The Future of

MBARI

Ocean

Observing

Systems

(MOOS)

Preface

"Oceans are critical--not just to our economy, not just to our food supply, not just to America's trade and security--but to the fabric of life itself." -Vice President Al Gore

No one can overstate the importance of understanding the oceans to maintaining the habitability of our planet. The oceans, which cover nearly three-quarters of the globe, circulate the heat and water that control our climate. Despite the successes of the most recent El Niño forecast, we still have insufficient information to predict annual to decadal and longer climate fluctuations. Nearly all active volcanoes and earthquake faults lie under the oceans, and our lack of knowledge of the latter in particular lead to poorly constrained hazard forecasts for coastal regions, where most of us choose to live. Life most likely started in the oceans, and our seas currently produce as yet unknown amounts of primary productivity through photosynthetic and chemosyntheic processes. The oceans help regulate the concentration of atmospheric carbon dioxide, an important greenhouse gas, and act to prevent its more rapid accumulation in the atmosphere through a variety of processes including sedimentation and dissolution. But even with fairly accurate records of the additional carbon dioxide released into the atmosphere by man's consumption of fossil fuels, our understanding of the magnitude of the CO_2 sinks is not accurate enough to make the equations balance.

All of these fundamental processes involve complex interplay of basic physical, chemical, biological, and geologic components in spatially vast and temporally varying systems. The traditional expeditionary mode of ocean exploration, the mainstay of ocean research in the past century, must be replaced with new research strategies that capture infrequent but significant events, provide a synoptic view on a regional basis, promote interdisciplinary studies, and lower the cost of acquiring the necessary information.

The purpose of this document is to lay out a rationale and plan for the Monterey Bay Aquarium Research Institution to undertake a major new development effort to build a prototype of such a system. There are a number of national initiatives currently being drafted or proposed to develop ocean observing systems, and it is certainly MBARI's intention to work closely with other research organizations, government agencies, and international partners to realize global ocean observations. Most of the current plans involve using existing technology and/or expanding current observing systems. What is lacking in many of the developing plans is a practical program for technology development that will set common standards for power and data management, allow seamless transport of instrumentation packages across a variety of platforms, permit great flexibility in the geographic location of instruments, and do this all at an affordable cost for both system acquisition and maintenance.

MBARI, because of its mission, its history, its funding structure, and the talent of its personnel, is ideally suited to take up this challenge. We present here the science requirements for ocean observing, tuned to the interests of our own staff, and a technological plan for supplying these needs. Throughout, the MBARI strategy is characterized by the principles of incremental development, portability, configurability, adaptability, compatibility, expandability, and leveraging so as to best meet the current and future needs of both internal and external research projects.

1. Executive Summary

MOOS workshop participants began by identifying a suite of compelling, and globally important, research topics that are integral to ongoing MBARI research and which will require a long-term observing system. Much of the discussion concerned episodic events that dominate processes in the ocean. Event dominated processes range from fluid flow through the crust to biogeochemical cycling of carbon at the air-sea interface. Observing systems that provide long-term data sets related to such episodic processes are an essential component of any project designed to sample this variability. They are required in order to develop predictive models of processes dominated by episodic events. These Science directions were divided into two major themes at the Workshop:

Theme A addressed "The Biology and Chemistry of the Oceans in Relation to the Solid Earth Cycle." The goal of this research is to develop quantitative, unifying principles that govern the formation and destruction of oceanic crust and its interactions with the hydrosphere and biosphere. The episodic or even catastrophic nature of seafloor events is obscured by limited periods of observation. A synoptic model of any of the major plate margin environments is precluded by the extraordinary temporal limitation of experiments that are dependent upon expeditionary science. Underlying linkages between the geophysical, geochemical, and microbiological processes are unconstrained by existing experimental designs. The scientific focus is thus placed upon multidisciplinary studies of subsurface fluid transport and venting, its control by tectonic or magmatic processes, and its control over the habitat and ecology of benthic communities. These issues would be addressed by studies of 1) the relationships between ground motion, mass wasting, and fluid flow in tectonically and/or volcanically active environments, 2) the modification of fluids by biological processes and the relationship between specific target populations and the local vent/seep environment, and 3) the quantification of major biogeochemical budgets such as greenhouse gases and hydrothermal effluent. The suggested implementation plans for these efforts include multidisciplinary sensor suites that monitor ground motion, fluid flow and chemistry, and microbial and macrofaunal analysis.

Theme B addressed "The Biology and Chemistry of the Oceans in Relation to Global Change." The overarching goal of such work is to understand the processes that control the structure of ecosystems in the upper ocean and the impact of ecosystem structure on biogeochemical processes. Scientific studies highlighted by participants in this group include: 1) an assessment of the role of the regional circulation in the redistribution of macro and micronutrients to the euphotic zone; 2) the identification of the impact of a variable nutrient supply on the community structure throughout the water column (including *in situ* bacterial processes); 3) distinguishing patterns in community structure and/or succession that derive from episodic events on time scales ranging from days to decades. The implementation plans for these scientific goals include the development of environmental, nutrient, and organismal sensors that can be deployed at multiple locations over a period of several years. Monterey Bay serves as an exceptional environment for the development of an observing system because of the wide range of environments and processes that may be found within the region.

As the MOOS plan is implemented, these Science themes will form a nexus between the scientific and engineering expertise of the MBARI staff. The requirements for long-term observations demand new tools and methods for oceanographic research. Both aforementioned Science themes share the need for a suite of oceanographic instruments on a variety of platforms. These instruments must be capable of characterizing environmental parameters that are subject to both long-term change and episodic events. The data sets generated by this system must be sufficient to test specific hypotheses concerning cause and effect relationships occurring within the ocean. Importantly, the observatories developed under this initiative should include highly mobile elements to enable their deployment in different regions of interest as the science demands. Finally, it was recognized that many of the components necessary for such a system are not yet generally available.

The technological response to the Science requirements takes the form of a MOOS system concept. The basic principles underlying this concept include incremental development, portability, configurability, adaptability, compatibility, expandability, and the leveraging of existing capabilities. The system concept consists of a cabled mooring supporting a network of intelligent instrumentation nodes extending from the surface, through the water column, to the seafloor. A riser cable provides power and communications to the instrumentation nodes; a satellite link provides bi-directional communications to shore. The system concept is based on the premise that the power and data throughput requirements of the system are relatively low: Solar arrays and batteries on the mooring can provide sufficient power; a Low-Earth-Orbit (LEO) satellite link can provide sufficient communications bandwidth.

