The Ocean Observatories Initiative: Wiring the Ocean for Interactive Scientific Discovery

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***Abstract*- The National Science Foundation's Division of Ocean Science has established the Ocean Research Interactive Observatory Networks (ORION) Program to operate and manage existing and future ocean observing sites funded by NSF including those constructed by the Ocean Observatories Initiative (OOI). The OOI is an integrated observatory system with three elements: 1) deep-sea buoys with capabilities appropriate to the experiments they will host with some designs capable of deployment in harsh environments such as the Southern Ocean, 2) a regional electro-optical cabled network consisting of interconnected sites on the seafloor spanning several geological and oceanographic features and processes, and 3) new construction or enhancements to existing facilities leading to an expanded network of coastal observatories. These three components are linked through a forward-looking cyberinfrastructure. This paper will provide an update on current activities related to the OOI Project and the ORION Program.**

I. INTRODUCTION AND DESCRIPTION OF THE OCEAN OBSERVATORIES INITIATIVE

A. OOI Infrastructure

In scientific discovery, there is a close synergy between scientific advancements, the need for new research tools, and innovations in enabling technologies. Recent advancements in telecommunications technologies, sensors, computational modeling, as well as data archival and computer networking make it possible to implement in-water measurement networks capable of recording environmental parameters at spatial resolutions and frequencies essential to understand the ocean system and its interactions with the atmosphere and solid earth. The ability to interact with *in situ* sensors emplaced on networked ocean observatories will also enable the alteration of sampling schemes to respond to environmental events. Ocean observatories will provide earth and ocean scientists with unique 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. Rapidly expanding observation and modeling capabilities will enable scientists to consider an entirely new set of interdisciplinary science questions that can then be used to guide and prioritize implementation strategies for upgrading existing, and deploying new observatories.

Sustained ocean observing systems hold the promise of revolutionizing ocean science within this decade. Enabled by technological advances and made timely by societal need, a wide range of ocean and earth observing systems are being planned, proposed, deployed and operated within the U.S. and internationally. With funding from the National Science Foundation’s (NSF) Major Research Equipment and Facilities Construction (MREFC) account, the Division of Ocean Sciences plans to construct an integrated observatory network, the Ocean Observatories Initiative (OOI). The OOI will be an integrated observatory system with three elements: 1) deep-sea buoys with capabilities appropriate to the experiments they will host with some designs capable of deployment in harsh environments such as the Southern Ocean, 2) a regional electro-optical cabled network consisting of interconnected sites on the seafloor spanning several geological and oceanographic features and processes, and 3) new construction or enhancements to existing facilities leading to an expanded network of coastal observatories.

The primary infrastructure for all components of the OOI consists of an array of seafloor junction boxes connected to cables on the seafloor or acoustically linked to individual instruments or instrument clusters. These junction boxes include undersea connectors that provide not only the power and two-way communication needed to support seafloor instrumentation, but also the capability to exchange instrumentation *in situ* when necessary for conducting new experiments or for repairing existing instruments. Depending upon proximity to the coast and other science and engineering requirements, the junction box is either terminated by a long dedicated fiber-optic cable to shore, or by a shorter cable to a surface buoy that is capable of two-way communications with a shore station.

When fully operational, observing sites that make up the OOI will host thousands of instruments producing tens of thousands of data streams that will be accessed and utilized by thousands of scientific and educational participants and automated processes. Managing an infrastructure of this scale that can acquire, process, archive and distribute the diversity of data streaming on a continuous basis requires a cyberinfrastructure architecture with capabilities not previously envisioned [1]. The OOI will provide the ideal platform to facilitate the development and testing of such a cyberinfrastructure system.

1-4244-0115-1/06/$20.00 ©2006 IEEE

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 SEP 2006**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **The Ocean Observatories Initiative: Wiring the Ocean for Interactive Scientific Discovery**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Science Foundation (NSF) Division of Ocean Sciences 4201 Wilson Blvd Arlington, VA 22201 USA**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002006. Proceedings of the MTS/IEEE OCEANS 2006 Boston Conference and Exhibition Held in Boston, Massachusetts on September 15-21, 2006. Federal Government Rights, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

OOI infrastructure is expected to meet the following user requirements:

- 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 protocol
- capability of autonomous underwater vehicle (AUV) docking to access new commands as well as data download/battery recharge
- access to deployment and maintenance vehicles that satisfy the needs of specific experiments
- facilities for instrument maintenance and calibration
- a data management system that makes data publicly available using the most advanced information technology and communications tools available
- an effective education and outreach program

