**[Title Page]**

***Implementation Plan***
***for the***
***DEOS GLOBAL NETWORK***
***of***
***Moored-Buoy Observatories***

**[Inside Cover]**

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## I. EXECUTIVE SUMMARY

**[done later]**

## II. INTRODUCTION

### (A) Purpose of this Report

Improving our capacity to measure physical, chemical, biological, and geological parameters on multiple time and spatial scales will have a significant impact on our understanding of fundamental Earth and oceanic processes. This need, and recent independent advances in the technologies associated with computation, data telemetry and multidisciplinary sensors, have motivated the scientific community to investigate the feasibility of creating long-term 'ocean observatories' where sensors are deployed at the air-sea interface, within the water column, and on and beneath the seafloor. Seafloor observatories will enable Earth and ocean scientists to study multiple, interrelated processes over timescales ranging from seconds to decades; to conduct comparative studies of regional processes and spatial characteristics; and to map whole-Earth and basin-scale structures.

This document provides a blue print and cost estimate for creating a DEOS GLOBAL NETWORK of moored-buoy observatories to collect time series observations for scientific research. It includes technical specifications for three potential moored-buoy designs and information on current prototyping efforts relevant to the engineering of those designs. An efficient data telemetry and management system is also described and prototype efforts highlighted. The Implementation Plan concludes with cost estimates and a proposed timetable for developing the GLOBAL NETWORK. DEOS planning has been sponsored by the National Science Foundation and its products are being factored into plans for the larger, more inclusive Ocean Observatories Initiative (OOI). Therefore, two sections of this document, one on Management and another on Data Grids, contain recommendations that are relevant to establishing a GLOBAL NETWORK under the aegis of the OOI program, and are written with the larger Initiative in mind.

### (B) Historical Background for this Report

Interest in establishing an extensive, continual, interactive sensor presence in the oceans has gained momentum since the late 1990s. Several reports including *Toward a U.S. Plan for an Integrated, Sustained Ocean Observing System* (NOPP), *An Integrated Ocean Observing System: A Strategy for Implementing the First Steps of a U.S. Plan* (NORLC), *A National Initiative to Observe the Oceans: A CORE Perspective* (CORE), *Observing the Ocean for Climate in the 21st Century* (based on OCEAN OBS 99 International Planning Activity), *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science* (NRC), *Scientific Cabled Observatories for Time Series* (SCOTS Report Commissioned by NSF and executed through CORE), and THE LATEST NRC REPORT have been helpful in establishing a community consensus for large scale sensing initiatives and paved the way for several national and international planning efforts that followed. One of these initial reports, *Ocean Sciences at the New Millennium* (Ocean Sciences Decadal Committee) 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*."

As an outgrowth of these studies, the National Science Foundation (NSF) established the Dynamics of Earth and Ocean Systems (DEOS) Steering Committee to advise NSF and other agencies regarding planning and implementation of a network of ocean observatories, including specifically, those envisioned under the Ocean Observatories Initiative (OOI). The objective of DEOS is to develop a sustained, nested and flexible ocean observation system supporting multidisciplinary research by providing meteorological, physical, chemical, biological and geophysical time series observations spanning multiple spatial scales. DEOS has provided a focus for coordinated scientific planning that has identified the science and engineering trends, opportunities, and challenges for making sustained research-based measurements from fixed ocean observatories. Specific operational needs include multidisciplinary sensors and systems that can collect high frequency, long-term data sets, data and state-of-health telemetry to shore-based laboratories, bi-directional communication for remote instrument control and software/firmware upgrades, and an ability to provide power for long-term instrument operation.

The DEOS program has explored two technologically distinct approaches for ocean observations: (1) observatories linked by submarine telecommunications cables to land and the Internet (c.f. the LEO-15, HUGO, H2O, and NEPTUNE projects), and (2) moored-buoy observatories providing the platform for telemetering data back to shore using commercial telecommunications satellites. The latter approach is central to the vision for the DEOS GLOBAL NETWORK.

One advantage of buoy-based ocean observatories is that they can be located in very remote ocean areas far from land, where the cost of laying a fiber-optic cable would be prohibitive. They can also be built and deployed for a fraction of the cost of a cabled observatory system. Other major advantages of buoy-based observatories are that they can be efficiently used for short term (2-3 year) studies, and they can be moved to locations in response to specific events (e.g., a submarine volcanic eruption). The limitations of this approach are the need to regularly service and maintain the buoy, limited power capacity and data telemetry bandwidth, and cost of satellite communications compared to fiber-optic cable.

Although moored buoys have been deployed in the deep ocean since the 1940's as platforms from which to acquire meteorological and oceanographic data, they are only beginning to be used for long-term seafloor observatory studies (e.g., TAO Array, Bermuda Testbed Mooring). Important questions exist regarding the design of such a buoy system including the optimal buoy type (spar- or disk-based floats), the mooring design (single-point or tri-moor), how best to isolate the cable connecting the buoy to the seafloor from wave and current forcing, the expected performance of the satellite telemetry system under different environmental conditions, the best means of supplying power to the buoy and to sensors on the seafloor or the mooring, the best means to accommodate diverse multidisciplinary sensors and systems, as well as the costs of buoy construction, installation, and maintenance. This document furnishes answers to many of these questions, which are central to the development of the DEOS GLOBAL NETWORK of moored-buoy observatories.

In response to increasing demands by researchers for sustained inter- and multidisciplinary observations and as a result of recent advances in technology, NSF has developed an Ocean Observatories Initiative (OOI). OOI is a proposed five-year capital acquisition project developed by the Ocean Sciences Division (OCE) of NSF. The impetus for OOI arises from the rapidly expanding developments in computational, robotic, communications, and sensor capabilities; and from the growing need in the scientific community to be able to study multiple, interrelated properties, variables, and processes over a wide range of time scales. OOI will provide the basic hardware and infrastructure needed to establish a network of ocean observatories with different capabilities to enable advances in ocean research, exploration, and education. The National Science Board has approved consideration of the OOI for Major Research Equipment and Facilities Construction (MREFC) account for Fiscal Year 2006.

OOI has three elements: (1) a lithospheric plate-scale observatory consisting of interconnected sites on the seafloor that span several geological and oceanographic features and processes, (2) several relocatable deep-sea observatories based around a system of buoys, and (3) an expanded network of coastal observatories. When funding becomes available for launching the OOI, a series of RFPs or Announcements of Opportunity will be issued for its implementation and subsequent operation. The location and types of observatories to be established will be determined through a competitive peer review process.

## III. SCIENTIFIC OPPORTUNITIES

### (A) Interdisciplinary, Multidisciplinary, Multipurpose Observatory Science

The DEOS Planning Program was established in response to a community-wide call to investigate the feasibility of developing infrastructure to enable long-term time series observations for the Earth and ocean sciences. As part of this planning process, representatives from the Earth and ocean science communities have identified many areas of scientific inquiry that could be furthered through DEOS infrastructure. Extensive lists of scientific themes relevant to observatory science have been published in several DEOS Planning Documents including the Neptune Feasibility Study, the British-DEOS Design Study, the Report on the CoOP Observatory Science Workshop, the Report from the Scientific Cabled Observatory for Time Series (SCOTS) Workshop, and in *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science*, among others.

Historically, time series sites such as the Ocean Weather Stations (OWS) have provided the data which has improved our understanding of the ocean and atmosphere. For example, simultaneous observation of surface forcing and temporal evolution of the vertical structure of the upper ocean at Ocean Station Papa provided the basis for early efforts to develop ocean mixed layer models. Unfortunately, only one OWS remains today and there is no global array of time series sites to replace them, despite the fact that modern mooring technology would allow a number of such sites to be established. The reasons for establishing a number of fixed time series sites were reiterated at the OOSDP/GOOS/CLIVAR Workshop on Ocean Time-series (Baltimore, 1997) and at OceanObs99 [Send et al., 1999, OTHERS]. These reasons include: investigating the variability of the ocean's interior (including the deep ocean), providing air-sea flux reference sites, monitoring and investigating water mass formation or transformation, measuring transport and variability of major current systems, and obtaining multidisciplinary observations. With the additional capabilities planned for under the NSF Ocean Observatories Initiative (OOI), time series sites would service the needs of an expanded user base and additional areas of the world's oceans could be explored.

This chapter does not attempt to recap all the ever-growing scientific needs that would be met by the establishment of a global array of ocean observatories. Instead, it is intended to summarize key capabilities of observatories that make them valuable resources for advancing oceanographic science and to illustrate this with several examples.

#### *(1) Key Attributes of Moored Observatories*

Moored observatories have unique attributes:

- They can provide information at high vertical and temporal resolution from the atmospheric boundary layer, down through the water column to the sea floor with fast sampling rates (milliseconds to minutes and faster) over durations of many years.
- The surface expression of a surface mooring and cable or acoustic links to the seafloor enables telemetry of data from all depths and adjacent sites; a cable could also allow power to be supplied along the mooring and to the seafloor.

- A large suite of sensors and instruments collecting multipurpose, inter-and multidisciplinary data can be deployed together to examine co-variability in the ocean.
- Critical locations can be instrumented (e.g., local currents, straits and passages, abyssal and near-surface layers, beneath ice, on the seafloor, and in remote regions deemed to be virtually unsampled or of exceptional importance (e.g., central gyres in the southern hemisphere, Southern Ocean, Bering Sea, etc.).
- Sustained presence allows rapid, episodic events to be captured (e.g., rapid mixed-layer shoaling, deep convection, algal blooms, hurricane response, mesoscale eddy passages).
- Accurate, calibrated records are made possible. Observatories are periodically recovered, serviced, and redeployed, so sensors can be checked, reconditioned, and recalibrated. Small climate change signals may thus be first detectable by ocean observatories.
- Moored observatories provide reference, calibration, and validation sites for instruments deployed on surface drifters, fixed depth and profiling floats, autonomous underwater vehicles, and gliders; for remote sensing data; and for shipboard observations.
- Moored observatories can serve as testbeds to foster the development and testing new instrumentation for virtually all in situ platforms, particularly when located within easy reach of coasts or islands.

***(2) Applications of Moored Observatory Data***

Time series observations from key locations around the world's oceans will provide the science community, policy makers, and society with the means to *detect* change; the data required to *describe, quantify, understand, model, and explain* these changes; and an improved capacity to *predict* variability and change. Time series data are useful for a wide range of users including: the research and development community (including testbed applications, model development); climate policy makers, signatories of conventions (e.g., IPCC); weather, ocean, and climate forecasters; disaster warning and mitigation agencies; fisheries managers and users; outreach and education agencies; the remote sensing community; and the national security community. Once data are available publicly and in real-time, the applications and user-base are likely to expand rapidly.

The missions of moored-observatories would include:

- observing variables relevant to physical, chemical, biological, and geophysical processes in the time-depth dimensions (e.g., water mass formation, ocean response to severe storms and hurricanes, and ecological, primary productivity, and biogeochemical variability including vertical carbon export);
- obtaining velocity and transport observations (at fixed places, i.e. Eulerian);
- observing flow and property variability in straits, passages, overflows, choke points (not just transports);
- obtaining surface meteorological observations, including surface wave spectra, and accurate air-sea fluxes to anchor basin scale flux fields;
- obtaining aerosol data (e.g., dust [iron] influx);

- ground-truthing and verification of remote-sensing, models, and forecasts;
- determining $CO_2$ concentrations and air-sea $CO_2$ fluxes (to resolve short time variability: diurnal, seasonal, inter-annual);
- determining ecosystem productivity and variability (including phytoplankton optically, and zooplankton and fish abundances acoustically);
- finding and quantifying the linkages and relationships among physical, biological, chemical and climatic parameters (many variables);
- studying water column ecosystem dynamics, carbon flux, particle export, and the oceanic and air-sea interfacial processes involved in the carbon cycle;
- observing ocean bottom processes and events (e.g., seismic, geodetic, electromagnetic, acoustic );
- observing benthic community structure changes; and
- monitoring pollution.

***(3) Illustrative Examples of Inter- and Multidisciplinary Observatory Science***
*Long-term Change in the Ocean's Interior.* Interior ocean observations are now being made at only a small number of time-series stations. The indications of variability and change provided by two such stations are summarized here to indicate the potential of such records.

Deep convection and long-term salinity changes. Long-term time series measurements of temperature and salinity along mooring lines coupled with surface meteorology support the examination of mechanisms that control deep convection (when surface water becomes dense enough to sink into the interior) and the possibility that continued freshening of the surface water could arrest this process. If this were to happen in the North Atlantic, it would impact the climate. In the past, upper-ocean salinity observations collected at ocean weather ship stations were used to determine the existence and movement around the North Atlantic of the Great Salinity Anomaly (Dickson, et al., 1988) and its descendants (Belkin, et al., 1998). New long-term observatories providing records of change in deep convection as well as temperature and salinity properties in the water column would be invaluable for tracking change in thermohaline circulation.

**Insert – figure from Lazier of decadal T/S change in high North Atlantic**

Deep interannual to decadal-scale water mass changes. One of the longest records of temperature and salinity variability comes from deep water (1500 – 2000 m) offshore Bermuda where Joyce and Robbins [1996] discovered a warming trend that may extend back in time to at least 1922. These observations were based on coarse (typically at intervals of one month or more) time series measurements. The ongoing Bermuda Testbed Mooring (BTM) and the recently funded MOSEAN NOPP Hale-Aloha mooring off Hawaii could be easily equipped with temperature and conductivity sensors to extend this record for the region, and simultaneously sample higher frequency (e.g., sampling intervals of minutes to an hour) variability to enhance interpretation (i.e., mesoscale variability needs to be resolved).

Observations of long-term, deep-ocean variability at other sites around the world are scarce, and installing temperature and salinity sensors throughout the water column on moored-buoys of the GLOBAL NETWORK will provide critical data, especially from depths beyond the reach of the ARGO profiling floats (i.e., greater than 1250 to 2000m). This data would be instrumental for illuminating how the ocean responds to global warming.

**Insert figure from T Joyce showing 30 year temp trend**

Acoustic thermometry. Another means of detecting and observing long-term change is through the use of acoustic thermometry (e.g., Dushaw et al., 2001). The principal difficulty with providing such information is that the ocean variance spectrum is "blue", i.e., dominated by relatively small-scale (mesoscale) processes. Spatial "point" measurements must be averaged over very long time periods to provide climate-related information, and even then, the trade-off between time and spatial averaging may not provide meaningful results. On the other hand, Acoustic thermometry has an advantage in that spatial averages are on a scale appropriate for climate problems, 5000 to 10,000 km. Mesoscale variance is reduced by a factor of 100 in a single measurement. Low-frequency transmissions will be made between established moored-observatories, creating an appropriately smoothed temperature field between moorings. By installing transceivers on each mooring, the number of measured paths increases geometrically with the number of moorings, rather than linearly as is the case with traditional point measurements on individual moorings. Further, problems with calibration drift (common for long-duration time series) are avoided; the only requirement is for timing precision to millisecond accuracy, which has been possible for years. Precision measurements of a few millidegrees temperature change can be expected.

**Insert--nice acoustic thermometry result**

One constraint associated with the use of acoustic thermometry has been the high start-up costs. Present architectures provide for principal power, timing, and data transmission requirements, and they require annual servicing. There may be difficulties associated with putting receivers on active surface moorings; the acoustic sources may be too large. Adjacent subsurface moorings are one solution, but it would be important to investigate the feasibility of placing receivers on moorings with surface expressions to facilitate data transmission. Concern about effects of acoustic transmission upon marine mammals has been and may continue to be a major constraining issue (edit as necessary).

*Surface Meteorology and Air-Sea Fluxes.* High quality measurements of surface meteorology and air-sea fluxes of heat, freshwater, momentum, and other constituents (such as CO2) are needed from ocean sites representative of different meteorological regimes (e.g., tradewind, tropical convective, stratocumulus cloud deck, and Southern Ocean sites). When these data are withheld, and not used to initialize atmospheric models, they provide a powerful independent data set for verifying and motivating improvements to numerical models of the atmosphere and of the coupled ocean-atmosphere system. These data are also used to ground-truth remote sensing data and to develop algorithms for converting what the satellites sense to surface meteorological and air-sea flux variables. The high quality data from long-running, fixed point time series sites are used to identify errors in climatological and contemporaneous meteorological and flux fields derived from ship data, from satellites, and from numerical models. Finally, these data are also used to anchor new, more accurate flux fields being developed with data from various sources using assimilation methods.

**Figure - one-year time series from the Arabian Sea showing errors in numerical weather prediction models and climatologies**

The importance of fluxes stems from the fact that energy exchanges between the ocean and atmosphere occur at or near the ocean surface. Sunlight that penetrates to the sea surface is scattered and absorbed in the upper ocean. The penetrative component of solar radiation varies in time and space (mainly with depth in the open ocean except near the surface where surface gravity waves become important) and is mainly modulated by phytoplankton and their products (detritus). It is now possible to quantify this biologically induced thermal effect by using combinations of buoy-mounted and subsurface moored state-of-the-art bio-optical instrumentation (e.g., spectral radiometers and/or other bio-optical sensors--reviewed in Dickey and Falkowski, 2001). As the ocean warms, there is heat loss by evaporation, by sensible heat transfer, and infrared radiation. Heat and moisture released by the sea surface drive the general circulation of the atmosphere. Heat and constituents such as $CO_2$ and particulates (e.g., dust) pass through the sea surface into the interior of the ocean where there is considerable storage. In addition, the lower atmosphere over the ocean is where human activities can be significantly impacted by uncertainties in the prediction of weather and climate. Direct, high quality time series of the air-sea fluxes allow us to quantify atmosphere-ocean coupling, to understand and attribute change observed in the ocean, and to determine the ocean's role in weather and climate variability.

It is envisioned that moored observatories will provide the essential key 'surface flux reference sites' [Taylor et al., 2000] in the world's oceans. Flux sensors mounted on buoys to measure surface meteorology and air-sea fluxes include those to measure mean variables (anemometers for wind speed and direction; air and sea temperature, humidity, and barometric pressure sensors; rain gauges; and radiometers to measure incoming solar insolation and incoming infrared radiation). Turbulent flux measurements can also be made.

*Biogeochemical Cycling*. High resolution, long-term biogeochemical and ecological data sets with broad temporal coverage (up to 10 orders of magnitude in time and space) are critical for quantifying, understanding, and predicting global climate change and perturbations of the ecology of the upper ocean. The need for quantification of the ocean's role as a sink for carbon dioxide ($CO_2$) has been emphasized by a number of researchers (e.g., recent review by Feely et al., 2001) with estimates varying by at least a factor of three (roughly 0.6 to ~2 Gt-C/yr) based upon uncertainty in the air-sea gas flux. The uncertainty due to variability in surface $CO_2$ levels remains unquantified. The dramatic increase of atmospheric $CO_2$ is well known. However, the increase of oceanic dissolved inorganic carbon (DIC) in the oligotrophic North Pacific [Karl et al., 2001] and North Atlantic Oceans (Bates, 2001) over the past decade has been more reported more recently as well. Furthermore, significant high frequency variability (hours to days to weeks) of $pCO_2$ has been observed at the Bermuda Testbed Mooring [Bates et al., 1998; Friederich personal communication] and MBARI [Friederich et al., in press] mooring sites.

Quantification of the ocean's role in the global carbon and other elemental cycles represents an observational challenge due to the importance of remote ocean regions and the documented variability in biogeochemical and specifically carbon uptake and release processes. Eulerian time series measurements of $CO_2$ exchange will be essential for resolving and understanding time-variability and responsible processes in critical and/or representative locations (in conjunction with research cruise and VOS-based measurements). Instruments analyzing $CO_2$ partial pressure now exist and can be moored autonomously for periods of up to one year [e.g., Friederich et al., date; Dickey et al., 2003 SEA TECH].

**FOLLOWING NEEDS TO BE EDITED AND INTEGRATED WITH TEXT ABOVE:**

Carbon observations are required by international treaties; need data for technological and political decisions; need ocean sinks and their changes. Need in-situ observations on appropriate space and time scales; relate these to satellite data; improve models. Need process studies for understanding surface ocean carbon (air-sea gas exchange, convection/mixing, nutrients and trace elements, ecosystem dynamics, .. Also water column and ocean bottom observations important for solubility pump. Not enough to put $CO_2$ sensors on moorings but need the other variables (physical, biological, ...). Requirements for moored buoy measurements: $pCO_2$, DIC, alkalinity, pH (each with accuracy) and ancillary physical/biological measurements.

Sites: historical places or funded sites, known signals (ENSO, NAO), biogeographical regimes, and ocean color sites. Table of funded and planned $CO_2$ sites exists. US carbon document has estimated number of samples required from known variability, and comes up with typically 12 per year - cannot do with ships.

Variability of $pCO_2$ is due to dynamics (wind, SST, salinity), biology, etc, and thus need to measure them all. Example from Med (DYFAMED) show that one loses much of the variability without continuous measurements. CARIOCA measures "everything". Need high-frequency wind data to calculate $CO_2$ air-sea flux, big difference if only daily values. Maybe that is reason for inability to close carbon budget e.g. at BATS. i.e. measure also wind if measure Delta $CO_2$. Biofouling not problem for $CO_2$ (Carioca uses Seabird antifouling and pump intake), buoy designed for 1 year, longest successful deployments have been 6 months.

Why need time series: ship sampling in the Pacific in the 80s yielded rather stable biology; but later moored time series showed VERY episodic changes, which are missed by ship and satellites (e.g. when clouds, or deep). Can also define provinces based on temporal variability, like NAO or PDO regimes (sites in the maxima of variability). Also need time series since we do not have climatologies in biology (don't have the mean and thus no anomalies).

*Interdisciplinary and Multidisciplinary Observatories.*
**(Should the material currently in Section IV(C) (BTM, O-SCOPE, MOSEAN etc.) that could perhaps be moved to this section???) The material in Section IV(C) needs to be about the technical architecture/components that relate to the three recommended moored-buoy systems. That section is not about science. Please see note in that section…..**

**In the last version of this report, Dickey suggested deleting all material from this section and inserting the following para:**
There are now several good examples of new insights obtained from moored concurrent, multi-sensor measurements (see review by Dickey and Falkowski, 2001). These include : the roles of seasonal and episodic forcing and eddies in increasing upper ocean nitrate and levels of primary productivity at mid- and high-latitudes (e.g., Dickey et al., 1998a, 2001 McNeil et al, 1999); monsoonal atmospheric and eddy forcing of productivity in the Arabian Sea (Dickey et al., 1998b), modulation of productivity in the equatorial Pacific through tropical instability waves, Kelvin waves, and El Nino/La Nina sequences (e.g., Foley et al., 1998); and variability in upper ocean heating caused by phytoplankton (e.g., see Dickey and Falkowski, 2001)). More details are provided below in discussions of time series programs off Hawaii and Bermuda.

**Here is the updated text from Weller (received at the same time as Dickey's edits):**
In the future, observatories should be partnerships among the disciplines, including physical oceanography, biology and geochemistry, geology, etc. Observations at Bermuda have been made for many years at Station S, and more recently collection of multidisciplinary time series has started at the Bermuda Area Time Series (BATS) site. Continuation of a unified Bermuda site, preserving the historical link and adding the new observations, is recommended. Additional sites in the interior of the ocean basins could be occupied in conjunction with air-sea flux reference sites, especially for monitoring water mass formation and transformation, or as long-term subsurface moorings. These would provide high vertical and temporal resolution, allowing local dynamics, storage, and variability to be described as well as supporting development of parameterizations and comparisons with ocean models. Determination of eddy statistics and development and confirmation of parameterizations of eddy processes would be one reason for such moorings. Discussions between the Ocean Observations Panel for Climate (OOPC) and the CLIVAR Ocean Observations Panel (COOP) are underway now to identify the locations for these sites and develop the international commitments that would support their occupation.

Sensors that would add capability include those for trace metals (incl. iron). They have developed a moored water sampler, for 12 samples, for analysis in the lab. Many sensors do not exist yet, also good for verification of sensors that do, and also can archive samples for later analyses of new variables. Has been deployed on BATS and ALOHA moorings. Actual data show large variability, up to 6x over weeks for iron. Verified causes: eddies, dust fluxes, biol. patchiness, hurricanes,... Now can manage with much smaller samples, thus future instruments would be smaller and take more samples. In some biological provinces iron information is very important (even profiles), in others not so essential.

**insert nice figure of multidisciplinary data showing covariability – maybe Arabian Sea, maybe HOTS or BATS**

Biology influences global biogeochemical processes and is a sensitive indicator of environmental change (and thus also better at testing physical models). (E.g. zooplankton correlation with NAO or long-term decrease in Diatoms and others at Porcupine Abysall Plane) Provinces: as traversing the ocean, the rate of change of plankton communities is not constant -> boundaries, provinces. In terms of community structure (entire food webs) this is not viable. Longhurst: used physical (wind) and topographic regions as a start. Then made 57 provinces using CZCS, vertical Chl distributions, nutrients, mixed-layer depth, stratification (not using zooplankton). Then he looked for commonalities between these provinces uses models, and came up with domains like polar, westerlies (nutrient limited spring production peak), subtropical (nutrient-limited winter production), trade wind (little seasonality, monsoon regime (large seasonal variability). Many time series located are on boundaries of domains, some are in interior (has a map). Does not mean that there is no variability in the interior, but the (e.g. mesoscale) variability may be characterstic of a region. In the past it was difficult to agree on a way proceed in biology, since there have been recent dramatic changes in the understanding of processes (zooplankton interaction); also no agreement on what should be measured; and lack of sensors. All this is very recent stuff. Primary production is very hard to observe (from space and with models).

Microorganisms are important, many recent discoveries, microbes are adjusted to environmental change and can easily respond. Manned time series sites were important for these discoveries, but moored sampling devices also exist now, as well as molecular probes.

Bermuda hydrostation S, biweekly sampling since 1954 (more climatic, CTD, oxygen, plus ancillary stuff) BATS biweekly/monthly sampling since 1988 (more biogeochemical, CTD, oxygen, PAR, fluorescence, beam attenuation, and many more). BATS supports lots of process studies too, including various moorings like BTM. Proposal out to put another 3 moorings around BATS to observe eddy field.

**HOT** (not HOTS) has 2 components, R.Lukas' physical station, and biogeochemical one (D.Karl). CD exists with 10 years of data, virtual cruise, also Deep-Sea volume. Cruises since 1988 nearly monthly, station is called ALOHA. There are other biogeochemical time series sites around the world. No mooring anymore there (funding problems). Also have an Antarctic program (COLD) on AA side of Drake Passage: ship-based (annual), bottom station (sediment traps, seacats, ice sonar), island met station, theme is ice variability (anticorelated with SOI) influence on biogeochemistry, Interdisciplinary time series moorings. E.g. JGOFS sites in Arabian Seam EqPac, MedFlux, MLML (at NABE), **BTM**. Very few ongoing biogeochemical moorings now, like BTM, no more HOT mooring. New sensors have been produced. BTM since 1994. Used to be test bed mooring, now also used for science (though funding still as test bed). 40-45 people put instruments on BTM or use/mode the data, Right near BATS site, most instruments above 200m, CARIOCA tethered to the buoy, also had been enhanced by Autosub in one year to get spatial surroundings. Plan now for "Sargasso Sea Observatory" for larger regional observing system. HOT mooring is in a re-proposal stage, similar to BTM mooring.

Interdisciplinary timeseries studies are now available which can target a variety of climate issues (e.g., Dickey, 1999). The ship-occupied station S and the nearby BATS (Bermuda - Atlantic Time-series Study) site, as well as the Bermuda Testbed Mooring (BTM) program, provide good examples, with data sets which enable sophisticated modeling of the system (e.g. Doney, et al., 1998), ground-truthing of remotely sensed data (e.g., Deuser, et al., 1990), and recognition of seasonal and interannual changes of climatically important quantities (e.g. carbon dioxide: Bates, et al., 1996; primary production: Lorenz, et al., 1992). Examples of new insights from moored concurrent, multi-sensor measurements include: the roles of seasonal and episodic forcing and eddies in increasing upper ocean nitrate and levels of primary productivity at mid- and high-latitudes (e.g., Dickey et al., 1998a; McNeil et al, 1999); monsoonal atmospheric and eddy forcing of productivity in the Arabian Sea (Dickey et al., 1998b), Figure 4; modulation of productivity in the equatorial Pacific through tropical instability waves, Kelvin waves, and El Nino/La Nina sequences (e.g., Foley et al., 1998); and variability in upper ocean heating caused by phytoplankton (e.g., Dickey et al., 1998b).

***Integrated Acoustics Systems for Ocean Observatories (Placeholder for P. Worcester)***
The concept of integrated acoustics systems to provide navigation and communications and to conduct acoustic measurements, all in support of science applications within the ocean's volume, is developed. The navigation function is analogous to the now-ubiquitous satellite based Global Positioning System (GPS), but because the ocean is opaque to electromagnetic waves and transparent to sound, acoustics systems are necessary. In the ocean, a series of nested systems are envisioned, from small-scales to regional to basin-scales as required. A small number of acoustic sources sending coded, low power signals can service unlimited numbers of inexpensive receivers. These sources can serve double duty by transmitting control data from users to remote instruments; if enabled as receivers, two-way acoustic communications links in large-scale networks can be established. Acoustic based instrumentation that shares the acoustic bandwidth with, and depends upon, the navigation and communications capabilities completes the concept of integrated acoustic systems.

This navigation and communications infrastructure is a prerequisite to the sustained presence of mankind in the ocean. Many applications require or are enabled by this infrastructure. Autonomous undersea vehicles (powered and gliding) can navigate themselves over the ocean bottom and through the water column without coming to the surface. They can obtain navigation fixes and communicate their data and status to users via acoustic modems to cabled or surface satellite telemetry systems without breaking away from their underwater missions. Profiling and drifting floats can more accurately measure the ocean's velocity structure, tagged fish and marine animals can be tracked with high precision, moorings can track their motion in ocean currents, and bottom-fixed instruments can measure seafloor motion.

The sources and receivers can serve multiple functions: sources as navigation and communications components as well as multi-static active transmitters, and receivers as communications components and as passive listening devices. With signal standards and protocols for managing the acoustic spectrum, the system will be an extensive multipurpose acoustics infrastructure, capable of supporting applications even beyond our present vision. Drawing a further analogy with GPS and its use for tomography of the atmosphere and ionosphere, the various acoustic sources and multitude of receivers can function similarly in the ocean. This has significant implications for observing the ocean's interior in real time, and measuring long-term climate variability. Receivers on globally distributed floats can also listen to ambient sound: wind and rainfall, seismic T-phases, marine mammals, and ships. Some of these natural sources of sound can in-turn be used as sources of opportunity for other purposes.

The provision of such a transformational infrastructure to the ocean community is expected to be one of the enabling technologies fueling a revolution in ocean observatories. This report examines the concept by addressing technical questions and implementation issues. The IASOO Committee is a newly formed specialty committee of the Acoustical Society of America. Broad community participation is encouraged.

***Wave Height Instrumentation/surface wave observations  (Placeholder for E. Terrill)***

## (B)  Measurement Categories

***(1) Core Measurements***

The initial OOI infrastructure will include the instrumentation needed to make specific key measurements, ensuring that the moored-buoy observatories will return critical data from the outset.  The cost of the core instrumentation will be included in infrastructure costs, and the data from the core measurements will be freely available.