An ancillary result of the Workshop was a consensus on the need for more *in-situ* instruments that can measure quantities such as iron, species composition, methane, biological activity, and seafloor geodesy. These instruments need to be more sensitive, more accurate, and lower power. They also need to be more reliable, more survivable, and less susceptible to bio-fouling and corrosion. In addition, there was overwhelming support for the development of an instrumentation infrastructure that defines a standardized plug-compatible interface to all instruments.

The MOOS Workshop recommendations include: 1) the identification of a suite of core development efforts essential to the success of MOOS; 2) the appointment of a group to perform the necessary MOOS system engineering; 3) the division of MOOS development into infrastructure and component projects; 4) the establishment of a parallel effort to support MOOS data management issues.

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2. Context

MBARI as an institution was founded in June of 1987, for the purpose of developing and exploiting new technology for scientific advances in oceanography. MBARI's founder, David Packard, initially identified remotely operated vehicles (ROVs), instrumentation for *in situ* chemical analysis, and computer/communications technology as areas particularly ripe for exploitation. In early 1988, the institute commissioned International Submarine Engineering (ISE) in Vancouver, B.C. to build the ROV *Ventana* with the stated purpose of demonstrating to the research community that unmanned submersibles are valuable research tools that can extend the scope and capabilties of manned ocean exploration. The success of *Ventana* led to the decision to build a next generation ROV, *Tiburon*, which could "go deeper and stay longer" and operate more quietly with higher precision than *Ventana*. The design, construction, and testing of *Tiburon* formed the centerpiece of MBARI's engineering effort beginning in 1991. *Tiburon* finally went operational for science in 1997, and at that point MBARI began to consider what would be its next major development project. *Tiburon* and *Ventana* were already demonstrating how ROVs could be used to explore, sample, and perform experiments in the deep sea. Work on creating new types of low-power, autonomous *in situ* sensors was progressing well, along with creative uses of computer technology to automate marine operations and data processing. It was time for a new challenge.

There were several very reasonable choices for the next major development project, each of which had precursory projects at MBARI that could ramp up into institutional efforts. The *Ventana 5000* project was looking into the feasibility of developing a next generation ROV with a 5-km depth range. But with *Tiburon* just coming on line, it seemed to make sense to get some more experience with that design (a 4-km depth vehicle) before undertaking yet another in-house ROV.

The *Otter* project, under the leadership of MBARI Adjunct Steve Rock from Stanford was developing tools for high-end functioning of autonomous underwater vehicles (AUVs). While a number of research laboratories were building a variety of AUVs with very different capabilities for specific missions, no one had yet demonstrated the use of AUVs for routine science operations in order to collect more information at lower cost. This seemed an ideal opportunity for MBARI. However, in order to perform truly unattended science missions with AUVs, it would be necessary to perfect the use of open ocean docking stations where a fleet of AUVs could transmit data back to shore, receive new instructions, and hopefully recharge batteries.

MBARI's Oasis Mooring project was demonstrating the value of two-way communications to unattended ocean moorings for collecting physical, chemical, and biological data from the upper water column to investigate biogeochemical processes on the time scales of hours to a decade. But to date it had still been necessary to use costly ship transects every few weeks to fill in more dense spatial information between the stationary moorings. Furthermore, integration of new sensors into the moorings always ended up being a time-consuming process on account of the lack of standard protocols for powering and communicating with instruments, which also negatively impacted our ability to collaborate with outside research groups interested in operating instruments on MBARI moorings.

MBARI had also made some initial attempts at installing ocean bottom observatories during the MOISE experiment in 1997. MOISE demonstrated the capability to install, service, and recover benthic instruments using ROVs, but it was not yet possible to maintain two-way communication between the sea floor observatory and the lab in order to monitor health of the instruments and download data.

Thus began to evolve the marriage of these various systems, the AUVs the moorings, and the benthic observatory, into MOOS, the MBARI Ocean Observing System. Cartoons of the various components of MOOS had been circulating around the institute for some time, and had even been published in the institution's *Retrospective*. On the national and international scene, a large number of planning efforts were underway to make networks of unattended ocean observatories a reality, but with confusion at the highest levels of how to fund the development and operation of such an ambitious effort, little progress was being made. This seemed like an ideal opportunity for MBARI to take a leadership role in tackling some of the difficult technological problems, while others sorted out the financial and political issues in global ocean observatories.

In order to begin developing an institutional plan for MOOS, MBARI held a workshop on February 22-24, 1999 at the Monterey Bay Aquarium. The effort was led by Dan Davis, and included Francisco Chavez, Bob Herlien, Ken Johnson, Gene Massion, Mike Matthews, Jeff Paduan (Naval Postgraduate School), Chris Scholin, and Debra Stakes on the steering committee. Approximately 45 MBARI staff members and adjuncts attended the 3-day workshop. The results of this planning effort are available in two forms: the full workshop proceedings, and this summary of the science justification and technological approach that resulted from the presentations and deliberations.

3. Scientific Directions

Clearly there is no rationale for a major MBARI effort into an integrated ocean observing system unless the MBARI scientists and adjuncts can identify a number of first-order research questions that they feel are only or best addressed using ocean observatories.

A. The Biology and Chemistry of the Oceans in Relation to the Solid Earth Cycle

Although the principal processes of the solid Earth cycle are recognized, the specific mechanisms by which fluid, energy, and mass are exchanged within active plate margins are relatively unconstrained. Thus, one of the most compelling research goals is the development of quantitative, unifying principles that govern the formation and destruction of the crust and mantle lithosphere, and its interactions with the hydrosphere and biosphere. Efforts to characterize these fundamental processes are precluded by:

a) limited periods of observation and data collection dictated by expeditionary schedules, especially those of submersibles;

b) no viable technical method to systematically build synoptic models of specific tectonic, biologic or hydrologic environments on the seafloor;

c) experimental designs constrained to “one-sensor observations” that may overlook fundamental linkages between contemporaneous processes;

d) Sampling schemes that miss episodic Earth processes; and

e) the inability to provide continuous scientific and technical oversight of experiments not connected to the laboratory by a two-way communication system.

Additional scientific requirements for future studies of the solid Earth cycle and its linkages to Chemistry and Biology are summarized in two recent reports:

FUMAGES (Future of Marine Geology and Geophysics)
http://www.joss.ucar.edu/joss_psg/project/oce_workshop/fumages/, and

FOCUS (Future of Ocean Chemistry in the US)
http://www.joss.ucar.edu/joss_psg/project/oce_workshop/focus/.

Scientists at MBARI encompass many of the disciplinary interests identified by the aforementioned national reports. We see an opportunity to focus on multidisciplinary studies of subsurface fluid transport and venting, its control by tectonic or magmatic processes, and its control over the habitat and ecology of benthic communities. Experiments and observations in the Monterey Bay area will serve as model for the development of new technologies required to address these issues. This, in turn, will enhance our capability to conduct other investigations outside of the Monterey Bay. In this regard, examples of research initiatives that require a MOOS infrastructure are given below. This list is not exhaustive, but it does reflect important research themes identified during the Workshop.