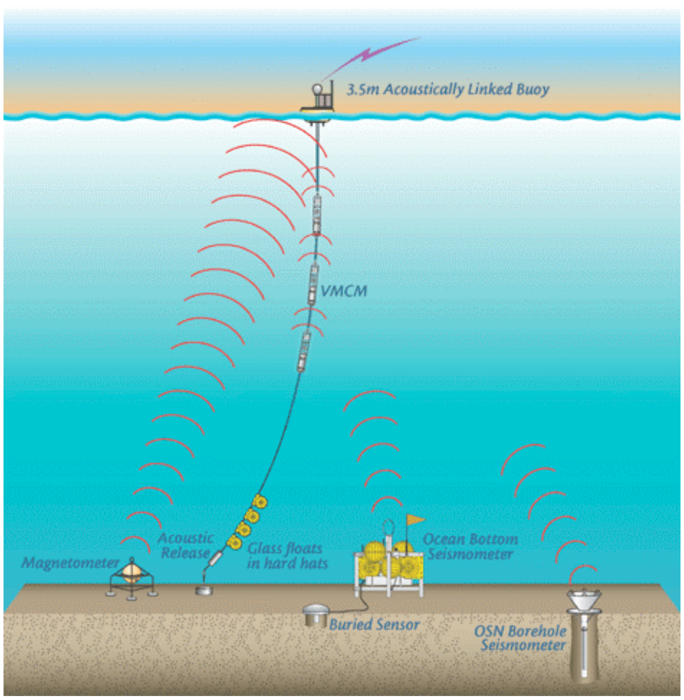

Figure 1. High-speed acoustic modems will be used to monitor operating conditions of instruments, upload data, and/or command changes in operation of deployed sensors (figure courtesy of Lee Freitag, WHOI).

An important requirement identified by the research community is the need to have an expandable system as well as to be able to increase the spatial "footprint" around a junction box by enabling investigators to conduct experiments at distances up to 100 km from a node. For lower bandwidth applications acoustic modems will be used to transmit data from instrumentation back to the node (Fig. 1) whereas fiber optic cable links may be required in cases where high bandwidth data transmission and/or high power will be required. The routine use of either of these capabilities still requires a level of engineering development. Another significant user requirement identified by the research community is the need to not only move laterally away from a node but to be able to measure vertically within the water column as well. Work is currently underway on various systems that will enable researchers to emplace water column sensors as well as perform vertical profiles within the water column (Fig. 2) [2].

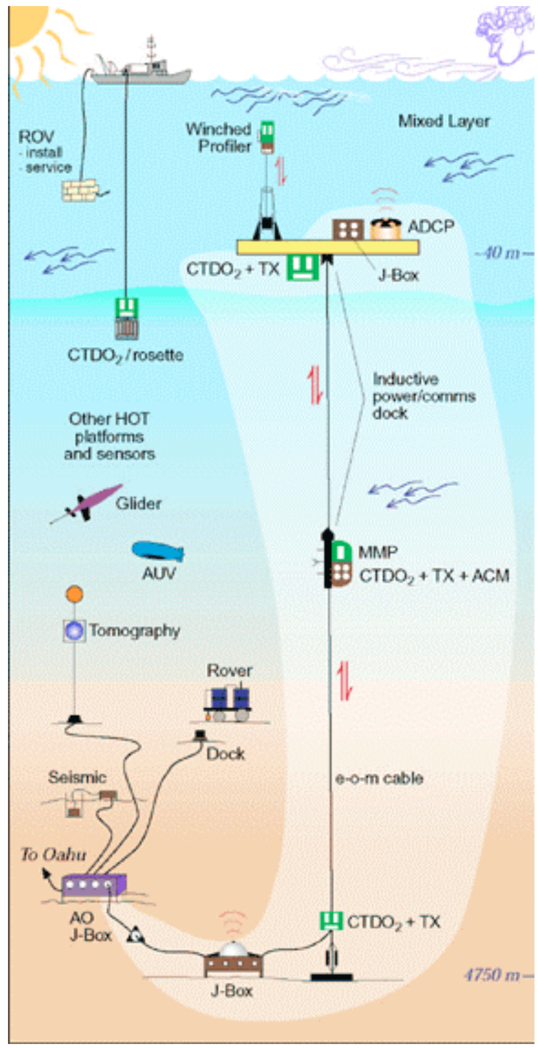

Figure 2. Schematic of a real-time cabled profiling mooring. This moored sensor network will consist of an instrumented profiler that will move between near-surface and abyssal fixed sensors under program control (figure courtesy of Bruce Howe, UW).