Core measurements must be:

- Relevant to needs.  Measurements should be in response to needs for information.
- Long term.  Measurements, once begun, should continue into the foreseeable future.  Continuity in the observed quantity is sought rather than in the method, and it is anticipated that more effective methods will become available with time.
- Systematic.  Measurements should be made with spatial and temporal sampling tuned to address the relevant processes and issues.  Further, measurements should be made with the precision, accuracy, and care in calibration required to provide continuity in the quality of data in space and time even though different methodologies may be used.

- Cost effective. To maximize the number of core observations using available resources, the observational methods used in the system must be economical and efficient.
- Timely. The ability for users to access and retrieve observations with sufficient timeliness to meet their needs. Some requirements are for real-time data delivery. In other cases there may be considerable time elapsed between measurement and data delivery.

Further community input will be required to select a specific set of core instrumentation. Potential candidates are: [*For this document, it was suggested that the three moored-buoy systems be costed by instrumentation package: one for process, one for geophysical, and one for flux studies. Note: no one has provided this information to Dan Frye yet.*]

*Surface Meteorology*

- Wind speed/direction
- Barometric pressure
- Air temperature/humidity
- Sea Surface Temperature (SST)
- Short/longwave radiation

*Physical Oceanography*

- T, S in the mixed layer
- T, S in the deep ocean (2000 and/or 4000 m sampling)

Even if the moored observatories are not dense enough to map patterns of change, moorings located in ocean (dynamical) provinces will be valuable, just as Bermuda is taken as representative for the subtropical gyre.

*Geophysics*

- Ocean bottom seismometer (1 sample/s, with a dial-up capability of 40 samples/s)

*Hydroacoustics/Acoustic Tomography*

- Hydrophone or vertical receiving array

*Biogeochemistry*

- Chlorophyll
- PAR

[*Others?????]*

***(2) Community Experiments***

Community experiments are defined as observations that are proposed separately from the basic observatory infrastructure, but from which the data are nonetheless nonproprietary. Community experiments would typically provide observations (a) required by two or more independent projects and (b) of long duration (beyond the length that an individual PI could be expected to provide support via individual proposals). Community experiments might be required to support ongoing educational programs, for example.

***(3) PI/Group Experiments***

PI/Group experiments are those proposed by a single PI or group for independent funding, taking advantage of the infrastructure provided by the moored buoy observatories. PI/Group experiments may result in proprietary data.

## (C) Proposed Locations of Observatories

Selecting a limited number of deployment sites for moored-buoy observatories is a challenging task. In this effort, DEOS has developed partnerships that have extended the consensus-building process across nations and disciplines. What has evolved is a philosophy for site selection where the value of the site is determined by (a) one or more meteorological, physical, chemical, biological or geological province(s) of the world's oceans; (b) its potential to provide key information to quantify important processes, and (3) the requirements for validating models, ground-truthing remote sensing, or observing change in the ocean.

The DEOS Steering Committee has used the work of the Time Series Science Team in determining preliminary locations for twenty moored-buoy observatories (see **Figure 1**). The Ocean Observations Panel for Climate (OOPC), together with the CLIVAR Ocean Observations Panel (COOP) and the Partnership for Ocean Global Observations (POGO) recommended the formation of the International Time Series Science Team to represent the scientific community's diverse interests, to develop consensus on the desired locations for time series stations, and to begin implementing different components of an integrated global ocean observing system.

The proposed locations for DEOS Moored-Buoy Observatories were determined by the following criteria:

- The DEOS GLOBAL NETWORK should provide long-term measurement sites for important oceanographic and climatic studies, including Ocean Seismic Network (OSN), the Global Eulerian Observatory (GEO), and the Acoustic Thermometry of Ocean Climate (ATOC) Programs.
- The DEOS GLOBAL NETWORK should be designed to complement and enhance observations from a wide range of other on-going or proposed observatory efforts, including those from ship-based and multi-platform research. These include the Global Ocean Observing System (GOOS), the Global Climate Observing System (GCOS), the Argos Float Network, the International Tsunami Warning Network, Ridge 2000, Global Ocean Eco-systems Dynamics, CLIVAR, Earthscope, MARGINS, the Integrated Ocean Drilling Program (IODP), the InterRidge initiative for long-term monitoring of northern Mid-Atlantic Ridge (MOMAR or MOnitoring the MAR), the International Ocean Network (ION), the Integrated Ocean Observing System (IOOS), OCEAND, GLOBEC, iAnZone,

SOLAS, Ocean Hemisphere and Archaean Park Projects, GSN, GEOSCOPE, IRIS, GEOSTAR, and others. Scientists involved with many of these projects have also been involved in the planning and design of the DEOS GLOBAL NETWORK.

- Sustained in-situ observations at fixed geographic locations of ocean/climate related quantities at a sampling rate high enough to resolve unambiguously the signals and processes of interest. "Sustained" means a plan or commitment for longer than one project or proposal period, and intention to pursue funding from "observing system programs" when available. Therefore, wherever possible, the observations should be achieved with autonomous instrumentation, in a moored or virtually moored mode. Where this option is not available (certain variables, logistical constraints, etc), ship-occupied time series may qualify an alternate approach, if at least seasonal variability can be resolved. The rationale for establishing a mooring-based system is that only this mode can deliver high temporal resolution which is critical for various observations or events. Also, only in this way can the long-term goal of unattended operation over many years be approached or remote glider-based methods explored.
- Transport sections using whatever technique are included in choke points and major boundary current systems (moorings, gliders, ship ADCP, tomography, etc.)
- Coastal time series are included when they are instrumented to have a multidisciplinary impact on the global observing system and if they are not part of a national coastal buoy network.
- Any implemented site fulfilling the criteria will become part of the system. However, this comes with the stipulation that site data must be delivered into the system and that individual sites demonstrate successful operation and value after 5 years. Data should be made public in real or near real-time or, in some cases, as soon as it is processed and post-calibrated for other data.
- Real-time data telemetry of operational variables will be pursued, i.e., every effort will be made if it is technically feasible and/or if there are operational users. The rationale for this requirement is that it facilitates (a) monitoring of instrument functionality (essential for targeting uninterrupted time series); (b) end-user requirements for real-time data (ocean forecasting, real-time assimilation, politicians to demonstrate Kyoto monitoring obligations); (c) outreach and education (online public information about ocean state and changes, ability to feed news about events to media); (d) verification and validation of remotely sensed and other autonomously collected data sets; and (e) event-driven sampling.

**(Delete?)** Ocean observatories would be established in key sites of water mass formation and/or transformation by air-sea interaction. Their observations aid in determining the depth of convection at a reference site, while simultaneous float data could be compared to give indications of its spatial variability, and tomographic observations might provide the horizontal extent/average. From the meteorological data obtained by these stations, accurate air-sea fluxes will be estimated, which is one of the forcing functions for the water mass transformation. Another controlling factor, the initial (fall) stratification (buoyancy content) can be determined with surface-mooring techniques (see below). The change with time of ocean heat and fresh water content can be determined, and compared with the surface fluxes allowing estimates of the horizontal advection/mixing. Altogether, such observations would provide insight into the mechanisms and variability of water mass transformation, and at the same time monitor changes at the origins of deep water masses and of elements of the thermohaline circulation. Links can thus be investigated with changes in these water masses or in the thermohaline circulation in other places of the ocean.

**(Delete?)** Well-instrumented surface moorings are recommended at a subset of locations in order to provide high quality, accurate reference data to be used to check, verify, and calibrate surface meteorological fields from models, remote sensing, and other in-situ measurements. Further, work in progress to upgrade the quality of the surface meteorology and air-sea fluxes on a global basis from the Volunteer Observing Ship (VOS) fleet is based on a strategy that will rely on the fixed reference sites. The reference sites will serve both as primary standards for quality control of the VOS data and as the basis for validating regional choices of flux formulae. The present drifting buoys provide a good example of how in-situ observations are used to calibrate satellite data; in their case, they provide the means to calibrate the AVHRR fields of SST. In addition to SST, the reference site surface moorings will provide surface winds, surface shortwave and longwave radiation, water depth, and rainfall for use in validating and calibrating remotely sensed values of these variables. (See also Taylor et al, this volume).

**(Delete?)** At key sites, sustained direct measurement of ocean currents is envisioned. The mass and heat transport variability of important current systems is presently hardly known. Long-term Eulerian measurements of e.g. surface and deep western boundary currents and of the dense overflows of Nordic Sea waters through the Denmark Straits and Faroe Bank Channel will help quantify changes in important elements of the climate system. Throughflow/outflow measurements will document the exchange (and its variability) between ocean basins or oceans and marginal seas, providing also integral information on the average basin processes. Different approaches will be available for such transport measurements, like boundary arrays of current meter moorings, dynamic height moorings on opposite sides of major ocean currents, acoustic transmissions or hydraulic reservoir height measurements. These data will prove valuable in detecting changes, in estimating ocean heat and property fluxes, and in constraining numerical models. Moreover, by instrumenting sites on opposite sides of ocean basins variations in the ocean's net meridional overturning circulation could be investigated.

**(Delete?)** Moored velocity and water property measurements will be made of the eddy to long-term variability of specific ocean regions. Both the multi-annual and the eddy time scale pose a problem for current climate models. Such models cannot yet be run routinely in the "eddy resolving" mode, and eddy processes need to be parameterized. Field experiments can be designed and performed to achieve this goal. Some will be focused limited duration process experiments, but others will need to be sustained measurements programs; for example, to document variability in eddy statistics. Efforts are also under way to assimilate statistical quantities into models. Fixed point, or Eulerian, measurements will be crucial for this. For the multi-annual timescale, very few observations of variability exist, apart from the ENSO observing system. The longest available record is of order one decade and there exist very few locations where currents have been observed for longer than 2 years over the water column. A network of moorings around the world would obtain a global picture of long term internal variability and its depth structure for comparison with that being obtained by altimetric satellites and numerical models.

The combination of physical, chemical and biological observations is a powerful argument for ocean observatories. A central theme for this work involves developing an understanding of how synoptic-scale and annual-to-interannual variations in atmospheric forcing and ocean circulation, stratification, and water mass properties and processes impact the ecosystem and biogeochemical properties and fluxes (e.g., nutrients, oxygen, productivity, plankton biomass, and trace metals). Fixed-point timeseries observations can also serve as a reference and provide background information for

For biology, biogeochemistry, and bio-optics, it has been suggested that sites to be occupied include 6 major biomes:
1) eastern boundaries 2) equatorial 3) western bound 4) westerlies 5) subtropical gyre 6) subpolar/polar gyre

Seafloor seismic sites are chosen to fill gaps in the global coverage now provided by land-based seismic stations. The ocean sites with the most value would be located 1,000 km from land.

The following map and tables (**Figure 1 and Tables 1-4**) reflect the sites that are currently operating or funded (green on map), or where plans/intentions exist that the Science Team considers sufficiently concrete to give a realistic chance of implementation during the pilot phase (red). The map and tables distinguish air-sea flux reference sites, transport sites (boundary currents, passages/throughflows, long sections), and more general observatories where any collection of physical and/or biogeochemical and bio-optical variables may be observed. The map and tables will be updated in January 2003 to reflect recent addition like the ASOF program and others **(WAS THIS UPDATED?).**

**FIGURE 1: Choice locations for DEOS Moored-Buoy Observatories (supplied by Weller)**

**Table 1: Atlantic Ocean Sites**

| **Lat / Long** | **Remarks** |
|---|---|
| 36N 70W | Gulf Stream extension, flux reference at critical site for air-sea coupling, exchanges of heat, CO2, freshwater; water column instrumented for water mass variability and modification studies |
| 32N 65W | BATS/Station S/BTM; historical time series record and test bed 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 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 |

**Table 2: Pacific Ocean Sites**

| Lat/Long | Remarks |
|---|---|
| 50N 145W | Former Ocean Weather Station PAPA, meteorology; physical, biogeochemical |
| 40N 150E | Kuroshio Extension, meteorology and air-sea fluxes, water mass variability |
| 9N 110W | East Pacific Rise RIDGE 2K site, tropical air-sea coupling (northward extension of TAO line at 110W), surface meteorology, water column, sea floor biology, hydrothermal vents, geophysics |
| 0 145W | Eq. Pacific multidisciplinary site, upgrade 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 |

**Table 3: Indian Ocean Sites**

| Lat / Long | Remarks |
|---|---|
| 15N 65E | Arabian Sea, meteorology; physical, biogeochemical |
| 12N 88E | Bay of Bengal, meteorology; physical, biogeochemical |
| 10S 90E | 90E ridge mukltidisciplinary site, surface meteorology, water column, sea floor |
| 25S 97E | Indian Ocean DEOS, geophysics, physical, meteorol., biogeochem. |
| 47.7S 60E | KERFIX follow-on, physical, meteorology, biogeochemistry |

**Table 4: Initial Southern Ocean Sites**

| Lat / Long | Remarks |
|---|---|
| 42S 9E | SW of Cape Town, meteorology, water column instrumentation, geophysics |
| 55S 90W | AAIW water mass formation region, meteorology, physical, $CO_2$,, geophysics |
| 47 S 142E | south of Tasmania, meteorology, physical, biogeochemical, geophysics |

**(D) Required Technology Development (This section needs to be fleshed out or deleted)**

Technology development is required for getting sites in the Southern Ocean going. Without surface met, the existing subsurface moorings in the Atlantic sector might be extended to 20m below surface for CO2, chlorophyll, nutrients. Any recommendations from this group will help (e.g. in Australia, New Zealand, France).

Work on met sensors needed: low power sonic anemometer, measure buoy mean tilts, improved longwave sensor, improved calibration procedures.

There is need for continued development and testing of interdisciplinary sensors and systems. These include: $pCO_2$, fugacity of $CO_2$ or $f(CO_2)$, dissolved oxygen $O_2$ or DO), dissolved inorganic carbon (DIC), pH, total alkalinity (TA), nutrients (macro- and micro-), chlorophyll, inherent optical properties (IOPs), and apparent optical properties (AOPs).

There has been a phenomenal increase in optical measurement capabilities, especially with the development of high spectral resolution sensors for both *in situ* and remote (satellite and airplane) platforms. Yet, there remains a need for better understanding and interpretation of our present optical measurements and for measuring additional optical parameters *in situ*. Several new systems are being developed for moored optical measurements (see Dickey, 2001b, Maffione, 2001). These include: flow cytometers, particle cameras using holographic and other methods, and spectral fluorometers. Optical instrumentation has been shown to be especially effective for biological studies and expansion to others is likely. For example, many envision the use of hyperspectral optical data for identification of phytoplankton species, at least by groups (e.g., Davis, 2001). This would lead to improved understanding of community succession and perhaps allow prediction of harmful algal blooms. It is anticipated that optical measurements may prove valuable for other disciplines as well. Optical measurements have already been demonstrated to be important for upper ocean heating rates and heat budgets. In the future, it may be possible to use optical signatures and measurements for remotely estimating mixed layer depth in some oceanic regions. In addition, increasing numbers of chemical variables will be measured from moorings (e.g., Tokar and Dickey, 2000; Dickey et al., 2000) and will be useful for understanding and modeling biological processes like primary and new production.

The temporal range of *in situ* measurements of several of the fundamental spectral optical variables (irradiance, radiance, absorption, scattering, etc.) can in principal capture most of the processes of interest. Spectral and coherence analyses are certainly powerful analytical methods. However, the processes of interest are often non-stationary, nonlinear, and out of equilibrium and thus not strictly amenable for conventional statistical methods. However, new techniques such as wavelets and fractals may well prove to be valuable analytical tools (e.g., Emery and Thomson, 1997). The development of optical time series programs, akin to the Mauna Loa $CO_2$ program, in key oceanic regions is feasible because we can now use well-calibrated radiometers deployed from dedicated and moorings-of-opportunity (e.g., shared use of moorings with programs such as CLIVAR, Global Ocean Observation System (GOOS), etc.). The temporal resolution of both airplane and satellite platforms are still rather coarse and suffer from cloud obscuration. However, there are plans for multiple ocean color satellite missions, which should improve both temporal and spatial coverage (Davis, 2001). In particular, some hyperspectral color satellites with spatial resolutions on order of 10's of meters are being planned for coastal observations; some color systems with similar resolutions are already being flown from aircraft. These capabilities will provide improved opportunities for comparing and synthesizing optical time series obtained from moorings and satellites.

A new thrust for time series observations will be toward fully three-dimensional observations, which will increase the spatial sampling domain (see Figure 2 in Dickey, 2001a). Moorings with fixed depth and profiling instrumentation will remain important and platforms such as autonomous underwater vehicles, gliders, drifters, offshore platforms, and profiling floats will become important components complementing moorings and satellites. Recently, bio-optical measurements have been made from AUVs at the BTM site, in Massachusetts Bay, and Monterey Bay (e.g., Griffiths et al., 1999; Yu et al., 2001). Increasingly, there is interest in utilization of optical data in near real-time and for data assimilation models (Bissett, 2001). Prediction of optical and bio-optical variables has become a realistic goal.

**Biofouling issues here?**

## IV. MOORED-BUOY INFRASTRUCTURE, PROTOTYPES, COSTS, AND TIMETABLE

### (A) Findings from the DEOS Moored-Buoy Observatory Design Study

The oceanographic community has considerable experience with simple moored-buoy systems deployed to acquire long-duration meteorological and oceanographic data. While much of the technology needed to establish a network of moored observatories already exists, additional developments and enhancements will be required to deploy an integrated, cost effective, globally functional moored-buoy observing system.

To evaluate the potential to establish a global network of moored buoys, a team of experts from Woods Hole Oceanographic Institution, Scripps Institution of Oceanography, Deep Oil Technology, and the Monterey Bay Aquarium Research Institute prepared the *DEOS Moored-Buoy Observatory Design Study* in 2000 with support from the National Science Foundation. Due to the broad spectrum of scientific needs identified in DEOS planning documents and described in *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science*, it was clear from the outset that no single buoy or mooring design would meet all of the needs of the scientific community. Therefore, the Design Study participants considered a range of specifications and designs and evaluated the trade-offs in performance and costs for these different systems. In particular, the DEOS Moored-Buoy Design Working Group evaluated three specific buoy and mooring designs on the basis of their costs and capabilities:

- A low-bandwidth design using acoustic modems to connect instruments on the seafloor (or in the water column) to the surface buoy which uses a conventional (discus) mooring. No power is delivered to the seafloor and solar panels (with batteries) are used to power a low-bandwidth satellite telemetry system on the buoy.
- Two high-bandwidth designs (one a tri-moored spar buoy and the other a single-point mooring discus buoy) using an electro-optical cable to provide power and communications to a seafloor junction box (and, in the discus design, to moor the buoy). Diesel power generation equipment on the buoy provides power to run the high-bandwidth satellite communication system and to operate instruments on the seafloor or on the mooring.

The Design Study found that:

- moored ocean buoys are a technically feasible approach for making sustained time series observations in the oceans and should be an essential component of any long-term ocean observing system, and
- *both* the low-bandwidth, acoustically-linked and high-bandwidth, cable-linked observatory concepts should be developed.

The *advantages* of the low-bandwidth, acoustically-linked observatory design include:

- Low cost buoy and mooring components;
- Incremental extension of proven technology;

- Uncomplicated logistics (installation, service and relocation of observatories can be managed by medium/large UNOLS ships without special handling equipment);
- Ease and relative low cost for installing and servicing science instrumentation (ROV not required for installation and maintenance);
- May be deployed quickly for rapid-response studies;
- Instruments can be installed on the observatory buoy mooring line; and
- No electro-optic cable or junction box to act as a single point failure.

The *disadvantages* of the low-bandwidth, acoustically-linked observatory design include:
- Limited data throughput;
- No power provided to bottom instruments;
- Additional cost to provide internal power and acoustic modem with each sensor;
- Acoustic link failure will interrupt data telemetry from the remote instruments, although it will not necessarily affect data collection for instruments conforming to V.B (?); and
- All subsurface instrument packages will have to be removed and reinstalled during annual maintenance unless they are designed to be serviceable by ROV. This could significantly add to time on station and could be detrimental to experiments requiring oriented sensors, precise location of sensors, or long-term continuity of measurements (e.g. seismology or geodesy).

The *advantages* of the high-bandwidth, cable-linked observatory design include:
- Data throughput is adequate for nearly all scientific applications;
- C-Band telemetry is inexpensive (per byte) compared to other options;
- Plenty of power is provided to instruments on the bottom and on the buoy;
- System is expandable for future applications;
- Maintenance from UNOLS vessels;
- Robust buoy will have an extended lifetime; and
- Commonality with NEPTUNE junction box interfaces allows interchange of instruments between both systems.

The *disadvantages* of the high-bandwidth, cable-linked observatory design include:
- Unit cost is comparatively high;
- Electro-optic cable service life is hard to predict and is costly to replace;
- Difficult and expensive to install (requires deep-rated ROV and dynamically positioned ship to install and maintain sensors);
- Deployment will require either leased commercial vessel (spar buoy) or UNOLS vessel with extensive special handling gear (discus buoy); and
- Potential concern about diesel exhaust impact on meteorological sensors. This contamination could be limited by a low duty cycle for diesel generators.

In terms of projected science requirements, which were estimated in the Design Study, the low-bandwidth option would be able to telemeter all required geomagnetic, geodetic, meteorological, and oceanographic data. Seismic data would be limited to partial telemetry based external event detection. Still photography on a limited schedule (e.g.

one picture per hour) is also within the capabilities of a low-bandwidth system. Acoustic data and video, on the other hand, are well beyond the capabilities of a Low-Bandwidth system. The high-bandwidth system is capable of telemetering all projected geomagnetic, geodetic, meteorological, oceanographic *and* seismic data, and it can manage a significant fraction of the estimated AUV, acoustic, and video data requirements. The high-bandwidth system can also supply power for the AUV dock and for acoustic sources used for basin-scale tomography measurements.

In general, the acoustically-linked, low-bandwidth approach has the advantage of lower cost and less complicated logistics at the expense of lower data rates, and an inability to provide power to the seafloor. Cable-linked buoy systems are more expensive to build, install, and operate, but offer much higher data rates and can provide significant power to operate seafloor instruments. Costs (including ship time) for the two different approaches, averaged over 10 years, differ by a factor of 2 or 3, while data rates differ by about a factor of about 100. Cable-linked, moored buoy systems, of either the spar or discus design, will be well-suited to applications which require very high-bandwidth and for which observations over a long time period (a decade or more) are needed. Acoustically-linked moored buoy systems will be the preferred solution when power does not need to be supplied to sensors, the data telemetry requirements are modest or systems need to be relocatable or deployed rapidly in response to transient events.

For high-bandwidth applications, both discus (single-point mooring) and spar buoys (tri-moors) are suitable. The discus approach is less expensive initially and simpler to install. However, a spar buoy with a 3-point mooring has the potential to be more reliable both in terms of satellite telemetry and the longevity of the mooring and electro-optic cable. Amortized over the 10-year operational life of the systems the cost to build, install, operate and maintain a spar system are only about 15-20% higher than for a discus buoy. The appropriate choice of approach will depend on the location (latitude, water depth), the anticipated system lifetime, the power and telemetry requirements of the sensors, and the need for continuous real-time data.

The DEOS Design Study concluded that

- A mix of capabilities with a small number of high-end systems, and a larger number of simpler, less expensive but less capable systems will best meet broader community needs, and
- Development and testing of prototype systems for both acoustically-linked and cable-linked moored-buoy systems must be pursued to answer questions regarding long-term reliability.

**(B) Recommended Designs**

Based on the findings of the Design Study and bolstered by additional community input, the DEOS Moored-Buoy Working Group recommends three designs for the GLOBAL NETWORK. These include the low-bandwidth, acoustically-linked system and the high-bandwidth cable-linked spar system investigated in the original Design Study, plus one additional design, that of a low-bandwidth, cable-linked system. The rationale for this decision is twofold:

- Since there is little cost differential between the high-bandwidth cable-linked spar or discus designs over the long term, the tri-moor *spar* buoy was selected because of its increased survivability potential.
- Additional community input as indicated that a second *low-bandwidth* design powering instruments below the surface via *EOM cable* would be well suited to the needs of the scientific community.

**Table 5: Primary Design Constraints for Moored-Buoy Observatories**

| | | **Telemetry Bandwidth** | |
|---|---|---|---|
| | | **Low** | **High** |
| **Power to the Seafloor?** | **No** | Low-bandwidth, acoustically-linked system | |
| | **Yes** | Low-bandwidth, cable-linked system | High-bandwidth, cable-linked spar buoy |

A technical description of the three systems is provided in the section below.

***(1) Low-Bandwidth, Acoustically-Linked System***
In a recent NSF-funded design study of moored-buoy observatories [DEOS Buoy Design Study, 2000], a range of specifications and moored-buoy designs were investigated based on the telemetry rates they could support. One concept, which was developed in this study, was that of a relatively low-bandwidth, acoustically-linked, moored-buoy system that uses acoustic modems to telemeter data from instruments on the seafloor (or in the water column) to a surface buoy, and from the buoy to shore via a satellite radio link (**Figure 2**). Because this design does not use EOM cables to connect the buoy to a seafloor junction box, it does not deliver power to the seafloor. The current bandwidth limitations of acoustic modems (~5 kbps) and low power satellite links (~2.4 kbps for Iridium), as well as the cost of satellite telemetry (~$1/minute for Iridium), limit data throughput to a few Mbytes/day. These bandwidth limitations, however, are more than offset in the acoustically-linked approach by substantially lower costs for the buoy and mooring components, less complicated logistics for buoy installation and servicing, and simpler instrument installation and retrieval. Specifically, an ROV is not required for mooring installation or system turnaround. Acoustically-linked buoys are thus ideally suited for use as relocatable observatory systems, and may be deployed quickly for rapid response studies. They also may be the system of choice for long-term, fixed observatory sites where data rates are moderate, but real-time or near real-time data are required such as the Global Eulerian Observatories (GEO) network of moorings envisioned by the international Time Series Science Team.

The following is a description of the technical specifications of the low-bandwidth, acoustically-linked system:

*Buoy and Mooring Design*. The mooring design for this system is a single-point, semi-taut design of a type used successfully by WHOI and others for many years (**Figure 2**).

It is relatively inexpensive to fabricate, and uses commonly available mooring components and hardware. Installation is straightforward using an 'anchor last' deployment technique, and the mooring can be maintained using medium or large UNOLS research vessels. An ROV is not needed for the installation or maintenance of the observatory system; however, an ROV may be required for sensor deployment in some cases (e.g., precise location of sensors relative to a seafloor feature like a hydrothermal vent). The surface buoy provides a platform for RF antennas, environmental sensors and batteries or solar panels. The mooring watch circle is about 3 km in diameter, which allows the use of directional acoustic transducers to optimize the acoustic link margin. The buoy and mooring system are designed for yearly servicing with all mooring hardware replaced annually. The buoy and its payload have a ten-year life.

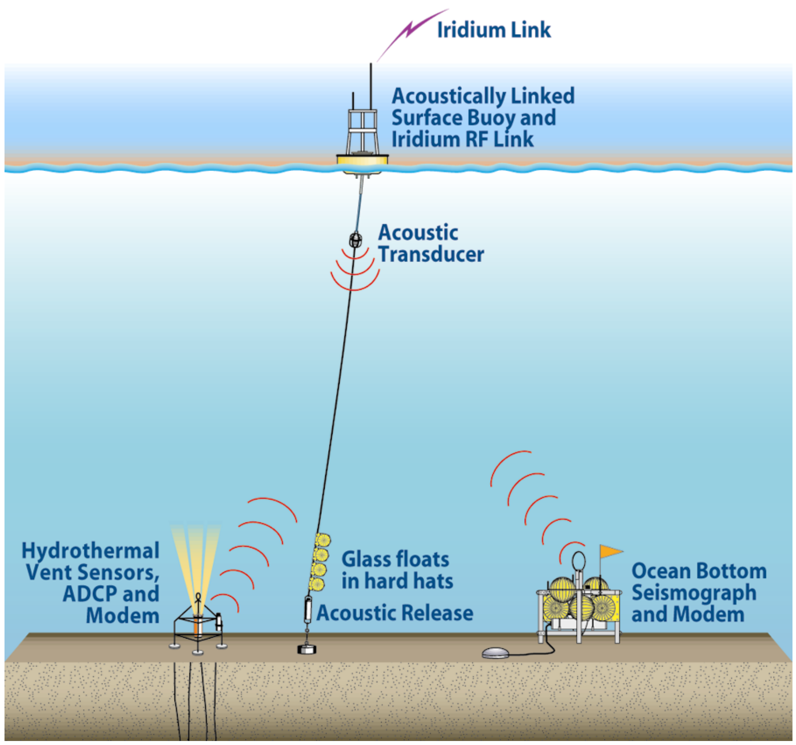


***Figure 2: Concept for a low-bandwidth, acoustically-linked observatory***

*Instrument-to-Buoy Telemetry*. The low-bandwidth design will use acoustic modems to telemeter data from instruments on the mooring or on the seafloor to the buoy. High data-rate, vertical acoustic communication in the deep ocean has been demonstrated in several experiments. This work demonstrated that there are no insurmountable technical issues associated with such a link, but these early systems were relatively large and power-inefficient because they were developed for use on a ship and manned submersible. Acoustic communication has also been used successfully to telemeter seismic data from the seafloor to the sea surface. During the 1998 Ocean Seismic

Network Pilot Experiment, a commercial acoustic modem was used to telemeter ~1 hour of 4-channel, 20 sample-per-second seismic data from two ocean-bottom seismographs deployed in 4500 m of water to a research vessel. The maximum reliable telemetry rate was 600 bits/s.

During the period from 1992 to the present, significant additional research and development work has been performed on bandwidth-efficient acoustic communication, including theoretical advances in modulation and receiver algorithms [Stojanovic, 1994, Johnson, 1997] and practical demonstrations [Freitag et al., 2000]. The current generation acoustic modem, known as the Micro-modem, have improved receivers for high-density signal constellations that allow more bits to be transmitted per Hertz of bandwidth, significantly improving overall power efficiency. In addition, integrated Doppler processing originally developed for fast-moving underwater vehicles has been adapted to the receiver, allowing automatic compensation for the acceleration of a wave-following surface buoy. This modem has been designed for remote oceanographic instrumentation systems and has been used successfully on several long-term, low-rate horizontal and vertical applications [Frye et al., 2000; Ware et al., 2001].