A.1 What are the relationships between ground motion, mass wasting, and fluid flow in tectonically and/or volcanically active environments?

Scientific Context

Geochemical and physical modifications of the seafloor are controlled by the movement of fluids, whether it be water in fault zones, magma erupting on a mid-ocean ridge or island arc, hydrothermal circulation in ocean crust and sediments, or methane deposits on continental margins. These fluids localize sites of geologic activity and modulate geochemical cycling between the solid Earth and the hydrosphere and atmosphere. A major research theme identified by the FOCUS report for the next decade is the identification and quantification of the advective chemical transport through the ocean ridge system (ridges and flanks), ocean margin sediments, and coastal aquifers. Fluid flow through these environments has greater importance than historically appreciated, and may strongly influence many oceanic chemical cycles. Greater understanding of the magnitude and variability of these advective transports will improve the budgeting of chemicals in the oceans and provide explanations for many regional processes affected by the flow, such as mineral formation and nutrient inputs.

Research Objectives

- Determine the periodicity of fluid venting and chemistry in a mid-ocean ridge and ridge flank environment, and look for contemporaneous physical phenomenon and their underlying drivers (e.g., tidal variability and its relation to fluid flow; seismicity and temperature as a monitor of fracture penetration; seismicity and thermal inflation as a monitor of magmatic intrusions).
- Identify the role of fluids in mass wasting events on islands and continental margins, especially their correlation with large Earthquakes and/or tsunamis.
- Estimate the variability of the composition, metamorphism, and structure of oceanic crust formed at ridges with different spreading rates based on proportion of volcanism, tectonism and hydrothermal discharge.

Project Implementation

- Deploy seafloor instrument packages to monitor ground motion in a variety of target areas. Candidate sensors include geophones, hydrophones, tiltmeters, pressure gauges, and flow meters. Most of these instruments already exist in a form suitable for marine installations, but some will require repackaging to be compatible with MOOS architecture. Ideally, the researchers who build these instruments would be motivated enough by the promise of MOOS to perform this repackaging, but in some cases MBARI may have to take on this task. Target areas to include mid-ocean ridges, ridge flanks with active venting, and continental margins. The wide variety of target areas requires that an ocean observing system be portable and adaptable.
- Develop water samplers and chemical sensors for a variety of target vent and seep environments. Samplers should include small-volume continuous samplers (e.g., osmosamplers) and large-volume discrete autonomous samplers to supplement samples collected by an ROV in expeditionary mode. New methods of measuring flow rates and sampling diffusive flow sites must be developed. Sensors for *in situ* chemistry should include Fe, Mn, pH, O_2, H_2S, salinity or chlorinity, and methane. Sensors should have response characteristics that permit them to be deployed in high-to-low temperature vents as fixed experiments or as part of an AUV instrument package.

A.2 How do microbial processes modify fluid chemistry within the oceanic crust? How is the microbial population modified by local fluid flow? How can we use the chemistry and distribution of seeps/vents and their resident fauna to map the subsurface structure/hydrology/biology of the oceanic crust?

Scientific Context

The precise physicochemical limits for life and the absolute boundaries of the biosphere remain undefined. Earth's microbiota have been discovered in settings that chemically and physically challenge the very fabric of life. Submarine ecosystems harbor some of the most unusual and extreme examples of life on Earth. How these systems adapt to and modify their environments have implications for the origin of life itself. Studies of the interaction of microorganisms with their environment, and models of their biogeochemical activities in natural settings require new methods, systems, and tools to identify, quantify, and directly monitor the activities of naturally occurring microbial species.

The compositions of fluids are diagnostic of the environments through which the fluids have passed. The metabolic processes of the microbial population in the subsurface hydrosphere may also profoundly modify the passing fluids. The distribution of seeps and vents must somehow be related to the subsurface distribution of aquifers, faults, and other permeable zones. Vents and seeps are thus "windows" into the subsurface, tracking the changing chemistry and movements of the underlying rocks, sediments, and, potentially, the biosphere.

Vent community structure may reflect population dynamics, larval distribution, or direct control by changing fluid chemistry. Chemosynthesis by free-living or symbiotic chemoautotrophic bacteria is the principal source of primary productivity in these systems, which are fueled by thermogenic (hydrothermal) or biogenic methane, sulfide, and other reduced compounds. Diverse groups of megafaunal species rely nutritionally on microbial production, and often have specialized morphological and/or physiological adaptations to persist in these environments.

Research Objectives

- Develop a predictive model of seep and vent community structure and function that integrates microbial and macrofauna populations and their interdependence on the physicochemical environmental conditions.
- Develop monitoring systems that capture coupled geological and biological events associated with active venting as well as episodic or catastrophic events such as turbidity flows or volcanic eruptions.

Develop the capability for adaptive sampling to allow the modification of sampling regimes as circumstances dictate.

Project Implementation

- Develop new methods and instruments to characterize *in situ* naturally occurring microbes in order to determine the dominant species, their distribution, abundance, and variability; this will require robust sampling, incubation, and archival techniques. Develop protocols to determine the major microbial activities and elucidate their interdependence on dominant biogeochemical cycles.
- Identify and quantify the population demography of key species in target vent/seep areas at all trophic levels. Determine the relative control by larval distribution, fluid chemistry, and nutrient availability.
- Required measurements include temperature, flow rates, fluid chemistry (sulfide, methane, iron), fluid particulate loads, and application of genetic probes to assess microbial abundance and community structure. Time-lapse video and image recognition could be employed to monitor community development and succession. These observations could be correlated with water-column chemistry via AUV transects.

A.3 *What are the most important biogeochemical seafloor processes that modify the chemical and thermal budget of the ocean? What is the volume and role of greenhouse gasses produced and/or sequestered by geological processes? How do we measure and recognize this in the geological record?*

Scientific Context

The exchange of heat and ions between the solid Earth and the oceans affects the chemical composition of the oceans. Although the mechanisms for convective transport are known (e.g., intrusion of basaltic magma, lithospheric cooling, compression, and groundwater head), the details of this transport and the extent of exchange resulting from these mechanisms is unclear. These processes can be elucidated in part by deploying ocean observing systems in representative environments such as mid-ocean ridges and flanks. However, such fixed observatories may not adequately address the cumulative impact of seafloor processes on the chemical composition of the ocean. Early estimates suggested that the entire ocean is processed through mid-ocean ridge hydrothermal systems every ten thousand years. This estimate failed to take into consideration the sizeable quantity of heat loss through diffusive and flank fluid flow. It also did not consider the potential impact of sub-seafloor microbial processes that might modify the fluid chemistry.

