwidth spar buoy system during the next two to three years.

REGIONAL OBSERVATORY PLANNING

Plate tectonics is a well-established paradigm for the slow geological processes of formation, movement, and destruction of the Earth's ocean crust. Crustal generation takes place along the crests of the huge underwater ridge systems that girdle the globe, while destruction occurs along convergent boundaries where oceanic lithosphere sinks back into the earth. However, these processes remain poorly observed: partly because they primarily take place in regions hidden by the oceans, and partly because to a large extent they occur through events that are highly intermittent in time (sub-sea volcanism in the case of crustal construction, subduction earthquakes in the case of destruction). Further progress in understanding these geophysical processes requires extended time-series measurements within the ocean over the scale of a tectonic plate. A plate-scale, regional observatory would enable acquisition of such extended time-series. In addition, cabled networks with real-time instrument control allow for "interactive sampling," in other words, (re-)deployment of sampling resources at the time and location of significant events.

While initially focused primarily on either such geophysical processes as the study of biological communities at hydrothermal vents, additional studies have identified significant contributions to other branches of oceanography that would result from the combined temporal and spatial resolution characteristic of a regional-scale observatory. Suggested uses include studying continental slope stability and subsea methane deposits and determining long-term variability of ocean circulation. The high power and bandwidth of a cabled observatory is particularly important to studies involving interactions between the physical environment of the ocean and its embedded marine ecosystems, studies not only of fundamental importance but also of special urgency given evidence of climate change.

Assessment of implementation readiness for a regional-scale cabled observatory requires consideration of the maturity of planning for identified scientific opportunities, as well as the extent to which technical challenges have been met or are likely to be met in the near future.

Status of Scientific Planning

The often unique scientific opportunities presented by high temporal resolution, long-term ocean measurements that can be provided only by cabled observatories have been extensively documented as a result of various broad-based community workshops and a series of recent reports (See Appendix C). The report *Ocean Sciences at the New Millennium* (National Science Foundation, 2001) identified six cross-cutting ocean science themes that are likely to provide the most important, most promising, and most exciting areas for ocean discovery and understanding over the next decade (Box 3-3).

The *Illuminating the Hidden Planet* report (National Research Council, 2000) identified major science problems under each of these themes for which geographically distributed, long-term, time-series observations would be either useful or very useful. The recent SCOTS workshop report provides detailed documentation of specific scientific problems within these themes that would be best addressed using the strengths of cabled ocean observatories (Dickey and Glenn, 2003). Many of these problems had also been identified during earlier science planning for the NEPTUNE plate-scale observatory in both the U.S. and Canada (NEPTUNE Phase 1 Partners, 2000; NEPTUNE Canada, 2000). A regional-scale observatory will complement the global observatory network, providing the higher temporal and spatial resolution data necessary to interpret the global-scale data for each of the interdisciplinary science questions listed above.

Although the general scientific rationales for a regional-scale observatory can be considered as firmly established by the reports referenced above, detailed planning is just beginning for those specific, rather than thematic, scientific objectives that are crucially dependent on cabled infrastructure. Additional disciplinary and interdisciplinary community workshops should be held to define “lead-off” science questions and innovative experiments likely to generate the most exciting scientific and educational results during the first few years of operation of a regional-scale observatory. These workshops should not only provide definition for these science questions but also begin to specify the instrumentation that scientists will expect as part of observatory infrastructure and the

BOX 3-3

Cross-cutting Science Themes Addressable with Regional-scale Observatories (National Science Foundation, 2001)

- Dynamics of the lithosphere and the Earth’s interior,
- Fluids and life in the ocean crust,
- Coastal ocean processes,
- Turbulent mixing and biophysical interactions,
- Ecosystems dynamics and biodiversity,
- Ocean and climate/biogeochemical cycling.

combinations of measurements that will be required at each experimental location.

Status of Technical and Engineering Development and Planning

A cabled observatory may use a network of modern telecommunications cables to support a wide variety of instruments on and beneath the seafloor and within the water column. A regional-scale cabled observatory facility could involve thousands of kilometers of cable, several shore stations, many science nodes, and possibly multiple-loop cable topologies as well as branches. Together, these elements will provide (1) a power distribution system; (2) a communication network for command and control, data transfer, and accurate timing; and (3) connections for long-term core sensors and community experiments as well as shorter-term experiment-specific sensors.

While technologies and methods developed by the sub-sea telecommunications industry provide a strong foundation for regional cabled ocean observatories, such systems are simple in comparison to the proposed NEPTUNE system. The design and implementation of such a complex system of sub-sea cabled observatories pose many additional technical challenges (NEPTUNE Phase 1 Partners, 2000).

The commercial submarine telecommunications industry focuses on moving data from one shore landing to another. In contrast, a sub-sea observatory must gather data from sensors distributed throughout an ocean volume, as well as on and under the seafloor, and deliver these data to shore while simultaneously enabling real-time control of power and control of a wide variety of instrumentation. These requirements demand challenging technological capabilities, including the following:

- ***Branching:*** a requirement for constructing arbitrary topologies (spur, ring, mesh, etc.) for optimizing sampling array design, allowing future addition of cable runs that might be necessary to adapt initial observatory design to changing scientific questions, and providing redundancy in routing signals and power, thus increasing the reliability of the system;
- ***Undersea nodes:*** highly reliable junction boxes for bringing signals and power to and from the primary cable;
- ***Power supply:*** the ability to provide different and time-varying amounts of power to multiple nodes on the cable;
- ***Communications protocols:*** the ability to add and drop two-way information at each node on the cable;
- ***Plug-n-Play instrumentation:*** standardized scientific instrument interfaces, dynamic network detection of changed (added/deleted/

replaced) sensors, automatic addition of necessary meta-data to sensor files, and automatic addition of data from new sensors to the archival stream;

- ***Accurate time base:*** highly accurate time registration, as will be required by certain classes of experiments;
- ***Failure detection/isolation/recovery:*** timely detection (and if possible, mitigation) of failure in individual system components, so that failure does not propagate through the entire system; and
- ***Command/control functionality:*** operational means of allowing the "owner" of an individual scientific instrument or experiment to control it in a way that is reasonably transparent, while protecting other deployed instruments and experiments and the network itself.

Technical planning for regional-scale observatories has primarily taken place within the framework of the NEPTUNE project, a proposed joint U.S./Canada plate-scale observatory designed to encircle and cross the Juan de Fuca tectonic plate in the northeast Pacific with about 3,700 km of fiber-optic/power cables (Figure 3-4). Experimental sites, established at approximately 30 nodes along the cable, would be instrumented to study geological, physical, chemical, and biological phenomena that vary on multiple scales of space and time over an observatory lifetime expected to be at least 30 years. Both spatial and temporal scales thus vastly exceed those of any scientific activity that has yet been attempted in the ocean. Since the scientific and technical challenges faced by NEPTUNE will be present in any alternate proposals for regional observatories, the results of the NEPTUNE technical planning process (NEPTUNE Phase 1 Partners, 2000) will be used to provide necessary specifics in the following discussion of the major areas of engineering development required for the successful implementation of a regional-scale observatory. These areas include power supply, data transmission, communications control and timing, data management and archiving, and sensors.

Power Supply

The NEPTUNE project is considering two options for power distribution. The first option is based on the conclusion of the 2000 U.S. NEPTUNE Feasibility Study that neither AC power nor the constant current serial DC power systems used in transoceanic telecommunications cables are appropriate for a submarine cabled observatory (NEPTUNE Phase 1 Partners, 2000). The feasibility study concluded that the desired system of multiple nodes, each with time-varying power requirements, would be best served by a parallel DC system capable of providing constant voltage to each scientific user. At each node, high voltage (6-10 kV) DC power

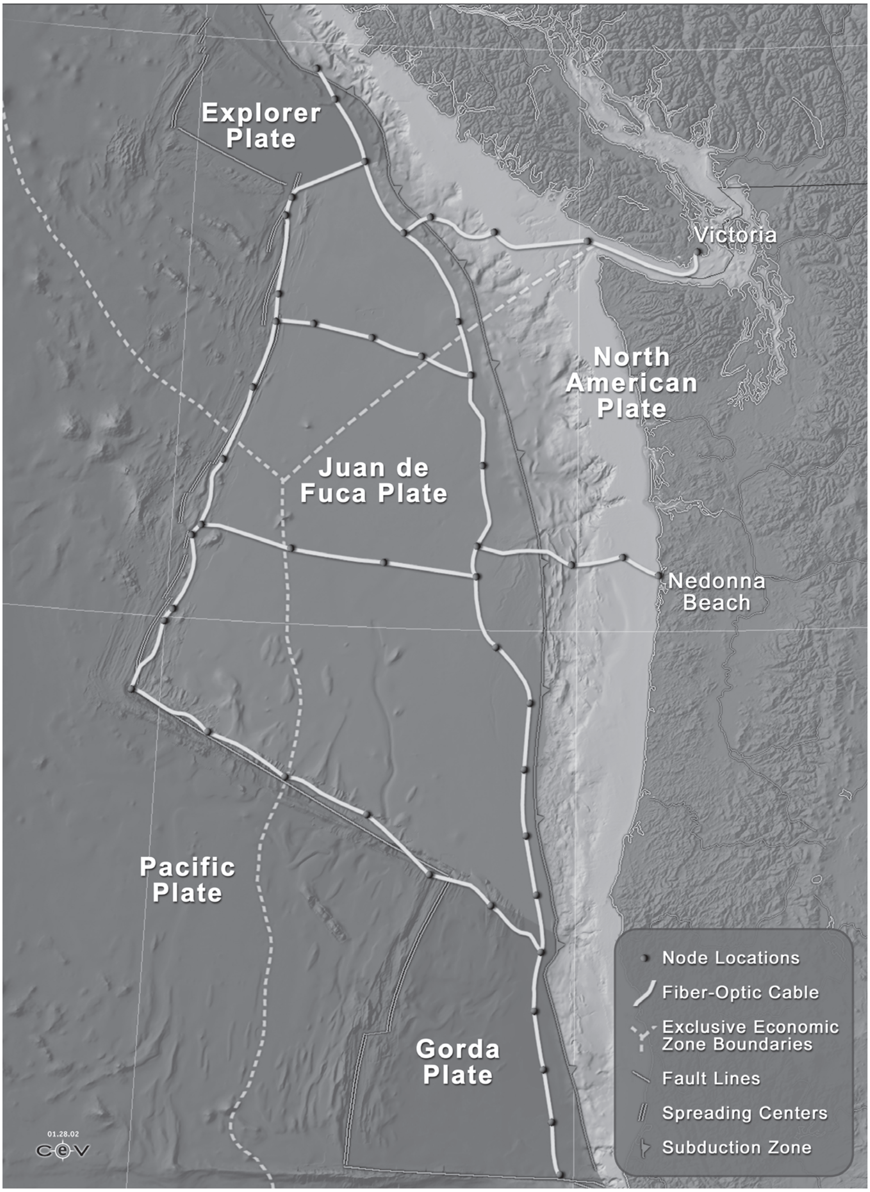

FIGURE 3-4 Backbone cable structure and primary seafloor nodes proposed for NEPTUNE, an international USA-Canada sub-sea observatory spanning the Juan de Fuca plate off the western coasts of British Columbia, Washington, and Oregon. Figure courtesy of the NEPTUNE Project (*www.neptune.washington.edu*) and produced by the Center for Environmental Visualization at the University of Washington.

would be converted to 400V and 48V supplies for scientific users. Duplicate, cross-linked power supplies in each node are planned to enhance reliability. Even so, the performance level required of individual components for the life of the system is still very high.

A second option currently being considered aims to reduce this problem by including circuit breakers in the branching unit where the side cable to a node joins the main (backbone) cable. Any fault that develops in a node or its branching cable would result in the isolation of that node without affecting the rest of the system. With such a system, the dependence on the reliability of individual nodes could be reduced (and could even vary throughout the network, depending on local scientific requirements) without any effect on the availability or reliability of other nodes. The first option has recently undergone a concept design review, the results of which are available at *http://neptunepower.apl.washington.edu*. A comparison of the two options (which share most hardware and control features) will be completed in the near future and will be further tested through the development of prototype hardware for laboratory and field-testing.

Communications, Control, and Timing

The 2000 U.S. NEPTUNE Feasibility Study, which was based on the assumption that a new, custom-designed cable would be laid, concluded that the two-way communication and interactivity requirements of a cabled scientific research observatory would be best met by extending the Internet into the deep sea (NEPTUNE Phase 1 Partners, 2000). Under NSF support, WHOI, in collaboration with Cisco Systems, has been developing a Gigabit Ethernet system that will provide the communications for a multi-node, cabled observatory. Each node will have packaging and add/drop transmission capabilities that will enable users to control their instruments, retrieve data, and access a time signal that will time-stamp all observations with an accuracy of one millisecond or better. The node routers will also serve as amplifiers for the optical signals moving along the cable, obviating the need for expensive optical amplifiers. The current development status of this communications system is described in a draft conceptual design report (NEPTUNE Data Communications Team, 2002).

The virtual collapse of the transoceanic cable industry subsequent to completion of the NEPTUNE feasibility study initially raised the hope that surplus conventional submarine cable might become available at relatively low cost, though that does not appear to be the case now. Use of this type of cable, which includes embedded optical amplifiers, would eliminate the need to space nodes at approximately 100 km intervals to amplify the optical signal and opens the possibility of starting with a sparse set of initial nodes that could be augmented as scientific demand and resources grow. However, the combination of Ethernet and conventional submarine telecommunications protocols introduce significant additional engineering complexity, and the cost of this alternative system may be significantly greater than the original NEPTUNE telecommunications design. A full comparison of the two options is currently under way, and will evaluate these options based on their life cycle costs, reliability, and flexibility and expandability by an independent panel of experts. A final decision on which design to pursue should be made by late 2003.

Data Management and Archiving System

Leadership of the Data Management and Archiving System (DMAS) planning for the proposed NEPTUNE regional-scale observatory has been provided by the Canadian National Research Council's Herzberg Institute of Astrophysics in Victoria, British Columbia, which is one of three Hubble Space telescope data repositories. A conceptual design study (*www.neptunecanada.ca/about/reports.htm*) incorporates key lessons learned from the astronomical community's experience with large data streams. These lessons include:

- the DMAS data management and archives must be science-driven;
- instrument and observatory control system design must support data management;
- collection, packaging, and validation of data and meta-data should be automatic;
- data must flow simultaneously to both the Principal Investigator (PI) and the archive;
- automating the process of quality control should be based on practical experience; and
- data archives should allow both public and privileged access to various data streams.

Major additional challenges faced by regional cabled observatories lie in the heterogeneous data types that will be generated from a wide variety of instrument suites and the need to support simultaneous execution of many experiments. Valuable experience will be provided by a prototype based on this design study and scheduled for implementation during 2003-2004 as the DMAS for VENUS, a funded Canadian testbed observatory. As part of this implementation, Canadian DMAS planners are working closely with engineers at MBARI, who are developing the Scientific Instrument Interface Modules (SIIMs). These interface modules will be inserted between scientific instruments and deep-sea cabled nodes and both will add essential metadata to the data streams and allow the network to recognize and accept data from newly installed instruments.

Testbeds

In addition to the technical issues described above, there are other major technical challenges involved in making the transition from the current oceanographic research techniques to effective use of a regional cabled observatory. Scientists must learn how to design, install, operate, and recover complex experiments, while engineers must design, build, test, and install new hardware in a challenging operating environment. Information managers must learn how to use huge streams of data (on the order of 1 Petabyte—10^{15} bytes—per year) of many different types. Operators must learn how to install instruments, service an array with minimal down time, protect a network from failures in any one of many individual instruments, keep a network running with high reliability, restore service rapidly in the event of a failure, and provide users with the ability to interact with their experiments as needed. It is widely recognized that technical challenges are best met through testbed sites, a sequence of cabled systems that will build the experience necessary to attain the full potential of a regional cabled observatory.

Two testbed systems are presently under development in support of the eventual establishment of regional-scale undersea observatories.

Victoria Experimental Network under the Sea

Funded by the Canada Foundation for Innovation and the British Columbia Knowledge Development Fund for a start in 2003, VENUS will lay a short single-node cable in Saanich Inlet (an anoxic fjord), a cable with multiple nodes across the Canadian portion of the Strait of Juan de Fuca, and another into the middle of the Strait of Georgia south of Vancouver (Plate 5). In addition to providing researchers with access to interesting and very different marine environments, VENUS will enable early testing of various technologies proposed for a regional observatory (more information available at: *www.venus.uvic.ca/*). Cables will be marine industry standard, with a central core steel tube containing eight optical fibers surrounded by steel strength wires, a single copper conducting sheath, and insulation. Installation will use commercial entities with extensive local experience in submarine telecommunications. As planned, VENUS will use the major components of the power system proposed for NEPTUNE. The VENUS communication system will connect each science node directly to shore, using dedicated fibers and commercial off-the-shelf hardware. Where possible, science nodes and SIIMs will use designs and components being developed for NEPTUNE and MARS. The VENUS Data Management System will be implemented by data managers at the Herzberg Institute of Astrophysics, based on initial planning carried out during the NEPTUNE feasibility study.

The VENUS installations placed, in relatively shallow water and using relatively short cables, will test the following components necessary for eventual establishment of a regional-scale observatory:

- single-cable multiple nodes;
- power system;
- communications system (simplified version);
- data management system;
- node design;
- SIIMs design; and
- ROV installation and maintenance.

Monterey Accelerated Research System

Funded through MBARI by the NSF and the David and Lucile Packard Foundation, MARS will involve the installation of a cabled test bed adjacent to Monterey Canyon in Monterey Bay, California (more information available at: *www.mbari.org/mars/*). Planned for installation in early 2005, MARS will extend the VENUS experience to longer cable runs (62 km) and deeper water (1220 m), and test a spur topology involving a branching node supporting an "extension cord" to instrumentation at a distance of several kilometers from the backbone cable (Plate 6). In this environment, the MARS testbed will further test both the DC power and communications systems being proposed by the MARS/NEPTUNE engineering group. Finally, successful deployment of MARS will (1) allow researchers to become accustomed to working with the type of nodes, SIIMs, and data management systems that will accompany a regional-scale installation; (2) provide the crucial experience required to develop operational skills (ROV-based installation and maintenance, system fault response and repair, and system control) that will be needed by operators and users of larger regional-scale observatories; and (3) supply education and outreach organizations with real-time and archived data products that can be used both immediately and in preparation for the more extensive data streams derived from regional-scale installations. Neither VENUS nor MARS provides in-water testing of the mesh (with branches and loops) cable topology or the high voltages and currents proposed by NEPTUNE for a regional-scale observatory.

BOX 3-4

Summary of Regional-scale Observatory Scientific and Technical Readiness

The present status of scientific and technological readiness for regional-scale observatories, as represented by VENUS/MARS/NEPTUNE, can be summarized as follows:

- General scientific rationales are well-established as a result of a large number of community-based planning meetings, some general (SCOTS) and others specific to funded (VENUS, NEPTUNE Canada, and MARS) and proposed (U.S. NEPTUNE) sub-sea observatories.
- There is a need for further definition of specific science projects that require the entire regional-scale and for the detailed array of experiments envisaged at specific nodes.
- Technical challenges are being addressed on a range of fronts, however, alternative designs have been proposed for both power and communications systems. All of these alternatives differ significantly from existing sub-sea systems and thus are sources of both significant risk and significant promise.
- A cabled observatory system of the scale of NEPTUNE using multiple nodes and a mesh topology is far beyond anything ever attempted.
- Two funded testbed systems will provide the necessary first steps of phased implementation; however, there is as yet no testbed for the mesh topology or the high voltages and currents being proposed for a regional cabled observatory.

COASTAL OBSERVATORY PLANNING

The coastal ocean is chronically under-sampled, which is especially problematic given mounting evidence that human activity is altering coastal waters by changing sediment deposition, erosion patterns, nutrient distributions, microbial food web structure, and fisheries (Hallengraeff, 1993; National Research Council, 1995; Jørgensen and Richardson, 1996; Rabalais and Turner, 2001). These human-induced changes will increase in the coming decades with projected coastal development and will be compounded by climate change and global sea-level rise. Unfortunately, research efforts in coastal waters have been hampered by inadequate infrastructure and logistical limitations for individual or small groups of scientists who need to measure the full breadth of time (seconds to decades) and space (cm to km) scales that affect coastal processes. There is a community consensus that traditional monitoring strategies are inadequate for studying many coastal processes of increasing societal relevance (Thornton et al., 2000; Jahnke et al., 2002).

To overcome these sampling shortcomings, the coastal ocean research community has been conducting interdisciplinary studies focused on developing integrated observation techniques. With the enabling technologies that have evolved from these efforts, the ocean sciences are currently poised to address pressing questions regarding spatial and temporal heterogeneity and change in coastal ecosystems. These technologies expand the range over which ocean phenomena can be observed and will make it possible to identify and study processes at previously impossible time and space scales. In addition, these envisioned systems offer the opportunity of *in situ*, real-time, interactive observations that cross conventional disciplinary boundaries, allow for adaptive sampling, and provide useful information to many marine-related user groups. The coastal community appreciates that to fully realize the potential of these new observation systems and to move understanding of the coastal environment to the next level, the community needs to leverage multi-disciplinary studies, sharing many of these resources along with the logistic costs.

Status of Scientific Planning

Scientific planning for the coastal component of the OOI has grown from nearly a decade of integrated research efforts conducted through the NOPP, the Department of Defense ONR, the NOAA EcoHAB Program and the NSF CoOP. Many of the central scientific problems for coastal waters were synthesized in two separate NSF sponsored workshop reports: *Coastal Ocean Processes and Observatories: Advancing Coastal Research* (Jahnke et al., 2002) and the *Scientific Cabled Observatories for Time-series* (Dickey and Glenn, 2003). In addition, the state of knowledge in near-shore processes and a community consensus on future near-shore research strategies were detailed in *State of Nearshore Processes Research: II*, from a 1998 workshop (Thornton et al., 2000). Finally, Ocean.US, which is designing a national operational IOOS, has highlighted many of the technical issues for coastal observatories in *Building Consensus: Toward An Integrated and Sustained Ocean Observing System* (2002) (Box 3-5).

While all these reports agree the OOI will provide major advances in our understanding of coastal processes and new tools for observing coastal processes, no clear consensus has yet emerged on the mix of observational technologies and approaches that will best address the major scientific problems identified in these reports. These approaches include relocatable arrays of moored buoys and radars (Pioneer Arrays), cabled observatories, and fixed, long-term moorings (Jahnke et al., 2002). These different technological approaches are discussed below in the context of a multi-faceted, multi-dimensional approach to interdisciplinary coastal research.

BOX 3-5

Scientific Themes Identified in Recent Coastal Observatory Reports

Coastal Ocean Processes: Cross-cutting science issues include synoptic-scale interactions between the coastal ocean and the atmosphere, and the impact of river supplied buoyancy, nutrients, sediments, and toxins on the physics, chemistry, biology, geology, and morphology of the coastal ocean. A major focus should be identifying potentially significant changes occurring within coastal ecosystems while simultaneously quantifying the importance of extreme events.

Fluids and Life in the Ocean Crust: Examples include drivers of change in the subsurface biosphere, the effects of sub-seafloor biology on pore fluid chemistry, circulation or fluxes, and the rate of biomass production by chemosynthetic processes.

Turbulent Mixing and Biophysical Interactions: Issues include the manner in which turbulence affects levels of primary production; phytoplankton community structure; the formation, dissolution and export of marine snow; and benthic community structure. These processes are particularly important in the coastal ocean.

Coastal Ecosystem Dynamics and Biodiversity: Issues include benthic and pelagic responses to hydrographic variations, hydrothermal activity for both deep hydrothermal vents and marginal cold-seeps, and the way in which human interactions impact microbial, fishery, and seafloor communities.

Ocean, Climate, and Biogeochemical Cycling: Efforts focus on understanding and predicting the impact of climate change and variability on ocean continental shelves. This area is central to quantifying the importance of carbon cycling in coastal waters and its significance within the global carbon budget. This problem also requires a quantification of episodic events within long time-series on biogeochemical cycling.

Pioneer Arrays

A relocatable observatory system would provide the coastal research community with a flexible observational capacity for collecting high-resolution, synoptic-scale measurements in a focused region spanning 100-300 km. The total observatory system, termed a Pioneer Array, would include an array of autonomous surface and subsurface moorings providing real-time data, coupled with land-based, multi-static, high-resolution, surface current radars and integrated with other available remotely-sensed (land-based, airborne, and satellite) data streams (Jahnke et al., 2002) (Plate 7). The motivation for such a relocatable observatory is to provide an infrastructure that is not permanently located at one geographic site, since coastal processes vary widely with location. For example, to address the question of elemental cycling on the continental shelves, measurements should be acquired on both broad shallow (Mid-Atlantic-type) and short canyon (Monterey-type) coastal shelves. To increase knowledge of near-shore processes, beaches on both broad and narrow shelves need to be studied not only because of the differences in the incident wave and current conditions but also to increase the understanding of the dominant processes on different beach genotypes (sandy, cobble, and muddy bottom material; open coast; and protected pocket).

The participants at the CoOP meeting proposed the Pioneer Array as a means to entrain the wider coastal scientific community by providing an asset available to scientists in different geographic locations, thus allowing the research community to identify the best study site for a specific process through peer-reviewed competitive grants (Jahnke et al., 2002). The geographic flexibility of the Pioneer Array is analogous to a ship on station for several years, providing data from an array of 20-40 real-time coastal buoys and multi-static arrays of high-resolution coastal radars. Coupled with the output of other available remote sensors, the Pioneer Array would provide continuous coherent data streams that could be used by data-assimilation models. Finally, the process studies conducted with the Pioneer Array could provide insight on the optimal placement of long-term time-series moorings.

The technology required for the mooring aspect of Pioneer Arrays is mature, although further work will be required to establish techniques to counter biofouling and fishing losses. Given that the overall goal is to provide a well-sampled ocean for interdisciplinary studies, the sensor arrays on the buoys will include operational and preoperational IOOS instruments but would also provide the flexibility to integrate more experimental instruments. This flexibility allows the OOI system to innovate components for the IOOS backbone. The CoOP workshop report recommended that three Pioneer Arrays be acquired as part of the OOI for process-oriented studies in the coastal regions of the U.S. (Jahnke et al., 2002).

Surface-based radar technology for remote sensing of surface current fields has experienced rapid growth and acceptance within the scientific community over the last few years. Like satellites, radars provide two-dimensional maps of surface currents, allowing for spatially focused sampling efforts (Plate 8). Experimental long-range systems demonstrated at several locations around the country can measure surface currents over a 200 km area with 6 km resolution. Higher resolution systems provide estimates for radial current vectors over 40 km areas with a resolution of 1.5 km. Some proposals for IOOS call for a national network of these long-range radar systems to support science, commercial shipping, and the U.S. Coast Guard. However, the 6 km resolution of this proposed national network lacks the resolution necessary to resolve many of the scales that are relevant for scientific efforts in coastal waters (on the order of 0.5-2 km). Coastal applications will require continued engineering and development to optimize the number of radar measurements given cost, footprint size, and resolution.

Coastal Cabled Observatories

Cabled observatories have been successfully deployed at several coastal sites for many years. Some examples are LEO-15, the FRF in Duck, North Carolina, and the MVCO (Appendix D). These systems offer ultrahigh bandwidth and significant power. Their data acquisition systems have multiple user ports that allow a variety of instruments to be plugged into the system. Data are telemetered back to shore via twisted pair or fiber-optic cable. The MVCO is the most recently deployed coastal cable system, designed and built by the same group who built the earlier LEO-15 system. Communication at MVCO occurs through commercial-off-the-shelf, Gigabit Ethernet network switches that communicate over a pair of fibers back to shore. The MVCO nodes include support for both serial and Ethernet connectivity for instrumentation, a guest-port management system, and a Gb/s link back to shore. The communications electronics have worked very reliably for the past two years. Scientists are able to easily connect to their instruments and collect data from them over the Internet, and can monitor and control their instruments via privileged services provided on an observatory website.

The major advantage of cabled coastal systems is the availability of power for sensors that would have to limit their data acquisition schedules if deployed on autonomous moored buoys. This feature greatly enhances the coastal community's ability to acquire synoptic data at the wide range of temporal scales (from seconds to storm events to decades) that drive coastal processes. Like a Pioneer Array, cabled observatories can provide a test-bed for new instrumentation because they are easily serviced by small vessels and divers. The SCOTS report strongly advocates the use of cabled observatories for coastal research (Dickey and Glenn, 2003).

Fixed, Long-Term Moorings

A third essential component of a coastal observatory system is an array of fixed, long-term moorings designed to provide measurements of key physical, chemical, and biological parameters and their long-term variability in order to detect subtle but important trends of environmental change in the coastal ocean in the coming decades (Figure 3-5). Indeed, one of the major rationales for establishing a seafloor observatory network for basic research is to advance oceanographic science beyond the ship-based expeditionary approach, in order to obtain "long time-series measurements of critical ocean parameters" (National Research Council, 2000). Such long-term observatories will likely be required at approximately 20-30 locations in order to cover significant regions of the coastal ocean and Great Lakes of the U.S. The CoOP Workshop addressed the issue of long time-series data acquisition and concluded that the coastal IOOS backbone could provide the necessary long-term observations in the coastal zone. However, to serve as useful platforms for research, the IOOS backbone or "Sentinel" moorings may require a broader suite of instrumentation (e.g., pCO_2 sensors, time-series sediment traps) than is presently envisioned. If the coastal component of the OOI was restricted to Pioneer Arrays and cabled observatories as recommended by the CoOP

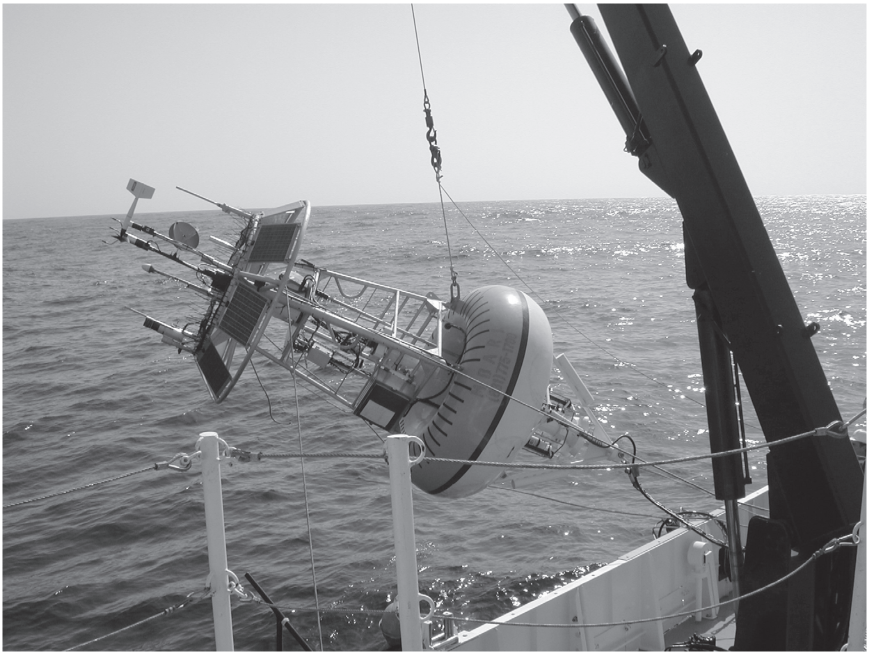

FIGURE 3-5 Launch of fixed, long-term coastal mooring in Monterey Bay. These buoys have provided detailed information on sea surface temperature, salinity, chlorophyll concentrations, and other data for more than a decade. The data are collected from sensors mounted on and suspended from the buoy, and are radioed to shore. Figure courtesy of Victor Kuwahara, ©2001 MBARI.

and SCOTS workshop reports, an important opportunity to establish long, continuous observations on the Atlantic, Pacific and Gulf Coasts and in the Great Lakes could be missed. There is a clear need for the coastal research community to determine a minimal list of key parameters and key sites needed to observe long-term changes in the coastal ocean. In addition the community should play an active role in the design and implementation of IOOS in order to ensure that the placement and instrumentation of long-term coastal Sentinel moorings meet both the operational and research needs of the ocean community.

Status of Technical and Engineering Development and Planning

The technologies required for coastal surface and subsurface moorings and cabled coastal observatories are relatively mature and offer the OOI immediate scientific results. At present, well-instrumented moored observatories using surface buoys are operational in multiple locations around the continental U.S. Long-term deployments are possible, but are not necessarily a cost-effective design criterion as coastal buoys can be easily serviced. The ease of accessibility is fortunate since biofouling rates are high in coastal waters. Corrosion rates are also significant and high wave stresses can dramatically reduce system lifetime. Finally, the proximity to coastal populations leads inevitably to encounters and losses, most commonly from fishing trawlers.

The ability to cost-effectively service coastal buoys frequently has the additional benefit of allowing moorings to also serve as platforms for testing newly developed instrumentation. While data telemetry from open-ocean sites is often a problem, coastal sites can combine line of sight radio-frequency modems, cell phone, and Iridium satellite links for real-time data transmission. Pilot deployments of integrated sensor packages that have successfully collected physical, biological, and chemical data have occurred off the coasts of California and Oregon and in the Gulf of Maine.

Traditional coastal radar sites are monostatic and consist of transmit and receive antennas. These antennas work together to measure the scatter of the transmitted signal off the ocean surface. Since these systems use the phase of the transmitted signal to interpret the signal from the receiver, they require that the transmitter and receiver be physically connected. However, using the GPS satellite-timing signal should make it possible to synthesize the transmitted signal at the receiver, allowing the transmitter and receiver to be physically separated and converting the monostatic backscatter system into a bistatic forward-scatter system. This synthesis increases the footprint of the system and allows transmitters to

BOX 3-6

Summary of Coastal Observatory Scientific and Technical Readiness

The present status of scientific and technological readiness for a research-based coastal observatory, can be summarized as follows:

- The scientific rationales for coastal observatories are well developed.
- There is a clear and urgent need to develop a community consensus on the appropriate balance between relocatable observatories, cabled observatories, and long-term moored measurements needed for coastal ocean research.
- The technologies required for Pioneer Arrays and coastal cabled observatories are relatively mature and offer the OOI immediate scientific results.
- Conditions in the coastal ocean offer extreme challenges due to corrosion, biofouling, human interference, sediment movement, and wave stresses. The methodologies successfully used by older coastal observatories to address these problems should be utilized when designing the next generation of coastal observatories.

be placed on moorings. Additionally, GPS timing allows the transmitters and receivers to be simultaneously operated at the same frequency in monostatic and bistatic mode, forming a multistatic radar array. Multistatic operation thus increases resolution, decreases the geometric dilution of precision errors nearshore, and potentially decreases the number of expensive monostatic systems that need to be purchased. For example, offshore points within view of multiple sites will experience a significant decrease in the expected error of the total current vectors because they contain N^2 rather than N component estimates. The greater number of points available means smaller radii averaging circles in the total vector calculation used, enabling the network to better resolve fronts. These developments will be necessary for coastal research efforts where effectively resolving currents is a key to success. The potential of radar arrays has been demonstrated over the past five years, and the OOI would allow for the development and deployment of high-resolution multi-static arrays, ideal platforms for collecting coherent surface current data in coastal waters.

4

Implementation of a Network of Ocean Observatories for Research

Many issues, some of them complex, must be addressed for the successful implementation of a seafloor observatory network for research. The following sections address many of these issues, including program management, infrastructure and sensor needs, factors affecting construction and installation, operations and maintenance, data management, and education and outreach. It is beyond the scope of this report to develop a comprehensive implementation plan for ocean observatories; instead, the goal of this chapter is to highlight some of the most important issues to be addressed in such a plan. The first task of the observatory management organization described below, should be the development of a detailed and comprehensive project implementation plan for each of the three major components of the OOI and the review of these plans by knowledgeable and independent experts.

PROGRAM MANAGEMENT

Even though the formal start of the OOI is not planned until FY 2006, a large amount of work must be done during the intervening years including detailed (node level) scientific planning, technical development, and exhaustive testing of critical observatory sub-systems. These activities will ensure that (1) the risks associated with the construction and installation of the more advanced observatory systems are minimized, (2) the initial science experiments at individual nodes are identified so as to provide an opportunity for an early scientific payoff once the observatories are in place, and (3) research scientists, educators, and the public have ready access to the data generated. For this reason, a management structure should be established as soon as possible, and in any case well before the initiation of the OOI.

Goals of the Management Structure

The development of a network of ocean research observatories will require a large initial investment in excess of $200 million (National Science Foundation, 2002). For this reason alone, the management system will be under intense scrutiny by Congress, NSF senior management, the U.S. Inspector General, and the marine science community (which has concerns about other programs being cut to cover observatory cost overruns), as well as international partners, who must satisfy the concerns of their own funding agencies. Therefore, the first tasks of the management structure should be to:

- develop a detailed implementation plan for the OOI;
- generate defendable cost estimates;
- put in place oversight mechanisms and fiscal controls to ensure that implementation tasks are completed on time and within budget;
- establish a scientific and technical advisory structure to obtain community input; and
- work collaboratively with international partners to seamlessly integrate complementary international activities.

Design, Construction, and Installation Phase

With respect to scientific planning and observatory installation, the management structure would oversee the following:

- defining science-based performance goals (based on broad community input);
- producing an annual program plan and budget;
- overseeing design, development and manufacture of observatory components and selecting contractors for those tasks;
- selecting contractors for installation of observatory systems;
- providing experienced oversight of contractors;
- managing liability issues;
- facilitating the development and implementation of standards (e.g., for user power; communications, and timing interfaces; metadata requirements; system, sub-system and component reliability; and information management and archiving);

- facilitating seamless system integration;
- ensuring comparability and inter-calibration of observations made by the OOI; and
- ensuring that the scientific and technical components of international collaborations are coordinated effectively.

Operations Phase

As observatories become operational, the management structure must take on these additional tasks:

- selecting observatory operators and putting in place appropriate review procedures;
- managing the operations, maintenance and administration budgets;
- ensuring that access to observatories is dealt with fairly and consistently;
- ensuring that the observatory infrastructure supports the highest quality science and provides researchers with the best available technology; including calibrated sensors and instrumentation, at the lowest cost consistent with the safe, efficient operation of the facility;
- establishing an appropriate budgetary balance between observatory operations and maintenance and enhancements to observatory infrastructure; and
- ensuring the program has a strong and innovative education and outreach program.

The Driving Philosophy

The philosophy of the OOI management structure should be one in which the day-to-day operation of different components is the responsibility of entities (academic or commercial) with appropriate scientific and technical expertise. The role of the program management organization should be one of coordination, oversight, and fiscal and contract management. The management structure will need to work with the scientific community to select, support, and periodically evaluate “community” experiments; define access requirements; provide technical support for individual investigator-initiated experiments; facilitate education and outreach access to selected data streams and products; develop protocols for scientists not involved in deploying experiments to access databases and archives; and negotiate access agreements with other users (such as for-profit entertainment industries and value-added enterprises). Operating rules for the observatories will have to take into account the needs of the scientific community, agencies interested in using or supporting the use of the facilities; international partners and collaborators, and other users, including the public.

Proposed Management Model: Roles and Responsibilities

An example of a management structure capable of addressing the goals and issues summarized above is presented in Figure 4-1. This structure is modified from a draft management structure developed by the NSF and the DEOS steering committee and is modeled after the highly successful management structure of the international ODP.