B. Scientific Justification for the OOI

The scientific problems driving the need for an ocean observing system are broad in scope and encompass nearly every area of ocean science as outlined in the OOI Science Plan "Revealing the Secrets of Our Ocean Planet" (http://www.orionprogram.org/) [3]. The research themes and opportunities outlined in this document have guided the implementation planning for the OOI and provided guidance for development of the more detailed science questions found in "Ocean Observatories Initiative (OOI) Scientific Objectives and Network Design" which was the input into the OOI "Blue Ribbon" science review (Table 1) [4].

TABLE 1

TEXT IN BOLD ARE THEMES FROM THE OOI SCIENCE PLAN AND THE ASSOCIATED SCIENCE QUESTIONS ARE FROM THE OOI "BLUE RIBBON" REPORT.

Climate variability, ocean food webs, and biogeochemical cycles. What is the ocean's role in storing anthropogenic carbon and how will the long-term increase in atmospheric CO_2 affect ocean chemistry and ecosystem structure and interactions?
Coastal ocean dynamics and ecosystems. How will climate change and human activity alter coastal ecosystems, habitats and living marine resources?
Turbulent mixing and biophysical interactions. What is the impact of storms and other extreme events, especially in the poorly studied Southern Ocean, on exchanges of heat, gases and nutrients within the earth-ocean-atmosphere system?
Fluid-rock interactions and the sub-seafloor biosphere. What is the planetary significance and evolutionary importance of microbial activity in the ocean and in the newly discovered sub-seafloor biosphere?
Global and plate-scale geodynamics. What processes control the size and frequency of earthquakes at oceanic transform and subduction zone fault systems?

Establishment of the OOI seafloor observatory network will stimulate a philosophical and intellectual reorientation within the oceanographic community. This new mode of investigation will build on and enhance the more traditional shipboard expeditionary approach by providing the means to collect unique, sustained, time-series data sets. The perspectives these data will provide will stimulate new paradigms in our understanding of the dynamic biological, chemical, physical and geological processes in the sea. Scientific discoveries arising from the OOI will provide new opportunities for ocean education and outreach through the capabilities for real-time data transmission and, particularly, real-time display of visual images from the seafloor. In addition, with the establishment of the IOOS, there will be an unprecedented need for oceanographers skilled in the use and manipulation of large, oceanographic, time-series datasets. The facilities comprising the OOI will provide the ideal platforms to train this new generation of oceanographers. The interpretation and assimilation of these data sets will provide new perspectives for biocomplexity and environmental research. Although expeditionary science will always provide an important platform for ocean research, the need to identify and respond to unexpected events and the need to collect data at appropriate temporal and spatial scales is essential.

In recognition of the fact that research related to the OOI will involve platforms and sensor systems that build on the OOI Conceptual Network Design (CND), but are not part of this design, the Ocean Research Interactive Observatory Networks (ORION) Program was established (Fig. 3). The ORION Program will coordinate the science driving the construction of this research observing network as well as: operation and maintenance of the infrastructure; deployment of instrumentation and mobile platforms into the observatory network; and planning, coordination, and implementation of educational and public outreach activities. The ORION Program will be the most complex initiative that ocean scientists have undertaken within the U.S. and it will transform the way that oceanographers study the sea.

Figure 3. Representation of the relationship between the ORION Program and the OOI.

C. Development of the OOI Conceptual Network Design and Programmatic Reviews

In 2005 the ORION Program Office asked for the assistance of the ocean research community in developing the OOI Conceptual Design by soliciting Request for Assistance (RFA) proposals. In late September 2005, an unconflicted review panel was convened at the ORION Program Office. Proposals were binned into three groupings based on a combination of factors including readiness and maturity of required technologies and proposed science. From these proposals the ORION Science and Technology, Engineering, Cyberinfrastructure, Sensors, and Education and Public Awareness Committees developed a draft Conceptual Network Design (CND) that was a baseline design for OOI infrastructure, including nodes locations and capabilities that should be available at experimental nodes. The OOI CND was posted on the ORION Project Office website in March 2006 (www.orionprogram.org) and discussed by 300 members of the ocean science community at the Design and Implementation Workshop (27-30 March 2006; Salt Lake City, Utah). Workshop participants were asked to review the plan, provide extensive feedback, and identify omissions. A revised Conceptual Network Design (CND) for the OOI has been posted on the ORION website.