Continental margins influence biogeochemical cycles to a much greater extent than their area might imply, while being especially susceptible to anthropogenic influence. Processes that occur disproportionately in margin environments, such as organic matter burial, mineral formation, and denitrification, affect the oceanic balances of many elements. Unraveling the highly variable complex of chemical, physical, geological, and biological linkages in margins will provide needed context for human colonization of the coastline.

Methane is produced in marine sediments by the microbial degradation of organic matter. The total pool of biogenic methane stored at shallow depths in marine sediments, either as gas hydrate or as dissolved in the pore waters, is very large. The interstitial methane reservoir from both biogenic and inorganic thermogenic sources may play a major role in continental margin sediment failures. There may also be sufficient exchange with the oceanic and atmospheric carbon pool to affect global chemical balances, perhaps to the extent of regulating the Earth's climate. Since this interstitial methane is also the "food and feces" of the deep-biosphere, it can be used to map the extent and significance of microbial processes occurring in the subsurface.

Although discrete seafloor sites can be mapped and sampled with an ROV or other seafloor instruments, it is difficult to sample such sites at a spatial and temporal resolution adequate to determine the total impact of seafloor seepage of fluids and gases on the water column. However, regular AUV surveys within a 40-km box using onboard geochemical sensors (e.g., methane, ethane, oxygen, carbon dioxide, particulates, and major elements) would provide unique constraints on the problem, especially when coupled with data on the integrated benthic flow. Moreover, the sampling topology of an AUV can be changed as the surveying proceeds.

Research Objectives

- Map the cumulative effect of mid-ocean ridge venting on the overlying water column for a ridge segment or plate margin. Determine the relative impact of focussed high-temperature discharge versus moderate temperature diffusive discharge.
- Quantify the exchange of greenhouse gases between sediments in a tectonically active area and the overlying water column.
- Determine the importance of hydrothermal and/or methane plumes in the distribution of microbial and larval species within the target area being monitored.

Project Implementation

- Deploy a network of moorings to circumscribe venting areas and use instrumented AUV's to monitor processes in the water column in conjunction with seafloor instrumentation.
- Sensors should include Fe, Mn, transmissiometer, methane, carbon dioxide, temperature, and sampling devices for collection of microbes and their nucleic acid; all of these devices must have response times matched to dispersal rates.

B. The Biology and Chemistry of the Oceans in Relation to Global Change

The case for ocean observing systems as major elements in biological and chemical oceanographical research is compelling. Most, if not all, of the national planning efforts and on-going research programs refer to the need to monitor and observe the ocean on multiple spatial and temporal scales. The NSF Disciplinary Reviews on Biological and Chemical Oceanography discuss this in great detail. The National Ocean Research Leadership Council has also discussed the need for long-term observations to establish linkages between the environment and ecosystems in their report, Toward a US Plan for an Integrated, Sustained Ocean Observing System. Similarly, the U.S. Carbon Cycle Science Plan, prepared at the request of the agencies of the U.S. Global Change Research Program, strongly endorses the need for sustained observations. Current research programs such as JGOFS (Joint Global Ocean Flux Study), GLOBEC (GLOBal ocean ECosystem dynamics) and ECOHAB (Ecology and Oceanography of Harmful Algal Blooms) all rely heavily on time-series observations and spatial monitoring programs. Not only do these programs require ocean observing systems to accomplish their scientific objectives, they also highlight the need to develop and refine relevant measurement and sampling technologies. These reports can be found at:

OEUVRE (Ocean Ecology: Understanding and Vision for Research)
http://www.joss.ucar.edu/joss_psg/project/oce_workshop/oeuvre/report

FOCUS (Future of Ocean Chemistry in the US)
http://www.joss.ucar.edu/joss_psg/project/oce_workshop/focus/report.html

An Integrated Ocean Observation Plan
http://core.cast.msstate.edu/NOPPobsplan.html

The Harmful Algae Page: Links to Additional Pertinent Information
http://www.redtide.whoi.edu/hab/links.html

Monterey Bay represents a natural laboratory where it is possible to address locally important science issues in the context of the global-scale programs noted above. Process-oriented understanding must be developed through long-term observations coupled with periods of intensive sampling and model testing. An understanding of coastal ecosystem variability exemplifies this scenario. Fundamental ecosystem processes such as primary production, larval recruitment, and population dynamics are influenced by a multitude of chemical and physical processes. Characterization of local mesoscale conditions contributes to a better understanding of both regional-scale El Niño events and global change. Examples of these types of multidisciplinary initiatives are given below. The questions listed below are not exhaustive but rather representative of issues discussed at the workshop. Pursuing these research objectives requires a new generation of ocean observing systems, and the technology developed for such systems is directly applicable to other large-scale programs within the United States and abroad.

B.1 What are the processes that regulate the supply of major and minor plant nutrients to the euphotic zone?

Scientific Context

One of the fundamental requirements in oceanography is to document and understand the source and magnitude of nutrient supply to the euphotic zone. This requirement is equally important in the subtropical gyres, high latitudes, and coastal environments. In eastern boundary regions, many processes, ranging from large-scale gyre circulation to fluxes across the sediment-water interface, influence nutrient supply. More recently, the role of humans as agents of nutrient supply has been demonstrated. Interestingly, major (nitrate, phosphate, silicate) and minor (trace metals) nutrient supply may or may not be coupled. The relative importance of these processes in the subtropical gyres, the high latitudes, and the coastal environments may be quite different. Therefore, in order to test hypotheses in a variety of settings, an ocean observing system designed for such investigations should be portable.

Research Objectives

- Estimate the magnitude of micro and macro nutrient supply in near-shore waters (0-25 km) and determine the important processes (coastal upwelling, tidal mixing, runoff, benthic flux, and resuspension of sediments,) that drive the nutrient supply.
- Compare the nutrient supply by near-shore processes to that occurring in offshore waters driven by a different set of processes (e.g., upwelling driven by the curl of the wind stress, upwelling associated with the meandering California Current, and aeolian deposition).

Project Implementation

- Establish time-series in near-shore and offshore environments where continuous measurements of macro and micro nutrients are made in concert with measurements of temperature, salinity, and currents.
- Use AUV's to survey between time-series stations to provide spatial context.
- Develop a suite of new sensors for major (nitrate, silicate and phosphate) and minor (iron, zinc, cobalt, copper) nutrients.
- Collaboration with other institutions that emphasize physical oceanography and modeling will be sought to complement MBARI's in-house expertise.

B.2 How do physical processes (circulation, mixing, and runoff) and nutrient supply affect community production and structure and, conversely, how do community production and structure affect the residence time of nutrients in the mixed layer and their transfer to depth?