The acoustic modems used with this system will be configured for high-bandwidth, phase-coherent communication in the 12 to 18 kHz band and will use baffled directional transducers with a beam pattern of about +/- 30 degrees to focus energy in the desired direction. The power used by the transmitter is 10 Watts and the uncoded bit rate is 10 kpbs. The net rate with error correction coding is approximately 5 kbps. A Micro-modem transmitting for about an hour per day translates to about 2 Mbytes of data per day using the 5 kbps data rate estimate. Data compression prior to transmission can significantly increase the total data throughput. This is sufficient to transmit 100% of the data recorded by a wide variety of low-moderate bandwidth sensors including meteorological sensors, water column physical, chemical and biological sensors, and seafloor geomagnetic, hydrothermal and geodetic instruments. A system such as this can also transmit selected portions of higher-bandwidth datasets, for example a seafloor seismometer. For example, one half hour of 40 sps seismic data can be sent with 0.4 Mbytes and have 500 kbytes available for other data sets. An alkaline battery pack sufficient to last for 15 months with a duty cycle of about one hours per day would weigh about 45 kg in air, exclusive of its pressure case, and will cost approximately $600. A Micro-modem installed on the surface buoy will use a small array of directional transducers to provide improved SNR through active beamforming and to reduce the effects of wave-generated noise and the interference from surface reflections. This modem can be programmed to poll one or more modems collecting data from instruments on the mooring or seafloor on a regular daily schedule, or can be commanded from shore to initiate a data request.

*Buoy-to-Shore Telemetry*. There are several options for low-bandwidth two-way satellite communication between the buoy and a shore station. Inmarsat-B offers a commercial on-demand (‘dial-up’) data service of 64 kbps. An Inmarsat-B telemetry link can deliver nearly 7 Mbytes of data per day at a cost of about $100. This data rate is consistent with the capabilities of an acoustic buoy-to-seafloor link operating at about 10% duty cycle.

The 'radome' of a typical marine unit has a diameter of 1.4 m and weighs 90 kg. Newer models with 1.0 m radomes weighing about 40 kg are available. The Inmarsat-B hardware is relatively high power (~80-200 watts in receive mode and ~150-300 watts when transmitting); however, since the system only needs to operate for about 15 minutes at 64 kbps to transfer 5 Mbytes, its total power consumption is well within the capabilities of a solar powered or combined solar/battery powered system. Commercial units are available for $25-50K. [Note: High speed (64 kbps) Inmarsat M-4 is available in most areas of the Northern Hemisphere, but pointing antennas suitable for use on buoys are not presently available. If they become available in the near term, Inmarsat M-4 would be a lower power, somewhat less expensive option than Inmarsat B for some proposed observatory locations.]

The Iridium satellite system is up and operating and beginning to be viewed as a fundamental tool for oceanographers. DOD has funded operation of Iridium through 2002 and has the option of extending this contract through 2007. Initial experience suggests that Iridium transceivers operate very reliably at quite low power (1W standby/receive; 5W transmit). Assuming an 8% duty cycle (~2 hrs transmit time per day), a reliable 2.4 kbps link can be maintained with a net power (out of the power source) of less than 1.5W. The hardware is small, the antenna is omni-directional, and the transceiver is easily interfaced using a small, low power computer. The ultimate limitation of the Iridium system is the cost per byte of data. Using a rate of $1 per minute, 1 Mbytes of data transferred to shore would cost $80 per day.

Globalstar is another good option for low power data telemetry. It offers good coverage near major land masses and a data rate somewhat higher than Iridium (9600 bps). Data telemetry costs are about $1.00 per minute. Orbcomm and Inmarsat M are capable of providing worldwide, 2-way communications at reasonable cost for very low data rate applications. Orbcomm has the advantage of very inexpensive hardware and an omni-directional antenna. Inmarsat M uses a small pointing dish antenna. Both operate at 2400 bps using modest power (15-50 watt in transmit mode). One of these systems can be used as the back-up/command link for the primary telemetry system. Iridium, Globalstar or Orbcomm are probably the most likely choices for the back-up link because they are the lowest power and least active (in terms of antenna pointing) of the options.

*Buoy Data Control System*. The data telemetry system on the surface buoy would be comprised of a satellite transceiver, Micro-modem, system controller, and alkaline battery and/or solar panels suitable for operation for at least 1 year. The buoy Micro-modem can be programmed to receive data transmitted from Micro-modems co-located with instruments on the mooring line or seafloor, and will forward error-free packets to the system controller. ARQ is implemented in the acoustic link and data re-transmissions are completed prior to the transfer of data to the controller. The system controller consists of a single-board computer with multiple serial ports and is responsible for power management and data collection of all buoy sub-systems. The system controller receives data sent from the Micro-modem and any additional buoy sensors, stores the information in internal memory and packets the data for transmission by the satellite modem. At preset intervals, the controller initiates an Iridium connection and forwards all of the recently stored data to shore. After transmission is completed, the Iridium link remains open to accept system control commands or requests for additional sensor data from shore. An Argos PTT is included in the surface buoy electronics system to provide position information and as a back-up method for transmitting engineering data that can be used as a diagnostic tool in case of a failure of the Iridium link.

*Power Requirements*. This design does not provide power to the seafloor; it is assumed that instruments on the mooring or on the seafloor will provide their own power for sensor operation, data logging and acoustic telemetry. The power generation requirements of this system are thus limited to providing power to sensors on the buoy, the buoy data control system, the acoustic transceiver on the buoy, and the satellite telemetry system.

**Table 6** summarizes the power requirements for an acoustically-linked, low-bandwidth buoy system equipped with Iridium and Argo satellite telemetry systems, an acoustic modem, GPS, met sensors and a light. Averaged over a 24-hour period, the total power requirements for this system are under 2.5 W.

**Table 6: Power Consumption for an Acoustically-Linked, Low-Bandwidth System**

| Load | Power<br>Standby % | Consumption<br>Active % | Average Power over 24 hrs |
|---|---|---|---|
| Iridium | 100 mW 100% | 1.25W 20% | 0.35 W |
| Controller w/7 serial ports | 1W 100% | 5W 8% | 1.4 W |
| Acoustic modems | 200 mW 10% | 25W 0.5% | 0.15 W |
| Met sensors | – | 0.5W 100% | 0.5 W |
| GPS | – | 1.0W 2% | 0.02 W |
| Argos | – | 0.12W 100% | 0.12 W* |
| Light | – | – | solar |
| | | Total | 2.42W |

* uses separate alkaline battery

These power requirements can be met by a combination of solar panels and alkaline D-cell batteries at most locations in the world's oceans. For example, for 15 months operation at a site in the northeast Pacific 2-4 solar panels can easily provide this power requirement. A battery pack consisting of 700 alkaline D cells will be used as a back-up to provide up to 6-months operation.

***(2) Low-Bandwidth, Cable-Linked System***

This mooring design, characterized by a low bandwidth satellite communication link to shore, and an electrical-optical-mechanical cable (EOM) to provide power and communication between the surface buoy and networks of upper water column and benthic instruments, is shown in **Figure 3**.  Basic capabilities and features include:

- Delivery of power and communications to networks of water column and benthic instrument nodes via an electrical-optical-mechanical cable
- Near real time bi-directional satellite communications to shore via low bandwidth satellite communication link such as Globalstar (~7.8kb/sec) or Iridium.  The communication link to shore will provide data snapshots, health status of instruments and the mooring platform, and command and control capabilities.
- Event detection and automated response (e.g. increasing sampling rates after detection of algal bloom or volcanic eruption)
- Single point mooring with the EOM cable serving as the mooring element
- Benthic instrument nodes connected with ROV laid EOM cables
- Networked instrument nodes which host science instruments and manage instrument configuration, power, high-volume data logging
- Automatic mooring configuration including device (instrument) discovery, initialization and operation
- Automated delivery of metadata with data streams to archive
- Surface following discus buoy, 2.4m diameter
- 50 Watt capacity solar and wind power generation and distribution system
- Deployment from a Class III UNOLS vessel
- Long term deployment of the benthic network, with yearly maintenance visits to replace or inspect critical elements
- Future capability to include AUV docking and vertical profiling

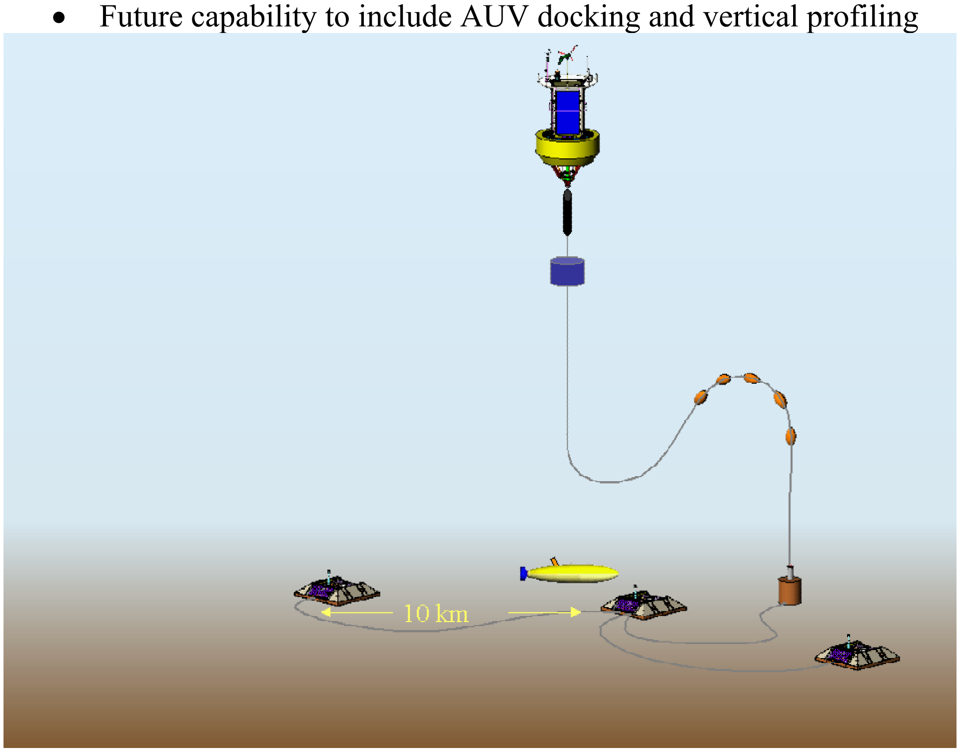

***Figure 3: Mooring design***

*General Description.* The mooring has an EOM cable, in a slack mooring configuration, to provide power and communication from the surface buoy to the water column and benthic network of instruments. A snubber hose elastic element containing a coilcord protects the EOM cable from excessive dynamic loads under extreme conditions. Power is generated on the surface buoy from solar panels and a wind turbine, which together provide on average 50W-75W depending on the time of year, for a mid latitude site such as Arcadia. Step up converters deliver 400V DC to water column and benthic nodes where the voltage is reduced to 40V for delivery to node instruments. The benthic network is capable of supporting several benthic nodes in a combination of star or line configurations, with node to node separations of up to 10km. Communications between the buoy surface node and other nodes is provided through optical fibers, although copper is an alternative media that could be considered. A standard EIA232/485 and TCP/IP 10 BASE-T interface is provided for instruments. Smart network technologies provide automated device discovery, configuration, and operation when an instrument is plugged into a node. These technologies also facilitate automatic association of instrument metadata (instrument ID, calibration coefficients, etc) with the instrument's data stream which is logged to onboard and shore-side data logs. This latter feature is critical to ensuring the data is associated with the correct metadata without the expense of this association being performed manually.

*Snubber Hose and Coilcord.* The mooring has a scope of 1.25 to provide resistance to current loading, and to reduce dynamic loads in most conditions other than in extreme storms in survival conditions where the cable is stretched out. Floats are attached to the mooring in critical locations to reduce loads on the cable at the buoy and to keep the mooring line near vertical at the anchor to prevent wear of the cable on the ocean floor.

Conventional mooring designs with a wave following buoy, readily accommodate the vertical and horizontal motions of the buoy in a seaway because of the low modulus of the mooring line. Nylon mooring lines can approach 30% elongation. However, with EOM cables there are two dominating restrictions that severely limit the acceptable strain on the cable. As cable strains reach 1.0% the optical fibers may fail. At even lower strains, the copper conductors experience age hardening that can lead to failure. These factors reduce the allowable strain of EOM cables to around 0.5%. So even with a slack design mooring, under high wind and current conditions, where the mooring is stretched out, in water depths of 1,000m, even 5m waves will induce the maximum allowable strain of 0.5%. So in order to survive the conditions where we wish to deploy the mooring (significant wave heights of 13m), it is necessary to incorporate an elastic snubber hose device. The snubber hose is a custom engineered assembly fabricated from multiple plies of rubber and special reinforcing fibers that can be stretched to 1.3 times its original length and is filled with fresh water. Coiled inside the snubber hose is a helixed cable similar to an oversized telephone handset cord called a coil cord. Molded into the coil cord are the optical fibers and copper conductors creating as assembly that can survive millions of cycles without experiencing fatigue damage. Incorporating the snubber at the connection between the buoy and the EOM cable significantly reduces the wave induced dynamic loads as well as minimizing periods when the cable loads go slack, another condition that is desirable to avoid.

*Cable Design.* To reduce the self weight of the mooring, and to provide the correct modulus match between the cable and the optical fibers/ copper connectors, the strength member is constructed with either kevlar or vectran. Steel cables, although 30% less expensive than those made of synthetic fiber, are much heavier in seawater, requiring large increases in buoy size and creating much higher system loads.

To protect the fibers from high ambient pressures and strain induced compression the fiber elements in the EOM cable are housed in a 1.3mm diameter stainless steel tube commonly called a "K-tube." The use of a protective tube for the optical elements, or a similar construction using small steel wire known as "Steelite," are the only proven methods for building deep submergence EOM cables. At the joint between the EOM cable and the snubber assembly, a transition termination unit is needed where the buoy cable loads are transferred and the optical and electrical elements are connected to the coil cord fibers.

*Dynamic Modeling*. To determine the static and dynamic response of the mooring, dynamic models of the mooring were run using extrapolations from 13 years of historical environmental data collected from the National Data Buoy Center archives. The numerical simulations calculated the static and dynamic tensions in the mooring cable at the surface buoy and at the anchor under a variety of different load conditions, including the design 25 year return period storm. This modeling was used to evaluate the impact of varying the snubber length, and changing the location of the snubber hose in the mooring. This trade study was undertaken because of the conflict between the snubber hose and the vertical profiler near the buoy. If the snubber hose were located directly at the transition from the buoy, placement of instrumentation in the water column directly under the surface buoy would be compromised, and would severely restrict the feasibility of incorporating a vertical profiler able to sample the water column up to the buoy. Models were run with different lengths of snubber hose under the buoy and with the snubber hose relocated to the anchor. It became clear that in order to not compromise the survivability of the mooring in severe weather conditions, the snubber hose needed to be at least 15m in length and had to be located near to the buoy. Unless these conditions were met, the dynamic range and frequency of the loads increased dramatically, and perhaps more importantly, the mooring would experience snap loading as the load transferred rapidly from high loads to zero load. As a result, this mooring is designed with a 15 m snubber directly under the mooring bridle. Dynamic mooring loads, during survival conditions off the California Coast are shown in **Figure 4**, for moorings with and without the snubber hose.

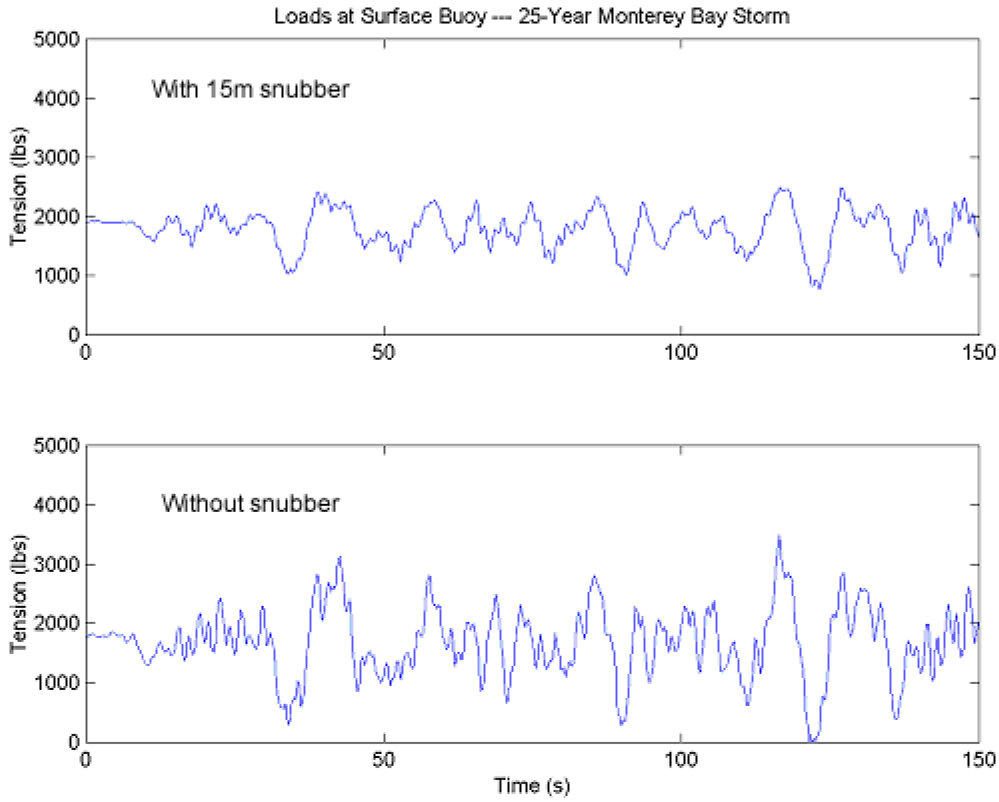


***Figure 4: Predicted dynamic loads with and without snubber for 25 year storm***

*System software.* The moored network consists of multiple nodes distributed throughout the water column and on the seafloor with each node hosting multiple science instruments. The moored network is intermittently connected to a shore network by a periodic satellite link.

System software enables instrument control and data acquisition over the network through standardized software interfaces. Human operators on ship or shore can utilize these interfaces. The interfaces can also be accessed by autonomous software components on the network (e.g., for autonomous event response applications).

The nature of the network presents some interesting challenges to system software design. The network configuration will be highly dynamic. Individual nodes may periodically alternate between "sleeping" and "waking" states to conserve power, effectively "dropping off" and "rejoining" the network. Instruments are periodically added to and removed from nodes. The instruments themselves will include a wide range of off-the-shelf sensors as well as novel devices; instrument interface protocols will thus be very diverse, as there are currently no widely recognized standards.

These challenges will be met with a variety of relevant technologies. Distributed object technologies, such as CORBA and Java RMI, enable object-oriented software design and implementation techniques in a network environment; the benefits of object-oriented software development are widely accepted. Smart network software technologies such as JINI enable extremely reliable system operation in the face of dynamic network configuration.

To address the diversity of sensors and protocols, and the need to automatically associate an instrument's metadata with its data stream, a device called a sensor puck is used. Most oceanographic instruments do not have built-in capability to participate in a TCP-IP network. Instead these instruments generally communicate with the host node's controller through a serial interface. Moreover the instrument itself usually doesn't have the capability to utilize high-level smart network protocols. The sensor puck is intended to provide a "bridge" between the serial, proprietary instrument domain and a sensor network domain. The puck is a simple low-cost device that stores information about an instrument. When plugged into a suitable computer (lab workstation, instrument node), information can be written to or read from the puck. While an instrument is being prepared for deployment, a technician "loads" a puck with information necessary to configure the instrument within the observatory, and then physically attaches the puck to its instrument. Thereafter the attached puck always travels with its instrument, no matter where it is being installed in the observing network. The information loaded into the puck encompasses whatever is necessary to enable automatic configuration and system integration of the instrument when it is plugged into the observatory network, and any other information required by observatory policies. This information may include structured descriptions of the instrument's sensor and data characteristics (metadata). The information can also include actual software code that is retrieved from the puck and executed by an observatory node when the device is plugged in; this code could implement distributed instrument control and data retrieval interfaces, allowing network-wide access to the instrument functionality. The puck concept is a powerful one; a given instrument puck is configured just once, enabling automatic configuration of its instrument no matter where it is installed on the network.

*Power System.* The design supports two categories of observations characterized by the power requirements. One is based on traditional low power, long deployment oceanographic instrumentation (current meters, CTDs, seismographs, etc) and the other on higher power, shorter duration systems (AUVs, active acoustics, etc). Under the study scenarios, the former group becomes feasible when continuous average power levels of 30 W or greater are available (about 88 kWh per year in energy terms), while the latter group is enabled at power levels of 100 W and above (880 kWh/year). Since 50 W is readily achievable with proven and available solar and wind systems, the current design takes the approach of developing the mooring and power distribution infrastructure to support the 100 W power level, but is initially being designed with a 50W solar and wind power system source. To provide the higher power levels, longer-term development of advanced energy generation (solar, wind or wave) are being pursued.

The cable power transmission system is a key component of the overall portable observatory mooring. Its design is driven by conflicting tradeoffs between power capacity, efficiency, mooring cable size, and personnel safety. As indicated above, the system requirements dictate a minimum electrical capacity of 100 W (ideally with growth potential) transmitted over the mooring riser cable, and 20 W transmitted over a benthic cable to a distance of 10 km. An AC-based transmission system is not suitable due to the continuous losses incurred by reactive current circulating through the cable capacitance. A seawater ground system should be avoided due to potential environmental impact (behavior of biota, etc) in the vicinity of the observatory components. This left a two-wire DC transmission system as the remaining choice for power distribution within the observatory.

The size and weight of the electrical component of the portable observatory cables must be minimized, in the case of the mooring riser in order to minimize weight and hydrodynamic drag, and in the case of the benthic cable in order to maximize payload for ROV deployment. The size and weight of a power transmission cable is a function of both the copper area, which determines electrical resistance, and of the insulation thickness, which must be sized to keep the insulation voltage stress below a reliable working limit.

As the operating voltage increases, the required conductor diameter decreases, while the required insulation thickness increases, both non-linearly. For any given combination of load power, system length, transmission efficiency, and voltage stress, there is one combination of wire size and insulation thickness that minimizes the diameter, and another that minimizes the weight, of the electrical portion of the cable.

Based on these analyses, the power transmission system will operate at 400 VDC. This voltage falls close to the minima of the applicable cable size and weight curves, is supported by an extensive range of commercial power conversion products intended for "universal off-line" (85 - 276 VAC) operation, and is one of the standard voltages planned for the NEPTUNE cabled observatory. These voltages have also proven tractable from a safety standpoint in several years of daily use aboard remotely operated vehicles, due largely to the deployment of effective ground fault detection systems. Further development of lock-out and tag-out procedures for use during buoy and subsurface service operations will continue to be an integral part of the program going forward.

*Benthic Nodes.* The mooring system can support five or more benthic instrument nodes, each containing its own node controller servicing several instruments. The benthic network topology may be a combination of linear or star configurations with the nodes separated by 10 kilometers by an ROV laid subsea EOM cable.

The EOM cable will be laid out from a specialized toolsled attached to the base of an ROV. ROV underwater mateable connectors are incorporated to connect the EOM cable to the benthic nodes. There are two main commercial companies that provide deep water rated ROV mateable connectors suitable for this application.

***(3) High-Bandwidth Cable-Linked Spar System***

In a recent NSF-funded design study of moored-buoy observatories [DEOS Buoy Observatory Design Study, 2000], a range of specifications and moored-buoy designs were investigated based on the telemetry rates they could support. One concept, which was developed in this study, was that of a high-bandwidth, tri-moored spar buoy with a separate cable to deliver power and fiber optic connection to a seafloor junction box. These systems are well-suited to applications which require very high bandwidth, and for which observations over a long time period (a decade or more) are needed. This design is capable of handling projected geomagnetic, geodetic, seismic, meteorological, and oceanographic data, and it can handle a significant fraction of the estimated AUV, acoustic and video data requirements. Another advantage of this design includes a commonality with NEPTUNE junction interfaces allowing interchange of instruments between both systems. While these systems are expensive to build and install, they will have extended lifetimes, and can be expanded to incorporate future applications.

The following is a description of the technical specifications of the high-bandwidth cable-linked spar buoy:

*Buoy and Mooring Design.* Spar buoys are attractive due to their stability in high sea state conditions. Spar buoy systems are found in a wide range of applications from relatively small instrumentation buoys to very large structures deployed by the offshore petroleum industry. The Marine Physical Laboratory (MPL) of SIO designed and has operated for almost four decades, the Floating Instrument Platform (FLIP) (Fisher and Spiess 1963; Fisher 1988). The stability characteristics of spar buoy systems are particularly advantageous for establishing reliable, high-bandwidth satellite data communications.

**Figure 5** shows a conceptual drawing of the spar buoy. The payload module for the high-bandwidth spar buoy design includes two 30K diesel generators, a C-Band satellite system, batteries, cooling system, and fuel bladder. The hull structure was designed to typical offshore standards. The system will be anchored by a three-point mooring system that is independent of the E/O cable, enabling the buoy to remain on station and operating if one mooring line fails.

One disadvantage of these designs is that they will require a deep-rated ROV and a dynamically positioned ship to install and maintain sensors and a specially-outfitted, leased commercial vessel to deploy the spar buoy. Maintenance can be performed by UNOLS vessels, however.

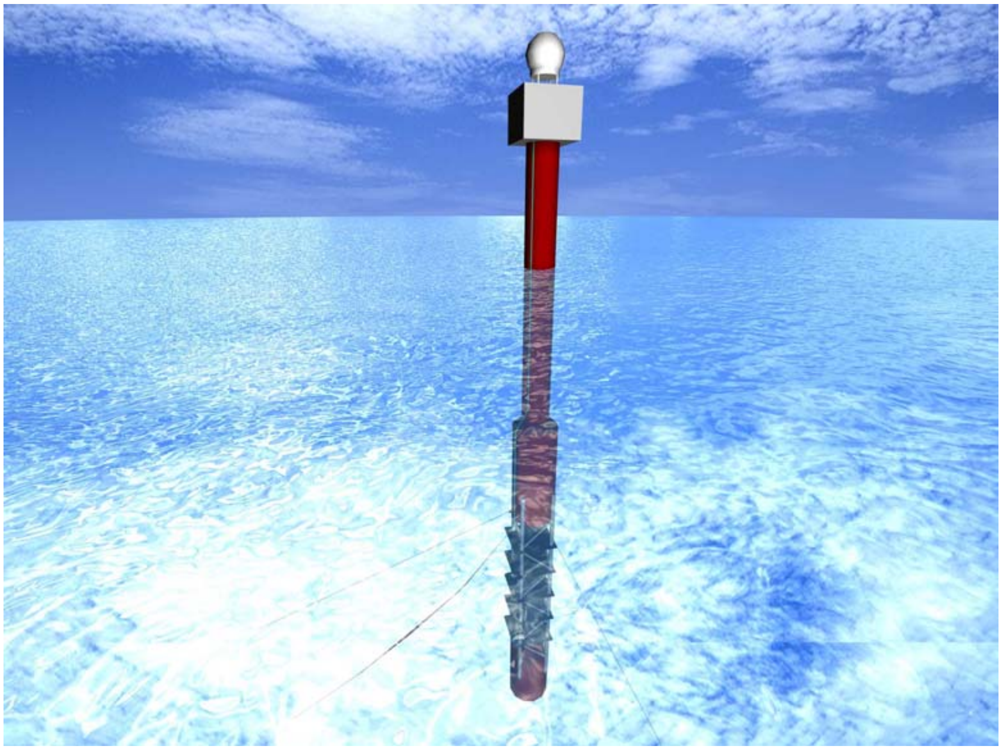

***Figure 5: Conceptual drawing of DEOS spar buoy design showing the radome and payload module (gray) and the hull (red). The spar is 40 m long.***

*Instrument-to-Buoy Telemetry.* The electro-optic (E/O) cable is designed to provide power to the seabed junction box and to transmit data. It consists of power conductors, fiber optic data lines and mechanical strength members. To meet the requirement for data throughput from the seafloor of greater than 50 Mbytes/day, the system will be equipped with commercially available network hardware in the junction box and on the buoy. A telemetry system built around network equipment would have the added advantage of extending Internet protocols down to the science ports.

The electro-optic cable of the high-bandwidth buoys will deliver up to 500 W of electrical power to a seafloor junction box. The power transmission system required to deliver 500 W over a distance of 8000 m (6000 m vertical and 2000 m horizontal) will run at a voltage between 300 V and 500 V assuming conductors with DC resistance equivalent to #10 AWG copper wires. The system will consist of a DC/DC converter on the buoy converting the main battery output voltage up to the appropriate cable transmission voltage. At the seafloor junction box, the cable voltage is converted down to the 48 V system bus voltage for junction box system power and distribution to the science connectors. Appropriate system protection will be provided by fuses and circuit breakers. System status parameters such as voltages, currents, power component temperatures, leak and ground fault status will be measured and telemetered back to shore continuously for remote monitoring.

The high-bandwidth buoy observatories will share with shore-linked cabled systems (e.g., NEPTUNE) a common interface to the junction box science ports (**Figure 6**). The interface standard will specify both mechanical characteristics of the junction box and connector ports such as distance between connectors, type of connector, orientation of locking tabs, and electrical parameters such as connector pin-outs, voltage, maximum current and communication protocols. Instrument data ports based on network protocols have replaced traditional RS232 serial data ports. In order to anticipate this transformation, and to maintain compatibility with the NEPTUNE junction boxes, the science ports will support only Ethernet capable instruments. Making the decision to design an Ethernet-based system allows us to take advantage of the constantly growing array of network hardware and software available off-the-shelf and eliminates the need for protocol converters and switches. An added benefit of IP at the science port is the ability to use existing and emerging sensor standards. These standards describe methods for embedding within scientific instruments, conversion factors, calibration data, application software and other information necessary to interpret sensor data correctly.

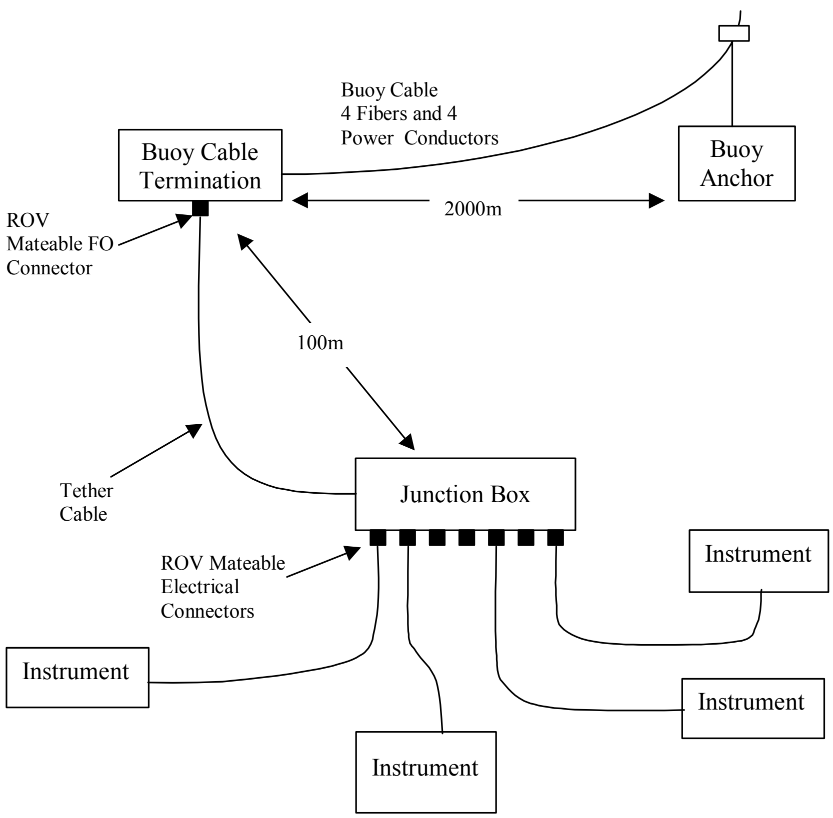


***Figure 6: Seafloor cable configuration for moored-buoy ocean***

The junction box science ports will use the 8-pin electric-only Ocean Design Nautilus connectors identical to the ones specified for NEPTUNE and used successfully at H2O. The Nautilus line of connectors has an excellent reliability record and has proven at H2O to be convenient to use electrically and mechanically. However, compatibility of this connector with high-speed Ethernet signals is unknown and needs to be investigated.
A conceptual design for the junction box is shown in **Figure 7**. Although many of the blocks will be backed up by redundant systems, these are not shown for the sake of simplicity. This system is designed to operate in two modes, a full power mode for normal full-capability operation and a low-power restricted capability mode for operation during periods when full power is not available (loss of generator power for example).