Recently, a "Blue Ribbon" review was organized to assess whether the ocean observing network proposed in the OOI CND will provide the capabilities for the ocean researchers to significantly advance knowledge of high priority questions challenging the ocean science community. In particular, this review assessed whether the network will enable researchers to answer high priority science questions that require *in situ*, real-time measurements across the three scales of the OOI. Input to the Blue Ribbon review was the "OOI Scientific Objectives and Network Design" document produced by the ORION Observatory Steering Committee [4]. This report described examples of high priority science questions within the broad science themes posed in the OOI Science Plan (2005) [3] that will be investigated using OOI infrastructure at the sites described in the OOI CND. The "Blue Ribbon" panel reviewed this document and provided individual written comments that were then discussed as a group. The results of this review were provided as input to the OOI Conceptual Design Review (CDR).

The OOI CDR (August 14th-17th, 2006) reviewed the scope and system level implementation plans for the OOI, including management plans and budgeting, and determined whether all major risks with this project have been identified and whether appropriate initial system development specifications (performance requirements, major system components, and interfaces) have been established for each sub-element of the OOI. The CDR Panel reviewed elements of the initial OOI Project Execution Plan and the project's plans for further development of the OOI to the Preliminary Design phase of project maturity.

II. SCIENCE PLANNING AND MANAGEMENT

The OOI Project is overseen by the ORION Program Office based at the Joint Oceanographic Institutions (JOI) Office in Washington, D.C. The ORION office serves as a centralized management entity for the OOI and will provide a long-term focus for NSF's ocean observing networks and programs, of which the OOI will be the first.

During the Concept and Development Phase of the OOI Project, the Program Office will establish Implementing Organizations for cyberinfrastructure as well as the coastal, regional, and global components of the OOI. The IOs will provide the detailed management and oversight OOI components and will report directly to the OOI Project Office. Establishment of the IOs ensure that day to day operations of the network are under the control of the groups implementing the construction activities as recommended by the NRC report "Enabling Ocean Research in the 21st Century". Specific responsibilities of the IOs as outlined in the RFP issued by JOI include:

- Program Management
- Requirements and Performance Definition
- Providing NSF with information required for NEPA compliance as well as acquiring necessary environmental permits required for system owners
- Implementation
- Integration Testing
- Commissioning and Acceptance
- Initial Operation of the System
- Operations of Science Investigations and Data
- Science Outreach and Education

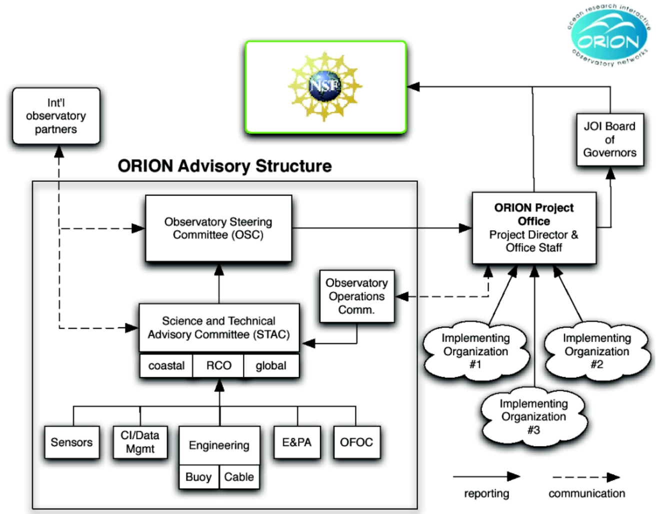

Figure 4. A schematic representation of ORION community advisory structure.