Scientific Context

Life in the ocean responds to changes in the chemical and physical environment. Although these responses begin at the species level, understanding the response of each species to different chemical and physical regimes is unrealistic. Instead, we must define and track important functional groups. For some organisms, like phytoplankton, we have a preliminary understanding of what constitutes these groups. For others, like bacteria and mid-water animals, we still need to catalogue the extant species and their role in the ecosystem. For decades we have known of successional cycles in phytoplankton, yet we still do not understand what drives them. Understanding what determines a dominant phytoplankton species or a functional group is a fundamental goal for biological oceanography, a goal that is particularly important for predicting the onset of harmful algal blooms.

Scientific Objectives

- Document and understand and how physical and chemical processes regulate phytoplankton community structure on episodic, seasonal, and interannual time scales.
- Identify the important functional groups of bacteria as well as pelagic and benthic animals.

Project Implementation

- Collect high-frequency multi-year time series of the abundance and growth rates of the important functional groups of phytoplankton using optical and molecular biological techniques, together with measurements of the chemical and physical environment.
- Collect spatial information of the abundance and growth rates of the important functional groups of phytoplankton along gradients in chemical and physical properties.
- Use water samples and video, collected using ships and ROV's to determine the important functional groups of bacteria and pelagic and benthic animals.
- Develop new instruments for identification of phytoplankton species and functional groups, and for phytoplankton functional group rate processes using optical sensors and molecular probes.
- Make these instrument systems robust and bio-fouling resistant.

B.3 How is energy transported from the coastal circulation and sunlight to the remainder of the ecosystem? In particular what roles do bacterial remineralization, dissolved material, zooplankton and subduction play in supplying organic material to mid-water and benthic animals and the sediments?

Scientific Context

The concept of a one-dimensional vertical biological pump to explain movements of carbon and other elements from the ocean's surface to mid-water communities and the benthos is invoked frequently. However, along continental margins the flux of particles, and dissolved organic material, is subject to horizontal physical displacements as well as biological modifications and injections of resuspended materials. In addition to the physical disturbances we know little about the remineralization of organic matter below the euphotic zone by bacteria and the relative importance of vertical motions of zooplankton, whose food sources derive from the euphotic zone, in transferring material to depth.

Research Objectives

- Determine the source of the organic matter reaching mid-water and benthic communities and how the quantity and quality changes over time.
- Determine the trophic linkages and the routes and rates of nutrient energy flux through the communities that occupy the full depth range of the oceanic water column.

Project Implementation

- To meet the objectives, an ocean observing system must link observations from the surface to the benthos. This requires deploying sensors and sample collectors that measure surface production and the amount and composition of organic material reaching mid-water and benthic communities.
- Deploy systems to characterize the deep-ocean physical environment.
- Collect data on and samples of mesopelagic, bathypelagic, and benthic communities.

C. Seafloor and Water-Column Observatories: Unifying Themes

There are surprising similarities in the technological approaches proposed for addressing the scientific questions outlined under Themes A and B. The science missions considered here all share a need for the deployment of a suite of instruments on a variety of platforms (AUV's, benthic observatories, moorings, etc.) in a variety of enviroments (shallow, deep, near shore, midocean). These sensor packages are needed to quantify gross environmental parameters subject to long-term change, to respond to and characterize episodic events of interest (adaptive sampling), and to test specific hypotheses concerning cause and effect relationships. Although it is intuitively clear that processes occurring in the upper and mid-water environments are linked to processes occurring on the seafloor, and *vise versa*, the extent and nature of such linkages are not well characterized. Identifying and quantifying the extent of such relationships can be accomplished only by integrating water-column and seafloor observations to the greatest extent possible. Therefore, upper water column and benthic observatories should be collocated – this is a principle that Workshop participants agreed should form a cornerstone of the MOOS initiative. Two-way communications between the instruments and the science user is needed to alter sample collection, to process protocols in real-time, and to check that all systems are functioning properly.

Many of the science missions will not take place in the proximity of a cable that can provide a direct power and data link to shore; therefore, the developed observatories must include autonomous power and communications elements to enable their deployment in different regions of interest as the science demands. Ideally, the observing system should be configured so that power and communications can be supplied either from a cable or from the autonomous elements for maximum flexibility and lowest maintenance costs at each deployment site.

Some of the sensors required for the envisioned science missions exist now, however, they could be developed further to improve their data output, reliability and deployment duration (e.g., reduction of biofouling on optical sensors, improve seismometer data storage, networking of sensors, etc.). In other cases the required sensors either do not exist or they exist only in prototype form (e.g., chemical sensors, sensors that perform timed and continuous fluid capture with DNA preservation, sensors that automate phytoplankton species identification, a field mass spectrometer, a short baseline tilt meter, etc.). Thus, concerted research and development effort is required now to realize new sensors that will facilitate the envisioned long-term research initiatives. Lastly, procedures must be implemented that reduce costs associated with data collection, quality control, archival, and display. These protocols need to be developed in parallel with the development of MOOS.

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4. Technological Response to Science Requirements

Our *MOOS system concept* is the technological response to the fundamental Science requirements for an ocean observing system which were discussed in the previous section. We begin by describing the basic principles underlying the system concept. We then describe the system concept itself without providing specific implementation details. We end with a supporting discussion of instrumentation development at MBARI.

A. Principles Underlying the MOOS Concept

In order to deliver an observing system with the desired capabilities, a multi-disciplinary system engineering effort will be required. The underlying principles for MOOS, which will drive the system design and specific system components, include *incremental development, portability, configurability, adaptability, compatibility, expandability, and leveraging.* The system engineering effort will develop a system specification that defines the system performance and incorporates these design principles. Since we expect MOOS to be developed across a series of individual projects, a MOOS system engineering group will ensure that the system specification continues to reflect user needs and that the individual components are developed in accordance with the overall system specification. We discuss the design principles in the following.

Incremental Development

The system will be developed incrementally over a period of five to ten years. By incremental development we mean that the basic core system infrastructure should be developed and deployed before the system is expanded; additional subsystems should be integrated and tested sequentially so as to insure system compatibility and robust operation. In this regard, scientists should identify a set of mission scenarios and a suite of core instruments that define the most scientifically productive and cost effective core system. Thereafter, they should identify progressively the mission scenarios and capabilities that they desire for succeeding versions of the system. The process for doing this must consider what is technically feasible in the early stages of development. Finally, prudence suggests that high-risk system components should be developed early on to provide a proof of concept; this effort should be carefully scoped to avoid unnecessary features and costs.