The ODP management model guided a complex program now in its fourth decade. It has shown itself to be flexible and capable of evolving in response to changing circumstances, yet stable enough to keep a multinational program operating year after year. This model, while an excellent starting point, does not fit the circumstances of the OOI exactly, and so has been modified to reflect the following important differences:

- While the structure of the ODP often tends toward prescriptive technical requirements, the OOI will need performance-based requirements, as the OOI will consist of many separate observatories using multiple technologies in pursuit of different objectives. In addition, disparate parts of the system will be in different stages of development at any given time.
- For the most part, the ODP utilizes standard technology developed for the oil exploration industry. The OOI will be utilizing more advanced technologies adapted specifically for ocean observatories and is likely to place a much greater emphasis on new technology development. As a result, the OOI technical advisory and management structure will need expertise to provide oversight of the operation of technologically sophisticated systems and engineering development projects.
- The NSF is the only agency in the U.S. providing ongoing support for the ODP. It is likely that the OOI will have a number of agency supporters at the federal (and possibly even state) level, particularly during the operational phase. Many of these agencies will be interested in supporting only a few observatories or a single observatory type.
- In the ODP, all international operating funds flow through the NSF and are managed as a single commingled pool. International funding for the OOI will mostly occur at the individual observatory level, or for a particular observatory type, and will likely be spent at the national level as part of a coordinated rather than commingled pool.
- In the ODP, all of the international partners belong to the entire program. In the OOI, international partners may be interested in participating only in a subset of the observatory system.

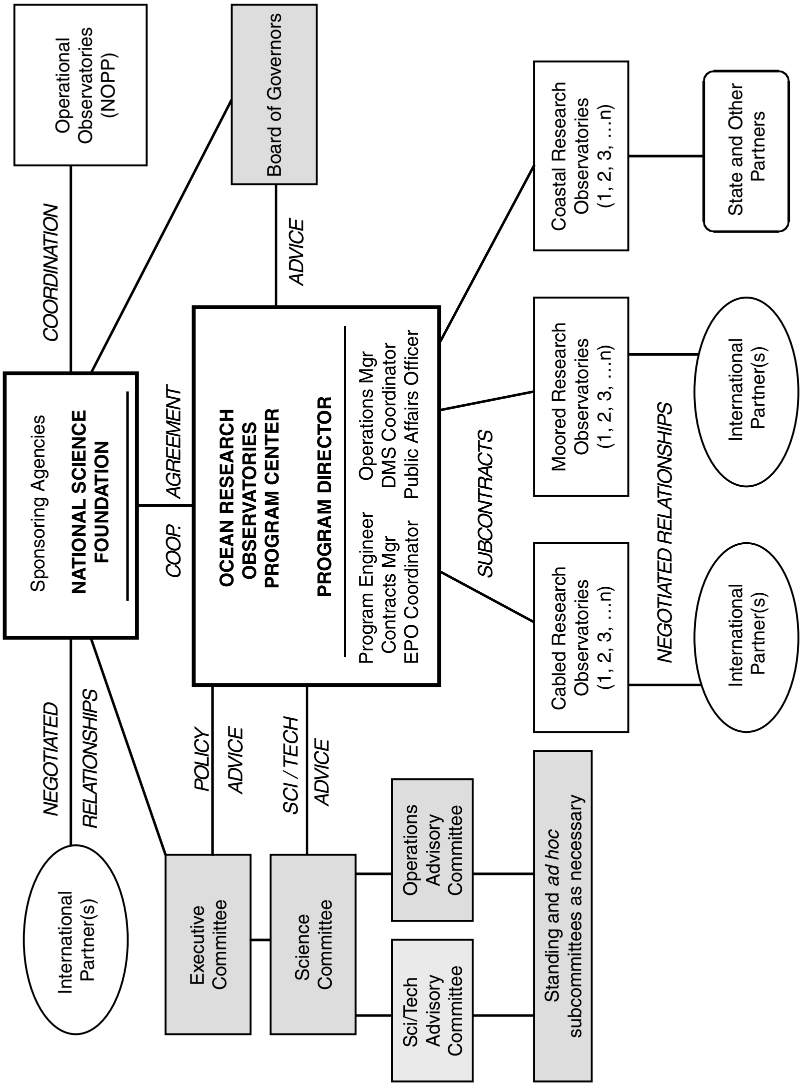

FIGURE 4-1 Proposed management structure of OOI Program Office. Modified from A. Isern, 2002.

The NSF will be the lead funding agency for the OOI. Other agencies that fund marine research may elect (and should certainly be encouraged) to support the OOI, but their contributions should be funneled through the NSF to ensure that the program is well coordinated and efficiently managed with clear fiscal accountability.

Coordination of the OOI with the IOOS, the GOOS, and other national and international observatory programs will be critical in the areas of infrastructure development, instrumentation, ship and ROV utilization, data management, and technology transfer. The NOPP in its role as a coordinator for federal agencies, academia, and industry, should be utilized to facilitate this organization among the different U.S. agencies supporting observatory research. The NSF will be responsible for developing appropriate coordination agreements with potential international partners, perhaps through bilateral Memoranda of Understanding.

The management structure of the OOI must ensure that the project is in compliance with NSF policies and procedures and other federal regulations. It is critical that a single entity have overall financial and management accountability for the program. In the case of the OOI, this could be the Ocean Research Observatories Program Center (OROPC). The OROPC would enter into a cooperative agreement with the NSF to manage the OOI. Ideally, the OROPC should be a community-based organization accountable to the scientific community it serves. It could be either a new 501(c)3 not-for-profit corporation formed specifically for this purpose, or a division of an existing 501(c)3 corporation with demonstrated expertise in managing technically complex research facilities. The latter is the preferred alternative. The OROPC would be advised by a Board of Governors, whose members would include senior industry leaders with experience in managing complex marine engineering projects as well as leaders of scientific institutions with expertise in managing research consortia responsible for major facilities. In addition to its advisory role, the Board would be able to provide Congress and senior agency management with an independent assessment of the OROPC's fiscal and technical management performance.

The OROPC's primary responsibility would be coordination and program oversight. It would have a comparatively small staff including; a Director, a Program Engineer, a Data Management Coordinator, an Education and Outreach Coordinator, a Public Affairs Officer, a Contract Manager (or equivalent) to oversee contracting and support annual audits, and other staff as necessary. The Program Director should be competitively selected and should be a person of the highest scientific and technical caliber with a demonstrated ability to manage an organization of this scope.

The OROPC would be advised by both an Executive Committee comprised of scientific and technology leaders, which would focus on policy issues, and by a Science Committee, which would provide scientific and technical advice derived from appropriate standing and *ad hoc* subcommittees channeled through standing Scientific, Technical and Operations Advisory Committees. In the tradition of the ODP, the OROPC would disregard advice from these committees only under exceptional circumstances and then only with the concurrence of the NSF. The Science Committee and its subcommittees and panels would consist of a broad, diverse, and interdisciplinary membership selected on the basis of excellence and creativity within their respective fields. Members could be selected from academia, industry, government, and the international community. International representation on the top four committees (Executive, Science, and the two Advisory Committees) should be determined by NSF agreements with international partners.

The actual design, development, manufacture, construction, installation, and operation of the observatories that compromise the OOI will be subcontracted by the OROPC to consortia, individual institutions, or private companies as appropriate. This decentralized management structure will promote maximum creativity and the tailoring of the management of each observatory system to the specific scientific goals and operational requirements of that particular system. Each operating entity will have flexibility of implementation (to encourage innovation), but will have to meet certain performance criteria in such areas as user interfaces, data management and archiving, access to education and outreach users, and maintenance and upgrade strategies. This structure will ensure that the entire system of observatories is more than just the sum of its parts and that research and educational users of both the facilities and data streams can move easily from one observatory to another. The OROPC will be responsible for working with the advisory structure to develop system-wide performance goals that balance the need for flexibility to encourage innovation with the desire to maintain maximum system functionality.

International participation could be at the level of the entire research observatories program, or with specific components of the program and might range from simple coordination of independently funded and managed efforts to an integrated, jointly funded observatory program. The management of the OOI will need to be flexible enough to accommodate these different modes of international participation, as long as the integrity and transparency of the entire system are not put at risk.

In the case of coastal research observatories, it is clear that the universe of potential state, local, industry, and other federal partners is much larger than for the open-ocean observatories. The partners will also differ markedly from region to region and will likely include operational observatories in some cases. Again, the NSF and the OROPC will have to be flexible in negotiating cooperative agreements that encourage broad participation without endangering the connectivity and synergism of the entire system. Over time, some observatories that are not part of the initial OOI may wish to join this research observatory network. The program will need to develop a process by which this incorporation can be undertaken, as well as different options for program participation (e.g., some existing programs may only wish to utilize the data management system while others may wish to become a full partner in the scientific planning, operation, and maintenance of the observatory network).

DEFINING "INFRASTRUCTURE" FOR OCEAN OBSERVATORIES

As noted earlier in this report, funding for the OOI is being sought through the NSF's MREFC account. This account was established to provide funding for major science and engineering infrastructure including the acquisition of:

> state-of-the-art tools that are centralized in nature, integrated systems of leading-edge instruments, and/or distributed nodes of information that serve as shared-use, networked infrastructure in advancing one or more fields of scientific study. (National Science Foundation, 2003, p. 1). [Note that in the MREFC context, "infrastructure" is used inter-changeably with "tools"].

While the three major components of the OOI described in Chapter 3 of this report clearly satisfy this definition of "infrastructure," there has been some confusion over what this infrastructure includes. From the OOI's inception, some of its proponents have argued that use of the MREFC should focus on acquiring the basic elements of an ocean observatory system (e.g., cables, moorings, junction boxes, shore stations, and facilities for data distribution and archiving), not on acquiring the instrumentation that would eventually utilize this infrastructure. Implicit in this approach is the assumption that funding sources other than the MREFC would provide support for instrument development and acquisition as well as the deployment and maintenance of these instruments at various observatory nodes. The mechanism for obtaining this crucial support would vary from project to project depending on the nature of the experiment, the sponsoring funding agency, and the role of the instruments in the overall observatory network. This mechanism would likely involve peer review, thus ensuring that only the most useful and best-justified instrumentation would be incorporated into the observatory system.

The rationale usually given for the above approach is that basic infrastructure funds are difficult to obtain. As a result, as much as possible of these funds should go toward acquiring basic hardware (e.g., cables, buoys, moorings and junction boxes). Risks of such an approach include a possible lack of available funding from other sources to acquire observatory sensors and/or the absence of a full suite of instruments that can utilize the observatory infrastructure once the construction and installation phase of the OOI is completed. Others, therefore, have argued that some sensors and instrumentation should be included as part of the observatory "infrastructure" even if doing so restricts the availability of resources for acquiring the cables, moorings, and junction boxes that comprise the facility. The difficulty with this alternate approach is determining which instruments and sensors should be included as part of the basic observatory infrastructure. The instrument lists developed in various ocean observatory workshop reports are long and costly. Including all, or even a significant fraction, of these instruments as part of observatory infrastructure could significantly reduce the number of observatory nodes that could be established with the limited funds available through the MREFC account. Another danger is that incorporating too many instruments into the basic infrastructure could discourage innovative production of new and better instruments.

In considering this trade-off, certain analogies with oceanographic research vessels should be considered. In the case of a research vessel, the ship itself is the basic infrastructure. Scientists typically bring their own specialized instruments and install them on the ship for each expedition, using the ship as a platform for acquiring their data. Most ships, however, also include a basic suite of instrumentation that is required by most investigators (e.g., a GPS, an echo sounder, and a conductivity-temperature-depth [CTD] profiler). By providing this basic instrument suite the ship operators ensure that every research vessel has a certain minimum scientific capability. This baseline capability is likely to be even more important at an ocean observatory, since the value of a node for specialized—and in some cases shorter-term—scientific experiments may be very dependent on the availability of long time-series data of certain basic physical, chemical, and biological properties at the site.

The critical question is thus not whether sensors and instruments should be considered as part of the basic observatory infrastructure (indeed they should), but deciding which sensors or instruments should be part of the basic observatory infrastructure (thus funded through the MREFC account), and which sensors should be acquired by the scientific programs utilizing the observatories (thus funded through the Research & Related Activities account at the NSF or by other agencies supporting ocean research).

In considering this question it is useful to define three classes of instrumentation that may be installed at ocean observatories. The first class of instruments, "core" instruments, include a basic suite of engineering and scientific instruments that are essential to the functioning of the observatory and its usefulness as a platform for basic research. Core instrument needs will vary widely for different classes of observatories and will depend on the scientific objective(s) of each node. Such instruments could include (1) engineering or system management instruments used to determine the system's operational status, and (2) commercial off-the-shelf (COTS) instruments that make basic physical, chemical, or biological measurements and provide essential scientific context for the observatory's effective use as a platform for scientific research. Data from core instruments should be available to anyone in real-time, or as soon as is practical, through the observatory data management system. Furthermore, the core instruments should be maintained and routinely calibrated to internationally-agreed upon standards so these data can be integrated with elements of other observing networks.

A second class of instruments, "community instruments," consists of specialized scientific instruments critical to the longer-term scientific objectives of a particular node. These typically will be proven and reliable ('observatory-capable') instruments that provide data of interest to a wide range of investigators and that need to be in operation over an extended period of time. Examples might include ocean bottom seismometers, cameras and video systems, mooring line 'crawlers,' or borehole fluid samplers. Data from community instruments also should be freely available in real-time or as soon as is practical.

The third class of instruments that will be used at most observatories will be those associated with individual, investigator-initiated experiments. These "investigator owned" instruments may be new or developmental, or may be specific to a particular scientific study or experiment. Data from such instruments may be proprietary to the investigator for some specified time period consistent with the data policy of the sponsoring funding agency (e.g., two years for the NSF). Data from these instruments must still be submitted to the ocean observatory data management system and should be made publicly available after the embargo period ends.

The core instruments, as defined above, comprise an essential element of the basic observatory infrastructure that should be supported through the MREFC even if that means a reduction in the overall size of the observatory facility. Shore-based facilities for data distribution and archiving are also part of the basic observatory infrastructure that should be supported through the OOI. In some cases a community instrument might also be important enough to the scientific rationale of a particular observatory that it should also be considered as part of the basic infrastructure. In most cases, however, funding for those science programs (e.g., CLIVAR, Ridge 2000, GLOBEC) or groups of investigators using the facility would seek funding for "community instruments" from sources other than the NSF's MREFC account via peer-reviewed proposals submitted to the NSF or other agencies supporting ocean research. Since core instrument needs will vary widely from observatory to observatory, it is inappropriate for this report to define a list of core instruments or to specify a certain percentage of MREFC funds that should be utilized for core instrument acquisition. The proponents of each observatory system will be in the best position to judge the trade-off between basic observatory hardware (i.e., the number of nodes) and the basic sensor requirements for that hardware given the finite resources available through the MREFC. The expectation, however, is that every observatory will require some core instrumentation.

Even if core instruments are included as part of the basic observatory infrastructure funded through the MREFC, they will constitute only a small portion of the longer-term instrument needs for ocean observatories. The total investment in sensors and instrumentation for observatory systems acquired through the OOI could, over time, approach the cost of the observatory infrastructure itself. The research community has expressed concern that the funding to acquire these instruments may not materialize and that, as a consequence, access to the observatory infrastructure will be delayed and the full scientific potential of ocean observatories will not be realized. The long-term scientific success of the research-driven observatory network will depend at least in part on the development of a program within the NSF's Ocean Sciences Division which will select peer-reviewed proposals for funding of new observatory sensors and instrumentation. Given the significant lead-time involved in constructing and acquiring new instrumentation, the NSF is encouraged to establish an "Ocean Observatory Instrumentation Program" well in advance of when these observatories become operational. As instrumentation needs at observatories will evolve continuously (see the following discussion), such a program will be needed as long as ocean observatories remain in operation. Other agencies with an interest in ocean research may also support acquisition of instrumentation for ocean observatories and the NSF is encouraged to explore these options, perhaps through an interagency mechanism such as the NOPP program.

SENSORS AND INSTRUMENTATION NEEDS

Making integrated physical, chemical, and biological observations in the oceans presents challenges quite different from those faced by atmospheric, terrestrial, or space scientists. Remote sensing via satellite is impossible in most of the ocean, excepting the very thin upper layer. To penetrate the ocean's depths, power for instrumentation and communications must be delivered in an 'ocean-proof' package, for instance via a shore-side cable or limited-lifetime *in situ* battery packages. Due to the considerable technical challenges and the time required for converting new technologies into robust, seaworthy packages, as well as the different nature of economic forces that could motivate industry investment in such development, ocean-going instrumentation lags far behind state-of-the-art technologies in other fields.

Even with all of the recent advancements in computer and sensor technology, the physical challenges of making measurements at the sea surface, on the seafloor and in the water-column remain vexing. Strong winds, high waves, platform motion, high salinity, pressure, and biological activity (i.e., biofouling) can all conspire to complicate sustained continuous deployment of new technologies at ocean observatories. Iterative cycles of designing, building, field-testing, troubleshooting, redesigning, and redeployment are required before instrumentation becomes seaworthy enough for routine use. The challenges of continuous and autonomous operation are even greater in the context of open ocean observatories. A major, sustained, and well-funded effort will be required to develop a new generation of instruments and sensors for ocean observatory science. The on-going work of sensor calibration, as well as the considerable maintenance instruments often need after a long deployment at sea, will also require a considerable investment in staff and facilities.

The development, calibration, and maintenance of new and robust instrumentation for quantifying the physical, chemical, and biological ocean will be a key element in achieving the true interdisciplinary promise of ocean observatories and implementing integrated studies and modeling of such ocean systems in real-time.

Current State-of-the-Art in Ocean Instrumentation

To offer a rough analogy, ocean observing systems are similar to complex living systems. Cables, fiber, and wire provide the backbone for physical support and the nervous system to deliver information and energy throughout the network. On-board computer systems perform brain functions, coordinate activity in the network, process information, and manage communications, both within the internal system as well as with external systems via cable, acoustics, or satellites. The sensors themselves see, hear, taste, and feel the ocean environment either directly, or via proxies, and report those data back through the observatory backbone and nervous system infrastructure. Thus sensors form the crucial part of the observatory network that allows for the acquisition of new information about the ocean.

Sensor development and implementation are difficult to discuss in a generic way, since the variety of sensors and instruments is large and will vary with specific problems, projects, and deployment scenarios. Nevertheless, careful planning of the development and deployment of new sensors and instruments will determine the ultimate impact of ocean observatories on knowledge of ocean processes and dynamics.

A "spectrum of maturity" currently exists with respect to readily available and routinely deployable ocean observatory sensors. Physical sensors, the mature end of the spectrum, represent the most reliable, robust, and routinely deployable instruments available. Instruments for measuring meteorological parameters, salinity, temperature, pressure, current speed, light quantity and quality, and seismic waves can be fairly routinely deployed in the ocean (Figure 4-2). Further along the spectrum, instruments for specific detection and quantification of ocean chemical parameters represent a maturing, but not yet fully developed area. For example, it has recently become possible to acquire continuous real-time, *in situ* measurements of carbon dioxide (Friederich et al., 2002) or non-conservative bioactive compounds like nitrate (Johnson and Coletti, 2002), but such data are not yet universally collected. More work is required in the area of chemical sensors that can measure a wider range of analytes with greater sensitivity, resolution, and reliability. The least well-developed instruments, though perhaps the most important for the coming century, are biological sensors. At present, only a few bio-monitoring devices are available, and these are relatively crude with respect to their sensitivity and specificity. Existing *in situ* biological instruments are largely bio-optical devices, measuring either light scattering as a proxy for biological particles or chlorophyll fluorescence as a proxy for phytoplankton for instance. Although development efforts for autonomous biological sampling and sensing instruments using molecular probes are underway (Scholin et al., 1998), the field is nascent and much more effort will be required to produce readily available and robust biological sensors.

Ocean Observatory Sensor and Instrument Development

The need for sensor development has been clearly articulated in a number of workshops and reports on the future of ocean observing systems and *in situ* instrumentation. Examples of such discussions include the NSF report *Ocean Sciences at the New Millennium* (2001); a previous NRC report on ocean observatories, *Illuminating the Hidden Planet* (2000); a workshop on *in situ* sensors (RIDGE, 2000); the SCOTS workshop (Dickey and Glenn, 2003); and the CoOP workshop (Jahnke et al., 2002). The rec-

FIGURE 4-2 A remote instrument node (RIN) under development at MBARI; the ROV *Ventana* is shown on the right. This RIN contains a variety of instruments for measuring water temperature, conductivity, and density as well as current speed, sediment load, and chlorophyll concentrations. This RIN will eventually connect to the MARS cabled observatory testbed. Figure courtesy of Todd Walsh © 2002 MBARI.

ommendations and conclusions of these reports all emphasize the critical need for the development of new sensors and instrumentation for ocean observatory science. A sampling of these recommendations is given in Box 4-1.

BOX 4-1

Report Recommendations for New Sensors and Instruments for Ocean Observatory Science

- No one technological approach can give synoptic, high-resolution or continuous views of the whole ocean or seafloor below. . . . There is an urgent need to develop sensors and sampling strategies to optimize the mix of these new platforms with ships and remote sensing in removing critical data gaps. (National Science Foundation, 2001, p. 150)
- Advances in sensor and AUV development must proceed in parallel with the development, design, manufacture and installation of basic observatory infrastructure. The development of biological and chemical sensors and instrumentation for long-term *in situ* measurements is of particularly high priority. . . . There will be no benefit to seafloor observatories unless scientists are using them to advance our knowledge and understanding of the oceans. (National Research Council, 2000, p. 108)
- Although significant progress has been made in recent years with instrument development, which can address some of these issues, the range of available instruments, development needs of new instruments, material property and deployment concerns, and signal processing and data transfer/storage requirements, are not fully appreciated by workers in the field, let alone the broader marine science community. (RIDGE, 2000, p. 1)
- A common theme that emerged from participants and reviewers alike was that sensors and systems are as important as cables and platforms. Many of the measurements required under the science sections cannot be made today. There is a real need for accelerated development of remote oceanographic sensor and sampling systems, interfacing standards, anti-fouling strategies, and autonomous platforms for sensor deployment and the retrieval of collected sediment, water and biological samples. (Dickey and Glenn, 2003, p. 7)
- Development of chemical and biological sensors is urgently needed. . . . We recommend that priority be given to developing sensors for biochemically active solutes, such as nutrients, trace gases, particulate and dissolved organic matter, and element speciation of selected trace metals. Such sensor systems would complement the development of other biological sensors such as the fast repetition rate fluorometer for estimating primary production, DNA microchip sensors[,] which can be used to identify particular species, and acoustical sensors for assessing populations of organisms ranging in size from zooplankton to fish. (Jahnke et al., 2002, pp. 13–14)

Instrument Reliability and Calibration

Observatory-capable instruments must meet international standards for accuracy and must maintain their calibration and sensitivity for long periods of time, at least for a period between six months to a year (the expected service interval for many ocean observatories). Ocean instrumentation often borrows and adapts technology from other developing fields, many with stronger economic drivers for development. As such, these instruments need to be adapted for the unique challenges of long-term deployment in the ocean environment. Problems common to nearly all ocean instrumentation include biofouling, corrosion, and physical damage due to the harsh ocean conditions. Generic solutions to these long-term deployment problems need to be addressed and, where possible, shared across the community. The international ocean observing community should agree upon routine calibration standards in order to document instrument performance and support the use of OOI observations for scientific research and integration with observations from other elements of global Earth- and ocean-observing networks.

Iterative Development and Deployment Cycles

Iterative design, development, and deployment cycles are necessary to achieve robust instrument designs and reliable, maintenance-free instrument operation. As a result, the development of new ocean instrumentation can be a lengthy process, often taking five years or longer. Easy access to a mooring (e.g., the BTM) or a cabled seafloor junction box (e.g., LEO-15, FRF, MARS), located close to shore for testing new technology and instrumentation can greatly accelerate the pace of developing and proving new instrumentation. These testbeds also provide a platform for establishing the comparability of a new technique with older methods that are being phased-out. The creation of centers for instrument development may also facilitate this process, but it is essential that such centers work in close collaboration with the scientists who will be using these instruments. The NSF, working in cooperation with other agencies, also needs to ensure that ongoing deployment and calibration activities can be sustained and that the staff and facilities for maintenance and calibration are up to the task of meeting the additional ongoing demand created by instrument development and deployment cycles associated with the OOI.

Multi-Instrument Interface and System Integration Issues

Some of the major goals of ocean observatories include integrating the data streams of individual sensors and instrumentation in real-time and allowing for synoptic measurement and correlation of data streams. Common instrument interfaces for Plug-n-Play operation, as well as integrative data handling, are part of the solution to these issues. Nevertheless the diversity of sensors that are likely to be developed, as well as the range of technologies utilized, will present challenges to full sensor suite integration. Obviously instrument and sensor developers will benefit greatly by communicating and integrating their efforts into the overall technological context of observatory infrastructure. Practically speaking, a range of 'interactivity' will probably evolve for different instruments, ranging from autonomous operation to highly integrative operation with other sensor suites. Both technology and the specific needs, goals, and science drivers for any particular sensor application will likely drive this range of interactivity.

Data Stream Management

As is the case with other system integration issues, data streams from particular sensors will be quite varied. Metadata, calibration and validation data, and raw and processed data streams are all instrument-specific. Data management architecture and instrument interfaces are unlikely to ever be totally standardized. A flexible system is likely to evolve, spanning a wide range of instrument interoperability and compatibility within the overall observatory infrastructure.

Sensor Development Funding and Anticipated Future Needs

National funding agencies have recognized the need for environmental sensor and instrument development, and a number of programs currently exist that could support sensor and instrument development for ocean observatories. These programs include the NSF's Directorate for Engineering and the Directorate for Computer and Information Science and Engineering; the NSF's Instrumentation Development for Environmental Activities (IDEA) program; the Oceanographic Instrumentation Development program within the NSF's Division of Ocean Sciences; the multi-agency NOPP; NOAA's Cooperative Institute for Coastal and Estuarine Environment Technology (CICEET); and the NOAA-funded Alliance for Coastal Technologies (ACT).

It is clear that the agencies supporting ocean research in the U.S. have already taken the need for sensor and instrumentation development seriously. However, the establishment of ocean observatories will increase the requirements and potential user base for ocean sensor suites far beyond those of today. Such increased demand will require new and significant resources for sensor and instrument development. A critical issue revolves around the time required for iterative development and deployment cycles before robust and mature instruments are available. If timed improperly, the observatory infrastructure could be obsolete or in need of replacement by the time many critical instrument and sensor suites are available. A major challenge for the national programs and funding agencies will be fitting the required iterative cycles inherent to instrument development into the fiscal cycles and current funding schemes for standard awards (typically two- to three-year funding cycles). Development and engineering milestones and timelines are often different from parallel scientific milestones and timelines, and the review and award process should be responsive to these differences.

If truly integrated interdisciplinary *in situ* observations of ocean systems are to emerge from the OOI, then a much wider variety of sensor suites, in particular those for sensing chemical and biological phenomena, will need to be aggressively developed in the very near future. If the same standard oceanographic parameters continue to be the only items measured, then only an incremental gain in scientific knowledge can be expected, even with the enhanced spatial and temporal resolution that observatories will provide. There will be little benefit from seafloor observatories unless a broad base of multidisciplinary ocean scientists use them to advance knowledge and understanding of the oceans. The research community as a whole has not yet attained this goal, and one consequence of the OOI should be to foster this evolution. Sensors and instrumentation are as important as cables and platforms, and their aggressive and immediate development is an absolute requirement if ocean observatories are to fulfill their potential promise. In addition sufficient support must be provided to maintain sensors and instrumentation, especially to ensure via calibration their accuracy, reliability, and comparability across all platforms of the OOI and other ocean-observing networks.

CONSTRUCTION AND INSTALLATION

The construction and installation of ocean observatories give rise to many issues. Although there are significant differences in the requirements for moored and cabled observatories, in both cases careful pre-installation planning and extensive shore-side and wet testing will be required to ensure the successful installation of these systems.

Moored Buoys

The oceanographic community has considerable experience with the fabrication and installation of both surface-expression and sub-surface moorings under a variety of conditions. Both types of moorings are easily fabricated, and prior experience has indicated the materials required. Torque-balanced wire rope, which is plastic-jacketed for corrosion resistance, is used for the upper part (1500 m) of a deep-ocean mooring to prevent fish bite and at all depths in shallow moorings. Nylon and dacron rope are used to allow for compliance and polypropylene rope is used where added buoyancy and stretch-resistance are needed. Select marine-grade, corrosion-protected fittings (shackles and swages) and chain; foam, aluminum, and steel buoy hulls; and synactic, steel, or glass subsurface flotation are also widely used. It should be noted that a range of manufacturers can build metal buoy hulls; by comparison, only a few manufacturers can fabricate hulls from closed-cell foam. Mooring cable and rope and related hardware can be purchased from commercial sources. Cutting, terminating, and strength-testing lengths of cable has traditionally been done in-house.

The bandwidth requirements for many oceanographic moorings are modest and can be accommodated by commercial satellite systems such as Inmarsat-B, Iridium, or Globalstar. Low-power transceivers and antenna systems are commercially available and can be purchased at very modest costs. Acoustic modems can be used to telemeter data from sensors on the mooring or on the seafloor to the buoy, although data rates are relatively low. Second-generation acoustic modems are available commercially and third-generation systems are under development. These modems can provide sustained data rates of 5 Kb/s (with error correction) at ranges of up to several kilometers. With exception of the large, severe-environment surface buoys (see below), the current trend is to make all of the mooring components discussed above easy to ship by designing them to fit inside standard 20–40 ft sea containers.

The presence of a dedicated winch (drum or traction) to deploy and recover the wire rope and synthetic line greatly facilitates mooring deployment. Deployment practices are well established and documented by groups such as the Mooring and Rigging Shop at WHOI. Installation can be handled by medium and large UNOLS vessels.

Heavily-instrumented deep-water surface moorings may require anchors approaching 10,000 lbs. That weight, plus the weight of the buoy hull (4,000 lbs with instruments), place constraints on crane and A-frame capacity and on the number of moorings that can be carried at one time. Deployments and recoveries are accomplished either over the side on the fantail or through the A-frame on the stern. Mooring deployments require moderate to calm weather (15 knot winds or less and waves smaller than 6 ft). The greatest dangers faced in high seas are the possibility that the buoy hull will swing, hitting the ship during either lift-off or the transition back onto the deck and the possibility that surge loads could approach the breaking strength of the mooring lines. In addition, complete cable-linked, low-bandwidth moorings will require an ROV for installation of a seafloor junction and connection to the EOM riser.

The high-latitude and/or high-bandwidth discus or spar buoy systems that meet the specifications outlined in the *DEOS Moored Buoy Observatory Design Study* (DEOS Moored Buoy Observatory Working Group, 2000) raise special construction and installation issues due to the size of the buoys and the weight of the mooring lines and anchors (Figure 4-3). Fabrication of large spar and discus buoys would be contracted to a commercial company (moored systems—typically very large spar buoys—have been in use for some time in offshore oil production). Several commercial VSAT C-Band antenna systems, designed primarily for shipboard use, are available and could be adapted for use on a large spar or discus

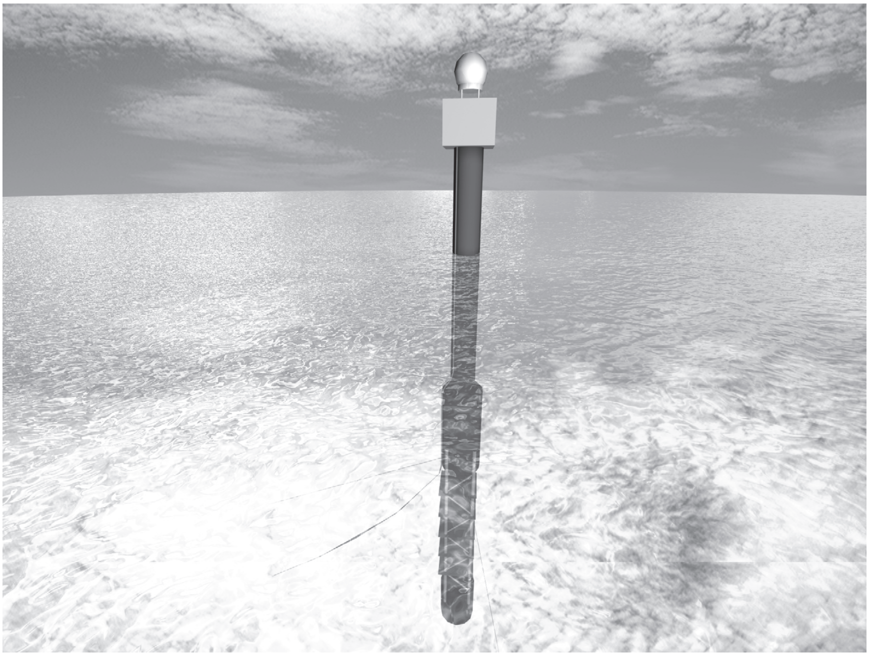

FIGURE 4-3 Artist's conception of a 40-m spar buoy design for a high-bandwidth moored-buoy observatory. The main module (gray box) will contain compartments for the electronics and communications electronics, generators, and batteries. A C-Band antenna radome is mounted atop this module. Fuel bladders are located in the spar. Deployment of this system will require two legs, one to install the mooring and spar buoy; a second to install the topside module. Figure courtesy of John Halkyard, Technip Offshore, Inc.

buoy. The generators required to power these systems are also commercially available, and there is considerable experience with their operation on unattended buoys.

The high-bandwidth discus or spar buoys described in the *DEOS Moored Buoy Observatory Design Study* (DEOS Moored Buoy Observatory Working Group, 2000) also entail special deployment requirements. In the case of the large discus buoy design, the weight of the anchor and the diameters of the steel and synthetic mooring lines are greater than can be handled by standard UNOLS winches and wires. In order to deploy these moorings from a global-class UNOLS vessel, an independent winch system would have to be installed to deploy and recover mooring components. Even the largest UNOLS vessels cannot deploy the large 40-m spar buoy described in the *DEOS Moored Buoy Observatory Design Study* (DEOS Moored Buoy Observatory Working Group, 2000), primarily due to deck-size limitations and reel and winch capabilities (which fall short of the 20,000+ lbs lift capability required). An offshore supply or anchor handling boat would be required for launching the mooring and spar buoy, and would probably be the best option for deploying the large 5-m discus buoys as well.

Installation of the spar buoy and mooring would require two separate stages: one for pre-installation of anchors and spring buoys, spar installation, and hookup to the mooring and a second for topsides module installation (DEOS Moored Buoy Observatory Working Group, 2000). These steps have to be performed in sequence, but not necessarily at the same time. While the first step will require a heavy-lift vessel, the topside installation of power, communications, and instrumentation modules could be performed by a global-class UNOLS vessel after the spar and mooring have been installed.

These deployment operations will be weather sensitive, but can be performed in seas up to about 2 m of significant wave height. Given the unpredictability of the weather at high latitudes, even during favorable times of the year, significant contingency time will need to be budgeted for installation operations.

Cabled Systems: New Installation

In contrast to moored buoys, the oceanographic community has very limited experience with the design, fabrication, and installation of submarine cable systems. However, the commercial telecommunications industry possesses a wealth of experience and the knowledge of the exploration industry is also increasing. Both can be drawn upon in designing, constructing, and installing research cable observatories. This section is intended to broadly outline the range of requirements and tasks required for the planning, installation, and maintenance of a submarine cabled observatory system.

The telecommunications industry's experience is particularly valuable, as it has installed and operated submarine cable systems for over 100 years with an exceptional record of success and reliability. However, there are important differences between commercial systems and ocean observatories.

Commercial systems operate with land stations on both ends of the cable with no connectors or variable loads on the ocean floor. Nearly constant power can be supplied from either end of commercial cables with no loops and few branch points. All branches on commercial cables terminate on shore in order to make it possible to control the power system. All commercial systems operate on constant-current power supplies. By contrast, the power supplied to observatories will vary over a large range of current and voltages. Furthermore, large observatory systems will have many connections and dead-end branches with variable power requirements, resulting in complex power and data systems and, as a result, likely lower reliability.

Commercial systems lose millions of dollars per day if a failure occurs, resulting in the necessity for rapid and immediate repair of the system. A data loss caused by the failure of a research observatory system will not cause excessive economic impact and it will not be necessary—or generally economically feasible—to make repairs within days of a failure, as with a commercial system.

As a result of the remote location of many observatory sites, scheduling a repair may take six months or more, depending on ship availability. The inaccessibility of many ocean observatory sites makes the reliability of the basic observatory infrastructure of paramount importance in the design, implementation, and operation of the proposed undersea network.

While commercial and research cable systems share a common need for high reliability of the basic infrastructure (e.g., cables, nodes, junction boxes), at a research observatory scientists must be given the opportunity to experiment with sensors, instruments, and experiments that may fail. Thus the reliability of individual sensors and instruments on a research observatory may be less than would be acceptable for an operational observatory or commercial cable. While new sensors or instruments should be tested first on land and in prototype ocean testbeds before installation, a cabled research observatory must be designed to protect the basic infrastructure from failures of individual sensors or instruments.

Commercial systems depend on highly explicit and rigid contracting to ensure uniformity, guaranteed compliance, and reliability. The failure of a contractor to perform a required task can result in costly legal action.

At research observatories this approach will be appropriate in those cases where the required tasks are routine and similar to industry procedures. Some procedures and systems at research observatories may be more experimental or developmental, however, in such cases a more flexible approach to contracting and performance will be required.

Planning the Installation and Maintenance of Submarine Cable Systems

Many logistical details require consideration prior to laying any cable, plugging in instruments, or collecting data at nodes. This section summarizes the scope of work for planning the installation and maintenance of a submarine cable system. This discussion is geared toward commercial systems given a wealth of experience from the commercial telecommunications industry and the exploration industry from which to draw.

Detailed system design

The characteristics of observatory systems will be driven by infrastructural capabilities. For example, the proposed communications bandwidths for buoyed observatories are orders of magnitude less than those of cabled observatories, not because the science is less demanding but because the capabilities of satellite links are far less than those of optical cables. Science will adapt to the available support assets. For ocean observatories, it is reasonable to take advantage of infrastructure that is available without considerable development, and given to apply those capabilities to observatory science. Development of the system specifications possible given existing technology, or with moderate modification of existing technology, will lead to reasonable performance expectations. Care should be taken to stay within reasonable development bounds to ensure high reliability and to prevent unexpected development costs.

Cable characteristics and topology will constrain available power, thus early determination of cable lengths, necessary slack, and other parameters are required before the power system can be modeled or power supplies and maximum loads determined. The power delivery of a cabled observatory system depends on the cable resistance, cable length, current, and voltage. Power loss from cable resistance increases as the cable length and as the square of the current, increasing the incentive to use low currents and high voltages. High voltages, however, are difficult to use in the ocean and most ocean cables and connectors are rated at 10 kV or less. Loops and branches complicate the assessment of the maximum power available to an observatory network. Furthermore, in such a system an increase in the power supplied to one node could affect power availability for other nodes. Heavy loads at nodes distant from power sources could also severely limit power available closer to shore. It might be more efficient to power nodes close to shore on separate cables from those powering distant nodes.