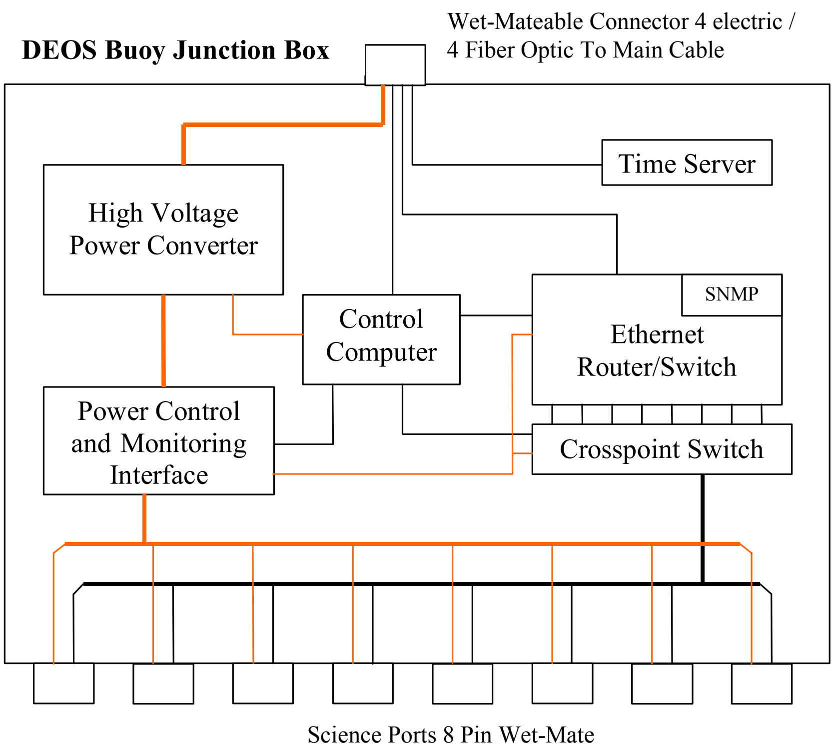


***Figure 7: Schematic diagram of seafloor observatory junction box***

In the normal operating mode, the voltage converter will provide all the power required by the junction box electronics and by the science users. The power control and monitoring interface will distribute and monitor power among all users under direct command of the control computer. The Ethernet Router/Switch handles all the science data flowing through the junction box concentrating the multiple science port data streams into one or two fiber data channels to the surface. A Simple Network Management Protocol (SNMP) agent running on the router (and possibly on other devices as well) allows for monitoring and control of basic data routing (and other) parameters.

In the case of partial power loss, the control computer can shut off all high power science users and internal junction box devices including the router and its fiber optic telemetry. This would leave only essential junction box systems and low-power science users with power. The control computer would have its own fiber-based telemetry system optimized for low power at the expense of high data rate. The control computer could continue to monitor power and balance loads versus power available until full power was restored. In the case of a momentary total power loss the control computer would be programmed to come up in a low-power safe mode to keep a high power user from crowbarring the power bus.

A spare fiber will be reserved for future implementation of a precision time standard of greater than 1 microsecond accuracy should one be required. For timing accuracy requirements on the order of 1ms the network-based Network Time Protocol (NTP) will be used. The time server for this system will be a computer located on the buoy which will use a GPS receiver to maintain its own time base. The junction box master clock is synchronized to the buoy server by estimating the time delay of network UDP packets.

*Buoy-to-Shore Telemetry.* Once the required or projected data volume exceeds about 5 Mbytes/day, the most cost-effective telemetry system available today is a VSAT C-Band system. No other telemetry option can provide this data throughput at a reasonable cost. For example, a requirement of 50 Mbytes/day can be met with a VSAT system operating on an 8% duty cycle (assuming a 64 kbps channel); continuous operation would provide 650 Mbytes/day. The infrastructure requirements on the buoy to operate a VSAT system are independent of duty-cycle, except for the fuel requirements that may affect overall buoy size significantly. In **Table 7** potential satellites and their beam power for candidate buoy deployment sites are shown.

**Table 7: Satellite Telemetry Coverage for Potential Observatory Sites**

| Site Name | Latitude | Longitude East | Possible Satellite | EIRP dbW |
|---|---|---|---|---|
| MOMAR | 37.5 | 327.75 | INTELSAT 601 Global | 26.5 |
| EPR 9°N | 9.0 | 260.0 | PANAMSAT 5 | 37 |
| Izu-Bonin (Marianas) | -15.0 | 150.0 | PANAMSAT 8 | 34 |
| Peru Basin OSN | -23.0 | 270.0 | INTELSAT 706 Hemi | 33 |
| NERO OSN | -15.0 | 90.0 | INTELSAT 704 Hemi | 33 |
| Equatorial Pacific OSN | 10.0 | 235.0 | INTELSAT 706 Hemi | 33 |
| North Atlantic OSN | 51.0 | 323.0 | Atlantic Bird-1 KU† | ? |
| Southeast Indian OSN | -51.0 | 132.0 | Palapa C1 | 32 |

† scheduled for 2001 launch EIRP=Effective Isotropic Radiated Power

A VSAT system requires a tracking antenna. The principal design requirement for this application is that the system be able to track a satellite to within a fraction of a degree during buoy motions induced by operational sea states, a potential problem mollified by the use of a tri-moored spar buoy. Several commercial antenna systems designed primarily for shipboard use are available. The Design Study Working Group calculated that the proposed Harris Electronics Systems C-Band unit could be expected to operate up to Sea State 6 on a spar buoy. For C-Band, the radome size will typically be 2.4 m to 3.5 m diameter and weigh approximately 400 kg. There is a trade-off between antenna size, data rate, and required RF transmit power that needs to be studied in more detail.

*Buoy Data Control System.* The primary data storage unit will be the data management computer housed on the buoy. Scientific instrumentation will be connected via cable to a network hub in the seafloor junction box, which will, in turn, communicate with the data management computer located on the buoy using a fiber optic link. The buoy data management computer is connected to shore using the 64 kbps satellite link and to nearby ships using a wireless bridge.

*Power Requirements.* The Design Study Working group estimated that a buoy design which supplies 500 W to the seafloor and telemeters ~500 Mbytes of data per day will require on the order of 5100 W of power on a continuous basis. To provide this power, the buoy would be fitted with diesel generators. The U.S. Coast Guard operates its large navigational buoys with diesel power, and the continuous operation of diesel generators on these buoys for periods of at least three to six months is well-documented (Dewey 1974).

The Moored-Buoy Design Study Team estimated that a pair of 10 kW diesel generators (one as back-up) on the buoy could provide the necessary power. Operating at 60% load, such a generator would consume approximately 50 liters of diesel fuel per day or 18,250 liters/year. On the other hand, if the generator ran part-time providing 6 kW to run the buoy system and enough power to charge a bank of batteries, a significantly larger generator would be required. For example, if the generator operated only 8 hours per day, approximately 24 kW would be needed, 6 kW to run the buoy and 18 kW to charge the batteries. A 30 kW generator operating at 80% load could provide the necessary power while consuming fuel at approximately the same daily rate as the smaller unit, run continuously. The battery bank required would be approximately 40 size 8D batteries with a total weight of nearly 3,000 kg.

### (C) Current Prototype Testing

Efforts to develop and test aspects of the three recommended buoy designs are detailed below.

#### *(1) Woods Hole Oceanographic Institution/University of Washington Low-Bandwidth, Acoustically-Linked Prototype System*

A group of investigators from Woods Hole Oceanographic Institution and the University of Washington have received funding from NSF to develop and test a prototype deep-water, acoustically-linked, moored-buoy seafloor observatory and conduct a 15-month-long demonstration project using this system on the Nootka Fault off Vancouver Island in the Northeast Pacific in 2004-2005. 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.

The prototype system is similar in design to the low-bandwidth, acoustically-linked design concept developed in the DEOS Buoy Design Study [2000], except that an Iridium satellite system will be used instead of Inmarsat-B (Fig. 1). The Iridium system was chosen because it operates at very low power (~1W receive; 5W transmit) compared to an Inmarsat-B receiver, the hardware is small, the antenna is omni-directional, and the transceiver is easily interfaced using a small, low power computer. The cost per byte is similar to Inmarsat-B.

Several different types of sensors such as an ocean bottom seismograph (OBS), an acoustic-doppler current profiler (ADCP), temperature, chemical and pressure sensors, hydrothermal flow meters, and a conductivity-temperature-depth (CTD) sensor will be interfaced to acoustic modems at two separate seafloor nodes in order to telemeter data from these sensors to shore via the buoy. In addition, since this is seen as a prototype for future multidisciplinary moored-buoy observatories, meteorological sensors will be included on the surface buoy, and current meters and temperature recorders will be placed on the mooring line in the upper ocean. Typical data throughputs are expected to be on the order of a Mbyte per day, but may be considerably higher during shorter periods of particular interest.

The OBS will record two data streams, viz., 1 sample-per-second and 40 samples-per-second on 4 channels (3 seismometer and 1 long-period pressure). The compressed data will be stored on disk, and any data packet on disk is available for retrieval via the data logger's serial port. (Note: data retrieval is not limited to the contents of a RAM buffer, and all of the data output by the digitizer is accessible ultimately when the seismograph is finally recovered.) The telemetry requirements and projected costs for the OBS are summarized in **Table 8**. The 1-Hz data stream will not be telemetered continuously, but will instead be sent as a block once a day. The 1 Hz data stream will provide a complete surface-wave (Rayleigh) record, and hence, by itself, will be very useful for regional structural studies. Given typical seafloor short-period noise levels, the 1-Hz data stream may also be adequate for shear-wave splitting measurements and receiver-function studies. The 1-Hz data stream is inadequate for regional seismicity studies, teleseismic and regional body-wave tomography, and high-resolution receiver function investigations. However, the bi-directional capability of both telemetry links allows the transmission from seafloor to shore of portions of the 40 Hz data stream on command from shore-based investigators. The selection of the appropriate time windows will be guided by preliminary hypocentral locations determined by regional land arrays, events in global catalogs such as the USGS Quick Epicentral Determinations (QED) catalog, inspection of the 1 Hz data stream, and the trigger times telemetered daily. The quantity of 40 Hz data telemetered will depend on whether the event of interest is at regional or teleseismic distances. The telemetry costs for the combined 1-Hz and 40Hz data streams (~$77/day) are comparable to upper-end costs for operating a Global Seismic Network station at a remote location on land (on order $20K/yr), and could be considerably less if the oceanographic community negotiates a lower tariff for Iridium service in the future.

| Table 8: OBS Data Telemetry Schedule | | | | |
|---|---|---|---|---|
| **TELEMETRY STREAM** | **SAMPLE RATE** (3 channels, / 2.2 compression) | **ACOUSTIC LINK** (5000 b/sec) | **IRIDIUM LINK** (1600 b/sec) | **IRIDIUM CHARGE** (@$1/minute) |
| 1 Hz seismometer stream | 4050 kbits/day | 13 minutes/day | 42 minutes/day | $42/day ($15,330/year) |
| 40 Hz seismometer stream | 3375 kbits/0.5 hour/day | 11 minutes/0.5 hour/day | 35 minutes/0.5 hour/day | $35/0.5 hour/day ($12,775/year) |
| TOTALS | 7425 kbits/day | 24 minutes/day | 77 minutes/day | $77/day ($28,105/year) |

The telemetry requirements of the sensors at the hydrothermal node (**Table 9**) are very modest (<600 kbits/day total). The first step to matching sensor data flow to the telemetry link is to format and compress the data stream from any given instrument. Typical instrument data interfaces utilize formats and encoding (e.g. ASCII) which are inherently wasteful when viewed from the cost standpoint of the proposed links, and thus significant savings can be gained using a loss-less, instrument-specific data filter. The filter may also include formatting that limits data sample size to the actual dynamic range of an instrument, for example 12 bits from an A/D converter is often padded to 16 bits for convenience in storage. A multiplexor-aggregator will be built to interface the output from ~6 chemical/physical sensors to an acoustic modem at this node.

| Table 9: Hydrothermal Node Telemetry Schedule | | | | |
|---|---|---|---|---|
| **SENSOR** | **SAMPLE RATE** | **ACOUSTIC LINK** (5000 b/sec) | **IRIDIUM LINK** (1600 b/sec) | **IRIDIUM CHARGE** (@$1/minute) |
| ADCP | 5760 bits/hr | < 1 min/day | 1.5 min/day | $1.5/day |
| CTD | 96 bits/min | < 1 min/day | 1.5 min/day | $1.5/day |
| Pressure | 32 bits/min | < 1min/day | < 1min/day | < $1/day |
| Temperature[1] | 192 bits/hr | < 1 min/day | < 1 min/day | < $1/day |
| Chemical[2] | 1920 bits/hr | < 1 min/day | < 1 min/day | < $1/day |
| Flow [3] | 8000 bits/hr | < 1 min/day | 2 min/day | $2.0/day |
| TOTALS | 552 kbits/day | 2 minutes/day | 6 minutes/day | $6/day ($2,190/year) |

*[1]1 measurement/5 min.; [2]10 measurements/5 min*

The development schedule for this project is outlined below:
*September, 2002 – August, 2003*

- design control/telemetry system and software
- design acoustic link protocols and perform deep water tests
- interface sensors and modems

- design and build buoy, mooring, power system
- design and build hydrothermal seafloor node

*September, 2003 – February, 2004*

- test deployment at Site D off US East Coast
- modify system based on test results

*March, 2004 – September, 2005*

- 3 month test deployment at Nootka fault site (June-August, 2004)
- turnaround in August/Sept. 2004
- 12 month deployment at Nootka fault site from Sept. 2004 – August, 2005

The Site D test is located in 2700 m of water about 150 miles southeast of Woods Hole. For this test, the seafloor node will consist of a single sensor, a hydrophone sampled at 200Hz powered by 100 lithium D cells. The acoustic modem will be packaged with the hydrophone instrument and its power supply. It will deliver about 400 Kbytes of data per day to the buoy. The test system will also include a simulator of the hydrothermal node placed 3-4 km from the mooring anchor to test acoustic communication outside the vertical sound channel. One Aanderaa current meter will be place on the mooring, and a met sensor suite will be on the buoy.

With the completion in 2005 of this 3-year development and testing program for the low-bandwidth, acoustically-linked moored buoy system, it should be feasible to begin routine construction and deployment of these systems in support of the NSF Ocean Observatories Initiative.

***(2) University of California, Santa Barbara/Woods Hole Oceanographic Institution Bermuda Testbed Mooring: Low-Bandwidth, Acoustically Linked Prototype System***

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Observations at Hydrostation S, located near Bermuda, started in 1954 by Henry Stommel (e.g., Joyce and Robbins, 1996), remain some of the longest continuous open ocean physical oceanographic records. In 1978, deep-ocean sediment trap particle collection was begun about 75 km southeast of Bermuda (depth of ~4500 m) and continues to the present (Ocean Flux Program (OFP); e.g., Conte et al., 2001). The Bermuda Atlantic Time-series Study (BATS; see Steinberg et al., 2001), established as part of the U.S. JGOFS program, was begun in 1988 with multi-disciplinary ship-based sampling near the sediment trap mooring site (~80 km southeast of Bermuda). The encompassing objective of BATS is to characterize, quantify, and understand processes that control ocean biogeochemistry, especially carbon, on seasonal to decadal time scales. BATS ship sampling is done monthly and every two weeks during the springtime. Ship-based bio-optical profiles (sampling in concert with BATS) and remotely-sensed ocean color data have been obtained at the BATS site since 1992 by the Bermuda Bio-Optics Program (BBOP; e.g., Siegel et al., 1996, 2001). One of the major accomplishments of the BBOP activity has been to demonstrate the importance of colored dissolved or detrital material (CDM) for biogeochemistry and remote sensing of chlorophyll in the open ocean (e.g., Siegel and Michaels, 1996). The Bermuda Testbed Mooring (BTM; Dickey et al., 1998b, 2001a) began in 1994 near the BATS site in order to collect high frequency data for studies and models of upper ocean biogeochemistry and physics, to develop and test new multi-disciplinary sensors and systems, and to provide validation data for satellite ocean color imagers including SeaWiFS, and to collect high frequency data for studies and models of upper ocean biogeochemistry and physics. BTM measurements were an important addition as processes with time scales of less than a few weeks (e.g., eddies, wind-events, transient blooms) cannot be resolved with monthly or bi-weekly shipboard observations and are aliased. Other platforms used at the BTM/BATS site have included drifters, profiling floats, moored profilers, an autonomous underwater vehicle (Griffiths et al., 2001), and satellites for sea surface temperature, color, wind vectors, and altimetry. Atmospheric sampling of dust and aerosols is done on the island of Bermuda as well and a ship-of-opportunity program is conducted between Bermuda and the east coast of the U.S. (Rossby, 2001). In fact, most of the platforms illustrated in Figure 8 have been deployed off Bermuda, though not simultaneously. Thus, the multi-platform approach for obtaining 4-dimensional data sets is quite feasible.

Autonomous sampling is clearly one of the major strategies for global bio-optical measurements. The BTM program has tested and utilized a broad range of autonomous sampling sensors and systems. These include new measurements of $pCO_2$, dissolved oxygen, nitrate, trace elements (e.g., iron and lead), several spectral inherent and apparent bio-optical properties, $^{14}C$ for primary production, and currents (Dickey et al., 1998b, 2001a OR 2002: CHECK). Some of the bio-optical systems designed to measure IOPs and AOPs and tested using the BTM are illustrated in Figure 1. The bio-optical systems (placed on the surface buoy and at 2 to 4 different depths) are used to determine relevant remote sensing parameters such as remote sensing reflectance (e.g., Dickey et al., 2001?; Zheng et al., 2003). The depths are optimally selected to enable extrapolation of subsurface radiance to the surface. An advantage of mooring validation is the high number of match-up data for satellite calibrations (data are collected regardless of cloud cover as well). The BTM is serviced at roughly 4-6 month intervals, allowing investigators to regularly exchange instruments in order to evaluate sensor and system performance. Time- series data collected from the mooring can be intercompared, intercalibrated, and interpreted using comprehensive shipboard data sets obtained during monthly or bi-weekly cruises as part of the BATS and BBOP programs as well as other related mooring and remote sensing programs.

Bermuda Testbed Mooring FIGURES SHOULD INCLUDE NEW BTM BUOY, A BTM MOORING DIAGRAM WITH TELEMETRY AND THE TELEMETRY FIGURE FROM 1998 PAPER SHOWING DATA TELEMETRY TO SHIP.
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Since inception, the BTM has been used by many ocean researchers and engineers in the national and international community spanning direct experimental instrumentation development to fundamental research (including the NSF JGOFS program) and education. The original surface buoy was built by WHOI and first deployed near Bermuda in 1989, then called ESOM (Engineering Surface Oceanographic Mooring). In 1993 the same mooring was deployed by WHOI under the name ALTOMOOR (Atlantic Long Term Oceanographic Mooring). Then, from mid-1994 to fall 2003 the buoy was deployed under the name BTM (Bermuda Testbed Mooring). One of the major accomplishments of the BTM program was also the development of inductive and acoustic modem technologies for near real-time data telemetry. These near real-time data were used for seatruthing bio-optical data for SeaWiFs calibration and validation. The original surface buoy was deployed at sea for over 3000 days withstanding harsh winter storms and hurricanes in an open ocean environment near Bermuda. Remarkable time series data were collected during the direct passage of Hurricane Felix over the BTM site in 1995. Although the buoy proved to be extremely robust and successfully withstood the forces of such a harsh environment, it began to show signs of severe wear and fatigue in the late 1990's.

A proposal was submitted by UCSB and WHOI to NSF in 2000 to: 1) design and build a next-generation interdisciplinary oceanographic buoy, 2) test and maintain the new buoy at the BTM site, 3) make the new buoy available to the community for instrumentation development and testing as well as interdisciplinary science activities, and 4) transfer the buoy design to the oceanographic community. The new buoy (shown in Figure ??) was deployed in September 2002. Some of the technical features of the new buoy include: reduced size for safer ship operations, removable instrumentation well, upgraded tower, improved and removable bridal, and overall total weight reduction. The buoy is equipped for satellite data telemetry. Argos has been used in the past and the Iridium system will be added in May 2003. The expected lifetime of the new buoy is about 10 years.

The buoy design is being used at present for at least 7 more buoys including the newly funded NOPP Multi-disciplinary Ocean Sensors for Environmental Analyses and Networks (MOSEAN) Hale-Aloha mooring to be deployed at the Hawaii Ocean Time-series site in October 2003. NSF serves as the lead agency for the MOSEAN project and Alex Isern is the program manager for MOSEAN. In summary, these buoys are specially designed for interdisciplinary measurements and can accommodate a variety of atmospheric (including aerosols), chemical, optical, acoustical, and biological sensors. They were also built to specifications such they can be transported in standard shipping containers around the world. Thus, they should be valuable for the global ocean time series observational network. The MOSEAN buoy and mooring will be located near the

NSF sponsored ANZCAN cable node so that the two projects can be used for testing and eventually for high bandwidth data transmission.

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Satellite telemetry via the Argos Data Collection System (DCS) is used for summary BTM data collection. However, a major engineering development aspect of the mooring project involved inductive telemetry of data from a number of subsurface sensors to the surface and then on to land-based stations via the R/V Weatherbird II (Fig. 5). Details are given in Frye et al. (1996) and a brief summary follows. The method entails use of inductive coupling via toroidal pick-ups on the mooring line. Inductive modems are interfaced to subsurface instruments and transfer data to the surface buoy. Data from each instrument is transferred via the insulated mooring line with a seawater return. No direct electrical connection or special termination is required. The data are stored and a subset of data are transmitted via Argos. The stored data can also be off-loaded by wireless ethernet telemetry when the R/V Weatherbird II is within range (about 2 km). The RF data are full bandwidth whereas the Argos data are limited to hourly averaged samples. The RF link transmits 10 Kbytes/sec during file transfer while the Argos link transfers about 1 Kbyte/day Full bandwidth data are also stored internally on all systems and downloaded after each deployment. The telemetered data are useful for the purposes of 1) tracking of the buoy in the event of mooring failure, 2) verifying operation of the system, 3) preliminary data analysis and quality control, 4) determining the need for more rapid mooring sampling or quick response/special shipboard sampling at the BATS site when events (e.g., hurricanes, mesoscale features, blooms, etc.) are underway, and 5) providing first-look data for satellite color sensor validation/algorithm development. The system's two-way communication capability further allows changing of instrument parameters from shore (e.g., gain adjustments) and for carrying out event specific experiments. The development of the telemetry aspect of this work is important in the long-term scheme of utilizing moored and drifter instrumentation arrays for remote sites as part of global ocean/climate observing networks.

***(3) Other Low-Bandwidth, Acoustically-Linked Prototype Systems (i.e., HOT, O-SCOPE, MOSEAN, GoMOOS Mooring Programs)***

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*The Hawaii Ocean Time-series (HOT)* program was initiated in 1988 in parallel with the BATS program program. The HOT measurements are conducted at the oligotrophic Station ALOHA (22°45'N, 158°00'W) site north of Oahu. HOT's main objective is to obtain a long time-series of physical and biogeochemical observations in the North Pacific subtropical gyre that will address several goals. These include: documention and understanding of seasonal and interannual variability of water masses, development of climatologies of physical and chemical variables, documentation and understanding of seasonal and interannual variability in primary production, new production and particle export from the surface ocean, quantification of the time-varying concentrations of carbon dioxide, and studies of ocean ecology. HOT's core measurements were provide a data set to improve existing C-N-P biogeochemical models. Selected data trends related to the intensification of N and P cycles, changes in microbial community structure and the role of high frequency physical events have been documented. An interdisciplinary mooring has been deployed at the HOT site in the past and the new NOPP MOSEAN program will deploy a new mooring, quite similar to the BTM, near the HOT site. Data collected by this deep-sea mooring are essential for detection and understanding of the mesoscale processes that contribute significantly to biogeochemical variability in this subtropical gyre habitat.

[FROM DICKEY: O-SCOPE FIGURES SHOULD INCLUDE BUOY PICTURES, MAYBE NOPP P MOORING DESIGN PLUS??? SEE OUR SEA TECHNOLOGY PAPER.]
*O-SCOPE.* The general objective of the NOPP O-SCOPE was to improve the variety, quantity, quality, and cost-effectiveness of interdisciplinary observations (Dickey et al., 2000) in anticipation of a global ocean observing network of strategically placed moorings and other platforms (e.g., Dickey, 2001b; Send et al., 2001). Basic program goals were to: 1) identify key variables to be measured, determine capabilities and limitations of available sensors, and define specifications for next-generation sensors, 2) design, develop, and test integrated interdisciplinary sampling systems and technologies for biogeochemical, bio-optical, and physical measurements (e.g., low-cost, easily deployed, reliable, robust), 3) design a testbed mooring program (e.g., deployment scheduling, sampling rates, instrument placement depths), 4) deploy next-generation interdisciplinary instrument suites on three testbed moorings, and 5) evaluate the performances of new instrumentation and telemetry systems.

Related scientific goals to the development of the proposed technologies included: 1) Quantifying trends in biogeochemical and bio-optical variables which could be caused by major changes in the ocean's thermohaline circulation and seasonal, interannual, and decadal changes in upper ocean bio-optical and biogeochemical variables including carbon fluxes; 2) Monitoring trends in "ocean health" in the form of chemical, biological, and optical indicators.
Within the project, the four primary instrumentation development and testing activities included:

- Next-generation biogeochemical sensors (e.g., carbon dioxide and dissolved oxygen);

- A long-path spectrophotometer for determination of pH and several other biogeochemical parameters;
- A miniaturized bio-optical sensor and sensor suites; and
- Methods for reducing the adverse effects of biofouling on instrumentation.

The instrumentation resulting from these efforts was tested using three primary moorings: the Bermuda Testbed Mooring located 80 km off Bermuda at 32N, 64W (4530 m depth), the NOAA Tsunami Warning Mooring at Ocean Weather Station P in the North Pacific at 50N 145W (4020 m depth), and the MBARI M1 Mooring in Monterey Bay at 37N 122W**.** Over the course of the project, extensive sea-truthing and other sensor verification efforts were conducted by NOPP investigators at each of these sites.

The project objectives placed a common set of requirements upon all of the sensor developmental groups. The sensors and sensor suites needed to 1) be capable of being installed on existing mooring platforms with minimum interference with other instrumentation, 2) operate autonomously for at least 3 to 6 months per deployment with sampling intervals of less than 1 hour, 3) provide stable measurements over several months without experiencing measurement data quality degradation, and 4) operate in the ocean environment with minimal fouling or other environmentally related degradation.

Most of the systems described above have data telemetry capabilities. Some of the data sets were distributed in near real-time using a website (http://www.pmel.noaa.gov/oscope/) developed by Dick Feely and Cathy Cosca; other O-SCOPE and complementary data were accessible through this website. The NOPP data were combined with historical data to determine the increase of dissolved inorganic carbon (DIC) over time. The DIC increase in the mixed layer near OWS P is consistent with the atmospheric increase over the same region.

The NOPP O-SCOPE project and associated development efforts resulted in several transitions leading to broader use of bio-optical and biogeochemical measurements. These included:

- Newly developed instrumentation were deployed on the NOAA Tsunami Warning System Mooring located at Ocean Weather Station "P" in the Pacific and two NOAA Tropical Atmosphere-Ocean (TAO) moorings in the equatorial Pacific as part of the NOAA Global Carbon Cycle Program.
- O-SCOPE sensors have been used for other NOPP projects (e.g., miniature interdisciplinary sensors for gliders).
- Bio-optical systems developed under O-SCOPE were used for the ONR HyCODE study at LEO-15 site off the New Jersey coast and are being used at present for a Japanese biogeochemical mooring program (3 moorings in North Pacific off Japan) and a Mexico-U.S. study in the Gulf of California.
- The O-SCOPE program led to the commercialization of new optical instruments by WET Labs, which have already sold over 200 miniature optical sensors (for multi-angle scattering and fluorescence); their sales continue to grow annually. In addition, the UCSB anti-biofouling copper shutter design was adopted by Satlantic, Inc. for its BioShutter that is used with its OCR-500 radiometer line of

instrumentation. These instruments are widely used for autonomous marine environmental observations and satellite ocean color validation applications.
- The development of a new low power $pCO_2$ sensor that was started during O-SCOPE resulted in a drifter-based instrument that was successfully deployed during a recent Southern Ocean iron fertilization experiment.

In summary, the O-SCOPE project facilitated the formation of a successful partnership among academic, government, and industrial partners, who developed, tested, and transitioned requisite next-generation technologies to the oceanographic community for long-term measurements and research of biogeochemical and bio-optical as well as physical processes. Several new biogeochemical and bio-optical systems for mooring (and other platforms) have been developed and tested at three mooring sites: Bermuda (BTM), Monterey Bay (MBARI), and OWS P in the North Pacific. The O-SCOPE project significantly accelerated interdisciplinary ocean measurement technology capabilities by 1) increasing data, in terms of raw numbers and the variety, which can be collected autonomously, 2) improving the robustness and reliability of interdisciplinary sampling systems, 3) reducing adverse biofouling effects on bio-optical and chemical and systems, 4) developing a system for near real-time telemetering and dissemination of data via the internet, and 5) enabling the commercialization and broad distribution of new bio-optical systems. The O-SCOPE activity represents one of the early coordinated efforts to advance autonomous interdisciplinary sensor and system technologies.