Scientific and technical advice to the ORION Program Office is provided by a committee structure with members from academia, industry, government and the international community, including scientists, engineers and educators with broad, interdisciplinary expertise in ocean-related problems. Committees making up this structure provide a critical interface with the user community. The Observatory Steering Committee is the top-level committee that oversees the operation of the advisory structure, advises the Project Office on policies and procedures for observatory operations, usage and data management, and is responsible for longer term program planning and development including fostering links with other national and international research programs and observatory systems (Fig. 4). The Science and Technical Advisory Committee is the main science and technical planning committee of the ORION Advisory Structure and is focused on shorter-term (year-by-year) science planning and technical development. The Engineering Committee will assist the Project Office in developing the technical descriptions and specifications for observatory elements and will identify areas of high technical risk and recommend ways to mitigate risk and will provide input on the cost analysis/tradeoffs for various observatory configurations. Other committees include a Sensors Committee, a Cyberinfrastructure Committee, and an Education and Public Awareness Committee.

III. THE OCEAN OBSERVATORIES INITIATIVE AND THE INTEGRATED OCEAN OBSERVING SYSTEM

At the NSF, the need to investigate environmental processes at the temporal and spatial scales at which they occur has been recognized across all disciplines. This realization has led to the proposal of numerous environmental observing systems. These include the OOI discussed in this paper as well as the National Ecological Observing Network, Waters Network, Long Term Ecological Research Network, and EarthScope. An internal working group at NSF has been established to help ensure that the research and observational activities of these programs are coordinated and that common development needs, such as those for cyberinfrastructure, are leveraged between programs.

More broadly, there is currently a great deal of ocean observatory activity being coordinated under the auspices of the National Ocean Partnership Program (NOPP) to develop an Integrated Ocean Observing System (IOOS; US component of the Global Ocean Observing System, GOOS). The IOOS will support the operational mission objectives of agencies such as NOAA, Navy, NASA, and Coast Guard whereas the OOI, under NSF leadership will focus on research and education aspects of an ocean observing system. Information from the IOOS will serve national needs for: detecting and forecasting oceanic components of climate variability, facilitating safe and efficient marine operations, ensuring national security, managing resources for sustainable use, preserving and restoring healthy marine ecosystems, mitigating natural hazards, ensuring public health (http://www.ocean.us.net/).

Data from ORION Program activities and OOI infrastructure will be interoperable with those of the National Integrated Ocean Observing System (IOOS) and thus of direct benefit to the applied research community. The outcomes of ORION research, and the increased understanding of ocean process this research will help the IOOS meet its societal goals and help ensure a robust evolution of the operational system. Improvements in modeling, simulation, and forecasting will directly contribute to the formulation of data products that will be central to the IOOS system. Furthermore, technological enhancements and developments arising from ORION research activities will be transitioned to the IOOS system and enhance the ability of this system to meet its goals.

Once fully implemented, the OOI and IOOS will have areas of overlap where common infrastructure may serve both the research and operational communities. The outcomes of research and technology development, which are an integral part of the OOI, will provide essential support for the IOOS. The resulting knowledge will feed into operational systems by identifying what measurements will best characterize changes in the ocean, how many measurements are required, and where they should be obtained.

Internationally, there has been significant activity associated with the Earth Observation Summit. This Summit attracted a distinguished group of governmental dignitaries who demonstrated their commitment to the collection of Earth observation data through the signing of a Declaration by thirty-three nations plus the European Commission. To further this goal, Summit participants launched the intergovernmental ad hoc Group on Earth Observations (GEO) to develop a 10-Year Implementation Plan for a Global Earth Observation System of Systems (GEOSS). NSF has been intimately involved in the U.S. effort and it is envisioned that the OOI will provide an important contribution to this “network of networks".

In addition to GEO, there are numerous opportunities internationally for collaboration and cooperation within the research community. Major initiatives such as the European Sea Floor Observatory Network (ESONET) and activities in Japan will provide excellent opportunities for collaboration with the OOI on both ocean technology as well as research. Recently, an MOU has been signed between NSF and the Universality of Victoria in Canada, which states the intention to cooperate on construction of the regional cabled observatory on the Juan de Fuca Plate. The Canadians have already received funding for this project, NEPTUNE-Canada, and have awarded a contract for construction of this seafloor network. Although NEPTUNE-Canada will begin construction of the northern loop prior to construction of the southern loop by NSF, both parties have agreed that these systems will be interoperable.

In addition to the programs listed above, there are other international research programs that include significant observatory-related research initiatives that OOI infrastructure could facilitate. Examples include: 1) the Ridge2000 program of scientific research on mid-ocean ridges and other tectonic spreading centers as well as the InterRidge initiative for long-term monitoring of the northern Mid-Atlantic Ridge; 2) the international MARGINS initiative to understand seismogenic zones in subduction settings, 3) the International Ocean Network activities to coordinate global network observatory efforts, 4) the international OceanSites Program for studying climate and ecosystems in the world’s oceans, and 5) the Integrated Ocean Drilling Program (IODP).