Once the decision is made to go forward, detailed designs of electronic systems and components of the cable must begin. One of the first priorities is to ensure that the network architecture contains compatible connecting equipment (the "Plug-n-Play" concept). To ensure this is the case, the cable provider must coordinate efforts with the operator to (1) determine complete fiber and copper requirements in the trunk line and all branches; (2) identify submerged electronics, repeaters, amplifiers, connectors and branching units; and (3) confirm transmission protocols and equipment specifications of sensors and data recording equipment.

Building issues on land are also important and must be addressed to install all the physical property and equipment necessary to operate and maintain the land end of any cable system. Detailed planning should be undertaken to ensure that protocols exist to address concerns regarding security, heat, humidity, and flooding.

Permitting

One of the most time-consuming and difficult processes in planning construction of any cable system is securing the rights to place the cable, both on land and under the water. Obtaining landing rights to cross coastlines and property easement rights to cross federal, state, county, city, and private lands can take months. To lay a cable one must first secure all federal, state, and local permits to land the cable, bury it along the land route, and construct terminal buildings. This may include performing Environmental Impact Assessments (EIA) and Environmental Impact Statements (EIS) for landing and sub-sea routes. The cable contractor or owner must also locate, and usually pay, all affected land owners. In some cases, finding all of the legal owners of a piece of land in coastal areas can be extremely difficult. In addition, determining the cost of a right of way can be a serious challenge.

Besides obtaining land rights, cable owners must also secure permits to cross existing undersea pipelines and cables, if any, and ensure those owners that no harm will come to their systems. The Minerals Management Service (MMS) of the Department of the Interior governs all pipelines and cables laid in U.S. waters, and each state has a department that controls the shallow ends to the high tide mark. An additional state agency may be legally responsible above the high tide mark and may share control with county and city governments. This entire permitting process can take a year or longer.

Submarine Cable Protection and Route Design

Submarine cables are vulnerable to damage from bottom fishing, anchor drag, currents, and other hazards that scour the bottom in shallow water (i.e., depths up to about 1,000 m). In addition, rough topography can result in cable "spans" where the cable is suspended above the ocean floor and vulnerable to damage. Such spans are a serious problem in volcanic terrain, where sharp outcrops could easily damage cables. Since many observatories will be located in shallow water or in volcanic settings, protection is a critical issue. Protection can take two forms, cable burial and cable armoring. The cable industry uses both burial and armoring to protect cables in shallow water but no such protection is used in deep water, where careful surveying is done prior to installation to avoid rough bathymetry and volcanic terrain. Burial of available commercial telecommunications cables in deep water is not possible for logistical reasons, and armoring would result in serious weight problems at depths greater than about 2,000 m. For observatories in deep-ocean volcanic areas, cable design must include armoring in appropriate sections and must account for adequate slack to prevent long spans. The most critical factor in determining adequate cable protection is knowledge of seafloor bottom characteristics. Such knowledge requires high-resolution near-bottom seismic, swath bathymetry, and sidescan data along the prospective cable route as well as knowledge of pipelines and other cables that will be crossed, resulting in a protection plan.

Before any actual work is performed or contracts awarded, environmental, geopolitical, meteorological, oceanographic, geophysical, industrial, and regulatory factors affecting installation and long-term security of the system must be investigated in a desktop study. The desktop study should include the following activities:

- A risk assessment must be performed to ensure that the most secure and environmentally friendly route is selected. While the general cable route will be driven by scientific objectives and required observatory node locations, the specific route must take risk into account. The risk of external damage to the cable or to components existing along the route, from seabed users (e.g., fishing, dredging, oil production) or natural threats (e.g., turbidity currents, mobile seabed, storms, volcanic or tectonic activity) should be evaluated as part of this assessment.
- Preliminary route design and route mapping should be produced.
- Burial specification and armor design for protection of the system should be specified.
- Concerns regarding pipeline crossings should be handled on a case-by-case basis. Some pipeline owners may require sand bags or con-

crete mats placed between the cable and their pipeline, while others may require only a plastic duct system.

- The initial cable and installation design should be proofed against existing industry capability.

Following the desktop studies, a physical route survey should be ordered and should include bathymetry, sidescan, sub-bottom (for buried systems), current, and other physical measurements. The purpose of this survey is to verify the initial route design and complete a threat analysis. Geotechnical measurements should be taken and analyzed on any portion of the route along which the cable will be buried.

System Production

Items that require a long lead time to acquire like the cable, terminal equipment, sub-sea components, and software will need to be ordered well in advance of installation. Contract management systems and procedures should be established to ensure system quality and timely delivery of all components. Any high risk or new design items that must be proof-tested well in advance of installation (in order to provide time to rebuild components that fail) should be given special attention at this time.

Installation Planning and Execution

Installation of a cabled observatory system is expected to be a significant fraction of its capital cost. Maintenance of a cabled system infrastructure should be less than that of an equivalent buoyed system since cabled systems do not contain consumables needing replacement on a regular schedule. Installation of long cable observatories will require the use of at least one cable ship, and may require two where there are branches in the topology. Connections to shore will require cable burial, construction of shore stations, and connection to the land-side power and communications infrastructure. Observatories utilizing less than about 100 km of cable could be installed from research vessels (temporarily) equipped with cable storage and handling equipment (provided that burial is not necessary), although use of a commercial cable-laying ship may be more cost-effective.

An important component of the installation of a cabled system is selecting the right contractor for the job. In commercial operations this selection usually occurs through a process that involves pre-qualifying contractors and then “going out for bid.” Pre-qualifying a contractor specifically includes ensuring that the cable-lay ship and burial tools are suited for the task. It also means ensuring that adequate resources are available for the duration of the job so that weather and other operational problems do not prevent timely completion.

Once the cable lay contractor is selected, the cable owner should produce system installation procedures. Additional permits, different from the long-term permits, must be obtained from all relevant authorities for the installation phase, including Notice to Mariners. Quite often a third-party installation contract management team of experts is hired to ensure proper installation. These experts would also work with the installation contractor on the production of "as-built" drawings and survey data for the entire sub-sea system and components.

System Maintenance Planning

To minimize costs, observatory system design must address reliability and maintenance issues. The greatest reliability concerns arise in those parts of the system that are the most difficult to recover, single-point failure locations, and locations that are the most vulnerable to failure. In a cabled system, such locations include the backbone cable system, junction boxes (Figure 4-4), and near-shore and rough topographic cable sections. Failure in the cable backbone will require an expensive repair by a cable ship. Considerable effort should be expended on identifying weak components, improving reliability by minimizing electronics in the backbone, using redundant systems, and protecting against faults. The most important hedges against failure will be the use of proven technologies and adequate testing of completed systems on land, at testbeds, and in the ocean during installation. Where possible, complex systems should be installed in stages to ensure that design goals are verified before the total system is in place.

Managers and technicians will need to be trained to operate the system. The establishment of a usable database to archive and test technical materials is important. At this point system restoration agreements and arrangements for land and ship-based maintenance and repair facilities should be in place.

Operational Planning

Once the cable is in place, long-term concerns will become a decisive factor. It is important, therefore, to determine in advance the method by which the system will be operated. In many cases, commercial systems share terminal facilities with a local telecom company. The H2O, for example, leases space in the Makaha Cable Station on Oahu, Hawaii. Building a facility dedicated specifically for cable landing is usually done for

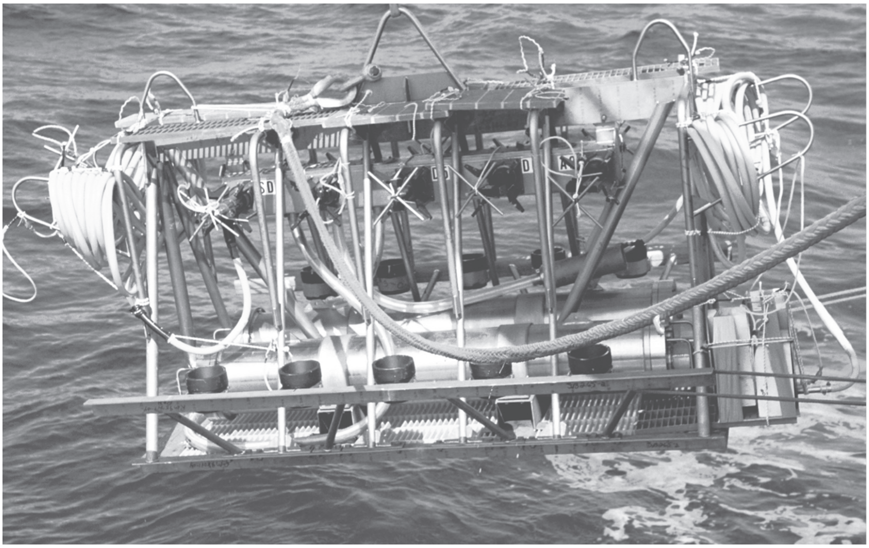

FIGURE 4-4 Deployment of the junction box developed for the H2O observatory. The junction box provides an interface for plugging instruments into the observatory network, providing power and two-data communication to the instruments. The OOI will provide support for junction boxes for both cabled and moored buoy observatories. Figure courtesy of Fred Duennebier, University of Hawaii.

security reasons or in cases where no facility exists in the area. The cable owners therefore must determine in advance whether they will build a dedicated facility or lease terminal facilities in an existing structure.

Once the physical facility is established, the Network Operations Center may be run and maintained by an employee or through a third party contract. Many commercial cables and terminal facilities are maintained through such long-term maintenance contracts.

A major factor in commercial cable systems is the "backhaul" issue. The backhaul route is that portion, or link, that can be shared with existing trunk lines (large cable systems). For example, if a company were to lay a cable to connect platforms in the Gulf of Mexico, originating in Venice, Louisiana, running through the outer continental shelf, and terminating in Galveston, Texas, the company would probably contract with existing terrestrial cable providers to furnish the continuous ring or loop required for redundancy, rather than owning and maintaining the entire cable, including all terrestrial legs.

Opportunities for Experimentation

Observatory design should maximize the opportunities for science experimentation and participation. Both the connection interface at the observatory and structures for data retrieval and command capability should be kept as simple as possible to encourage participation by groups lacking highly-skilled engineering support. It should be possible to have several connection levels, ranging from very capable, high-power, high data-rate interfaces for complex experiments to simple connections for analog sensors. An important management decision involves selecting the point at which the observatory infrastructure ends and user experiments begin. The observatory operator may control core and community sensors, but at some level experimenters should be allowed to experiment—without observatory management oversight of—as long as operations stay within power and bandwidth constraints. Testing of innovative ideas, prototype sensors, and even high school experiments should be encouraged. It is strongly advised, however, that new or experimental hardware be evaluated at a system testbed prior to installation on an observatory.

Cabled Systems—Reused Cables

There are three ways to re-use retired cables: (1) in-place use, (2) partial relocation, and (3) complete relocation.

In-Place Re-Use and Partial Relocation

In-place use utilizes the cable in its original location. The cable is cut and science nodes are placed on the cut end, and possibly along the cable, as was done on the H2O (Petitt et al., 2002). Partial relocation cuts the cable and hauls some cable and repeaters aboard a ship until enough is on board to allow placement of an observatory at a location away from the original cable path as with ALOHA (University of Hawaii, 2002). Both of these scenarios have the advantage of using the original cable station infrastructure, eliminating the cost of bringing the cable to shore. In-line observatory nodes can be placed on the cable by performing an operation similar to a cable repair. Since telecommunications cables come ashore at two different locations, at least two observatories can be established from each cable system.

Re-use by Complete Relocation

It should be possible to separate long sections of cables and repeaters and move them to other locations. Moving large sections of cable has been accomplished by the military (D. Gunderson, AT&T [retired], personal communication, 2003). Such relocation is the most costly way to re-use cables, since it involves the use of a cable ship, the shoring of the cable, and construction of new cable station infrastructure. It also requires that the cable section to be moved is not crossed by a newer cable. However, relocation can also support observatories where they could not be supported by other methods.

OPERATION AND MAINTENANCE

The operation and maintenance (O&M) of ocean observatories will require a significant, long-term commitment of resources and facilities. Observatory operation will also require a high level of interaction between the scientific community and observatory operators since observatories are still an evolving research tool. While power and bandwidth might initially seem unlimited, demands on the facility infrastructure could exceed capabilities. For example, an event could occur (e.g., a seafloor eruption or a harmful algal bloom) that would create simultaneous calls on resources by multiple observatory users. Therefore policies developed to apportion available power and bandwidth under standard operational conditions must also provide flexibility for intensified redeployment of resources during such episodic events. In general, prioritization of use of community assets, including community instruments and ROVs, will likely be an important, on-going operational issue over the lifetime of an ocean observatory. Interference between experiments may also be a significant concern: light, chemical, or radiated acoustic noise might be a requirement for some users, but a source of interference for others.

Moored Buoy Observatories

Open-ocean moorings should be designed for an operational life of 10 years (Figure 4-5). They will require annual service, with a three to five year refurbishment interval. Coastal moorings will require more frequent servicing, probably at least every quarter. Refurbishment of moored observatories could involve replacing mooring components or sub-systems on the buoy (e.g., the satellite antenna system, power generators, acoustic modems). Due to the hostile environment in which these moored observatories are likely to operate, these maintenance and refurbishment costs are expected to be relatively high. Annual maintenance and refurbishment costs are estimated to be 20% of the capital cost of the buoy and mooring (DEOS Moored Buoy Observatory Working Group, 2000) and higher costs can be expected in remote regions.

FIGURE 4-5 Surface moorings such as this one will need to be serviced annually, requiring up to one month of ship time (including transits) for each of the widely spaced moorings of the OOI global observatory network. Figure courtesy of Woods Hole Oceanographic Institution.

Operationally, the most important environmental limitation for open-ocean moorings will be the effect of sea state on the satellite telemetry system. The DEOS specification calls for operation at pitch, roll, and yaw rates of less than 10 degrees per second. However, recent experience with a C-Band antenna on a large UNOLS vessel as part of the Real-time Observatories, Applications, and Data Management Network (ROADNet) high seas project (see Chapter 3) suggests this requirement is too stringent and that these systems may be able to operate in much higher sea states than previously thought (beyond sea state 6). Tri-moored spar buoys at high-latitude sites and other areas that frequently experience bad weather are likely to experience smaller motions and deliver higher communication efficiency than a discus buoy. There will obviously be a strong seasonal variation in sea state at some sites, and there may be sustained periods where no data can be transmitted to shore. However, these data would be recorded on the buoy and can be either transmitted later or retrieved during annual servicing.

Biofouling is also a persistent problem for coastal moorings and frequent servicing will be required to keep instruments operational. Other major hazards for coastal moorings are fishing activity and vandalism.

Small- or intermediate-class UNOLS or comparable commercial vessels can be used to maintain coastal moorings. Open-ocean mooring maintenance will require large UNOLS or commercial vessels. Typical maintenance tasks will include replacing or repairing sensors and communication systems, removing biofouling, and, in the case of high-bandwidth systems, refueling. Mechanical components, electronics, and even diesel generators for the high-bandwidth buoys should be fairly easily exchanged utilizing standard UNOLS ship equipment. The modular nature of the spar topside unit allows it to be replaced separately from the rest of the spar buoy—a UNOLS vessel could conduct these operations. Recovering the mooring for a spar buoy, however, would require a commercial workboat-class vessel. In the case of a three-point spar mooring, the spar buoy can be recovered for repair or replacement without recovery of the mooring.

Long-term operation of cable-linked moored observatories will require the use of ROVs. In some cases an ROV may be needed even for acoustically-linked observatories to ensure proper placement of sensors, although in many cases this will not be necessary. If a buoy is lost, *Argo*'s transmitters would allow the GPS position of the buoy to be tracked and recovered by a vessel chartered for this purpose.

Cabled Observatories

Many of the operational issues associated with cabled observatories have been described in the SCOTS report (Dickey and Glenn, 2003). Maintenance costs and logistics will vary widely for different cabled observatories. The cables associated with existing cabled observatories, for example, H2O, LEO-15, FRF, and MVCO have been relatively robust, requiring minimal maintenance. However, it should be noted that if a cable is damaged or cut, repair would represent a significant cost, thus O&M budgets will need to include a contingency fund for such occurrences. A stand-by maintenance contract with a cable company would most likely be used for cable repair, as these repairs cannot be completed by a standard UNOLS vessel. The cost of such a contract would depend on the required response time. Due to the fact that repairs for a research observatory will not be as time-critical as for a commercial telecommunications cable, the observatory operator should be able to negotiate a competitive price for this contract.

The majority of cabled observatory maintenance costs are likely to be associated with nodes and instruments. Basic node maintenance (e.g., repair or replacement of a junction box) may not be required every year. Shallow water nodes such as those at LEO-15, FRF, and MVCO are routinely serviced by divers and small coastal vessels. Node maintenance and replacement at open ocean sites, however, will require ship and ROV assets. Routine node maintenance may either be contracted or conducted from a UNOLS vessel, although node replacement may require a vessel with a heavy lift capacity (see Chapter 5). A sufficient spare inventory should be maintained so that nodes can be replaced, rather than repaired, at sea. However, the level of spares that can be maintained will be dependent on the overall operations budget, which will need to be balanced against research needs.

The installation and servicing of instrumentation and experiments at observatories will require the largest amount of ship and ROV days each year. It would be prudent to plan on annual instrument servicing at nodes at open-ocean sites and more frequent servicing at coastal sites. Since much of this work is unlikely to be routine, observatory instrumentation work is probably best conducted by UNOLS vessels outfitted with ROVs.

Given the expense of instrument maintenance, reliability and calibration standards will need to be developed for core science and community instruments before deployment. Operations and maintenance plans should include a commitment to rigorous testing and calibration of core and community instruments to ensure the quality of observatory data. Sensors should be calibrated in the lab prior to deployment, and again after recovery, and should be as close as possible to their condition when recovered (i.e., with weathering and biofouling intact). An effort should also be made to make *in situ* checks and calibrations, using standards and new sensors brought to the observatory sites by ships. Standardization of these calibration procedures should be pursued across observatory sites within the coastal, regional and global networks and across various groups and nations to ensure comparability across all observatory systems. Where biofouling and sensor aging are serious problems, it may be possible to periodically switch sensors to new units. Shallow coastal sites will likely require more frequent servicing, but instrument revisits in this setting are less expensive and more easily accomplished. Maintenance of deep-water instruments will necessarily be less frequent; therefore instrument design and calibration should take these factors into account.

Observatory Operation and Maintenance Costs

The operation and maintenance of the observatory infrastructure acquired as part of the OOI will require a substantial, long-term financial commitment on the part of the NSF. Experience demonstrates that these maintenance costs are often initially significantly underestimated (Chapter 2).

The DEOS Steering Committee provided information for this report on projected O&M costs for the OOI. While these projections are rough, as would be expected at this stage in program development, they do provide a useful estimate of the potential costs. The DEOS projections are included in this report to provide some guidance to the NSF concerning the level of resources that may be required.

Table 4-1 summarizes projected annual costs for the three main OOI components: a global observatory network, a regional-scale cabled observatory, and coastal observatories. The global network is assumed to consist of 20 nodes at widely separated locations in the world's ocean. Half of the sites are assumed to be occupied by low-bandwidth moorings (acoustically-linked or cabled) with the remainder comprised of either high-bandwidth, cabled moorings or sites using retired telecommunications cables. The O&M cost estimates are based on the *DEOS Moored Buoy*

TABLE 4-1 Estimates of Ocean Observatory Operations and Maintenance Costs

Observatory Type	Approximate Annual O&M Costs
Global Network Observatory[a]	
O&M (20 nodes)	$7M
Ship time (20 months/yr; 10 with ROV; 10 without)	$15M
Contingency	$2M
Regional-Scale Cabled Observatory[b]	
O&M (30 nodes)	$11M
Ship time including ROV (4–8 months/yr)[c]	$3.6 to $6.3M
Contingency	$1.5M
Coastal Observatory[d]	
O&M	$4M
Ship time (3 months/yr)	$1.5M
Contingency	$0.5M
Total	$46 to $49M

[a] Costs based on data from DEOS Moored Buoy Observatory Working Group (2000).

[b] Costs based on data from NEPTUNE Phase 1 Partners (2000) and updated figures provided by NEPTUNE Office.

[c] NEPTUNE cost estimates assume 3 days/node for sensor maintenance and 1 day/node for node maintenance annually. The NRC Committee recommended budgeting one week/node for nodes and sensor maintenance.

[d] Very crude estimate based on operation of existing coastal observatories.

Observatory Design Study (2000). NEPTUNE has been used as an example of a regional cabled observatory with 30 nodes over a 500 × 1000 km area. The O&M costs are based on the NEPTUNE feasibility study (NEPTUNE Phase 1 Partners, 2000) and updated figures have been provided by the NEPTUNE Office. Coastal observatories are assumed to be a mix of moorings and cabled observatories. Since the required coastal observatory infrastructure is not well-defined at this point (see Chapter 3), the associated O&M costs for this OOI component are of necessity the most speculative.

A number of important assumptions have been considered in these cost projections. The O&M costs apply to observatories after initial installation and commissioning as operational systems and they include labor and project management. Nodes for both moorings and cabled observatories are assumed to be serviced annually. Ship costs for a Class I UNOLS vessel are assumed to be $20,000/day with an additional $10,000/day for ROV costs. Although vessel costs for servicing coastal observatories can vary widely depending on the type of vessel; $10,000/day has been assumed for this cost projection. Commercial charter rates for ships and ROVs are market-driven and vary significantly from year to year, however, these figures should be representative of longer-term average costs. Contingency costs are included for unscheduled maintenance and other unforeseen costs (estimated here at ~10% of annual O&M plus ship costs).

Based on 2003 fiscal calculations, the figures shown in Table 4-1 indicate that O&M costs, not including ship time, for the OOI could run about $25M annually. If ship time is included, these costs approximately double, approaching $50M annually. By comparison, the FY 2002 budget of the ODP was approximately $46M for operating the *JOIDES Resolution*, a drilling vessel and associated program activities (drilling and science support services, information services, publications, administration). The OOI O&M costs are thus not out of line with other major geoscience initiatives.

Nonetheless, the oceanographic community has expressed concerns that the costs associated with operating and maintaining ocean observatories will drain resources from other areas of the ocean sciences (e.g., funding, ship and ROV assets, intellectual resources) and negatively impact non-observatory ocean science. This fear is based to a significant degree on concerns that funding levels will not be adequate to support this new facility or that these costs will initially be significantly underestimated. In order to allay these concerns, the NSF needs to take steps to ensure that observatory program costs and infrastructure needs for ships and ROVs are accurately estimated early on, that budgets are augmented by amounts sufficient to operate whatever is acquired, and that management oversight and fiscal controls be implemented to ensure that the observatory program operates within budget.

The funding profile for the OOI shown in Figure 1-5 indicates the NSF is projecting O&M costs of about $10M/yr in 2011 when the infrastructure is fully installed. The figures shown in Table 4-1 suggest a more realistic estimate is $25M/yr, not including ship time, and twice that figure if ship time costs are included (it is not clear if the O&M costs shown in Figure 1-5 include ship costs or not). None of these estimates include the cost of funding the scientific research that this new infrastructure will enable. These costs are difficult to estimate, but certainly could amount to a significant fraction of the annual O&M costs. A successful observatory program will require sufficient funding for *both* maintenance and operation of the observatory infrastructure *and* the science and instrumentation that this infrastructure will enable. The NSF needs to take appropriate steps now to ensure that sufficient resources are in place to meet these needs by the time the observatory infrastructure is in place.

NATIONAL SECURITY ISSUES

Ocean observatories have the potential to provide public access to technology or data that could raise significant national security concerns. The most obvious issues relate to the U.S. Navy submarine fleet and hydrophone and geophone arrays that may be used with seafloor observatories, although other sensors could raise security concerns as well. The issue of submarine security and ocean observatories has occurred several times in the past; however, the new capabilities of the proposed observatories combined with near-continuous operations raise issues well beyond those of the past. In the past, oceanographers have had access to small arrays of hydrophones, geophones and seismometers (e.g., the Wake Island and Ascension Island systems), but these arrays had a very limited capability to detect and track a low signal-to-noise source such as a submarine unless it was very close. The towed arrays currently used for seismic reflection and refraction profiling have a greater capability. The arrays are several kilometers in length, have a large number of sensors, and operate in frequency bands (5–400 Hz) relevant to anti-submarine warfare (ASW), but since these arrays operate in an active mode with large air gun and/or explosive acoustic sources, only record in limited time segments, and are not stationary, they do not raise concerns for submarine security. Consequently, oceanographic research has not been a problem for submarines; indeed they have benefited immensely from the basic science accomplished with these systems.

The scientific community has had access to the Navy SOSUS arrays for seismicity, marine mammal, acoustic tomography, and a few other applications. This access, however, was allowed only to investigators with security clearances; time-series data could not be published; large uncertainties existed regarding receiver location; and prior review of any related publication was required. All of these restrictions are not generally acceptable to either the scientific community or its many referred journals, so use of these data has not been widespread.

Shortly after the end of the Cold War and the demise of Russian submarine operations, there was a period when the Navy desired scientific usage of the SOSUS arrays. The reasons for this usage are uncertain, though it could possibly have been used to justify 'dual usage' or to transfer the cost burden for operating and maintaining these systems to another entity. Since then no efforts have been made to encourage 'dual usage' except within these same security constraints. Nevertheless, a panel of scientists convened to document the possibilities of using SOSUS for scientific purposes (Joint Oceanographic Institutions, Inc., 1994). When the approval process reached senior levels of the Navy, the policy of restricting use to cleared individuals operating under the above protocols remained in place.

All submarines radiate acoustic signals (a signature) from a variety of sources, including machinery, structural resonances, propellers, and turbulence. Measured submarine signatures are highly classified since they can be readily exploited for submarine detection, classification, and tracking. Arrays of hydrophones and/or geophones with sufficient array gain and state-of-the-art signal processing are used to detect, track, and classify a surface ship. The capability for such measurements involves many factors; however, several are relevant to deep-sea observatories and are discussed below.

Location

The proximity of an observatory to a submarine operating area is important since signatures are louder and at shorter ranges. The proposed NEPTUNE site is in a sensitive location since the proximity of a *Trident* SSBN station (Submarine Ship Ballistic Nuclear) located in Washington State raises concerns as submarines leave and enter port. A highly capable hydrophone or geophone array at a node with large horizontal line array (HLA) and/or large vertical line array (VLA) could acquire the acoustic signature of an SSBN. There are also nonacoustic "signatures" used in ASW; however, classification of such information restricts a complete listing. Such signatures are highly classified because they can be exploited for detection and compromise the stealth of these submarines. There are also other modalities by which such arrays could be used for detection. In addition, some of the proposed OOI global network sites raise concerns because they may be near regions of SSBN operations.

Array Capability

Hydrophone or geophone arrays with many sensors and wide apertures lead to large array gains and high resolutions, and both of these capabilities are critical in detecting and tracking a quiet submarine. NEPTUNE nodes with a capability similar to the existing SOSUS arrays certainly could prove a concern. Furthermore, the distributed nature of the entire NEPTUNE system will provide a significant enhancement capability in terms of improved tracking by triangulation and increased signal to noise levels. NEPTUNE's array configuration (the number and location of sensors) at each node, as well as the rest of the sensor suite, is not specified at present, so a determination of the threat to submarine operations cannot be made. A single sensor at each node may not pose much of a threat, but a SOSUS level array at each node certainly would attract the Navy's attention.

Continuous Observations

Continuous data acquisition by an observatory raises operational constraints for submarines by potentially eliminating any opportunity to escape observation. Potential solutions might be to turn off, delay, or degrade observations by pre-arrangement with the U.S. Navy; however, even knowledge of such scheduling is valuable information regarding the transit or location of submarines. Another alternative employs extensive noise masking, which entails its own set of operational problems and may degrade scientific observations.

There are other security issues related to system configuration and control. The junction boxes used with ocean observatories would be designed to accept a wide variety of instrumentation operating with the system protocols for power and communication to shore. The openness and flexibility of these junction boxes are important for the scientific community as new and improved instruments become available during the proposed lifetime of the observatories. However, this openness raises issues over network configuration control. Procedures need to be put in place so access to the junction boxes is controlled and the Navy has full advance disclosure about the capabilities of the instruments connected to the boxes. Moreover, the Navy will not be comfortable if data streams are encrypted or other actions are taken to limit its availability, and will want real-time access to the data. The Navy may want to perform some data processing for ASW purposes solely to assure that sensitive information is not compromised. Implementing such requirements represents significant costs that are yet to be determined.

Since the *Trident* SSBN fleet is a primary component for U.S. national security, the Navy will not accept siting sensors (e.g., NEPTUNE) where the data derived compromise the fleet's stealth and operational capability. Resolving this possible conflict between the desire of the research community to use the most capable instruments available in the best possible locations and national security concerns could lead to an impasse among the Navy, the new Department of Homeland Security, and the NSF.

The NOPP National Ocean Research Leadership Council (NORLC) already has a security subcommittee, an inter-governmental infrastructure which may be capable of working out these security problems. There are two particular concerns: (1) these difficult problems will certainly require resolution especially if the OOI expects to maintain the schedule described elsewhere in this report; and (2) submarine security concerns the operational Navy whereas NOPP has more of a research focus, making operational Navy participation in these discussions imperative.

Discussions will need to take place to establish observatory security policies well in advance of any observatory installations, and will need to involve senior officials at the NSF, the NOPP-NORLC, the U.S. Navy, and the U.S. Department of Homeland Security. As observatories become operational, an on-going process will be needed in order to address security concerns as they arise and to regularly review security policies and procedures.

It is imperative for the NSF and other supporting agencies to initiate this dialogue with the Office of the Secretary of the Navy (SECNAV) as soon as possible. The SECNAV is the appropriate office because it can represent the concerns of the entire Navy in these discussions. Any observatory systems compromising submarine security or other Navy capabilities will represent a threat to national security and could be challenged at the highest levels by the Navy. With the present schedule, installation of observatory systems is not terribly far off, making it critical that the policies impacting national security are put in place soon, lest their absence potentially delays deployments.

DATA MANAGEMENT

There have been a number of planning activities over the past few years to develop requirements and policies for an ocean observatory data management system. Although there are differences in the requirements and policies recommended by participants in these various workshops and reports, there are a number of overarching themes that address key issues for an ocean observatory data management system. The requirements and policies adopted in this report are based on the following four documents:

- *Illuminating the Hidden Planet* (National Research Council, 2000);
- Ocean.US IOOS-Data and Communications (DAC) sub-system (Appendix V.8 in Ocean.US, 2002a) (Please note that the IOOS Data Management Plan was released for formal review on April 16, 2003 after this report had been sent to review, therefore conclusions drawn in that report are not available here.);
- The *Argo Data Management Handbook* (Argo Data Management Committee, 2002); and
- NEPTUNE planning documents (NEPTUNE Canada, 2000; NEPTUNE Phase I Partners, 2000; NEPTUNE Data Communications Team, 2002).

Recommendations for an OOI data management implementation plan have been developed based on those requirements. Further, the OOI initiative will take advantage of the work that these listed activities have accomplished. The plan provided in this report provides guidance for developing an integrated, cost-effective data management strategy for global, regional, and coastal ocean observatories (see Appendix B for definitions of any unfamiliar terms).

There are several challenges that an ocean observatory data management system must address:

- ***Heterogeneity of data sets:*** Data products are generated from various instruments and have different characteristics in format, metadata, resolution, validation of data, and other similar characteristics.
- ***Absence of existing infrastructure:*** Data archive centers exist for some data types that will be collected by ocean observatories but do not exist for others. Moreover, the responsibility for supporting oceanographic data management centers is divided among several different agencies.
- ***Integration of data products from observatories:*** In order to access data products from multiple sources, data need to be quality-controlled in a uniform manner and coordinated by data processing centers for all observatories. At present, there is a lack of coordination between data providers and data users.
- ***Data volumes:*** The observatories being planned as part of the OOI will potentially generate huge volumes of data (on the order of 1 petabyte/year). The system needs to be scalable to accommodate data volume growth.

Due to the variety of disciplines involved in ocean observatory research and the different requirements of each observatory type, a distributed data management architecture should be adopted in order to be cost effective and manageable. The observatory systems proposed for the OOI share common needs to address metadata and data standards, data processing strategies, and information sharing. In order to develop a highly automated and cost-effective data handling system, however, the command and control and data management models will need to be implemented differently for each observatory system due to differences in instrument configurations, data volumes, and real-time data delivery requirements. Table 4-2 summarizes the data management system requirements for the OOI and their impact on the software and hardware data management system design.

Ocean Observatories Initiative Data Management Architecture

The software system architecture defines the performance and relationship of various data management services including data processing, data archiving, data mining, operational and science user interfaces, and data distribution services. Each service will be described by a set of components allowing for the construction of the software system. Additionally, the system should be designed to leverage a distributed systems architecture to allow for scalability across multiple servers, both locally and geographically. These design guidelines have been proven to support large data management systems in both commercial and research environments.

The data management sub-system (DMS) interfaces with sensor network operations, science users, archive centers, program management, algorithm developers and calibration engineers, and ancillary data sources. The recommended OOI-DMS design priorities are:

- high speed of data product processing and delivery to science users;
- advanced level of full process automation to enhance speed and to minimize labor cost;
- high adaptability of system to shift between processing priorities in the case of an unscheduled event;
- scalability of the system to consistently support rapidly growing data collection and increased processing demands; and
- ability to extend the system to incorporate new algorithms, processors, delivery medium, processing centers, and command stations, as well as new observatory nodes.

Architecture

The purpose of the software architecture is to define a reference DMS that includes components that can be integrated to serve a variety of ocean observatory requirements. It should allow for any number of data types to be integrated into the system. A key goal of the architecture should be to achieve the scalability and performance requirements necessary to support the observatory system. The architecture should include components that facilitate the capture, location, interpretation, and distribution of science products. The final data management framework architecture should have the following goals:

- ***Scalability and reusability***, to accommodate different observatory requirements and data sizes;
- ***Hardware independence***, to provide hardware configuration that is not driven by the framework;
- ***Database independence***, to provide a database that is not driven by the framework;
- ***System adaptability***, to allow for observatory or project specific features that can be plugged into the framework;
- ***Location independence***, to allow data sharing from multiple distributed repositories for analysis, decision-support, and knowledge discovery;
- ***Ease of use***, to provide data management framework software that is portable and easy to install and manage;
- ***Autonomy***, to enable a rule-based management to support autonomous operations; and
- ***Interface efficiency***, to provide an Application Programming Interface (API) to interface with user analysis tools.

A key principle in implementing these goals is to separate the data architecture from the technology architecture. The data architecture specifies standard models for describing and exchanging data that can evolve over time. For example, XML is a part of data architecture that specifies data interchange format. On the other hand, JAXR is a Java™ technology architecture that provides API for handling XML registries in Java™. If a new technology emerges, it can still take an advantage of XML data architecture. However, if application specific data architecture is used (e.g., Microsoft Word format), it is hard to take advantage of new technology without affecting data architecture. The technology architecture specifies basic communication middleware between geographically distributed data systems, a common software component framework, and methods

TABLE 4-2 Requirements and Design Impacts of Data Management Systems

Requirements	Design Impact
Data from ocean observatories must be readily available to the scientific community and the general public.	Requires professionally managed DMS and data repositories. Develop a middleware framework for interoperability among heterogeneous, cooperating systems. Develop API to interface with various data access methods.
The OOI-DMS should be integrated with the data management strategies proposed for IOOS/GOOS.	Develop a "free market" of globally accessible ocean science information, including officially sanctioned OOI data and products, as well as products and analyses from other sources.
The OOI-DMS should provide the up-to-date status of observing elements and maintenance schedules.	Requires fault tolerance with real-time data delivery. Support special orders of various level products. Interface to health of DMS, system monitoring, data acquisition requests, and planning.
The OOI-DMS should provide data in real-time or near-real-time to end users.	Develop NSF and community driven data and metadata archive standards for the three observatory types.
Data summaries and metadata should be available in near real-time.	Develop capabilities for automatic generation of descriptive metadata associated with data. Need data discovery services that allow rapid location and access of data based upon queries formulated by machines or humans. Provide unambiguous citations and linkages, assuring users of the version of data provided.
The OOI-DMS should provide reliable continuous deliveries of real-time data streams from observing system downlink sites to operational modeling centers and the scientific community.	Develop highly automated and cost-effective systems, with built-in feedback mechanisms for rapid detection and suggestions for repairing problems. Recognize needs of all users and coordinate and/or implement required actions. Use Spiral Model (IEEE Computer 21, May 1988) for development of systems and technology insertion for stability of the system.

continues

TABLE 4-2 Continued

Requirements	Design Impact
Data products must be preprocessed and permanently archived with standard data formats. Data or data products from different observatory systems must be readably available to users.	Develop comprehensive, well-documented and supported standards and protocols to guarantee interoperable delivery of all observations and numerical products. Develop a hardware resource management plan must also be developed.
Data from core and community instruments should be available without restriction to any interested user or the general public.	Possess sufficient data transport capability to handle large-volume exchanges of raw data and model outputs between modeling centers and high volume users. Develop robust network capability. Standardize interfaces.
Data products from core instruments should be supported by basic observatory operating costs. Data products from community instruments and "investigator-owned" experiments should be supported by responsible funding agency.	Develop data management plan for data from all three types of instruments: core instruments, community instruments, and "investigator-owned" experiments.
The OOI-DMS should assist researchers in the integration and management of their datasets by providing support for the transition of experimental information into synthesized data products.	Develop a scalable data management framework. Develop a componentized architecture for Plug-n-Play capability of data processing and assimilation procedures.
The OOI-DMS should facilitate educational outreach using seafloor observatory infrastructure and information.	Enable diverse communities to easily utilize the varied and distributed forms of marine data in a wide range of current and future computer applications.
Existing data management systems COTS software should be used if possible.	Provide opportunities to engage the private sector as a powerful development engine in creation of value-added products targeting the needs of specific user groups.

SOURCES: Data from National Research Council, 2000; NEPTUNE Phase I Partners, 2000; Appendix V.8, Ocean.US, 2002a.

for using the data architecture. Allowing the data and technology architecture to evolve independently will extend the life of the OOI-DMS.

Components

Although there will be differences in managing data from the three types of observatory systems, some common features apply, such as: development strategy, metadata and data standards; and software architecture to allow data management and data archival. These components are described by addressing the importance of software development strategy, standardized metadata and data formats, archive policy, and educational outreach. Figure 4-6 illustrates the components that would be required to support DMS in a typical observatory network (Hughes et al., 2001).

Several recommendations in this report are adopted from the IOOS DAC components definition (Appendix V.8 in Ocean.US, 2002a). Furthermore, any existing components that have been developed by the research community which may include metadata format, data format, interchange protocols, and API, should be adopted for this effort if feasible.

Metadata Management

A distributed DMS similar to that required for ocean observatories should develop metadata standards to specify contents and formats of the metadata. A Data Management Committee should exist at the OOI program level (Figure 4-1) to establish simple guidelines and extensible standards for metadata and to develop a data and metadata search and retrieval framework to enable searches across multiple data repositories established by the observatory program. This committee should also develop well-documented and reliable standards and protocols to guarantee interoperability among all data centers. Development of standards and protocols should be coordinated with other national and international programs.