[FROM DICKEY: MOSEAN FIGURES SHOULD INCLUDE NEW HAWAII MOORING DIAGRAM]
*MOSEAN*. The NOPP Multi-disciplinary Ocean Sensors for Environmental Analyses and Networks (MOSEAN) project is directed toward new technologies that will lead to increased observations that are essential for solving a variety of interdisciplinary oceanographic problems of societal importance. These include: biogeochemical cycling, climate change effects, ocean pollution, harmful algal blooms (HABs), ocean ecology, and underwater visibility. The collective MOSEAN sensors will be able to sample key variables that are vital to solve problems of nearshore to coastal to open ocean environments. The MOSEAN partnership will develop, interface, test, and demonstrate new interdisciplinary sensor suites. Measurements with emerging biological, chemical, and optical sensors will be the primary focus of the study. The sensors and systems will be designed for use with a variety of autonomous, unattended sampling platforms including both stationary-type (e.g., moorings, offshore platforms, and towers) and moving-type (e.g., autonomous underwater vehicles (AUVs), gliders, drifters, and profiling floats). The MOSEAN sensors and systems will be capable of measuring key chemical, biological, and optical variables to complement physical data suites on time scales as short as minutes and space scales down to a meter for periods on order of months and horizontal space scales on order of 100's of kilometers. The sensors will be designed with capabilities of real-time and/or near real-time data telemetry. The first phase of the effort will focus on development and testing of proto-type sensors utilizing two testbed moorings: nearshore (Santa Barbara Channel) and in the open ocean Pacific (at the HOT site off Hawaii). The results of MOSEAN will be beneficial for a broad range of ocean observational needs that have been articulated in several recent U.S.

agency (e.g., NOPP, ONR, NSF, NOAA, OCEAN.US) and international (GOOS, IGBP, JGOFS, GLOBEC) documents and reports. Increased numbers of ocean observations are of the utmost importance, thus MOSEAN investigators will promote widespread use of the newly developed sensors and systems through technology transfer to other scientists, government agencies, and the private sector. A recent OCEAN.US recommendation is for deployment of about 500 coastal moorings (http://www.ocean.us.net/projects/wsPost.php). One of the MOSEAN goals is to facilitate maximum utilization of these (and other stationary and moving platforms) by developing comprehensive interdisciplinary measurement systems as described below.

*GoMOOS.* TECHNICAL DESCRIPTION, FIGURES.

***(4) MBARI Ocean Observing System (MOOS) Test Mooring***
In 2000, MBARI started a development program to design and prototype a new mooring based observing system that incorporated an electrical-optical-mechanical (EOM) cable delivering power and providing communications to atmospheric, upper water column and benthic instruments. As part of a risk mitigation plan for the program, in late 2002, the MOOS test mooring (MTM) was deployed in 1860m of water in Monterey Bay. The mooring was instrumented with sensors to monitor its performance to enable the design team to compare in-situ measured loads with predicted loads, and to test the survivability of the high risk elements of the design. Of particular importance was the testing of the cable terminations at the mooring and anchor, and the survivability of the coil cord, snubber and EOM cable under storm conditions.

*MOOS Test Mooring.* In 2001 and 2002, an engineering team at MBARI designed, fabricated, and deployed a test mooring to verify the design of many of the high risk components of the EOM mooring. Alongside the MOOS test mooring deployment in December 2002, prototypes for the new mooring controller (based on the StrongArm processor and its associated software systems) and the Shore Side Data System were deployed and tested.

The configuration of the MOOS test mooring is shown in **Figure 8**. Twenty floats are distributed over the lower third of the mooring to form an S-tether.

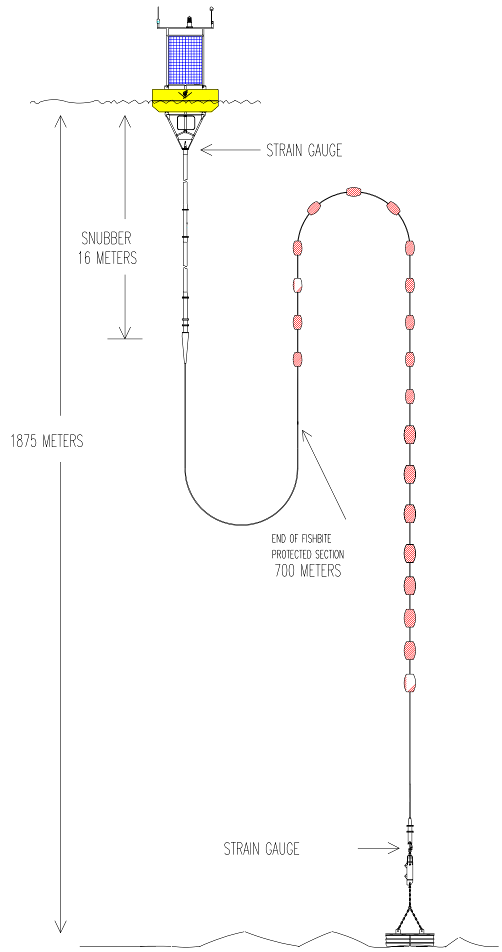



***Figure 8: MOOS Test Mooring***

The test mooring was designed to meet the following requirements:

- survive a 25 year storm off the California coast (49 kts wind, 13.0m significant wave height, 70 cm/sec surface current).
- deploy in a location with 1,860m water depth.
- generate average 60W power from solar and wind energy sources.
- deploy off the Point Sur vessel (UNOLS class III vessel). This limited the diameter of the mooring buoy to 2.5m, a maximum weight of 3500 lbs, and a maximum height of 5.5m.
- retain 15% reserve buoyancy during a 25 year return period storm event.

*Cable Selection*. A bid was released requesting cable designs from 5 manufacturers with advanced capabilities of designing and manufacturing synthetic EOM cables. The Southbay design chosen has four 8 micron single mode fibers protected from ambient pressure loads by a central stainless steel K-tube. The upper section of the riser cable is protected from fishbite with a steel armored section. There are six 15AWG conductors rated for 400V. The breaking strength of the EOM cable is 35,000 lbs with a design working load of 6,000lbs.

*Snubber and Coilcord.* Two 8 meter lengths of snubber hose were inserted between the buoy and the riser cable. The snubber hose, shown in **Figure 9**, was manufactured by Thermoid Corporation. The coil cord inside the water filled snubber hose included four single-mode fibers and was manufactured by Cortland Cable and jacketed and coiled by Whitney-Blake Corporation. The coilcord uses Vectran as a central strength member, and is protected by a neoprene rubber outer jacket. The selection of the optical fiber and the lay of the fiber in the coilcord were critical to the success of the performance of the mooring due to the small radius of the fiber in the coilcord. Testing of the optical performance of the first coilcords at MBARI showed that the optical transmission was unacceptable and that only certain fibers could be used for this application. The coilcord was subjected to fatigue testing for many weeks in a test jig at MBARI prior to deployment.

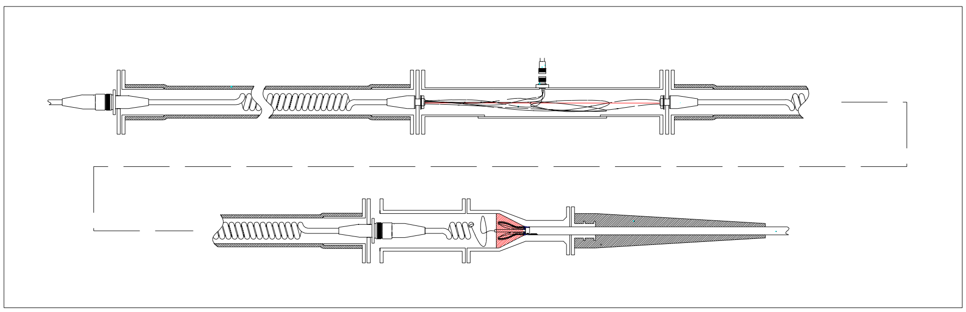


***Figure 9: Snubber design***

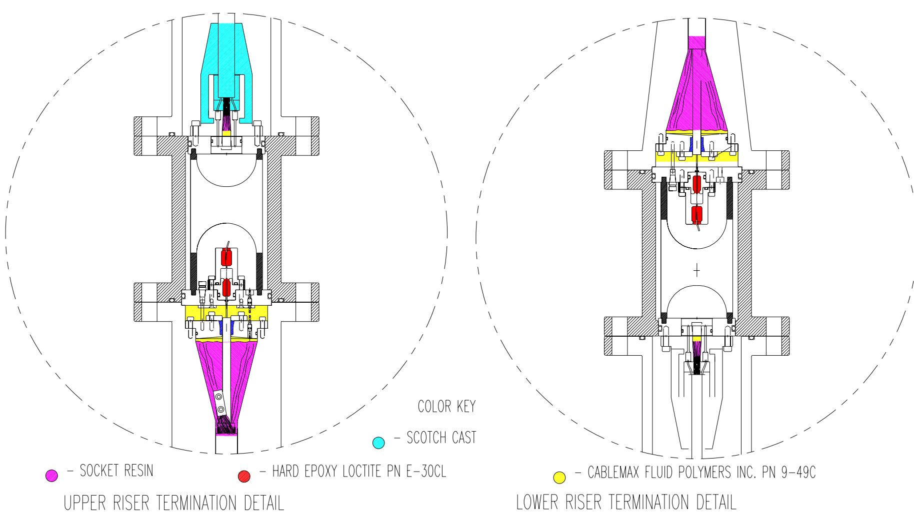



***Figure 10: Termination design***

*Cable Termination.* The cable termination design at the bottom of the snubber and coilcord is shown in **Figure 10**. A critical design feature for this termination is to restrain the cable kevlar strength members so that the strain on the K-tube in its seal is limited to less than 0.7% under maximum cable loads. The design was assembled and tested to maximum design loads numerous times in a test jig and optical transmission of the fibers tested to ensure that the K-tube had not been damaged under the test loading. The design was then tested to 2.25 times the maximum loads predicted for the 25 year storm.

*Power Generation.* For the test mooring 4 Siemens solar arrays were installed each rated for 150W at standard conditions, along with a Southwest Windpower wind turbine rated for 300W in 25 kts of wind. Eight Concorde 84 Amp-hr AGM batteries provided a reserve of 6kWh (at end of life) to allow the mooring to be powered for a period of 8 days with no sun or wind.

*Test Mooring Instrumentation.* Instruments were selected to allow the in situ mooring loads to be measured and compared to the predicted model loads. Strain gauges designed by Sensing Systems were installed where the snubber assembly attached to the base of the buoy and at the base of the mooring cable just above the anchor. A turns counter algorithm using heading information from a KVH compass was installed on the mooring to measure if mooring rotations built up to levels that would cause EOM cable twisting and subsequent hockling. Wave height, wind direction and wind strength were derived from a NOAO buoy moored 5 nautical miles SW from the test mooring deployment site. GPS location was logged to provide information on the location of the mooring in its watch circle. The optical fibers were joined in pairs with each pair consisting of a single fiber running to the bottom of the mooring, where it was spliced to a second fiber running from the bottom back up to the top of the mooring. In this manner there were two fiber loops running between the bottom and the top of the mooring to check the status of the fibers. Testing the continuity of these two fiber pairs allowed the condition of the fibers and the K-tube to be continually monitored. Power generation from each solar panel and from the wind generator, and the power use, were also monitored.

To provide the widest possible deployment weather window, to minimize field handling complexity, and to achieve the greatest personnel safety, an anchor last deployment was adopted with the system being capable of being deployed from a Class III UNOLS vessel. The mooring buoy was deployed first (see **Figure 11**) and then the cable paid out from the Pengo deck winch as the RV Point Sur moved slowly away from the floating buoy. After all of the cable had been paid out and the football floats attached, the anchor was then released on free fall. During deployment the anchor loads were monitored. The measured anchor loads shown in **Figure 12** (max 3791 lbs) corresponded well with the predicted loads (3652 lbs). The anchor setback shown in **Figure 13** (210m) corresponded well with the predicted setback (233m). The anchor set back is the distance the anchor moves towards the buoy during the descent after the anchor is released off the ship.

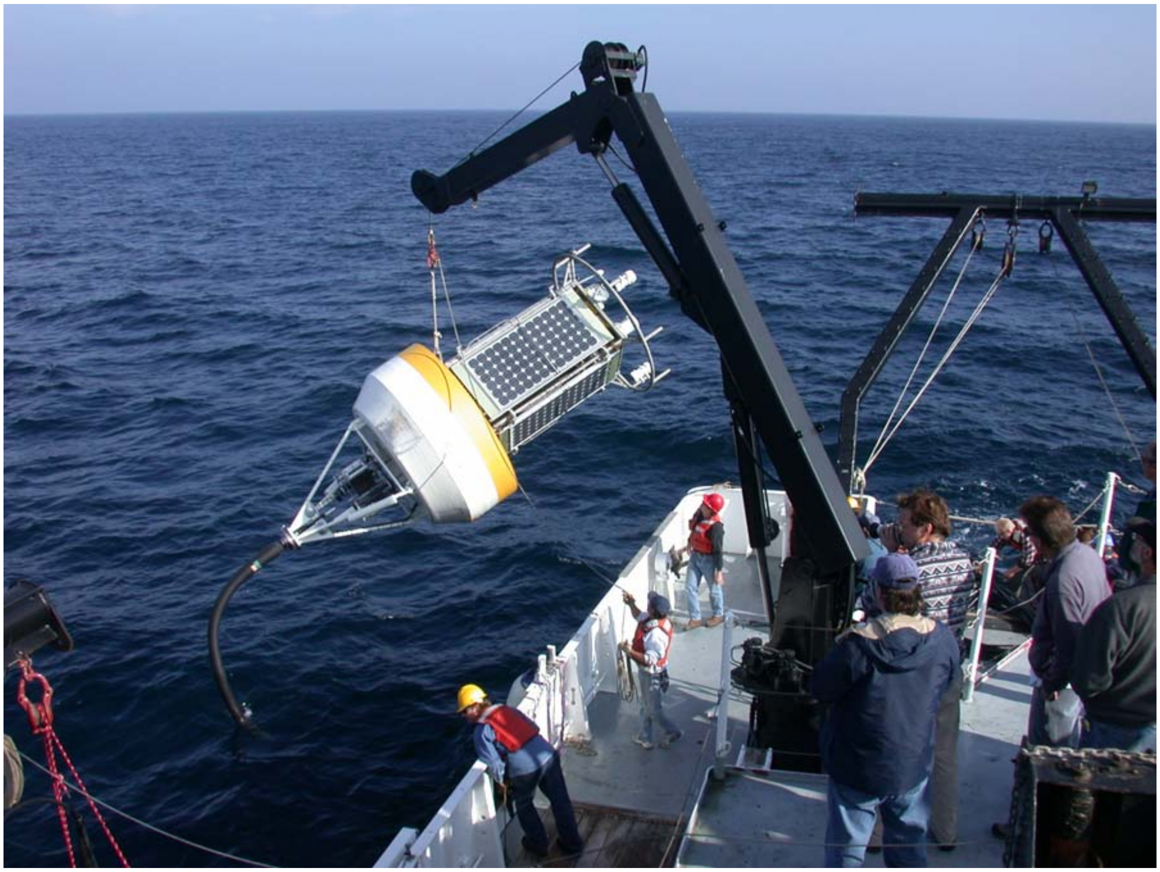


*Figure 11: Deployment of MOOS mooring off the back of the Point Sur*

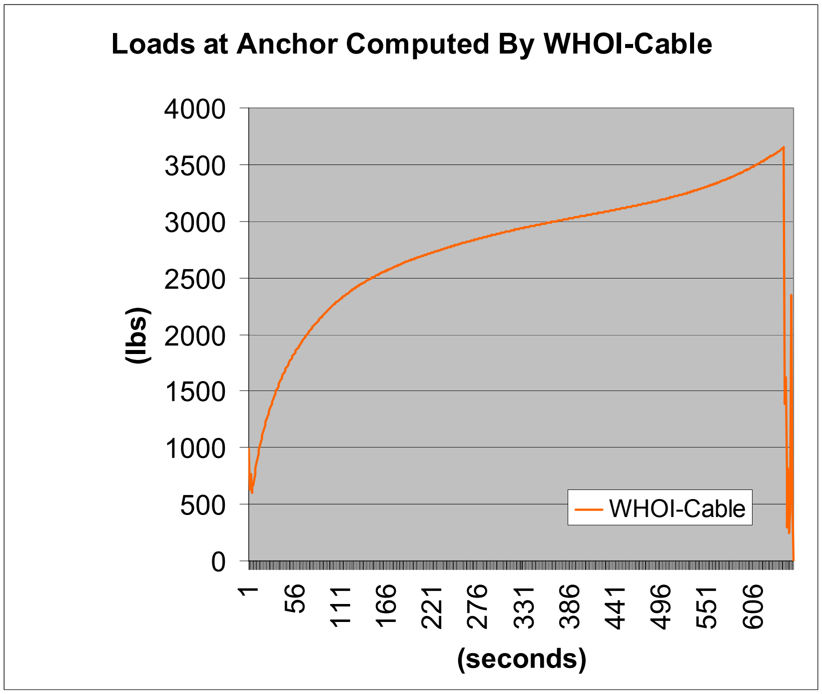



*Figure 12: Anchor drop loads*

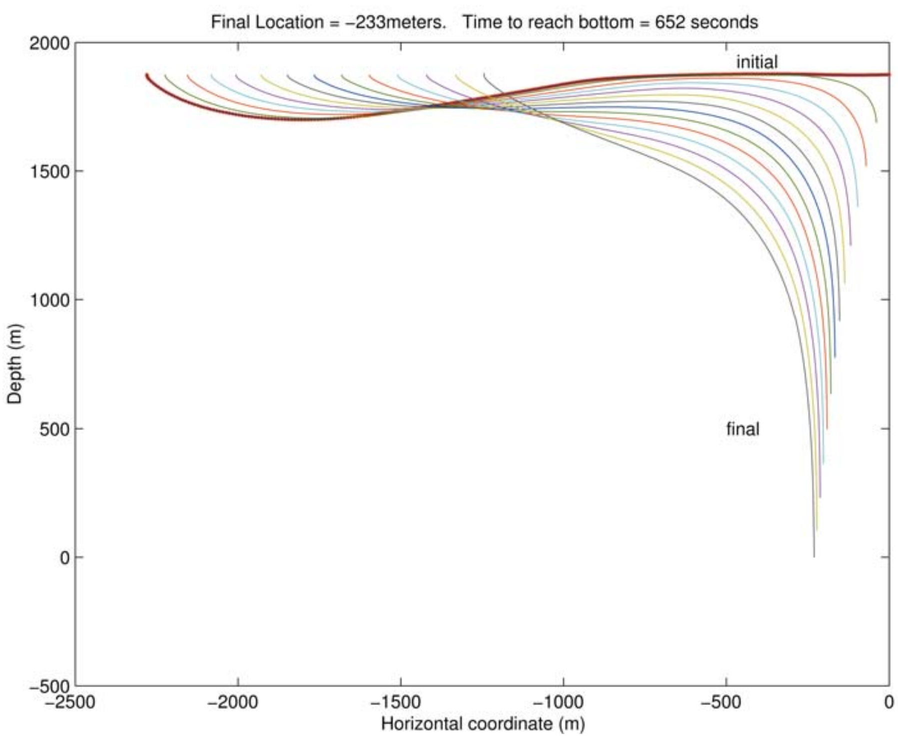



*Figure 13: Anchor setback*

Shortly after the deployment a series of severe storms moved into Californian waters and the test mooring was subjected to extreme loads for an extended period of time. This provided an opportunity to test the loads on the mooring during high wind and wave conditions. During the storm, sustained (5-second) peak gusts exceeded 50 knots and the significant wave height reached 27 feet. The measured and predicted loads at the buoy and at the anchor under these conditions are shown in **Figures 14 and 15**. The storm uncovered a problem with attachment of the football floats to the mooring line that is currently being addressed.

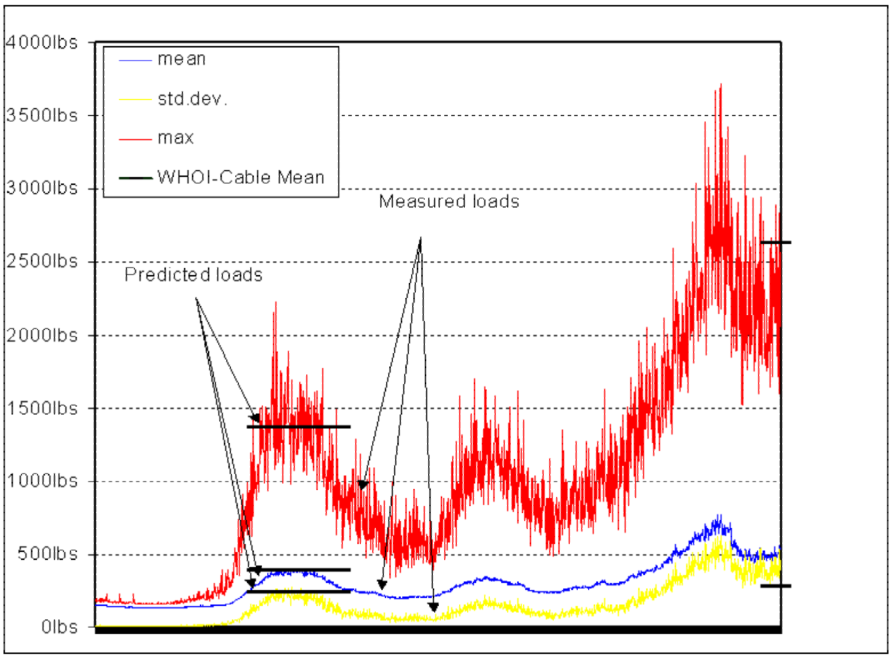



*Figure 14: Measured and predicted loads at buoy*

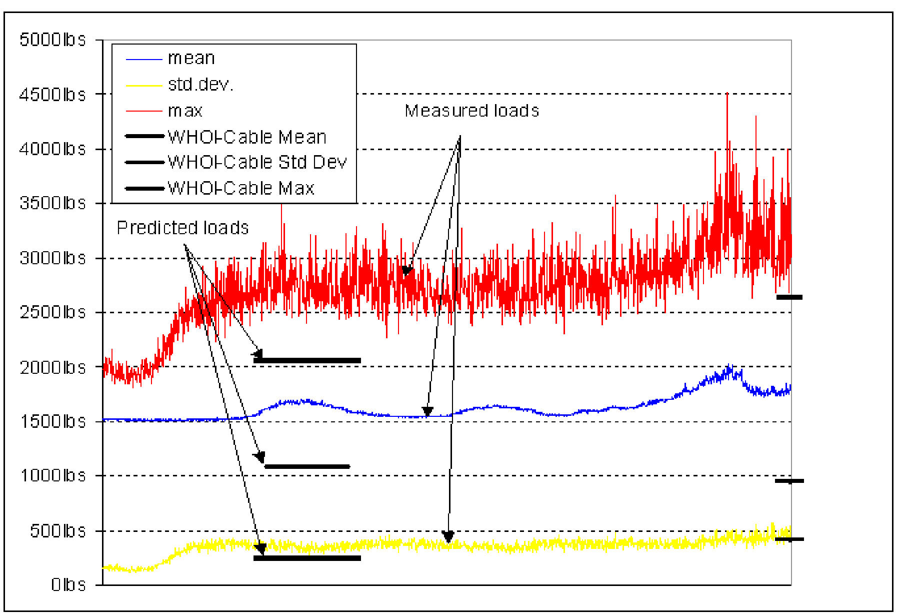


*Figure 15: Measured and predicted loads at anchor*

*Benthic Nodes and Cable Laying.* The other major test deployment of MOOS technologies involved design, fabrication and deployment of the benthic nodes and the laying of fiber optic cable using an ROV. In a parallel effort with the mooring design, a cable laying toolsled was designed and constructed to enable the ROV Ventana to lay EOM cable between benthic nodes. To test the ROV operating procedures, the design team planned to deploy three benthic nodes, two of them in the axis of Monterey Canyon at depths of 320m and 540m. Plans called for the cable laying toolsled to lay cable between these nodes. The benthic nodes were instrumented with ADCP's, current meters and optical backscatter instruments to allow measurements to be made to determine the magnitude of, and mechanisms for, sediment transfer down the canyon axis during turbidity flows.

The cable laying toolsled (see **Figure 16**), is capable of carrying and laying four kilometers of cable. Currently the capacity of the RV Point Lobos RV crane and the level of the variable buoyancy on the ROV Ventana (the latter can be overcome by releasing temporary floatation from ROV as the cable is laid) limit the length of cable that can be laid. The toolsled is designed to allow the cable spool to be dropped and picked up later in case of an emergency. A hydraulically operated pinch allows the tension on the cable to be manually adjusted as the cable laying proceeds at 1 knot.

*Figure 16: Cable laying toolsled on ROV Ventana*

The benthic nodes were successfully deployed in July 2002 (see **Figure 17**) and test pieces of cable were laid with the ROV cable laying toolsled. Before the benthic nodes could all be connected with the EOM cable, a massive canyon transport event took place. Following this event one of the benthic nodes could not be located and the other was moved 540 ft down the axis of the canyon. However prior to this event the procedures for laying the cable with the toolsled were tested and proven.

***Figure 17: Deployment of benthic nodes***

*MOOS Mooring Controller, Software Infrastructure, Portal and Shore Side Data System.* Two other MOOS projects deployed and tested prototypes during the MOOS mooring test deployment in December 2002, namely the New Mooring Controller (NMC), based on the StrongArm processor, and the Shore Side Data System.

NMC served as a testbed for many of the features contemplated for the MOOS mooring system. NMC software was developed using object-oriented design methodology and was implemented in Java. The software implements a mooring distributed object with Java RMI; this makes the mooring's interface accessible to shore via the satellite link. A shore-side Java portal object was implemented to manage and regulate network traffic across this low-bandwidth link. The portal provided the interface between the mooring and the shore-side data system.

For the bi-directional communication link between the test mooring and shore a Globalstar satellite link provided data transfer rates of 7kb/sec. The system was configured to establish a connection every 2 hrs, and to transfer the test data to the Shore Side Data System through the portal. The onboard instrument drivers appropriately generate metadata and associate it with the instrument data that was logged to onboard storage, and ultimately transferred to the shore-side portal and data system.

***(5) High-Seas ROADNet: High-Bandwidth Satellite Communications***
As one of the key design features of the high-bandwidth buoys is their satellite communications system, a pilot experiment called High-Seas ROADNET has begun to gain experience with commercially available C-Band antenna systems. For these experiments the oceanographic research vessels of the UNOLS fleet are being used as

platforms at sea. The primary focus of the High-Seas ROADNet project is to facilitate cost-effective, real-time shore-side delivery of large quantities of data for quality control, archiving, research, and visualization (For more information see http://roadnet.ucsd.edu/).

In early 2002 a satellite terminal was installed on the R/V Roger Revelle, and service leased from a commercial teleport to provide a 64 kbps full-period connectivity between the ship and the public Internet. Funding has now been secured to implement the hub teleport in San Diego and ship systems for the R/V Melville and the R/V Thomas G. Thompson.

This prototype network provides for real time data delivery of large quantities of underway data (e.g., continuous multibeam profiling) to shore for quality control, archiving, and real-time data availability. This system also offers a multitude of valuable services for the research vessels (**Table 10**).

**Table 10: Services delivered via ROADNET High-Seas Project**

| Service | Typical Use |
|---|---|
| **Voice** | Telephone services for entire ship. Interconnection of ship's PBX with UCSD phone system making shipboard telephones UCSD extension numbers. |
| **Data** | Transfer of large files of oceanographic data between ship and shore. Email |
| **Web** | Browsing for information. Database queries. Internet commerce. On-line banking for ship's compliment. |
| **Video** | Teleconferencing. Store-and-forward high-quality picture transmission. Streaming video |

*System Architecture.* The architecture of the satellite communications system is designed to accommodate multiple high Bandwidth buoys whose principal traffic patterns will be inbound from the buoys to the shore. It is based on a "star" configuration, with each buoy having a direct satellite connection to the shore teleport. Data from each buoy to the Teleport will be carried on dedicated satellite circuits that are sized according to requirements or needs of the particular buoy's data collection rate. Data from the Teleport out to the buoys will be carried on a single shared satellite circuit. This shared carrier architecture allows the buoys to use the extra bandwidth that may be available, as other buoys have fallow periods of communication (for example, during maintenance).

The use of a single land-based "hub" facility as the center of communications allows the investment in and management of a single Earth station facility to be shared among all of the ships.

*The Shipboard System.* The system installed on the R/V Roger Revelle (**Figures 18 and 19**) is manufactured by Seatel, Inc., of Concord CA. As the R/V Thomas Thompson is a near identical sister ship to the R/V Roger Revelle, its installation will be similar.

***Figure 18: The C-Band antenna located starboard side aft above the bridge of the R/V Roger Revelle. The R/V Thomas G. Thompson is a sistership.***

It consists of a 2.4 meter radial offset antenna with a 3-axis servo controlled stabilization system housed in a 3.7 meter diameter radome. The antenna beam direction is locked onto the signal transmitted from the satellite by the 3-axis servo to a precision of better than 0.2 degrees under the following conditions.

Tangential acceleration < 0.5G in 6 seconds
Roll stabilization amplitude < ± 25 degrees
Pitch stabilization amplitude < ± 15 degrees
Rate (all axes) <90 degrees/s
Acceleration (all axes) <60 degrees/$s^2$

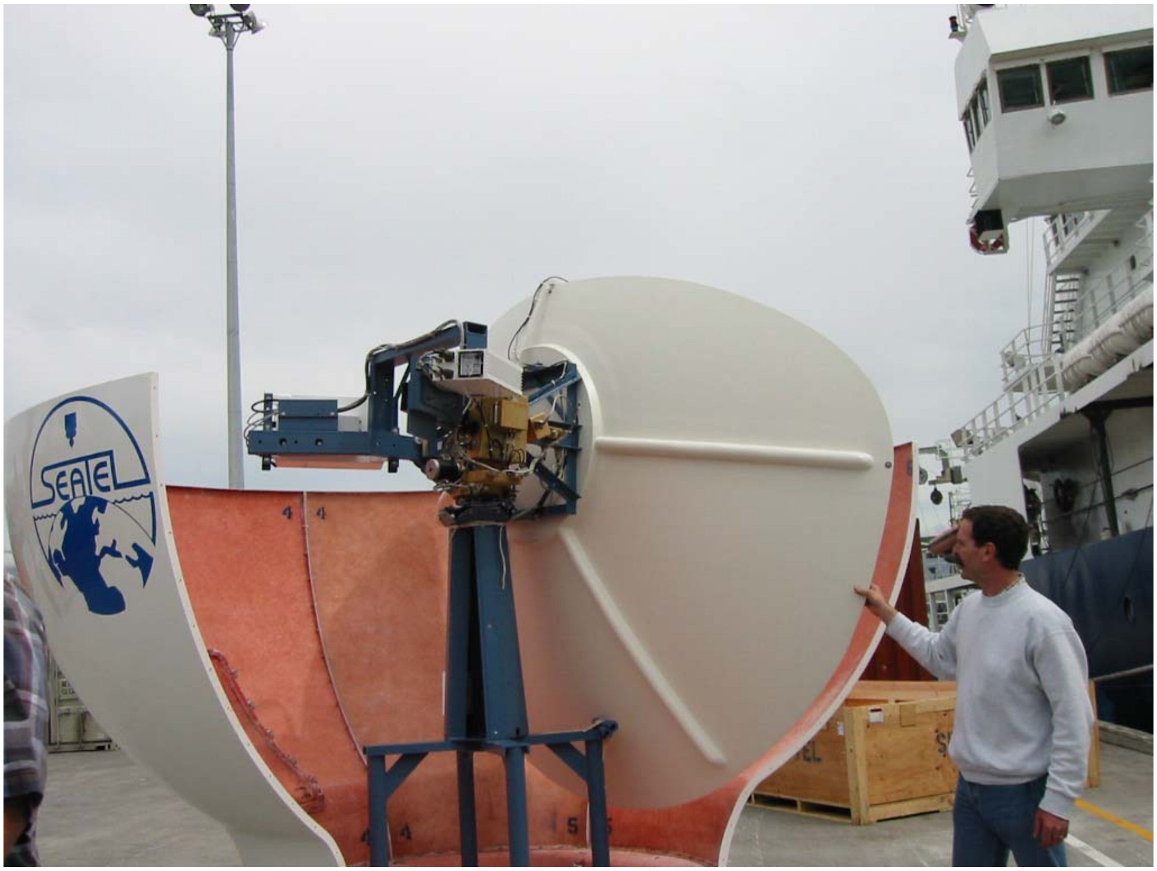



***Figure 19:  The SeaTel Antenna with the radome half completed.***

*The Shore-Side Teleport.*  The prototype shore-side Teleport is located at the San Diego Supercomputer Center (SDSC) on the UCSD main campus (**Figure 20**). The SDSC is a major node on the Internet providing a convenient wide-band gateway.