IV. CYBERINFRASTRUCTURE

The widespread proliferation of the Internet and other communication technologies, especially wireless and acoustic transmission from remote sensors, coupled with the decreasing cost, size, and weight of a variety of sensors is resulting in a major paradigm shift in both environmental science and engineering. Increasingly, spatially extended, intelligent networks, of multi-variable intelligent sensor arrays are seen as the appropriate tools for studying complex real-world systems. The OOI is one such array (Fig. 5).

The increasing demand for sensor arrays raises a number of cyber-infrastructure issues including how to: effectively collect, manage, archive and distribute data from such systems; establish mechanisms and protocols for rapid data transmission; describe protocols for two-way communication with sensors and dynamic control of sensor networks; access to remote computing resources for processing and visualization of the data collected; how to manage heterogeneous data streams that include high-bandwidth streams, such as video data and broad-band seismic data, and low-bandwidth streams such as those from temperature sensors, and that include physical, chemical and biological data; dynamically manage sampling schemes at nodes with limited power budgets when multiple sensors share the same power source; develop software tools for the analysis of the multidisciplinary, spatially extended, intermittent datasets that will emerge from such observing systems; develop knowledge representation software to ensure that these data are easily accessible and effortlessly shared across disciplines; ensure the integrity of the communications and control systems for such observing networks together with the integrity of the data management and archiving systems; and automate data quality control.

The establishment of cyber-infrastructure that can accomplish these tasks will be critical to ensure broadest use of the data collected from all sensing networks such as the OOI. It is through this capability that the power of this new paradigm will be most evident. For example, in environmental science, the ability to compare data from multiple, potentially unrelated disciplines will enable researchers to decipher unanticipated interactions between systems to advance our understanding of Earth’s environment. Concerns related to cyber-security, and in some cases, intellectual property, will significantly impact networked sensor systems. Solutions must be sought that will not hinder free and open exchange of most data but that will also protect the network and its sensors as well as provide the ability to restrict access to highly sensitive data when needed. Finally, the integration of GRID-based systems to convert the raw environmental data into information and, finally, knowledge will become an increasingly important issue as sensor networks become increasingly ubiquitous.

To better define the issues outlined above and to search for creative solutions to these issues, there is much discussion in the environmental, engineering, and computer science communities. From these discussions, numerous workshops are being planned that will bring together a variety of researchers to help catalyze collaborative research between engineers, environmental scientists, computer scientists, statisticians, and mathematicians to address these important issues.

In addition to existing efforts there are also system design partners that are proving to be essential to the establishment of a robust cyberinfrastructure for the OOI. The NSF- and SURA-sponsored Marine Metadata Initiative is a focal point for broad-based community input to address technical issues relating to marine metadata and data management. Its work will contribute to a common Data Management and Communications (DMAC) framework to support the OOI as well as IOOS. Thus the effort supports the international marine community, augmenting and connecting existing metadata initiatives by other organizations (MMI: http://marinemetadata.org/). Data management and archiving protocols are being developed by the IOOS Data Management and Communications (DMAC) Steering Team and its associated Expert Teams and Working Groups. The DMAC Subsystem will include a data and communications infrastructure that consists of a suite of components: standards, protocols, facilities, software, and supporting hardware systems (http://dmac.ocean.us/index.jsp). Inter-observatory instrument operability and access, an event detection and response framework, and a policy-based security and governance framework are being developed by the NSF-ITR funded LOOKING Project (http://lookingtosea.ucsd.edu/). LOOKING is a research effort into the identification, synthesis, and assemblage of existing and emerging concepts and technologies into a coherent viable cyberinfrastructure design. The goal of this effort is to federate ocean observatories into an integrated knowledge grid. From a scientific perspective, LOOKING is developing a viable design for the cyberinfrastructure of a coherent and durable research network that supports dynamic harnessing of resources ranging from physical assets (e.g., instruments, network segments, power, compute/storage/visualization grids), through retrospective informatics and analytic services, to coupling of real-time sensing networks with predictive modeling services. The design is to address scalability, extensibility, and reconfiguration. From a system engineering perspective, LOOKING is defining the system-level cyberinfrastructure architectural requirements, developing working prototypes that enable the seamless operation of a federated ocean observatory strategy, and implementing elements on test-beds of opportunity. Once the cyberinfrastructure is defined and prototyped, revisiting existing and emerging hardware designs under a strong system-engineering framework will be required to ensure compatibility to produce a state-of-the art ocean observatory cyberinfrastructure.