Based on these guidelines, the primary activities to be conducted by the data centers are:

- implementing and maintaining a comprehensive OOI data discovery service;
- ensuring that linkages between data and metadata are maintained with reliability;
- developing data mining techniques and an analysis framework to recognize features and find clusters in large datasets (i.e., capability for event notification and automatic science discovery);

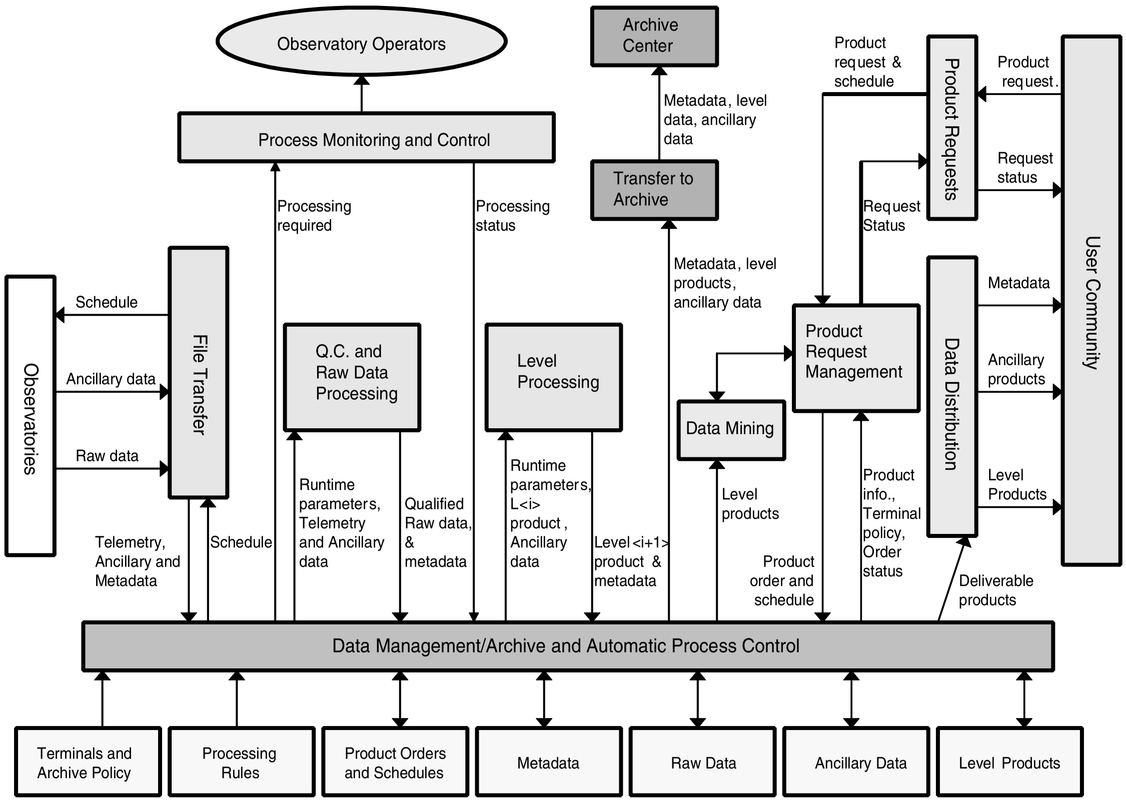

FIGURE 4-6 Distributed DMS Components for the OOI. Modified from Hughes et al., 2001.

- developing data translation middleware to geographically project, register, and subsample data products (i.e., co-registration).

To sustain the large amount of data to be handled by the OOI, a special focus should be given to providing education, training, and tools to increase OOI effectiveness in metadata generation and management.

Data Archive

The ocean sciences community has not yet widely accepted that data should be made freely available to the rest of the community in a timely manner. For example, the history of WOCE demonstrates how difficult it has been to make WOCE data acquired over the past ten years available to the public, and the struggles the data processing centers have undergone attempting to make these data available in a uniform fashion (Appendix V.8, Ocean.US, 2002a). The research community also lacks a centralized or coordinated system for archiving and distributing oceanographic data. While some data types are managed through NOAA's National Oceanographic Data Center (NODC), not all investigators submit their data to NODC, nor does the NODC archive all of the many kinds of data collected by ocean researchers today. In many cases, data archiving and distribution has thus become the responsibility of individual investigators, institutions, or programs. As a result, valuable data are generally not widely available and may be lost over time.

Experience shows that the ocean observatory program cannot rely on individual investigators to manage, archive, or disseminate observatory data. Data must be professionally managed and distributed through established data centers according to nationally and internationally agreed upon standards. Due to the interdisciplinary nature of the data to be collected at ocean observatories, they will not be archived in a single central archiving center for these data, but rather in a network of distributed centers dedicated to particular data types (e.g., seismological, oceanographic, biological, or geodetic). The program will need to provide tools for scientists to search and retrieve data across this distributed network of data centers (a "virtual" data center or "data grid" concept).

The OOI program should have an open data policy with all data from core instrumentation and community experiments available in as near real-time as possible. Data archive centers will therefore require sustained funding to support data archival and distribution even beyond the end of the program. It is also important that hardware upgrades, maintenance, and media migration are conducted and funded as a part of the operation of data archive centers.

User Outreach, Applications, and Products

A main concern of the OOI-DMS is providing data products in an efficient, reliable, and timely fashion. To achieve this ambitious goal, the OOI needs to establish and maintain contact with outreach program developers. The OOI must continually determine the adequacy of the quality and timing of release of OOI products in relation to user needs. In particular, these products should include the following:

- quality-controlled collections of observations maintained by OOI-DMS and archive centers according to commonly agreed upon quality control procedures;
- a minimal, guaranteed geo- and time-referenced data visualization capability accessible through a standard Web-browser; and
- information on products produced by outside groups utilizing OOI data.

To accomplish this goal, two key user interfaces will need to be created: a science user interface and an operational user interface. The science user interface allows scientists to enter product requests. Requests for previously captured data will be processed and products staged for download by the data distribution function; requests for products that have not been acquired will be recorded by the system, which will schedule the user for notification and distribution once acquired. An operational user interface will allow system operators to manage the data system.

As the size and complexity (in temporal and spatial resolution) of data sets grow, so will the inadequacy of an information discovery process that can descend only to the level of a data set. Data mining techniques should be included to allow the user the ability to identify and retrieve "features" such as "a decrease in transport of the Gulf Stream" or "abnormal seismic activity along the Juan de Fuca Ridge."

Data System Security

Data should be protected based on policies adopted by the global, regional, and coastal observatory community. Some data products might be restricted to the U.S. due to International Traffic in Arms Regulations (ITAR). To protect network infrastructure, communication between sensor network and commanding centers should include the capability to authenticate users and encrypt data.

The following methods are available for adhering to various security measures:

- public key infrastructure-based data encryption and user authentication;
- a secure network and firewall;
- authentication based on user profiles and data profiles;
- a log and monitor function;
- security plans for data management systems; and
- risk assessment and countermeasures.

A security plan should cover data management system security requirements, hardware and software architecture, network interconnections and internal architecture, and system components. It should also cover non-technical security features such as personnel, user training, physical security during the development and operational phases, and daily cycle of operation. Finally, risk assessment and countermeasures should be discussed to prevent operational failure, to increase data sensitivity, and to protect command and control components. Such an assessment will be extremely important for regional and coastal cabled observatories due to concerns over homeland security.

Administration and Operation

From an administrative and operational standpoint, the OOI-DMS should:

- guarantee day-to-day system operations (e.g., for data acquisition, data and metadata portals, monitoring, and evaluation of system performance);
- guarantee liaison with product and archival facilities;
- ensure "help desk" functions and software development; and
- establish and publicize policies.

Implementing Observatory-Specific Components

The three OOI components (global, regional, and coastal) will each have different data management needs. A regional cabled network will produce huge volumes of data from a diverse set of sensors on a single telemetry link, while the global network will generate smaller data volumes, but from a globally distributed network of nodes, each of which uses a different telemetry link to shore. The coastal network is likely to be a mix of these two scenarios. Data management capabilities and operational scenarios must therefore differ in order to efficiently manage the flow of data generated by the networks.

Data Transport

Data management capabilities already exist for some components of the global and coastal observatory networks, (e.g., NODC, IRIS, *Argo*). Since some of these capabilities are not completely coordinated, however, issues may arise with regard to interchanging products and distributing data in a timely manner. A common interchange format and a data dictionary should be developed through working groups and joint research opportunities for the national and international science community.

As specified in the IOOS recommendations, depending on the ocean observatory network the following topics need to be addressed and implemented by surveying existing implementations and adapting them to fit the ocean observatory network:

- robust networking technology to transmit data between sensor subsystems, assembly centers, modeling centers, product generating centers, archival centers, and data users in both real-time and delayed modes;
- extensible data model(s) that assure interoperability of diverse classes of transmitted data, which should be created if an appropriate model does not exist;
- software strategies that translate data, as accessed from diverse data management systems, into an interoperable data model, which should be created if none exist; and
- software strategies that assure security, performance monitoring, and fault detection of the OOI data management network, which should be created if none exist.

Global Observatory

Although data processing will be implemented at a national level, the network to support a global observatory will provide data for several international research programs ranging from climate studies to global seismology. Data requirements may differ significantly from site to site both in the volume of data acquired and in the type of link to shore, depending on the type of mooring. Real-time or near-real-time data delivery will be required for many instruments on this network, including data from meteorological, oceanographic, and seismological sensors. The difficulty of implementing a data management system for the global observatory network therefore lies in the distributed network of nodes shared internationally rather than the amount of data generated. As a result, it is important to agree on quality control procedures, standards for data distribution, data-level processing, and version controlling among the network. As experience from the *Argo* program has indicated, techniques for uniquely tagging and tracking the versions of data sets must be developed.

The global network data management system should include a distributed processing framework among international data centers, a unique Web portal to access these data annotated with quality statements among the network, and standardized quality control procedures to be developed for real-time and delayed mode data.

Regional Observatory

A regional observatory based on a cabled seafloor network has similar data processing requirements to a satellite system in that huge amounts of data (Tb/s or greater) will be acquired in real-time. The issue of implementing either software or hardware networking capabilities needs to be addressed in the future, and creative solutions to these problems will need to be devised. Solutions may include techniques to reduce the demand for large data transfers (e.g., more effective sub-setting, server-side analyses) as well as improved delivery (e.g., higher bandwidth, new compression schemes).

Resource management of power consumption, instruments, networks, and AUVs should be handled by autonomous capabilities by monitoring product requests and data access and production, and through process monitoring and control. Although a distributed framework will be used for data management, centralized coordination of observation planning, data process requests, and access is required.

Coastal Observatories

Since coastal observatories may include both relocatable moorings and fixed cabled or moored observatory systems, they share requirements with both global and regional observatories. A scalable, componentized capability in the data management architecture should be developed to accommodate future observatory needs. Use of middleware is critical for merging existing capabilities with new capabilities to be inserted into the architecture. These functions include metadata profiling, data translation, APIs, and service-oriented components such as Common Object Request Broker Architecture or Java™ message service.

Command and Control

While it is not clear at this point whether instrument command and control at ocean observatories will be a data management function or an operations function, the DMS should provide interfaces to a command

and control system to provide information on scheduling, instrument control and monitoring, telemetry processing, network security, and maintenance. Constant feedback regarding data acquired versus observations planned should be available for planning and scheduling purposes. Another important aspect of this component is predicting system overloads and providing information for instrument and system monitoring in order to guarantee continuous operations. This component should also include autonomous control capability for network resources and data flow.

EDUCATION AND PUBLIC OUTREACH

Research directorates of funding agencies like NASA and the NSF are increasingly encouraging the integration of science and education and greater scientist involvement in education and public outreach (EPO). The NSF's Geosciences Directorate has developed new programs for geoscience education and outreach to teachers, students and the public, and the NASA strategic plan makes it the responsibility of its strategic enterprises to "embed" education and outreach into its programs.

In testimony before the Committee on Science, U.S. House of Representatives, 28 April 1999 Daniel S. Goldin, NASA Administrator, stated that:

> No longer is it an acceptable practice to say, "we are too busy." Research, knowledge generation and education are all equal components of the NASA mission. We must combine our traditional methods of involving the education community with new and innovative ways so that the impact NASA has on education is greater. (U.S. House, Committee on Science, 1999, p. 123)

On the same date Dr. Rita Colwell, Director of the NSF, testified before the same committee that:

> All researchers—whether at a university, a national lab or circling the Earth in a space station—should link their inquiries with the education of the next generation. (U.S. Congress, 1999, p. 77)

Seafloor observatories have the potential to provide unique opportunities for educational outreach by conveying the excitement of discovery of ocean sciences to the public (National Research Council, 2000). Many aspects of observatory research are suitable for education and outreach programs, especially the capability of observatories to transmit real-time video and data from acoustic and optical sensors. Examples of possible outreach efforts presented in the *Illuminating the Hidden Planet* (National Research Council, 2000) report include:

- real-time image and data feeds into museum and aquarium exhibits via the Internet;
- incorporation of real-time image and data feeds in K-12 curricula (e.g., The JASON Project™ [see Appendix B]);
- development of curriculum modules for K-12 students that incorporate research results and scientists' profiles;
- establishment of summer research (sabbatical) programs for K-12 teachers using observatory data to facilitate interaction with scientists; and
- development of public Web sites containing real-time images and data, and publicizing exciting science at observatories via public television.

Large sectors of the American public are functionally illiterate in the sciences—most cannot explain the mechanism responsible for the four seasons of the year (Goodstein, 2002). The U.S. scientific research community has an obligation to aid American educators in improving the science literacy of its citizenry. The National Science Education Standards (NSES) provide a consensus on what educators and scientists nationwide believe students should know and subsequently be able to understand and apply at various K-12 grade levels (National Research Council, 1996). The NSES also address the need for best teaching practices, preparation and professional development programs for teachers, and implementing systemic reform of education.

EPO should be an important objective of the observatory effort in order to involve K-12 students and the interested public in the excitement of ocean sciences research. The EPO program should use ocean research data to help students and teachers meet NSES, not just to entertain (National Research Council, 1996).

The ocean observatory EPO program should be implemented through a collaborative effort with the National Sea Grant Program and with the recently funded Centers for Ocean Sciences Education Excellence (COSEE). Sea Grant has long been involved with K-12 education and public outreach, coupling research marine scientists in universities with educators to promote the benefits of (primarily) Sea Grant-funded marine research. In general, Sea Grant EPO managers are science educators with expertise in marine and aquatic science content, educational pedagogy, and pre-college curriculum development. These highly qualified marine and aquatic educators work within an established infrastructure and have made valuable contacts in many pre-college schools, museums, science centers, and aquariums across the country.

The eight COSEE are nationally coordinated programs for ocean sciences education in both formal and informal sectors. These regional centers and other similar facilities and programs will help facilitate the integration of research into high-quality educational materials, promote a more ocean-literate society, provide opportunities for teacher preparation for pre-service teachers and professional development programs for in-service teachers, undergraduate faculty, and administrators, as well as other audiences.

The most cost-efficient means of establishing a viable EPO program within the seafloor observatory network program is to avoid redundancy and take advantage of the existing Sea Grant and COSEE programs. Using funds provided by the NSF, designated Sea Grant and COSEE offices could expand their EPO efforts to encompass the broader aspects of ocean science research associated with the national seafloor observatory network. This leverage of expertise would mean involved Sea Grant programs would have to accommodate a more global perspective in order to ensure that all aspects of the global, regional, and coastal observatory networks are utilized in the EPO activities.

It is recommended that the OOI program office contain an EPO coordinator to oversee and coordinate EPO activities going on at various levels within the OOI. One role of the EPO coordinator should be to assist observatory program principal investigators as they establish EPO collaboratives and partnerships with appropriate Sea Grant, COSEE, and related EPO program managers. Principal investigators should be able to select the Sea Grant or COSEE program for their EPO activities based on individual inquiries, programmatic needs, or assessments that are not necessarily based exclusively on office location. Other factors that must be considered are the qualifications of individual prospective Sea Grant, COSEE, or other appropriate EPO managers who will be involved in the observatory program through possible matching funds or resources provided by these agencies, professional organizations, academia, the private sector, or industry.

The EPO coordinator should establish specific goals with the designated EPO officer (whether Sea Grant or COSEE) associated with each observatory program. Goals should include the establishment of specific partnerships between the observatory research program and K-14 schools, museums, aquariums, and other public outreach institutions. There should be a clear expression of the manner in which the EPO programs address advancement of scientific literacy through the integration of identified ocean sciences concepts within the NSES.

One of the most promising potential activities mentioned in *Illuminating the Hidden Planet* (2000) is the establishment of paid land or sea summer internships for K-14 teachers. These internships will allow classroom teachers to gain hands-on, inquiry-based experiences in many aspects of ocean sciences research. These internships and pre- and in-service accredited teacher workshops (two to three days) or institutes (three to four weeks) are perhaps the most effective ways to excite and engage teachers about science; to enhance their content knowledge, esteem and effectiveness in their schools; and to encourage them to develop new innovative teaching strategies using the opportunities provided by the seafloor observatory network.

An excellent example of this enhanced effectiveness is the NSF-sponsored Research and Education: Volcanoes, Exploration and Life (REVEL) Project operated by the Department of Oceanography at the University of Washington. REVEL is described as a program that allows:

> the interaction of highly-motivated science teachers hungry for opportunities to engage in science and innovative scientists pursuing cutting-edge research. The scope of this research encompasses a wide variety of scientific problems that range from the origin of life to new aspects of biotechnology. (REVEL Project, 2003, p. 1)

Approximately 50 science teachers have been involved in the REVEL Project since its inception in 1996. Many of these teachers have participated in research cruises aboard the *R/V Thomas G. Thompson*, and have become highly motivated in science education as a result of their oceanographic experiences. There are also other model EPO programs that can be emulated by the OOI.

The NSF or, once it is established, the OOI Program Office, should solicit proposals for a workshop to address the EPO issues raised in this report and to develop a specific EPO implementation plan for ocean research observatories, including recommending a budget for EPO activity. This workshop should consist of 20–30 individuals, including educators with strong links to Sea Grant, COSEE, aquariums, science centers, and science museums. Some of the workshop participants should include research scientists who are leading the establishment of the national observatory network in order to ensure an effective and mutually proactive dialog between the research and education communities is established from the outset. A similar Education Workshop, sponsored by the NSF, was conducted by the Integrated ODP in Narragansett, Rhode Island in May 2003, involving approximately 80 formal and informal teachers, educators, and scientists. A report from this workshop should be available by summer 2003.

PHASING OF OBSERVATORY CONSTRUCTION AND INSTALLATION

The OOI is expected to provide approximately $200 million dollars over a five-year period, beginning in FY 2006, for the acquisition and installation of ocean observatory infrastructure (Figure 1-5) (National

Science Foundation, 2002). This section discusses scientific planning, engineering development, and system testing needs over the next two to three years; describes the factors that might affect the phasing of implementation of each of the three main OOI components; and recommends an implementation strategy for the five-year OOI-MREFC program.

It was beyond the scope of this study to develop a detailed cost analysis for the construction and installation of each OOI component (coastal, regional, and global). Planning for each of these elements has developed largely independently of the others, and important decisions on the exact proposals have yet to be made. Although precise cost estimates are thus impossible to make at the present time, the development of a detailed and comprehensive project implementation plan and cost analysis for each of the three major components of the OOI, and the review of these plans by knowledgeable and independent experts is needed as soon as possible. These plans should be completed by the end of 2004 and reviewed in early 2005. If the total cost of the infrastructure envisioned for the OOI exceeds the resources available through the MREFC, the scope of each proposed component, as well as each component's relative priority will need reassessing.

Pre-Installation Planning and Development Needs

A program as large and complex as the OOI requires an extensive planning and development effort prior to installation of the MREFC-funded infrastructure. These activities have been under way for some time (Chapter 3) but much remains to be accomplished; planning and development work will need to be accelerated between now and the beginning of construction and installation. Significant levels of additional funding (several million dollars over the next two to three years) will be required to support these activities.

An essential first step for pre-installation planning is the establishment of the OOI Program Office, described in the first section of this chapter, to oversee and coordinate these planning activities. It is recommended that this office be established by the end of 2003. The Program Office's first task should be the development of a detailed and comprehensive project implementation plan, as outlined above.

The Program Office also needs to oversee scientific and technical planning to better define locations, scientific objectives, and core instrument and infrastructure requirements of specific observatory nodes and observatory systems. Scientific planning will allow individuals, groups, and programs to compete through a peer-reviewed mechanism for research time, bandwidth, and power usage on observatory infrastructure. This process should begin immediately and should involve the broadest possible cross section of the ocean sciences community. The process may include planning workshops, solicitation, and review of proposals from individuals and community groups, and the establishment of science and technical advisory committees to the Program Office.

A third major task of the OOI Program Office should be the development of both a comprehensive data management plan for the OOI and a strategy for an innovative and effective EPO program.

In addition to scientific and program planning, development and testing of the more advanced observatory infrastructure components envisioned for the OOI is required prior to the beginning of the MREFC (these needs have been outlined in some detail in Chapter 3). Funding has been secured for prototyping and testing of some critical sub-systems, and for the establishment of testbeds for cabled and moored buoy observatories (e.g., the Acoustically-linked Ocean Observing System [ALOOS], MARS, MOOS). However, additional funding will be required to complete this development and testing work prior to the construction and installation phase of the MREFC. Of particular importance is testing of the power and communications sub-systems for the multi-node, looped-network topology envisioned for the NEPTUNE-type, regional-scale cabled observatory, as well as the design, prototyping, and testing of critical sub-systems for the high-bandwidth, cable-linked moored buoys (i.e., EOM cable, C-Band antenna, and diesel power generation). The technical feasibility and cost-effectiveness of utilizing retired telecommunications cables for some global network observatory sites should also be thoroughly evaluated during this period.

Ocean Observatories Initiative Implementation Strategy

The proposed OOI MRFEC funding profile shown in Figure 1-5 will increase from $27 million dollars in FY 2006 to approximately $80 million dollars in FY 2008 and will decrease to approximately $43 or $44 million dollars in FY 2009 and FY 2010. While it is not clear how much flexibility there may be in changing these proposed year-to-year expenditures, the DEOS Steering Committee or, once it is established, the OOI Program Office should review this funding profile and determine if it is optimal for the OOI's specific requirements.

In considering possible phasing of construction and installation of the ocean observatory infrastructure over this five-year period, a number of different criteria have been considered including scientific and technical readiness, risk, cost considerations, timely payoff, and leveraging opportunities. Table 4-3 summarizes these criteria for each of the three OOI components. The following sections discuss, these criteria and offer recommended phasing strategies. As there is insufficient information available to develop a five-year construction and installation budget, tasks have been assigned to one of three different phases (early, middle, late) for the five-year OOI MREFC program.

Global Observatory Network

Scientific planning for the global observatory network is mature and has proceeded to the level of identifying specific sites and multidisciplinary instrumentation requirements for each node (Chapter 3; Figure 3-1). Site selection is being coordinated at the international level and there are significant opportunities to leverage the investment the NSF makes with additional nodes funded by other nations (Appendix E). The low-bandwidth, oceanographic mooring design proposed for many low- and mid-latitude sites is already in use for oceanographic and meteorological applications and additional buoys can be built and deployed as soon as funds are available. Priority has been given to sites that fill gaps in the present time-series observatory system and that meet interdisciplinary research needs (DEOS Moored Buoy Observatory Working Group, 2003). The opportunity for early scientific payoff for these sites is high, especially for climate and oceanographic research applications.

The high-latitude and high-bandwidth buoy systems proposed as part of the global program will, however, require additional prototyping and testing before large-scale construction and deployment of these systems can begin (Chapter 3). The proposed high-latitude sites are characterized by severe weather, including high surface winds and seas, which will require new engineering approaches for buoy and mooring design to ensure survivability. The high-bandwidth buoy systems that have been proposed are also new, and will require validation and testing of critical sub-systems (e.g., EOM cable design and terminations, C-Band antenna performance, and reliability of unattended diesel generators), preferably by initial deployment of a prototype system at a low or mid-latitude location.

These considerations suggest phasing for installation of global observatories (Box 4-2), assuming that the OOI is divided into three phases of approximately one and a half to two years each.

Regional-Scale Observatories

Through the efforts of the U.S. and Canadian NEPTUNE groups, scientific and technical planning for a plate-scale cabled observatory in the

TABLE 4-3 Phasing Criteria for Seafloor Observatory Implementation

	Global Network
Scientific Readiness	Scientific objectives well-defined; scientific planning very mature with ~20 potential multidisciplinary observatory sites identified. Good coordination at the international level.
Technological Readiness	Low-to-mid latitude, low-bandwidth acoustically-linked moorings feasible now; cable-linked and high-latitude moorings need prototyping and testing of critical sub-systems (EOM cable, C-Band antenna, power generation) before large scale deployment; re-use of telecom cables needs feasibility study.
Risk	Low for low-to-mid latitude, low bandwidth systems; moderate for low-to-mid latitude high-bandwidth systems; high for high-latitude systems; should consider cable re-use to minimize risk at some high latitude sites.
Financial Considerations	Unit cost is about $1 million dollars to several million dollars/node; total costs scalable by number of moorings acquired.
Timely Payoff	Depends on science, but opportunities for early payoff are high, particularly in remote regions.
Leveraging Opportunities	High, with international collaboration with other nations (Japan, United Kingdom, Europe).

Northeast Pacific is well advanced (NEPTUNE Phase I Partners, 2000). As described in Chapter 3, however, a large, plate-scale cabled observatory like NEPTUNE presents some major engineering challenges. The progress in developing and testing new technology to meet these engineering requirements and the long lead times required for many of the tasks in-

Regional-Scale	Coastal
Scientific objectives well-defined; scientific planning for NEPTUNE-like system mature, but need better definition of location, scientific objectives and infrastructure requirements of individual nodes.	Scientific planning still in early stages; relative importance in OOI of mobile Pioneer Arrays, cabled observatories, and long time-series sites requires more community input. Relationship to IOOS coastal sites needs definition.
Major progress made in the design of power and telemetry systems but final design decisions have not been made. Two testbeds are under development for validation of major sub-systems. Need full system integration test using a multi-node, loop network topology.	Pioneer Arrays and Codar use standard "off-the-shelf" technology; use of simple cabled systems in coastal environment demonstrated; more complex cabled observatories with mesh topology or multiple nodes need development; issues with damage from fishing, corrosion, vandalism need to be addressed.
Moderate-to-high because power and communication systems are new and because of the complexity of multiple-node, multiple-loop network topology; risk can be minimized by validating designs using testbeds and a phased installation.	Risk for coastal radar systems very low; risk for mooring arrays low-to-moderate; risk for cables low.
Desirable to acquire cable and sign installation contracts early to take advantage of present depressed market conditions; phased installation will increase total costs.	Requires further definition of components of coastal OOI. Does not appear that phasing will have a major impact on costs.
Given significant lead time required for route surveys and permitting, not likely to be operational until late in five-year period.	Early payoff possible with operation of first Pioneer Array or augmentation of existing coastal observatories.
High, with collaboration with Canada and possibly other nations.	High, through leveraging of funding from state and other federal agencies, IOOS.

volved in installing a NEPTUNE-like cabled observatory will place strong constraints on the funding timeline of the OOI MREFC.

Power and communications systems for a system like NEPTUNE will be significantly different than systems used with conventional submarine telecommunications cables. The multi-node, multiple-loop network

BOX 4-2

Phasing of Installation for Global Observatories

Phase 1

- Construction and deployment of three to five low- to-mid latitude, relocatable, low-bandwidth buoy/moorings acoustically-linked to the seafloor;
- Construction and test deployment of a prototype low-bandwidth buoy/mooring system linked by EOM cable to a seafloor junction box;
- Construction and test deployment of a prototype high-bandwidth buoy mooring system at a low-latitude, accessible site; and
- Construction and deployment of a cable re-use observatory, if initial studies are favorable and if the cable is in suitable location.

Phase 2

- Construction and deployment of three to five low-mid latitude, relocatable low bandwidth buoy/moorings (acoustically-linked or EOM-cable-linked to seafloor);
- Construction and test deployment of a prototype high-latitude buoy/mooring system; and
- Construction and deployment of additional cable re-use observatories, if the initial deployment is successful.

Phase 3

- Establishment of approximately five high-bandwidth nodes at low to mid latitudes (either moorings or cable-reuse depending on feasibility); and
- Establishment of approximately 5 high-latitude nodes (moorings or cable-reuse depending on feasibility).

topology of NEPTUNE is also unprecedented for a submarine cable system. These engineering and technical issues are being addressed on a number of fronts. Engineering design studies have been completed or are under way for both the power and telemetry sub-systems and two testbeds (VENUS and MARS) are under development for validation of these system designs. As presently funded, however, MARS will provide only a partial test of the key power and data telemetry sub-systems since its relatively short, single-cable, single-node design will not test the operation of these sub-systems with the more complex multi-node, looped network topology of a NEPTUNE-like observatory. A full system integration test of all major sub-systems (power, telemetry, timing, and command and control) with a multi-node, looped network topology is recommended before the full deployment of such a network. This test could be accomplished by augmenting the MARS testbed with an on-land, full-configuration test or with a phased deployment of the full network by initially installing only one of the three planned loops. While a phased two-stage installation of a looped network will cost more than a single installation, the reduction in risk brought about by this approach may be worth any additional cost.

Important logistical considerations will also affect the timing of installation of a NEPTUNE-like system. Obtaining the necessary permits, especially near cable landfalls, can take up to two years. Cable routes need to be surveyed prior to installation in order to assess bottom characteristics and topography for hazards. Time is required to fabricate and test the cable. In addition, nodes must be designed, ordered, manufactured, and tested, both individually and in their final configuration. Given the present depressed state of the telecommunications industry, significant cost savings may be achieved by purchasing cable and contracting for installation sooner rather than later; the NEPTUNE system may not use standard submarine optical amplifiers or cable power systems, however, so non-standard cables will likely be needed. The operation of the major sub-systems (power, telemetry, and timing), and the operation of the system as a whole, need to be simulated and validated through extensive computer modeling and physical testing throughout the construction and installation phase.

These considerations suggest the phasing for installation of a NEPTUNE-like, regional-scale cabled observatory over the five-year MREFC (Box 4-3).

Coastal Observatories

As described in Chapter 3, scientific planning for coastal observatories in the context of the OOI began in 2002, but there is still no community consensus on the appropriate balance between spatial mapping and high-resolution time-series. Additionally, it is essential to establish a number of long-term time-series sites in U.S. coastal waters, including the Great Lakes, using cables and buoys. There is, however, no agreement on whether this need can be met by the moorings that Ocean.US is planning to deploy as part of the coastal IOOS, or whether the OOI will require moorings specifically dedicated to coastal ocean research. The coastal community will need to develop a consensus on the appropriate balance of Pioneer Arrays, cabled observatories, and long-term measurement sites required to meet future coastal research needs. This consensus can be achieved by bringing together the diverse coastal community, including representatives from Ocean.US. Discussions should focus on implementation with pragmatic consideration given to the appropriate mix of relocatable and permanent observing systems. This planning effort should

BOX 4-3

Phasing and Installation of Regional-Scale Observatories

Phase 1

- Complete sub-system (power, telemetry, timing) and system design, complete simulation and testing of sub-systems and systems with extensive computer modeling;
- Validate system and sub-system designs with prototypes and testbeds;
- Test multi-node, loop network designs;
- Initiate permitting process, conduct cable route surveys;
- Purchase cable (if funding permits) and evaluate the cost of storage;
- Design, construct, and test nodes, and proof experiments; and
- Compete final network configuration design.

Phase 2

- Complete cable purchase fabrication, and cable testing;
- Complete concept testing of nodes in testbeds;
- Purchase and manufacture nodes test components;
- Complete permitting process;
- Validate multi-node, loop network design by on-land full-configuration testing;
- Modify system and sub-system designs as necessary;
- Construct first shore station;
- Install first backbone loop connected to single shore station; and
- Install nodes and core sensors on first backbone loop.

Phase 3

- Conduct system integration tests, validate system and sub-system modeling;
- On successful operation of first sub-system, install 2nd and 3rd backbone loops, 2nd shore station, and nodes and core sensors;
- Install community instruments and initial science experiments at nodes; and
- Commission a full system, begin operation of network.

identify the number and location of long-term time-series sites and the instrument requirements at these sites.

While additional scientific planning is needed, the available technologies for coastal observatories are relatively mature and installation of these systems is feasible within the five-year MREFC time frame. However, some important technical challenges exist. Biofouling and corrosion remain significant problems for long-term observations in the coastal ocean and a major effort to mitigate their affects is required. Coastal moorings have not been outfitted with bistatic radar arrays and they rarely integrate the new generation bio-optical sensors required for biogeochemically relevant measurements. For the coastal radar arrays, the development of multi-static arrays will require further development of synchronous timing technology that allows different radars to use the same radio frequency. Coastal cables are largely limited by a lack of robust multi-sensor auto-profiling of the water column.

Until a community consensus is reached on the infrastructure required for coastal research observatories, any implementation plan will, of necessity, be rather notional. The following plan (Box 4-4) assumes construction of two Pioneer Arrays, the establishment of a coastal instrument testbed, a new coastal cabled observatory, and the augmentation of the IOOS national network of long-term coastal time-series moorings with additional instrumentation to make them suitable for interdisciplinary coastal research.

BOX 4-4

Phasing of Installation for Coastal Observatories

Phase 1

- Complete design of Pioneer Array;
- Construct and field test a prototype Pioneer Array;
- Establish a coastal cable observatory testbed for development of new instrumentation and an auto-profiling capability, which could be accomplished cost-effectively by upgrading an existing coastal cable facility (although cost-effectiveness should not be the sole criteria for choosing the site);
- Develop and test instruments to augment measurement capabilities at IOOS coastal mooring;
- Develop GPS timing in order to provide high resolution multi-static radar arrays; and
- Choose a new site for a coastal cable observatory that would expand the range of environments that are currently sampled at existing coastal cable facilities.

Phase 2

- Evaluate performance of prototype Pioneer Array, refine design, address any problems;
- Begin acquisition of 2nd Pioneer Array;
- Install new coastal cabled observatory; and
- Augment IOOS coastal moorings with core and community instruments to make these sites suitable for long time-series coastal research.

Phase 3

- Deploy 2nd Pioneer Array;
- Install core and community instruments at new coastal cabled observatory site; and
- Augment IOOS coastal moorings with core and community instruments to make these sites suitable for long time-series coastal research.

BOX 4-5

Phasing of a Data Management System

Phase 1 is primarily a design phase, providing the first step in guaranteeing the compatibility of different data products, distribution, and archiving systems.

Phase 1

- Define metadata and data formats;
- Design telemetry packet design to guarantee instrument control and data flow from an instrument to data collection centers;
- Agree on near-real-time data quality control (QC) procedures;
- Establish a data management architecture to define data flow for collection, real-time validation, real-time distribution, delayed-mode QC, and product generation. (For open ocean observatories, this task must be done in collaboration with international entities involved in global observatory development);
- Leverage the efforts of other agencies and groups that are building large community data management systems (e.g., IOOS, GOOS);
- Define data security requirements; and
- Test data management system for open-ocean observatories deployed in Phase 1.

During Phase 2, data processing capabilities should be implemented for the core instruments at global and coastal observatories and prototyping of a data management system for regional cabled observatories can begin.

Phase 2

- Put in place QC and standardization of data handling procedures at data collection centers;
- Have data collection centers establish a system for distribution of observatory data to users through new or established data centers (e.g., NODC, IRIS, DMC);
- Put in place initial data management system for coastal observatories;
- Prototype data handling system for regional cabled observatories begins; and
- Develop mechanisms and policies for exchange of observatory data at the international GOOS and national IOOS levels.

During Phase 3, data processing capabilities should be implemented for core, community, and individual investigator instruments for all observatories that are part of the OOI.

Phase 3

- Expand data management system for global and coastal components to include high bandwidth buoys or cabled observatories;
- Put in place operational data management system for regional cabled observatories;
- Archive ocean observatory data at new or established data centers and integrate data distribution and archiving functions with IOOS and GOOS; and
- Use data products for EPO activities.

Data Management System Implementation

Establishment of the OOI-DMS will need to be phased and coordinated with observatory installations (Box 4-5). Even though the operators of each observatory system will manage data functions individually, coordination at the program level will be necessary to guarantee compatibility across observatory types. A Data Management advisory committee should be established by the OOI Program Office to oversee the implementation strategy outlined in Box 4-5.

5

Related Facility Needs for an Ocean Observatories Network

Both the installation and maintenance of ocean observatories and the conduct of complementary scientific studies will place significant demands on the UNOLS fleet as well as on deep submergence assets in the U.S. oceanographic community. In many cases these needs can be met using vessels and deep submergence vehicles currently available within the academic community; in other cases additional assets will need to be added to the academic pool or leased from industry. This chapter offers a preliminary assessment of these needs, although a more thorough study is currently being undertaken by a UNOLS Working Group on Ocean Observatory Facility Needs.

SHIPS

Ship requirements for the OOI can be broadly divided into two phases: (1) installation and (2) maintenance and operations. These requirements differ significantly for moored buoy and cabled observatories, as summarized in Table 5-1.

Moored Buoy Observatories

Installation Ship Requirements

Many of the sites functioning as part of the global network will utilize buoys and moorings that are similar to present surface and sub-surface moorings; the hardware on the seafloor for such sites will be similar to presently deployed oceanographic instrumentation. These buoys can be installed by a large, global-class UNOLS vessel, which provides the carrying capacity, cranes, sea-keeping, and endurance characteristics needed to work at most global locations. Buoys that are acoustically linked to seafloor instruments will not require an ROV for installation. Those buoys are linked by an EOM cable to a seafloor junction box, however, they will require a deep-ocean ROV for installation of the junction box and seafloor instruments. One month of ship time use should be anticipated per site, allowing time for transit, extra days for weather, and extra days for uncertainties (such as those associated with which ports are assigned), and roughly a week for working at the site (i.e., time for recovery, deployment, in-situ comparison of shipboard and observatory sensors, and shipboard science at the observatory site) (Table 5-1).

Both high-latitude sites and sites where high-bandwidth is desired will require larger buoys capable of stability in high seas and of supporting on-board power generation. A candidate 40 meter (approximately) surface spar buoy was described in the DEOS Moored Buoy Observatory Design Study (2000), but its size and amount of mooring line exceed the capabilities of even the largest UNOLS vessels primarily due to their lack of deck space and reel and winch capabilities (DEOS Moored Buoy Observatory Working Group, 2000). Commercial offshore Class 2 construction vessels, anchor handling tug boats, and Navy fleet tugs are all ideally suited for launching the spar and mooring and could be chartered for this purpose (Figure 5-1). The subsequent installation of the topside module and instrumentation, seafloor junction box, and seafloor instruments could then be performed by a large UNOLS vessel (or its commercial equivalent) after the spar and mooring have been installed, although some special handling equipment would be required on the vessel and operations would be weather sensitive. While a commercial tug could be used to tow the buoy, a large, capable vessel would have the ability to carry the spar buoy on deck and could carry more than one spar buoy at a time. Such a vessel would offer the advantages of faster transit and protection from buoy wear and tear from towing. The ship will require dynamic positioning capability and a deep-ocean ROV in order to install the seafloor junction box and instrumentation.