The Teleport will house the central router with a direct connection to the Internet. This router, and related software systems, allows the management and control of the shared circuit out to the ships. This will allow the prioritization of certain applications (FTP or VoIP) over other less critical applications (web traffic), as well as insure the bandwidth is distributed equitably and efficiently among the ships. This router also can be used to provide any necessary security.


***Figure 20: Shore-side Teleport hub antenna. By using a single, shared 7m class Earth station at the Teleport, 2.4m antennae can be used on the buoys. This minimization of buoy antenna size is critical due to the more difficult physical environment, requiring specialized motorization and tracking equipment.***

**(D) Data Management**

There are several fundamental design constraints that need to be addressed for communications and data management for the proposed GLOBAL NETWORK. The major differences in telemetry bandwidth and power availability necessitate two independent designs for the low- and high-bandwidth systems. However, both systems must be flexible enough to:

- Allow for command and control of instrument packages and computers from shore,
- Accommodate new sensor packages,
- Provide short term and long term local data storage and archiving,
- Allow for prioritization of data transfer through the satellite telemetry to accommodate limited bandwidth and telemetry outages due to sea state or low power,
- Operate a backup telemetry link, and
- Allow for a backup data management computer system on each buoy.

A major design constraint is the expected data collection rates for each type of sensor (see **Table 11**). The basic data communications model for all GLOBAL NETWORK buoys will be a Local Area Network (LAN). Based on the current state-of-the-art for networks, each instrument package that connects to the GLOBAL NETWORK LAN will use the TCP/IP protocol to guarantee data integrity and completeness. Using the concept of a LAN, the distinction of command and control packets from sensor data packets disappears, each packet being an IP packet destined for a specific address.

**Table 11: Expected Data Collection Rates**

| Data Category | Data Volume w/ compression | Yearly data w/ compression | 1 Year Data Transfer @1 Mbit/s |
|---|---|---|---|
| **Uses Satellite Telemetry for Both Systems** | | | |
| Geomagnetism | 4 kbyte | 1.5 Mbyte | 12 sec |
| Meteorology | 30 kbyte | 10.7 Mbyte | 86 sec |
| Seismology (1 sps) | 450 kbyte | 160 Mbyte | 0.36 hrs |
| Water Column Oceanography | 614 kbyte | 219 Mbyte | 0.49 hrs |
| **Uses Satellite Telemetry for High Bandwidth Systems** | | | |
| Still Photography (hourly) | 2 Mbyte | 0.7 Gbyte | 1.6 hrs |
| GPS time and location | 4.2 Mbyte | 1.6 Gbyte | 3.6 hrs |
| Sea Floor Geodesy | 8 Mbyte | 2.9 Gbyte | 6.6 hrs |
| Seismology (40 sps) | 18 Mbyte | 6.4 Gbyte | 14.6 hrs |
| Hydrophone (1) (300 sps) | 33 Mbyte | 11.8 Gbyte | 26.9 hrs |
| **Uses Satellite Telemetry for High Bandwidth Systems Limited Subsets of Data Only** | | | |
| AUV data | 400 Mbyte | 142.6 Gbyte | 325 hrs |
| Acoustic hydro. arrays (2) | 1.0 Gbyte | 365 Gbyte | 830 hrs |
| Video | 1.5 Gbyte | 547.5 Gbyte | 1246 hrs |

***(1) Low-Bandwidth Buoy***

*Data Telemetry.* The low-bandwidth buoy design has 5 Mbyte/day data transfer between the buoy and the shore at a rate of 64 kbps, and uses acoustic communications between seafloor instruments and the buoy at a rate of 4.5 kbps (**Figure 21**). IP protocols will be used over acoustic links to allow for standard communications interface which is useable by many types of sensor packages. Based on power and bandwidth limitations, only 100% of the data from the lower bandwidth sensors shown in **Table 12** can be telemetered on a daily basis (e.g. geomagnetic, meteorological, oceanographic, and geodetic instruments). All of the data from higher bandwidth sensors (e.g. seismic and acoustic sensors) cannot be sent in near real time, except for limited time segments. For example, 6 hours of 40 sps seismic data can be sent with 4.5 Mbytes and have 500 kbytes available for other data sets. The specific time windows for seismic data would be defined by (1) larger events detected by the Global Seismic Network, (2) 1 sps data stream (very effective), and (3) event detection.

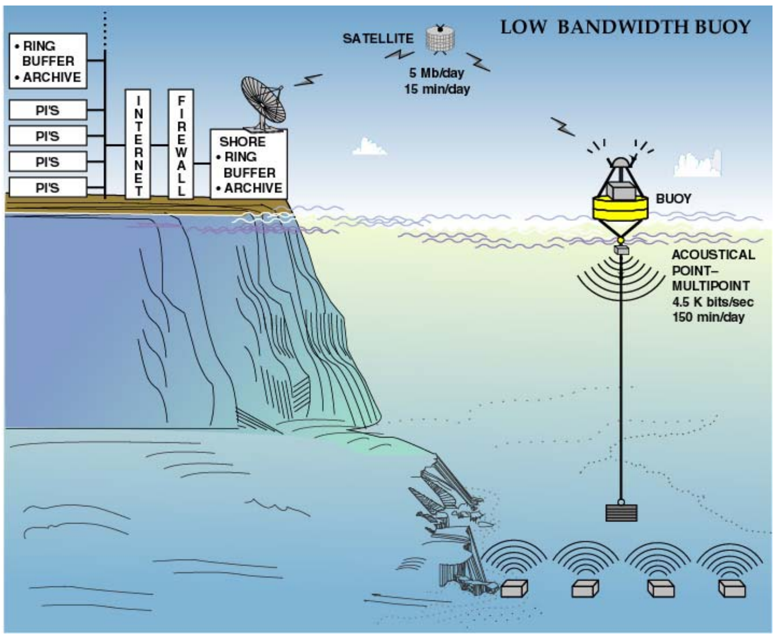



***Figure 21: Low-Bandwidth, Acoustically-linked Buoy***

| **Table 12: Estimated Sensor Power and Data Requirements** | | |
|---|---|---|
| **Data Category** | **Average Power (W)** | **Acquisition Rate (duty cycle)** |
| Air-Sea Interaction/ Meteorology | 2 | 30 kbytes/day (100%) |
| Oceanography | 2 | 0.6 Mbytes/day (100%) |
| Hydroacoustics | 5 | 27 Mbytes - 1 Gbyte/day (2.5-100%) |
| ATOC Sound Source | 50 | (2.5% duty cycle) |
| Seismology | 2 | 18 Mbytes/day (100%) |
| Seafloor Geodesy | 8 (seafloor) + 30 (buoy) | 8 Mbytes/day (7% or 12 hrs/week) |
| Geomagnetism | 2 | 4 kbytes/day (100%) |
| Still Photographs | 0.2 | 2 Mbytes/day (1 photo. per hour) |
| Video | 15 | 1.5 Gbytes/day (1 hour per day) |
| AUV data | 150 (recharge) | 400 Mbytes/day (100%) |
| | | |

The communications protocol used for the satellite link will be TCP/IP to allow direct access to each instrument package from the shore for command and control; however, the capability for upgrades of firmware and software may be limited because of the low data rate. The data communications bottlenecks are fundamentally different for the low-bandwidth buoy than for the high-bandwidth buoy since it will take 150 minutes to transfer 5 Mbytes from the seafloor to the buoy and 15 minutes to transfer data from the buoy to the shore. This disparity in data rates will demand a procedure where once a day, a short connection over the satellite link to the data management computer on the buoy is established to send a set of data requests. Then the data management computer extracts requested data from the seafloor instruments, storing data locally on the buoy. Once all requested data are recovered, the buoy data management computer re-links to the satellite and transmits the data back to shore.

*Data Storage and Retrieval.* Given that the expected aggregate rate of data acquisition for the low-bandwidth system will exceed the available satellite or acoustic bandwidth, the primary data storage facility will be locally stored in each instrument. Data can be recovered in any one of three ways. The highest priority data sets can be recovered through the satellite telemetry system assuming that the available bandwidth is adequate. Data could also be recovered using a radio link to a ship that is within line-of-sight using high bandwidth wireless technology. For large datasets, the instrument packages will be retrieved when a ship services the observatory.

*Computer and Network System.* Starting from the seafloor, each instrument will be an IP-based device capable of sending data and receiving command and control information from the buoy or directly from shore. Each instrument will be connected via acoustic modem directly to the buoy (see **Figure 21**). Instead of the network hub used in the high-bandwidth buoy, a point-to-point acoustic communications link will need to be implemented to service the data telemetry requirements from each seafloor instrument. The buoy data management computer is connected to shore 15 minutes per day using the 64 kbps satellite link, and can also connect a nearby ship using wireless technology. On shore, a data management computer that is isolated from the public Internet by a firewall will receive the data. Data can then be sent immediately over the Internet using secure protocols to each PI and community data can be available immediately. The firewall restricts access to buoy and instrument control. An archive of all telemetered data will be maintained at the data management computer located on shore as well as by each PI. Another important function of the buoy data management computer is to automatically execute shutdown procedures for control, power generation, and telemetry systems when error conditions are detected and reboot these systems when the error conditions are cleared.

*Timing Systems.* No common timing standard can be provided in the Low-Bandwidth system. All timing for instruments will have to use the existing technology for autonomous seafloor systems used today.

***(2) High-Bandwidth Buoy***

*Data Telemetry.* The high-bandwidth buoy will have nearly continuous data communications at 64 kbps (or greater) between the buoy and the shore, and a fiber optic connection from the buoy to a seafloor junction box (**Figure 22**). The fiber data telemetry link between the buoy and a seafloor junction box will be of sufficient bandwidth to allow real-time data communications for all proposed sensors. The high-bandwidth satellite link between the buoy and the shore installation will allow real-time data communications except for continuous real time video or hydroacoustic arrays (which would require local storage on the buoy). The communications protocol used for the satellite link will also be TCP/IP to allow direct access to each instrument package from the shore for command, control, and upgrades of firmware and software.

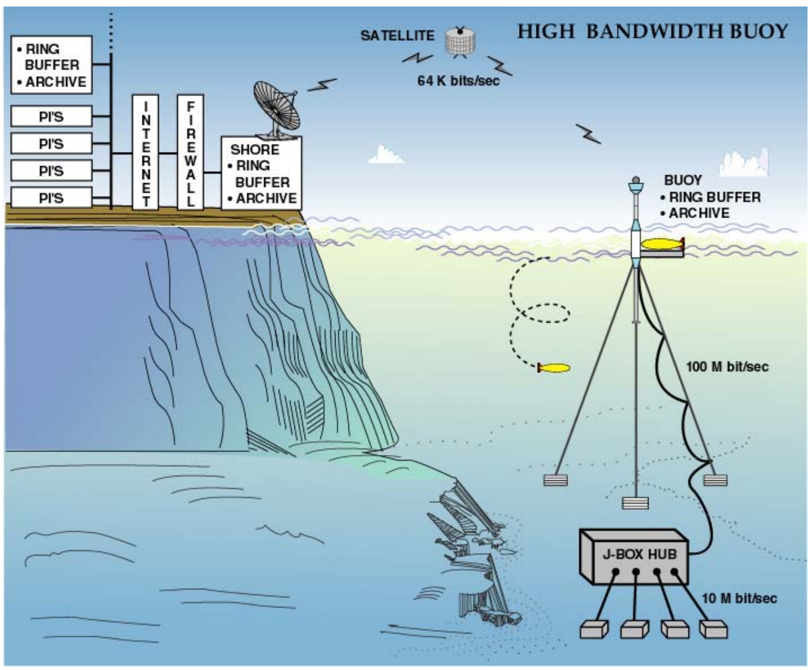



***Figure 22: High-Bandwidth, Cable-Linked Buoy System***

The instrument command and control requirements are straightforward to implement. However, data management and telemetry are more difficult. The principal data communication bottleneck will occur across the satellite link between the buoy and the land installations. The proposed data link for the high-bandwidth buoy will only allow for a limited amount of data, 690 Mbytes/day, to be transferred to scientists on shore assuming full efficiency. The actual data rate may be as low as 230 Mbytes/day (see section on Satellite Communication Systems). Looking at the expected data rates in **Table 12**, and assuming data compression factors of 2-3, all data from geomagnetic, meteorological, oceanographic, geodetic and seismic sensors can be sent in near real-time from the High-Bandwidth buoy satellite telemetry system. However, data from higher bandwidth sensors (e.g. hydroacoustic arrays, video) cannot be sent in near real time, except for limited time segments. In the case of acoustic arrays, selected channels could be sent continuously since the data from each hydrophone will generate only 2.4 kbps of data. Processed data, such as selected beams, could also be sent in near real time. The steady-state real-time data flow for most sensors will be no more than one third of the total available bandwidth. This will permit retransmission of high priority data in situations where high sea states or satellite communications problems interrupt normal telemetry. This requirement also allows for telemetry of event segments from high data rate experiments, as well as for providing sufficient bandwidth for command and control functions.

*Data Storage and Retrieval.* The primary data storage unit will be the data management computer housed on the buoy. If connectivity between the buoy and an instrument is lost, seafloor data storage built into the instrument data logger package can be utilized. Each instrument will provide any necessary power backup.

Data will be recovered in any one of four ways. The highest priority data sets will be recovered through the satellite telemetry system. Data can also be recovered using a radio link to a ship that is within line-of-sight using a high-speed wireless link. The third procedure will be to board the buoy during normal maintenance operations and remove the disks on the data management computer. For large datasets, this will be the preferred mode of data retrieval to minimize the time on station for servicing. Also, to minimize servicing time, all large datasets must be telemetered from instruments in real time to the buoy, otherwise it will be too time consuming to upload 1 years worth of data from the seafloor. Finally, if communications are lost between the buoy and the seafloor, the instrument packages with local data storage can be retrieved.

*Computer and Network System.* Each instrument will be an IP-based device capable of sending data and receiving command and control information from the buoy or from shore. Each instrument will be connected via cable to a network hub located in the seafloor junction box (see **Figure 7**). The network hub will communicate with the data management computer located on the buoy using a fiber optic link. All computers and sensor devices will be directly addressable from shore.

The buoy data management computer is connected to shore using the 64 kbps satellite link, and can also connect to a nearby ship using a high bandwidth wireless link. On shore, a data management computer that is isolated from the public Internet by a firewall receives data. Data can then be immediately sent over the Internet using secure protocols to each PI and community data can be available immediately. The firewall restricts access to buoy and instrument control and is not designed to limit speed of data access. An archive of all telemetered data will be maintained at the data management computer located on shore as well as by each PI. Another important function of the buoy data management computer is to automatically execute shutdown procedures for control, power generation, and telemetry systems when error conditions are detected and reboot these systems when the error conditions are cleared.

*Timing Systems.* Two levels of timing systems will be provided. A GPS based NTP server will provide timing accuracy over the network within several milliseconds. A separate dedicated timing signal will be provided from the buoy to the junction box to provide sub-microsecond timing accuracy.

***(3) Current Prototype Testing***

*(a) ROADNET Prototype.* The NSF-funded Real-time Observatories, Applications, and Data management Network (ROADNet) is developing new technologies to deliver integrated seismic, oceanographic, geodetic, hydrological, ecological, and physical sensor data to a variety of users in real-time via the Internet. For example, ROADNet is currently collecting a limited set of continuous GPS, gyroscope, and photographic data from the RV Revelle (For additional information see http://roadnet.ucsd.edu/).

ROADNet concentrates on the challenges associated with building wireless networks to stream remote sensor data, and with the integrated information management system that will deliver these data in real-time to a variety of users, including researchers, policymakers, natural resource managers, educators, and students.

ROADNet has developed Virtual Object Ring Buffers (VORBs) to access, integrate, and disseminate real-time data streaming from heterogeneous sensor arrays. In a prior project, Object Ring Buffers (ORBs) were used to capture real-time data in seismic networks. ROADNet extends the concept of ORBs to "Virtual ORBs" (VORBs), which can exchange data across federated sensor networks, accommodate dynamic reconfiguration of networks, and facilitate access to databases and persistent archives.

ROADNet employs San Diego Supercomputer Center's Storage Resource Broker (SRB), a core infrastructure for building efficient, large-scale data management systems that span multiple administration domains, multiple types of storage systems, and multiple types of data access environments. The SRB provides capabilities for storing replicas of data, for authenticating users, and for controlling access to documents and collections.

The technologies developed through this research will create a system that will

- dynamically adapt downstream processing, cataloging, and data access interfaces when sensors are added or removed from the system;
- provide for real-time processing and monitoring of data streams--detecting events, and triggering computations and other actions;
- integrate heterogeneous data from multiple (signal) domains; and
- provide for large-scale archival and querying of "consolidated" data; and
- provide access control systems that rank user priority at the network (bandwidth consumption) level and authorize data delivery at the Internet interface.

Many of these interactions will be mediated through XML wrappers, which will provide the basis for data discovery. A rule-based programmable interface will be developed to reconfigure and prioritize data capture and analysis dynamically from this multiplicity of sensor networks. The use of efficient stream processing capabilities together with the ever increasing networks speeds will guarantee that the resulting system scales well.

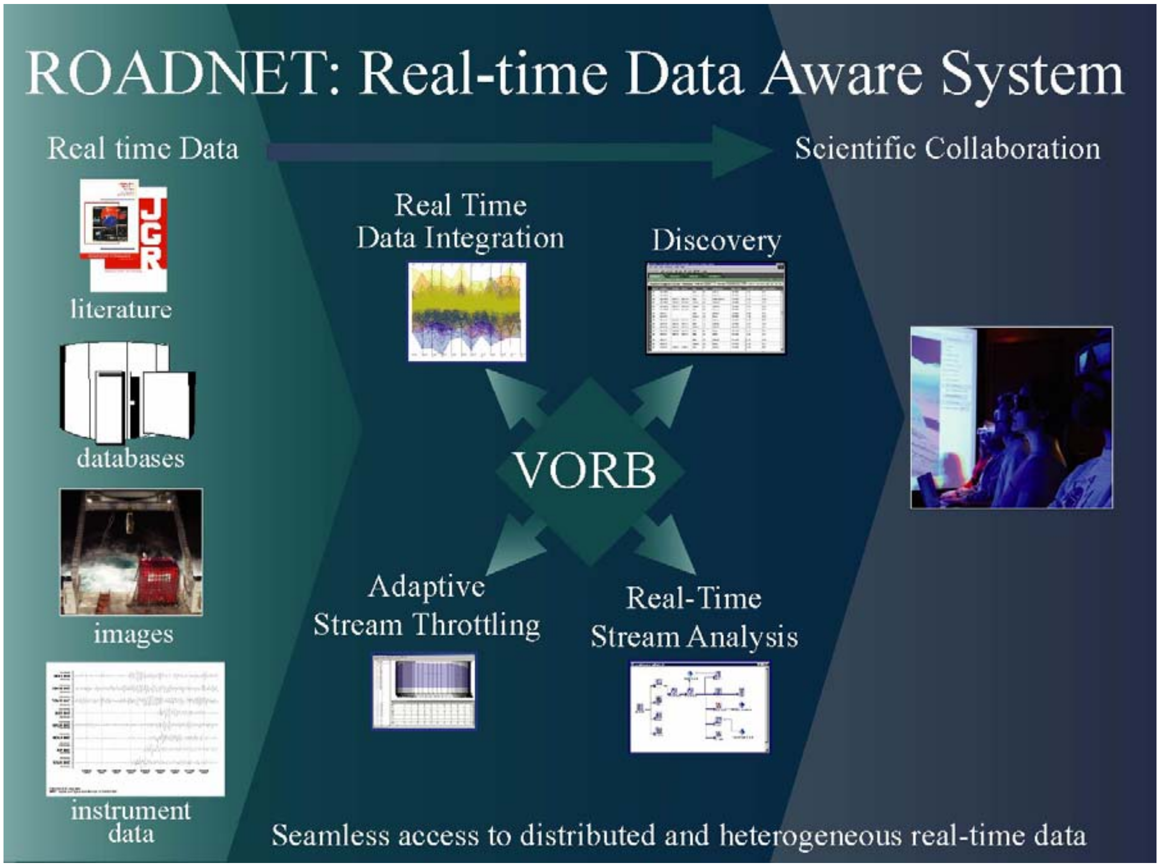



***Figure 23: ROADNet***

ROADNet research has implications for the success of large-scale NSF initiatives including OOI, EarthScope, NEON (National Ecological Observatory Network), and NEES (Network for Earthquake Engineering Simulation). Each of these large scale initiatives aims to collect real-time data from thousands of sensors, and each will require new technologies to process, manage, and communicate real-time multidisciplinary environmental data on regional, national, and global scales (**Figure 24**).

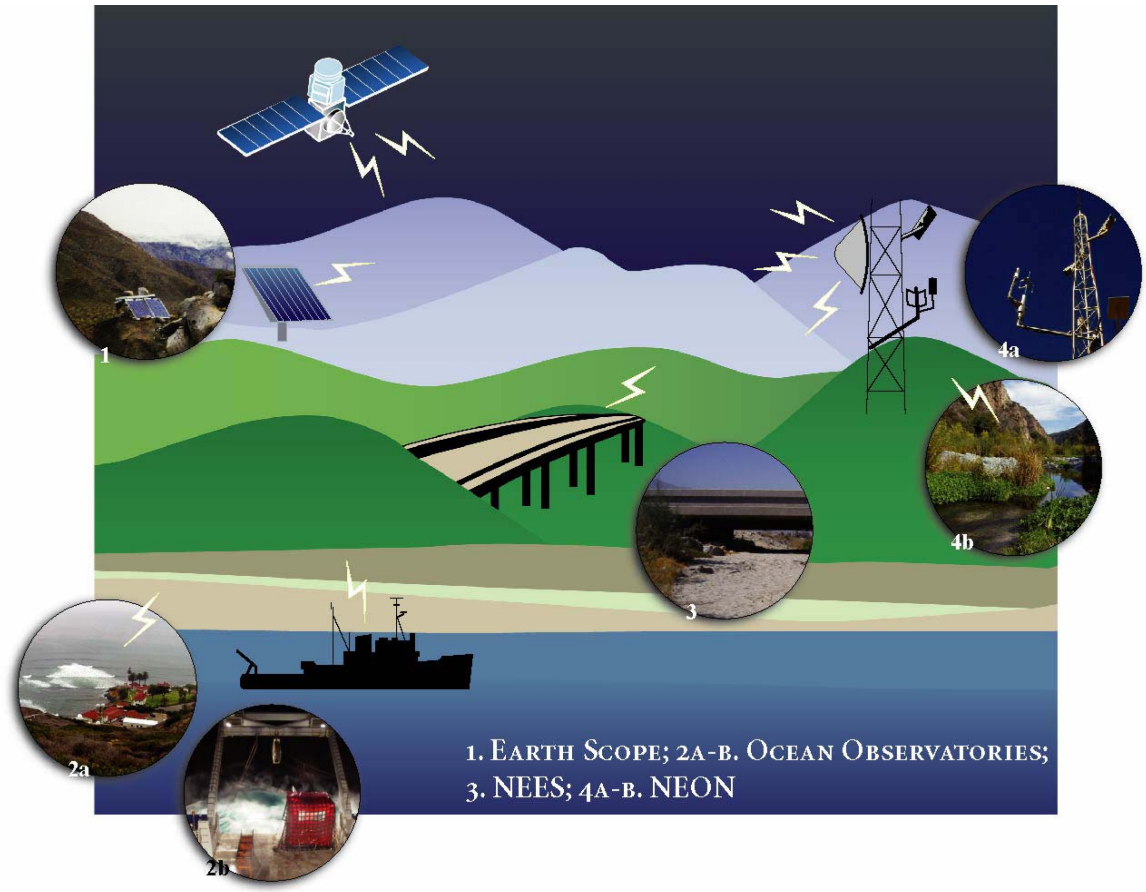



***Figure 24: Multidisciplinary observatory initiatives requiring new technologies to process, manage, and communicate real-time multidisciplinary environmental data on regional, national, and global scales***

*(b) Smart Network.* The Instrument Software Infrastructure (ISI) project at MBARI has developed designs and prototype implementations for oceanographic sensor networks, including a bench-top smart network of puck-equipped instruments developed in 2001. The smart network was implemented with Java-based JINI technology. The puck proof-of-concept device was implemented with a low-cost Rabbit semiconductor and compact flash. When a puck-equipped instrument was plugged into the bench-top node's serial port, the node automatically detected the device and downloaded metadata and distributed object software from the instrument's puck; the node then automatically launched the instrument's distributed object, enabling it to join the smart network.

Several ISI concepts and actual software components have been deployed as part of the New Mooring Controller (NMC) project described elsewhere in this document.

**(E) Estimated Costs to Develop, Install and Maintain the GLOBAL NETWORK**
This section details preliminary estimates of the costs associated with various aspects of the GLOBAL NETWORK of Moored-Buoy Observatories that will be useful to those

engaged in planning to the OOI. Because costs are so difficult to determine accurately, extra care has been taken to be clear about how the costs were estimated, which tasks they include, and what assumptions were used. In this way, it should be possible to improve the cost estimates as better information becomes available. A summary of costs are presented in **Table 13**, where the cost estimates are segregated by major task so that totals can be determined based on the overall assumptions about the number of sites, the types of moored systems deployed at each site, and the types of instrumentation deployed. Additional information supporting these estimates is provided in **Appendix A**. Several important categories of costs were estimated as part of the DEOS Moored-Buoy Observatory Design Study [2000] and these are used in this report as well, with a number of additions as explained below. However, other costs categories that are essential to the development of the GLOBAL NETWORK were not addressed in that study, so these additional costs have been estimated here so that a more complete cost estimate is available to people developing the resources needed to implement the network.

In the DEOS Moored-Buoy Observatory Design Study, costs were estimated for two typical ocean sites with water depths of 3000m and 6000m. Costs for several versions of the observatory infrastructure (low-bandwidth, high-bandwidth, etc.) were broken down into Capital Costs, Installation Costs, Annual Operating and Maintenance Costs, and Ship time. To provide the necessary information without making the number of combinations too complex, we have developed costs for a typical oceanic site about as far from shore as the Nazca site ($23^0$ S, $90^0$ W) in 4500m of water for each of the three moored buoy approaches. Typical ship and cruise costs are shown in a modular form so that more accurate costs can be calculated when the deployment sites are defined. Ship costs have

| *Table 13: Estimated funds needed to develop three moored-buoy observatory designs and to implement a GLOBAL NETWORK of moored-buoy observatories. The costs shown are based on a site in 4500m of water that requires cruises of 18 to 23 days to conduct the service work. Total network cost can be estimated by multiplying the per system cost by the number of systems of each type installed in the network. One time costs for each design are shown in the table above the per system costs.* | | | | | | |
|---|---|---|---|---|---|---|
| | **Mid Lat Acoustic** | **High Lat Acoustic** | **Low/Mid Lat Cabled** | **High Lat Cabled** | **Mid Lat Spar** | **High Lat Spar** |
| | | | | | | |
| **One Time Engineering Costs (NRE)** | | | | | | |
| Design Mods- Acoustic High Lat | | 200,000 | | | | |
| Design Mods- Cabled High Lat | | | | 800,000 | | |
| EOM Cable Development | | | 750,000 | | 250,000 | |
| C-Band Mods for Spar | | | | | 250,000 | |
| Diesel Genset Mods for Spar | | | | | 250,000 | |
| Vessel Mods for Spar Installation | | | | | 1,500,000 | |
| Spar Design and Prototyping | | | | | 3,200,000 | 1,150,000 |
| | | | | | | |
| **Network Fabrication/Operation** | | | | | | |
| | | | | | | |
| **CAPITAL COSTS** | | | | | | |
| Buoy | 50,450 | 60,540 | 50,450 | | 150,880 | 181,056 |
| Mooring | 83,910 | 100,692 | 301,410 | | 1,146,297 | 1,375,556 |
| Buoy Payload | 32,500 | 39,000 | 32,500 | | 50,500 | 60,600 |
| Telemetry System | 27,000 | 32,400 | 7,000 | | 176,000 | 211,200 |
| Power Generation System | 8,600 | 10,320 | 8,600 | | 68,300 | 81,960 |
| T-Box | 0 | 0 | 17,500 | | 17,500 | 17,500 |
| Junction Box | 0 | 0 | 214,500 | | 214,500 | 214,500 |
| Seafloor Network | 0 | 0 | 220,000 | | 220,000 | 220,000 |
| Subsurface Mooring | 0 | 0 | 0 | | 0 | 210,000 |
| Surface Mooring | 0 | 0 | 270,000 | | 270,000 | 0 |
| Instrumentation | | | | | | |
| Labor | 177,000 | 177,000 | 180,000 | | 315,000 | 315,000 |
| Contingency | 75,892 | 83,990 | 162,392 | | 427,795 | 491,474 |
| Site Specific Engineering | 37,086 | 40,963 | 80,636 | | 207,368 | 237,541 |
| **TOTAL CAPITAL COSTS** | **492,438** | **544,906** | **1,544,988** | | **3,264,140** | **3,616,388** |
| | | | | | | |
| **INSTALLATION COSTS** | | | | | | |
| Mobilization | 27,360 | 27,360 | 51,720 | | 51,720 | 51,720 |
| Cruise | 59,500 | 59,500 | 304,500 | | 304,500 | 304,500 |
| Demobilization | 10,580 | 10,580 | 19,360 | | 19,360 | 19,360 |
| Other Costs | 35,000 | 35,000 | 70,000 | | 70,000 | 70,000 |
| **TOTAL INSTALL W/O SHIPTIME** | **132,440** | **132,440** | **445,580** | | **445,580** | **445,580** |
| | | | | | | |
| **Installation Shiptime** | **396,691** | **591,890** | **693,940** | | **1,583,940** | **2,375,910** |
| | | | | | | |
| **ANNUAL OPER & MAIN COSTS** | | | | | | |
| Mobilization | 24,860 | 24,860 | 46,720 | | 46,720 | 46,720 |
| Cruise | 59,500 | 59,500 | 304,500 | | 313,300 | 313,300 |
| Demobilization | 10,580 | 10,580 | 19,360 | | 19,360 | 19,360 |
| Other Costs | 35,000 | 35,000 | 70,000 | | 70,000 | 70,000 |
| Telemetry Charges | 36,000 | 36,000 | 36,000 | | 36,000 | 36,000 |
| Replacement Parts | 32,197 | 48,836 | 147,697 | | 259,628 | 263,353 |
| **TOTAL ANNUAL W/O SHIPTIME** | **198,137** | **214,776** | **624,277** | | **745,008** | **748,733** |
| | | | | | | |
| **Annual Ship Costs** | **396,691** | **591,890** | **693,940** | | **693,940** | **693,940** |
| | | | | | | |

been estimated at $20,410 per day for large UNOLS ships, at $13,679 for intermediate UNOLS ships, and at $18,000 for non-UNOLS ships. Labor costs for each cruise are estimated at $500/day for each of 6 people. If ROV operations are needed, the ROV costs are estimated at $10,000 per day including the labor to operate the ROV. For the purposes of this costing analysis we have assumed that a cruise to the observatory site requires 8 days of transit to the disembarkation port, 2 days of in port mobilization, and 18 to 23 days to steam to the site, perform the at sea operations, and return to port. The range of cruise times reflects the complexity of the operation. For example, a low bandwidth system without ROV operations takes 18 days on the intermediate ship and a high-bandwidth system with complex seafloor network requires 23 days with an ROV. One day of in port demobilization is also included, but return transit to the ship's home port is not.