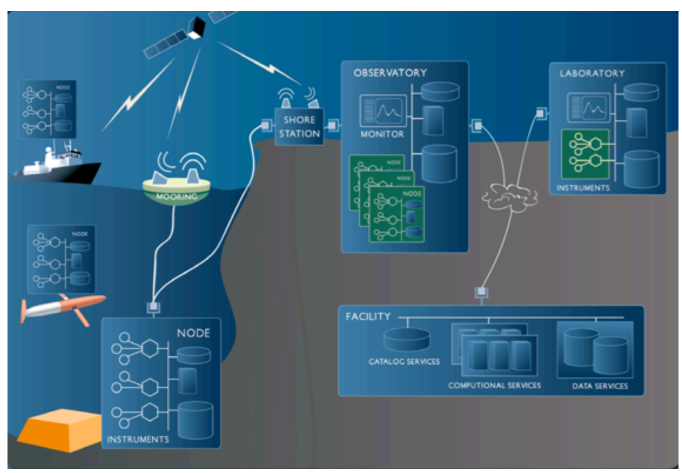

Figure 5. Graphical representation of the OOI cyberinfrastructure.

To address these challenges and to promote Cyberinfrastructure for Environmental Observatories (CEO) more broadly, NSF recently released a solicitation requesting proposals for the development of practical environmental cyberinfrastructure prototypes and a demonstration of their capability to answer significant environmental research questions. Specifically, these challenges include: integrating multiple, existing information management systems in different environmental research disciplines; bridging the semantic representations of multiple disciplines within environmental research; expanding the range of resources that can be used by workflow orchestration tools, or other AI-based techniques, to assist users in developing complex, multi-stage processing tasks; supplying technology to support user-configurable event-detection and the execution of event-triggered responses in real-time or near real-time data streams; and providing the ability for users to configure virtual observatories to bring together data streams from sensors in different observing systems. The CEO solicitation focused on projects that tackle the issue of how to integrate data from different types of observing systems with different disciplinary foci. It encouraged projects that develop prototypes that support a wide collection of users and which can be readily generalized. It also urged projects to leverage existing cyberinfrastructure development efforts. Two important objectives of this solicitation were: to help ensure that information infrastructure technologies needed to support the widespread use of cutting-edge research from large environmental observing systems are available when needed, and to help environmental research communities and information technologists gain expertise with the technological challenges of deploying such infrastructure so that cyberinfrastructure design can be integrated properly into observatory design and cyberinfrastructure deployment can be integrated properly into observatory deployment.

V. CONCLUSIONS

Sustained ocean observing systems emphasize real-time datasets for event response and adaptive sampling, well-sampled spatial and temporal contexts for limited duration or process-study experiments, and sustained operation to observe long-term trends and capture rare episodic events. Collaborative science is greatly facilitated by this infrastructure, with the widespread availability of increasingly multi-disciplinary datasets stimulating previously unfeasible cross-correlation analyses in the search for new associations or causal relationships. Currently operating observing systems are increasingly being used in combination with interdisciplinary numerical models through advances in model development, coupling, validation, and assimilation activities. These rapidly expanding observation and modeling capabilities are enabling scientists to consider an entirely new set of interdisciplinary science questions. In turn, the new questions can be used to guide and prioritize implementation strategies for upgrading existing, and deploying new observatories.

The OOI will begin building a network of ocean observatories to facilitate the collection of time-series data needed to understand the dynamics of biological, chemical, geological and physical processes. These new observational capabilities will have significant impacts on the ocean research community by providing the means to carry out fundamental research on natural and human-induced change on time scales ranging from seconds to decades. The scientific problems driving the need for an ocean observing system are global in scope and encompass nearly every area of ocean science and there will be significant societal benefits from OOI research. Scientific discoveries arising from the OOI will provide new opportunities for ocean education and outreach through the capabilities for real-time data transmission and, particularly, real-time display of visual images from the seafloor. Because of the broad impact of the OOI on education and training, from conception to conclusion, this initiative will be a source of inspiration and innovation through the combination of cutting-edge technology and research to study the complex interactions of processes on, above, and below the seafloor.

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