Coastal moorings like those envisioned for the Pioneer Array or for long-term time-series sites are fairly simple to install using small or intermediate-class UNOLS vessels or their commercial equivalent. Allowing for installation of buoys and moorings, *in situ* comparison of shipboard and observatory sensors, and weather contingency time, about two days of ship time per mooring is estimated.

TABLE 5-1 Estimated Ship Time Needs Associated with OOI Global, Regional and Coastal Observatories

Observatory Type	Specifics	Number of Nodes
Global Moorings	Installation low-bandwidth	1 node/ 10 sites
Global Moorings	Installation high-bandwidth	1 node/ 5 sites
Global Cable Re-use	Installation minor move	1 node/ 5 sites
Global Moorings or Cabled	Maintenance high-bandwidth and severe environment	10
Global Moorings	Maintenance Mid-latitude/Tropical	10
Regional Cabled	Installation of backbone cable loops	—
Regional Cabled	Installation of nodes/core sensors	30
Regional Cabled	Maintenance of backbone cable	—
Regional	Maintenance of nodes and sensors	30
Coastal Moorings	Installation	75
Coastal Cable	Installation	1-2
Coastal Moorings	Annual maintenance	75
Coastal Cable	Annual maintenance	<5

NOTES: Assumptions: Global observatories—20 global nodes, including 10 low-bandwidth acoustically-linked or cabled-linked moorings, 5 high-bandwidth, cable-linked moorings, and 5 cable-reuse nodes with sub-surface moorings; annual maintenance assumed at all nodes. Regional observatories—3700 km of cable and 30 nodes; 1 week/node to install node and core sensors; annual maintenance of nodes and core sensors. Coastal observatories—two 30-node Pioneer Arrays and 15 cabled or moored long time-series sites. Note: table does not include science ship time requirements beyond those required for annual observatory operation and instrument maintenance.
SOURCES: Based on data from DEOS Moored Buoy Observatory Working Group, 2000; and NEPTUNE Phase 1 Partners, 2000.

Ship type	Ship-months	Comments
UNOLS global class	10 (one time)	ROV not needed if acoustically-linked
Industry charter (1 leg) UNOLS (1 leg)	10 (one time)	ROV needed for installation of junction box/seafloor sensors
UNOLS global class	5 (one time)	ROV needed for installation of junction box/seafloor sensors
UNOLS global class	10/yr	ROV required for servicing or installation of seafloor sensors
UNOLS global or ocean class	10/yr	ROV not required for acoustically-linked moorings
2 ship industry cable laying	5 (one time)	Assumes 3700 km of cable (12% buried)
UNOLS global class	8 (one time)	ROV needed; probably carried out over 2 field seasons
Industry cable laying	0.5/yr	Stand-by maintenance contract with industry
UNOLS global or ocean class	4-8/yr	ROV needed; work may be limited to May-Sept in Northeast Pacific
UNOLS regional class	5 (one time)	2 Pioneer Arrays; ROV not required
Cable laying	2 (one time)	Assumes one cabled observatory
UNOLS regional or local	5/yr	2 Pioneer Arrays; ROV not required
UNOLS regional or local	1/yr	Divers or ROV (in deeper water) required

FIGURE 5-1 Photo of the *Midnight Arrow*, an offshore energy industry Class 2 sub-sea construction vessel. Vessels like this with a heavy lift capacity, large load capacity, and ample deck space would be ideally suited for deploying large spar buoys and moorings and seafloor node installation, maintenance, and replacement. Figure courtesy of Torch Offshore, Inc.

Operation and Maintenance Ship Requirements

The open-ocean moorings that are part of the global observatory network will require significant large-ship and deep-ocean ROV time for maintenance. Annual maintenance will be required for surface moorings due to biofouling, sea air corrosion, battery replacement, diesel refueling, and buoy turn-around. Routine maintenance of both the low-bandwidth and high-bandwidth moorings can be accomplished using a large, global-class UNOLS vessel, so long as the necessary maintenance does not include recovery of a large spar buoy. Mechanical components, electronics, and even diesel generators for the high-bandwidth systems can be designed for servicing or replacement at sea using standard UNOLS winches and cranes. If a large spar buoy must be replaced, a commercial workboat or heavy-lift vessel will be required. EOM cable-linked moorings with seafloor junction boxes will require dynamic positioning and a deep-ocean ROV to service or install instrumentation. Fatigue considerations, especially for the high-latitude or other severe environment sites, will require periodic refurbishing or replacement of the moorings, while routine replacement/refurbishment of buoys will likely be necessary about every three to five years. Approximately one month of ship time per node (including transits to and from the site) should be anticipated for maintenance of the remote global network sites. Coastal moorings will also require regular servicing, probably at least quarterly, by a small- or intermediate-class UNOLS vessel or the commercial equivalent. Two days of ship time annually per mooring (a conservative estimate) will be required for coastal mooring maintenance.

One special requirement of moored buoy maintenance is the lack of flexibility in ship scheduling. Due to limited battery life and fuel availability and the need to replace biofouled and weathered sensors, ship visits to a select site will need to occur regularly (approximately once every 12 months) with little leeway (within a two week period). This requirement, together with the remote locations of many of the global observatory sites and small operational weather windows at high latitudes, introduces a powerful constraint on the UNOLS ship scheduling process, especially if between 15 and 20 sites distributed across all of the major ocean basins must be visited annually. Ship scheduling will also be complicated by observatory failures that require emergency repair and by repair of failures in remote locations during severe weather months, both of which will likely involve significant delays. On the positive side, periodic visits to remote sites in the ocean will provide an opportunity for other science efforts to study regions that would otherwise seldom be visited. It should be noted that coastal moorings do not suffer from this problem due to their much greater accessibility.

Cabled Observatories

Installation Ship Requirements

Installation of cabled observatory systems will employ both industry and UNOLS vessels and will require detailed pre-installation cable route surveys using high-resolution seafloor mapping systems and bottom sampling. In addition, the amount of survey time needed depends on the length of the cable route and the need for near-bottom and surface mapping. These requirements can be met using existing UNOLS assets, although they could also be contracted through industry. A commercial cable-laying ship (Figure 5-2) will be required to install the backbone fiber optic cable and bury it where necessary (under 2000 m water depth). Plans for the proposed NEPTUNE system, estimate that 159 days (approximately 5 months) of ship time are needed to lay approximately 3700 km of cable, including post-lay inspection and burial (B. Howe, Univer-

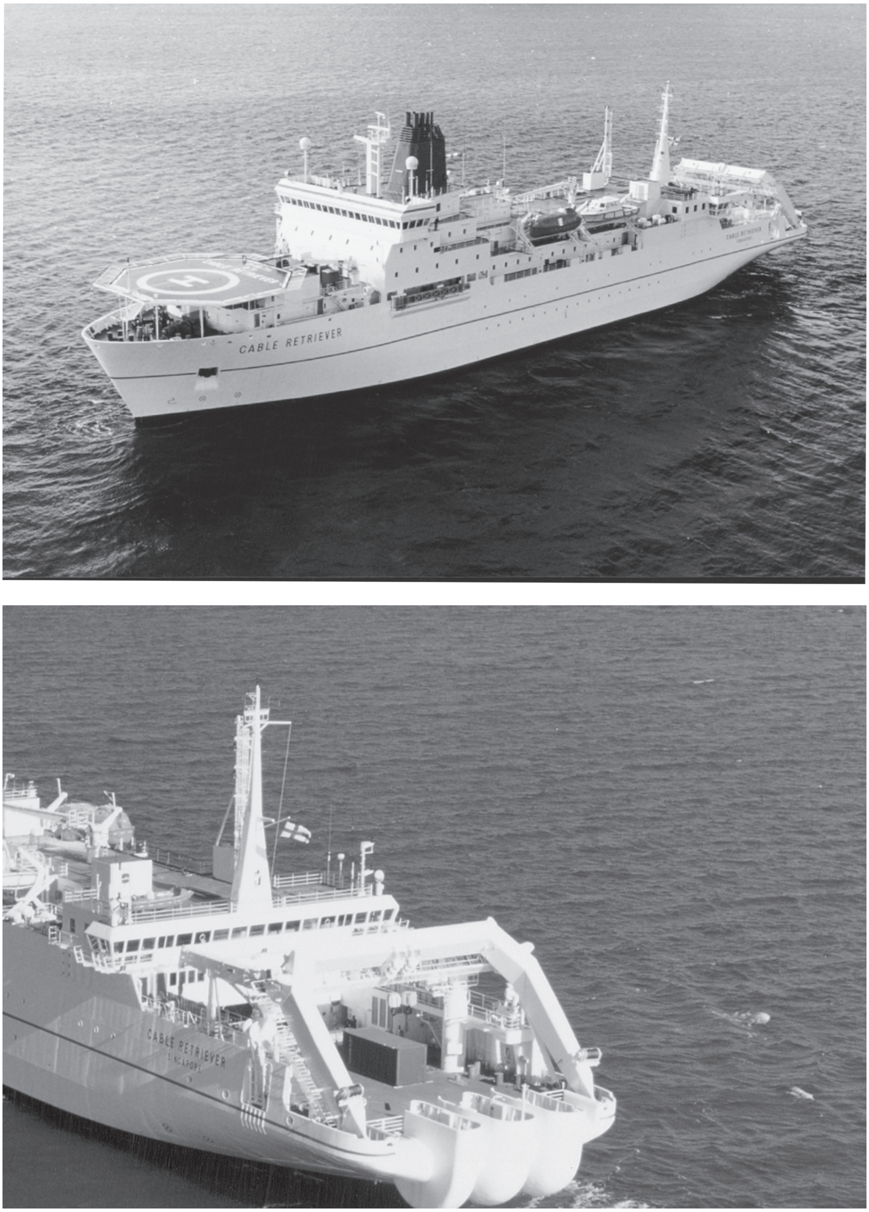

FIGURE 5-2 Photo of the *Cable Retriever*, a state-of-the-art, purpose-designed, all-stern working cable ship, equipped with an ROV (full view top; rear view bottom). This 117 m long vessel has a storage capacity of some 2,475 tons of cable. Specialized vessels such as this will be required for observatory cable installation and repair. Figure courtesy of Global Marine Systems Limited.

sity of Washington, personal communication, 2003). Installation of cabled systems with loops and branches may require the use of two cable ships. If installation is phased, this work could be divided over two field seasons. Subsequent node, core instrument, and community instrument installation can be achieved using a large UNOLS vessel equipped with dynamic positioning and an ROV. Assuming one week of ship time per node (about two days for node installation and five days for sensor installation), approximately eight months of ship time would be required to install a 30-node network like NEPTUNE, including transits. Given weather constraints in the Northeast Pacific, this work would probably be done over two successive field seasons.

Requirements for installation of cables for coastal observatories are similar to those described above, although all cables will need to be buried. Node and instrument installation can be accomplished by smaller UNOLS vessels, and in shallow water, by divers.

At global sites that prove feasible for re-use of retired telecommunication cables, a large UNOLS vessel or commercial cable vessel can be used to retrieve the cable, cut it, and install a termination frame and junction box. An ROV will be required for installation and the vessel must possess dynamic positioning capability. At most sites it should be possible to complete the basic installation with one month of ship time per node, though additional ship time will be required for installation of sensors or ancillary observing systems (e.g., a surface or sub-surface mooring).

Operation and Maintenance Ship Requirements

Standard submarine telecommunications cables are engineered for extremely high reliability; the main risk to these systems is damage or cutting from fishing activity. While failures of the backbone cable are expected to be uncommon, a stand-by maintenance contract with a cable company will be needed to repair cable breaks since these repairs cannot be done with a UNOLS vessel.

It is expected that regular service will be required for both network nodes and sensors. The *NEPTUNE Feasibility Study* (2000) budgeted four months per year for regular annual maintenance of its proposed 30-node system (one month per year for node maintenance; three months per year for instrument servicing). At H2O, however, only two experiments have been deployed but more than one month of ROV time on site has been used in five years; such a rate suggests that at least one week of ROV on-site time may be required annually per observatory node for node and instrument service about eight months per year for a 30-node system. This work can be completed using a standard large UNOLS vessel (or commercial equivalent) equipped with dynamic positioning and a deep-ocean ROV. Weather conditions and the sea state limitations of current-generation ROVs will likely limit these operations to the summer months in the Northeast Pacific, and could require two ROV-equipped vessels each season. Maintenance of shallow-water, coastal, cabled observatories can be accomplished from local or regional class UNOLS vessels using divers; though an ROV will be required in deeper water.

The University National Laboratory System Capabilities and Research Observatory Requirements

While Table 5-1 is, at best, a rough estimate of the ship time requirements associated with the installation and maintenance of the observatories that will be acquired as part of the OOI, it illustrates the very significant demands ocean observatories will place on the UNOLS fleet. The installation of 15-20 global observatory sites, a regional NEPTUNE-like cabled observatory, and coastal observatories consisting of both moorings and cabled sites is likely to require over four ship-years (assuming 300 operational days per year) including 1 ship-year on industry contract vessels (for both cable laying and spar buoy installation). Maintenance of this infrastructure will require at least an additional three ship-years annually. These estimates do not include ship time requirements for observatory-related science beyond those required for installation and maintenance of the basic infrastructure, and core and community experiments. That figure, though hard to estimate, could conceivably be another one or two ship-years or more per year.

It will be difficult for the UNOLS fleet to support the demands of research observatories while still adequately meeting the need for more traditional ship-based expeditionary research by the academic community. Open-ocean observatory operations require ships with (1) ample deck space and winches capable of handling large loads for mooring and seafloor node installation or replacement, (2) the endurance to operate in remote areas of the world's oceans and at high-latitudes, and (3) the capacity to accommodate relatively large numbers of scientists and engineers. Except when servicing low-bandwidth, acoustically-linked moorings, such observatory operations will also require dynamic positioning capability and the ability to operate a deep-ocean ROV. The only UNOLS vessels with these capabilities are the large (70-90 m long) global-class vessels (*Thompson*, *Revelle*, *Melville*, *Atlantis*, and *Knorr*). *Atlantis*, however, is more or less dedicated to manned submersible operations and all of the other vessels in this class are currently heavily subscribed for expeditionary research. It is thus unclear how the UNOLS fleet can meet the ship demands outlined in Table 5-1 for ocean observatory installation and operation without having a major negative impact on the availability of these ships for other research. For example, 3 ship-years of global-class vessel time would require that the *Thompson*, *Revelle*, and either *Knorr* or *Melville* be completely dedicated to observatory operations each year. This problem will be exacerbated if NOAA increases its utilization of UNOLS global-class ships as the IOOS is established or if the proposed Ocean Exploration Program moves forward. Since the demand for these ships for expeditionary research is expected to remain high, the increased need for large vessels by ocean observatories will have to be met, at least in part, either by adding new vessels to the UNOLS fleet or leasing comparable vessels on the commercial market. Coastal observatories face less pressure on available vessels, as the present small- and intermediate-class UNOLS vessels can support coastal observatories. In addition, the ship time requirements are not as large as for open-ocean observatories (Table 5-1), and this vessel class is presently somewhat underutilized, so it should be able to accommodate increases in ship time demand.

The NOPP's Federal Oceanographic Facilities Committee (FOFC) has developed a plan for renewal of the U.S. national academic research fleet over the next two decades (Federal Oceanographic Facilities Committee, 2001). This plan calls for no new global-class vessels in the UNOLS fleet until 2018, but the addition of six new "ocean-class" vessels between 2002 and 2016. Although smaller than global-class vessels, this new vessel class is expected to encompass some of the capabilities of both the intermediate- and global-class vessels in the UNOLS fleet today (Federal Oceanographic Facilities Committee, 2001). In addition, ocean-class vessels will be designed to support ROVs and some will be capable of operating at high-latitudes and at ice-margins. The first of these new ocean-class vessels, the *Kilo Moana*, began service in 2002. The *Kilo Moana* is a Small Water-plane Area Twin Hull (SWATH) vessel that allows for better heavy-weather performance than similarly-sized conventional monohull ships. However, the SWATH design may not achieve ocean observatory requirements for heavy lifting and mooring deployment.

The present UNOLS Fleet Renewal Plan does not adequately address the ship requirements of the ocean research observatories that will be acquired through the OOI. Ocean observatory science will not reduce the need for ships (overall ship usage will actually increase) but the kinds of ships needed will change. Open-ocean observatories will require ships with larger decks, heavy-lifting winches, and dynamic positioning and ROV capabilities, that will need to operate in remote ocean areas and at higher sea states than present ships. It is not clear how well the new ocean-class vessels in the UNOLS Fleet Renewal Plan will meet these requirements for open-ocean observatories. Furthermore, no funding has been identified for these new vessels; given the long lead time for acquiring new vessels, the first of these vessels will probably enter the fleet late this decade, at the earliest. Within UNOLS, this leaves open-ocean observatory operations dependent on the existing five, already heavily subscribed global-class UNOLS vessels, two of which are slated to be retired (without replacement) in the middle of the next decade. Such a scenario will not be adequate to both meet the ocean observatory ship time requirements outlined in Table 5-1, and still support other research needs in the oceanographic community. This problem will become critical as the installation of these observatory systems begins in 2007 or 2008. The long lead-time in acquiring new vessels means that this problem requires the immediate attention of FOFC, UNOLS, and the NSF.

One option that should be investigated is the acquisition of a large, heavy-lift (20,000 lbs) vessel by UNOLS for use in mooring and seafloor node installation, maintenance, and replacement. These vessels are readily available new or used, for lease or purchase, from both the offshore energy industry and the submarine telecommunications industry (Figure 5-1). The availability and cost of a commercial vessel will be a function of the overall economy and the state of those particular industries. These market-driven variations can be quite large, making short-term leases somewhat unattractive. A longer-term lease (5 or 10 years), however, can protect against these market swings, a situation that has worked very well for the ODP. Alternatively, a vessel could be purchased and operated by a UNOLS member institution, an approach that has been used by UNOLS for acquiring a multi-channel seismic vessel for use by the academic community. The advantage of either a long-term lease or outright purchase is that scheduling would be under the control of the academic community, not industry. Such a vessel could also be specially outfitted for use as a research platform and could, in combination with the existing UNOLS global-class vessels, begin to meet the large ship needs of both observatory and expeditionary science until the beginning of the next decade. Over the longer-term, however, UNOLS will require additional observatory-capable vessels, obtained through either lease or purchase, to meet the requirements of ocean observatory science.

DEEP SUBMERGENCE ASSETS

ROVs will likely be the work-horses of deep-ocean observatories, as such resources will be needed for installation of seafloor observatories, connecting moorings to seafloor junction boxes, installing experiments, and servicing or repairing instruments and network equipment on the seafloor. ROVs' durability on the ocean bottom, heavy-lift capability, and high available power make them indispensable assets for observatory operations.

ROV technology has been advancing rapidly, both within industry and within the oceanographic research community, and systems are now available that can meet most ocean observatory requirements. Even more capable ROVs can be expected to be available in the future. There are several hundred ROVs available commercially, and systems have been designed for a variety of missions (search and recovery, inspections, cable laying, surveying, and underwater construction) at which they are extremely capable (see following section). Most ROVs used in the offshore energy business are designed for use in relatively shallow water, but some now operate in depths up to 3,000 m. The U.S. oceanographic research community is now also routinely using a small number of ROVs. The *Jason II*, available through the U.S. National Deep Submergence Facility (NDSF), can work at depths of up to 6,500 m (Figure 5-3). MBARI operates two ROVs: *Ventana*, rated to depths of 1,830 m, and *Tiburon*, which can work in depths of up to 4,000 m. *Ventana*'s operations, however, are generally limited to Monterey Bay and *Tiburon*'s to the U.S. West Coast; neither of these ROVs are part of the U.S. National Deep Submergence Facility. The Canadian Remotely Operated Platform for Ocean Science (ROPOS), which is rated to 5,000 m depth, is also sometimes available to researchers working in the Northeast Pacific.

Two important operational considerations for ROV use in the context of ocean observatories are water depth and sea state. Many sites for both global and regional observatories are in water depths greater than 3,000 m, making many of the hundreds of commercial ROVs unsuitable for use. There are a comparatively small number of deep-ocean ROVs, available either commercially or within the U.S. academic community, capable of operating in water depths of up to 6,000 m, although this situation may change rapidly in the next few years as the energy industry moves into deeper and deeper water. The ROVs used by the academic community, such as *Jason II*, are generally limited to operations in sea states less than 4. This restriction will significantly limit operations in winter months at many locations (e.g., the Northeast Pacific) and over much of the year at some high-latitude sites. Some industry ships and ROVs can operate in sea states as high as 7. Upgrading the dynamic positioning systems and ROVs used on large UNOLS vessels to operate at higher sea states would significantly expand the operational window at many observatory sites.

Table 5-1 provides an estimate of ROV time requirements for installing and operating OOI global, regional and coastal observatories. Ten to fifteen ship-months of ROV time could be required for installation of the global observatories and up to eight ship-months for a large, regional

FIGURE 5-3 ROVs like the *Jason II* (above), will be the work-horses of ocean observatories. ROVs will be needed for installation of seafloor observatories, connecting moorings to seafloor junction boxes, installing experiments, and servicing or repairing instruments and network equipment on the seafloor. *Jason II* was designed for detailed survey and sampling tasks that require a high degree of maneuverability. *Jason II* is operated by the U.S. National Deep Submergence Laboratory at WHOI. Figure courtesy of ©Woods Hole Oceanographic Institution.

cabled observatory. Comparable amounts of ROV time will be required annually (about two ship years) to meet operations and maintenance requirements of these ocean observatories. Most observatory sites will require deep-ocean ROVs (rated to depths over 3,000 m). Due to the short weather window in the Northeast Pacific, a large cabled observatory like NEPTUNE may require two ROVs operating each summer in order to service the system.

A single deep-ocean ROV, *Jason II*, as the only ROV available through the U.S. National Deep Submergence Facility will clearly be inadequate for both observatory and general science support. The availability of more ROV assets is imperative if observatories are to be fully utilized. Table 5-1 suggests that two deep-ocean ROVs largely dedicated to ocean observatory work will be required by 2008 or 2009, when installation of the high-bandwidth global and regional cabled observatories begins. The addition of a second ROV to the U.S. National Deep Submergence Facility, along with seasonal use of ROPOS in the Northeast Pacific, would begin to provide the needed deep-ocean ROV assets. In the longer-term, however, a third ROV will probably be required in UNOLS to fully meet both expeditionary and observatory research requirements. One or more of these ROVs should be work class, and possess numerous hydraulic outputs and controls for tools for routine observatory maintenance and servicing.

Human-occupied vehicles (HOVs) are not likely to play a major role in routine observatory installation and servicing due to their lack of power, short dive duration, lack of heavy-lift capability, avoidance of suspended cables, and limited vessel-to-surface communication capabilities. However, because HOVs are not tethered to the surface (making them highly maneuverable), they may be useful in some instances for conducting scientific investigations around observatory sites and for initially establishing experiments and locating sensors in areas of complex topography (e.g., a hydrothermal vent field).

MAINTENANCE AND CALIBRATION OF INSTRUMENTATION

The OOI will enable cutting edge science at new and remote locations in the world's oceans using many sensors, some specifically developed to take advantage of the OOI. The full potential of these new measurement capabilities can only be met if the infrastructure exists to service and maintain observatory instrumentation and to conduct the routine calibration of sensors and instrument systems needed to document and ensure their accuracy. Such work is essential to establish the quality and comparability of OOI observations.

Instruments deployed at sea for up to 12 months, as envisioned for the OOI, may require extensive maintenance. Calibration requires proper facilities, including calibration standards, baths, and chambers, as well as considerable staff support. In recent years, the number of U.S. groups engaged in deploying moorings and maintaining moored instrumentation has decreased in number and the size of many of the groups that remain has decreased. OOI planning should consider the staff and facilities needs for the repeating cycle of pre-deployment instrument preparation and calibration, deployment, and post-deployment calibration and servicing associated with the core and community instrumentation envisioned for the OOI. For instrumentation that is labor intensive to service and calibrate, costs for each cycle can approach the cost of acquiring the hardware. The certification and maintenance of calibration infrastructure can also be a significant ongoing cost.

OTHER ENABLING TECHNOLOGIES

The first satellite-borne ocean sensing systems quickly revealed that ship-borne oceanographic measurements are aliased to varying degrees of severity by temporal variability in ocean processes. If ocean observatories are not to repeat this history with spatial (rather than temporal) aliasing, it is essential to acknowledge *from the outset* that time-series from fixed locations in the ocean can provide temporally and vertically well-resolved measurements but that these measurements cannot be properly interpreted without accompanying information on horizontal spatial variability. It is thus essential to develop and use sampling strategies that enlarge the footprint of observatory sites in order to provide spatial information at a resolution sufficient to separate advective (spatial) changes from true temporal changes. Since the appropriate horizontal resolution will vary depending on the specific processes being addressed at a particular observatory node, the most cost-effective mechanism for providing this information will also vary. Using secondary moorings attached to a primary cabled node may be sufficient for some sites and processes. Others will require more widely-spaced, fixed sites, communicating with an under-sea node by acoustic telemetry. Still others may require more flexible mapping operations, in which multiple gliders or AUVs are directed in real-time.

Significant advances have been made in underwater acoustic telemetry in recent years, making this a promising technology for extending the reach of individual observatory nodes. Instruments equipped with acoustic modems on subsurface moorings or on the seafloor within several kilometers of an observatory node can be linked acoustically to the node without the expense of laying additional cable. Data can also be transmitted acoustically from an underwater vehicle to a receiver located two to three km distant, potentially allowing real-time control of an AUV during a survey. The newest generation acoustic modems use high-bandwidth, phase-coherent communication and directional transducers and can provide data throughputs of up to 5 kb/s (with error checking) (Freitag et al., 2000). Continued support of underwater acoustic telemetry development should provide increasing range, bandwidth, and reliability for these systems.

There has been much interest in the use of AUVs to extend the footprint of observatories well beyond that possible by cables or acoustic links (Figure 5-4). Possible AUV missions might include:

- repeat high-resolution seafloor or geophysical mapping to identify changes related to geological activity;

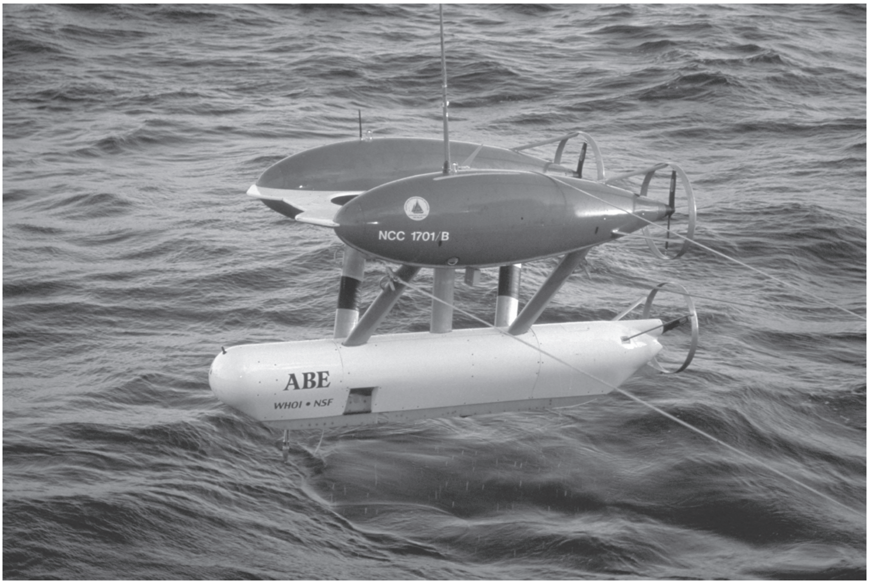

FIGURE 5-4 WHOI's *Autonomous Benthic Explorer* (ABE) is one of a growing number of AUVs being developed in industry and academia. This technology is still in the early stages of development and a number of important issues remain before AUVs are routinely used at ocean observatories. However, the base of technology and expertise in AUVs is growing at an accelerating rate and they are likely to play an increasingly important role in observatory science by the end of this decade. Figure courtesy of © Woods Hole Oceanographic Institution.

- water column mapping to determine variations in physical or chemical properties in a volume of ocean around an observatory node;
- measurement of fluxes; and
- response to transient events detected by observatory monitoring.

AUV technology is still in its infancy and not yet ready for observatory applications. Docking for data retrieval, obtaining commands, and transferring power are not yet routine. Problems related to operating reliably for long periods without maintenance also need to be solved before AUV support of observatories will become a reality. However, the U.S. Navy and the offshore energy industry have shown a growing interest in AUVs and the base of AUV technology and expertise is growing at an accelerating rate. By the end of this decade, when these research observatories are fully operational, it is likely that AUVs will be playing an increasingly important role in observatory science and operations.

Gliders (an AUV with ballast tanks rather than propellers or motors) are another emerging new technology for water column mapping (Eriksen et al., 2001), although they are also in a developmental stage and the process of devising control systems for deployments of multiple instruments is just beginning. The observatories funded by the OOI will undoubtedly become testbeds for the development of the next generation of AUV and glider technology. While these technologies are not crucial to the installation phase of the OOI, they are likely to be important for realizing the full scientific potential of ocean observatories.

ROLE OF INDUSTRY IN OCEAN OBSERVATORIES

The energy and telecommunications industries can be involved in many aspects of ocean observatories, from supplying the cables, buoys, and instruments for observatory infrastructure to the ships, ROVs, and support services needed to maintain and operate this infrastructure over the long term. Since the academic community does not manufacture most of the items necessary to build a seafloor observatory, industry will supply many of the components that comprise the infrastructure. Academic institutions and various government agencies own or long-term lease vessels, ROV systems, and other assets that could be used to install and maintain observatories. Examples are the UNOLS fleet and ROV systems like *JASON II*. This section describes the commercial resources that could be used to install, operate, and maintain ocean observatories and the potential role of industry in ocean observatory operations.

Vessels

More than 1,000 commercial vessels are engaged in the offshore energy business. A single company operates 188 vessels in U.S. waters and an additional 327 internationally. Another large U.S. firm operates more than 300 vessels, the older and smaller of which are typically 55 m long with low and long back decks. Newer vessels range from 85–100 m long and have much higher freeboard, and are powered by engines ranging from 3,000 to more than 10,000 horsepower. While current missions include things as simple as delivering groceries to installing anchor piles in 2,100 m of water, commercial offshore supply boats or anchor handling tug boats are ideally suited for launching or removing large spar buoys and moorings and for seafloor node installation and replacement. As noted above, UNOLS should consider acquiring a heavy-lift workboat for observatory operations, either through outright purchase or through a long-term, multi-year lease.

The offshore telecommunications industry employs an additional fleet of cable-laying vessels, augmented by maintenance vessels very similar in size and capability to the offshore energy vessels. The considerable experience of these cable-laying companies represents a valuable resource for observatory design and installation. The academic community should consider using these commercial vessels for installation and maintenance of ocean observatories. A particular window of opportunity to negotiate very favorable leasing agreements for cable-laying vessels will exist for at least the next few years given the depressed state of the telecommunications industry.

Buoys and Floating Platforms

The offshore energy industry has years of experience in building and operating large, moored platforms, often in very hostile environments. As the oceanographic community begins to consider acquiring large moored buoys, it will benefit from tapping into that experience. Although the smaller buoys currently in use by the academic community are typically built in-house, the larger systems under consideration should be designed and built commercially. One company (Maritime Communication Services, a division of Harris Electronics Systems) offers a commercial moored buoy system known as OceanNet that is designed for high-bandwidth, high-power applications. This system consists of a large 5.2 m discus buoy equipped with diesel generators, a 2 Mb/s C-Band satellite telemetry system, and a fiber-optic riser cable connected to a seafloor junction box. This complete "turn-key" system, including operation and maintenance, can be leased on a long-term basis. As the market for ocean observatories grows, other similar systems may become available. The cost-effectiveness of commercially leasing observatory systems should be thoroughly evaluated as part of the development of an observatory implementation plan.

Underwater Assets: Remotely Operated Vehicles and Autonomous Underwater Vehicles

ROVs have served as productive tools in the offshore energy and telecommunications industries and the military for more than a quarter of a century. Due to the physiological limitations of the human body at great depths and the practical limitations of cost effectively deploying manned submersibles, working beyond the world's continental shelves would not be economically feasible without ROV systems and, to an increasing extent, AUVs.

Hundreds of work-class ROV systems are in operation worldwide in both the offshore energy and telecommunications industries. Six major contractors engaged in the offshore energy business operate over 80 percent of these ROVs; most of the remaining systems serve industry in the hands of smaller companies. Many specific task systems, such as mine hunting, are deployed by the military and a few thousand smaller observation or inspection class systems are in use in lakes, rivers, and coastal areas. The work-class systems range in size from that of a sub-compact car to a dump truck. As much as 750 hp is available in propulsion through multiple thrusters, with typical power in the 100 hp range. Many systems are capable of operating in depths of up to 3,000 m.

Sensors and tools include multiple digital color video cameras, high-resolution sonar, and many job specific tools, sensors, and data collectors. Payloads of 1,000 lbs are not uncommon, with some systems capable of 1,600 lbs of vertical thrust. Manipulators are strong enough to lift more than 200 lbs and dexterous enough to tie a knot in a piece of rope.

AUVs have been in use by the military and the scientific community and are being introduced to the offshore industry for use as survey tools. These devices now carry sensors, such as sonar and video, but have no ability to perform work tasks. They will evolve—as did the ROV—and will become essential tools of the future. This evolution will include step changes, such as hybrid systems and parking garages on sub-sea production facilities.

Manned submersibles are in very limited use in the offshore industry. Given the capabilities of present work class ROVs and today's optical and sensor technology, the offshore industry does not see manned submersible as a cost-effective or efficient tool for their needs. More than 50 years of offshore (energy) vessel operations and a quarter of a century of ROV experience is available from industry, which learned hard lessons at great cost, not to taxpayers, but to corporations and individuals during the industry's evolution into the safe and efficient community of today. Those lessons fueled the development of the ROV and are going to take those systems to another level as ROV/AUV hybrids and, ultimately, true AUV systems are developed. Vessel operations efficiency and safety records are outstanding in the offshore energy business. All in all, the ocean research community would be wise to draw on this hard-earned experience.

6

Relationship of the Ocean Observatories Initiative to Other Observatory Efforts

The research-driven OOI is part of a broader national and international effort to establish long-term observatories in the ocean, both for conducting basic research and for operational oceanographic needs. This chapter discusses the relationship of the OOI to these other programs, at both national and international levels.

RELATIONSHIP BETWEEN THE OCEAN OBSERVATORIES INITIATIVE AND INTEGRATED AND SUSTAINED OCEAN OBSERVING SYSTEM

Current operational observatories consist principally of sea level sites, the various national weather sites (for example, the U.S. National Data Buoy Center's coastal weather buoys and shore weather stations), the equatorial buoy arrays in the Pacific TAO and the Atlantic PIRATA arrays, and the growing fleet of Argo profiling drifters. In many cases these sites or systems have limited sensor suites with accuracies chosen to meet near-term prediction and monitoring needs rather than the more demanding requirements planned for the research-driven OOI. If the OOI can develop the technology and demonstrate the potential for cooperative occupation of the operational sites and/or the payoff of adding more accurate and more multidisciplinary sensor suites to these sites, it would capitalize on existing operational investment and greatly increase the contribution of these operational observatories to the U.S. ocean sciences community.

The most fundamental relationship between the OOI and operational ocean and Earth observing systems at the national level is that of the OOI and the proposed U.S. IOOS, an operational observing system being planned for NOPP by Ocean.US. The IOOS mission is to provide data of societal interest to "customers," including the fishing fleet, shippers, and surfers. IOOS data are oriented toward supplementing current knowledge and sensors will use tested technology. In contrast, the NSF's OOI focuses on developing new knowledge and technology that will advance understanding of the oceans. By addressing the ocean research community's needs for time-series measurements of ocean processes, the OOI will provide the infrastructure needed to advance knowledge and understanding of the ocean/atmosphere/Earth system, as well as the technical capabilities for monitoring that system. Brief descriptions of the OOI and the IOOS are provided below, followed by analyses of the specific contributions of OOI to IOOS and vice versa and of the strong complementarity and synergy between the two programs.

The Ocean Observatories Initiative

The OOI will provide necessary information for ocean scientists striving to advance our basic understanding of processes that operate unseen in the oceans on or below the sea floor. An ocean observatory "telescope" will consist of many instruments that together will allow scientists to "see" beneath the sea surface for extended periods of time. The research observatories within the OOI will be able to resolve processes occurring on time scales as short as milliseconds and on spatial scales as short as millimeters, and these research observatories will often utilize instrumentation still under development. In addition, real-time data from OOI observatories will allow "interactive" ocean science; observational resources can be rapidly (re)deployed in response to detection of major events such as volcanic eruptions, earthquakes, harmful algal blooms, or debris flows. Archival data will be required for scientific analyses involving both the original purposes for which the data were gathered, as well as unforeseen applications, carried out by both the original investigator and a broader community that will use the products of the OOI observatories. Archival data will also be used for testing the parameterizations of unresolved fine-scale processes that are necessary for numerical models, and for the development of education and public outreach materials.

The Integrated and Sustained Ocean Observing System

The IOOS is designed to provide timely information to directly address societal needs in areas ranging from reliable monitoring of climate change to safe routing of oil tankers to optimal management of our nation's fisheries (commercial and recreational). The IOOS planning documents (Ocean. US, 2002a,b) list seven major areas of societal importance that will be served by sustained observations in both U.S. coastal waters and international, open-ocean waters and by operational modeling and analysis tools that will use these observations to create data products. Such products include:

- detection and prediction of change in the marine environment;
- mitigation of natural hazards;
- improvement to safety and efficiency of marine operations;
- national security;
- reduction of public health hazards;
- protection and restoration of marine ecosystems; and
- sustainability of marine resources.

The IOOS is being developed to be fully compatible with the international GOOS (Summerhayes, 2002), initiated in 1998 and modeled after the World Weather Watch (WWW) of the World Meteorological Organization (WMO). Open-ocean IOOS/GOOS observations will focus on weather and climate forecasting, geophysical hazards, and international security. Coastal-ocean IOOS/GOOS observations will provide coastal and near-shore constraints for operational models of U.S. territorial waters, producing forecasts that are increasingly needed by federal, state, and local agencies, as well as non-governmental organizations and that address one or more of the seven major areas of societal importance listed above.

The planned U.S. IOOS will be deployed at fixed geographic locations, with a necessarily coarse spatial scale (with the exception of satellite measurements), and will use only well-tested and robust technologies. In addition to real-time data delivery over the Internet, archived data will allow for assessment of long-term changes in the marine environment and provide context for research programs, hind-cast testing of pre-operational numerical models, and development of EPO materials.

While the OOI and the IOOS have been described separately above, the hypothesis-driven basic research conducted at OOI observatories and the development of operational oceanography through the IOOS program are, in fact, *critically interdependent*, with each program supplying ingredients essential to the other and academic researchers playing pivotal roles in both. This degree of interdependence implies that mechanisms should be sought to make the planning and operation of both programs equally interdependent, starting in the present planning stages for both programs.