In addition to the tasks associated with the Capital, Installation, Operating and Ship time costs, certain other tasks must be accomplished before the GLOBAL NETWORK can be implemented. These additional tasks are described below.

***(1) Component Development and Testing***

The following tasks need to be done before the final system designs can be completed for the low and high bandwidth cabled designs.

*Determining Data Rates for the Low-Bandwidth, Acoustically-Linked System.* This approach is the most mature of the three moored-buoy approaches. It has been used successfully in the NOAA Deep-ocean Assessment and Reporting of Tsunamis (DART) program (http://www.pmel.noaa.gov/tsunami/Dart/). There are no fundamental, high-risk technologies associated with this approach, although questions remain about the acoustic-link performance that is achievable under realistic environmental conditions. The primary issue that needs to be resolved during this phase is the average data rate that is achievable, 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. The maximum horizontal range over which useful data rates can be achieved needs to be determined for both seafloor and moored instruments. It is expected that these issues will be resolved adequately by on-going research efforts to allow detailed engineering designs to be prepared for the DEOS buoy system at the start of the next phase.

*EOM Cable Development and Field and Laboratory Testing Program for Single Point Moorings.* The highest-risk subsystem in the low-bandwidth, cable linked design is the electro-optical-mechanical (EOM) cable used to moor the discus buoy, provide communications with the seafloor, and provide small amounts of power (20 watts) to the junction box (See **Appendix B**). We have little experience with EOM cables in single-point surface moorings using discus buoys. We do not currently know the expected operational lifetime of EOM cables in this application, nor do we know how factors such as sea state and currents affect this reliability.

The tasks that need to be done are (i) EOM cable design and selection, (ii) EOM termination design (including bending relief), (iii) design of the junction between the discus buoy and EOM cable, and (iv) testing and verification of the designs. The cable needs to be designed to keep the strain within acceptable limits for the fiber optic and copper conductors. The selection process will consider choice of strength member, provision for fish bite protection, and the effects of cyclic loading and bending due to the motions of the wave-following discus buoy. Testing and verification of the cable design needs to include both testing on shore and actual deployments at sea:

- Shore testing: cyclical loading in axial tension of the cable and termination, cyclic bending, resistance to hockling, simulation of deployment loads and handling
- At-sea testing: multiple deployments and recoveries, one or more longer term deployments under winter storm conditions

The MBARI MOOS program is working on these issues, but additional funding may well be needed. The estimated cost for these activities is estimated at $750K.

*Identification and Laboratory Testing of Candidate EOM Cables for Tri-moored Spar Buoys.* The highest-risk subsystem in the high-bandwidth, cable-linked spar system is again the EOM cable used to provide communications with and power to the seafloor, as was the case for the low-bandwidth, cable-linked system (See **Appendix B**). The EOM cable requirements differ substantially in the two cases, however, because the EOM cable is not load-bearing in the spar buoy system. The original design envisioned using standard oceanographic armored cable for data and power. We have little or no experience with EOM cables used in this way, do not currently know the expected operational lifetime of EOM cables in this application, and do not know how factors such as sea state and currents affect this reliability. Modeling needs to be extended to predict the type of loading the cable can be expected to experience. The tasks that need to be done are similar to those for the low-bandwidth cable linked system: (i) EOM cable design and selection, (ii) EOM termination design (including bending relief), (iii) design of the junction between the spar buoy and EOM cable, and (iv) testing and verification of the designs. Design and testing for resistance to hockling will be particularly important, because the cable will likely experience relatively low tensions.

The projected costs to test the EOM cables for the tri-moored spar buoy are estimated to be $250K.

*Testing and Modification of C-Band Telemetry Systems for Use on Spar Buoys.* Testing of the C-band satellite communications system will be continued and expanded as part of the ROADNET project. This effort should include identification of any design changes required to improve the long-term reliability of the buoy antenna system and testing of a modified antenna system on board ship. The estimated cost of this effort is $250K.

*Testing and Modification of Candidate Diesel Generator Systems for Use on Spar Buoys.* Although we do not consider this subsystem as high-risk as the EOM cable design, it is not sufficiently mature to be confident of reliable, unattended operation for 12-month periods. The estimated costs to further test this system are $250K.

*Design and Testing of the Seafloor Junction Box.* Common to both the low-bandwidth and high-bandwidth cable-linked systems (but not to the low-bandwidth, acoustically-linked system) is the need for a seafloor junction box between the various instrument systems and the EOM cable to the surface. The moored-buoy junction box will be designed to appear to the user to be identical to the plate-scale cabled observatory junction box, except for the amount of power that will be available in the differing approaches. There are, nonetheless, issues that need to be resolved to design a convenient user interface, including those involving device discovery, automatic port configuration, and metadata handling and delivery. MBARI will be working on these issues as part of the MOOS project. Close coordination will be needed between the cabled observatory and moored-buoy observatory to ensure a common seafloor junction-box interface protocol. While important, these issues are not considered high-risk. The estimated costs to develop and test this system are $**XXX**.

***(2) One Time Engineering Costs***

Initial engineering work needs to be done to develop the complete system designs and documentation packages that will be used to build the deployed systems. Note that the original design study developed costs for systems after the initial development phase. This initial engineering work includes systems engineering, component design and test, initial buoy and mooring design, prototype testing and specialized buoy and mooring design for harsh environments. Some of this work has already been funded under the acoustically linked buoy observatory program (WHOI and UW) and under the MBARI MOOS program. One time engineering costs associated with each of the design approaches are shown and described below. A prototype test of the spar buoy design has yet to be initiated and is discussed below under the section on Spar Buoy NRE.

***(3) Contingency Costs***

The DEOS Design Study did not include contingency costs in the original budget estimates. Here the original cost estimates have been increased by 20% to cover the uncertainties associated with the fabrication of each observatory system. The level of uncertainty is higher in the initial units that are built and lower in the subsequent units and the value of 20% represents the average uncertainty over a build of 5 to 10 systems. There may well be opportunities for cost reduction, which will be addressed in the systems engineering effort.

Original estimates did not include site specific engineering for each node. This site specific engineering will include modifications to the mooring system, development of installation plans and management of the particular installation. A nominal 10% of the capital cost is considered reasonable for this effort.

***(4) Fabrication, Installation and Maintenance of Seafloor Cable Networks***

The original Design Study provided costs for the moored systems out to the initial junction box, but did not look at the costs associated with seafloor cable networks. Here a typical seafloor network is assumed to consist of two seafloor nodes in addition to the junction box connected by 10 km of cable. The capital cost of such an array is estimated to be about $220K based on MBARI's experience with the MOOS mooring system.

***(5) Surface and Subsurface Mooring Costs***
Fabrication, installation and maintenance of vertical moorings that are wired into the seafloor arrays or RF-linked to the observatory buoys were not budgeted in the previous Design Study. These moorings allow measurements to be made in the water column and may be a necessary part of the more heavily instrumented observatory sites. A surface mooring supporting near surface instruments located in the vicinity of the buoy observatory and connected to it by a short range RF link is estimated to cost about $270K based on WHOI's experience with surface moorings. A long subsurface mooring that is wired into a seafloor node will cost about $210K based on WHOI's experience and taking into account the added cost for EOM cable and underwater mateable connectors.

***(6) Spar Buoy Installation Costs***
A spar mooring is installed in two phases: first the buoy and mooring are installed without the buoy instrumentation packages. A method for doing this was outlined and costed in the original Design Study. Secondly, the instruments (including telemetry and power packs), in the form of a topsides module are installed using a UNOLS vessel. The exact method for doing this with regard to available deck equipment was not investigated. The costs included were assumed to be the same as those required for the installation of a 5m discus buoy. Installation of the spar topsides may require additional modifications to the spar itself, e.g. a ballast system for controlling spar freeboard, which were not included in the original estimates. A cost allowance is provided here for the ballasting system. An additional cost for the spar installation is a one time cost associated with modifications required to ships that are used to install and service the spar system. These modifications have not been examined in detail, but it is prudent to include a budgetary estimate of $1.5M to cover this cost category.

***(7) Replacement Costs***
A 20% annual system replacement cost was included for the single point moored buoys in the Design Study, but not for the spar system. Spar replacements costs are included in this analysis. Replacement costs for the seafloor network and networked moorings are also included in the present analysis. A higher replacement allowance is included for the high latitude cases to account for increased component failure due to more severe environmental forcing.

***(8) Sensor and Instrumentation Costs***
Costs are included for the acquisition, installation and maintenance of sensors and instruments that are considered to be part of the observatory infrastructure. These instruments include engineering sensors to monitor system status and performance, a basic array of meteorological sensors, a basic array of physical oceanographic sensors, an OBS, and a tomography receive array and source. *(Note: this topic needs to be addressed and budgeted by working group 4)*

***(9) Acoustically-linked Buoy NRE***

While the prototype development of the acoustically linked discus buoy and mooring has been funded, the extension of this design to harsh environments in the Southern Ocean or to areas with extreme currents has not been investigated. We estimate that the work needed to develop designs specific to these additional sites will require about $200K of funding for modeling and buoy and mooring design modifications, if we plan to use this design in environments more severe than those anticipated offshore of Western Canada.

***(10) Low-Bandwidth Cabled Buoy NRE***

The low bandwidth cabled observatory developed at MBARI is designed for moderate wind and sea states. It will take a substantial effort to re-design this system for significantly more severe environments and it is not presently envisioned as a suitable system for the most severe conditions (high latitudes or high currents). MBARI has estimated that about $800,000 will be required to revise the existing design for deployment in the most severe locations at mid-latitudes, excluding areas of extreme currents.

As mentioned above, it is necessary to conduct a development effort to design and test a reliable and cost effective EOM cable for the low bandwidth cabled observatory.

***(11) Spar Buoy NRE***

Systems engineering is required specifically for the high bandwidth spar system. The previous Design Study developed a conceptual design based on a number of assumptions. Additional engineering work is required to update the basic spar high bandwidth configuration before committing to a configuration, operational plan, and a final budget. This task will include a review of the basic design criteria based on the current scientific requirements. This effort would also fill in gaps in the previous study, for example methods for installing and maintaining the instruments using UNOLS vessels. It would also examine opportunities for cost reduction; e.g., methods for installing the spar that wouldn't require high cost service vessels.

This study will also address the issue of communication with the seafloor network of instruments, specifically subsea and surface instrumented buoy systems and their interconnections. For example, the spar may be designed for multiple instrumentation cables, which might connect it to remote seafloor experiments. This approach could reduce the need for seafloor connections and ROV operations.

This work would also include detailed planning for a prototype test, which would take about six months and would involve 3-6 people representing naval architecture, power, communications and marine operations disciplines. Considerable interaction with vendors would be expected.

Detailed development of the drawings and specifications for the actual prototype spar system is an extension of the systems engineering work. Included in this task are confirmatory model tests to verify the motions and mooring loads. Vendors would be surveyed and specifications prepared for procurement of the initial system. These specifications might be modified for site specific applications (e.g., the mooring would change depending on water depths and anticipated sea state).

A separate effort of equal magnitude would be required to define the system configuration and operation for the high latitude spar. The high latitude environment is sufficiently more severe than the low/medium latitude environment, both in operational and survival modes, that it may require an extensive re-configuration of the spar and the marine operations methods. It is expected that the systems engineering for the high latitude design could be deferred until the low/mid latitude system is more fully developed.

***(12) Prototype Development for the Spar Buoy System***

There is a large industrial experience base on spars, including the FLIP and numerous oil production spars in the Gulf of Mexico. **Figure 25** illustrates the existing oil production spars showing the relationship of scale to the DEOS spar.

We do not believe it is necessary to test the spar buoy or it's mooring as the technology for this is well advanced. Instead, the primary objectives of the prototype test will be:

- An end-to-end test of the power, data and communications capability over an extended period in an ocean environment.

- The workability of the proposed methods for installation, operation and maintenance of the equipment on the spar, e.g. setting the topsides with a UNOLS vessels or vessels of opportunity.

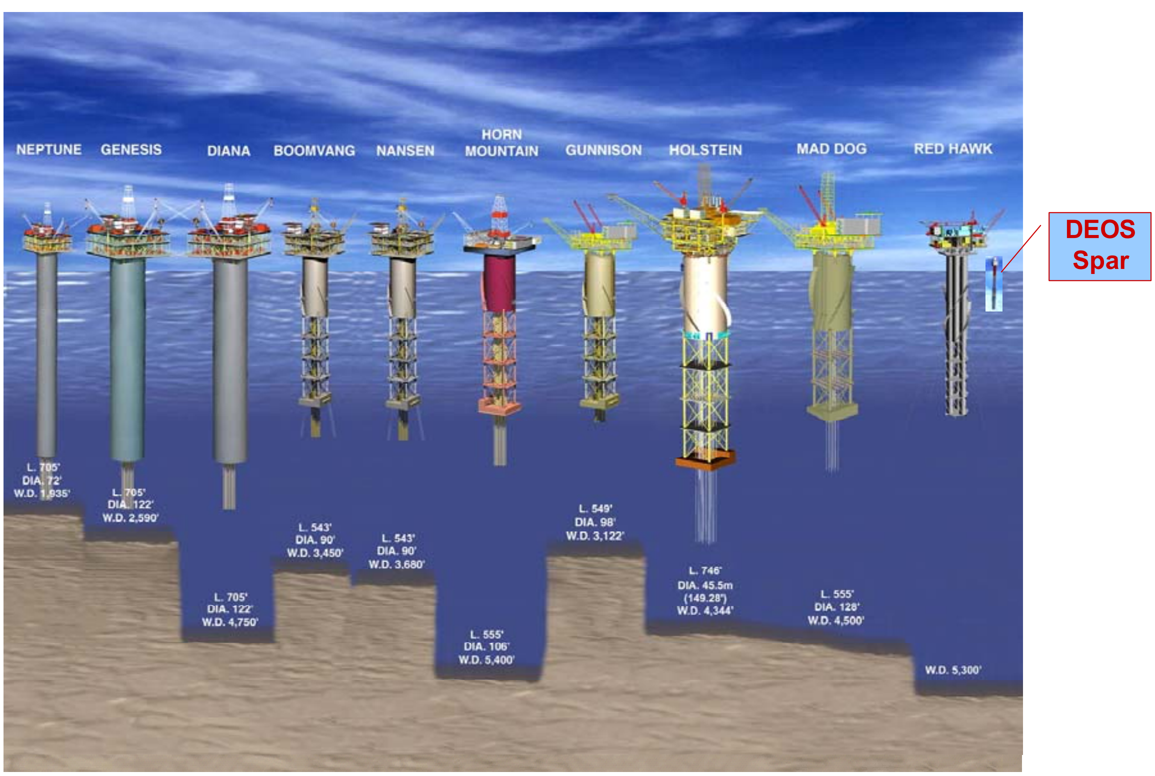


***Figure 25: Oil Drilling and Production Spars (Technip-Coflexip) and DEOS Spar***

The spar mooring would be selected for a convenient site close to a service base where the equipment can be serviced if it fails during the test. Possible sites include the Pacific near Southern California, the Gulf of Mexico, or Bermuda. We have estimated that the spar prototype program will cost of order $2M with some of the equipment fabricated available to be used in an operational mode following the prototype tests.

## V. REAL-TIME DATA GRIDS FOR THE OCEAN OBSERVATORY INITIATIVE

### *(A) Information Management Goals of the OOI*

The Ocean Observatories Initiative (OOI) aims to produce continuous, long-term measurements of a wide range of physical, chemical, geological, and biological variables for research and education. An integrated data management system is envisioned, one that will allow users to seamlessly exploit multiple data sets from a variety of sensors,

- enabling researchers to undertake complex, multidisciplinary studies and to more effectively collaborate across disciplines;
- promoting Earth and ocean science education, and an understanding of the scientific process;
- improving and expanding the effectiveness and utility of shared-use platforms and sensors; and
- providing a important testbed for cutting-edge information technologies.

Considering that a vast majority of environmental data collected today is not being captured in a way that makes it available to multiple users, it will be a challenge to create a real-time (or near real-time) data management system for OOI that will meet the information requirements spelled out in several community-driven documents including, among others, *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science.* These requirements characterize a system that

- captures, processes, controls for quality, and integrate real-time data streaming from different sources--collected for different purposes, on different time and spatial scales, and measured by different methods;
- makes heterogeneities in platforms, physical location and naming of resources, data formats and data models, supported programming interfaces, and query languages transparent to the user;
- adapts to new and changing user requirements for data and data products;
- dynamically reconfigures with the addition or removal of observational equipment and/or scientific instrumentation;
- provides Internet access to integrated data collections along with visualization, data mining, analysis, and modeling capabilities; and
- builds on or extends current data collection initiatives (e.g., digital libraries), promoting broad-based user access and long-term data stewardship.

Taken together, these features describe or define a system with a high level of functionality. As OOI plans move forward, it will be important to get a clear read on

- the state of the art in information technology,
- the benefits and trade offs implied in selecting system features, and
- the resources required to develop, deploy, and maintain the OOI information system.

The next two sections characterize two distinct levels of potential functionality for the GLOBAL NETWORK's data management system. These two levels represent extremes on a hypothetical continuum. These levels are not mutually exclusive, and they could be deployed sequentially in a phased development plan. Although the information is specific to the GLOBAL NETWORK, it contains insights relevant to the more inclusive Ocean Observatories Initiative.

***(B) Meeting Minimum System Requirements with Today's Technologies***

The core of the GLOBAL NETWORK's data telemetry and distribution system will consist of middleware that enables users to access real-time data. The middleware, which will be used on the data management computers located on the buoy and on shore, should have the following attributes:

- A server-client approach for managing the ring buffer;
- Real-time data processing;
- Multiple simultaneous read and/or write clients;
- Clients can be anywhere that is network reachable;
- Data packets may be of any size, format, information content;
- Highly robust and error-free;
- Adaptive to data bandwidth availability;
- Receive and process data from all types of instruments;
- Exchange data with other data servers;
- Reliably transfer near real-time data over satellite TCP/IP connections;
- Prioritize datasets to be telemetered;
- Optimize the use of available telemetry bandwidth;
- Locally archive data;
- Recover data from local archives after telemetry outages;
- Provide network security shielding instruments from unauthorized manipulation, unauthorized addition of sensors, and providing access control, where needed, to data;
- Allow near real-time wireless data telemetry between buoy and ship concurrently with near real-time satellite telemetry to shore; and
- Update metadata in real-time for automatic processing and for data archives.

The data management system that provides these functions creates a data network that is reliable, flexible, and enables users to access real-time data streams. The data network would address system and data interoperability issues, but it would not address semantic interoperability and information integration issues: i.e., techniques that move beyond simple distributed access to data files. In addition, this system does not include features for persistent archives or for user tools and interfaces. Commercial software packages can provide most of these capabilities for the GLOBAL NETWORK, and they should be leveraged to minimize development time and costs. A fundamental design principle is that instruments and sensors being sampled adhere to TCP/IP standards. This is, today, generally not the case in oceanography, but it is essential for a suite of sensors that will likely grow geometrically in number with the advent of the OOI.

**(C) *Envisioning Real-Time Data Grids***

In practice, scientific data collections

- are designed to meet the specific needs of an experiment or agency,

- are created by unique experimental platforms and methods,
- make measurements at different time and spatial scales, and
- employ different data (and metadata) formats and management systems.

Until recently, these inherent characteristics have had a negative impact on the broader utility, and subsequent longevity, of many scientific data collections. Thankfully, rapid developments in information management technologies are, for the first time, enabling us to move beyond these inherent constraints and to discard old communications, networking, and data management paradigms. The need for an interoperable infrastructure that enables new science based on distributed computing, data sharing, and information integration, is driving many national-scale projects in several disciplines [Withey et al., 2002]. Furthermore, the exponential growth in storage density and network speed, with doubling times of significantly less than a year, has eliminated the need for centralized data archives.

Several key factors are driving new technologies for managing scientific data collections:

- The development of an appropriate information model (XML) for describing scientific data.
- The ability to organize collections dynamically using XML Document Type Definitions (DTDs).
- The use of XSL style sheets to create interfaces to collections that can be tailored to the requirements of separate user communities (or domains).
- The development of interoperability systems that support the federation of data collections across heterogeneous software and hardware systems [Rajasekar and Moore, 1999; Moore, 2001].

With these new technologies, access and management of scientific data collections becomes a matter of manipulating an associated information model. This is an active area of research. Our data management toolkit is being expanded by community-led efforts to develop digital library services, parallel compute platforms, distributed computing environments, and persistent archives. There is a strong synergy between these efforts; each requires an ability to manage knowledge, information, and data objects. This synergy has had a significant but unforeseen consequence: *although the requirements driving infrastructure development within specific communities are different, development efforts have converged on a uniform architecture* [Rajasekar and Moore, 1999; Moore, 2001]. This architecture provides a suite of functionalities seamlessly assembled to form a “Grid.”

Data Grids, today’s cutting-edge technologies for information management and data manipulation, are distributed networks that tie together data management, computational, and visualizations resources. The end-to-end system typically provides support for

- Information Discovery – ability to query across multiple information repositories to identify data of interest,
- Data Handling – ability to read data from a remote site for use within an application,

- Remote Processing – ability to filter or subset data before transmission over the network,
- Data ingestion or publication – ability to add data to collections for use by other researchers, and
- Analysis – ability to use data in scientific simulations, for data mining, or for creation of new data collections. [Moore, 1999; Rajasekar and Moore, 2001]

These services are implemented as middleware that hide the complexity of the diverse, distributed, heterogeneous resources that comprise Data Grids.

*It is important to note that existing and evolving Grid projects deal with static data files and that considerable technical innovation will be required to tackle the unique challenges associated with the management and manipulation of continuous streams of data from myriad sensors in real time.* These new technologies have the power to transform GLOBAL NETWORK data collections into a multidisciplinary, real-time data grid for research and education.

Technology research and development should focus on:

- Network design flexibility that accommodates new data sources, ever-increasing data rates and volumes, changes in Internet performance, and variations in user demands and display devices.
- Real-time data delivery and quality control to facilitate personalized, seamless, and transparent access to sensor data streaming from the field and in archival data collections.
- System design that maximizes network reliability and configurability, enabling system components to be reconfigured as determined by shifting priorities for data capture based on real-time environmental events and triggers (i.e., earthquakes or oil spills).
- Integration and dissemination of information for time-critical analysis facilitated by XML-mediated query processing.
- Continuous archives of raw, processed, and analyzed data.
- Access control systems that rank user priority at the network (bandwidth consumption) level and authorize data delivery at the Internet interface.
- Development of visualization technologies.

**Figure 26: Data Access Architecture for Open Grid Architecture**
Found as a link on webpage (http://www.npaci.edu/DICE/Pubs/#TechnicalReports) under

**Persistent Archives for Data Collections**
Reagan W. Moore
*SDSC, UC San Diego*
**SDSC TR-1999-2. October 1999.**

The proposed architecture is based on a Grid-type infrastructure design adapted for real-time data collection and integration. The core of the design consists of

- A data handling system that will enable access to data repositories and fast data caches across a distributed network connecting heterogeneous storage systems.

The data caches will be used for data staging of real-time data which will be moved after preliminary processing to near-line storage. Handling real-time data accumulation and management across distributed caches and archival storage systems is a key IT research goal.

- An information discovery system that will integrate multiple metadata repositories and enable users to discover data based on data characteristics instead of location. The information discovery system of the knowledge network will manage multiple levels of metadata, from IT-centric metadata to discipline-standardized metadata to sensor/application-level metadata. Metadata integration at multiple levels and across disciplines, from ocean sciences metadata to geodetic metadata to seismic metadata, will be a primary research goal.
- An integrated execution system which will provide operations on data and data streams at multiple locations in the data management corridor, including near-sensor operations such as data validation to data storage sites; operations such as subsetting, metadata extraction and reformatting; and near-application operations such as data layouts and presentation. Extraction of metadata from real-time data flow, as well as metadata fusion across multiple sensor data, is an essential research goal.

To achieve these goals requires an architecture that is flexible, scalable, and distributed, which deals with diverse formats of real-time and stored data and seamlessly integrated method executions, and provides dynamic metadata discovery. The key feature is the development and integration of these components to generate a higher-order, multidisciplinary, combined functionality that can be used for large-scale data processing and sharing.

***(D) Getting Started***

The specific functions and goals of the GLOBAL NETWORK's data management system will, with community input, evolve over time. In order to specify and prioritize data system requirements, further development and discussion of the following issues will be required.

- What does it mean to have an "open data policy" given bandwidth limitations and design-induced telemetry constraints? Will technological constrains dictate that users be ranked according to their "bandwidth priority", giving some greater access to real-time data than others? Will observations and measurements accumulated via core instrumentation, community experiments, and individual investigator-initiated studies have different data policies?
- What standards, if any, can be applied to the GLOBAL NETWORK systems to enhance overall system interoperability and scalability, maximize data availability, minimize duplication of effort, and reduce costs?
- How can NSF and other funding agencies give PIs incentives to produce data products that are suitable for public distribution, create educational curricula that utilize the system, and develop novel information technologies that can be appended to the basic data management framework?
- How can a mechanism to ensure the persistence of time series observations be established and funded over the long-term? What minimum subset of

technologies will make it possible to migrate a collection forward in time indefinitely? How can a distributed archive system leverage multiple existing archives in various subdisciplines? Is it useful and necessary to archive not just the raw or processed data, but also the results of analyses and modeling?

- How can the expertise from digital library initiatives (e.g., DLESE, NSDL) be tapped effectively? These initiatives have already developed information models and data manipulation technologies that broaden the potential user base and engage the educational community.
- How can collected data, associated computations and assimilations, and research end products such as refereed publications be coupled efficiently to develop a useful knowledge base integrating Earth and ocean science?

## VI. MANAGEMENT OF THE OCEAN OBSERVATORY INITIATIVE

The overarching management of the Ocean Observatory Initiative has been defined by the DEOS Steering Committee and will be described below. The President's Budget for FY04 included language describing this management, which is consistent with the recommendations of the DEOS Steering Committee. To wit:

> *The management structure proposed for the acquisition and implementation phase of the OOI is based on a structure that has been successfully used by the Ocean Drilling Program. In this structure, management, coordination, and oversight of the OOI will be the responsibility of the Executive Director of the OOI Program Office, to be established through a cooperative agreement with NSF. This Director will be accountable to an Executive Committee under which will be established Scientific and Technical Advisory Committees. The Executive and Advisory Committees will draw their membership from individuals with expertise in ocean observing science and engineering. Experiments utilizing OOI infrastructure will be selected on a peer-reviewed basis. This project will be coordinated with the National Integrated Ocean Observing System (IOOS) that will support operational mission objectives of agencies such as the National Oceanic and Atmospheric Administration (NOAA), Navy, the National Aeronautics and Space Administration (NASA), and the Coast Guard.*

The overall organization was designed to meet several management goals and the management of the global portion of the OOI must be consistent with these goals as well as the language above, which foresees a competitive selection of the operator(s) of the various components.

### (A) Goals of the Domestic Organization

The organization of the Ocean Observatory Initiative should accommodate the following goals:

- design and implement an Ocean Observatory Initiative with creativity and vision;
- ensure the highest quality, long-term science in keeping with the founding vision;
- ensure use of the highest quality technology, consistent with efficient and effective observations;
- ensure an adequate budget for a robust initiative;
- ensure an efficient organizational structure in which separate functions are performed by separate entities, as appropriate;
- ensure efficiencies through utilizing existing capabilities;
- place power and authority at the lowest possible level consistent with getting the job done, and;
- ensure a program with strong education and outreach capabilities.

### (B) Organizational Overview

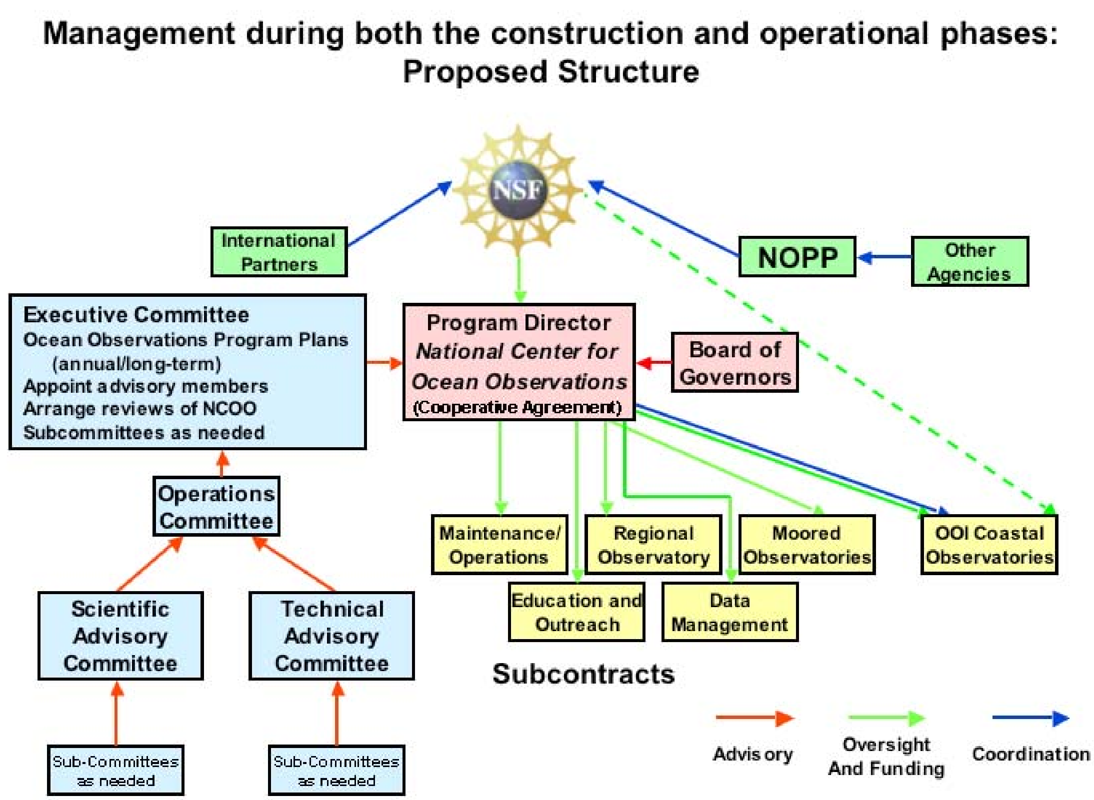
The DEOS Steering Committee recommended the creation of the National Center for Ocean Observations (NCOO), which will be the principal implementing entity for carrying out the Ocean Observatory Initiative (**Figure 27**). The NSF will support the budget through a Cooperative Agreement and will be engaged in budgetary oversight, and administering the competitive process for the selection of the NCOO entity in FY04.