Portability

There is a specific Science requirement for system portability. By portability we mean that the entire system, or modular components thereof, can be configured and deployed for a specific scientific mission at a specific site using only modest resources. Portability will allow us to deploy multiple systems at arbitrary sites both inside Monterey Bay and farther afield. In addition to amortizing the development costs of universal system components, portability will result in the efficient use of resources through the repeated re-use of the same system. Finally, if feasible, a portable system should support a direct connection to a shore-based submarine cable.

Configurability

There is a Science requirement for the system to be configurable. Configurability can be as simple as reconfiguring the system to serve a different scientific purpose for a limited period of time; it can be as complex as the deployment of a separate subset of the system at a remote site. The challenge is to identify early on the system components that should be designed to be configurable for multiple uses.

Adaptability

Adaptability is configurability in real time. In addition to a background monitoring capability, there is a Science requirement that the system be capable of detecting and responding to episodic events. The spatial and temporal measurement resolution of the system is defined by an array of instrumentation nodes. Real-time bi-directional communications with the instrumentation nodes realizes the principle of adaptability by providing the capability of monitoring the system in real-time and dynamically altering the spatial and temporal resolution in response to episodic events.

Compatibility

System compatibility means standard interfaces. The *interface problem* refers to the situation whereby each instrument must be individually interfaced to a particular platform; each interface has unique hardware and software; each instrument has a unique configuration. The corresponding *quality control problem* refers to the problem of managing the configuration information and the measurement data from numerous individual instruments. In this context, system compatibility implies an *instrumentation infrastructure* that defines a standardized plug-compatible interface to all instruments. Such an infrastructure could take the form of an implementation-independent interface within a distributed-object network architecture. In such architecture, the instrument would appear as a standardized instrument object containing complete state and behavior information. The availability of such information on the network for each instrument would contribute considerably to a practical solution to the quality control problem.

Expandability

A system that will be developed incrementally over an extended period of time should be designed with *expandability* in mind. Expandability means considering how the future capabilities of the system can be achieved within the context of the current system design and implementation. Expandability also means including the potential for unplanned capabilities.

Leveraging Existing Capabilities

MBARI has extensive engineering and operational capabilities in the form of existing ROV's. These capabilities should be *leveraged* to facilitate the development of the ocean observing system. One possibility includes using ROV's to deploy, maintain, and retrieve a benthic network. Other possibilities include using ROV's to deploy instruments, to replace or recharge batteries, or to complement the data gathering capabilities of the observing system. In addition, MBARI-developed instrumentation hardware and software, including those advanced capabilities developed for the ROV's, should also be leveraged to facilitate the development of the observing system. Finally, MBARI possesses the technological capability and experience necessary to develop and manage a complex system infrastructure over an extended period of time. That such development capability is unique within the oceanographic community provides MBARI with an opportunity to make significant contributions to the community.

B. The MOOS System Concept

The primary Science requirement for an ocean observing system is for greater spatial and temporal measurement resolution to support a variety of scientific studies and experiments, both on the seafloor and in the water column. There is also a clear requirement for the development of a system that could be deployed in locations beyond Monterey Bay. In some cases, the primary need is for instrumentation compatibility between an MBARI system and other observing systems.

The Workshop organizers and participants recognize that the primary focus of the discussions has been on the field component of the observing system and not the shore-based component. In light of the conclusions of the Workshop, we recognize that a comparable effort needs to be made in addressing the important and challenging issues surrounding the shore-based component. Properly speaking, the system includes the shore-based component; however, for the purposes of this report, we will focus primarily on the field-based component of the system.

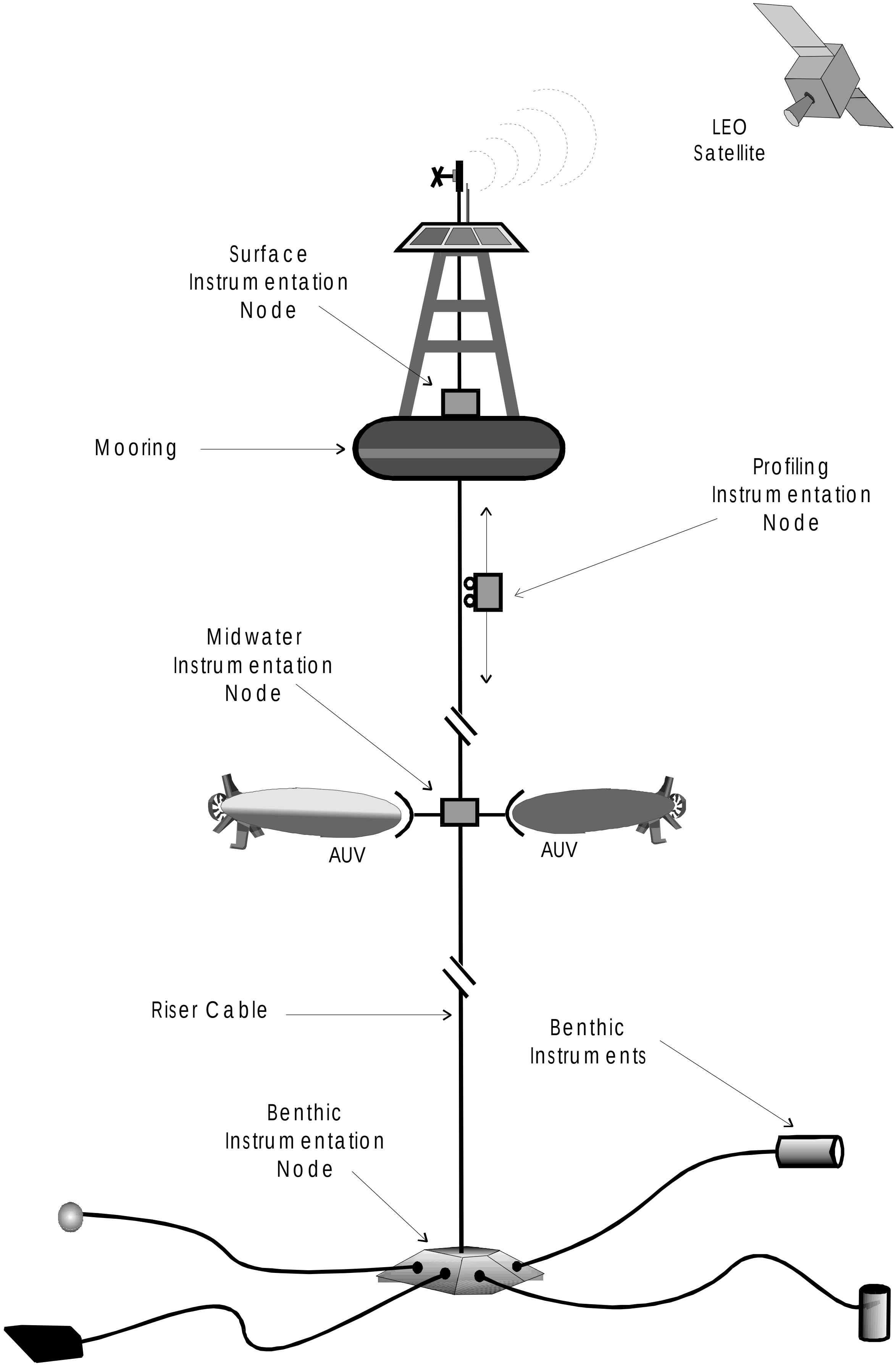
To achieve the desired spatial and temporal measurement resolution, there was consensus that some form of AUV capability is required. The exact nature of this capability will be defined by the specific Science requirements. Most of the discussion revolved around the type of system infrastructure required to provide power and communications to a suite of instruments including AUV's.