The Importance of the Ocean Observatories Initiative to the Integrated and Sustained Ocean Observing System

The body of knowledge obtained by previous oceanographic research and technical development has provided a foundation for the initial design and implementation of IOOS. However, due to present technological limitations, initial IOOS deployment is largely in coastal, mid-latitude and tropical waters and centers primarily on observations of the physical properties of the ocean and the sea surface. The IOOS needs new technology in order to both expand into more challenging environments using more capable platforms with more diverse sensors and to make possible high-bandwidth, real-time observations at the seafloor, throughout the water column, and at the sea surface. Because the IOOS is funded and operated by operational agencies, it will not have a major role in the development of new technology, rather the OOI will produce the new technology the IOOS needs. At the same time, the OOI will support new science with its new high resolution multi-disciplinary observations and lead to better understanding of the processes at work and the way in which these processes can be routinely sampled. Thus the OOI will ensure that the IOOS will reach its full potential as a tool for observation and forecasting of the total marine environment. To be able to address all of the seven societally important areas identified above, IOOS requires the research and development activities of the OOI, which will provide progressive enhancements of knowledge, methods, and tools to expand and improve upon the initial implementation stage. On both scientific and technological fronts, the OOI is a critical research and development component of the IOOS (Box 6-1).

The Importance of the Integrated and Sustained Ocean Observing System to the Ocean Observatories Initiative

The planned observational backbone of IOOS will provide the OOI research community with important benefits as well, primarily by providing the broader observational context for OOI systems (Box 6-2). These IOOS data streams will relieve researchers of the need to collect this essential background information themselves, allowing them to focus on resolving poorly known ocean processes and developing new technologies. IOOS will therefore greatly increase OOI productivity and the rate of progress in ocean research and technology development.

In addition, the operational (assimilative) coupled physical-biogeochemical models that will be supported by IOOS for now-casting and forecasting will provide OOI researchers with important information at both the experiment planning and the execution stages. Such information

BOX 6-1

Benefits of the Ocean Observatories Initiative to the Integrated and Sustained Ocean Observing System

- Advances in fundamental scientific knowledge of ocean processes necessary to achieve the longer-term operational goals of the IOOS;
- New sensors and associated algorithms, especially those for making *in situ* biological and chemical measurements, which will undergo extended testing at OOI facilities—those sensors that emerge as stable and reliable will be candidates for addition to the IOOS observational backbone;
- New ocean access technologies (power supply, communication) designed for and proven at OOI facilities, and that could eventually be incorporated into the operational IOOS networks;
- Development of the capability to make observations in remote and extreme environments in the oceans where such measurements are not currently feasible;
- High temporal resolution data essential for testing parameterizations of processes unresolved by present numerical models, since improved parameterizations, particularly of biophysical interactions, are essential for the forecast modeling component of IOOS;
- Higher spatial resolution of re-locatable parts of the OOI (arrays either moored or deployed around cabled nodes), providing "nested" observational capacity to resolve processes with scales shorter than the IOOS footprint; and
- Innovation and improvement in operational ocean models, based on continuing advances arising from interactions between the OOI and the research modeling community.

includes (1) design-stage simulations of the variability of the ocean environment at an observatory site (expected to vary geographically and seasonally) and (2) deployment-stage descriptions of the time evolution of the ocean "volume" surrounding an OOI observatory. Both contributions would improve the success rate and return-on-investment of OOI research experiments.

"Complimentarity" and Synergy Between the Ocean Observatory Initiative and the Integrated and Sustained Ocean Observing System

Both the OOI and the IOOS are presently scheduled to commence in FY 2006, reducing opportunities for each program to contribute to the other during the intervening period. For example, IOOS data and data-assimilation models will not be available to guide spatial design of OOI observatories. Once fully implemented, however, the OOI and the IOOS will provide areas of overlap within which their combined infrastructure will serve to enhance the productivity of both the operational and research science communities. A present-day example of the success of such synergy is the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) array that stretches along the equator in the Pacific Ocean (more information available at: *www.pmel.noaa.gov/tao/index.shtml*). Originating as a research tool, this moored ocean "observatory" has now achieved operational status, providing early warnings of El Niño events and their significant societal and economic repercussions. However, research scientists continue to use TAO moorings as platforms for testing new instrumentation and the TAO array itself as a coarse-scale grid in which to embed finer-scale process studies. The results of such process studies, combined with the multi-year archived TAO data set, allow other researchers to improve and test theories and models of the equatorial ocean and its atmospheric teleconnections, consequently driving improvements in the operational models used for El Niño predictions. Implementation of both the OOI and IOOS would enlarge the scope of these demonstrated synergies to include both the global scale crucial to climate variability/change and the coastal and estuarine scales directly affecting a large and growing proportion of the U.S. population.

BOX 6-2

Benefits of the Integrated and Sustained Ocean Observing System to the Ocean Observatories Initiative

The present elements of the nascent IOOS, including the TAO and coastal buoy arrays provide experience that will guide the OOI in its:

- Choice of sensors, instruments, and materials;
- Development of data quality, calibration, and instrumentation maintenance protocols in the face of biofouling, corrosion, and other challenges; and
- Development of archiving, data sharing, and interfaces to the public.

The planned observational "backbone" of IOOS will provide the OOI research community with an efficient means of accessing:

- The coarse-grained spatial ocean background in which OOI science observations and experiments will be embedded;
- The atmospheric forcing functions essential for driving numerical models and for understanding observations of physical and biogeochemical processes in the upper ocean; and
- The long-term time series that will provide the historical context of local and far-field ocean conditions.

Another area where integration of OOI and IOOS efforts will be essential is in data distribution and archiving. The integration of data management systems for research- and operationally-driven observatories will promote the assimilation of data from new sensors and instruments developed through the OOI into operational models, and will make it easier for researchers to utilize the larger-scale observational data and model forecasts developed by IOOS. The sharing of data management infrastructure also makes sense from cost and efficiency perspectives.

Given the complementarity and synergy between the NSF's OOI and the proposed NOPP IOOS outlined above, the *combination* of these two program initiatives is essential to the development of predictive skills in the oceanographic sciences and to the generation of public engagement with the oceans that is necessary to form a solid basis for efforts to protect and preserve them. Given the costs of both the IOOS and the OOI, and the likely participation of the research community in both, it is crucial that the coastal components of these two programs be fully coordinated in all stages of development and operation.

RELATIONSHIP BETWEEN THE OCEAN OBSERVATORIES INITIATIVE AND OTHER NATIONAL OCEAN AND EARTH OBSERVING SYSTEMS

The NSF-supported OOI will have close ties to ocean and Earth observing systems supported by other agencies including NOAA, NASA, USACE, the U.S. Geological Survey (USGS), and ONR. These multiagency efforts should be coordinated through the NOPP.

National Oceanic and Atmospheric Administration

At present NOAA supports a major fraction of the Pacific equatorial TAO array as an operational commitment. Under the NOAA Office of Atmospheric Research (OAR) Office of Global Programs (OGP) Climate Observations program a small number of surface flux reference sites will be occupied. NOAA's OAR also contributes to the PIRATA array in the tropical Atlantic. The NSF presently provides part of the support for NOAA's BATS and HOT stations, but neither agency has undertaken severe environment sites or worked to exploit the full multi-disciplinary potential of the sites now in the water. Completion of the U.S. planned commitment to the global array developed by the international TSST (Appendix E) would require more resources and new development and is not presently feasible. These national efforts look to the OOI for support and technology development.

National Aeronautics and Space Administration

Although NASA has no program to support *in situ* observations in the oceans, many NASA missions observe ocean and climate changes via satellite. Five major satellite systems are currently flying, including *Aura*, *Aqua*, *Jason-1*, *TOPEX-Poseidon*, and *Terra*. In addition, two Japanese spacecraft carry NASA's scatterometer instruments. These satellite systems provide valuable information regarding ocean surface temperature, circulation, ocean color, surface winds, and other parameters used for developing weather predictions and forcing climate forecast models. Satellite data also provide information on the horizontal variability of upper ocean properties on a large spatial scale, data which is essential for the proper interpretation of temporally and vertically well-resolved measurements at fixed observatory sites. Satellite missions can in turn take advantage of *in situ* measurements taken from OOI and other ocean observatories for validating satellite instrument measurements.

NASA and the ocean science community also have important collaborations in the area of data management. For example, the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC) produces and distributes ocean data products to the science community and has developed and published application interfaces to adapt PO.DAAC data to the Distributed Oceanographic Data System (DODS). PO.DAAC scientists are also involved in data management issues associated with a pilot Southern California GIS Data Center collaboration with regional coastal planning agencies, the Global Ocean Data Assimilation Experiment (GODAE) High-Resolution Sea Surface Temperature (GHRSST) processing and archive center, and Ocean.US IOOS data management and distribution system planning.

The U.S. Army Corps of Engineers

The USACE, in their role as coastal engineers for the U.S., has in place programs to collect ocean data relevant to near-shore researchers, managers, and engineers. Their FRF in Duck, North Carolina (see Chapter 2 and Appendix D) has collected several decades of continuous data on waves, tides, currents, meteorology, and the concomitant beach response at the Outer Banks. This facility has also been used as a test bed for new instrumentation and models and as a platform from which to execute intensive, short-duration experiments. In addition, the USACE supports the Coastal Data Information Program (CDIP) at Scripps Institution of Oceanography (for additional information, see: *http://cdip.ucsd.edu/*). The CDIP collects coastal data on wind, temperature, and wave direction on the U.S. West Coast and Hawaii, and models the swell direction for beaches in the

Southern California Bight needed for near shore material transport model projections. The USACE Regional Sediment Management (RSM) program recently began establishing data collection and modeling centers for material transport analysis along coastal sections defined by its common watershed material source and natural or man-made sinks (for additional information, see: *http://gis.sam.usace.army.mil/Projects/RSM/*). These RSM centers provide multi-variate and multi-dimensional data (both *in situ* and remote) in a GIS framework that are of value to near shore researchers. Included in the RSM effort is the reformatting of over 100 years of bathymetric data along the nation's coastlines into a GIS reference system. Many coastal efforts of the OOI and USACE are synergistic and should be identified and leveraged by other programs.

The U.S. Geological Survey

The USGS provides the underlying geological framework for the world's oceans and the U.S. coastline upon which a physical, biological, and chemical understanding of Earth processes can be built and referenced. The USGS operates various time-series observational programs that may be of direct value to the OOI, including the national network of stream flow gauges, volcano observatories, and the coastal mapping of temporal changes in shoreline and bluff locations and subaqueous bottom substrate. For example, HUGO data became far more valuable when combined with data from the USGS Hawaiian Volcano Observatory.

The Office of Naval Research

ONR carries out diverse programs in areas of research in air-sea interaction and ocean biology, chemistry, physics, optics, geology, and acoustics. Under these research programs, moorings, coastal towers, cabled observatories, and the research platform FLIP (Floating Instrument Platform) have seen much use. ONR supported much of the development and use of present open ocean subsurface and surface mooring capability and also contributed to the development of ocean instrumentation. It is likely that ONR investigators would both contribute instrumentation and seek opportunities to use the platforms developed under the OOI for their research.

RELATIONSHIP BETWEEN THE OCEAN OBSERVATORIES INITIATIVE AND INTERNATIONAL RESEARCH-DRIVEN OBSERVATORY PROGRAMS

A number of international groups have provided guidance on the development of ocean observatories including: the OOSDP under the International Ocean Commission (IOC) and United Nations Educational, Scientific and Cultural Organization (UNESCO); the OOPC under IOC, UNESCO, and the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM); CLIVAR's COOP; and the ION. An international TSST with members drawn from various disciplines has developed plans for a global network of time-series sites that would meet interdisciplinary needs (see Chapter 3 and Appendix E). Although these various international planning efforts have clearly expressed the scientific potential of ocean observatories, a need remains for a commitment of significant infrastructure support to make sought-after observatories possible. The OOI will represent an important contribution by the U.S. to these international efforts.

Planning for ocean observatories has been going on in a number of nations, much of it done in close collaboration with efforts in the U.S. Japan has the largest existing network of seafloor observatories, and has considerable experience both in powering seafloor instruments from shore and in real-time telemetry of data from those installations. In 1996, the Ministry of Education, Science, Sports and Culture in Japan funded the Ocean Hemisphere Project (OHP) to establish a network of multidisciplinary ocean observatories in the Pacific basin. The OHP network includes island stations and seafloor observatories making seismic, electromagnetic, and geodetic measurements, including three broadband seismometers installed in the ODP drill holes in the western Pacific. Japanese scientists are currently conducting a feasibility study of a next-generation submarine cable network around the Japanese Islands known as the Advanced Real-Time Earth monitoring Network in the Area (ARENA), which has a mesh network topology and power and communication requirements very similar to the proposed NEPTUNE observatory. There are many opportunities for potential collaboration, both technically and scientifically, as the NEPTUNE and ARENA projects move forward.

NEPTUNE itself is a joint U.S./Canada project led by the University of Washington (U.S.) and the University of Victoria (Canada), and its scientific and engineering planning is fully integrated between the two countries. Canada has committed to providing about 30 percent of the cost of the entire NEPTUNE project. The Canadian portion has received conditional funding from the Canadian Foundation for Innovation (CFI); one of the conditions being to secure matching funds, presently being sought from the British Columbia Knowledge and Development Fund (BCKDF). The Canadians will be installing a shallow water cabled observatory, VENUS, off British Columbia in 2004, which will serve as an important testbed for the development of NEPTUNE and next-generation coastal cabled observatories.

Another major international ocean observatory program with close ties to the NSF's OOI is the B-DEOS program. The B-DEOS program plan calls for the establishment of multidisciplinary moored ocean observatories at three sites: south of the Azores on the Mid-Atlantic Ridge, on the Reykjanes Ridge south of Iceland, and in the Drake Passage-East Scotia Rise-South Sandwich Islands area. The proposed systems are hybrids between conventional discus buoys and spar buoys. These buoys have significant power generation capability, a high-bandwidth satellite communication system, and an electro-optical riser to a seafloor junction box similar to the high-bandwidth moored systems DEOS has proposed for many of the OOI global sites. The B-DEOS and the OOI global program share many common engineering and scientific requirements, as well as numerous opportunities for future cooperation, both in the development of next-generation moored buoy technology and in subsequent operations, logistics, and scientific studies in the remote ocean areas where many of these moorings may be deployed.

All of these programs look to the U.S. OOI as a key building block, representing part of the total financial commitment needed to develop, build, deploy, and initially maintain ocean observatories on regional and global scales. It is anticipated that the U.S. OOI will be joined by other national commitments to the global ocean observatory infrastructure, perhaps in the same fashion that many nations have partnered to field the global array of profiling Argo floats. The scientific planning, management, and operational structure of the OOI needs to be organized in such a manner as to leverage these various national efforts into what will eventually evolve into a truly international ocean observatory program.

7

Findings, Conclusions, and Recommendations

This chapter presents the findings, conclusions, and recommendations regarding the implementation of a seafloor observatory network for oceanographic research. These findings and recommendations are based on input from various reports and workshop documents (Appendix C), experience with existing observatories (Chapter 2), presentations made to the NRC Committee by authorities in the field, and the expertise of NRC Committee members. This input was discussed in detail and the findings presented here are a distillation of the outcomes of those discussions.

FINDINGS

- **By exploiting rapid advances in the development of computational, robotic, communications, and sensor capabilities, the NSF's OOI will provide the infrastructure to enable a new era of ocean research in the 21st century.** The advanced capabilities of the OOI, will include high-bandwidth, two-way communication; access to data in real-time or near-real-time from sites in even very remote parts of the world's oceans; real-time, interactive instrument control; availability of significant amounts of power to operate instruments that would not otherwise be feasible to use; and the development of systems that can withstand severe environments. These capabilities promise to greatly advance the study of Earth and ocean systems in the coming decades (see Chapters 1 and 3).
- **The network of research-driven ocean observatories envisioned by the OOI would facilitate major advances in basic knowledge of the**

oceans at a time when there is an increasing need to understand the oceans in order to address important societal concerns such as climate change, natural hazards, and the health and viability of the ocean's living and non-living resources. By providing a mechanism to carry out fundamental research on natural and human-induced change in the oceans on time scales ranging from seconds to decades; enabling the development of new experimental approaches and observational strategies; and improving access to oceanographic data by researchers anywhere in the world, the OOI will be a catalyst for new discoveries and major advances in basic knowledge that will be essential to address important societal concerns involving the world's oceans (see Chapter 1).

- **The OOI will greatly improve the ability of operational ocean-observing systems such as the IOOS and GOOS to observe and predict ocean phenomena.** The research-based OOI is an important complement to the proposed IOOS, an operational system driven by the needs of potential users and designed to improve the safety and efficiency of marine shipping, mitigate effects of natural hazards, reduce public health risks, improve weather and climate predictions, protect and restore a healthy coastal environment, and enable sustainable use of marine resources. The OOI, in contrast, is driven by basic research questions and its principal products will be improved understanding of the oceans and new and improved technologies. The OOI will thus provide the key enabling research for IOOS, including fundamental advances in observatory platforms and, through the research of investigators using the OOI, basic understanding of sensor technology that will enable IOOS to meet its longer-term operational goals. The IOOS will provide the OOI with an important larger-scale framework of observations and background data necessary for interpreting the process-oriented experiments that are the centerpiece of basic research (see Chapter 6).
- **The scientific motivations and benefits of research-based ocean observatories are well-defined in existing workshop reports and related documents for the three major components of the OOI: global observatories, regional observatories, and coastal observatories.** The documents listed in Appendix C and referenced in Chapters 1 and 3 demonstrate that seafloor observatories represent a promising new approach for advancing basic research in nearly every area of marine science.
- **Scientific planning to define the location, experiments, and instrument requirements of specific observatories varies significantly among the three OOI components, and additional planning is needed before the design of these systems can be finalized.** Although the general scientific rationales for ocean observatories are well-established, the specific locations, scientific experiments, and instrument requirements of

proposed observatories; the mix of systems that will be part of the OOI (cables, moorings, etc.); and the interrelationships among these systems require further definition. Due to the importance of scientific planning at this level for the definition of OOI infrastructure requirements, it is essential that this planning be funded and carried out for all three OOI components over the next two years (see Chapter 3).

- **There is currently no community consensus on the appropriate balance among relocatable observatories (Pioneer Arrays), cabled observatories, and long-term time-series measurements needed for coastal ocean and Great Lakes research.** The recent CoOP workshop report recommended that relocatable Pioneer Arrays—which would enable relatively short-term, process-oriented studies in the coastal regions of the U.S.—be the main focus of the coastal OOI, (Jahnke et al., 2002) while the subsequent SCOTS workshop report emphasized the unique opportunities for coastal research provided by fixed cabled observatories (Dickey and Glenn, 2003). It is clearly necessary to reach agreement on the optimal mix of these two different coastal research strategies. A third essential component of a coastal observatory system is an array of fixed moorings designed to provide measurements of physical, chemical, and biological variability over long time frames, such as those associated with natural decadal variability or the even longer time scales of natural and/or anthropogenic climate change. While the CoOP workshop report recognized this need, it concluded that IOOS would provide the backbone of necessary long-term observations in the coastal zone (Jahnke et al., 2002). However, it is not yet clear whether the proposed IOOS "sentinel" moorings would be suitably placed or suitably instrumented for basic research in the coastal ocean and Great Lakes (see Chapter 3).
- **NSF policies and procedures for the MREFC account require that a single entity have overall financial and management accountability for the program. Thus although the OOI encompasses a diverse group of researchers from many different disciplines working in both the coastal and open ocean, management of ocean observatory construction, installation, and operation will have to be done through a single Program Office.** This central Program Office will provide coordinated, program-wide scientific planning and oversight, fiscal and contract management of observatory installation, maintenance and operation, standard and protocol development for data management, and education and outreach activities. The greatest challenge for the Program Office will be integrating three very disparate communities with different scientific goals, infrastructure requirements, and cultures into a single coherent program (see Chapter 4).
- **The maintenance and operation costs of the infrastructure associated with the OOI could run $20-30 million annually (not including**

ship time). With ship time included, these costs could double, approaching $50 million per year. There are concerns in parts of the community that these costs could drain resources from other areas of ocean science and monopolize assets such as ships and ROVs, or that overruns in the construction and installation costs of more technically advanced observatory systems could impact the acquisition of other observatory components. While substantial, the operation and maintenance costs for the OOI are not out of line with other major geoscience initiatives. By comparison the budget of the Ocean Drilling Program (ODP) in FY 2002 was approximately $46 million for operation of the *JOIDES Resolution*, a scientific drilling vessel and other associated program activities (drilling and science support services, information services, publications, administration). Nonetheless, the levels of funding that will be required to maintain and operate this research-based observatory network are substantial and, based on estimates in this report, significantly greater than the $10M/yr figure in the OOI funding profile included in the FY 2004 NSF Budget Request. In order to allay fears that observatory O&M costs will divert resources from other areas of ocean science it is essential that such costs be accurately estimated and budgeted ahead of time, that facility O&M costs be clearly separated from science costs, and that strict fiscal oversight procedures be instituted to ensure that the program operates within its budget (see Chapter 4).

- **The capabilities of some proposed observatory systems raise national security issues that will need to be addressed before these systems are installed.** These issues exist for both cabled observatories and moorings and include the location, capabilities, and observing times of hydrophone arrays and other sensor types. Other concerns include the integrity of the observatory system (ensuring there are no unauthorized sensors on the observatory infrastructure) and the openness of data collected by the system (thus prohibiting data encryption by individual users) (see Chapter 4).
- **Ocean observatories will require substantial amounts of ship and ROV time for installation, operation, and maintenance and will place significant demands on the scheduling of UNOLS vessels for regular servicing of observatory nodes in remote ocean locations.** Installation of 15-20 global observatory sites, a regional cabled observatory (e.g., NEPTUNE), and coastal observatories consisting of both moorings and cabled observatories are likely to require over 4 ship-years (assuming 300 operational days per year), including over 1 ship-year for industry contract vessels for both cable laying and spar buoy installation. Maintenance of this infrastructure is estimated to require at least 3 ship-years annually, most of that on global-class UNOLS vessels or their commercial equivalent. Observatory operations will also require large amounts of ROV time

(10-20 months per year). Both work-class and science-class ROVs will be needed to meet observatory requirements. The need for regular servicing visits to observatory nodes, sometimes located in remote regions, will place particular demands on the UNOLS ship scheduling process, especially for the large global- and ocean-class UNOLS vessels (see Chapter 5).

- **There are insufficient large global-class vessels and ROVs in academia to support ocean observatory installation and maintenance needs while continuing to meet on-going expeditionary research requirements. Without a commitment from NSF to augment ship and ROV capabilities to meet these needs, the scope and success of the ocean observatories program could be jeopardized and other types of ocean research requiring these assets could be negatively affected.** All of the global-class UNOLS vessels are currently heavily subscribed for expeditionary research and these ships will not be able to meet the demands for ocean observatory maintenance and operation without unacceptable consequences for other ocean sciences research. The single deep-ocean ROV available through the U.S. NDSF is also inadequate for both observatory and general science support. This problem will become critical in 2007 or 2008 as the installation of these observatory systems begins. A significant expansion of the large ship capability in UNOLS and the number of ROVs available through the NDSF will be required by 2010 to avoid a major negative impact on other areas of ocean research due to the establishment of ocean observatories. Because of the long lead-time in funding and constructing new UNOLS vessels, contracting commercial vessels and ROVs to meet observatory requirements could prove an attractive option (see Chapter 5).
- **The offshore energy and telecommunications industries have extensive experience in the design, deployment, and maintenance of submarine cables and large, moored platforms, and have assets (ROVs, cable-laying vessels, heavy-lift vessels) that could be used for ocean observatory installation and maintenance.** There are a variety of ways for the observatory community to utilize the technology and expertise developed in the commercial sector. Options range from contracting with industry for specific services (e.g., fabrication of observatory infrastructure components, installation of cables or large moored platforms, and the maintenance and servicing of these structures), to leasing platforms (e.g., ships, ROVs, AUVs, or moorings), to participating on technical and engineering advisory committees in the OOI management structure. Industry may, in some circumstances, provide a cost-effective approach for providing services or facilities for the installation and maintenance of the ocean observatory infrastructure (see Chapter 5).
- **The infrastructure requirements of the different OOI components (global, regional, and coastal) share many common elements, but**

also have important differences due to factors such as proximity to land, power and data telemetry requirements, and maintenance logistics. Coordination at the program level will be needed to leverage the common elements of these different observatory systems. The different technical, operational and logistical requirements of these systems, however, suggest that day-to-day management of the three OOI components will need to be handled separately (see Chapter 4).

- **The technology already exists for certain types of observatories (e.g., low-bandwidth deep-sea buoys, coastal moored observatories, simple cabled observatories) and deployment of these systems can begin as soon as funding is available. Next-generation observatories (e.g., multi-loop, multi-node cabled observatories; high-bandwidth, electro-optical-mechanical, cable-linked moorings; Arctic and Southern Ocean observatories, relocatable coastal observatories) require additional prototyping and testing of critical sub-systems, but should be technologically feasible within the five-year time frame of the OOI (2006-2010).** A review of the status of engineering development for both moored buoys and cabled observatories indicates that progress is being made in addressing the major engineering development issues facing the more advanced observatory systems. Major conceptual and engineering design studies have been completed for plate-scale cabled observatories and for next-generation moored buoy systems. Funding has been secured for cabled observatory test beds in shallow and deep water, and a prototype low-bandwidth, relocatable moored buoy system. However, additional funding for prototyping and testing of high-bandwidth and/or high-latitude buoy systems and cabled networks with multiple-node, multiple-loop topologies will be required before these systems are installed (see Chapter 3).
- **The availability of retired telecommunication cables may represent a significant opportunity for ocean observatory science. Because the availability of these cables is a relatively recent development, it has not been factored into earlier planning of the OOI.** More than 35,000 km of electro-optical telecommunications cable on the ocean floor will be retired in place by industry within the next few years. These cables, which may either be used in place or, in some cases, relocated, could provide high-bandwidth and power to remote regions of the oceans, although a number of logistical and technical issues must be addressed in order to determine whether or not relocation is a cost-effective approach for any particular proposed site (see Chapter 3).
- **While a number of observatory-capable physical, geophysical and bio-optical sensors are available, a very limited number of sensors exist for making chemical and biological measurements at ocean observatories, or for making observations in more challenging environments**

such as the Southern Ocean or the Arctic. Biofouling and corrosion remain major impediments to making long-term unattended measurements in the oceans. In addition to the development of new bio-chemical sensors, research is also required to standardize sensor-observatory interfaces, improve sensor reliability, provide *in situ* sensor calibration, reduce biofouling, and minimize sensor-related environmental disturbance that could interfere with other measurements. Due to the long lead-time in the development and production of new sensors, this effort will need to begin well in advance of the completion of observatory installation (see Chapter 4).

- **The total investment in sensors and instrumentation that will eventually be made for use with the observatory systems acquired through the OOI over its first decade of operation could approach the cost of the basic infrastructure itself. The core suite of instrumentation that will be funded through the MREFC will represent only a small portion of this total.** The various workshop reports and planning documents referenced in this report include long lists of sensors and instrumentation for ocean observatories that would enable a broad spectrum of both disciplinary and interdisciplinary ocean research. The approach that the NSF has adopted draws the majority of funding for these observatory sensors and instrumentation from the scientific programs or projects utilizing the infrastructure (whether supported by the NSF or other agencies) rather than through the MREFC account. This approach is somewhat analogous with the way in which the academic research fleet has been managed, where each vessel is equipped with a basic suite of instrumentation but scientists or programs are typically responsible for more specialized instruments utilized on a particular expedition. Nonetheless there are concerns in the research community that these other funding sources may not materialize and that, consequently, access to the observatory infrastructure will be delayed and its full scientific potential will not be realized (see Chapter 4).
- **To ensure the comparability of measurements made at different OOI observatories, and to realize their full potential for research and to observing networks, observatory sensors will need to be calibrated according to international standards.** The core and community instruments at ocean research observatories will need to be maintained and routinely calibrated to internationally-agreed upon standards so that these data can be integrated with other elements of global Earth and ocean-observing systems. Instrument calibration requires proper facilities, including calibration standards, baths and laboratories, and considerable staff support (see Chapters 3 and 4).
- **The installation and maintenance of ocean observatories, and the conduct of complementary studies, will require a number of highly**

trained marine technical support staff that greatly exceeds existing personnel resources. In addition, observatory operation will place significant demands on instrumentation inventories and resources, including maintenance and calibration facilities. Highly trained marine technicians are already a scarce resource; with the advent of ocean observatories dependent upon advanced technologies this resource could well become a limiting one. Although not part of the observatory infrastructure costs, the pre-deployment instrument preparation and calibration, deployment, and post-deployment calibration and servicing associated with the core and community instrumentation envisioned for the OOI will require a significant investment. For instrumentation that is labor intensive to service and calibrate, costs at each turn-around can approach the cost of acquisition of the instruments. The certification and maintenance of calibration infrastructure can also be a significant ongoing cost (see Chapter 4).

- **While archive centers exist for some data types that will be collected by ocean observatories, they do not exist for others. Without a coordinated data management and archiving system, data obtained at ocean observatories may not be generally available due to a lack of data standards, quality control, or centralized archives, and the great scientific and educational potential of ocean observatories may not be realized.** The ocean science community lags behind many disciplines (e.g., seismology, space science) in using modern data management systems to archive and distribute the data it acquires and in making data available on-line to investigators, in real-time or near-real-time. As a result, some data products are not deposited in centralized archives and valuable data are lost or are effectively irretrievable. Experience demonstrates that the ocean observatory program cannot rely on individual investigators to manage, archive, or disseminate observatory data. Data must be professionally managed and distributed through established data centers according to a policy that guarantees data is made available to the ocean science community and to the general public (see Chapter 4).
- **Seafloor observatories will provide unique opportunities for education and public outreach (EPO) by utilizing real-time data through the interactivity of the Internet to help students, teachers, and the general public understand the relevance and excitement of ocean research to their everyday lives.** Nearly all aspects of observatory research can be incorporated in educational or public outreach programs, but the opportunity for real-time display of video images and the potential to interact remotely with instrumentation at the observatory will excite and engage students and the general public alike to learn more about the oceans. Real-time access to information from the oceans will provide an underwater laboratory that can be used to motivate students to learn the basics

of mathematics, physics, and chemistry needed to become more ocean-literate citizens (see Chapter 4).

CONCLUSIONS AND RECOMMENDATIONS

- **The NSF should move ahead with funding for the OOI and establish the infrastructure for a network of ocean observatories for research.** Seafloor observatories will offer ocean scientists new opportunities to study multiple, interrelated processes over timescales ranging from seconds to decades, to conduct comparative studies of regional processes, and to map basin-scale and whole-Earth structures. The scientific planning and technical developments necessary to establish a portion of a seafloor observatory network for basic research are sufficiently advanced to proceed with a major investment in this infrastructure at this time.
- **Coordination among the OOI, IOOS, and other national and international observatory efforts will be critical in the areas of infrastructure development, instrumentation, ship and ROV utilization, data management and technology transfer. Mechanisms should be put in place through the National Oceanographic Partnership Program (NOPP) to facilitate this coordination among the different U.S. agencies supporting ocean-observing systems.** The NSF-funded OOI will serve as a key building block in a broader international effort to develop, build, deploy, and maintain ocean observatories on a global scale for both basic research and operational needs. It is anticipated that the U.S. OOI will be joined by other national efforts in what will eventually evolve into a truly international ocean observatory program. However, to fully realize the potential of this observatory program good coordination is essential among the partners in this effort, at both the national and international level.
- **A process should be instituted immediately by NSF through the Dynamics of Earth and Ocean Systems (DEOS) Steering Committee, or the OOI Program Office, once it is established, to define better the scientific goals, locations, instrument, and infrastructure requirements of specific observatories. In addition, a consensus needs to be developed within the coastal research community on the appropriate balance between relocatable observatories (Pioneer Arrays), cabled observatories, and long-term moorings that best meet the largest range of specific requirements for coastal and Great Lakes research.** Scientific planning at this level is required to ensure that the observatory infrastructure (including core instrument suites) is well matched to science requirements and to identify initial experiments early-on so there is an immediate scientific payoff once the observatories are in place. This planning should be implemented for all three OOI components over the

next year, well in advance of the installation of the first observatories. This process should involve the broadest possible cross section of the ocean sciences community, and may include planning workshops, solicitation and review of proposals from individuals and community groups, and the establishment of science and technical advisory committees to the OOI Program Office. It is essential that this process also include representatives from Ocean.US, in order to clarify the respective contributions of IOOS and the OOI to long-term coastal observations, identify overlap in the facility needs of the research and operational observing systems in the coastal region, and initiate coordination and joint planning between the two programs.

- **A management model for the OOI based on that used successfully for many years by the Ocean Drilling Program (ODP) should be adopted, with some modifications. The program should be managed by a community-based organization, preferably with experience in managing large oceanographic research and operational programs.** While the ODP management model is a good one, there are important differences in the requirements for managing the OOI including the need to manage multiple, different operating facilities; the need to coordinate efforts in long-term ocean observatories with a number of different federal funding agencies; a much greater need for new technology development; and a less structured involvement at the international level in program participation. The philosophy of the OOI management structure should be one in which the day-to-day operation of different OOI components are the responsibility of the entities with appropriate scientific and technical expertise (scientific institutions, consortia, or private industry), while the role of the program management organization should be one of coordination, oversight, and fiscal and contract management. The OOI program management office needs to be established by the end of 2003, to oversee scientific planning and technical development in preparation for the construction and installation of the observatory infrastructure, some of which involves extensive advance planning.
- **The OOI Program Office, once established, should conduct a thorough systems engineering design review of each of the three OOI components; develop a detailed implementation plan and risk assessment for each observatory system; produce detailed cost estimates for construction, installation, maintenance, and operations; have these plans reviewed by an independent panel of experts; and put in place oversight mechanisms and fiscal controls to ensure that implementation tasks are completed on time and within budget.** The OOI program is a large, complex, and technically challenging endeavor. In order to mitigate the risks—both technical and financial—associated with this investment, it is essential to develop a detailed implementation plan with

specific milestones and regular review by independent experts. Observatory system operators must address reliability issues such as timely response to system damage or failure, mean time between failures, and other factors that would affect the life cycle cost and functionality of the system for scientific research. The program must balance the desire to push the envelope technologically with the need to provide a reliable, functional, and cost-effective infrastructure for conducting observatory science. It is essential that the resources for observatory construction and installation available through the MREFC account be matched with accurate and realistic cost estimates for each observatory component. If necessary, the scope of proposals will have to be adjusted to what can be realistically accomplished within budgetary constraints.

- **The OOI Program Office should develop an operations policy that addresses allocation of research time, bandwidth, and power usage among potential users for each of the three OOI components. Prioritization of proposed experiments should be based on the quality of the proposed science as judged by a peer-review process.** One of the highest priorities of the Program Office will be to ensure fair and equitable access to observatory infrastructure by all funded investigators. The program management will need to work with the scientific community through a science advisory structure to select, support, and periodically evaluate community experiments; define access requirements and provide technical support for individual investigator-initiated experiments; develop protocols for scientists not involved in deploying experiments to access data bases and archives; and negotiate access agreements with other users (such as for-profit entertainment industries). Operating rules for the observatories will have to take into account the needs of the scientific community, agencies interested in using or supporting the use of the facilities, international partners and collaborators, and other users.
- **A successful observatory program will require sufficient funding for both the operation and maintenance of the observatory infrastructure and for the science that this infrastructure will enable. The NSF needs to take appropriate steps to ensure that sufficient resources are available to meet these needs by the time the observatory infrastructure is in place.** The O&M costs associated with the infrastructure acquired through the OOI MREFC have been estimated at approximately $25 million per year, not including ship time. If ship time is included, that figure doubles (Table 4-1). This estimate does not include the cost of funding the scientific research that this new infrastructure will enable. While these costs are difficult to estimate, they could amount to a significant fraction of the annual O&M costs. Sufficient funding for observatory science and related O&M costs will be essential if the full potential of observatory science is to be realized and in order to ensure that the obser-

vatory program does not drain resources from other areas of ocean science.

- **The NSF should work with the appropriate staff from the Office of the Secretary of the Navy in cooperation with the National Ocean Research Leadership Council (NORLC) to establish, as soon as possible, policies addressing the national security issues raised by the potential capabilities of ocean observatories.** While these concerns are significant, they can be addressed and resolved. Moreover, the U.S. Navy is eager to benefit from the science enabled by observatories. Establishing these security policies at a senior level as soon as possible—and well before observatories are installed—is extremely important. A delay resolving security concerns may hinder deployment or operation of the observatory infrastructure. As observatory capabilities evolve more sophisticated sensor systems, an ongoing process will be needed in order to review national security concerns involving the NSF, the U.S. Navy, and the U.S. Department of Homeland Security. This process must also ensure the integrity of the telemetry and configuration control of the observatories such that all sensors connected are controlled and known.
- **UNOLS and its Deep Submergence Science Committee (DESSC) should develop a strategic plan that identifies the most cost-effective options for supplying the required ship and ROV assets for observatory operation and maintenance and NSF should commit the necessary funds to acquire these assets. This plan should consider both the addition of new vessels and ROVs to the UNOLS fleet and the contracting or long-term leasing of commercial vessels or ROVs for observatory operations.** The present UNOLS Fleet Renewal Plan does not adequately address the ship requirements of the ocean research observatories acquired through the OOI. There is an immediate need for a study to identify the ship and ROV facilities required to support global, regional, and coastal observatories and to develop a plan to provide these assets within the context of the five year OOI construction and installation schedule. This study should assess pre-installation (e.g., cable route mapping) and installation requirements (e.g., cable laying, mooring deployment, and sensor installation) as well as needs for the operation and maintenance of the observatory system. The strategic plan should consider a mix of academic and commercial assets in order to find the most cost-effective means of supporting future observatory needs. In particular, this plan needs to address the way to best meet observatory requirements for large, global-class, heavy-lift capacity vessels for mooring and seafloor node installation, maintenance, and replacement and the manner in which the research community's access to ROVs for observatory operations should be augmented. On the basis of this report, FOFC and UNOLS should reassess the Academic Fleet Renewal Plan to ensure that the capabilities of the

academic fleet in the future are well matched with the needs of both observatory and expeditionary science and the NSF should commit the necessary resources to implement this plan. Without a commitment from the NSF to augment ship and ROV capabilities to meet these needs, the scope and success of the ocean observatories program could be severely limited and other types of ocean research requiring these assets could be negatively affected.