The NSF will work with the National Ocean Partnership Program (NOPP) to coordinate efforts in long-term ocean observations including operations and maintenance, the acquisition and maintenance of ships and shipboard facilities; for example, ocean-depth-capable ROV's, and the application of methods and technologies developed through research to operational ocean observation programs.

The principal corporate governance of the not-for-profit NCOO will be a Board of Governors consisting of senior management (e.g., Deans, Directors, Chancellors, CEOs, etc.) within the business, academic, and research communities from participating companies and institutions.

NCOO will develop the overall observation initiative, basing its activities on the content of an Ocean Observations Plan developed by an advisory structure consisting of an Ocean Observations Committee and an Advisory Panel Structure. It will solicit, review, and approve specific proposals, and contract with facility providers to provide necessary services. Normally, it will act as the central governing body for a federation and will generally not directly carry out accessory observation functions (e.g., maintenance of a seagoing technical staff, operating a data management center). It will make decisions concerning the development and use of new technologies in support of the initiative and will make every effort to utilize the resources and expertise of government, the academic community, and the private sector.

**Figure 27:**



The staff of the NCOO will consist of a Director, an Education Coordinator, a Public Affairs Officer, a Development Officer (to seek additional sources of funding), a Government Affairs Officer, a Chief Financial Officer (or equivalent) to oversee contracting and support annual audits, and such other staff as necessary. The Director will be competitively selected, should be a person of the highest scientific excellence in vision, and have a demonstrated ability to manage an organization of this scope. The NSF will approve the selection of the director.

It is expected that the principal portion of NCOO's budget will be in support of the Observatory Plan, and supporting contractors will include institutional, commercial, and governmental entities. It seems likely the maximum creativity and excellence will arise from a program that is primarily decentralized, the organizational center of which is NCOO.

**(C) Advisory Structure**

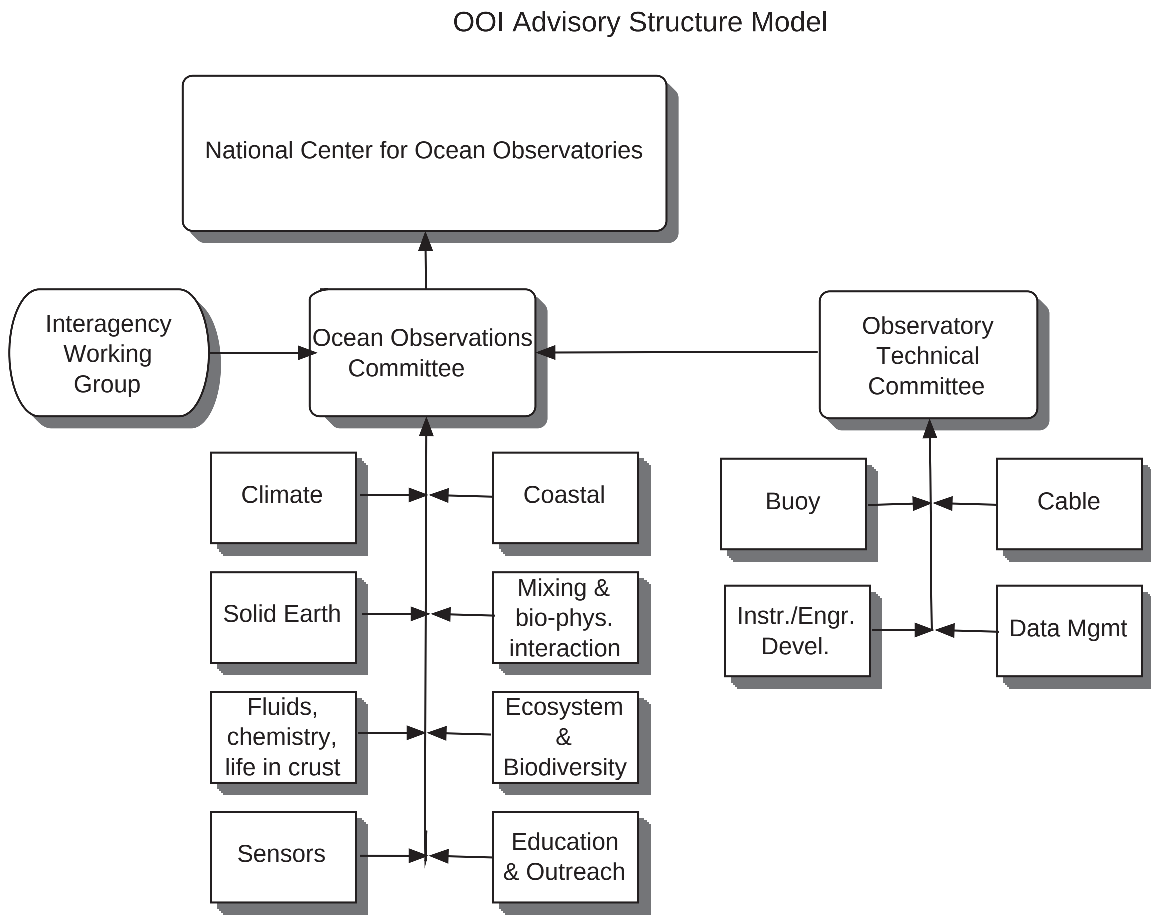
The advisory structure consisting of an Ocean Observations Committee and an Advisory Panel Structure will advise NCOO in assessing priorities and specific proposals. The Board of Governors will appoint the members of the advisory structure. **Figure 28** illustrates a model for the advisory structure consistent with the NRC report, *Illuminating the Hidden Planet*.

***(1) Ocean Observatory Committee***

The Ocean Observatory Committee will provide advice, assembled through an appropriate advisory structure, in the form of program plans designed to implement the ocean observatory initiative. The first task of the Committee, to be formed in 2004, will be to produce a long-range (5- to 10-year) plan for ocean observatories. Each year, a more detailed implementation plan will prioritize programs to be conducted in the following year as well as technological development and new infrastructure. The annual plan must be consistent with the resources projected for the coming year and cannot be a simple shopping list of projects and equipment. The development of both the long-range and annual plans will require continuous coordination between the Committee and the NCOO. A member of the academic or business community should chair the Committee and an allowance for an office at the Chair's institution or company should be made; the tasks associated with community and NCOO coordination are substantial. The office must rotate on a fixed cycle, and the long-range plan should be updated and revised on a similar schedule.

The Committee and its subcommittees and panels will consist of a broad, diverse and interdisciplinary membership drawn from the relevant disciplines and selected on the basis of excellence and creativity within their respective fields. Members can be selected from academia, business, government, and the international community.

**Figure 28:**




**(D) Assessment and Review**
The NCOO will be established for an initial ten-year period. The NCOO will be reviewed every three years to evaluate its performance and will be audited annually. The NCOO Board of Governors will be responsible for appointing the auditing firms and the evaluation committees. In the case of the evaluation committees, the membership must not include anyone currently involved in the advisory structure or the NCOO itself. Members of the Board are not eligible to serve in this regard. NSF will review the NCOO no sooner than the first three-year evaluation period and no later than the end of the tenth year to evaluate its achievements and future prospects in order to facilitate an informed decision regarding a new solicitation and the continuation of the initiative.

**(E) Rationale**
In the proposed structure, separate functions are performed by separate entities. For example, execution of the exploration plan is the task of NCOO. The Board of Governors, tasked with annual audits, the selection of the Director of NCOO, and the appointment of the committees to conduct the three-year reviews, carries out monitoring. NSF will fund the NCOO as an independent entity through a cooperative agreement. NSF will receive and review the audits and evaluations conducted by the Board of

Governors. The observatory plan (the Plan) will be provided by OOC, and NCOO will be responsible for carrying out that plan.

Although the oceanographic community's experience centers around the use of not-for-profit corporations for this task, an institution or company could also operate the NCOO. The Center will not be housed at an individual institution or company; these arrangements rarely achieve broad community support. The most appropriate organization is more of a virtual center with a network rather than a site; interdependence flourishes when members recognize that they are also part of a larger whole. Such an organization gains strength from spreading responsibility across many decision points, and centers exist to coordinate and not to control. The leader, the President of NCOO, is actually the leader and coordinator. The organization requires compromise between centralization and federation.

A bit of centralization and a bit of autonomy is needed—the compromise is a federation, much like the U.S. government, NATO's Partnership for Peace, the Federated Harvard University Library, NASA's Earth Science Information Partners, and the Association of Research Libraries Federation. In a complex world of important interrelationships and constant change, a network of this kind is inevitable.

**(F) Global Ocean Observatory Office**

The Ocean Observatory Initiative global program will be coordinated through a Global Ocean Observatory Office. The goal of the Office is to coordinate efforts of contractors involved in providing infrastructure for global observations. It will establish working groups between member institutions to:

- Ensure data compatibility and quality control
- Coordinate hardware and software compatibility between systems
- Manage outreach and education
- Schedule buoy installations and support
- Prepare proposals and reports in support of the global observatory

An Executive Director will manage the Office at one of the member institutions and will serve as a center for a federation of activities at the various contractors. When the NCOO issues an RFP requesting infrastructure, installations, or services related to the global portion of the OOI, the Global Ocean Observatory Office will coordinate the submission of proposals in response. However, budgets will be negotiated between member institutions and the NCOO if the Office is successful in the competition.

## VII. TIMETABLE FOR DEVELOPING THE GLOBAL NETWORK

**From Frank Vernon re Data Management:**

| | |
|---|---|
| Year s 1-2 | Acquire underway data (e.g. ADCP, Seabeam, gravity, magnetics, meteorological data) from RV Revelle, Melville, Thompson into ROADNet. $150k for hardware and systems integration<br>Test ROADNet system on acoustic buoy system. $100k for hardware and systems integration |
| Year s 3-4 | Initiate Data Collection Center which is responsible for maintaining buoy-shore communications and maintaining the data communications and data distribution systems. Data delivered to appropriate national data centers and/or DLESE. 2 FTEs plus $300k for hardware and software.<br>Information Technology Program Officer (1 FTE at national office) |
| Year s 5-6 | Continue DCC operations maintaining buoy-shore communications and maintaining the data communications and data distribution systems. 2FTEs plus $100k/year. Data delivered to appropriate national data centers and/or DLESE.<br>Information Technology Program Officer (1 FTE at national office) |

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**From Peter Worcester re prototyping and engineering:**
**TIMETABLE FOR NETWORK DEVELOPMENT**

Because of the cost, complexity, and technical challenges associated with building a twenty-node network of moored-buoys, the Global Network will employ a phased implementation strategy that allows adequate time for prototyping and testing prior to observatory deployment. The Global Network is a five-phase program, described below. Phase One, now complete, included community-developed design and feasibility studies, science reports, and white papers. During Phase Two, which is beginning, the conceptual system designs will be refined, and high-risk subsystems will be prototyped and tested, both on shore and at sea. Phase Three commences with the beginning of funding for the OOI. It will begin with a program review to assess the status of the three approaches to moored-buoy design and will include letting contracts for the detailed system design, fabrication of the first complete prototype units, and at sea testing of those prototypes. This phase also encompasses the development and testing of data management technologies and the creation of the Science and the Education and Outreach Plans. During Phase Four fabrication and installation of additional units to complete the Moored-Buoy Observatory will occur and routine operation of the moored-buoy system will begin. Phase Five is the Operations Phase. The timing of the various phases differs somewhat for the different moored-buoy designs, reflecting the differing degrees of maturity of the various approaches.

**Phase One: Feasibility and Planning**
This phase, now complete, included efforts to produce the design and feasibility studies, science reports, and white papers. Capstones of this phase include the Moored-Buoy Observatory Design Study and this document, the Feasibility Study and Implementation

Plan for the DEOS Global Network of Moored-Buoy Observatories. While some system development and prototyping was accomplished during this phase, the majority will be undertaken during Phase Two.

**Phase Two: [NOTE: much of this text is included in IV. Sections (C), (D) and (E)]**
***Engineering: Conceptual Design and Prototyping***
Although moored ocean buoys are a technically feasible approach for making sustained time series observations in the oceans, there are some questions regarding the design and development of moored-buoy observatories that need to be addressed prior to preparing detailed engineering construction plans and drawings. During Phase Two, which is beginning, the conceptual system designs will be refined, and high-risk subsystems will be prototyped and tested, both on shore and at sea. Some of this effort is already underway, including:

A WHOI project to build and deploy a low-bandwidth, acoustically-linked discus buoy system.

A MBARI project to build and deploy a low-bandwidth, cable-linked discus buoy system (MOOS).

The SIO sponsored ROADNET and High-Seas ROADNET Projects. The primary focus of the High-Seas ROADNET project is to facilitate cost-effective, real-time shore-side delivery (via satellite) of large quantities of data for quality control, archiving, research, and visualization. The ROADNET project is developing technologies that enable real-time processing and integration of data, that build a capacity to query streaming data, and that incorporate the use of large-scale persistent data archives.

These efforts are described in more detail in Section XXX.

Further efforts are needed, however, which will require additional funding. The specific issues and tasks during this period include:

*Low-bandwidth, acoustically-linked system*
This approach is the most mature of the three moored-buoy approaches. It has been used successfully in the NOAA Deep-ocean Assessment and Reporting of Tsunamis (DART) program (http://www.pmel.noaa.gov/tsunami/Dart/). We do not believe that there are any fundamental, high-risk technologies associated with this approach, although there are questions associated with the acoustic-link performance that is achievable under realistic environmental conditions. The primary issue that needs to be resolved during this phase is the average data rate that is achievable, 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. The maximum horizontal range over which useful data rates can be achieved needs to be determined for both seafloor and moored instruments. We are optimistic that these issues will be resolved adequately by the on-going WHOI research effort to allow detailed engineering designs to be prepared for the DEOS buoy system at the start of the next phase.

*Low-bandwidth, cable-linked system*
The highest-risk subsystem in this moored-buoy approach is the electro-optical mechanical (EOM) cable used to moor the discuss buoy, provide communications with the seafloor, and provide small amounts of power (20 watts) to the seafloor. We have little experience with EOM cables in single-point surface moorings using discus buoys. We do not currently know the expected operational lifetime of EOM cables in this application, nor do we know how factors such as sea state and currents affect this reliability.

The tasks that need to be done are (i) EOM cable design and selection, (ii) EOM termination design (including bending relief), (iii) design of the junction between the discus buoy and EOM cable, and (iv) testing and verification of the designs. The cable needs to be designed to keep the strain within acceptable limits for the fiber optic and copper conductors. The selection process will consider choice of strength member, provision for fish bite protection, and the effects of cyclic loading and bending due to the motions of the wave-following discus buoy. Testing and verification of the cable design needs to include both testing on shore and actual deployments at sea:

- Shore testing: cyclical loading in axial tension of the cable and termination, cyclic bending, resistance to hockling, simulation of deployment loads and handling
- At-sea testing: multiple deployments and recoveries, one or more longer term deployments under winter storm conditions

The MBARI MOOS program is working on these issues, but additional funding may well be needed during this phase.

*High-bandwidth, cable-linked spar system*
The highest-risk subsystem in this approach is again the EOM cable used to provide communications with and power to the seafloor, as was the case for the low-bandwidth, cable-linked system. The EOM cable requirements differ substantially in the two cases, however, because the EOM cable is not load-bearing in the spar buoy system. Nonetheless, we have little or no experience with EOM cables used in this way, do not currently know the expected operational lifetime of EOM cables in this application, and do not know how factors such as sea state and currents affect this reliability. Modeling will be needed to predict the type of loading the cable can be expected to experience. The tasks that need to be done are similar to those to be done for the low-bandwidth cable linked system: (i) EOM cable design and selection, (ii) EOM termination design (including bending relief), (iii) design of the junction between the spar buoy and EOM cable, and (iv) testing and verification of the designs. In this case testing and verification of the cable design will only include shore testing, because no spar buoy will be constructed in this phase. Design and testing for resistance to hockling will be particularly important, because the cable will likely experience relatively low tensions.

In addition to the EOM cable, other subsystems that should be further developed and tested during this phase include (i) the high-bandwidth C-band satellite telemetry system and (ii) the diesel power system. Although we do not see these subsystems as being as high-risk as the EOM cable design, neither is sufficiently mature to be confident of reliable, unattended operation for 12-month periods. Testing of the C-band satellite communications system will be continued and expanded as part of the ROADNET project. This effort should include identification of any design changes required to improve the long-term reliability of the buoy antenna system and testing of a modified antenna system on board ship.

During this period a detailed conceptual design of the spar mooring needs to be completed. This design will be needed in part so that modeling of the expected cable loading will be sufficiently realistic to be meaningful. The design also needs to consider the issues associated with the use of a spar buoy as a measurement platform. The relatively large C-band radome could interfere with meteorological measurements, for example, unless a robust mast is designed that both places the instruments above the radome and does not interfere significantly with the telemetry link. Similarly, the approach to making the near-surface measurements important to air-sea flux studies needs to be thought through. Should one plan on installing a separate mooring to support the air-sea flux measurements that would radio data to the spar for subsequent relay to shore, for example, or should the instruments be suspended from a boom attached to the spar? Finally, the design should be aimed at minimizing and fully detailing costs and at maximizing long-term reliability.

Funding will be needed to support these efforts.

*Seafloor junction box*
Common to both the low-bandwidth and high-bandwidth cable-linked systems (but not to the low-bandwidth, acoustically-linked system) is the need for a seafloor junction box between the various instrument systems and the EOM cable to the surface. The moored-buoy junction box will be designed to appear to the user to be identical to the plate-scale cabled observatory junction box, except for the amount of power that will be available in the differing approaches. There are nonetheless issues that need to be resolved to design a convenient user interface, including those involving device discovery, automatic port configuration, and metadata handling and delivery. MBARI will be working on these issues as part of the MOOS project. Close coordination will be needed between the cabled observatory and moored-buoy observatory to ensure a common seafloor junction-box interface protocol. While important, we do not view these issues as high-risk.

The goal is to have in hand by the end of Phase Two sufficiently detailed conceptual designs to write the specifications required to do the detailed engineering designs required to begin fabrication of complete prototype systems.

**Phase Three:**

***Engineering: Detailed Design, Fabrication, and Testing of Prototype Moored-Buoy Systems***

Phase Three commences with the beginning of funding for the OOI. In view of the engineering issues and the substantial resource commitment necessary to build and operate a global network of moored-buoy observatories, prototypes of each of the moored buoy designs should be developed and tested before being replicated. This phase will begin with a program review to assess the status of the three approaches to moored-buoy design. It will include letting contracts for production of detailed engineering and construction plans and drawings, fabrication of the first complete prototype units, and at sea testing of those prototypes for one-year periods. The initial test sites will be selected for both logistic convenience and scientific interest to the ocean sciences community.

Standardization of subsystems between the various approaches will be a goal of the design work, where feasible.

During this period it will be important to continue to evaluate new developments in satellite telemetry methods, sensors, power systems, and other subsystems with an eye to simplifying these designs to minimize costs and maximize long-term reliability.

**Phase Four:**
***Engineering: Fabrication, Installation, and Operation of Additional Moored Buoy Systems***

The detailed designs will be modified to incorporate what is learned during the testing of the prototype units at the beginning of Phase Four. A phased program of fabrication and installation of additional units will occur. Routine operations of the moored-buoy system will begin.

**Phase Five: Operations**
By the end of the five-year OOI the complete moored-buoy system will be in place and routine operations will be underway. Phase Five, the Operations Phase, will focus on sensor and network maintenance and operation, data management, and education and outreach efforts.

**Detailed Engineering Timeline**
Figure X provides a rough timeline for the engineering development of the moored-buoy observatory, from testing of high-risk subsystems through conceptual design and development and continuing through actual installation and operation. (This is in Worcester PDF file posted on SIO Network)

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More will come from costs group etc.

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## APPENDIX A: DETAILED COST INFORMATION

This will include 4 tables of costs currently located under tabs: OTHER, ANNUAL, INSTALL, and CAPCOSTS in the excel document NEW DEOS COSTS which can be found, for the moment, at

http://dropbox.ucsd.edu/~cskeen/Moorings%20Working%20Group/

## APPENDIX B: DESIGN CONSIDERATIONS FOR EOM CABLES

The oceanographic community has extensive experience in using traditional single-point surface moorings that are attached to the sea bottom with elastically compliant nylon rope. However, the use of electro-optical-mechanical cables in deep-ocean surface moorings is relatively new. The challenge associated with the use of such a cable comes from the need to combine the copper conductors, optical fibers, and a synthetic or steel jacket strength member into one package. If this is not done properly, the conductors and optical fibers could fail even if the cable itself does not break. This is because the copper conductors and optical fibers cannot experience strain of more than 0.5% before they break (in the case of copper) or fatigue (in the case of optical fibers).

This has not posed a serious problem with steel armor EOM cables, which can be designed to be very stiff in order to limit overall cable stretch. Synthetic EOM cables (with typical strength members made from Vectran® or polyester) are attractive for the discus buoy mooring because of their high axial strength-to-weight ratio, but they can stretch more than 0.5% under typical operating conditions Because of this, conductors and fibers of synthetic cables must be spiraled around a center core material, which reduces strain when the cable is subjected to axial tension or bending. The core material could be a non-load bearing filler material as in traditional steel armored EOM cable designs where the strength member is wrapped around the outside of the cable, or the core material could be the strength member itself, where now the conductors and fibers are wrapped around the outside of the cable (i.e. the reverse of the traditional design). Even if the optical fibers are not overstretched, they can experience signal loss due to excessive bending (i.e. bending radius should not be less than 25 mm) or, in the case of traditional synthetic cable designs, due to local contact pressures caused by the outer strength member squeezing the inner optical fiber bundle. Using a stainless steel tube to encapsulate the fibers can eliminate the latter effect at the expense of increased complexity in terminating the cable ends.

These cable design issues become more or less important depending on what type of mooring system is being considered, and they can impact the design of the mooring itself. For example, the discus single-point mooring will use the EOM cable as the strength member as well as a power and communications cable. Also, the limited reserve buoyancy of the surface buoy requires the use of synthetic cable over much of the mooring. Here, special care is needed in designing the mooring to prevent overstretching of the EOM cable. This includes using attached floatation to create an “S-tether” shape and placing an elastically compliant “snubber” hose beneath the buoy. Proper design of cable terminations, which are used to breakout the conductors and the optical fibers at the anchor and the buoy, is an issue for the discus mooring where the EOM cable is under tension. With the moored spar buoy, the EOM cable may be attached independent of the mooring legs and be unloaded. Because of the spar buoy’s large reserved buoyancy, it may be possible to use steel armored EOM cable from the buoy all the way to the sea floor. This would lessen concerns of overstraining the conductors and optical fibers. However, limiting cable bending would still be a design issue.

Most failures of moored EOM cable have occurred because of bending fatigue. In armored cables, the failure is due to the stress caused by the friction between the two layers of wire moving relative to each other. In synthetic cables especially Kevlar®, failures are associated with the reduction in breaking strength due to abrasion and kinking of the jacket fibers. For both the discus mooring and the moored spar buoy, identification of areas of potential excess bending of the EOM cable and the proper design of the bending-relief will be key to the long-term survival of the EOM cables. While we have proven tools for predicting bending fatigue of steel armored cables, comparable techniques for synthetic cables do not presently exist. Also, failure of conductors and optical fibers cannot be predicted at this time.

As a prelude to deploying their MOOS mooring, MBARI conducted a study of the performance of "off-the-shelf" synthetic EOM cables from six different vendors. The study showed that none of the candidates was the "perfect" cable in terms of the material used for the strength member and how the conductors and optical fibers were incorporated. The ultimate choice of the EOM cable for the MOOS mooring ended up being a compromise. A lesson from this study is that the present synthetic EOM cable designs will most likely need to be modified for use in the discus mooring. Also much still needs to be learned about the long-term performance of moored EOM cables (steel armor and synthetic) in the deep ocean to determine a proper maintenance schedule.
A development and field-test program of a synthetic EOM cable (and its terminations) would be valuable before deploying one as part of a global ocean observation network. This would include defining specifications for a synthetic EOM cable, working with cable manufacturers to modify existing designs or create a new design, laboratory testing of samples to determine strength and fatigue characteristics, and a full-scale field deployment. Possible choices for steel armor cable exist (e.g. the UNOLS 0.68-inch fiber optic oceanographic cable) and could be tested as part of a large systems engineering test of the spar buoy tri-moor.

## APPENDIX C: ACRONYMS AND URLS

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| ARGO | http://www-argo.ucsd.edu/ |
| ATOC | Acoustic Thermometry of Ocean Climate<br>http://atoc.ucsd.edu |
| BATS | Bermuda Atlantic Time Series<br>http://www.bbsr.edu/cintoo/bats/ |
| BTM | Bermuda Testbed Mooring<br>http://www.ucsb.edu |
| CLIVAR | CLImate VARiability and Predictability<br>http://www.clivar.org/ |
| CoOP | Coastal Ocean Processes<br>http://www.skio.peachnet.edu/coop/ |
| COOP | CLIVAR Ocean Observations Panel<br>http://www.clivar.org/organization/oop/index.htm |
| CORE | Consortium for Oceanographic Research and Education<br>http://www.coreocean.org/ |
| DLESE | Digital Library for Earth System Education<br>http://www.uop.ucar.edu/uop/dlese.html |
| DEOS | Dynamics of Earth and Ocean Systems<br>http://www.coreocean.org/Dev2Go.web?id=208645&rnd=2736 |
| Earthscope | http://www.earthscope.org/ |
| GCOS | Global Climate Observing System<br>http://www.wmo.ch/web/gcos/gcoshome.html |
| GEO | Global Eulerian Observatory<br>http://uop.whoi.edu/geo/ |
| GEOSCOPE | http://geoscope.ipgp.jussieu.fr/ |
| GEOSTAR | Geophysical and Oceanographic Station for Abyssal Research<br>http://giove.ingrm.it/GEOSTAR/ |
| GLOBE | Global Learning and Observations to Benefit the Environment<br>http://www.globe.gov/globe_flash.html |

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| GLOBEC | GLObal Ocean ECosystem dynamics<br>http://www.pml.ac.uk/globec/main.htm |
| GoMOOS | Gulf of Maine Ocean Observing System<br>http://www.gomoos.org/ |
| GOOS | Global Ocean Observing System<br>http://ioc.unesco.org/goos/ |
| GSN | Global Seismographic Network<br>http://www.iris.washington.edu:8080/GSN/ |
| H2O | Hawaii-2 Observatory<br>http://www.whoi.edu/science/AOPE/DSO/H2O/ |
| HOT | Hawaii Ocean Time-series program<br>http://www.soest.hawaii.edu/HOT_WOCE/ |
| HUGO | Hawaii Undersea Geo-Observatory<br>http://www.soest.hawaii.edu/HUGO/hugo.html |
| iAnZone | International Antarctic Zone Program<br>http://www.ldeo.columbia.edu/physocean/ianzone/ |
| InterRidge | http://triton.ori.u-tokyo.ac.jp/~intridge/ |
| ION | International Ocean Network<br>http://www.seismo.berkeley.edu/seismo/ion/ |
| IOOS | Integrated Ocean Observing System<br>http://www.ocean.us/documents/mel.jsp |
| IPCC | Intergovernmental Panel on Climate Change<br>http://www.ipcc.ch/ |
| ITWC | International Tsunami Warning Network<br>www.geophys.washington.edu/tsunami/general/warning/warning.htm |
| IRIS | Incorporated Research Institutions for Seismology<br>http://www.iris.edu |
| JGOFS | Joint Global Ocean Flux Study<br>http://usjgofs.whoi.edu/ |
| LEO-15 | Long-term Ecosystem Underwater Observatory |

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| | http://www.whoi.edu/science/AOPE/dept/OSL/LEO/ |
| MARGINS | http://www.ldeo.columbia.edu/margins/Home.html |
| MBARI | Monterey Bay Aquarium Research Institute<br>http://www.mbari.org |
| MOMAR | Monitoring the Mar, an InterRidge initiative<br>http://ofgs.ori.u-tokyo.ac.jp/~intridge/momar/ |
| MOSEAN | Multi-disciplinary Ocean Sensors for Environmental Analyses and Networks<br>http://www.ucsb.edu |
| NDSL | National Science Digital Library<br>http://nsdl.org/render.userLayoutRootNode.uP |
| NEON | National Ecological Observatory Network<br>http://www.nsf.gov/bio/neon/start.htm |
| NEPTUNE | www.neptune.washington.edu |
| NOPP | National Oceanographic Partnership Program<br>http://www.nopp.org/ |
| Ocean.US | National Office for Integrated and Sustained Ocean Observations<br>http://www.ocean.us/ |
| OCEANS | |
| ODP | Ocean Drilling Program<br>http://www.oceandrilling.org/ |
| OOI | Ocean Observatories Initiative<br>http://www.geo-prose.com/projects/ooi.html |
| OOPC | Ocean Observations Panel for Climate<br>http://ioc.unesco.org/oopc/ |
| O-SCOPE | Ocean-Systems for Chemical, Optical, and Physical Experiments<br>http://www.ucsb.edu |
| OSN | Ocean Seismic Network<br>http://www.joi-odp.org/OSN/OSN.html |
| PIRATA | Pilot Research Moored Array in the Tropical Atlantic |

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|---|---|
| | http://www.pmel.noaa.gov/pirata/ |
| Ridge2000 | http://ridge2000.bio.psu.edu/ |
| RIDGE | Ridge Inter-Disciplinary Global Experiments<br>http://www.nsf.gov/geo/egch/gc_ridge.html |
| SIEZE | SEIsmogenic Zone Experiment<br>http://www.ldeo.columbia.edu/margins/SeismZone.html |
| SIO | Scripps Institution of Oceanography<br>http://www.sio.ucsd.edu |
| SOLAS | Surface Ocean Lower Atmosphere Study<br>http://www.uea.ac.uk/env/solas/welcome.htm |
| TAO | Tropical Atmosphere Ocean Project<br>http://www.pmel.noaa.gov/tao/ |
| WHOI | Woods Hole Oceanographic Institution<br>http://www.whoi.edu |