The system concept depicted in Figure 1 consists of a mooring with a network of intelligent instrumentation nodes extending from the surface, through the water column, to the seafloor: A riser cable provides power and communications to the instrumentation nodes; a satellite link provides bi-directional communications to shore; AUV's dock at instrumentation nodes; a vertically mobile instrumentation node profiles the upper water column. The fundamental premise underlying the system concept is that the power requirements and the data rates of the system are relatively low: Solar arrays and batteries on the mooring can provide sufficient power; a satellite link can provide sufficient communications bandwidth. This premise is based on the observation that the oceanographic processes that we wish to observe are fundamentally information limited: Increasing the sampling resolution beyond a certain upper bound provides no additional information about the process. Although the maintenance of a mooring-based system is substantial, and although the available power and communications bandwidth is limited, the close adherence of the system concept to the aforementioned underlying principles, especially those of incremental development and portability, makes it the preferable concept.

By intelligent instrumentation node we mean a physical node that would acquire and preprocess data from a suite of instruments, implement the underlying network communications protocol, manage power distribution, and support remote system configuration. By preprocessing we mean qualifying the instruments as operating within specification, detecting and eliminating non-Gaussian measurement phenomenon, filtering the measurement data to reduce noise, and compressing the data to reduce the required communications bandwidth. The node would be defined by a set of mechanical, electrical, and software interface standards and protocols, which would allow a wide variety of instruments to be connected to system. The necessary interface standards include cable types, connector types and pin-outs, electrical signal levels, as well as communications and distributed-object network protocols.

System electrical power on the order of 10 Watts would be provided by a combination of solar cells and storage batteries similar to the existing *Oasis* moorings. Such a power system is adequate for the needs of low-power instruments. High-power components such as AUV's would require auxiliary power sources such as fuel cells or conventional generators.

Low-Earth-Orbit (LEO) satellite system would provide bi-directional data communications to shore with data rates on the order of 100kBps. Several such systems are currently being deployed and should be operational in time for the initial deployment of MOOS. Data transmission costs would remain low due to the affordability demands of the Personal Communication Service (PCS) market. Bi-directional communications would enable remote system testing and configuration. In the absence of a satellite link, communications to near-shore system components could also be provided by radio links.



MOOS System Concept

Figure 1

As an example of what a network might look like, we envision the following system. The housing at the surface expression of the mooring includes a commercial Ethernet hub that provides network connections to instrumentation nodes at the surface and distributed along the mooring riser cable. A vertically mobile node periodically profiles the upper water column. A dedicated port connects to a second hub at the bottom of the mooring. This hub feeds an instrumentation node that provides a number of Nautilus connectors with a standard pin-out for power and network connections. An instrumentation node would use the MBARI-developed *SideARM* processor to acquire and preprocess measurement data and make it available to the network in the form of a (CORBA) distributed instrument object using the TCP/IP network protocol. A commercial terminal server provides RS232/422 connections to the nodes for legacy instruments without Ethernet ports. Ideally, this approach would be adopted by, or would at least be compatible with, other observing system such as the Neptune project, creating instrument interface compatibility between systems.

C. Instrumentation Development at MBARI

Although not intended to be a major theme of the Workshop, considerable discussion revolved around the issue of instrumentation development at MBARI. The conclusions of these discussions, which have become an important result of the Workshop, are described in this section.

We define a *sensor* to be a device that produces an analog signal that represents the physical state of a medium; we define an *instrument* to be a system that combines one or more sensors with sundry processing elements to convert the analog signals into standardized digital measurement data. Figure 2 shows a block diagram of a prototypical instrument.

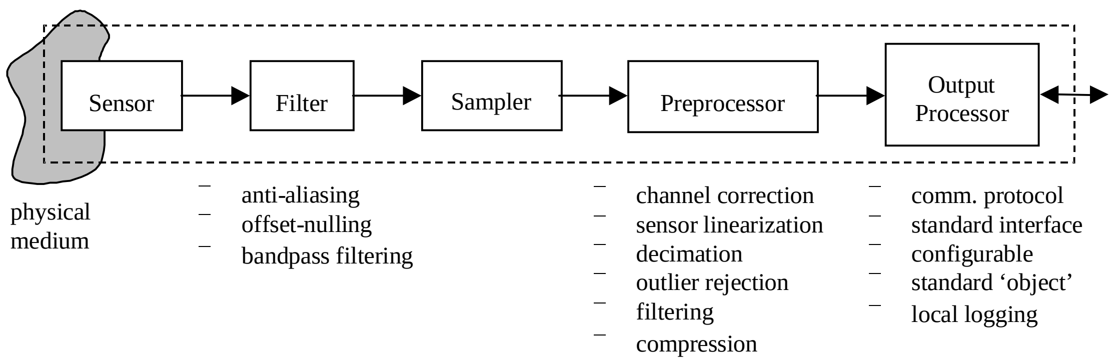


Figure 2: Prototypical Instrument

There is a general need for more *in-situ* instruments that can measure currently unobservable quantities such as methane, microbial activity, and seafloor geodesy. These instruments need to be more sensitive, more accurate, and lower power. They also need to be more reliable, more survivable, and less susceptible to bio-fouling and corrosion.

The development of a highly sensitive oceanographic sensor usually requires the specialized expertise of a research scientist. As Figure 2 illustrates, however, developing a new instrument implies developing both new sensors and intelligent ways of processing the sensor signal within the instrument itself. Finally, when viewed as a system, an instrument needs to be properly engineered for accuracy, reliability, and compatibility.

Many needed sensors exist only in prototype form and have yet to emerge from the research laboratory as viable components in a suite of robust and reliable instruments that can be deployed long term in a ocean observing system. To counter this situation, MBARI enjoys the position of having both active instrument development comparable to leading academic institutions and developmental funding comparable to commercial manufacturers. Instrument development at MBARI should serve the Institute's mission of understanding the ocean. To the extent that such understanding is gained from long-term observing systems, MBARI should pursue selected instrument development with the goal of producing in a timely manner a product that could be successfully deployed long term on an observing system. Instrument development at MBARI should continue to take place within individual core research projects; all development efforts must respond to clear set of science requirements, undergo validation and calibration tests, and be ultimately demonstrated at MBARI by addressing important research questions.