- **In order for the more advanced moored buoy and cabled observatory systems to be ready of installation in the 2006-2010 time frame, the NSF will need to provide significant levels of funding over the next 2-3 years for completion of prototyping and testing of critical sub-systems, and for the establishment of testbeds where the performance of these systems and new observatory instrumentation can be evaluated.** Engineering and operational experience exists for some simple mooring and cabled seafloor observatory configurations, but more advanced systems (e.g., multi-loop, multi-node, cabled observatories; high-latitude buoys; and high-bandwidth buoys) have not been built and present some significant technological challenges. While these more advanced systems should be feasible within the five year time frame of the OOI, adequate prototyping and testing of all major subsystems, including the establishment of one or more pilot observatories, is required in order to minimize risk in the deployment of these advanced systems. This may require an additional investment of several million dollars between now and 2006.
- **The technical feasibility, costs, and benefits of using retired telecommunication cables to provide power and bandwidth for some proposed OOI sites should be fully explored by a committee with appropriate scientific and technical expertise.** The re-use of retired telecommunications cables may represent a significant opportunity for the ocean observatory community, but one that will likely exist only for a relatively short time. Due to a lack of appropriate expertise and time, this report does not evaluate the many technical, logistical, and financial issues associated with cable re-use for specific proposed observatory sites. It is strongly recommended, however, that NSF, perhaps through DEOS, constitute a committee with the appropriate expertise to thoroughly evaluate the potential benefits of utilizing retired telecommunications cables to provide power and bandwidth to some of the proposed observatory sites.
- **A core suite of instruments should be installed on every observatory node and funded as part of the basic observatory infrastructure, not only to test system functionality, but also to provide the essential scientific context for the observatory's effective use in basic research.** While the majority of funding for scientific instruments and experiments used with ocean observatories are expected to come from project-related sources, a core instrument suite at each node is an essential element of

observatory infrastructure that should be supported through the NSF's MREFC grant program, even if doing so means that fewer resources are available for acquiring the cables, moorings, and junction boxes that comprise the basic system infrastructure. Such core instruments could include: (1) engineering or system management sensors used to determine the operational status of the system and (2) COTS instruments that make basic physical, chemical, and biological measurements essential to a broad spectrum of ocean research. Data from these core instruments should be available to any interested investigator in real-time, or as soon as is practical, through the observatory data management system. Core instrument needs will vary widely for different classes of observatories and will depend on the scientific objective(s) of each node. The proponents of each observatory system will be in the best position to judge the trade-off between resources invested in observatory hardware (i.e., the number of moorings or kilometers of cable) and those invested in core instruments.

- **A separate, well-funded observatory instrumentation program at NSF, and contributions from other agencies with an interest in ocean research, will be required to obtain the full suite of sensors and instruments needed to fully exploit the scientific potential of the ocean observatory infrastructure.** A program within the NSF's Ocean Sciences Division in which peer-reviewed proposals to acquire new observatory sensors and instrumentation are eligible for funding will be essential to the long-term scientific success of the research-driven observatory network. Peer review will ensure that investments in new instrumentation are based on the strongest scientific rationale and potential payoff. Given the lead-time involved in constructing and acquiring new instrumentation, the NSF is encouraged to establish an "Ocean Observatory Instrumentation Program" well in advance of these observatories becoming operational. As instrumentation needs at observatories will evolve continuously, a program like this one will be needed as long as the observatories remain in operation. There may be significant potential for support for ocean observatory instrumentation from other agencies with an interest in ocean research, and the NSF is encouraged to explore these options, perhaps through an interagency mechanism such as the NOPP.
- **The NSF should augment its programs in instrumentation development, support, and calibration for observatory-capable sensors, including increasing grant duration to ensure that instrumentation groups have the capability to support the needs of the OOI. High priorities include the development of chemical and biological sensors, sensors less subject to biofouling and corrosion, sensors capable of surviving in more extreme environments, and more accurate sensors.** A major effort will also be required to develop a new generation of instruments and sensors for ocean observatory science. Sensor technology, particularly *in*

situ chemical and biological sensors, is not sufficiently advanced to take optimal advantage of the planned observatory infrastructure. In addition, improvements in many existing sensors are needed in order for them to operate unattended for long periods of time in an observatory setting, especially at high latitudes in the Southern Ocean or Arctic, as well as to mitigate problems such as biofouling. Given the magnitude of this need for ocean observatory science, a special program in observatory sensor development may be needed both to develop new instruments and to transition them from a research tool to an observatory-capable sensor.

- **The NSF should work with other agencies engaged in long-term ocean observations to ensure that the national resources for instrumentation, maintenance and calibration facilities, and technical staff are in place and have the necessary funding stability to support the OOI.** In recent years, the number of groups in the U.S. engaged in deploying moorings and maintaining moored instrumentation has decreased and the size of many of the groups that remain has decreased. The present infrastructure is inadequate to meet the considerably expanded needs for instrument maintenance and calibration that will arise from the establishment of both research-driven and operational observing systems in the coming decade. The NSF needs to work with other agencies supporting Earth and ocean-observing systems to ensure that adequate support is available for both facilities and support staff for observatory instrument maintenance and calibration. The workforce training needs faced by the academic community are shared by industry, which may create opportunities for industry-academic partnerships to meet these needs.
- **The NSF should work with other interested agencies in the U.S. and in other nations that are involved with establishing ocean-observing systems in order to ensure that centers are established and funded to process and archive data collected by ocean observatories, and to make these data readily accessible for basic research, for operational needs, and to the general public.** Data from ocean observatories must be professionally managed and distributed through established data centers according to nationally and internationally agreed upon standards. Due to the interdisciplinary nature of the data that will be collected at ocean observatories, data will not be stored in a single central archiving center, but rather in a network of distributed centers dedicated to particular data types. The program will need to provide tools for scientists to search and retrieve data across this distributed network of data centers, which data archive centers will require sustained funding to support data archival and distribution even beyond the end of the program.
- **The OOI program should have an open data policy with data from all core instrumentation and community experiments made publicly available in as near to real-time as possible.** An open data policy

will maximize the scientific utilization of ocean observatory data. By making it easier for scientists anywhere in the world to access these data, such a policy will, over time, significantly increase the size of the research community working on ocean-related problems. An open data policy will also encourage the use of observatory data or data products for education, in public policy and decision-making, and for use by the general public. In the case of purely experimental instrument data, raw data with a good documentation should be archived even if quality control procedures cannot be determined.

- **Standards for data interchange, for data and metadata formats, and for archiving methods should be established for all types of ocean observatories and should be coordinated and integrated with other research-based international observatory efforts, IOOS, and GOOS.** There should be a Data Management Committee at the OOI program level to establish guidelines and extensible standards for metadata and to identify or develop a data and metadata search and retrieval framework to enable searches across multiple data repositories established by the observatory program. This committee should also identify or develop well-documented and reliable standards and protocols to guarantee interoperability amongst all data centers. Development of standards and protocols should be coordinated with other national and international programs.
- **Education and public outreach activities for observatory science should be coordinated at the program level by a professional staff supported by funding at both the program and project level. Observatory education programs should be designed to meet National Science Education Standards, and carried out as a collaborative effort with the National Sea Grant Program and the Centers for Ocean Science Education Excellence (COSEE).** Many aspects of observatory research make it ideal for education and public outreach programs, especially the capabilities of observatories for real-time transmission of video and for real-time instrument control. Education and public outreach needs to be an important objective of the observatory effort in order to involve students, teachers, university faculty, pre-college teachers, K-12 students, and the interested public in the excitement of ocean science research and the release of this data. Education programs should harness this excitement to help meet NSES, however. Implementation of an education and public outreach program through collaborative efforts with the National Sea Grant Program and COSEE is strongly encouraged.
- **The NSF or the OOI Program Office, once it is established, should solicit proposals for a workshop to address the EPO issues raised in this report and to develop a specific EPO implementation plan for ocean research observatories, including recommending a budget for EPO activities.** Experience has shown that education and outreach efforts

will be more successful and more cost-effective if they are part of the initial observatory design and not an afterthought. The success of the EPO program will only be realized if there is a meaningful financial commitment to this effort at all program levels, and if individual investigators are provided the incentives and the support to incorporate innovative ways of presenting their data to K-12 students, pre-college teachers, and the general public.

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Appendix A

Committee and Staff Biographies

COMMITTEE MEMBERS

Robert S. Detrick, Jr. (*Chair*) obtained his Ph.D. in 1978 in Marine Geophysics from the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program in Oceanography. Dr. Detrick has worked as a Senior Scientist at the Woods Hole Oceanographic Institution (WHOI) since 1991. His research focuses on oceanic crustal structure, thermal evolution of the lithosphere, tectonics of accretionary plate boundaries, and the dynamics of the oceanic upper mantle. Dr. Detrick is currently the Chair of the Department of Geology and Geophysics at Woods Hole. He served as Vice-chair on the previous National Research Council seafloor observatory study, officially called the *Committee on Seafloor Observatories: Challenges and Opportunities*. Dr. Detrick is a former member of the Ocean Studies Board.

Arthur B. Baggeroer received his Sc.D. from the Massachusetts Institute of Technology (MIT) in 1968. He is currently the Ford Professor of Engineering and holds the Secretary of the Navy/Chief of Naval Operations Chair for Ocean Science in the Department of Ocean and Electrical Engineering at the Massachusetts Institute of Technology. His areas of expertise include applications of signal and array processing to ocean and structural acoustics, sonar, ocean engineering, remote sensing, and geophysics. Dr. Baggeroer has been a member of the National Academy of Engineering since 1995, and currently serves on the Ocean Studies Board and the

Naval Studies Board. In addition, he has served on several of The National Academies' committees and panels. He was the former Director of the Massachusetts Institution of Technology-Woods Hole Oceanographic Institution Joint Program for oceanography and ocean engineering.

Edward F. DeLong holds a Ph.D. in Marine Biology from UC San Diego, Scripps Institution of Oceanography. He is a senior scientist and head of the microbial oceanography group at the Monterey Bay Aquarium Research Institute (MBARI). In addition, he is an adjunct professor at UC Santa Cruz and a Courtesy Professor at Stanford. Dr. DeLong's research interests include marine microbial biology, microbial evolution and ecology, and genomic approaches in environmental microbiology.

Frederick K. Duennebier earned his Ph.D. in Geophysics from the University of Hawaii in 1972. He is a geophysicist at the University of Hawaii. His research interests include seismic studies in remote locations, marine geophysical instrumentation, ocean floor observatories, and volcano seismology in the marine environment. He is currently involved with three ocean bottom observatory efforts (HUGO, H2O, and ANZCAN-ALOHA). He has been the principal investigator on multiple deep-sea and seafloor studies sponsored by the National Science Foundation, the Office of Naval Research, and the U.S. Navy.

Ann E. Gargett earned her Ph.D. in Physical Oceanography from the University of British Columbia in 1970. She is currently a Professor of Oceanography at Old Dominion University. Her research interests include ocean mixing processes and new observational techniques to measure these processes, especially in coastal areas as well as biophysical interactions of planktonic organisms with turbulence. She is currently a member of the Scientific Steering committee for the Coastal Ocean Processes Project (CoOP) and the Scientific Steering Committee of Scientific Cabled Observatories for Time Series (SCOTS). In addition, she served on the Science Committee for NEPTUNE Canada during 1999-2001.

G. Ross Heath obtained his Ph.D. in Oceanography from the Scripps Institution of Oceanography in 1968. He is a professor of Oceanography and Dean Emeritus of the College of Ocean and Fishery Sciences at the University of Washington. His research interests are in the geochemistry of deep-sea sediments and its application to paleoceanography, paleoclimatology, deep-sea ferromanganese nodules, and the interaction of radioactive wastes with deep-sea sediments. He has worked on cabled deep-sea observatories and is a consultant on the NEPTUNE program. He has served on thirteen NRC committees and panels, including the Ocean Sciences Board (predecessor to the Ocean Studies Board), Board on Radioactive Waste Management, and as Chair of the Board on Ocean Science and Policy.

Jason J. Hyon received his Master of Science in Electrical Engineering (MSEE) from the University of Southern California in 1988. He is a deputy manager of the Earth Science Data Systems section at the Jet Propulsion Laboratory in Pasadena, California. In this position, he oversees ground data system developments for NASA Earth science missions, including MISR and ASTER on *Terra*; AIRS on *Aqua*; TES on *Aura*; *Topex/Poseidon*; and SeaWinds on *ADEOS*. His interests include real-time system development, data distribution and archival mass storage system design, volume and file structure standard, and Internet/Intranet-based multimedia database systems. He has developed and managed information management systems for the Department of Defense and Department of Energy.

Thomas C. Johnson earned his Ph.D. in Oceanography from the University of California at San Diego in 1975. He is a Professor of Geology and Director of the Large Lakes Observatory at the University of Minnesota-Duluth. His research interests are acoustic remote sensing of large lake basins using high-resolution seismic reflection profiling, side scan sonar and multi-beam sonar, sedimentary processes in large lakes, and paleoclimatology based on the analysis of lake sediment cores. He formerly served on the faculty of Duke University for eleven years. He was a Fulbright Scholar in 1993-1994 in France. He serves as a member of the Great Lakes Research Managers Council, International Joint Commission, and as a member of the Steering committee of the International Decade for East African Lakes (IDEAL).

Andrew (Drew) Michel has over 35 years of technical and senior management experience in deep water operations. He formed the first major commercial ROV operation in the offshore industry in 1976 and founded the first engineering consulting firm dedicated exclusively to ROV Technology in 1986. He is the owner and principal consultant of ROV Technologies, Inc., a partner and board member of the TSC Holdings Group of Companies and serves on the board of directors of Torch Offshore. He is a senior member of the IEEE and a fellow in the Marine Technology Society, serving as chair of the MTS ROV Committee. He is the co-chair of the annual Underwater Intervention Conference and was a steering committee member in 2001 for the Society of Petroleum Engineers' annual North America Forum Series on Subsea Technology. He is vice chairman of the National Ocean Industries Association Technology Policy Committee. He served on a previous NRC Committee on the Nation's Needs for

Undersea Vehicles. In 1990 he was a recipient of the Engineering News Record award for Outstanding Engineering Achievement. He was the 1997 recipient of the Lockheed-Martin Award for Ocean Science and Engineering for his overall contribution to the development of ROV technology.

Joan Oltman-Shay has a B.S. degree in Applied Physics and Electrical Engineering from the University of California, San Diego, an M.S. degree in Applied Ocean Sciences, and a Ph.D. in Oceanography from Scripps Institution of Oceanography. She is currently the president of NorthWest Research Associates, an earth-science research group owned and operated by the Principal Investigators, and an affiliate in the School of Oceanography of the University of Washington. Dr. Oltman-Shay's research interests include nearshore fluid and sediment dynamics, remote sensing of the nearshore environment, design and application of sensor arrays for ocean wave directional measurements, and the design, development, and field testing of *in situ* sensor packages and real-time data acquisition systems. Her previous National Academies experience includes being a member of the Steering Committee for the Symposium of Oceanography for Naval Special Warfare, the Chair of a Committee to Review the USGS Coastal and Marine Geology Program, and a member of the Committee on High-Priority Science to Meet National Coastal Needs.

Sylvie Pouliquen earned a Ph.D. in Computer Engineering from the Institut National des Sciences Appiquées in Rennes, France in 1983. She is currently the head of the Coriolis project at IFREMER (Institut français de recherche pour l'exploitation de la mer, or the French Research Institute for Exploitation of the Sea) located in Plouzané, France. The Coriolis project is a collaboration between 7 French institutions with the goal of building a real-time and delay mode *in situ* data center for several structures to collect, validate, and distribute ocean data to scientific communities and modelers. The Coriolis project also organizes data collection at sea from profilers, oceanographic vessels, drifting moorings. Dr. Pouliquen's research interests include satellite altimetry and *in situ* data management. Dr. Pouliquen also serves as the co-chair of the Argo Data Management Committee, and as the head of one of the two Global ARGO Data centers in the world. Formerly, Dr. Pouliquen headed IFREMER's CERSAT Satellite Data Centre for nine years.

Oscar M. E. Schofield obtained his Ph.D. in Biology from the University of California, Santa Barbara in 1993. He is currently a tenured associate professor at the Institute of Marine and Coastal Science at Rutgers University. His research interests include the environmental regulation of primary productivity in aquatic ecosystems, ecology of phytoplankton and the implications for biogeochemical cycles in the oceans, hydrological optics, and developing integrated ocean observatories. In addition to being an invited scientist for several workshops on ocean observatories, he has been one of the principal investigators responsible for developing the shelf-wide ocean observation system in the Mid-Atlantic Bight.

Robert A. Weller received his Ph.D. in 1978 from Scripps Institution of Oceanography. He is the Director of the Cooperative Institute for Climate and Ocean Research at Woods Hole Oceanographic Institution and has worked at the Woods Hole Oceanographic Institution since 1979. His research focuses on atmospheric forcing (wind stress and buoyancy flux), surface waves on the upper ocean, prediction of upper ocean variability, and the ocean's role in climate. He serves as the Secretary of the Navy Chair in Oceanography. He has been on multiple mooring deployment cruises and has practical experience with ocean observation instruments.

NATIONAL RESEARCH COUNCIL STAFF

Joanne C. Bintz earned her Ph.D. in Biological Oceanography from the University of Rhode Island Graduate School of Oceanography. Dr. Bintz has conducted research on the effects of decreasing water quality on eelgrass seedlings and the effects of eutrophication on shallow macrophyte-dominated coastal ponds using mesocosms. She has directed National Research Council studies on *The Review of the Florida Keys Carrying Capacity* and *Chemical Reference Materials: Setting the Standard for Ocean Science*. Her interests include coastal ecosystem ecology and function, eutrophication of coastal waters, seagrass ecology and restoration, oceanographic education, and coastal management and policy.

Nancy A. Caputo received a master's of public policy from the University of Southern California and a bachelor's degree in political science/international relations. During her tenure with the Ocean Studies Board, she has assisted with the completion of three reports: *A Review of the Florida Keys Carrying Capacity Study* (2002), *Emulsified Fuels—Risks and Response* (2002), and *Decline of the Steller Sea Lion in Alaskan Waters—Untangling Food Webs and Fishing Nets* (2003). Ms. Caputo has previous professional experience researching fisheries management in the northeastern and northwestern United States, socioeconomic assistance programs for fishing communities, and habitat restoration programs. Her interests include marine policy and science, oceanographic education, coastal management, and habitat restoration.

Appendix B

Acronym List

AAIW	Antarctic Intermediate Water
ABE	Autonomous Benthic Explorer
ACT	Alliance for Coastal Technologies
ADEOS	Advanced Earth Observing System (Japan)
AIRS	Atmospheric Infrared Sounder
ALOHA	A Long-term Oligotrophic Habitat Assessment Station
ALOOS	Acoustically-Linked Ocean Observing System
API	Application Programming Interface
ARENA	Advanced Real-Time Earth Monitoring Network in the Area
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ASW	Anti-Submarine Warfare
AUV	Autonomous Underwater Vehicle
AWI	The Alfred Wegener Institute
B-DEOS	British-Dynamics of Earth and Ocean Systems
BATS	Bermuda Atlantic Time-series Station
BCKDF	British Columbia Knowledge and Development Fund
BIO	Bedford Institute of Oceanography (Canada)
BTM	Bermuda Testbed Mooring
C-GOOS	Coastal Global Ocean Observing System
CCSP	Climate Change Science Program

CDIP	Coastal Data Information Program (Australia)
CERSAT	Centre ERS d'Archivage et de Traitement (see ERS)
CFI	Canadian Foundation for Innovation
CICEET	Cooperative Institute for Coastal and Estuarine Environmental Technology
CIS	Central Irminger Sea
CLIVAR	Climate Variability and Predictability Programme
CO_2	Carbon Dioxide
CoOP	Coastal Ocean Processes Program
COOP	Coastal Ocean Observations Panel
CORE	Consortium for Oceanographic Research and Education
COSEE	Center for Ocean Sciences Education Excellence
COTS	Commercial Off-The-Shelf
CRAB	Coastal Research Amphibious Buggy
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
CTD	Conductivity, Temperature and Depth
DAC	Data and Communications (subsystem of IOOS)
DART	Deep-Ocean Assessment and Reporting of Tsunamis
DEOS	Dynamics of Earth and Ocean Systems
DESCEND	Developing Submergence Science for the Next Decade
DESSC	Deep Submergence Science Committee (of UNOLS)
DMAS	Data Management and Archiving System (referring to NEPTUNE's system)
DMS	Data Management System (for OOI)
DODS	Distributed Oceanographic Data System
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EM	Electro-Mechanical
ENSO	El Niño Southern Oscillation
EOM	Electro-Optical-Mechanical
EPO	Education and Public Outreach
ESTOC	European Station for Time-series in the Ocean Canary islands
EU	European Union
FLIP	Floating Instrument Platform
FOFC	Federal Oceanographic Facilities Committee
FRF	Field Research Facility (in Duck, North Carolina)
FY	Fiscal Year

GCOS	Global Climate Observing System
GEO	Global Eulerian Observatory
GHRSST	GODAE High-Resolution Sea Surface Temperature
GLOBEC	Global Ocean Ecosystem Dynamics Programme
GODAE	Global Ocean Data Assimilation Experiment
GOOS	Global Ocean Observing System
GPS	Global Positioning System
GSN	Global Seismic Network
H2O	Hawaii-2 Observatory
HAW-2	Hawaii-2 Observatory’s telecommunications cable
HLA	Horizontal Line Array
HOT	Hawaii Ocean Time-series program
HOV	Human Occupied Vehicle
HUGO	Hawaii Undersea Geo-Observatory
IDEA	Instrumentation Development for Environmental Activities
IDEAL	International Decade for East African Lakes
IfMK	Institut für Meereskinde an der Universität Kiel
IFREMER	Institut français de recherche pour l’exploitation de la mer
IGBP	International Geosphere-Biosphere Programme
IOC	International Ocean Commission
ION	International Ocean Network
IOOS	Integrated and Sustained Ocean Observing System
IRIS	Incorporated Research Institutes for Seismology
ISS	Integrated Study Site
ITAR	International Traffic in Arms Regulations
IUSS	Integrated Undersea Surveillance System
JAMSTEC	Japan Marine Science & Technology Center
JCOMM	Joint Commission for Oceanography and Marine Meteorology
JGOFS	Joint Global Ocean Flux System
JPL	Jet Propulsion Laboratory
KERFIX	Kerguelen Fixed Station (of the Kerguelen Islands Time-Series Measurement Programme)
KNOT	Kyodo North Pacific Ocean Time-Series Station
LDEO	Lamont Doherty Earth Observatory
LEO-15	Long-term Ecosystem Observatory (at 15 Meters Depth)

MARS	Monterey Accelerated Research System
MBARI	Monterey Bay Aquarium Research Institute
MISR	Multi-angle Imaging SpectroRadiometer
MIT	Massachusetts Institute of Technology
MMS	Minerals Management Service
MONCOZE	Monitoring the Norwegian Coastal Zone Environment
MOOS	MBARI Ocean Observing System
MOVE	Meridional Overturning Variability Experiment
MREFC	Major Research Equipment and Facilities Construction
MTS	Marine Technology Society
MVCO	Martha's Vineyard Coastal Observatory
NASA	National Aeronautics and Space Administration
NDBC	National Data Buoy Center
NDSF	National Deep Submergence Facility
NEPTUNE	NorthEast Pacific Time-series Undersea Networked Experiments (U.S.)
NOAA	National Oceanic and Atmospheric Administration
NODC	National Oceanographic Data Center
NOPP	National Oceanographic Partnership Program
NORLC	National Ocean Research Leadership Council
NRC	National Research Council
NSF	National Science Foundation
NSES	National Science Education Standards
NTAS	Northwest Tropical Atlantic Station
O&M	Operation and Maintenance
OAR	Office of Atmospheric Research (at NOAA)
ODP	Ocean Drilling Program
OGP	Office of Global Programs (at NOAA)
OHP	Ocean Hemisphere Project
ONR	Office of Naval Research
OOI	Ocean Observatories Initiative
OOPC	Ocean Observations Panel for Climate
OOSDP	Ocean Observation System Development Panel
OROPC	Ocean Research Observatories Program Center
OSN	Ocean Seismic Network
OWS	Ocean Weather Service (U.S.)
OWS	Ocean Weather Ship Station M (in Norway)
PAP	Porcupine Abyssal Plain
PI	Principal Investigator
PIRATA	Pilot Research Moored Array in the Tropical Atlantic

PO.DAAC	Physical Oceanography Distributed Active Archive Center
POGO	Partnership for Observation of the Global Ocean
QC	Quality Control (of data)
REVEL	Research and Education: Volcanoes, Exploration, and Life (at UW)
RIDGE	Ridge Inter-Disciplinary Global Experiments
RIN	Remote Instrument Node
ROADNet	Real-time Observatories, Applications, and Data Management Network
ROPOS	Remotely Operated Platform for Ocean Science
ROV	Remotely Operated Vehicle
RSM	Regional Sediment Management
RSMAS	Rosenstiel School of Marine and Atmospheric Science
SCOTS	Scientific Cabled Observatories for Time-series
SDSC	San Diego Supercomputer Center
SECNAV	Secretary of the Navy
SEED	Standard for the Exchange of Earthquake Data
SIIMs	Scientific Instrument Interface Modules
SIO	Scripps Institution of Oceanography
SOEST	School of Ocean and Earth Science and Technology (University of Hawaii)
SOLAS	Surface Ocean Lower Atmosphere Study
SOSUS	Sound Surveillance System
SSBN	Fleet ballistic missile submarine
SWATH	Small Water-plane Area Twin Hull
TAO	Tropical Atmosphere Ocean Project
TES	Tropospheric Emission Spectrometer
TOGA	Tropical Ocean Global Atmosphere
TRITON	Triangle Trans-Ocean Buoy Network
TSST	Time-series Science Team
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNOLS	University–National Oceanographic Laboratory System
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
US JGOFS	United States Joint Global Ocean Flux Study

VENUS	Victoria Experimental Network Under the Sea
VLA	Vertical Line Array
WHOI	Woods Hole Oceanographic Institution
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
WWW	World Weather Watch
XBT	Expendable Bathythermograph

GLOSSARY

Acoustics: a science that deals with the production, control, transmission, reception, and effects of sound.

ANZCAN: a retired Australia-New Zealand-Canada Trans-Pacific telecommunication cable.

Argo: GODAE global profiling float project (not an acronym). For additional information, see *http://www.argo.ucsd.edu/.*

Autonomous Underwater Vehicle (AUV): a vehicle that can function without tethers, cables, or remote control, they have a multitude of applications in oceanography, environmental monitoring, and underwater resource studies.

Bandwidth: the data transfer capacity of an electronic communications system.

C-Band: one of ten satellite communication frequency ranges. Its range is between 5.9 and 6.4 GHz for uplink and between 3.7 and 4.2 GHz for downlink. C-Band is mainly used for domestic and commercial satellite communication systems.

Calibrate: to standardize a measuring instrument by determining the deviation from a standard so as to ascertain the proper correction factors.

Climate Variability and Predictability Programme (CLIVAR): an international research program addressing issues of natural climate variability and anthropogenic climate change.

Commercial Off-The-Shelf (COTS): a product that is used "as-is." COTS products are designed to be easily installed and to interoperate with existing system components. Almost all software bought by the average computer user fits into the COTS category: operating systems, office product suites, word processing, and e-mail programs are among the myriad examples.

Consortium for Oceanographic Research and Education (CORE): a non-profit, Washington, DC-based organization that represents 73 of the nation's academic institutions, aquaria, non-profit research institutes and federal research laboratories with the common goal of promoting and enhancing the visibility and effectiveness of ocean research and education. For additional information; see *http://www.nopp.org/Dev2Go.web?Anchor=idune&rnd=8075*.

CTD Profiler (conductivity, temperature, and depth): a physical measurement system that utilizes modular sensor technology to allow absolutely synchronous sampling of the conductivity, temperature, and pressure sensors.

Data pull: in which a client acquires data from a source by requesting data.

Data push: in which a source disseminates data to a client.

Delivery medium: the means through which data is delivered using different media (e.g., on line via the Internet, on CD-ROM, DVD, tapes) as needed by users.

Discus Buoy: a buoy with a circular, disk-shaped hull.

Earthscope: an undertaking to apply modern observational, analytical, and telecommunications technologies to investigate the structure and evolution of the North American continent and the physical processes controlling earthquakes and volcanic eruptions.

Eulerian: in this context, something that is fixed rather than free-floating.

Geodetic: concerning a branch of applied mathematics concerned with the determination of the size and shape of the earth and the exact positions of points on its surface and with the description of variations of its gravity field.

Geomagnetism: terrestrial magnetism.

Geophysics: a branch of earth science dealing with the physical processes and phenomena occurring in the earth and in its vicinity.

GeO-TOC: formally TPC-1, the first U.S.-Japan trans-ocean telecommunications cable in the Pacific (now retired).

Gimbal: a device that permits a body to incline freely in any direction or suspends it so that it will remain level when its support is tipped.

Glider: an AUV with wings and ballast tanks rather than propellers or motors, which allows them to have a much greater time in water, since they are not limited to the amount of battery power they carry.

Global Ocean Data Assimilation Experiment (GODAE): an experiment in which a comprehensive, integrated observing system would be established and held in place for several years and the data assimilated into state-of-the art models of the global ocean circulation in near real-time. For additional information, see *http://www.bom.gov.au/bmrc/ocean/GODAE.*

Global Ocean Ecosystem Dynamics (GLOBEC): one of the 9 core projects of the *International Geosphere-Biosphere Programme* (IGBP). The aim of GLOBEC is to advance understanding of the structure and functioning of the global ocean ecosystem, its major subsystems, and its response to physical forcing.

Global Ocean Observing System (GOOS): a system to implement operational observation programs for the oceans and coastal areas. It is sponsored by the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the International Council for Science (ICSU), the United Nations Environment Programme (UNEP), and the World Meteorological Organization (WMO), with its GOOS Project Office at IOC in Paris. For additional information, see *http://ioc.unesco.org/igospartners/g3os.htm#Global%20Ocean%20Observing*.

Hydrophone: an instrument for listening to sound transmitted through water.

International Ocean Network (ION): a committee established in June 1993 with the goal of facilitating international cooperation in the development of ocean-bottom observatories.

in situ: Latin, the natural or original position or place.

Interface: the place at which independent and often unrelated systems meet and act on or communicate with each other.

The JASON Project: a real-time multi-disciplinary education program, started by Robert Ballard in 1989 and administered by the JASON Foundation for Education, that uses multi-media tools (online chats with researchers, online journals, digital labs, live broadcasts from scientific expeditions, etc.) to educate students and enhance the classroom experience.

Jason II: a remotely operated vehicle (ROV) put into service in 2002, designed and operated by the Woods Hole Oceanographic Institution. *Jason II* operates at depths up to 6,500 meters and can install, service, repair and recover a variety of ocean observatory equipment, as well as perform its own detailed survey and sampling tasks (see Figure 5.3).

Java™: a programming language developed by SUN to run codes in hardware independent environments. For additional information, see *http://java.sun.com/*.

JAXR (The Java API for XML Registries): enables Java software programmers to use a single set of APIs (application programming interfaces) to access a variety of XML registries. In this context, an XML registry is an enabling infrastructure for building, deploying, and discovering web services. For additional information, see XML in this glossary.

Joint Global Ocean Flux Study (JGOFS): an international and multidisciplinary program to assess and better understand the processes controlling regional-to-global and seasonal-to-interannual fluxes of carbon between the atmosphere, surface ocean, and ocean interior, and their sensitivity to climate changes.

Lagrangian: in this context, a buoy or instrument not fixed in one place.

Level 0: a primary raw data stream collected directly from the instrument.

Level 1: raw data corrected from instrumental error to which calibration factors have been applied.

Level 2: raw data converted to geophysical units, that have had QC checks applied to measurements. In other words, formatted data with metadata.

Level 3: a derived or calculated data product that applies statistical methods to one or more measured data (Level 2) used as input.

Level 4: further processing based on the Level 2 and/or Level 3 data that merges datasets of different types.

MARGINS: a program that seeks to understand the complex interplay of processes that govern continental margin evolution.

Monterey Accelerated Research System (MARS): a cabled observatory to be located in Monterey Bay recently funded by the NSF. It proposed a testbed for a high power, high bandwidth, regional cabled observatory. For additional information, see *http://www.mbari.org/mars*.

Mooring: a device (e.g., a line or chain) by which an object is secured in place.

National Oceanographic Partnership Program (NOPP): established in 1997 through Public Law 104-201 to promote an improved knowledge of the ocean and to coordinate and strengthen oceanographic efforts by building partnerships among federal agencies, academia, industry, and other members of the oceanographic community. Sponsored by the Navy, the NSF, NOAA, NASA, and the Alfred Sloan Foundation. For additional information, see *http://www.nopp.org*.

Ocean Drilling Program (ODP): an international partnership of scientists and research institutions organized to explore the evolution and structure of Earth. For additional information, see *http://www.oceandrilling.org*.

Ocean Observing System Development Panel (OOSDP): a panel established in 1990 to formulate a conceptual design of a long-term, systematic observing system to monitor, describe, and understand the physical and biogeochemical processes that determine ocean circulation and the effects of the ocean on seasonal to decadal climate changes as well as to provide the observations needed for climate predictions.

Ocean Observations Panel for Climate (OOPC): a panel established in 1995 to develop the scientific basis for an ocean observing system for climate. For additional information, see *http://ioc.unesco.org/oopc/about.html*.

Ocean Seismic Network (OSN): a Joint Oceanographic Institutions' program responsible for coordinating ongoing efforts to develop a global network of permanent seismic observatories on the deep ocean floor as part of the planned Global Seismic Network.

Partnership for Observation of the Global Ocean (POGO): an organization that aims to bring together major oceanographic institutions under a single umbrella.

Pilot Research Moored Array in the Tropical Atlantic (PIRATA): a project that proposes to deploy and maintain, between 1997 and 2000, an array of 12 buoys with the principal objective of describing and understanding the evolution of sea surface temperature, upper ocean thermal structure and air-sea fluxes of momentum, heat and fresh water in the tropical Atlantic. For additional information, see *http://www.ifremer.fr/orstom/pirata/pirataus.html*.

Pioneer Array: a proposed relocatable observatory system for coastal research.

Remotely Operated Vehicle (ROV): an undersea vehicle operated from and tethered to an above water platform.

Ridge 2000: an interdisciplinary initiative to study oceanic spreading ridge systems as an integrated whole. It is a follow-on program of the RIDGE program. Ridge 2000 is not an acronym. Ridge 2000 is sponsored by the NSF. For additional information, see *http://ridge2000.bio.psu.edu*.

Spar Buoy: a buoy with a long straight hull.

Telemetry: a highly automated communications process by which measurements are made and other data collected at remote or inaccessible points and transmitted to receiving equipment for monitoring, display, and recording.

TPC-1: the first U.S.-Japanese trans-ocean telecommunications cable in the Pacific (now retired). Also see GeO-TOC.

University-National Oceanographic Laboratory System (UNOLS): an organization of 63 academic institutions and National Laboratories involved in oceanographic research joined for the purpose of coordinating oceanographic ships' schedules and research facilities. For additional information, see *http://www.unols.org/unols.html*.

VSAT (Very Small Aperture Terminals): small, software-driven earth receiving stations (typically 0.9-2.4 meters, or 3-8 feet, though larger units are available) used for the reliable transmission of data, video, or voice via satellite.

XML (Extensible Markup Language): the universal format for data on the Web. XML allows developers to easily describe and deliver rich, structured data from any application in a standard, consistent way. XML does not replace HTML, rather, it is a complementary format.

World Ocean Circulation Experiment (WOCE): a program designed to improve the ocean models necessary for predicting decadal climate variability and change.

Appendix C

Observatory Workshops and Workshop Reports

RECENT WORKSHOPS & RESULTING REPORTS

Nearshore Research Workshop

The Nearshore Research Workshop was sponsored by the NSF, NOAA, ONR, USACE, and USGS. Held in St. Petersburg, Florida on September 14-16, 1998, the workshop provided 68 scientists and engineers an opportunity to assess the current state of nearshore science, and identify research strategies, important scientific questions, and the infrastructure needed to address these questions.

Thornton, E., T. Dalrymple, T. Drake, E. Gallagher, R.Guza, A. Hay, R. Holman, J. Kaihatu, T. Lippmann, and T. Ozkan-Haller. 2000. *State of Nearshore Processes Research: II*. NPS-OC-00-001. Naval Postgraduate School, Monterey, CA. [Online] Available: *http://www.coastal.udel.edu/coastal/nearshorereport/nrwreport/html* [July 12, 2003].

OOPC and CLIVAR International Conference on Ocean Observing for Climate

The OceanObs ’99 Conference was held in Saint Raphael, France on October 18-22, 1999. Participants discussed an international strategy for an ocean- and climate-observing system.

Koblinsky, C.J., and N.R. Smith, eds. 2001. *Observing the Oceans in the 21st Century*. GODAE Project Office, Bureau of Meteorology, Melbourne, Australia, 604 pp.

UNOLS Workshop: Developing Submergence Science in the Next Decade (DESCEND)

The DESCEND workshop was held on October 25-27, 1999 at the National Science Foundation in Arlington, Virginia. The workshop provided 119 scientists, engineers and federal agency representatives an opportunity to discuss deep submergence science and technology.

Fryer, P., K. Becker, J. Bellingham, C. Cary, L. Levin, M. Lilley. 1999. *DESCEND Meeting Workshop Proceedings*. [Online] Available: *http://www.mlml.calstate.edu/unols/dessc/descend/descend.html* [July 12, 2003].

The National Research Council Symposium on Seafloor Observatory

The NRC Committee on Seafloor Observatories held a symposium on January 9-12, 2000 in Islamorada, Florida. Approximately 70 participants from all fields of earth and ocean science, engineering, and planetary exploration provided input on the scientific and technical needs associated with the establishment of a network of seafloor observatories.

National Research Council. 2000. *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science.* National Academies Press, Washington, DC. [Online] Available: *http://www.nap.edu/catalog/9920.html* [July 12, 2003].

Integrated and Sustained Ocean Observing System Workshop

The IOOS workshop was held on March 10-14, 2002 at Airlie Center in Warrenton, Virginia. Over 100 attendees worked from Sunday evening to Friday noon in intensive group sessions to complete a phased and prioritized implementation plan. The documents below reflect the sessions of this workshop.

Ocean.US. 2002a. *An Integrated and Sustained Ocean Observing System (IOOS) for the United States: Design and Implementation.* Ocean.US, Arlington, VA, 21pp. [Online] Available: *http://www.ocean.us/documents/docs/FINAL-ImpPlan-NORLC.pdf* [July 12, 2003].

Ocean.US. 2002b. *Building Consensus: Toward an Integrated and Sustained Ocean Observing System.* Ocean.US Workshop Proceedings. Ocean.US, Arlington, VA, 175pp. [Online] Available: *http://www.ocean.us/documents/docs/Core_lores.pdf* [July 12, 2003].

Office of Naval Research/Marine Technical Society Buoy Workshop 2002

The Buoy Workshop 2002 was held on April 9-11, 2002 in Seattle, Washington and was conducted with support from the Ocean Engineering and Marine Systems Group of the Office of Naval Research, and by the Marine Technology Society, based in Columbia, Maryland. For more information, see *http://www.whoi.edu/buoyworkshop/2002/program_final.html* [July 12, 2003].

Scientific Cabled Observatories for Time-series Workshop

The SCOTS Workshop was sponsored by the NSF and held on August 26-28, 2002 in Norfolk, Virginia. The workshop was convened to gain community input to define the scientific problems that require or would most effectively be addressed by regional-scale cabled observatory networks. In addition participants were asked to analyze the impact and feasibility of scientific questions considering current and emerging technological capabilities, determine the optimum locations for cabled observatories, and develop a phased implementation plan for the establishment of cabled observatories.

Dickey, T., and S. Glenn. 2003. *Scientific Cabled Observatories for Time-series (SCOTS) Report.* Draft. National Science Foundation, Arlington, VA, 92 pp.

Coastal Ocean Processes and Observatories: Advancing Coastal Research

The Coastal Observatory Science Workshop was held on May 7-9, 2002 in Savannah, Georgia and attended by 64 scientists from 20 states and Washington, D.C. as well as Canada and Great Britain. A total of 35 universities, government agencies, and other institutions were represented. A hard copy of the full report can be requested from the CoOP Office or can be attained via the internet (see below).