Although instrument development should remain a core activity of the Institute, MBARI is also in a position to pursue the grander vision of dealing more effectively with the interface and quality control problems. MBARI currently deploys a variety of instruments on a number of different platforms. Each instrument is individually interfaced to a particular platform, and each interface requires unique hardware and software. We refer to this situation as the *interface problem*. Corresponding to the proliferation of such individually interfaced instruments is the problem of instrument and data quality control. Each instrument has unique configuration information, including operating modes, calibration data, and modeling parameters, which creates a context for the corresponding measurement data. Such configuration information is used to preprocess the measurement data before it is suitable for analysis or archiving. We refer to the problem of managing both the configuration information and the measurement data from numerous individual instruments as the *quality control problem*.

In recognition of the of the growing complexity and seriousness of the both the interface problem and the quality control problem, there is overwhelming support for the development of an instrumentation infrastructure, which defines a standardized plug-compatible interface to all instruments as illustrated in Figure 3. In addition to standardized hardware, the communication interface to the instrument takes the form of an implementation-independent (CORBA) interface within a distributed-object network architecture. In such architecture, the instrument appears as a standardized instrument object containing complete state and behavior information, which includes measurement data and configuration information. Network clients with interest in the measurement data have a standardized access to this information. The availability of such state and behavior information for each instrument contributes greatly to a practical solution to the quality control problem.

The aforementioned instrumentation infrastructure offers a modern and potentially revolutionary way of solving two historical nemeses: the interface problem and the quality control problem. We consider it to be part of the ‘grand vision’ in the sense that it strives to solve two difficult infrastructure problems in an intelligent manner with the potential of considerable resource savings. Because of its funding situation and cohesive staff, MBARI is in the unique position of being able to build an infrastructure that could set the standard for the entire instrumentation community.

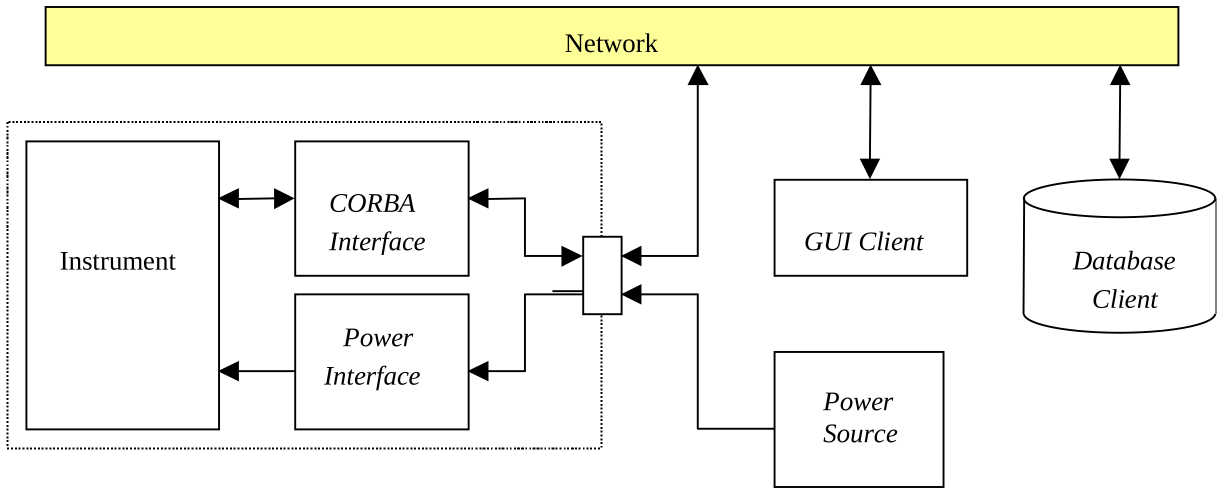


Figure 3: Standard Instrument Interface

5. Recommendations

The scientific and engineering presentations, and subsequent discussions, at the MOOS Workshop led to surprising commonality in the vision for a MBARI Ocean Observing System. A system concept for MOOS, which implements this vision, has been described in some detail in the preceding sections. It was clear from the Workshop discussions that as part of the system engineering efforts required to bring MOOS to fruition, key elements of the system would require early development in order to assess and mitigate risk. In particular, Workshop participants identified several core elements of the MOOS implementation that would require rapid development or proof of concept. We present these core elements as a suite of recommendations that should be considered by MBARI Management during the implementation of MOOS:

1) A suite of core technical developments will be essential for the implementation of MOOS. These include the following:

   a. Integration of scientific observations from the surface to the benthos. A feasibility study for a moored riser that carries data and power between the seafloor and the surface should be an early consideration.

   b. Optimization of the remote observing system through near real-time interaction with the facility by the science and engineering staff. Strategies for two-way communication should be an early consideration.

   c. Development of capabilities to provide three-dimensional data. AUV's may provide spatial resolution in the water column. On the seafloor, an array of instruments separated in space and connected to the mooring riser will be required. Methodologies for connecting a benthic array to a mooring riser would be required. A cable-following vertical profiling system would be required.

   d. Expansion of the available suite of sensors for geophysical, biological, and chemical properties. The development of a new generation of sensors will be essential to bring the MOOS concept to fruition.

   e. Modularity and portability of the system for deployment in a variety of environments and with other observing systems, e.g., the Neptune cabled system. Compelling observatory based science extends far beyond the confines of Monterey Bay, and the MOOS system configuration may depend strongly on the area in which it is deployed.

2) The implementation of MOOS will require a broadly based effort within MBARI. A MOOS system engineering group should be constituted to define the details of an implementation and operational strategy. This group must ensure that the needs of the scientific end-users of the project are closely integrated with the system design. They must also ensure that any system strategy undertaken by MBARI will have a viable user base from the beginning, either internally or through external partnerships.

3) An effort should be made to divide the MOOS system development into infrastructure and component projects.

4) A complete realization of the MOOS system concept will likely involve both high-risk projects and long-term, incremental development. Project proposals that exploit MOOS technology, most likely involving efforts in Monterey Bay, will help ensure continued system development by providing short-term payoffs.

5) Shore-based efforts in support of the operational observatory will be critical elements. In particular, data management is likely to involve prolonged operational costs that may outweigh the initial capital investment. A parallel effort to support observatory data management, validation, and visualization will be needed with the goal of reducing the associated costs and improving the quality of the product.