Jahnke, R., L. Atkinson, J. Barth, F. Chavez, K. Daly, J. Edson, P. Franks, J. O'Donnell, and O. Schofeld. 2002. *Coastal Ocean Processes and Observatories: Advancing Coastal Research.* Skidaway Institute of Oceanography Technical Report TR-02-01. Skidaway Institute of Oceanography, Savannah, GA. [Online] Available: *http://starbuck.skio.peachnet.edu/coop* [July 12, 2003].

SELECTED REPORTS/DOCUMENTS ON OCEAN OBSERVATORY SCIENCE

Bleck, R., A. Bennett, P. Cornillon, D. Haidvogel, E. Harrison, C. Lascara, D. McGillicuddy, T. Powell, E. Skyllingstad, D. Stammer, and A.J. Wallcraft (The OITI Steering Committee). 2002. *An Information Technology Infrastructure Plan to Advance Ocean Sciences.* Office of Naval Research, and the National Science Foundation, Arlington, VA. [Online] Available: *http://www.geo-prose.com/projects/pdfs/oiti_plan_lo.pdf* [July 12, 2003].

Brink, K.H., J.M. Bane, T.M. Church, C.W. Fairall, G.L. Geernaert, D.S. Gorsline, R.T. Guza, D.E. Hammond, G.A. Knauer, C.S. Martens, J.D. Milliman, C.A. Nittrouer, C.H. Peterson, D.P. Rogers, M.R. Romand, and J.A. Yoder. 1990. *Coastal Ocean Processes (CoOP) : Results of an Interdisciplinary Workshop.* Contribution No. 7584. Woods Hole Oceanographic Institution, Woods Hole, MA, 51pp.

Brink, K.H., J.M. Bane, T.M. Church, C.W. Fairall, G.L. Geernaert, D.E. Hammond, S.M. Henrichs, C.S. Martens, C.A. Nittrouer, D.P. Rogers, M.R. Roman, J.D. Roughgarden, R.L. Smith, L.D. Wright, and J.A. Yoder. 1992. *Coastal Ocean Processes: A Science Prospectus.* Technical Report WHOI-92-18. Woods Hole Oceanographic Institution, Woods Hole, MA, 88pp.

Clark, H.L. 2001. *New Seafloor Observatory Networks in Support of Ocean Science Research.* National Science Foundation, Arlington, VA, 6pp. [Online] Available: *http://www.coreocean.org/Dev2Go.web?id=232087&rnd=5565* [July 12, 2003].

Consortium for Oceanographic Research and Education (CORE). *A National Initiative to Observe the Oceans: A CORE Perspective.* Consortium for Oceanographic Research and Education, Washington, DC. [Online] Available: *http://www.coreocean.org/resources/nopp/initiative.pdf* [July 12, 2003].

DEOS Moored Buoy Observatory Working Group. 2000. *DEOS Moored Buoy Observatory Design Study.* Woods Hole Oceanographic Institution, Woods Hole, MA. [Online] Available at: *http://obslab.whoi.edu/buoy.html* [March 26, 2003].

Dickey, T., and S. Glenn. 2003. *Scientific Cabled Observatories for Time Series (SCOTS) Report.* Draft. National Science Foundation, Arlington, VA, 92pp.

Frosch, R., and the Ocean Observations Task Team. 2000. *An Integrated Ocean Observing System: A Strategy for Implementing the First Steps of* *a U.S. Plan.* National Oceanographic Partnership Program, Washington, DC. [Online] Available: *http://www.nopp.org/Dev2Go.web?id=220672&rnd=20328*.

Henrichs, S., N. Bond, R. Garvine, G. Kineke, and S. Lohrenz. 2000. Coastal Ocean Processes: Transport and Transformation Processes over Continental Shelves with Substantial Freshwater Inflows. Coastal Ocean Processes (CoOP) Report No. 7. University of Maryland Technical Report UMCES TS-237-00. University of Maryland Center for Environmental Science, Cambridge, 131pp.

Klump, J.V. K.W. Bedford, M.A. Donelan, B.J. Eadie, G.L. Fahnenstiel, and M.R. Roman. 1995. Coastal Ocean Processes: Cross-Margin Transport in the Great Lakes. *Coastal Ocean Processes (CoOP) Report No. 5.* UMCES TS-148-95. University of Maryland Center for Environmental Science, College Park, MD, 133pp.

NEPTUNE Phase 1 Partners (University of Washington, Woods Hole Oceanographic Institution, Jet Propulsion Laboratory, Pacific Marine Environmental Laboratory). 2000. *Real-time, Long-term Ocean and Earth Studies at the Scale of a Tectonic Plate.* NEPTUNE Feasibility Study prepared for the National Oceanographic Partnership Program. University of Washington, Seattle. [Online] Available: *http://www.neptune.washington.edu/pub/documents/documents.html#Anchor-NEPTUNE-33869* [March 26, 2003].

Smith, R.L., and K.H. Brink. 1994. *Coastal Ocean Processes: Wind-Driven Transport Processes on the U.S. West Coast.* Coastal Ocean Processes (CoOP) Report No. 4. Woods Hole Oceanographic Institution Technical Report WHOI-94-20. Woods Hole Oceanographic Institution, Woods Hole, MA, 134pp.

The Marine Research and Related Environmental Research and Development Programs Authorization Act of 1999. H.R. 1552.

The Oceans Act of 2000. Public Law 106-256, 2000. S. 2327.

University of Maryland Center for Environmental Science.1998. *Coastal Ocean Processes: Wind-Driven Transport Science Plan. Coastal Ocean Processes. CoOP Report No. 6.* UMCES TS-170-98. University of Maryland Center for Environmental Science, Cambridge, 18pp.

Vincent, C.L., T.C. Royer, and K.H. Brink. 1993. *Long Time-series Measurements in the Coastal Ocean: A Workshop.* Coastal Ocean Processes (CoOP) Report No. 3. Woods Hole Oceanographic Institution Technical Report WHOI-94-20. Woods Hole Oceanographic Institution, Woods Hole, MA, 96pp.

Appendix D

Ocean Observation Programs Mentioned in This Report

Argo

Argo is a joint GODAE and CLIVAR project consisting of a global array of 3,000 free-drifting profiling floats that will measure the temperature and salinity of the upper 2000 m of the ocean in real-time. There are currently 700 active floats in the water. Prospects for achieving a complete 3,000-float array by the end of 2005 are strong. The first scientific results will be available in 2003. For additional information, see: *http://www.argo.ucsd.edu/*.

Bermuda Atlantic Time-series Station

BATS was established as part of the US JGOFS program in 1988, with multi-disciplinary ship-based sampling near the original 1977 sediment trap mooring site (~80 km southeast of Bermuda). The objective of BATS is to characterize, quantify, and understand processes that control ocean biogeochemistry, especially carbon, on seasonal to decadal time-scales. For additional information, see: *http://www.bbsr.edu/cintoo/bats/bats.html*.

Bermuda Test Mooring

The BTM, funded by the NSF, was deployed in June 1994 and provides the oceanographic community with a deep-water platform for developing, testing, calibrating, and intercomparing instruments. The mooring is located approximately 80 km southeast of Bermuda. Instruments are being used to collect meteorological and spectral radiometric measurements from a buoy tower. Subsurface measurements include currents, temperature, conductivity, optical properties, and nitrate and trace element concentrations.

Hawaii-2 Observatory

The H2O was installed in 1998 on a retired AT&T submarine telephone cable (HAW-2) that runs between Oahu and Hawaii and the California Coast. The facility consists of a seafloor junction box and scientific sensors located in 5000 m of water about halfway between Hawaii and California. Instruments are connected to a junction box using an ROV. Present instrumentation includes a seismometer, a geophone, a hydrophone, and a pressure sensor. It is the first seafloor station of the GSN.

Hawaii Undersea Geo-Observatory

HUGO was installed in July, 1997 at Loihi Volcano, about 30 km Southeast of Hawaii (Duennebier, 2002). The observatory was operational until April 30, 1998, when the 47 km electro-optical cable to shore developed an electrical short circuit in the rough volcanic terrain. HUGO is an example of a near-shore observatory using a short (unrepeatered) optical cable. For additional information, see: *http://www.soest.hawaii.edu/HUGO/hugo.html*.

Long-Term Environmental Observatory

LEO-15 at 15 meters depth was established in 1996 with the installation of an electro-fiber-optic cable extending 5 km offshore of the Rutgers Marine Field Station off the central coast of New Jersey. The cable provides power and two-way communication to bottom robotic winch profilers. LEO-15 was designed to be an integrated system to assimilate data into forecast models, which can be used to adjust the sampling patterns of the field assets. Specific components of the LEO-15 network include meteorological, cable, remote sensing, and AUV observational components. For additional information, see: *http://marine.rutgers.edu/mrs/LEO/LEO15.html*.

Martha's Vineyard Coastal Observatory

The MVCO was constructed in 2000 and installed near South Beach in Edgartown, Massachusetts. The MVCO includes a small shore lab, a 10-m meteorological mast and an electro-optic cabled subsurface node mounted in 12 m water depth. The meteorological and sub-sea instrumentation are connected directly to the shore lab via a buried cable. The core set of instruments at the meteorological mast will measure wind speed and direction, temperature, humidity, precipitation, carbon dioxide, solar and IR radiation, and momentum, heat and moisture fluxes. The core oceanographic sensors at the offshore node measure current profiles, waves and temperature, salinity, turbidity, fluorescence, carbon dioxide, and near-bottom wave-orbital and low-frequency currents.

Monitoring the Norwegian Coastal Zone Environment (MONCOZE)

Monitoring the Norwegian Coastal Zone Environment (MONCOZE), funded by the Norwegian Research Council and the oil industry, is a shelf-wide observatory constructed in 2002 in the Norwegian Sea. It consists of a network of coastal surface and radar networks, ocean color and synthetic aperture satellite remote sensing. The objective of this observatory is to develop and demonstrate an environmental monitoring and prediction system for Norwegian coastal waters with a focus on dominant physical and coupled physical-biochemical interactive processes with the Norwegian Coastal Current and its boundaries.

Monterey Accelerated Research System

MARS will be installed with funding from the NSF and the David and Lucile Packard Foundation. It is designed to serve as a test bed for a future regional-scale cabled observatory. The cable will extend over 60 km offshore to an instrument node at ~1.2 km depth. Extension cords may be run by ROVs from the cable node up to several km away to provide flexibility in siting instruments.

North East Pacific Time-series Undersea Networked Experiments

The NEPTUNE project proposes to use fiber-optic cable to connect ~30 instrumented nodes on the Juan de Fuca plate in the northeast Pacific. Instruments connected to the nodes would provide physical, chemical, geological, and biological data in real-time. Details of the NEPTUNE project can be found at: *http://www.neptune.washington.edu/*.

Ocean Weather Service

The OWS was established after World War II for the primary purpose of guiding trans-ocean-voyaging aircraft. The U.S. and four other countries established 13 sites in the North Atlantic and Pacific Oceans (labeled alphabetically, starting with "A") that were continuously occupied by ships. In the 1970s, satellites began to provide jet aircraft with the positioning and weather information they needed. The program ended in 1981.

Pilot Research Moored Array in the Tropical Atlantic

PIRATA is a project that proposes to deploy and maintain an array of 12 buoys between 1997 and 2000, with the principal objective of describing and understanding the evolution of sea-surface temperature, upper-ocean thermal structure and air-sea fluxes of momentum, heat and fresh water in the tropical Atlantic. For additional information, see: *http://www.ifremer.fr/orstom/pirata/piratausm.html*.

Sound Surveillance System

The U.S. Navy began installation of SOSUS in the mid-1950s for use in antisubmarine warfare. SOSUS is a fixed component of the U.S. Navy's Integrated Undersea Surveillance System (IUSS) used for deep ocean surveillance during the Cold War. The system consists of bottom-mounted hydrophone arrays connected by undersea communication cables to facilities on shore. The individual arrays are installed primarily on continental slopes and seamounts at locations optimized for undistorted long range acoustic propagation. For additional information, see: *http://www.pmel.noaa.gov/vents/acoustics/sosus.html*.

Tropical Atmosphere Ocean Array

The TAO array consists of ~70 moorings in the tropical Pacific Ocean, telemetering oceanographic and meteorological data to shore in real-time via the Argos satellite system. The array is a component of the El Niño/Southern Oscillation (ENSO) observing system, the Global Climate Observing System (GCOS), and GOOS. Support is provided primarily by NOAA and Japan Science and Technology Center with contributions from France's IFREMER. For additional information, see: *http://www.pmel.noaa.gov/tao*.

U.S. Army Corps of Engineers Field Research Facility

The FRF is located on the Atlantic Ocean, in the town of Duck, on the Outer Banks of North Carolina. The FRF was established in 1977 by the USACE for the purpose of nearshore (beach face to nominally 10 m depth) field observations and experiments for coastal research and engineering. The FRF has maintained a long-term (25 year) monitoring program of coastal waves, tides, currents, local meteorology, and the concomitant beach bathymetric response at the site. For additional information, see: *http://www.frf.usace.army.mil*.

Victoria Experimental Network Under the Sea

VENUS is a proposed project to conduct coastal oceanography with a network of instruments located 4 km into Saanich Inlet from Pat Bay near Victoria and Vancouver, Canada. The three proposed cable lines include sections in the Strait of Georgia, Saanich Inlet, and the Juan de Fuca Strait. VENUS is intimately related to the proposed NEPTUNE observatory. For additional information, see: *http://www.venus.uvic.ca*.

Appendix E

Time-Series Group
Global Observatory Sites

Atlantic Ocean Sites

OB	FL	TR	Latitude/ Longitude	Status	Remarks
x			75N 3.5W	operating (AWI)	Greenland Sea, physical
x	x		66N 2E	operating (Norway)	Ocean Weather Ship Station M (OWS “Mike”), Norwegian Sea, physical, meteorology, biogeochemical
x			60N 36W	funded (EU)	Central Irminger Sea (CIS), physical, biogeochemical
x			57N 53W	operating (BIO, IfMK)	Bravo, Labrador Sea, physical, CO_2
x	x		49N 16.5 W	funded (EU)	Porcupine Abyssal Plain (PAP), meteorology, physical, biogeochemical
x	x		40N 70W	partially funded (WHOI)	Station W, meteorology, physical
	x		36N 70W	recommended	Gulf Stream extension flux reference
x	x		30N 42W	planned (DEOS)	North Atlantic DEOS, geophysics, meteorology, physical, biogeochemical
x			33N 22W	operating (IfMK)	K276, Azores Front/Madeira Abyss. Plain, physical/ biogeochemical

OB	FL	TR	Latitude/ Longitude	Status	Remarks
x	x		32N 65W	observatory operating (US)	BATS/Station S/BTM, physical, meteorology, biogeochemical
x			29N 16W	funded, partially operating (EU)	European Station for Time-series in the Canary Islands (ESTOC), physical, meteorology, biogeochemical
x			27N 77W	planned (RSMAS)	Abaco, physical
x			16N 60W	operating (IfMK)	CLIVAR/MOVE western site, physical
x	x		15N 51W	operating (WHOI, IfMK)	NTAS and MOVE eastern site, meteorology, physical
x			0N 20W	recommended	biogeochemical sensors on existing PIRATA mooring
	x		10S 10W	recommended	flux reference on existing PIRATA mooring
x			31S 39W	planned (WHOI, IfMK)	VEMA channel, physical
x	x		35S 15W	recommended (DEOS)	South Atlantic DEOS, geophysics, meteorology, physical, biogeochemical
x			40S 53W	recommended (Brazil/ Argentina)	Malvinas Confluence, physical
		x	78.5 N 9E-5W	operating (Norway, Germany)	Fram Strait, physical, ice
		x	8-66N 29-24W	operating (Iceland, IfMK)	Denmark Strait overflow
		x	64-59N 3-9W	operating (Norway, Faroer, Scotland)	Iceland-Scotland overflow, 3 sections, physical
		x	53N 50-53W	operating (IfMK)	Labrador Sea export
		x	44–41N 45-49W	operating (BIO, IfMK)	Grand Banks boundary current
		x	36N 5.5W	planned (EU)	Gibraltar transport
		x	27N 77-81W	operating (RSMAS)	Florida strait transport
		x	16N 50-60W	operating (IfMK)	CLIVAR/MOVE deep transport
		x	9-13S 33-36W	operating (IfMK)	CLIVAR upper transport

Pacific Ocean Sites

OB	FL	TR	Latitude/ Longitude	Status	Remarks
x	x		50N 145W	recommended	Site P ("PAPA"), meteorology; physical, biogeochemical
x			50N 165E	planned (JAMSTEC)	Northwest Pacific, biogeochemical, physical
x			44N 155E	planned (JAMSTEC)	KNOT (short for Kyodo North Pacific Ocean Time-series) Northwest Pacific, biogeochemical, physical
	x		40N 150E	recommended	Kuroshio Extension, meteorology
x			32N 120W	operating (MBARI)	MBARI deep biogeochemical mooring
x	x		23N 158W	observatory operating (SOEST)	HOT, meteorology; physical, biogeochemical
x			20N 115E	planned (Taiwan)	South China Sea
	x		2N 156E	recommended	Warm Pool flux reference on existing TAO/TRITON mooring
x	x		0N 165E	recommended	flux & biogeochemical sensors on existing TAO/TRITON mooring
x	x		0N 145W	observatory operating (MBARI)	flux & biogeochemical sensors on existing TAO/TRITON mooring
	x		0N 170W	recommended	flux reference on existing TAO/ TRITON mooring
	x		0N 110W	recommended	flux reference on existing TAO/ TRITON mooring
x	x		20S 85W	operating (WHOI)	Stratocumulus deck off Peru, meteorology; physical
x			30S 73W	operating (Chile)	deep water off Chile, physical
x			33S 74W	planned (Chile)	200 nautical miles off Chile, physical
x	x		40S 115W	planned (DEOS)	South Pacific DEOS, geophysics, meteorology, physical, biogeochemical
x	x		35S 150W	planned (DEOS)	South Pacific DEOS, geophysics, meteorology, physical, biogeochemical

Indian Ocean Sites

OB	FL	TR	Latitude/ Longitude	Status	Remarks
x	x		15N 65E	recommended	Arabian Sea, meteorology; physical, biogeochemical
x	x		12N 88E	recommended	Bay of Bengal, meteorology; physical, biogeochemical
x	x		0N 90E	planned (JAMSTEC)	TRITON north, meteorology; physical
x			0N 50E	recommended	Indian Ocean monsoon array, physical, meteorology
x			0N 65E	recommended	Indian Ocean monsoon array, physical, meteorology
x			0N 80E	recommended	Indian Ocean monsoon array, physical, meteorology
x	x		5S 95E	planned (JAMSTEC)	TRITON south, meteorology; physical
x			9.5S 113E	operating (Indonesia, Germany)	south of Indonesia, biogeochemical
x	x		25S 97E	planned (DEOS)	Indian Ocean DEOS, geophysics, physical, meteorology, biogeochemical
x	x		47.7S 60E	recommended	KERFIX (Kerguelen Fixed Station) follow-on, physical, meteorology, biogeochemistry
		x	3N-12S 116-125E	planned (LDEO, SIO)	Indonesian throughflow, several locations, physical

Southern Ocean Sites

OB	FL	TR	Latitude/ Longitude	Status	Remarks
	x		42S 9E	recommended	SW of Cape Town, meteorology
x			55S 0E	operating (AWI, Norway)	Weddell Sea, physical, several moorings
x			63S 42.5 W	operating (LDEO)	Weddell Sea, bottom water, physical, several moorings
x			66S 0W	operating (Norway, AWI)	Maud Rise/Weddell Sea, physical, several moorings
x			73.5S 35W	funded (Norway/UK)	southern Weddell Sea, ISW overflow, physical, 2 moorings
x	x		55S 90W	recommended	Antarctic Intermediate Water (AAIW) formation region, meteorology, physical, CO_2

OB	FL	TR	Latitude/ Longitude	Status	Remarks
x	x		47S 142E	planned (CSIRO, WHOI)	south of Tasmania, meteorology, physical, biogeochemical
x			43.5S 178.5E	operating (New Zealand)	off New Zealand, physical, biogeochemical, CO_2, 2 moorings
		x	56-62S 70-63W	planned (UK and WHOI)	Drake Passage transport

SOURCE: Sites list developed by the international Time-Series Science Team of CLIVAR and GOOS; Modified from Figure 1, DEOS Global Network Implementation Plan (2003); and data from Robert Weller, Woods Hole Oceanographic Institution, and Uwe Send, Institut fur Meereskunde, Kiel, Germany, personal communication, 2003 (Weller and Send are the co-chairs of the International Time-Series Science Team. An International Time-Series Science Team white paper is currently being written on this topic and is available online: *http://ocean-partners.org/TSsite/index.htm*.
NOTES: OB = Observatory; FL = Air-Sea Flux reference site; TR = transport site; see Appendix B for remaining acronyms.

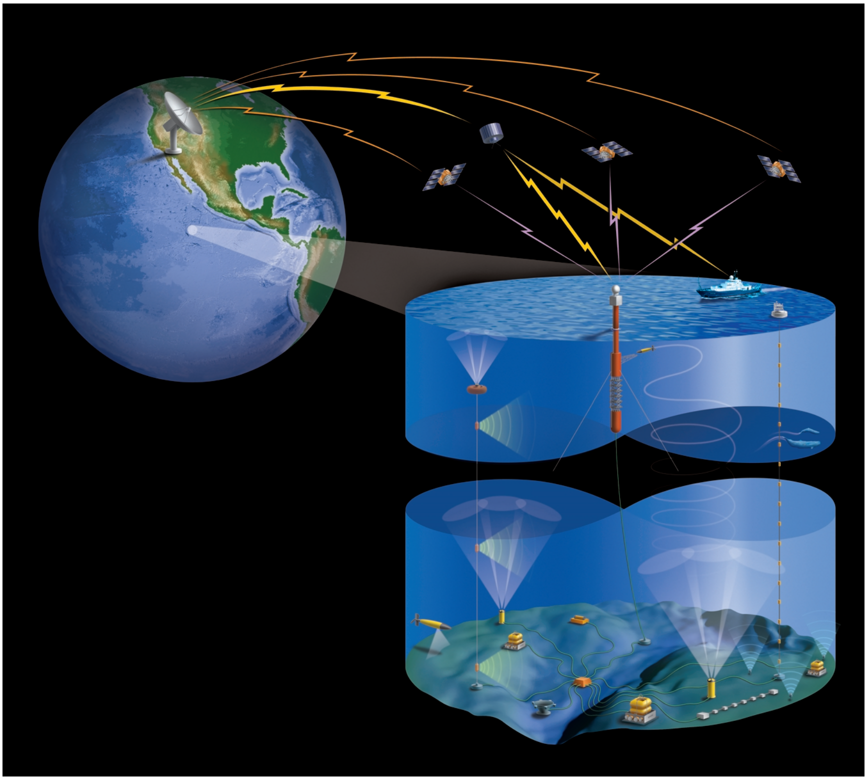

PLATE 1 One component of the OOI is a global network of 15-20 moored buoys, linked to shore via satellite, that support measurements of air-sea fluxes, physical, biological, and chemical water properties, and geophysical observations on or below the seafloor. Figure courtesy of John Orcutt, Scripps Institution of Oceanography.

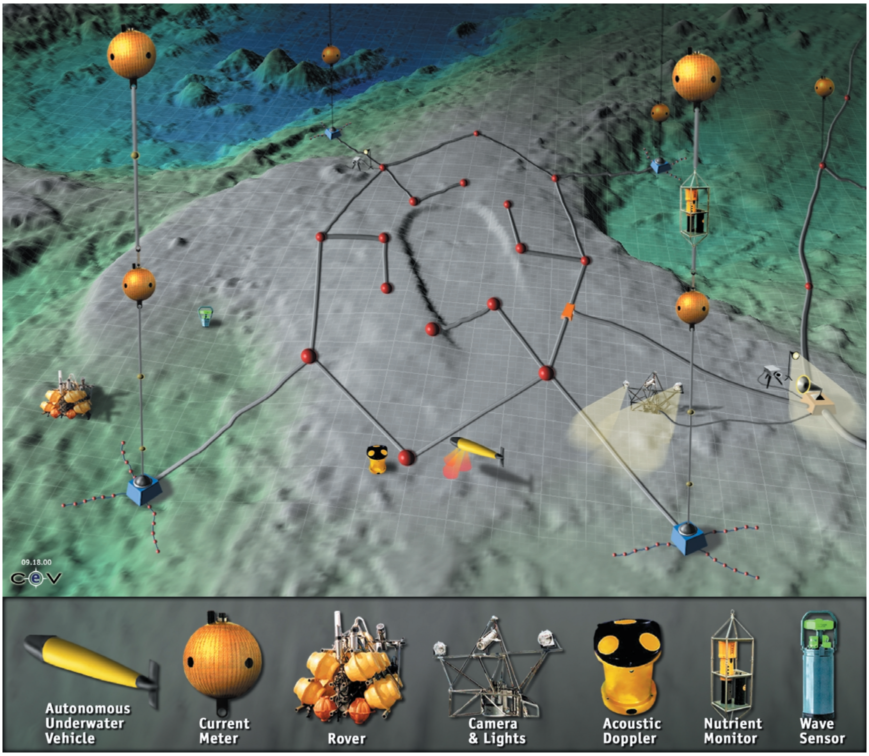

PLATE 2 Artist's concept of a cabled observatory node located atop an active submarine volcano. A variety of systems, including moorings, AUVs, bottom rovers, cameras, current profilers, and physical, chemical, and biological sensors, are used to make *in situ* measurements of volcanic, hydrothermal, and biological activity. The data are telemetered in real-time to scientists in laboratories on shore. Image provided courtesy of the NEPTUNE Project (*www.neptune.washington.edu*) and produced by the Center for Environmental Visualization at the University of Washington.

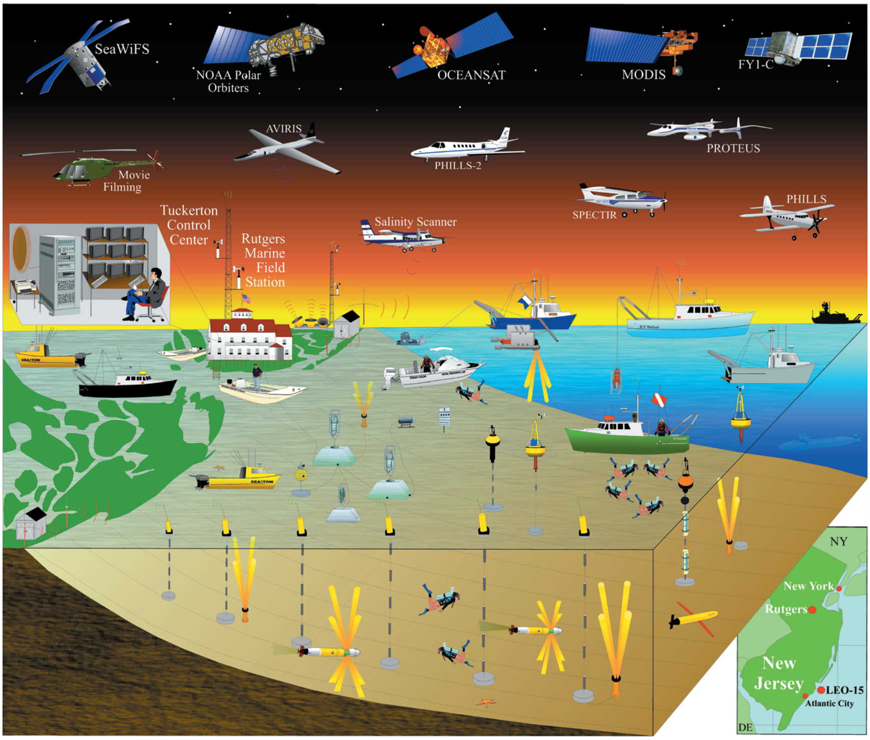

PLATE 3 A conceptual diagram illustrating a multi-component coastal ocean observatory that includes surface and subsurface moorings, cabled seafloor nodes, coastal radars, ships, airplanes, and satellites. Image provided courtesy of Oscar Schofield, Rutgers University.

PLATE 4 Conventional surface (left) and sub-surface (right) moorings currently operational at many tropical and mid-latitude sites designed to measure meteorological, air-sea, and upper-ocean properties. Figure courtesy of Jayne Doucette, ©Woods Hole Oceanographic Institution.

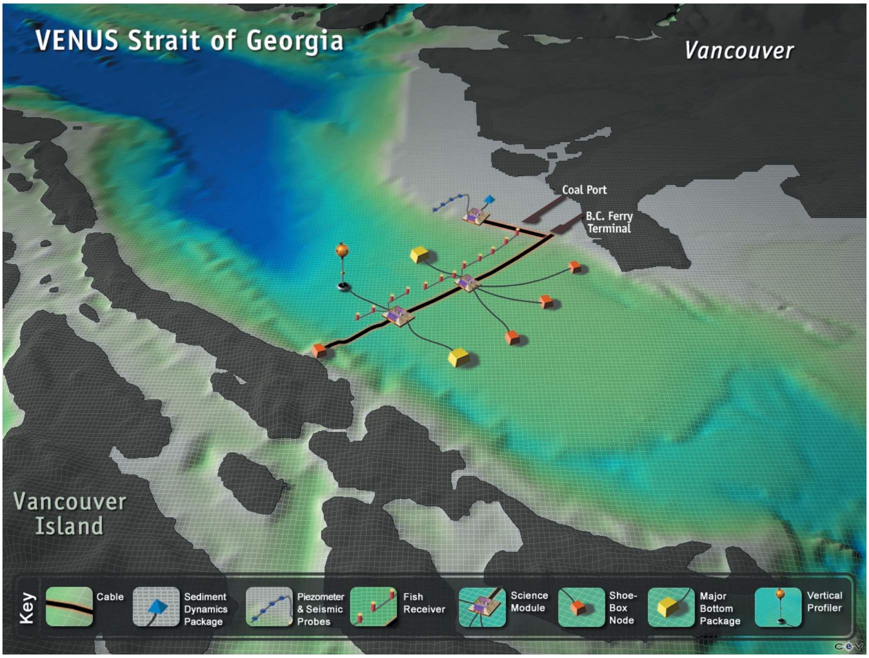

PLATE 5 A schematic of a coastal subsea observatory being installed in the Strait of Georgia, British Columbia, Canada, as part of the VENUS testbed. Figure courtesy of the NEPTUNE Project (*www.neptune.washington.edu*) and produced by the Center for Environmental Visualization at the University of Washington.

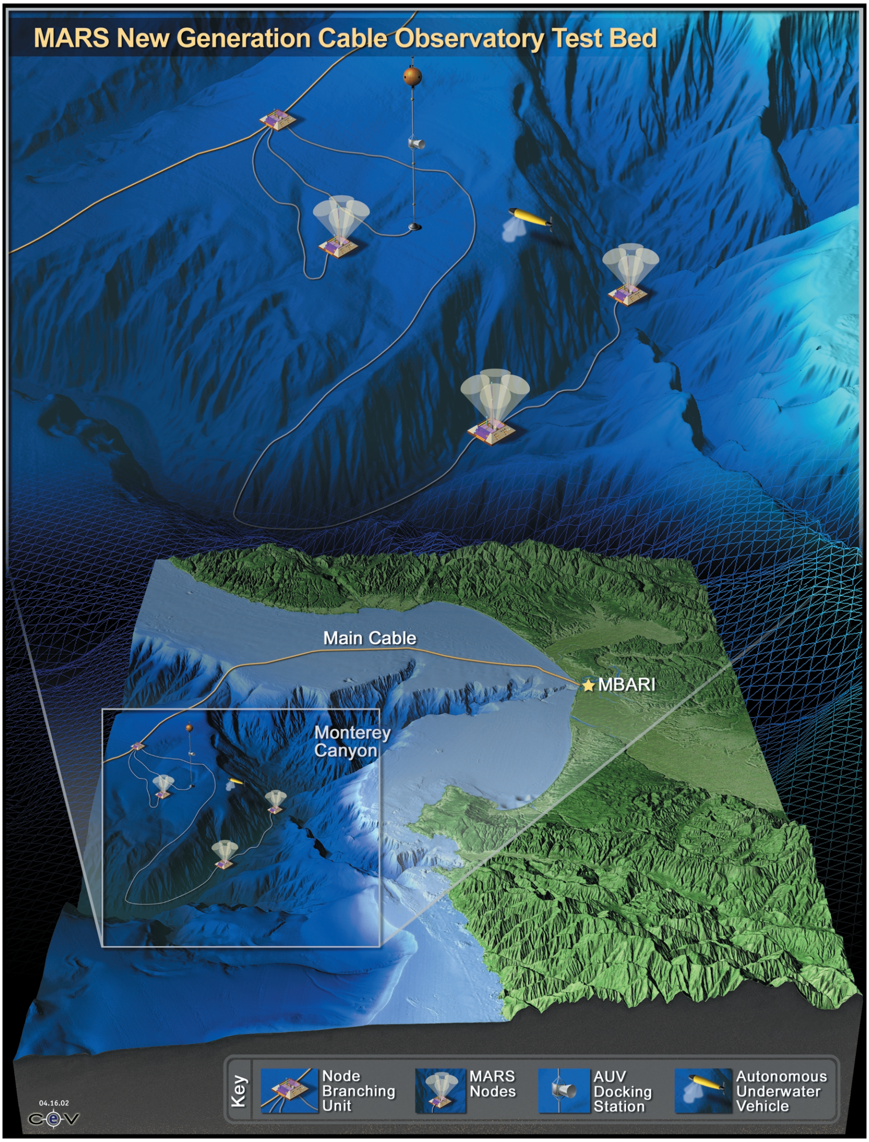

PLATE 6 A schematic of the MARS testbed, a subsea observatory that will extend into deep water off Monterey, California. Figure courtesy of the NEPTUNE Project (*www.neptune.washington.edu*) and produced by the Center for Environmental Visualization at the University of Washington.

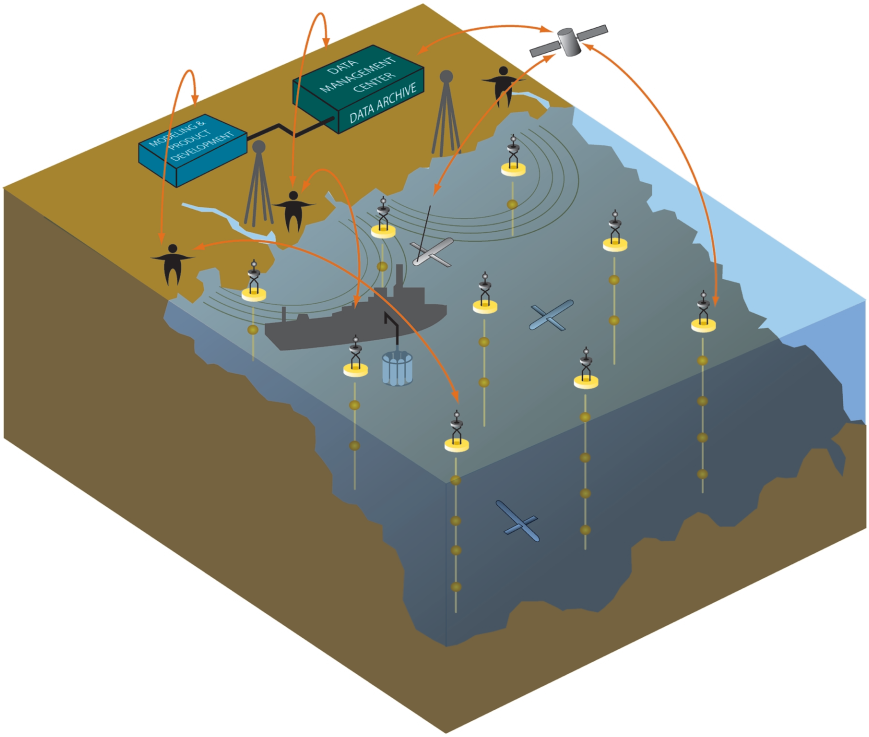

PLATE 7 Illustration of the Pioneer Array concept including relocatable moorings, coastal radars, ships, and satellites for collecting high-resolution, synoptic-scale measurements in a focused region spanning 100-300 km. Also included are a land-based data management center, and a modeling and project development center. Figure courtesy of Richard Jahnke, Skidaway Institute of Oceanography.

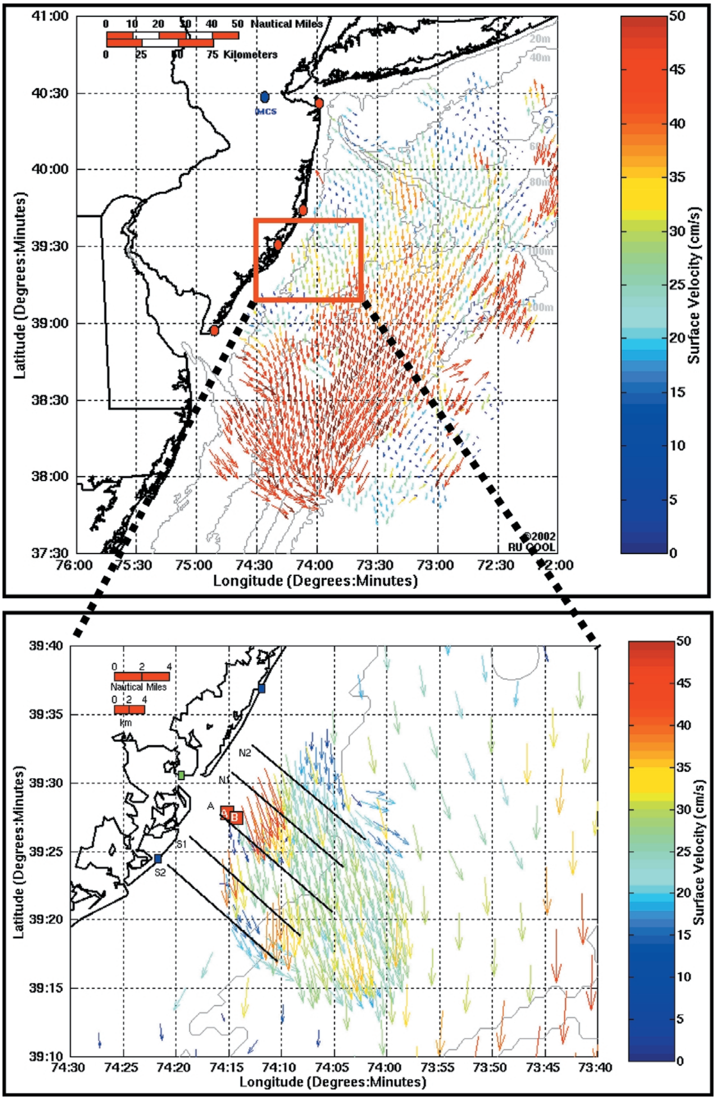

PLATE 8 An example of the potential for nested maps of surface currents measured with high-frequency (HF) radar arrays. *Top:* The footprint of a standard long range HF-radar for off the coast of New Jersey has a spatial resolution of 6 km, proposed to form one part of the IOOS observational backbone. *Bottom:* The footprint of a high resolution HF-radar system, which has a spatial resolution of 1.5 km. Given that many coastal processes operate on spatial scales of 1-2 km, it has been suggested that nesting multi-static arrays of high-resolution HF-radar units within the IOOS national array would have high scientific value. Figure courtesy of Oscar Schofield, Rutgers University.